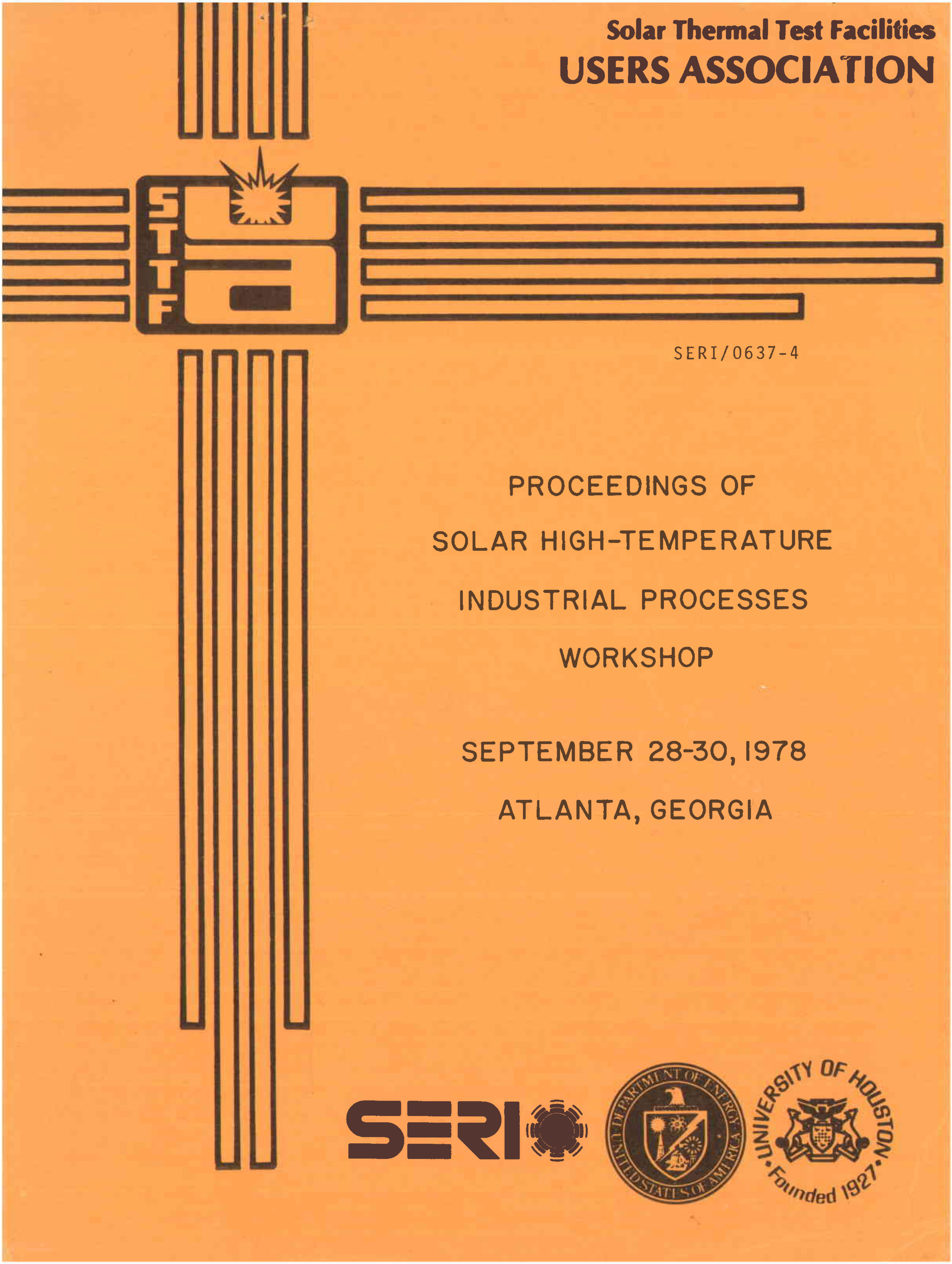
Solar Thermal Test Facilities
USERS ASSOCIATION



SERI/0637-4

PROCEEDINGS OF SOLAR HIGH-TEMPERATURE INDUSTRIAL PROCESSES WORKSHOP

SEPTEMBER 28-30, 1978
ATLANTA, GEORGIA

SERI

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by

Solar Thermal Test Facilities
Users Association

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SUMMARY

F. B. Smith
STTF Users Association

The purpose of the workshop was to bring together people from industry, government and government contractors to discuss the use of solar central receiver technology for high-temperature (500°F or higher) industrial processes, and to consider experiments that might be run on the high-temperature solar facilities.

To date, most solar central receiver work has been directed toward solar electric power generation (e.g., the Barstow 10-MW_e Plant planned for 1980), but this work indicates that additional significant fuel savings might also result from direct use of high-temperature solar thermal energy for industrial fuels and chemicals processes. Industrial processes use about one-third of the nation's total energy, and perhaps one-half or more of that amount is at temperatures higher than 500°F--generally beyond the range of trough collectors but well suited to central receiver collectors.

Many commercial processes which might otherwise use solar operate 24-hours-per-day and require closely controlled heat input, but some (e.g., drying or dehydrating processes) can operate in a batch mode with less demanding temperature controls. Also, the very high radiant temperatures available from central solar facilities open up possibilities for development of entirely new fuel and chemical processes which may operate successfully during solar daylight hours.

Another point of interest is that projected cost effectiveness of solar high-temperature energy depends heavily on future cost of mass-produced heliostats, which in turn depends upon annual heliostat production levels. Consequently, any additional heliostat production stemming from industrial process application will advance the date when solar energy becomes competitive for electrical power generation as well as industrial processing.

These matters were discussed during the workshop by approximately 100 people from the institutions shown on Figure 1. During the first part of the workshop, government, government contractor, and Users Association speakers reviewed solar central receiver status and plans (Sections I-VI). Present status is indicated by the Barstow plant to be built in 1979, which will collect about 50 MW of thermal solar energy to produce 1450 psi, 950°F steam and generate 10 MW of electricity. Higher performance systems using molten salts, liquid metals or high-temperature gas are also being developed and tested.

H. M. Webb, of Aerospace, gave a broad view of solar possibilities for the 500-2500°F range (Section VIII). Various possibilities for transmission of solar generated high-temperature energy from the solar collector field to remote users at distances up to several hundred kilometers were then discussed by several speakers in Section IX, Chemical Conversion and Transmission of Solar Energy Section. These discussions included SO_2-SO_3-O_2 systems, NH_3-N_2-H_2 systems, the West German EVA-ADAM methane-water process, and chemical heat pipes.

About 18 papers on solar possibilities for chemical fuels and process heat were included in Sections X and XI. These covered subjects ranging from ammonia, borax, carbon monoxide, gypsum, and hydrogen through metal ore reduction, secondary oil recovery and heat treatment.

Luncheon speakers were Martin Gutstein, Department of Energy, who spoke on DOE's Solar Thermal Fuels and Chemical Program, and Clifford Selvage, US Representative to the International Energy Agency, who spoke on Solar Central Technology in Europe.

Costs and economic factors were discussed by many speakers, especially in Sections VIII and XII. Although early demonstration plants are not expected to compete with fossil fuels in the near term, many projections show competitiveness in the long term--especially if DOE's heliostat cost targets can be met.

Since this was the first meeting of its kind and since the number of subjects varied over a wide range, this workshop should be viewed only as a first step which provided a brief introduction to some, but not all, of the solar central receiver possibilities for high-temperature industrial processes.

SECTION I - INTRODUCTORY COMMENTS

WELCOME

J. D. Walton, Jr.
Georgia Institute of Technology

It's a real privilege to welcome this group to Atlanta and to Georgia Tech. Ever since we began to get involved in the high-temperature conversion of solar energy into some sort of useful form of energy, or useful products, and began thinking about having a fairly large-scale facility here at Georgia Tech to do that kind of work, I have been looking forward to having this group here so they could see what we are doing.

I will speak a a little later about our facility and what you will see there. It's a very interesting topic to me personally, and I hope that, as a result of this workshop, we will come up with some interesting projects that the Association will be interested in participating in through their activities.

STTFUA CHAIRMAN WELCOMING ADDRESS

A. F. Hildebrandt
University of Houston

I would like to add my welcome to that of Jessie Walton and Frank Smith. I will briefly cover the history, purpose and status of the STTF Users Association.

Some of you may be thinking, "The others I know, but who is the Users Association?" A year or two before initiation of construction of the Sandia Solar Thermal Test Facility, many of us were concerned that if the Government was going to spend 20 million dollars to construct such a unique solar facility (it is now the largest, highest powered, but not the highest temperature, facility in the world), how could we assure that it would be made available to experimenters in universities, other industries, or even individuals, in addition to the major then-ERDA contractors working specifically on central solar electric R&D. After the usual study, negotiations, committee meetings, etc., the answer to that question was to organize a users association with these purposes:

- -- Point of contact for STTF users
- -- Review proposals, recommend funding priorities to Government
- -- Provide funding, with Government approval
- -- Disseminate information

DOE Washington Headquarters and Sandia are largely responsible for the large central receiver and heliostat developments that are supporting the design and construction of the Barstow facility, but the Users Association (with some oversimplification) is responsible for "everything else," which is outlined in the following role statement:

- To act as the point of contact for users of the STTFs and as primary access link between users and STTFs.
- To solicit and review proposals and make recommendations to SERI/DOE regarding utilization of the STTFs.
- To disseminate STTF information on a regular basis.
- To provide funding for STTF users, subject to SERI/DOE program approval.

In general, the Users Association's responsibility is to explore, encourage, and where appropriate, to provide financial support for other potential users of the facility provided, of course, their proposed experiments are believed to be sound and of potential benefit. We not only encourage and support the type of uses to be discussed during the next two and a half days, we also, where appropriate, support more basic research investigations involving the use of the high-temperature solar facilities. The Users Association is a non-profit corporation, incorporated in the State of Texas, funded to a small extent by members' dues, but largely by the Department of Energy via a SERI contract to the University of Houston. I am president of the Association, and Frank Smith is the Executive Director. The offices are located in Albuquerque at 1507 First National Bank Bldg. East., 5301 Central Avenue NE, Albuquerque, NM 87108.

Our primary purpose, and therefore the "bottom line" purpose of this workshop from the Users Association's point of view, is to develop a better definition of the kinds of industrial processes where central receiver solar technology might be applicable, and from that to define experiments which might be run on one or other of the Solar Thermal Test Facilities.

In addition to the Sandia Solar Thermal Facility and the Georgia Tech Facility, we also have cooperative and reciprocal agreements with the U. S. Army White Sands Solar Facility at White Sands, New Mexico, and the French CNRS Solar Furnace in Odeillo, France. Richard Hays of White Sands will describe the White Sands facility in more detail. Claude Royere of Odeillo was unable to attend because of pressing schedule problems. The capabilities of the four facilities cooperating are included in the hand-out material given when you registered, in case you wish to consider some use of one of the facilities.

The status of the STTF Users Association is as follows:

Number of associates - 97

Number of industrial associates - 11

Proposals/experiments: 14 received, of which 3 have been funded, 6 have been recommended for funding, 4 were not recommended for funding, 1 was withdrawn

Total amount currently funded: $37,693

Total outstanding recommended for funding: $106,992

I would like to take this opportunity to recognize the extensive voluntary support from the various committees and from the Executive Committee. Members of the Executive Committee who are here are Terry Cole, Fred Manasse, Tom Springer, John Russell and Jessie Walton. Bob San Martin has resigned from the Executive Committee and is on his way to Washington, D.C. to assume the position of head of the Distributed Powers Systems in the Solar Technology Division of the Department of Energy. We wish him well in developing that program. John Gintz, Chairman of the Proposal Review Committee, is accorded special thanks for doing an outstanding job.

Thank you.

SERI PLANS FOR THE STTFUA

Dr. K. J. Touryan
Solar Energy Research Institute

SERI has been given management responsibility for the Solar Thermal Test Facilities Users Association. My purpose for attending this meeting is to see first-hand how we at SERI can encourage industry and the universities to use these test facilities effectively. To this end, I will first outline the SERI overall plans and objectives, and then offer recommendations of how one could maximize the use of the Solar Thermal Test Facilities.

Following the 1973 oil embargo, during the ensuing US energy crisis, ERDA decided to establish a Solar Energy Research Institute (SERI) to provide major national focus and coordination for solar energy research efforts.

The ERDA studies recommended that instead of being established as a Federal laboratory, SERI should be operated by a private entity under contract with the Federal Government. Accordingly, in March 1976, an RFP was issued by ERDA calling for a management plan, a management team, and an initial site with an option for future site. In July 1976, ERDA received 20 proposals offering sites in 16 states. In March 1977, after evaluation, ERDA awarded Midwest Research Institute the contract to establish and operate SERI in Golden, Colorado.

SERI was formally opened on July 5, 1977, and in October 1977, ERDA's function was assumed by the newly created Department of Energy. Since that time probably the most significant event in this chronology was the Sun Day visit of President Carter on May 5, 1978, which exercised the option on the permanent SERI site located on top of what is locally known as South Table Mountain.

Figure 1 shows the current organization of SERI. In a rapidly growing and changing organization like SERI, such charts need to be updated periodically. However, the major divisions of the SERI organization that would impact STTFUA are Research, Analysis and Assessment, and Technology Commercialization. Another division of interest still on the drawing board, is a Program Management Division. There exists a chronological sequence of events that takes place as ideas and concepts flow through the process from Research to Analysis and Assessment and to Technology Commercialization. The remaining three divisions shown on Figure 1 perform basic support functions to facilitate the flow from research to commercialization.

At present, program management for the STTFUA at SERI is conducted by staff* in the Research Division with help from the Special Programs

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*Dr. Charles Bishop in SERI's Systems Analysis Branch is the STTFUA Program Manager.

Office. My own acquaintance with the solar test facilities has been limited to the Sandia 5-MW STTF, through my involvement there as Manager of the Sandia Fluid and Thermal Sciences Department. During the past month as a member of the SERI research staff, I have been introduced to the STTF Users Association and their efforts to utilize, effectively, the various solar thermal test facilities in the US and in France. It is clear to me that this task is an important one and demands careful attention from the SERI technical staff.

I would like to take this opportunity to offer some observations and recommendations of how one could maximize the use of the solar thermal test facilities. My recommendations are based on the results of past STTFUA workshops and numerous discussions with individuals at SERI and at Sandia Laboratories-Albuquerque, who know about the capabilities of these facilities and have a keen interest in their use. First, let me offer the following observations:

1. Workshops, similar to the present one, are useful in introducing the capabilities of the STTF to the solar community and can generate ideas for using these test facilities. However, they seem to be falling short of their intended objectives of providing effective and widespread use of these facilities. The process of education and idea generation is a slow one.

2. Large-scale tests cannot be conducted unless they are preceded by bench-type experiments. Asking a group to plan tests for the 5-MW Solar Tower without preceding it with smaller-scale experiments is the same as asking aerospace engineers to use the NASA-Ames 20-ft wind tunnel without giving them a chance to screen their tests in smaller, cheaper wind tunnels. Not many groups (universities or industries) have Omnium-G level facilities to develop concepts that could graduate to the bigger STTFs.

3. A corollary to the above is that good ideas for experiments and tests are generated in the laboratory or in the field during the very process of performing tests and experiments. They are not easily conceived on paper or in an office, away from the bench and the actual hardware.

Let me give you then, the following recommendations for your consideration:

1. Some degree of proliferation of small-scale solar thermal test facilities such as Omnium-G's should be allowed on various university campuses. The universities can be selected on the basis of regional considerations and/or ongoing solar research activities (on a competitive basis).

2. With the small-scale solar test facilities on campus, proposals can be generated for experimental research and submitted either

to the STTFUA or the SERI/DOE University Research Committee* for possible support. The results of these experiments could eventually be fed into the STTFs as full-blown tests.

3. The STTFUA funds can be used not only to support independent "track 2" experiments, but could be used to support mission oriented "extended track 1" tests, after the specified objectives of track 1 tests have been completed. For example, using STTF funds, the EPRI supported Brayton Cycle tests on the 5-MW Solar Tower could be further instrumented and evaluated for life-cycle or other information by university groups, after the EPRI dictated mission has been accomplished and before the test has been disassembled. These type of tests, of course, will require very carefully planned logistics and coordination. Whether they can be done in practice remains to be seen.

4. The STTFUA workshops and information dissemination should continue in order to solicit industry and university participation in the STTFs, and as a forum to present experimental results.

With these observations and recommendations I will let the workshop take its course, and hope new ideas will be generated that could lead to the effective utilization of these large-scale solar thermal test facilities.

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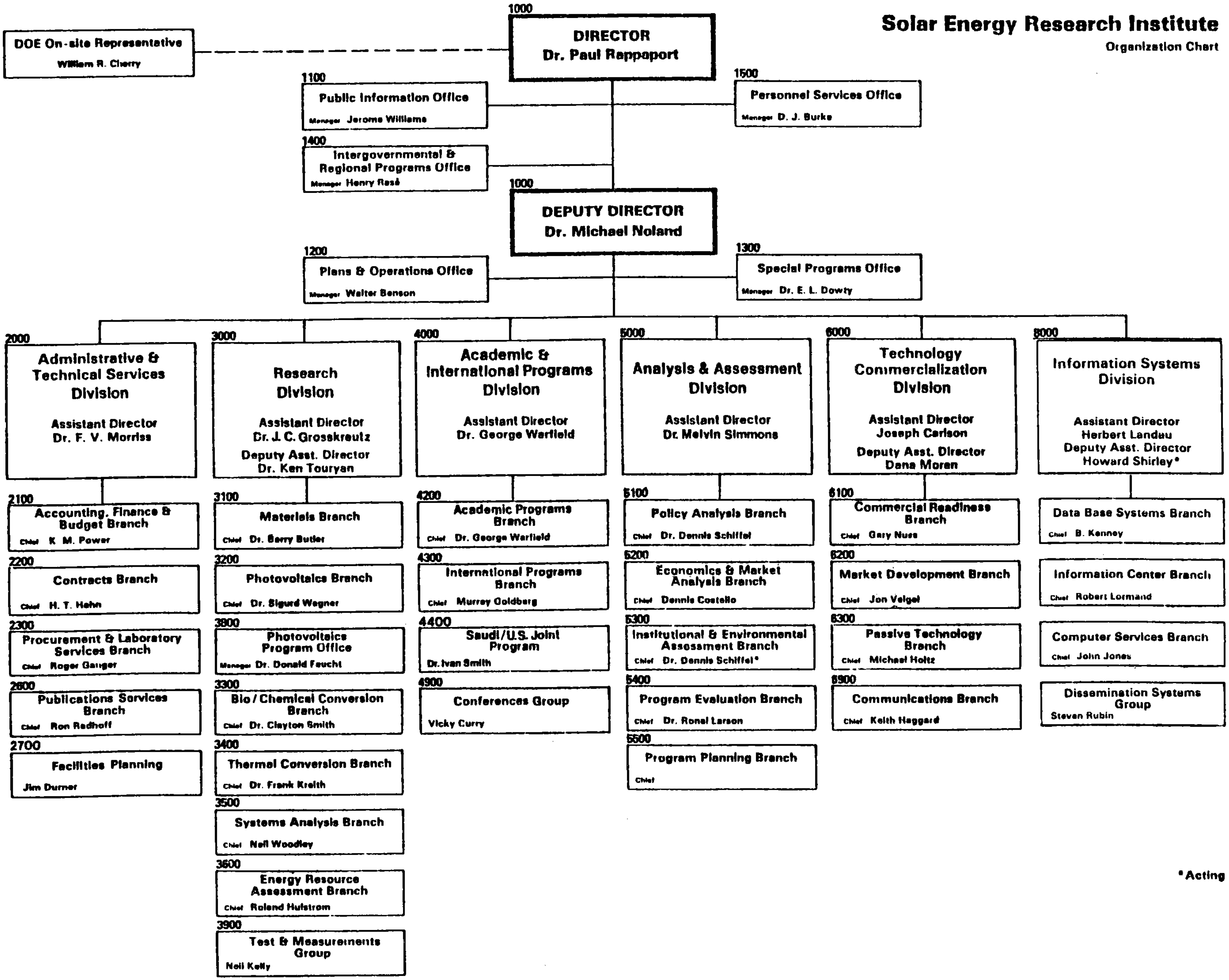
*As of today, the SERI University Research funds are still under negotiation.

Figure 1


Solar Energy Research Institute
Organization Chart
1000
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1100
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1400
Intergovernmental & Regional Programs Office
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DOE PLANS AND PROGRAMS

G. W. Braun
Department of Energy

Today I will briefly give you an update on the Solar Thermal Power Program and talk in general terms about industrial applications of solar thermal technology. The Solar Thermal Program has been and is now very heavily oriented toward electric applications. However, I think all of us realize that there is a broader range of applications for the high-temperature capability of solar concentrating collectors, and I think this workshop is a very valuable means of exploring some of the applications that deal with the direct use of heat.

With reference to Figure 1, I'll just touch on where we stand. In FY 78 we placed three test facilities in operation. In the past year we have been working to get them operating in a disciplined manner. I wouldn't say we are there yet. As a matter of fact, we had one significant incident last week at the Albuquerque STTF, with damage to the elevating module. Although it will not result in a delay in all of the testing, it appears it will result in a substantial delay in the testing of the McDonnell Douglas receiver. As you know, this test program is in direct support of the Barstow central receiver pilot project. On the other hand, we are proceeding with testing of the gas-cooled receiver EPRI developed with Boeing. That will go forward near the schedule anticipated before this incident.

Relative to the 10-MW central receiver project, we have selected contractors for the two major pieces of this project. McDonnell Douglas was selected as the design integrator, dealing with all of the nonconcentrator parts of the system. McDonnell Douglas and Martin Marietta were selected to go through a competitive prototype phase on the heliostats which will lead to bids in the fall of 1979 for roughly 2000 heliostats.

Preliminary design on the Shenandoah large-scale total energy experiments has been completed and we are near that point on the Fort Hood total energy project. Based on these efforts, we will be able to evaluate whether to proceed on these projects based on significantly better design definition and cost information.

Figure 2 shows anticipated FY 79 accomplishments. Relative to the Barstow project, perhaps the most significant event is not the groundbreaking--you can break ground for a project and that has very little programmatic impact--but receiving the bids on the heliostat field. That will be a real bellweather for the economics of central receiver technology in general.

We will have the second irrigation experiment complete through construction and into initial operation. Again, perhaps the most significant event relative to trough technology that goes along with an irrigation experiment, will be placing the Willard 25-hp irrigation experiment in energy production operation. We've gone through a year of design modification and getting preliminary operating experience. The time has now come to prove that the system is an energy producer.

As I mentioned on the Shenandoah, Ft. Hood and one other total energy experiment for which the Thermal Program has responsibility, we will, based on reviews of the preliminary design, be able to decide whether to go into construction and finish the projects and take them into operation.

Another major event in the coming year will be the selection of a site and a selection from among three conceptual designs of a 1-MW electric power plant intended for small community applications.

In Figure 3 I will give you an update in terms of the budget. As you're aware, I think, the budget for the solar thermal power program is on a plateau between FY 78 and '79, with the level of funding in the large power area, which is really the central receiver technology development area, increasing moderately from '78 to '79, and funding of distributed receiver development, under the small power label, remaining relatively constant. What we call advanced technology, which is really advanced development of nonconcentrator subsystems, shows some budget growth between '78 and '79. In '79, as you can imagine, there is very little in the way of new starts. I believe our numbers recently indicated that roughly 95 percent of the FY 79 budget will go to projects that are essentially a continuation of ongoing work. In each of the three program areas, large, small power and advanced technology, however, there will be at least one major start that provides some new activity and impetus for these programs.

Looking to FY80, I think it's fair to say that there is no one I know of who can state what the budget situation will be in FY 80. DOE is at the point of submitting a budget to OMB. However, at the same time, the results of the solar Domestic Policy Review, that is the results of the nationally conducted public meetings and the DOE response to the outcome of those meetings and the DOE response to the outcome of those meetings, is within less than a month of going to the President.

There are, as you would expect, differences between the sense of the Domestic Policy Review, and what that would indicate the FY 80 budget should be, and what has been developed internally. The case is open, as far as I know, as to what comes back. My guess would be that in the thermal power area we're looking to substantial budget growth in only one of the program areas, and that is the advanced technology program. The requirements to complete the Barstow project will take the dotted line up to a little more than 36 million dollars. Overall, the budget for the thermal power area may increase in the range of perhaps 20 percent. Of course, the effect of the Domestic Policy Review input could alter that, and no budget becomes real until OMB and the Congress have had their say.

I would like to spend a little time giving you my perspective relative to industrial applications of solar thermal technology, Figure 4. Looking at the industrial sector of the national energy market, that's about a quarter of the end-use energy that we use. If you take into account the primary energy that's used in generating electricity in support of that sector of the national market, it's more like one-third.

Within that sector, nearly 65 percent, I believe, of the energy goes to the production of heat, 40 percent to the production of steam. Steam, as you

There is another interesting aspect of this chart. The bars indicate energy requirements for all industries: food, textiles, paper, chemicals, and primary metals. The interesting aspect is that as you go toward the left, the temperature requirements for those sectors of the industrial market increase. I think there is a message in this chart that, perhaps, unlike the electric sector, i.e., the utility market for solar power systems, this particular market is extremely disaggregated, even more than the chart itself would indicate.

There is a bit of serendipity in the fact that the area of major industrial growth at this time and in the future stands to be in the southwestern Sunbelt states. Figure 5 indicates that roughly 25 percent of the industrial energy requirement of the country is there now, 15 percent in Texas and roughly 5 percent in California, and that represents a significant market.

The significance of Figure 6 is that the projected costs of central receiver systems are consistent with the goals that we've established for central receiver technology. We can foresee coming within a range of cost for solar heat that is the same range within which you see things like liquid natural gas, coal liquification, coal gasification, shale oil, and other fossil energy options. Accordingly, achieving the cost goal for these thermal concentrated collector technologies becomes a significant issue for the national energy program.

Figure 7 shows the program structure. As in the past, the structure is defined in terms of applications. But if you look closely at the thermal power program, it really is a program to develop concentrating collector technology. In that sense, we have basically four types of collectors under development, and each has its own inherent modularity and its own inherent temperature capabilities based on possible concentration ratios. We have the linear collections, the trough systems, that are capable of operation somewhat above 550°F in fairly small sizes per trough. Heliostats, being part of central receiver systems, take the role of producing much higher temperatures, and scale up to much larger sizes. The parabolic dish technology has the same high-temperature capability as the central receiver, but the individual modules are much smaller. We are also looking at and funding some development work related to stationary concentrating devices such as the fixed dish with the linear receiver.

Looking at trough technology, my sense of things is that that is best adapted to applications where efficiency related to thermodynamic considerations is not the issue, but where you simply need the heat at the temperatures that are within the trough's capability, or where you can apply the trough to systems that compensate for the thermodynamic limitations by using the heat that's rejected from an electric production process. The dish technology seems to lend itself well to small applications where the thermodynamic constraints require high temperatures. The central receivers for large-scale applications would seem to me to be the most versatile technology, being able to deliver bulk power as well as drive total energy and process heat systems and ultimately, hopefully, drive processes that produce fuels from renewable materials.

I just gave you a thumbnail sketch from my own perception. Looking to status of the industrial development of these concepts, you can see from Figure 8 that the rough industry is well out ahead in terms of the capability to supply collectors. There are businesses which are able to take an order for trough collectors and fill it. In fact, I would say the trough collector technology is somewhere between the second and third generation of design development. As far as trough systems are concerned, however, we're probably about two or three years behind the status of component development, particularly in terms of O&M characteristics of systems that are comprised of a large number of trough-type collectors. Our focus in the coming years will be on developing reliable system packages involving troughs.

The dish technology is kind of an ironic thing in that, no thanks to DOE, there is a system package available commercially. However, in terms of the capability of the industrial sector to respond to supplying system packages involving dishes and small engines, that capability really does not exist. There is no capability for supplying large numbers of these systems based on the number of companies and their capabilities at present. In the central receiver area, there is a very substantial effort underway among a number of companies developing heliostats. However, again, the system capability really rides on the 10-MW central receiver project, and that system capability will begin to emerge in 1981 with the initial operation of that system.

Figure 9 should give you a sense of some near-term activity in the DOE programs related to industrial applications. In the central receiver area, I think many of you are well aware that we have undertaken with SERI to thoroughly evaluate the potential for retrofitting power plants in good direct insolation areas with central receiver systems to save oil and gas. Also, in my judgment, the focus for central receivers for the near-term applications should be on the electric utility market. That is the most well-defined area. We have good utility interest and momentum with the utility industry to push this technology forward and into their hands. What we are now calling a program strategy analysis will give us, I think, a good definition of how to proceed with a demonstration program relative to repowering.

The fuels and chemicals area, as you well know, has been initiated in Marty Gutstein's purview. This is, in fact, one of the few things that we are able to start based on the FY 79 budget, but we think it's an extremely important initiative and I think you'll hear more about it later.

In terms of trough technology, we've been working hard back at Headquarters to achieve a degree of program coordination between the solar thermal power program, which is sort of the technology engineering development side of the DOE program, and the industrial process heat program, which is under a different assistant secretary. We want to better spend the dollars available to both programs by coming up with a program plan where we are doing the right things in energy technology to support the applications and objectives of the industrial process heat program. I believe the near-term focus will be on the trough applications where we see some very near-term opportunities to use technology which is emerging for applications requiring steam in the range of 300-600°F. We expect to have a joint program plan, which we may

may not publish, but which at least will keep us on track in terms of doing things that are complementary. We plan joint solicitations relative to trough technology, including those aimed at stimulating the development of low-cost manufacturing techniques and a look at the possibility of using trough technology for tertiary oil recovery, which is, I might add, a major potential application.

My recollection is that the oil reserves in this country can be enhanced a significant percentage by steam stimulation. The limitation on doing that at present is essentially environmental restrictions on burning the oil that you bring out of the ground in order to produce steam to put back in the ground to get more oil out. We're going to look very closely at that and, hopefully, get industry involved in design studies and work that would give us a better definition of the possibility of using solar technology to circumvent the environmental constraint.

In dish technology, we have the Shenandoah project moving along very smartly. Our focus in the total energy program for the future is based on studies that we've completed recently and will certainly be on the industrial sector. That appears to be the best place to learn about the total energy and cogeneration capabilities of solar thermal technology.

Figure 10 is a chart which I have borrowed from someone. This will simply give you the various technologies that are under development in the solar programs and can be looked at in two ways. These technologies can be looked at in terms of their potential or in terms of their limitations. If you look at them in terms of their limitations, you tend to dismiss them rather lightly. Particularly in the case of the thermal power area, if you look at it in the context of strictly near-term electric applications, you tend to be, perhaps, much less excited than if you look more broadly in terms of the ultimate potential markets. It really spans all sectors of the national energy market. Of course, in the electric area, thermal electric technology is in direct competition with photovoltaics. Hopefully, that's not all bad. The hope is that both programs are successful and provide technology spinoffs to one another in the process.

I would not, however, identify competition as the key issue for either of the programs. What I see in the future is an evolution of thermal concentrating collector technology toward applications of broader and broader impact, starting with those we've already identified, such as repowering, industrial total energy, and industrial process heat applications, and moving on as the temperature and storage capabilities that go with the concentrators emerge, to provide a very significant impact. However, we still have not fully dealt with those problems that have kept solar thermal technology from being commercially applied for a hundred years.

If you go back a hundred years, the technical and scientific feasibility of thermal conversion approach was demonstrated then. It was at our fingertips, but some very significant problems prevented it from being used economically. The greatest problem was simply producing equipment with a performance that could be reliably predicted and which could be supplied at affordable costs relative to available alternatives, which, in the past, of course, were fossil resources.

Dr. Blieden: Could you comment on the petroleum industry evaluation, just what that is?

Mr. Braun: You probably noted in one of the charts that we have had some proposals in the past to look at the use of solar-produced steam for heavy oil recovery. In response to some recent solicitations, we've gotten additional proposals and, in fact, additional unsolicited proposals. We have made contact with some elements of the oil industry in California, where this application would be primarily focused, to better understand the industry perspective. It's our intention, based on this reaction and the understanding that we've gotten, to try to probe further. We have the agreement of the people involved to take the information that we give them and conduct their own feasibility evaluation and share the results with us. We also plan to follow up on the interest that appears to exist, and formally solicit studies to define projects that would make sense.

FY78 Accomplishments

- **Three Test Facilities Operational for**
  - **Mid-Temperature Troughs and Dishes**
  - **Central Receiver Subsystems**
  - **Advanced Receiver Development**
- **Selection of Barstow Design Integrator and Heliostat Prototype Phase Contractors**
- **Complete Preliminary Designs for Ft. Hood and Shenandoah Large-Scale Total Energy Experiments**

Figure 1

FY 79 Projected Accomplishments

- **Barstow 10 MW Pilot Plant Groundbreaking**
- **Coolidge 200 HP Irrigation Experiment Initial Operation**
- **Complete Design/Initiate Construction of Three Large-Scale Total Energy Experiments**
  - **Shenandoah, Georgia**
  - **Blytheville, Arkansas**
  - **Ft. Hood, Texas**
- **Select Site and Design Concept for 1 MW Small Community System Experiment**

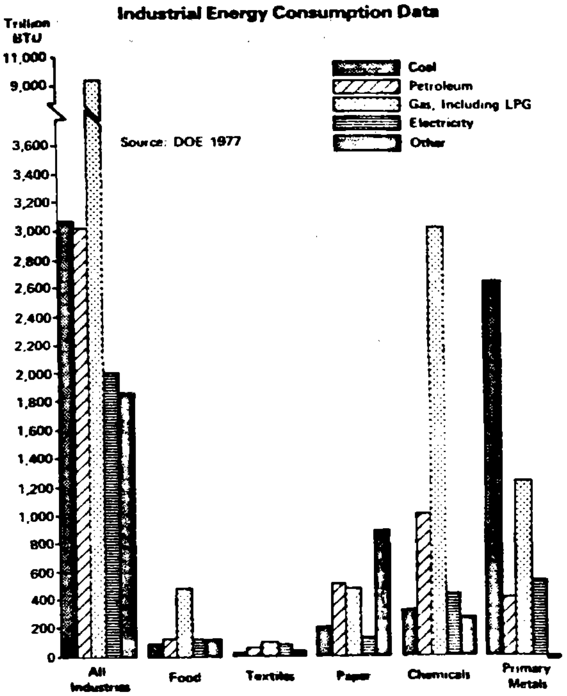
Figure 2

Budget Status

($ M)

	FY78	FY79
Large Power	21.8	27.0
Small Power	28.1	28.0
Advanced Technology	10.2	14.0
Barstow	41.0	28.0
Capital Equipment	3.0	3.0
Total	**104.1**	**100.0**

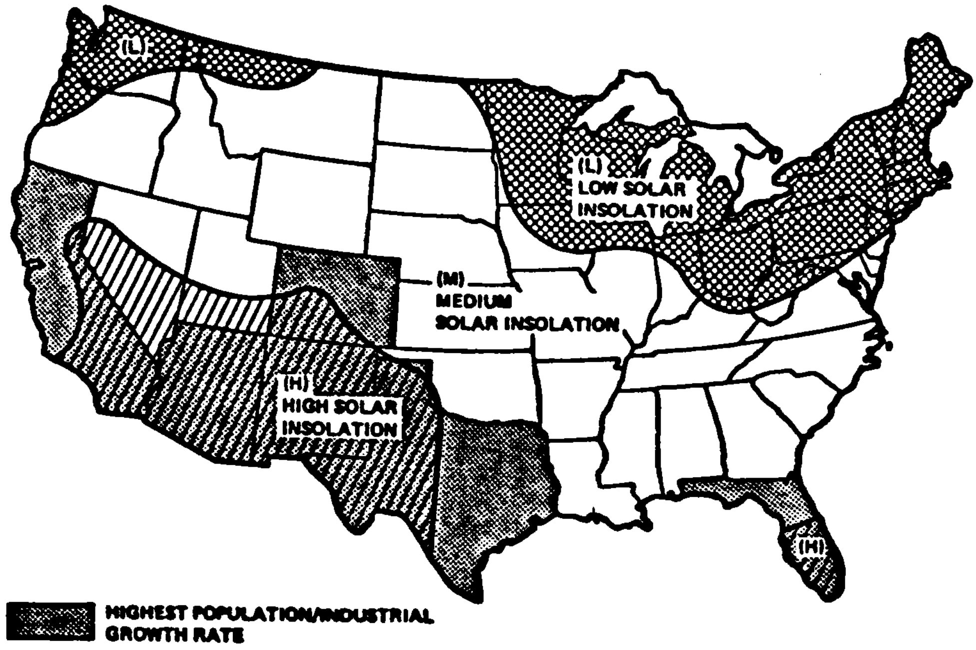
Figure 3



Industrial Energy Consumption Data

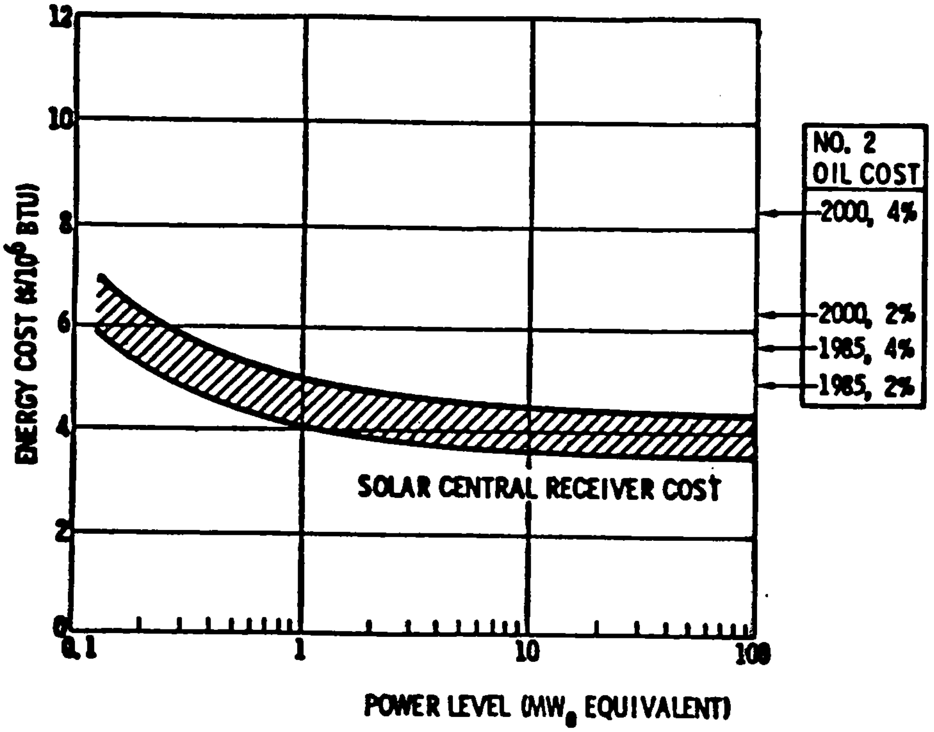
Source: DOE 1977

Figure 4



SOLAR INSOLATION RELATIVE TO POPULATION AND INDUSTRIAL GROWTH RATE

Figure 5



SOLAR CENTRAL RECEIVER SYSTEM ENERGY COST COMPARISON

Figure 6

Systems/Applications Matching

	Flat Plate	Trough	Bowl	Dish	Central Receiver
Process Heat	√	√			√
Total Energy		√	?	√	√
Small Electric/HP			?	√	
Bulk Power				?	√
Fuels					√

Figure 7

Program Elements

Large Power

Central Receiver Applications
- Greater than 10MW
- 1,000-1,500°F

Small Power

Distributed Receiver Applications
- Trough/Dish/Bowl
- 5 KW-10 MW
- 500-1,000°F

Advanced Thermal Technology

Advanced Materials and Components

Dish Stirling Power Module

High Temperature Receivers and Subsystems for Fuels and Chemicals Manufacture

Figure 8

Industry Status

	First System Experiment	Product Development (No. of Companies)
Troughs	1977	Greater than 10
Dishes	1980	Less than 5
Central Receiver	1981	10

Figure 9

Near-Term Activity Related to Industrial Applications

Central Receiver

- Repowering Venture Analysis
- Fuels and Chemicals Program

Troughs

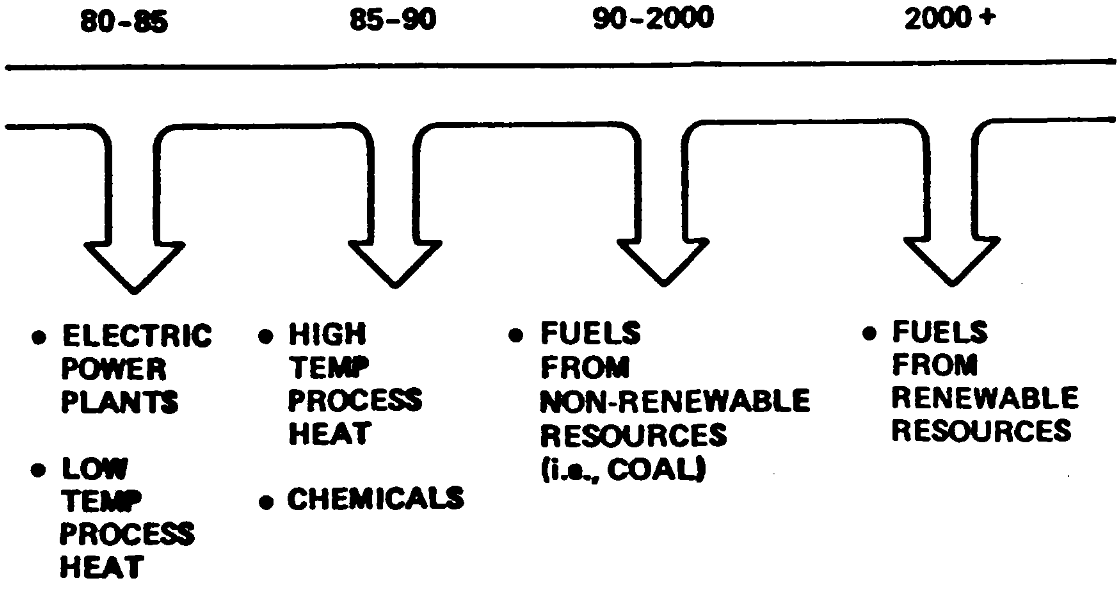
- ET/C&SA Program Coordination
  Program Planning
  Joint Solicitations
  Evaluation of Solar Steam Drive for Recovery of Heavy Oil

Dish

- Shenandoah Project
- Industrial Total Energy

Figure 10

THE POTENTIAL OF SOLAR THERMAL



80-85	85-90	90-2000	2000 +
• ELECTRIC POWER PLANTS • LOW TEMP PROCESS HEAT	• HIGH TEMP PROCESS HEAT • CHEMICALS	• FUELS FROM NON-RENEWABLE RESOURCES (i.e., COAL)	• FUELS FROM RENEWABLE RESOURCES

Figure 11

SECTION II - WORKSHOP PLANS AND OBJECTIVES

SOLAR HIGH-TEMPERATURE INDUSTRIAL PROCESSES WORKSHOP PLANS AND OBJECTIVES

F. B. Smith
STTF Users Association

INTRODUCTION

As many of you probably know, much attention is being given to use of solar energy for industrial process heat. Up to now, most of the interest has been in temperatures less than 500-600°F, since most of the solar collectors considered up to now have had top operating temperatures of about 500-600°F.

In my mind, two major considerations point to a need for consideration of solar applications at temperature ranges well above 500°F: (1) About one-half of the total energy used for industrial processes in this country is at temperatures greater than 500°F, and (2) central receiver solar thermal technology for delivering large quantities of thermal energy at these higher temperatures is being rapidly developed. For example, as you will learn shortly, R&D solar test facilities with stagnation temperatures up to 3600°F are in operation, and a 50-MW_t central solar electric power plant developing steam at 950°F and 1450 psi to generate 10-MW of electric energy will be built next year to begin supplying power to the California grid about 1981 or 1982.

I believe that we will learn from this workshop that:

- High-temperature industrial process energy needs are large.
- Solar technology to meet many of those needs is being rapidly developed.
- The major challenge will be cost reduction.
- There are grounds for optimism that solar energy costs will be reduced to competitive levels.

HIGH-TEMPERATURE INDUSTRIAL PROCESS HEAT NEEDS

Several high-temperature industrial process studies have been made within the past few years. Figure 1 shows the findings of two of those studies. Battelle estimated that from 10 to 17 Q's per year will be required over the next two decades and that about 65 percent of that energy use will be at temperatures greater than 350°F. Intertechnology Corporation's findings indicate that from about 17 to 37 Q's will be needed and that from 50-75 percent will be at temperatures greater than 500°F.

Figure 2 from Intertechnology's Report shows that if terminal temperatures only are considered, 75 percent of industrial process energy use will be at temperatures above 500°F. If one excludes the energy used for preheating from 60-212°F, the portion in excess of 500°F is still about 50 percent.

SOLAR HIGH-TEMPERATURE TECHNOLOGY

Approximate specifications for four high-temperature solar test facilities are shown in Figure 3. These are the four facilities cooperating with the Users Association. Central solar receiver technology is illustrated by Georgia Tech's Solar Advanced Components Test Facility shown in Figure 4. There are 550 one-meter diameter mirrors on the ground, each of which tracks the sun and focuses on the central receiver at the top of the central tower. This facility collects up to 400 kW of thermal energy at temperatures up to 2000-2500°F. Figure 5 shows Sandia's 5-MW Solar Thermal Test Facility in Albuquerque, a larger facility with 222 36m^2 heliostats which collect 5 MW of thermal energy. The Barstow, California 50-MW Thermal (10-MW electric) Facility to be built next year is shown in Figure 6. The first two--Sandia and Georgia Tech--are R&D facilities for technology development. The third is a pilot electric power plant. In addition, construction of other plants for repowering some existing oil-fired electrical power plants should begin within the next two or three years.

Thus far, most central solar R&D being supported by DOE, EPRI, and other institutions is aimed at using solar energy to generate electric power. But any central receiver solar plant that can deliver, for example, steam at 1500°F and 1500 psi for driving a turbine to generate electric power can obviously provide energy for other high-temperature industrial requirements, especially those where fossil fuel can be supplemented by solar, or those which do not require 24-hour-per-day continuous operation.

Much work is being done on improvement of heliostats and on thermal receivers for collecting, delivering, or storing energy in the form of hot gas, molten salts, liquid sodium, etc., as well as steam, at temperatures up to 2000-2500°F. Some of the processes which might utilize direct solar thermal energy in this way are:

- Aluminum Production
- Cement, Concrete Products
- Ceramics
- Copper
- Enhanced Oil Recovery
- Glass
- Gypsum
- Iron, Steel Manufacturing Processes
- Lime
- Metal Heat Treating
- Molybdenum
- Vinyl Chloride

OTHER SOLAR CENTRAL RECEIVER POSSIBILITIES

In addition to direct use of solar-generated steam, hot gas, sodium, or molten salts to supply on-site processes, there are also possibilities for chemical conversion, transmission and storage of solar thermal energy which can supply high-temperature Btu's to process plants at remote distances, up to possibly 100 miles or more. These are discussed in several papers in the

Chemical Conversion and Transmission session. There are still other possibilities of locating traditional-type industrial processes on top of towers for direct use of the high-temperature solar radiation reflected from heliostat fields. And finally, since stagnation temperatures of solar radiation are much higher than normally used in even the highest temperature industrial processes--up to 3000 or 4000°F--the possibilities for development of entirely new industrial process methods are opened up. Some of these possibilities are:

- Ammonia Production or Fertilizer
- Coal Gasification, Carbon Monoxide Production
- Direct Reduction of Metallic Ores
- Hydrogen
- Methanol
- Petroleum Products
- Phosphoric Acids
- Styrene
- Sulphuric Acid
- Terephthalic Acid

CHALLENGES

The two major challenges are: (1) Continued development of better technology, and (2) reduction of costs. Both of these subjects are discussed in the following papers. Regarding costs, I am convinced that DOE's intensive cost-reduction efforts will significantly lower solar electric power generation costs (which hinge largely on tracking mirror or heliostat costs, which in turn depend upon how many heliostats industry will be expected to produce each year). In addition, if a few large practical applications of solar central to industrial processes can be identified as well, the national demand for receivers and heliostats will be sufficient that American industry will bring solar production and construction costs down to competitive levels within the next five to 10 years. If so, the Q's supplied by solar energy can offset many millions of barrels of imported oil. These are the kinds of things we want to begin to explore at this workshop.

The institutions represented here are:

INDUSTRY

Aerospace Corporation
ARCO Solar, Inc.
ARDEV Company
Atomics International
Battelle Pacific
Bethlehem Steel Corporation
Black & Veatch
Cabot Corporation
Cities Services Company
Dow Chemical Company
E-Systems, Inc.
Exxon Research & Engineering
Ford Motor Company
General Atomic Company
General Electric Company
Industrial Research Institute
Institute of Gas Technology
International Nickel Company
J. E. Sirrine Company
Kettering Research Laboratory
Martin Marietta Corporation
McDonnell Douglas Astronautics
Mitre Corporation
Owens Corning Fiberglass
PRC Energy Analysis Company
Rockwell International Corp.
Rocket Research Company
Sanders Associates
(continued)

INDUSTRY (continued)

SCS Engineers
Shell Development Corporation
Solar North
SRI International
TRW Systems
Union Carbide Corporation
US Borax Research
VEDA, Incorporated
Westinghouse Electric
W. R. Grace & Company

GOVERNMENT

Department of Energy
Jet Propulsion Laboratory
Los Alamos Scientific Laboratory
Lawrence Livermore Laboratory
Oak Ridge National Laboratory
Naval Research Laboratory
Sandia Laboratories-Albuquerque
Sandia Laboratory-Livermore
Solar Energy Research Institute
Tennessee Valley Authority
White Sands Missile Range

UNIVERSITIES

Colorado State University
Georgia Institute of Technology
Massachusetts Institute of Technology
Oak Ridge Associated Universities
Princeton University
University of Arizona
University of Houston
University of New Hampshire
Yale University

The workshop was planned and organized by the Solar Thermal Test Facilities Users Association. Primary support came from the Department of Energy via a subcontract from Solar Energy Research Institute, Golden, Colorado. A great deal of assistance in planning and organizing the technical program came from Sandia Livermore, Institute of Gas Technology, Oak Ridge National Laboratory, Naval Research Laboratory, and the University of Houston. Georgia Tech is our host.

In all, we have about 38 industries, 11 government agencies, nine universities, and two international institutions (France and West Germany) represented.

WORKSHOP OBJECTIVES

The objectives of the workshop are:

- To acquaint industrial representatives with possibilities of solar central receivers for industrial process heat.
- To get their views and assess their interests.
- To determine which processes show promise.
- To consider interface with electric power utilities and possibilities of heliostat cost reduction through mass production.
- To consider next steps, including R&D and experiments on solar thermal test facilities.

SUMMARY

I consider the workshop, beginning at this point, to be a two-way tutorial session: Today and part of tomorrow, solar people from DOE, DOE contractors, SERI, the UA, the solar R&D facilities--including a guest expert from West Germany--will be describing solar central and related technology for the benefit of industry's industrial process people. Following that, we hope that those of you who are closely acquainted with industry's actual high-temperature processes--their technical requirements and their cost considerations--will inform the rest of us as to your needs, problems, expectations, concerns, etc. Then, from this mutual exchange--which will include cost considerations--I believe we will find areas of common interest that we will want to explore further in Friday morning's discussions and which hopefully, in the future beyond this workshop, may lead to further industrial process applications of high-temperature solar energy and further conservation of fossil fuels.

In summary, I would like to emphasize the last objective: The "bottom line" purpose of this workshop is to develop a better definition of the kinds of industrial processes where central receiver solar technology might be applicable, and from that to define experiments which might be run on one or other of the Solar Thermal Test Facilities--i.e., Sandia, Georgia Tech, White Sands, or Odeillo.

Again, let me welcome all of you to the workshop and express the Users Association's appreciation to those who have helped so much in putting the program together. To all others, we are most grateful for your presence and interests and we hope that by the end of the workshop you will feel amply rewarded for your efforts.

INDUSTRIAL PROCESS ENERGY

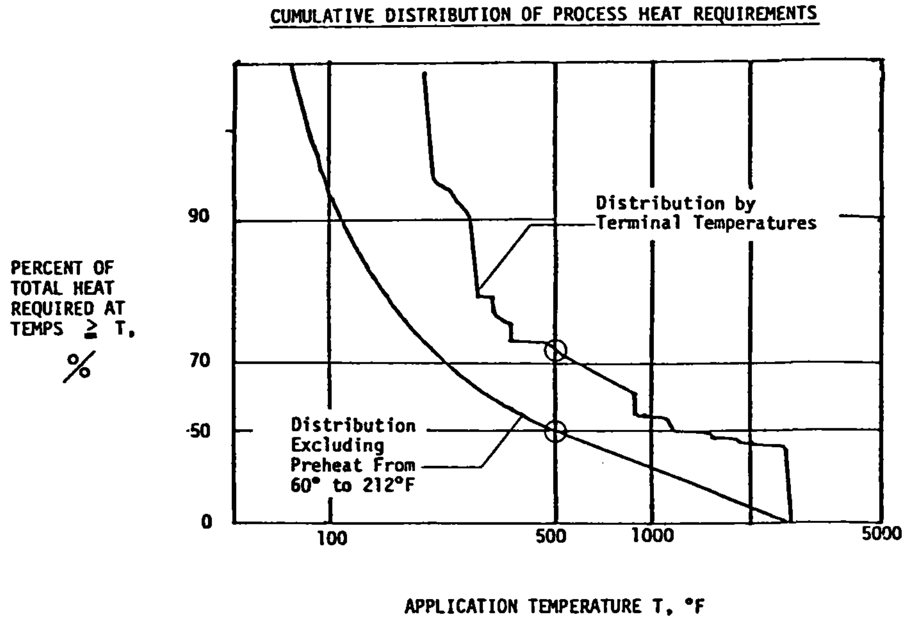
BATTELLE: 20 INDUSTRY EXTRAPOLATIONS

	TOTAL Qs	% > 350°F
1978	10.0	65
1985	12.4	65
2000	16.8	65

INTERTECH CORP:

1974	16.6 Qs	72% > 550°F
1985	23.0 Qs	
2000	37.0 Qs	

FIGURE 1



DATA FROM
INTERTECHNOLOGY CORPORATION
WARRENTON, VA

FIGURE 2

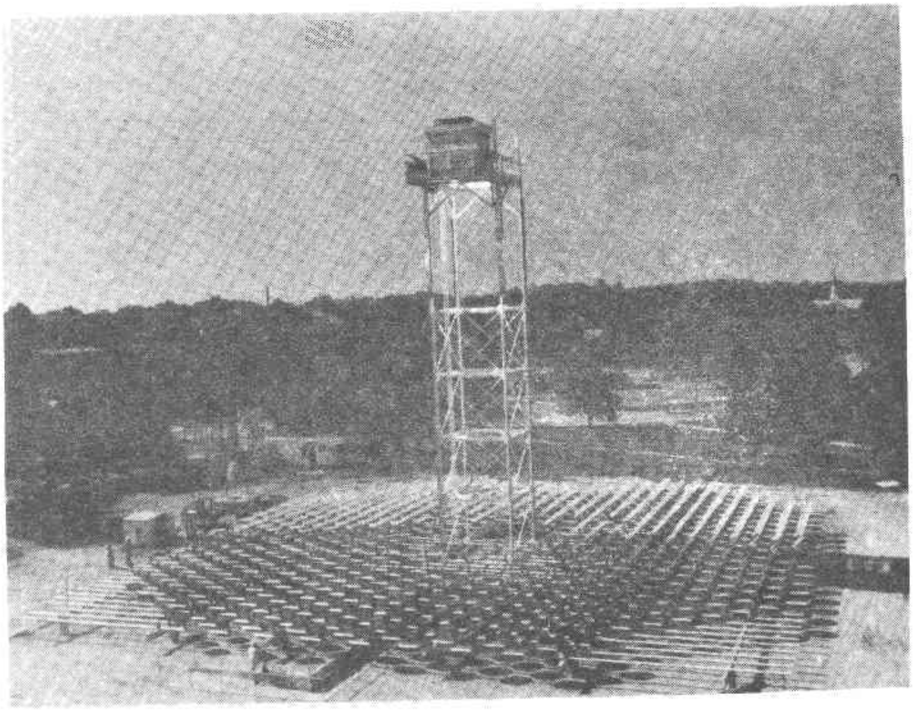
APPROXIMATE SPECIFICATIONS FOR STTFs AND SOLAR FURNACES

FACILITIES	SANDIA	GEORGIA TECH	WHITE SANDS	ODEILLO
TOTAL THERMAL ENERGY, kW_T	5000	400	30	1000
NUMBER OF HELIOSTATS	222	550	356	63
HELIOSTAT SIZE, M	6 x 6	1.1D	0.6 x 0.6	6 x 7.5
TOTAL HELIOSTAT AREA, M^2	8257	532	137	2835
TEST AREA DIAMETER*, M	2 3	0.3 1.0	0.08 0.15	0.25 1.0
PEAK FLUX , W/CM^2	250	275	400	1600
MAX. CALCULATED EQUILIBRIUM TEMPERATURE✱, K	2600	2700	2900	4100

*THE FIRST NUMBER IS AREA RECEIVING APPROXIMATELY ONE-HALF OF TOTAL ENERGY; SECOND NUMBER IS AREA CAPTURING 95% OF TOTAL ENERGY.

✱SMALL AREA AT CENTER OF BEAM.

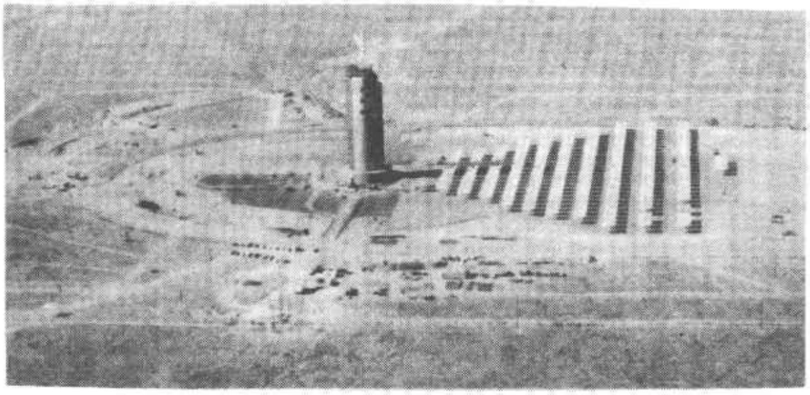
FIGURE 3



GEORGIA TECH 400-kW SOLAR ADVANCED COMPONENTS TEST FACILITY

This facility utilizes 550 round mirrors, each 111 cm in diameter. The mirrors are mechanically linked through a common clock-controlled drive mechanism so that they move together to track the sun and focus its radiant energy on a test area centrally located 20 m above the mirror field. Nominal black-body equilibrium temperatures are about 2000-2500°F. An experimental receiver tested with this facility generates 700 pounds/hour of 100°F, 1700 psi superheated steam. A hot air receiver developed by Sanders Associates is also being tested. This facility is also available through the STTFUA for experimental work by industrial or university solar researchers.

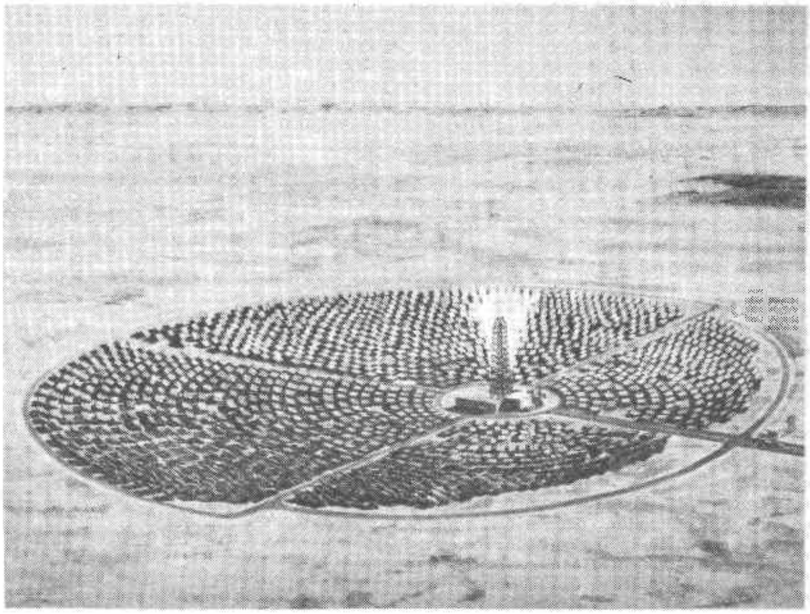
Figure 4



SANDIA 5-MW SOLAR THERMAL TEST FACILITY

This facility consists of a 200-ft tower with 222 400 ft^2 heliostats capable of directing 5 MW of thermal energy to various locations on the tower. Each heliostat consists of 24 4'x4' mirrors focused to produce a concentrated beam of solar radiation on a target test area. Approximately 1 MW of thermal energy is available within a 1-m diameter circle, 2.5 MW within a 2-m circle, and 5 MW within a 3-m circle. The experiment tower is 200 feet high with test bays located at the 120-, 140-, 160-, and 200-ft levels. Receivers currently scheduled for test on the Sandia facility include designs by Martin Marietta, Boeing Engineering and Construction, McDonnell Douglas, Minneapolis Honeywell, and Black and Veach. This facility is also available through the STTFUA for experimental work by industrial or university solar researchers.

Figure 5



BARSTOW 10-MW ELECTRIC (35-MW THERMAL) FACILITY

This 10-MW solar electric pilot plant will be built near Barstow, California, starting in 1979. It consists of a 300-ft tower surrounded by a circular field of about 2000 410-ft^2 heliostats focused on a central steam boiler on top of the tower. The 30 MW of 950°F, 1450 psi steam produced by this boiler will drive a turbine to generate 10 MW of electric power. Similar design could provide high-quality steam for various other industrial process heat purposes. It is predicted that this technology will be cost competitive with oil in the post-1985 period.

Figure 6

SECTION III

SOLAR THERMAL FUELS AND CHEMICALS PROGRAM

M. U. Gutstein
Department of Energy

Thank you, Al.

I wish to add my welcome to the attendees of this Users Association workshop on High-Temperature Industrial Processes. When Frank Smith, the Executive Director, called me a week ago to invite me to talk, I told him I would do so because I felt it was a personal challenge. It's always a challenge to work with the Users Association; for example, about a month ago I was asked to assist one of the Association's experiments at Odeillo. I found myself helping to expedite the shipment of molybdenite ore to France--the ore contains some uranium. I was on the phone making calls to California and to the International Affairs Office of DOE helping to smooth things along. That same day, I was called by a Secret Service Agent who wanted to question me. I thought I must be doing something wrong--I could see the newspaper headlines: DOE Solar Program Ships Uranium Out of the Country--questioned by the Secret Service--what am I doing? Well, I didn't go to jail. My secretary was applying for a position at the Secret Service and they asked me to provide some background information. Incidentally, she got the job. It surely is a challenge working for the Users Association.

I was asked by Frank to talk about a Solar Thermal Fuels and Chemicals Program; that is, the development of processes to produce fuels and chemicals using the high-temperature heat from solar energy. What I thought I would do is outline my justification for such a program, how such a program might be structured, and indicate the status of this area at DOE. I expect this talk will be somewhat provocative to those in this room; hopefully, it will encourage your thinking about this field. Much of what I will talk about represents my own thoughts on the matter, not DOE's. Please, don't go running off to your congressman repeating what I said and claiming that it reflects DOE policy. It doesn't. But I intend to talk frankly.

Why do we, the nation, need a Solar Thermal Fuels and Chemicals Program? Another DOE program? Let me try to answer this question.

Let's start at the beginning: what are the true energy needs of the country? I believe these to be liquid hydrocarbons and, possibly, natural gas. (The case for the latter is not as clear to me as it is for petroleum. Gas seems to be found all over, both domestically and elsewhere in the North American continent.) Together, oil and gas satisfy, I'm told, some 75 percent of our energy needs. Almost all of our transportation energy needs are derived from petroleum--about half of our oil, I think, goes into this sector. According to Jim Dollard at DOE HQ, some 40 percent of our energy is devoted to process heat--much of which is furnished by oil and gas. Clearly, as domestic oil and gas supplies decrease, we will need replacements.

What has been the Federal R&D (ERDA and DOE) response? All sorts of ways of making electricity! The Fast Breeder, Fusion, MHD, High-Temperature Gas Turbines, Fuel Cells, Thermionics; yes, even a Solar Electric program. In each of these programs, there are alternate ways of making electricity: open cycle and closed cycle turbines, alkaline and molten salt fuel cells, liquid metal and gas-cooled reactors, magnetic and laser fusion, on and on. Even within the solar program, there are photovoltaics, solar thermal, OTEC and winds! Within the solar thermal program, there are steam, Brayton, organic and Stirling engine options. I believe there must be upwards of 100 ways of making electricity. It's as if electricity was disappearing off the face of the earth and this in spite of huge coal deposits and sizeable uranium deposits for light water reactors to meet our needs well into the next century.

Well, much of what DOE is doing in the electric power field, one could claim, is aimed at replacing precious gas and oil used in boilers and turbines. And, isn't DOE supporting a coal synthetic fuels program?

My reply is that the utilities constitute about 25 or 30 percent of our total energy market. Of this, perhaps half comes from oil and gas. So we are looking at a 15-percent effect. The DOE coal program is about 5 or 6 percent of the total DOE budget. By contrast, the nuclear and fusion budgets, combined, are significantly larger. How serious is the DOE coal program?

Will this emphasis on electric power continue? In the face of inflation problems and a Proposition 13 tax revolt--I don't think so.

For the Solar Thermal program in particular, a Fuels and Chemicals program provides the proper focus--on fuels and energy-rich chemicals and, yes, high-temperature process heat. And it provides the proper programmatic balance to weather future cutbacks in electric power R&D that I believe will come. This is because a Fuels and Chemicals Program could serve all of the energy needs of the country, not just the 15 percent of the market we are working on now. Moreover, if you think about it, solar thermal and biomass are the only two renewable energy resources that can provide fuels--and I believe solar thermal will be less restrictive in supply than biomass. (In this, I discount making fuels from electricity--that is, by electrolysis--as being too inefficient and costly.)

Let me get a little more technical now. Latest estimates of the direct insolation indicate that the Southwest region is excellent for this resource. However, if you move outside of the Southwest, the direct insolation falls off quite a bit. These estimates suggest that solar thermal electric may be regional in nature--that is, limited to the Southwest, unless you postulate long-distance electric power transmission, say to the Northeast. Frankly, that prospect seems unclear to me. But if I make a fuel which can be transported in a pipeline--I can ship it transcontinental distances. Indeed, the pipelines are already in place and are nearby. Although the resource may turn out to be regional, it can still be made to serve national energy needs.

Finally, the production of a fuel using solar thermal energy provides an additional attractive feature compared to electricity. That is, it can decouple the availability of the sun from the demands for the energy. The pipeline can be the storage subsystem.

In summary, a Solar Thermal Fuels and Chemicals program can be justified on the basis of its potential

1) to meet the national needs for transportable fuels in a more environmentally acceptable way,
2) to utilize the existing pipeline system to deliver energy on a national scale, and
3) to decouple the energy resource from the energy demand.

What would be the content of such a program? I believe the program should have at least two elements: near-to-intermediate term emphasis which identifies and develops specific fuels and bulk chemical processes having a potential for some impact on national needs; and a far-term, more research oriented effort, aimed at providing a substantial portion of the fuels requirements for the entire nation and based entirely on renewable materials and energy.

What are the near-to-intermediate term processes? I really don't know. Some of the papers at this workshop discuss processes that might fit the bill. Calcining of lime or gypsum, bauxite digestion, styrene dehydrogenation, maybe. The closest yet is the intermediate Btu gas from coal using solar energy--better yet, would be one that generates a liquid fuel from coal or any other hydrocarbon resource. Some have suggested biomass or shale. None of these solar thermal possibilities have been looked at, not even on the back of an envelope, but I'm encouraged based on the data of the Lawrence Livermore work on solar thermal synthetic gas from coal.

For the far term, high-efficiency thermochemical cycles for the decomposition of water or CO_2 attract the imagination. I liken these processes to the mammals that came in the Age of the Dinosaurs. They are puny, very fuzzy, not much to look at. But watch out--they're egg eaters and they'll inherit the earth eventually. It's only a matter of time. If the CO_2 content of the atmosphere is judged to be a serious problem ten years from now, these thermochemical processes may be crucial if we are to continue our economic growth well into the next century.

Let me digress a little at this point. The current administration has placed a lot of emphasis on near-term developments in the field of energy. Much of the R&D dollars are used to demonstrate particular energy systems or plants before the 1985 time period, even if these demonstrations are less then economically optimum. We all understand why this is being done. I personally believe, however,--and I'll bet many of you agree--the government ought not determine what particular power plant or process gets used in near term--industry and the marketplace should do this. It may be appropriate for the government to influence the marketplace by appropriate regulations, subsidies, tax breaks or other incentives. The real government R&D role ought to be for the long term--the high risk but high payoff areas. DOE should be asking such questions as: How much worse off would the country really be if, instead of importing oil, we used some of the money to build up an equivalent domestic fuel supply system? What kinds of energy supplies will we need, say, 50 years from now? Can we risk building up a coal-derived fuels industry by the year 2000 or 2025 only to have to shift to a renewable resource? Can the nation afford this? Can we start to develop both coal and renewable energy systems in parallel? I have never heard these questions asked, let alone heard the answers. The questions require imagination and leadership. The answers provide a basis for a long-term strategy and an R&D program the Federal government should be supporting even now.

I can't supply the answers--but I'd like to supply some imagination. The sun falling on about 2 or 3 percent of the land area of the Southwest, if harvested, could supply enough energy to meet most if not all of the current US energy needs today. Perhaps, by the year 2050, about 5 percent of that land area would be needed to do the same job. Utilities, chemical and petro-chemical companies could, over several decades, little by little, install collectors to harvest the solar energy to make transportable fuels, fertilizers and chemical feedstocks from water and air for the rest of the country, provide some electric power via cogeneration, and, using the waste heat, produce desalinated water for irrigation purposes. This concept, I call it the Southwest energy breadbasket, isn't original with me. It offers energy independence, employment, less environmental intrusion. It is suggestive of the kinds of opportunities that need to be examined to evolve a long-range R&D strategy for the Government.

Finally, what is the status of the DOE Solar Thermal Fuels and Chemicals program? During FY78, we commissioned JPL to prepare a Fuels and Chemicals program plan. A draft of this will be available soon. I hope to get industry comment and support for this plan during the early part of FY79. The intent is to define a program to be conducted jointly by the Advanced Technology Branch of Solar Thermal and DOE's Division of Energy Storage Systems. In addition, during FY78, the program supported various studies of potential near-term solar thermal processes--much of what has been reported at this workshop.

For FY79, my intent was to get started on detailed process studies by the mechanism of an RFP issued to industry. Unfortunately, the Advanced Technology Program is unable to support such a solicitation this year. It will have to be deferred until FY80. One of the problems of the Fuels and Chemicals program is the lack of a program manager. I cannot serve in this capacity at DOE HQ--a full-time manager is needed. It is the intent of the Advanced Technology Program to solicit for this management function in FY79 outside the DOE family. The role encompasses planning of the program, soliciting industry for R&D work in fuels and chemicals processes and issuing contracts, monitoring progress under these contracts, and reporting progress to DOE and industry. The use of an industrial program manager by DOE is unusual, although NASA, I'm told, has gone this route in the past. If there is interest in the program manager role by industrial firms, I will try to answer any questions during the workshop.

Finally, as I indicated, our overall budget for solar thermal has not increased in FY79 and the Fuels and Chemicals program is not well known at upper DOE management levels. These are not unrelated facts. I personally believe the Solar Thermal Community--I mean HQ, laboratories, industry and universities--has not sufficiently educated the outside world as to the potential benefits of Solar Thermal. I mentioned I would seek industry support for a Fuels and Chemicals program. This support cannot be a passive blessing of the document itself; industry and universities have to actively support it if it is to be more than what we have now, basically, a low-level R&D program. If you believe in this program, tell people about it.

SECTION IV

SOLAR CENTRAL TECHNOLOGY IN EUROPE

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I have to say when you have two people working for you like Tom Brumleve and Al Skinrood and you oppose something that is as publically acceptable as solar energy, it's impossible to stay out of it. Both of them, as many of you who know them are aware, are very persuasive. I was rather reluctant to get into solar because our primary business at Sandia Laboratories was nuclear weapons. We had become involved in solar as a result of being involved in the causes of peaceful uses of nuclear energy--and I was reluctant to let go of what I thought was very important but so publically unacceptable. It is nice to be involved in something that is publically acceptable.

As Tom pointed out, I was in on the ground floor of the development of the International Energy Agency's small solar power system project. Much of its character today is not what I wanted, but it's always a compromise when you're dealing with nineteen countries and are trying to develop something in which your basic guidance is given from the top--from the International Energy Agency (IEA) Secretary and/or the Committee for Research and Development. It was to build something, a hardware program, using off-the-shelf technology, something that could be done in three or four years. So, that's the real constraint caused the creation and development of the project in the IEA about which I'll talk.

I first want to apologize for subjecting you to a few graphs and slides. I felt you would like to see some photographs of some of the hardware because Dave Gorman, for one, was with me in Marseilles when I took the picture of the French heliostats that I'm going to show you. Also, many of you, or some of you at least, have been to Claude Royere's solar furnace at Odeillo.

Let me start out with Figure 1 which lists the active programs on central receiver plants. It displays each of the programs including those that are in the United States. On top is the EEC community, which is the community of all of the European countries, except Spain, Greece and the Communist countries, that is. It is a program they have put together that is going to be built in Italy. It is a 1-megawatt power tower program using water and steam as the receiver coolant. Part of the heliostats are to be provided by France and part by Germany.

The next program shown is France's THEMIS program, which started out to be a 3-1/2 megawatt electric system and is now down to a 2-megawatt system. It will be built very near Odeillo. The site has been selected and the last word I had is that it was on schedule except that they ran into some difficulties with bigger rocks than they expected, and more of them, so it slowed them down. But they hope to be back on schedule very soon. They are doing a second round of heliostat development, and I'll show you a little of that as we get into this talk. It uses Hi Tec, a molten salt, as the receiver coolant and for energy storage. I will go into it in a little more detail on each of these as we progress.

FIGURE 1. SOME CENTRAL RECEIVER PLANTS TO BE CONSTRUCTED

COUNTRY/ LOCATION	SPONSOR/ CONTRACTOR	ELECTRICAL OUTPUT	DATE OF COMPLETION	COST ESTIMATE £m	REFERENCES -GENERAL -COSTS
EEC Sicily	EEC Ansaldo/Cethel/ ENEL/MBB	1 MW	1980	4.5	P P
FRANCE	CNRS/EdF Cethel				P
Targasonne	Themis I	2 MW	1980	8.8	40
Odeillo	THEM	64 MW	1976	-	
IEA Almeria	IEA DFVLR/ International Consortia	500 kW	1980	7.3	P 40
ITALY Genoa	CNR Francia/ Genoa Univ.	100 MW_t*		-	33 -
JAPAN Shikoku	Mitsubishi	1 MW	1982	3.6	40
SPAIN Almeria	CEE	1 MW	1980	8.5	39 40
USA					
Barstow	DOE McDonnell Douglas S. Calif. Edison	10 MW	1981	67.7	P,36 41
Albuquerque	DOE Sandia Labs Martin Marietta	5 MW_t*	1977	11.6	P,37 42
Atlanta	DOE Georgia Tech Ansaldo (Italy)	400 kW_t*	1977	-	P,38 -

*Test facilities only--no electricity generated.

The next one, which I'll go into in greater detail because I know more about it, is the Small Solar Power System (SSPS) project to develop two solar thermal electric systems. One is to be a distributive system, and the other s power tower system using sodium as the receiver coolant and for energy storage.

In Japan, Mitsubishi is doing a system that I know very little about other than it is planned to be 1 megawatt. Japan is a member of the IEA. They participated in the development of the IEA/SSPS project but when it came to signing the contract and implementing the agreement that called for money and some other contributions, they decided to stick with their own national program and avoid international involvement.

The Spanish national program is to build a 1-megawatt electric power tower system using water steam as the coolant and Hi Tec as the receiver coolant, similar to what was done in research fields in the United States, but they're a little different.

There you see basically the power tower programs that are presently being designed; components are being developed and/or tested, and they are being built. There is one other that isn't listed on the chart in which the US and CNRS built a receiver in which the coolant was oil. They demonstrated a collection-conversion of radiant energy to thermal energy storage, and then conversion to steam to generate 60 kilowatts of electrical energy. It was worthwhile because it developed interest on the part of the French people and throughout Europe. There was a terrible mismatch in the turbine generator: the turbine was rated 1 megawatt and the alternator attached to the shaft was 60 kilowatts. So, the efficiency of the system was bad. But, they didn't really need to convert it to electricity, as all of us know. The thing one is interested in is radiant-to-thermal conversion. You want to measure how well that does. They did the electricity for public relations, for publicity, and they got it.

I will be a little more detailed about each of these, except the Barstow plant, because I think you have heard enough about that one in the last few days.

Looking at Figure 2, CESA I is the Spanish program and it is run by the Center for Energy Studies. It's the first one they're doing and it is also 1 megawatt, and that's why the CESA I. They are planning on 275 heliostats and have the first one on test at present just outside Madrid at INTA, near Torrejon. It is a takeoff on a Martin design which was a generation beyond the type of thing that Martin provided the STTF. However, it uses a similar mechanism for focusing the beam from each of the facets as is used at the STTF. The Spanish, as do most of the people in Europe, have a very strong nationalistic pride with very strong emphasis on their government officials and energy groups to show that whatever is built within their country has a strong national input. The Center for Energy Studies, headed by Juan Temboury, is under a great deal of pressure from the government to make the system, that is mostly funded by the Spanish government, "look Spanish." I put those words in quotes because I want to emphasize that that's what Juan Temboury hears. I serve as a consultant to Juan and we go over that often. Well, what makes it look Spanish? It's difficult to take a heliostat design, as an example, or a receiver design and make it look any kind of nationality, but it will look a little different in whatever way they can do it, and they will be basic designs by Spanish companies.

FIGURE 2: SOLAR THERMAL ELECTRIC POWER GENERATION PROJECTS IN THE PLANNING STAGE

	COUNTRY	FACILITY; LOCATION; DIRECTED BY	RATING; EFFICIENCY	DATE OF COMPLETION; COST ESTIMATE*	MODE OF COLLECTION; CONCENTRATION RATIO	TRANSFER MEDIA/TEMP; STORAGE/CAPACITY; PRIME MOVER
TOWER CONCEPTS	USA	Barstow S. California DOE, S. Cal. Ed, et al	10 MW_e 19%	1981 ~220 MIO DM	1720 Heliostats (40 m^2); ~500	Water/510°C; Thermal Oil/3 Hours; Steam Turbine
	SPAIN	CESA I Almeria, Spain CEE	1 MW_e 18%	1981 ~32.5 MIO DM	275 Heliostats (36 m^2); ~1100	Hi Tec/520°C; Hi Tec/3 Hours; Steam Turbine
	(IEA)	SSPS-A Almeria, Spain DFVLR	0.5 MW_e 15%	1980 ~28 MIO DM	148 Heliostats (40 m^2); ~300	Sodium/600°C; Sodium/4 Hours; Steam Turbine
	FRANCE	THEMIS I Targasonne CNRS; EDF	2 MW_e 16%	1981 ~34 MIO DM	380 Heliostats (45 m^2); ~425	Hi Tec/430°C; Hi Tec/6 Hours; Steam Turbine
	(EEC)	- Sicily ISPRA	1 MW_e 14%	1981 ~12 MIO DM	365 Heliostats (12 m^2); 90 Heliostats (50 m^2); ~500	Water/510°C; Hi Tec & Steam/ 0.5 Hours; Steam Turbine
	JAPAN	- Shikoku Mitsubishi	1 MW	1982 ~14 MIO DM	Heliostats (?)	Water/

*Nonrecurring Cost Elements Included

The reason this particular heliostat turned out looking a little like Martin's is that Martin sent a couple of people over to work with one of the companies in Spain, and that's how the technology got handed off.

The US government does support the Spanish program through the US/Spanish Treaty of Friendship. As a part of that treaty we have agreed to some technological transfer in the energy areas; specifically, the solar energy area. We've had a hard time getting all of that put together; in fact, it's been over two years that I've been involved in trying to get it put together, and we're getting to a point where we do believe that the money, the work, and the people involvement can take place. I said that a year ago, but I think I'm closer now.

The IEA I'll get to a little later, but as you can see it involves 148 heliostats; I believe the number is now 155. It is a third generation by Martin. Martin is one of the contractors to the IEA, and the contractor to the DFVLR, which is the German NASA, and the operating agent for the IEA/SSPS project. The prime center at home is a company whose principal reason for existence is the development of nuclear power and nuclear power stations, so they certainly know the sodium business and the power business. Martin brought them the solar business so there's now a solar power company consortium that seems to be working very well. We'll know more about that in a couple of weeks.

You can see some of the temperatures that we're dealing with in these kinds of systems. The 600°C will be a little lower than that in the interest of being conservative and because of a little fear that they were building a receiver that was different. That was the only component that was different so they were a little concerned about whether it was going up to the maximums at which they would normally work.

THEMIS, as I said before, uses Hi Tec as the receiver cooling fluid. They are working the Hi Tec at a lower temperature, I think, than most of us think you could work it at. I know Tom Brumleve feels very strongly that one could go to a little over 500°C without any major problems, but they have chosen 430°C, which is considerably below where we think you could work with it. But, they are being conservative; it's their first time out. They can always change and run at a higher temperature, but their design is about 430°C . They're using 380 heliostats. The chart says 43 square meters per heliostat. All of their heliostats are designed to 50 square meters and you'll see some pictures in a few minutes.

The European Economic Community (EEC), I point out here, has 365 heliostats provided by MBB. That was when their heliostat design was 12 square meters per heliostat. The other half of the total area of the field is provided by France, with theirs being 50 square meters per heliostat. As water steam it is a Francia designed, Ansaldo manufactured boiler with no energy storage.

Back to the IEA, Figure 3 is an artist's concept of that effort and shows the two systems together; that is, the power tower system to the north and the distributed system to the south. I've said a few words about the power tower system and nothing about the distributed system, but we'll get to that in a minute.

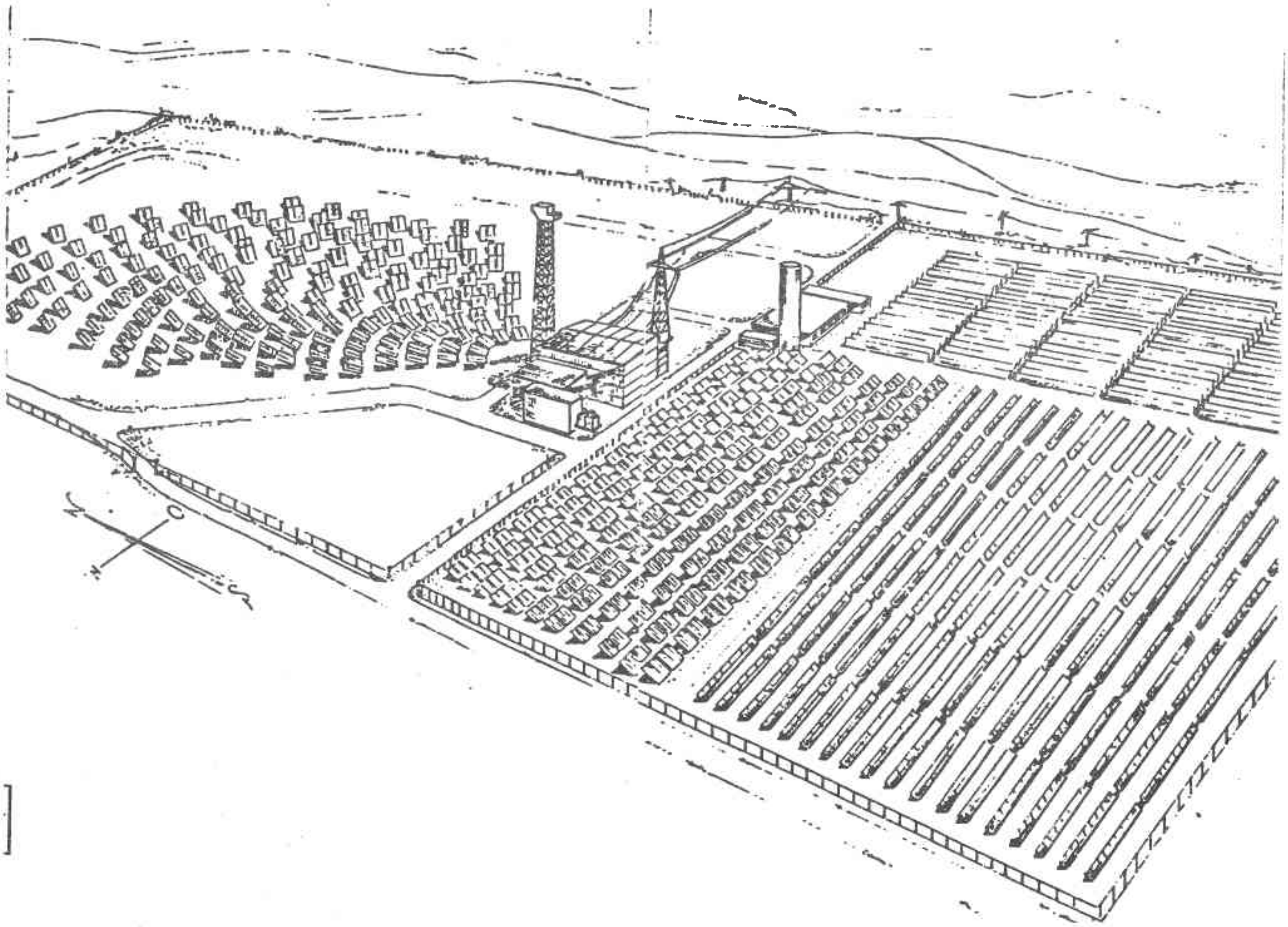


Figure 3

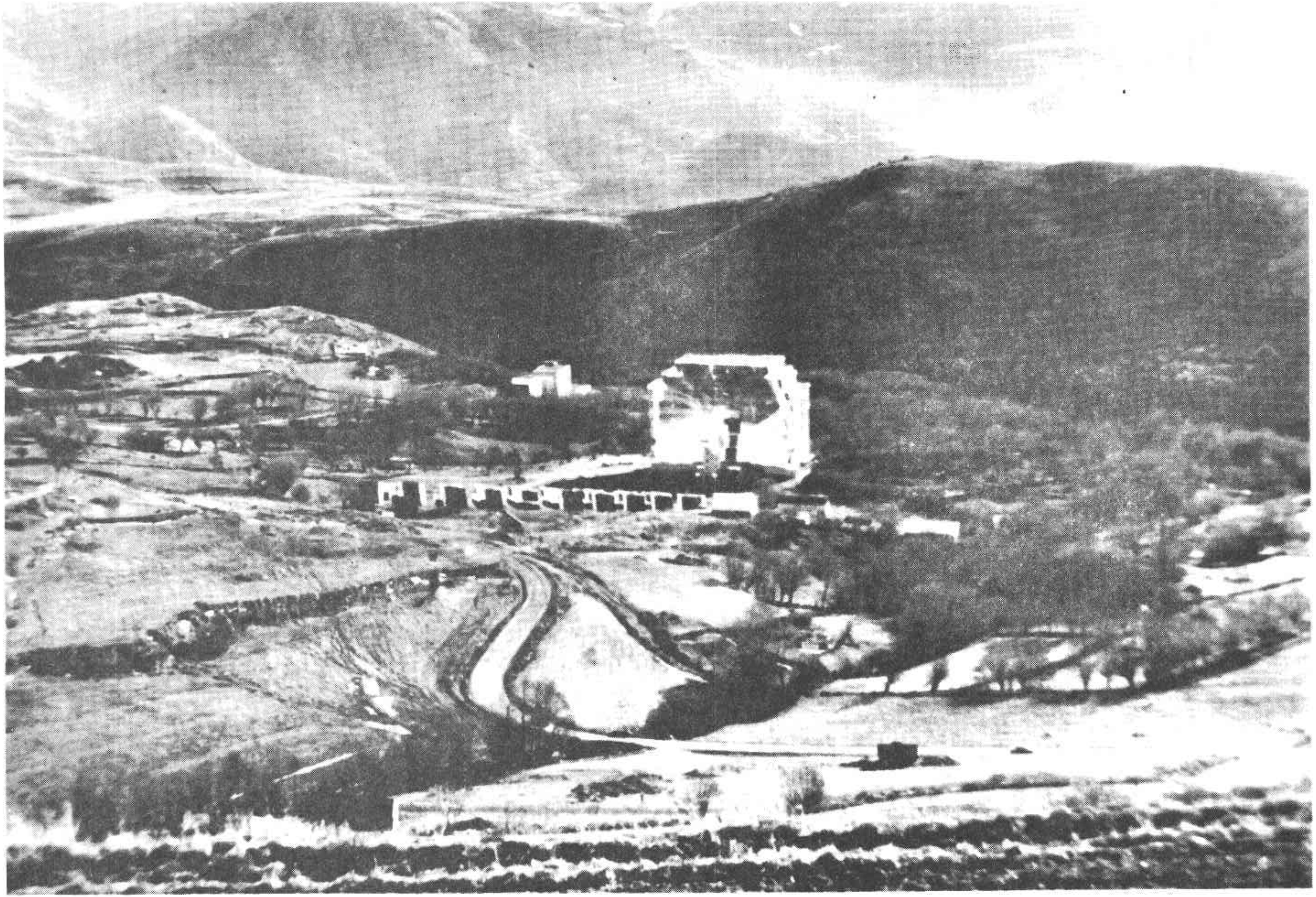
Both of these systems are to be built in Spain at the same location, a site provided by the Spanish government in southern Spain just 40 kilometers north of Almeria, a seaport on the Mediterranean. It is a point of good insolation. The conditions are such and the land availability such that it is very similar to Barstow, except for the number of hours per year. Sunlight is not as good as at Barstow because the latitude is a little farther north.

Both of the systems will produce 500 kilowatts of electricity where the insolation is above 700 watts per meter square. It's a pretty tough requirement for a distributed system to meet at all times of the year. Acurex of California is the designer and prime contractor of the distributed system. They have a subcontractor in every one of the ten participating countries. Think about their management problems for a while. It's pretty tough, and that has been their biggest problem.

But, they've had to put in parabolic troughs for two-thirds of the field and two-axis tracking systems made by a German company, MAN, for the other third of the field. They've had to put in east-west and north-south fields and the double-axis track in order to handle the requirements. It is, therefore, an experiment although it started out not to be an experimental or test facility. It was going to be a demonstration facility, but all of the collector fields and the distributed system are tied in parallel. That is, they are circulating oil to convert the radiant heat to thermal energy, and they're all coming into the same storage tank with the inlet temperature of the storage tank held the same and, therefore, varying the flows so we will be able to assess the contributions by each of the fields for all times of the year. Most of us believe that we know what is without going to such a large system, but going to such a large system will give us some information and perhaps even some surprises. We've seen surprises before, so there's strong belief that we should go ahead and build this system. There are other reasons for having three different fields in the Acurex collector system. They are using the same collector that they're putting in at Coolidge, Arizona, which is also essentially the same one they put in at Willard, New Mexico, for the US irrigation project. The reason they included the other one is that the IEA decided they needed a European-type collector. The MAN double-axis track and parabolic trough collector was the only one that was available.

I think I've said enough about that and I'd like to show you some pictures of some of the pretty things in Europe.

Of course, I'll start out with the solar furnace (Fig. 4), which is a beautiful thing, because I thought Claude Royere would be here but, unfortunately, he wasn't able to come. All of these deal with a lot of glass, a lot of glass and a lot of reflection and they get impressive--that includes the building that's out here north of Atlanta, by the way. That is beautiful. It's all glass all the way around. It's very confusing to see where the floors are. But, this is a beautiful facility and, as you know, it's been operating since 1970 or thereabouts. It became very degraded over the last three years to the point where they were down close to 500 kilowatts thermal rather than 1 megawatt thermal. This last year France was able to fund complete replacement of all the glass on the heliostats and the fairly inexpensive but very difficult task of cleaning the parabola.



Selvage No. 4, CNRS 1000 KW
Solar Furnace, Odeillo

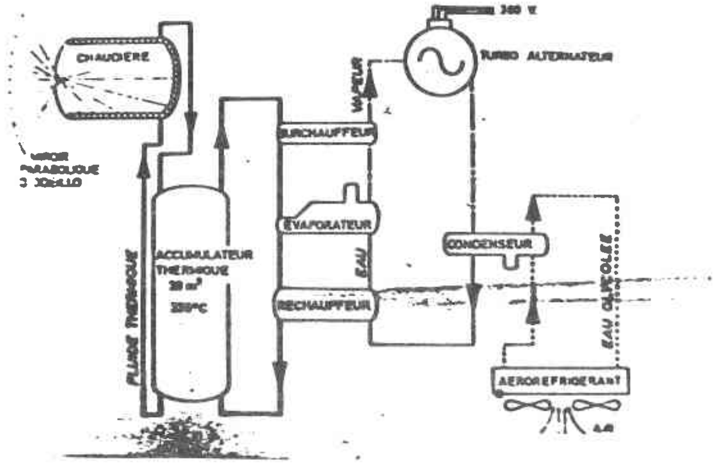
I was at the furnace on July 17 visiting Claude, who was in the process of finishing the replacement of the glass and the cleaning of the parabola. They recognized that the plate glass they had on the heliostats was of such quality it was a shame to replace it all. So, they took the glass off of all the facets of the heliostats, chemically stripped and cleaned it, had it replated, resilvered, revarnished, and then reinstalled the mirrors. So, they saved the glass that they had and they are now back up to probably a little better than 1 megawatt thermal. It looks absolutely beautiful.

I talked a little bit about the experiment that the French conducted with their furnace using oil as the heat transfer fluid and circulating the oil in the receiver, with an outlet temperature of 340°C for an oil we are a little concerned about at 300°C (Fig. 5), excuse the fact that you can't see the receiver. They operated it for a very short period of time. They would collect the energy in a 30-cubic meter storage tank, then heat exchange to water, develop the superheated chain to provide for the electricity. That was on line in November 1977, and was a very successful experiment.

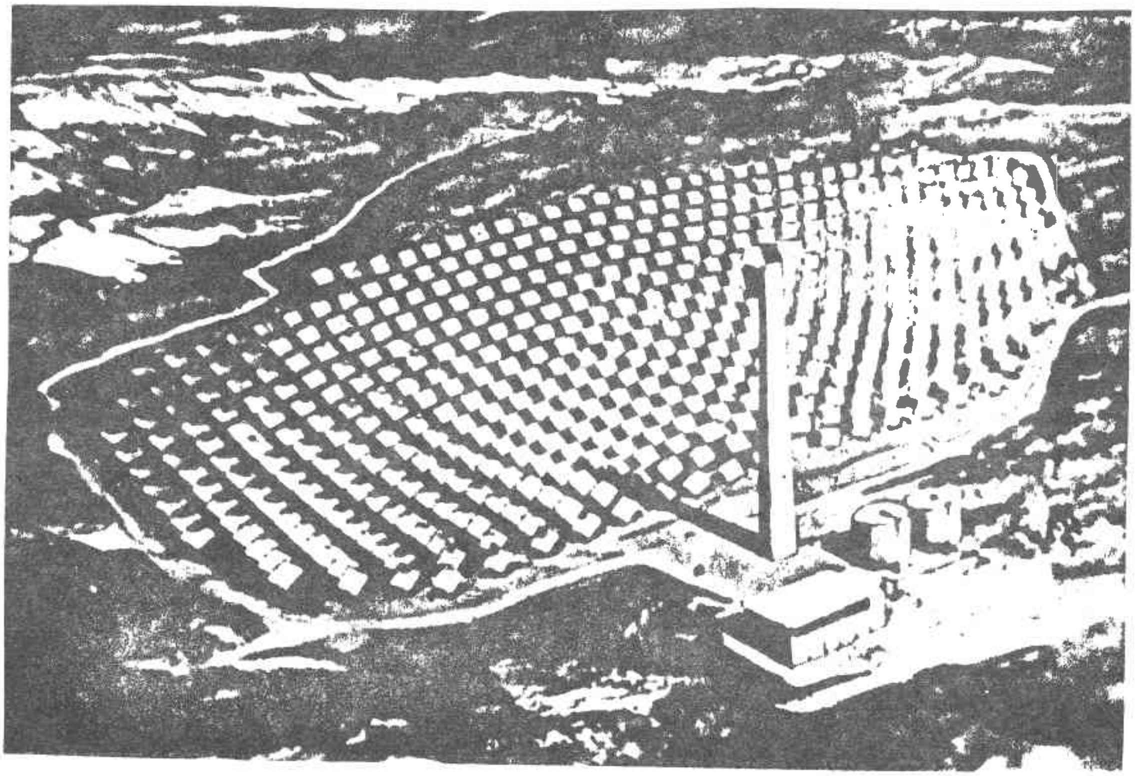
The next French experiment is THEMIS and Figure 6 is an artist's concept of that project, which I think some of you have seen. It is a power tower program with each of the heliostats being 50 square meters. They use Hi Tec as the coolant and as the energy storage. Figure 7 is the heat flow schematic. (The problem with these figures is that I used by camera to copy them for the slides because I had no other artistic help.) The mirrors redirect radiant energy to the receiver. They have hot and cold storage tanks for the Hi Tec and they change again to steam to drive the turbine to generate the electricity.

Here are some pictures of the heliostats. They're under test in Marseilles in southern France right on the Mediterranean. There were five different heliostats operating the day we were there. I've been there three times and the time Dave Gorman and a group from Boeing and Martin and ourselves were there, the wind was gusting to 90 kilometers per hour. Etievant, who is in charge of the THEMIS project, was elated by the fact as he had always wanted to try to operate near the maximum wind conditions they could expect and they had never been able to do that. So, while we were there he had the contractors for each of the designs on location operating the heliostats and directing the reflected image. I'll show you a picture of one of these heliostats that they are working on at the EDF. Figure 8 is a Renault design. It looks rather familiar in that it is a basic yoke design. There are some interesting differences from the things that we've seen before. Bear in mind that for encoding the position of the reflective surface, there are large arcs with copper strips on a Teflon backing--you can see a piece of that sticking out between one set of mirrors. In Figure 9 you can see the back arc almost in the center of the heliostat, which is where they get the optically encoded position of where the heliostat is pointing.

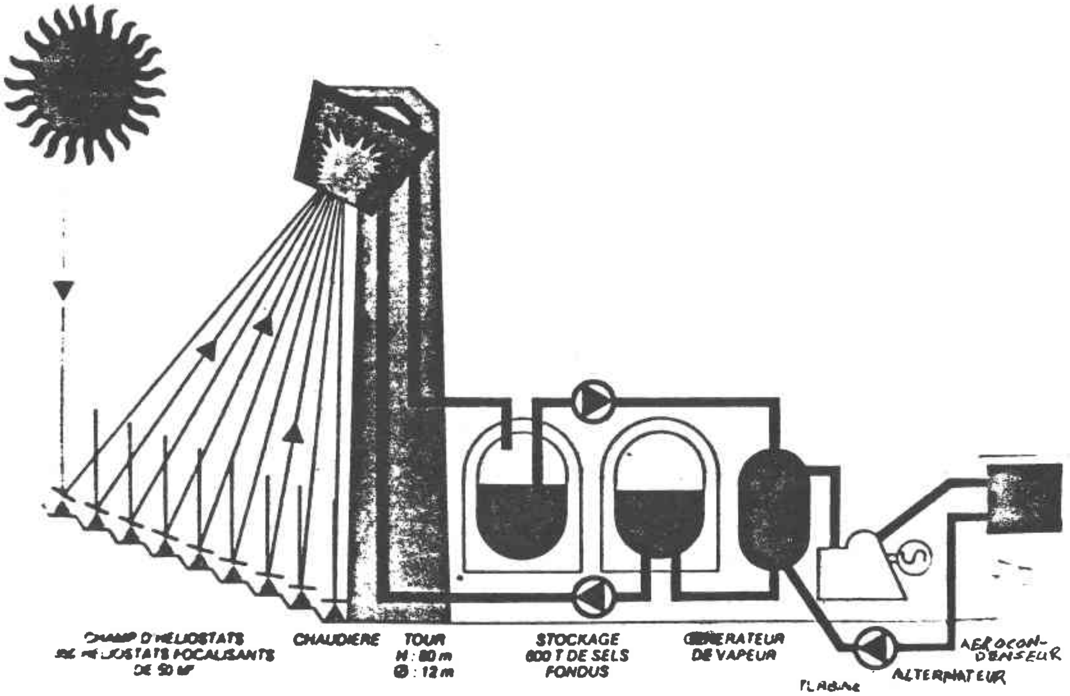
Another heliostat is shown in Figure 10. This one was designed by Aerospatial, the same company that manufactured the air bus. It looks like one of the better designs from the standpoint of being lightweight and marginally able to survive the environmental conditions that were specified in the development specs. Each of the red elements has a circular disc where they can pull the center and push the edges to focus each of the facets (Fig. 11). The method



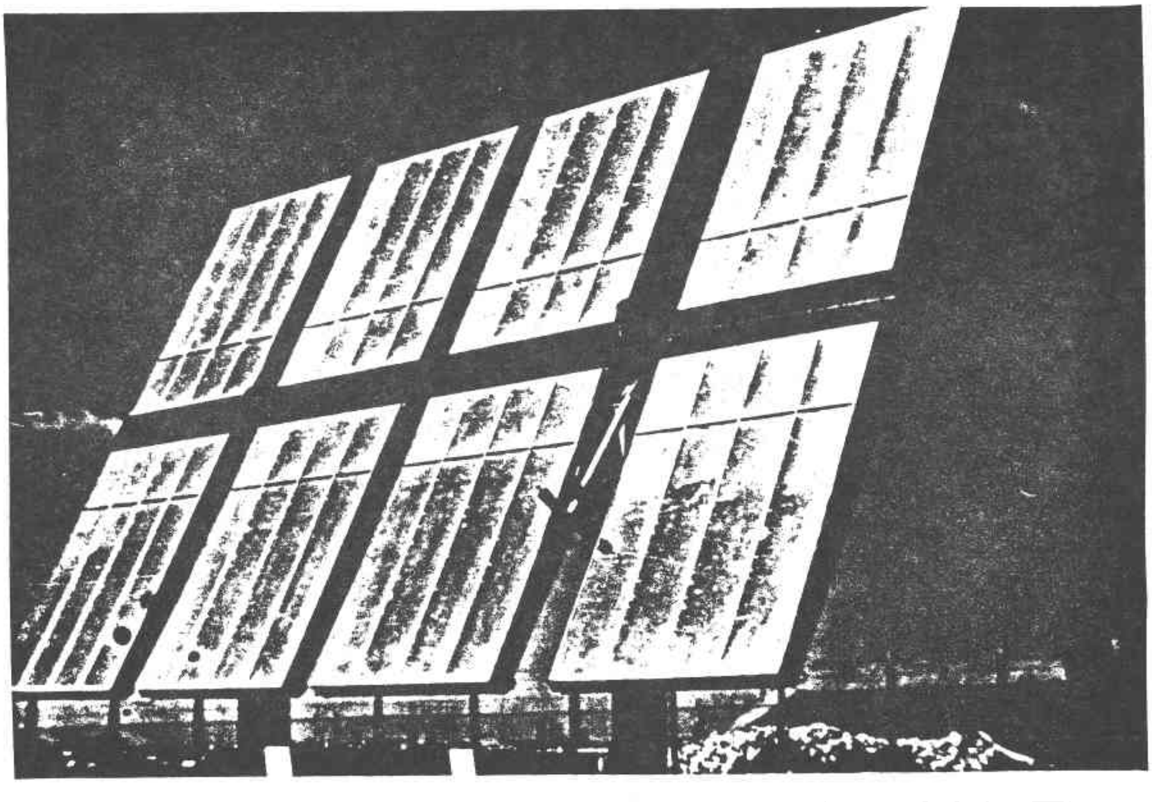
Selvage No. 5, Flow Schematic
for CNRS Electric Power Experiment
1976-1977



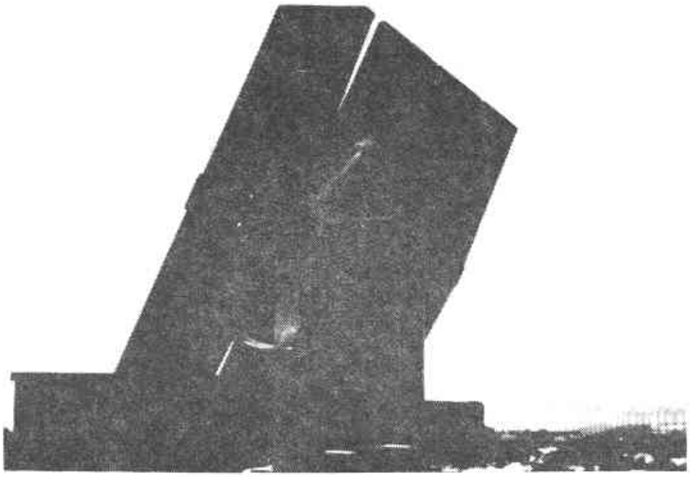
Selvage No. 6, Artist's Concept
for Project THEM, France



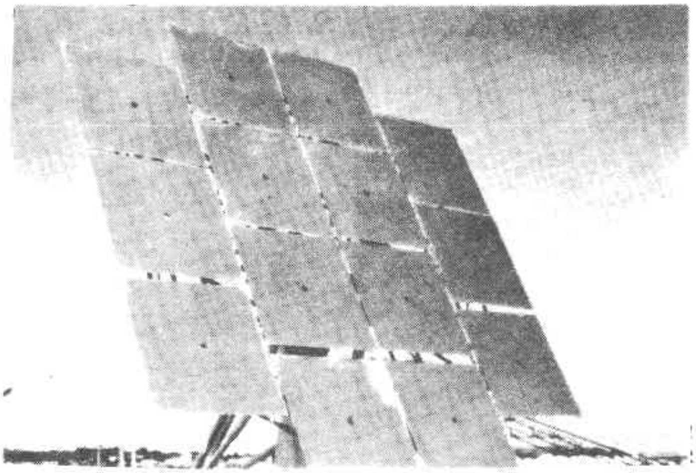
Selvage No. 7. Flow Schematic
for Project THEM, France



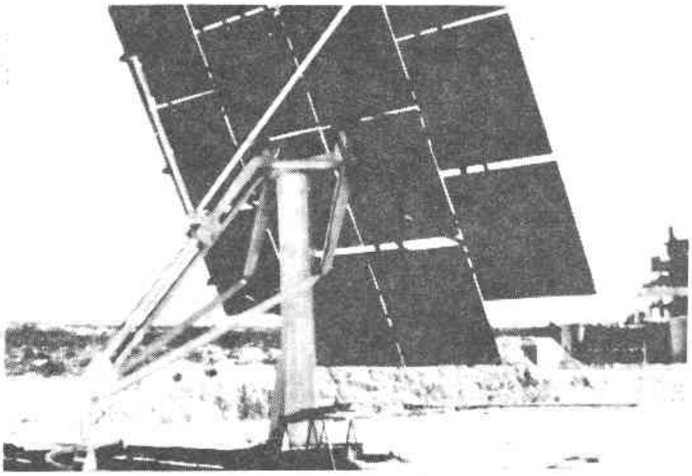
Selvage No. 8, Project THEM
Heliostat, Renault



Selvage No. 9, Project THEM
Heliostat, Rennault



Selvage No. 10, Project THEM
Heliostat, Aerospatial



Selvage No. 11, Project THEM
Heliostat, Aerospatial

for azimuth and elevation tracking is unique, certainly different than anything we've seen in the United States or at any of the other companies, with a motor-driven cable on the back to drive the elevation mechanism up and down the back arm. Figure 12 is a closeup look at each of the facets so you can see the method that they use to focus the image from each of the facets.

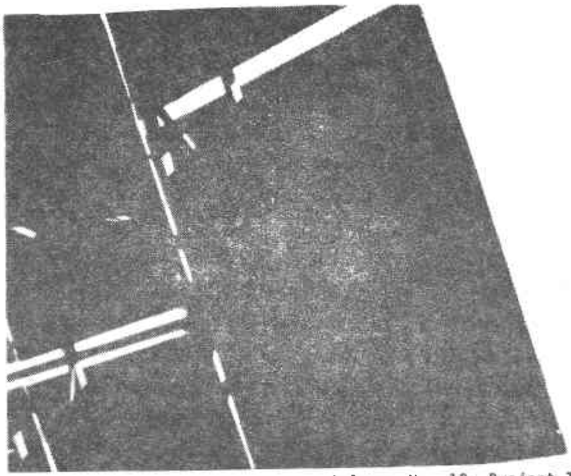
Figure 13 is a design by St. Goban. Again, all of these are 50 square meters in total surface area give, or take a little. St. Goban is an international company noted throughout the world primarily for float glass lines. They have nine float lines in Europe. They are also a US company but don't make glass in the US, just shingles for houses. This, of course, is silvered glass and very, very sturdy; in fact, too sturdy, and undoubtedly very expensive. You can see the back side of the structure in Figure 14. It does look similar to the McDonnell Douglas design and to the newer Martin design. However, this is much stronger, much heavier than is needed for the conditions, and the French recognize this as well.

You can see two other designs showing in the back. The one right in back of the St. Goban, in the middle, is a CNRS design built by a small French company. Figure 15 is the front side of that same mirror. In Figure 16, a closeup, you can also see the Mediterranean in the background. Figure 17 shows the mechanism with the cables driving it up and down the back bar that's in the upper right-hand corner of the picture.

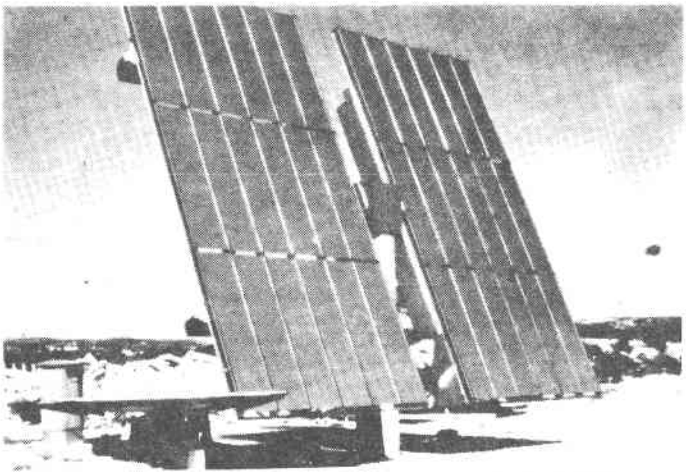
Figure 18 shows the image on top of a tall tower. At 90 kilometers an hour, it is very stable. Everybody was pleased and it made Etievant say we need a second-generation design. So, for some selected units, but not all of the five he had on test at Marseilles, he gave contracts to do a design that took out the costs, the same kind of thing that we're going through. Our designs were not as conservative the first go-round as theirs, but they certainly are going ahead. You can see some of the other images down on the ground. They're measuring the quality of the image with a photocell-type of ray that was mounted on the side of a truck trailer down near the ground so the angles were wrong. But, when they put it on the tower there was a nice image.

Another experiment in France which is a credit to French scientists, I would say, is the French Pericles experiment, Figure 19. It is done at an astronomical facility owned and operated by CNRS but operated for CNRS by astronomers. They took on a solar task because they figured they knew something about where the sun was and how to calculate all those kinds of things. They did a beautiful job.

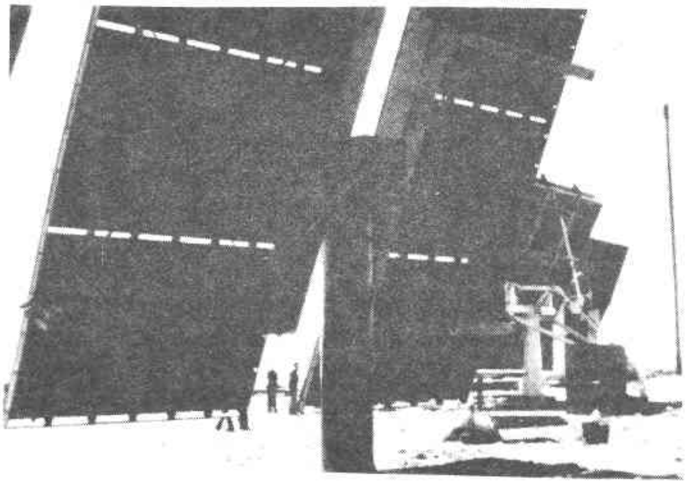
This picture (Fig. 20) was taken by Gerry Braun in February. At that time, the Pericles staff, Mr. Authier, was in the process of mapping the flux at night under a full moon. He would use only the two days before or the two days after a full moon as long as there were no clouds in the sky. They were, therefore, able to map the flux at the focal point. This is a fixed mirror, moving receiver-type of system and they were able to map the flux without danger to personnel and/or instrumentation with rather easily designed flux monitoring equipment they could put at the focal point. In fact, they could walk in it themselves because it was only the moon they were concentrating on so it was very safe and very practical.



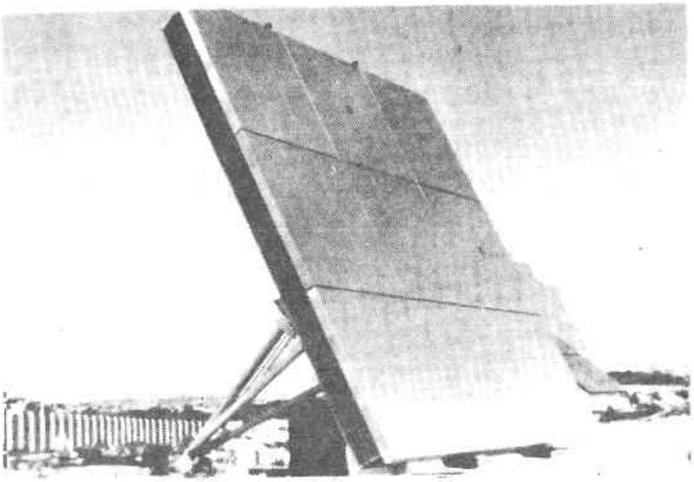
Selvage No. 12, Project THEM
Heliostat, Aerospatial



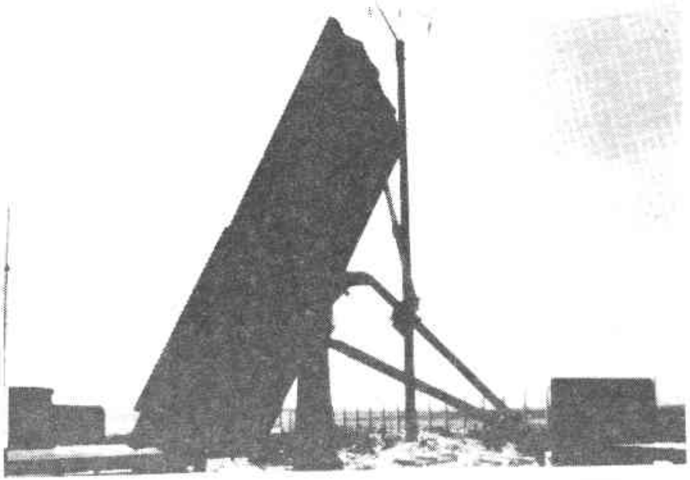
Selvage No. 13, Project THEM
Heliostat, St. Goban



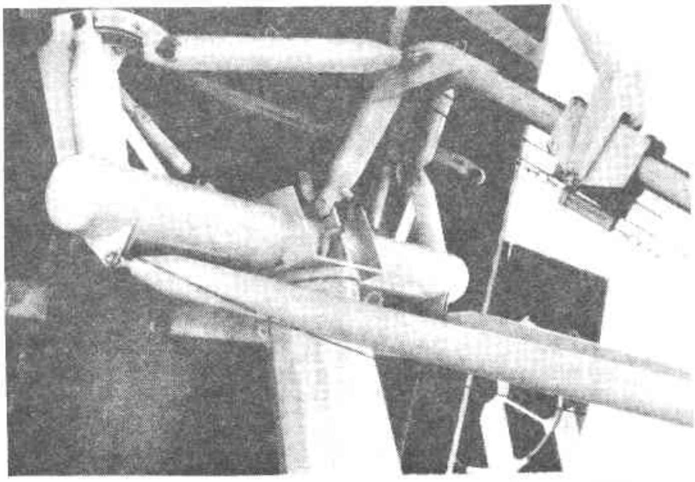
Selvage No. 14, Project THEM
Heliostat, St. Goban



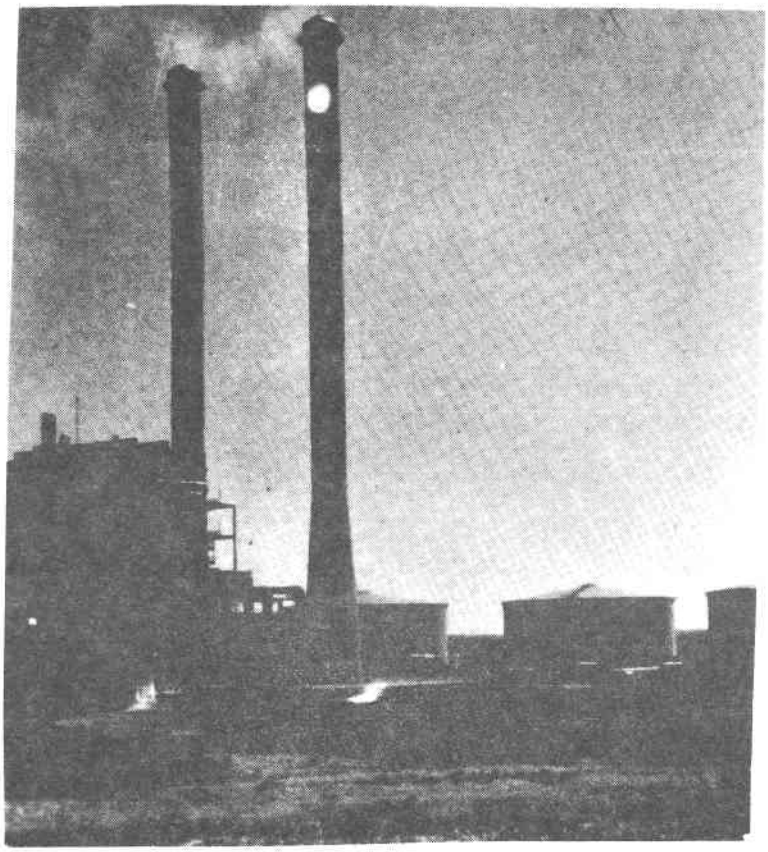
Selvage No. 15, Project THEM
Heliostat, CNRS



Selvage No. 16, Project THEM
Heliostat, CNRS

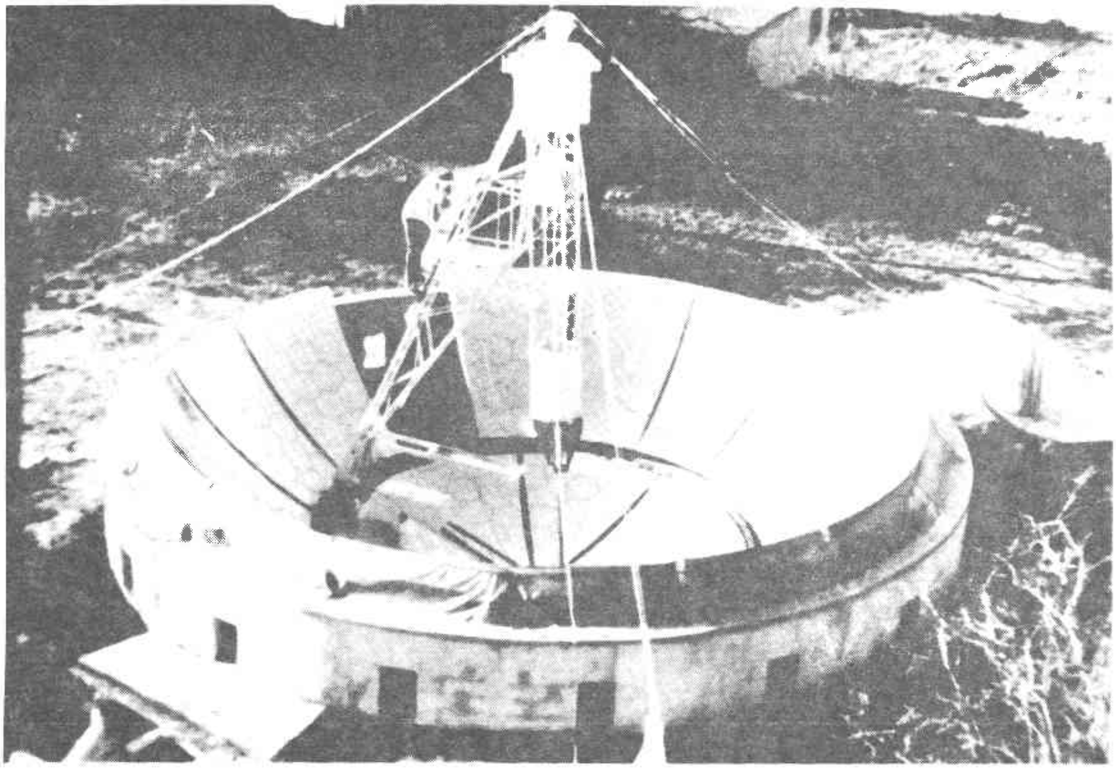


Selvage No. 17, Project THEM
Heliostat, CNRS



Selvage No. 18, Peoject THEM
Heliostat Images on Tower
at Marsailles

Selvage No. 19, Pericles



Selvage No. 20, Pericles Moving-
Focus Dish Reflector

They found there were some differences between what the measured and what they had calculated and they modified their receiver design and their radiant-to-thermal conversion philosophies as a result of that work. It is a beautifully done experiment with cost borne in mind but not the controlling factor.

Here's one of their panels (Fig. 21), which is a part of a sphere done in very lightweight concrete with very thin glass glued to the surface.

Figure 22 is a picture of the THEK I parabolic dish temperature experiment, again done by the French at one of their universities. Whereas the Pericles experiment is an experiment in pure science, the THEK is done on a shoestring, still by CNRS and the professors of the university, but they seem to get turned down every time they ask for more money to do another experiment, typical of universities, I guess, when asked for more money. But, they continue to plug along and to do a fairly decent job with almost no funding.

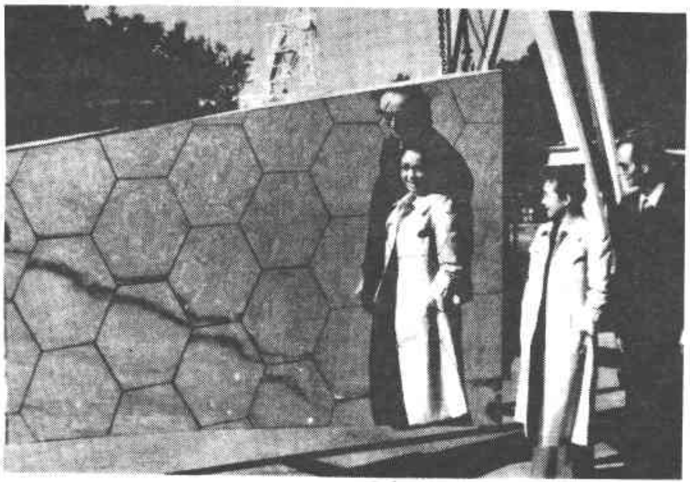
Figure 23 shows the first dish I've seen with the kind of system that made use of hydraulic actuators. The receiver is not installed as it is broken down. The actuators aren't the problem, it's some of the plumbing. But they couldn't operate it so postponed it until they had the receiver installed.

The second parabolic system, again at Marseilles, is shown in Figure 24. It is a CNRS design that uses the same basic approach that the CNRS heliostats use, that is, a mechanism that runs around a track to give you the azimuth and elevation tracking by pulling cables on the reflective part on an incline shaft. The mirrors are triangles mounted by a support at each of the corners, and you can see a couple of the mirrors installed. The alignment and insulation of the mirrors is very difficult because you must align each segment of the mirror, and as you move out you cannot disturb the ones that you already set. You take what you've got in terms of where they are, or you must start all over again. It's a very difficult operation and, therefore, the design is probably not too practical to manufacture.

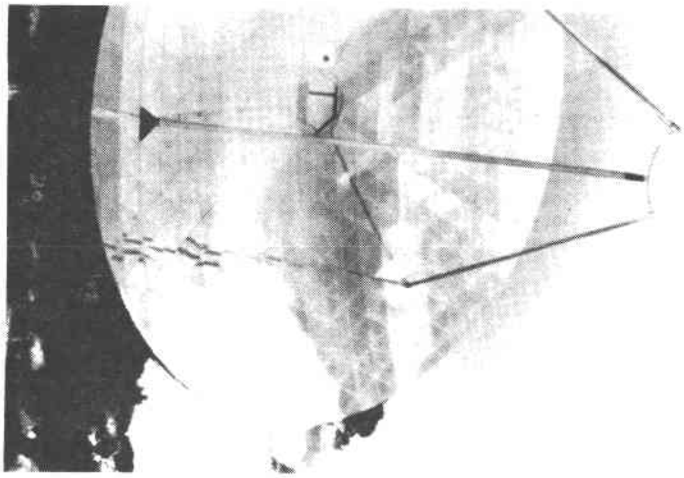
Figure 25 is a heliostat from Germany by MAN. It is the only one of this type that they have built and it is under test. I apologize for a few of these pictures because they were taken on the Fourth of July in a terrible rainstorm. We work on the Fourth of July in Europe because it isn't a holiday.

The back side of a 40-square meter heliostat is shown in Figures 26 and 27. It can be stowed face down. It has a pedestal and standard orbital drive mechanism. As a counterbalance weight, each of the mirror facets can be focused by pushing a ring on the outside and pulling on the center.

Figure 28 is the MAN facility and MAN-designed parabolic dish they are building. They will move to Spain for testing before very long. The Germans and Spanish have a program for the development of a 50-kilowatt electric system and that's one of the reasons that the MAN Company, which is basically a truck and bus manufacturing company, has been contracted by the German government to administer research and technology in Germany to develop solar-type things. The 50-kilowatt electric system that will be started in Spain and operated by the Germans, with most of the funding coming from Germany, will be

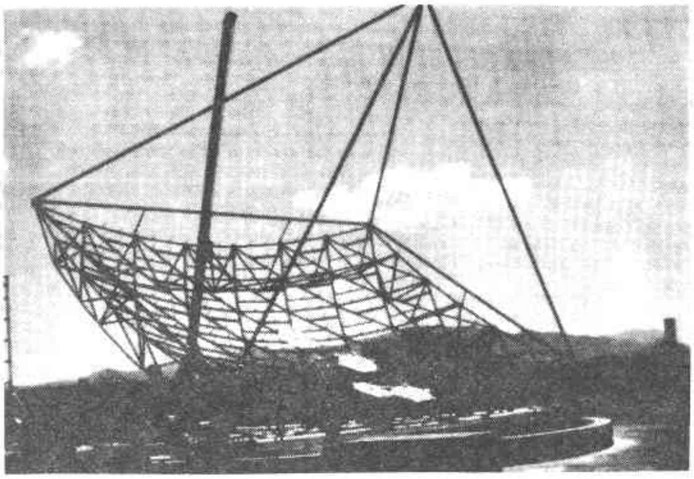


Selvage No. 21, Panel from Pericles Dish

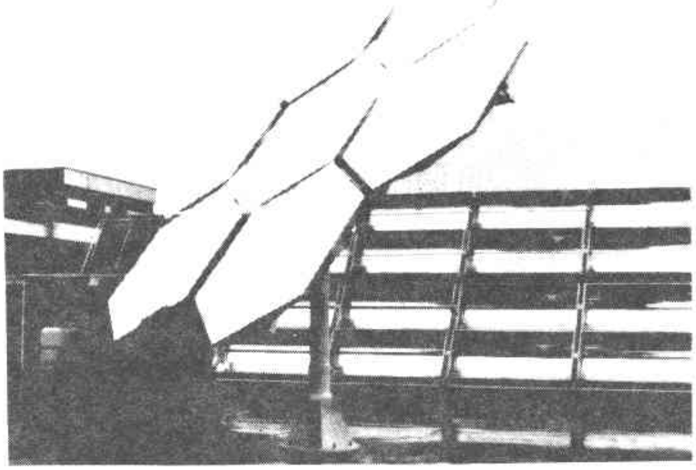


Selvage No. 22, THEK I Dish

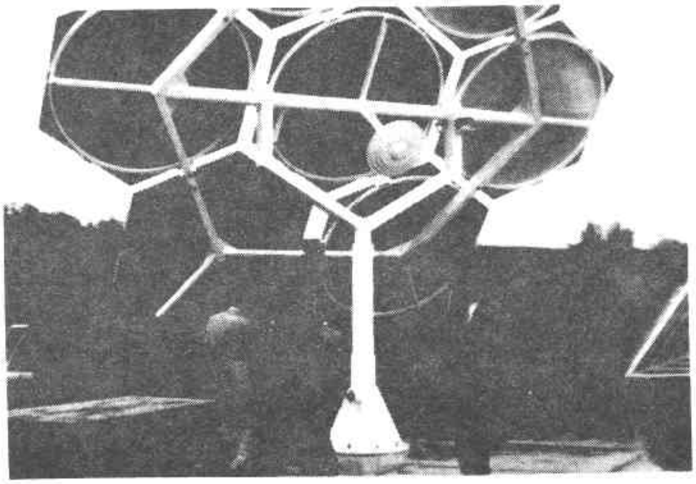
Selvage No. 23, THEK I Dish



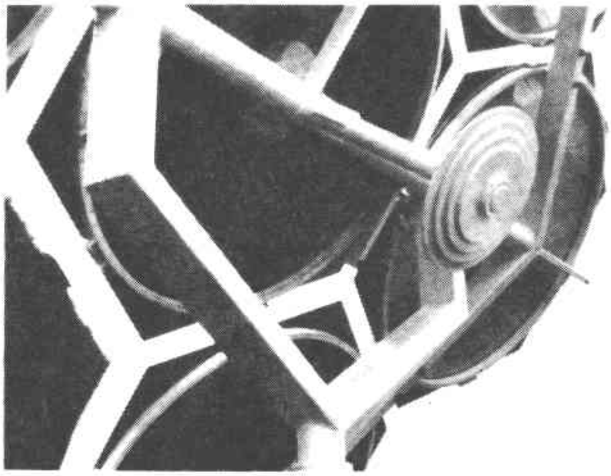
Selvage No. 24, THEK II Dish, CNRS



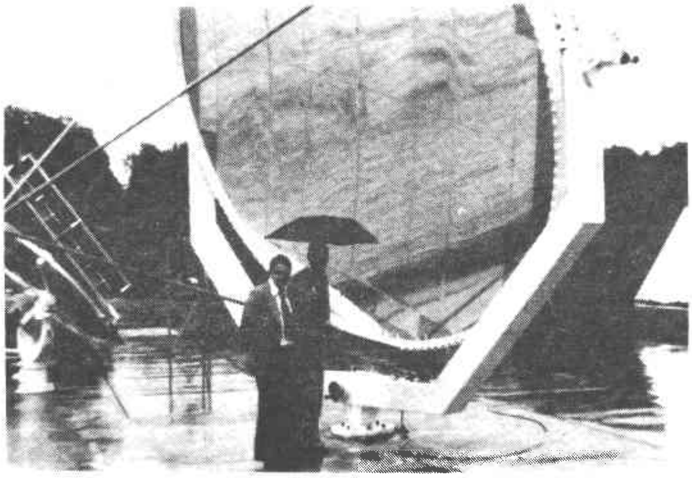
Selvage No. 25, Heliostat , MAN, Germany



Selvage No. 26, Heliostat, MAN, Germany



Selvage No. 27, Heliostat,
MAN, Germany



Selvage No. 28, Parabolic Dish,
MAN, Germany

a parabolic distributed collector-type of system that operates as a tracking-type. It's essentially the same unit that will be used in the SSPS project distributed system, see Fig. 3, the artist's concept of the SSPS system and the CNRS system that's north of this that I showed earlier. This beautiful picture was given to me by J. D. Walton and was made by Acurex, who, of course, is selling their products and pressing for continued and expanded international involvement by the IEA.

I have very little more to say about the SSPS, particularly the distributed system, except that it is operating at 290°C. They have limited-temperature collecting fluid, primarily because of fear and some experience Acurex had at Willard, New Mexico, and some of the experiments at Albuquerque that show the selective coating, the black chrome on the receiver, changed characteristics over a very short period of time if they operated at 300°C, so the outlet temperature of the cooling oil was set at 290°C. The thermal-to-electric conversion equipment for this distributed system is by Sundstrand--designed, built and tested up to at least 1500 operating hours. It is a 600-kilowatt organic Rankine cycle system. Sundstrand is under contract to the Department of Energy to build six of these systems. The first one will be delivered to the Coolidge, Arizona, project. It is derated to 150-kilowatts electric and will pump water at the Coolidge project. The second one will be what it was originally intended to be, a bottoming cycle in the power stage, and the third one will come to the SSPS project.

The sodium system for the SSPS project is portrayed in this line drawing in Figure 29. In apology for not showing more photographs of the kinds of things that will be done for the SSPS project, I want to say we're in a position where the first week in October is the final report by the contractor. All we have at this point are pictures of things that will be used in those experiments that were developed for other reasons. The work on the sodium system is taken right from one of those sodium loops that they designed for a reactor or materials research program. The receiver, in this case, is the new element. It is designed to operate at a peak of 600°C but they're trying to control the outlet sodium temperature at 540°C, which is somewhat derated from the maximum that you could use. There are some good reasons for that. One, as I've said before, is to decrease the risk in the thermal cycling and the higher temperature of the receiver itself. The other is the fact that when you're dealing at 500 kilowatt electric net output, the mass flows of steam in a turbine are so small that you really cannot make effective use of the higher temperature limits. Clearly, if one were building a 10-megawatt system, one could make more effective use of the higher temperatures that are possible with such a system.

It occurred to me this morning when I listened to a little bit of your talk that the very fact that this type of system is capable of operating at sodium outlet temperatures greater than 600°C may, in fact, be of interest to the high-temperature metals and chemicals work that you are addressing in this workshop.

This is a first step. This is not any real new technology except for the receiver. The receiver is the only thing that hasn't been built before for this type of a system and even before that both American companies and many European

SYSTEM SCHEMATIC

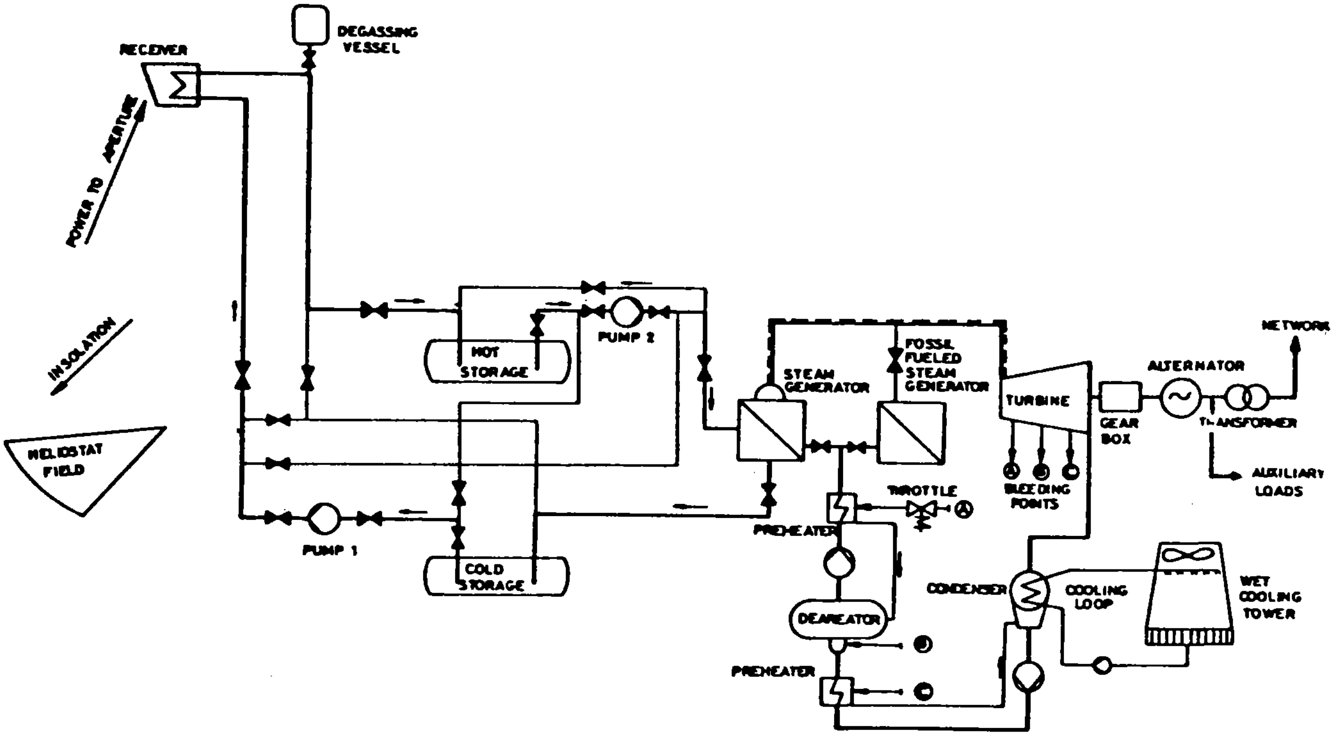


Figure 29

companies had built gas-fired sodium heaters which, in fact, are similar to if not exactly the same as a sun-powered sodium heater. One of the reasons, in fact, that sodium was elected for the system was that water was being used in two places in Europe--Spain and the European Economic Community program in Italy--and Hi Tec was being used by the French in their THEMIS program. And, it looked like you could not get Brayton cycles done in three years--the temperatures, at least, that people were proposing for study in Madrid. So, it appeared that sodium was possible, and, also, all ten countries that joined this project had sodium technology so all were able to contribute, to participate, to understand, and to, finally, compete with each other and with us in marketing such a system and striving for the design and fabrication responsibilities. So, sodium was finally selected. It was a difficult, tedious task to get to a point where sodium was seriously considered, but it was. The then Chairman of the Research and Development Committee of the IEA, Dr. Smith Kuster, finally made the decision that Brayton was a little too far off, and that sodium was probably a new candidate and we should at least proceed to stage one. Stage one comes to an end in October with the detailed design of a system using sodium.

As a matter of fact, the work that has been done in trying to improve or bring the efficiencies of the thermal conversion through electricity system up, that is, the turbine generator up, have been very impressive in that we are told--we'll see if we build one-- that we can get a little over 27 percent conversion efficiency with that turbine and turbine generator system, which seems very good in light of the very small size of the system. Figure 30 is a chart of the distributed collector systems.

One of the real problems with solar systems is cost and cost projection being competetive with the market. Consequently, one of the staff listed all of the systems that we knew of that had been built or were being built and they were costed out and/or were actually priced, and put them on these charts (Figures 31 and 32), which show us the size of the plant and the cost. This is in, as you'll notice, Deutsch marks per kilowatt electric, and I'll apologize for that, but our SSPS project has been in Deutsch marks, and although I'm paid in dollars, I spend in Deutsch marks. You'll notice some rather interesting numbers, the cost of the Barstow plant is shown and it's probably the largest. It's also the biggest plant that is even contemplated at this point.

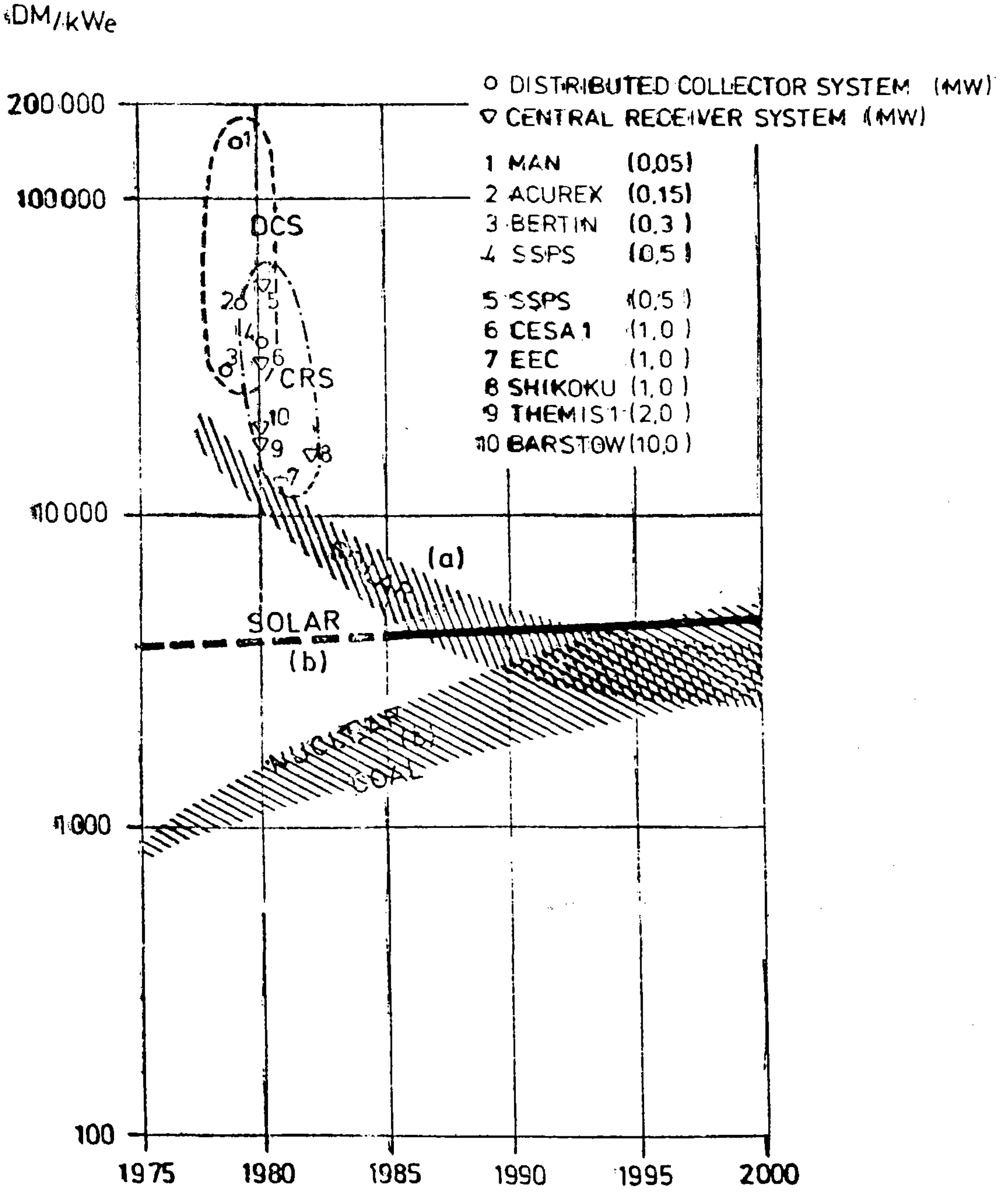
The SSPS project is number 4 and number 5. These were costs at the midpoint and we're really not sure what the cost will be at the end of stage one. You will notice a very interesting one is number 7, which is the European Economic Community cost. This is supposed to be a 1-megawatt system but the unfortunate part about this is that everybody isn't working to the same set of requirements. The European Economic Community 1-megawatt system is 1 megawatt on July 21 at noon. The SSPS 500-kilowatt systems are 500 kilowatts electric any time of the year, whenever the insolation is above 700 watts per meter square.

When one tries to relate what the rating of the EEC system would be at the same requirements, you come out that it's about 600 kilowatts rather than the 1 megawatt that they've rated the system. When you do that, you find that they're almost the same in cost.

FIGURE 30: SOLAR THERMAL ELECTRIC POWER GENERATION PROJECTS IN THE PLANNING STAGE

	COUNTRY	FACILITY; LOCATION; DIRECTED BY	RATING; EFFICIENCY	DATE OF COMPLETION; COST ESTIMATE*	MODE OF COLLECTION CONCENTRATION RATIO	TRANSFER MEDIA/TEMP; STORAGE/CAPACITY; PRIME MOVER
DISTRIBUTED COLLECTOR	(IEA)	SSPS-B Almeria, Spain DFVLR	0.5 MW 8%	1980 ~19 MIO DM	Parabolic Troughs ~35	Thermal Oil/300°C; Thermal Oil + Rocks/ 4 Hours; Organic Rankine Turbine
	FRANCE	- Corsica	0.3 MW	1978 ~9 MIO DM	Parabolic Troughs; ~20	Thermal Oil/200°C Thermal Oil + Rocks/? Organic Rankine Turbine
	USA	DWIF Arizona	0.15 MW	1979	Parabolic Troughs; ~35	Thermal Oil/200°C Thermal Oil + Rocks/114 m^3; Organic Rankine Turbine
	GERMANY	- Kairo BMFT	0.01 MW 7%	1978 ~5 MIO DM	Parabolic Troughs (200 m^2) and Heat-Pipe Collectors (400 m^2); ~10 (Parabolic Troughs Only)	Water/250°C Water/3 Hours (3 kW$_e$); Radial Freon Turbine
	GERMANY	- Almeria BMFT	0.05 MW 10%	1979 ~9 MIO DM	Parabolic Troughs (300 m^2); ~10	Thermal Oil/250°C; Oil + Cast Iron/0.5 Hours (3 m^3); 2-Stage Steam Screw Expander

*Nonrecurring Cost Elements Included

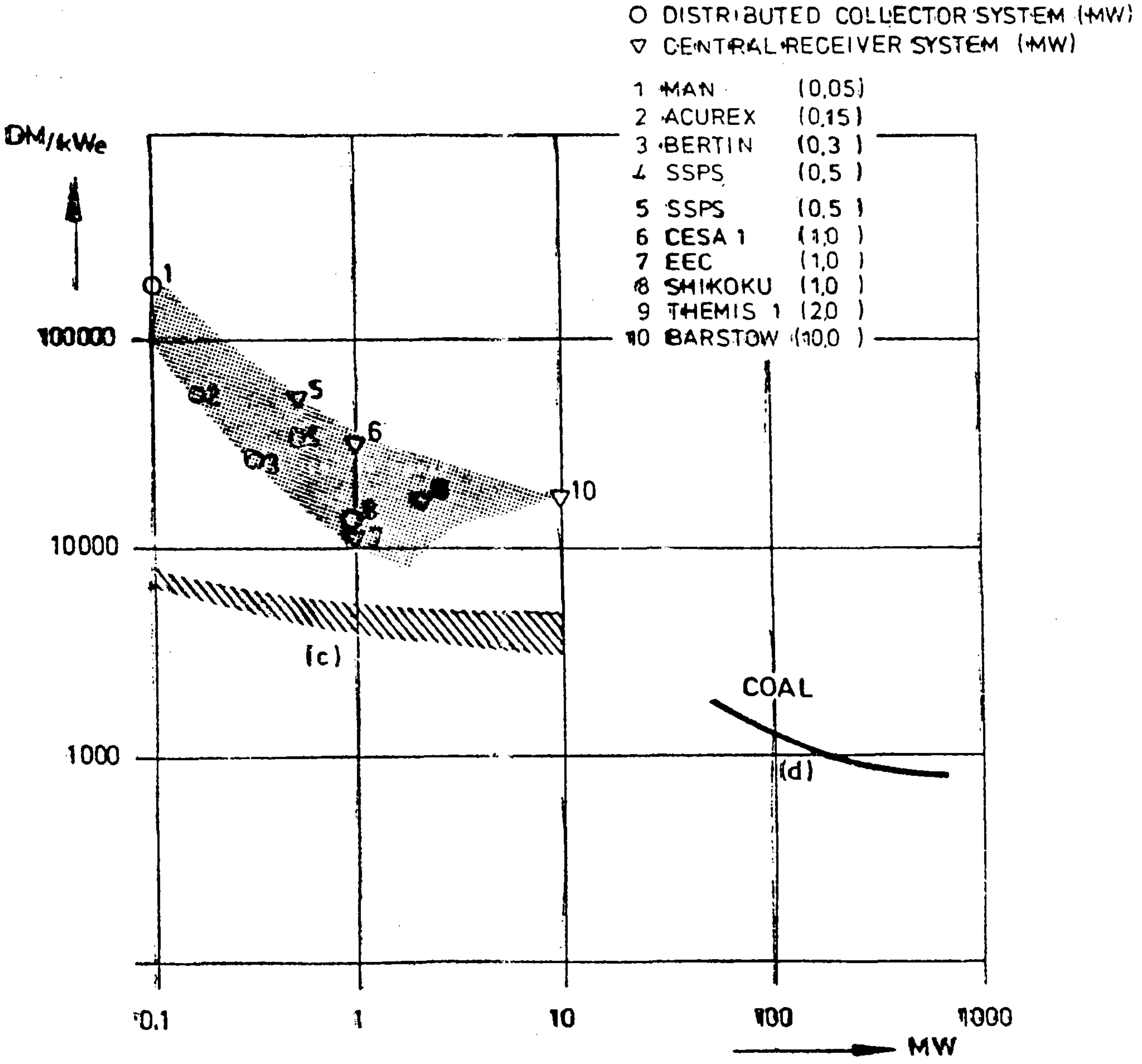


REF:
(a) PROGRAMME PIRDES, CNRS 1977
(b) CAPUTO, TRUSCELLO: SOLAR THERMAL
ELECTRIC POWER PLANTS.....
PROC. 11th IECEC / USA

INVESTMENT COSTS FOR PLANNED SOLAR THERMAL POWER PLANTS VERSUS COST PREDICTIONS (a) and (b)

IEA-SSPS
OPERATING A
DFVLR

Figure 31



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(c) Vergl. ANALYSE VON SONNENKRAFTWERKSKONZEPTEN
MBB BERICHT UR-314-76

(d) DINGELDEIN, Ch W HULS

ESTIMATED SPECIFIC INVESTMENT COSTS
FOR PLANNED SOLAR POWER PLANTS
(PRICE BASIS 1976/77)

IEA-SSPS
OPERATING AGEN
DFVLR

Figure 32

Clearly, we think that costs are coming down, will come down, as we build more of the systems. The European community is very, very interested in solar energy and is working diligently and vigorously on a broad spectrum of programs, Figure 33. I have only shown you a very few of these, those that are central receiver or related to high concentration, such as the parabolic dishes. There are multinational programs between Germany and Egypt, and Germany and Mexico. They have a very, very large developing program with a new agreement just recently signed between Germany and Mexico to develop solar energy. They will develop solar energy primarily as a larger irrigation project, but there will also be a solar thermal-to-electric conversion project where 50 percent of the funding will be paid by Germany and 50 percent by Mexico.

There are some rather extensive efforts being conducted between Germany and Saudi Arabia, as there are between the US and Saudi Arabia. They also look very interesting; the Saudi's are very interested in solar energy, as well.

France is very active, as are almost all of the small countries within their own countries. There is a segment of the French scientific and technical community that feels all of France's energy needs can be satisfied by solar and water. There is, in fact, a study that's been published in France--I have a copy--that is called Practic Alter, the plan to alter the community. They start out with the present situation where their energy comes from water--hydroelectric--nuclear, coal, oil and gas. At the end they show only solar, water and wind. They do require some conservation techniques such as that energy demands in some areas go down. It's very controversial--very optimistic but very controversial. It has hit the French scientific community and rattled around at fairly high levels. It has, in fact, caused or helped to bring about the creation of the Energy Commissariat, headed by Mr. Durant, increased awareness, and an increased budget in France. That is only one example, but one that's probably easier to identify with because France is one of the larger countries in Europe and also a forerunner in the solar energy business.

Germany looks upon their ability to develop internal solar energy as nil. They do get the sunshine, of course; that's why they're able to grow grapes, and they do grow some nice wines, and they're able to grow nice forests. But, they are realists and know that they have a very low probability of economically being able to do solar thermal-to-electric conversion programs within the borders of Germany. But, they have their eye on Spain and they have been negotiating and are negotiating more particularly as people like Jerry Weingart publish studies which are very real and very well done that indicate you can satisfy all of Europe's electrical energy needs by building solar thermal electric plants in southern Spain and piping the electric energy over existing transmission lines for less than you'd be paying for energy ten years from now in northern Europe. His study identifies a couple of soft points. One is the cost in transmitting the energy. But, there is an electric grid right here that ties every one of the European countries together. They have a very fine community in terms of understanding what their electrical needs are and their generating systems should be so that under normal conditions electricity isn't transmitted more than 500 kilometers. But, they're quite capable right now of providing all of the energy needs over that grid that goes from Spain to

June 1978

COUNTRY PARTICIPATION IN IEA COOPERATIVE PROGRAMMES AND PROJECTS IN ENERGY RESEARCH, DEVELOPMENT AND DEMONSTRATION

		AUSTRIA	BELGIUM	CANADA	DENMARK	GERMANY	GREECE	IRELAND	ITALY	JAPAN	LUXEMBOURG	NETHERLANDS	NEW ZEALAND	NORWAY	SPAIN	SWEDEN	SWITZERLAND	TURKEY	UNITED KINGDOM	UNITED STATES	EUROPEAN COMMUNITIES
	ENERGY RESEARCH, DEVELOPMENT AND DEMONSTRATION STRATEGY		*	*	*	*		*	*	*		*		*	*	*	*		*	*	*
	ENERGY CONSERVATION																				
1	URBAN PLANNING						⧆													*	
2	WIEHL/ESSLINGEN					⧆														*	
3	BUILDING ENERGY LOAD DETERMINATION			*	*				*							*	*		*	⧆	
4	HEAT PUMPS	*			*	*		*	*			*	*			*	*			*	
5	COMBUSTION															*			*	⧆	
6	CASCADING	*	*	*		*				*		*				*	*			⧆	
7	HEAT TRANSFER/HEAT EXCHANGERS															*	*		⧆	*	
	COAL TECHNOLOGY																				
8	TECHNICAL INFORMATION SERVICE	*	*	*		*			*	*		*	*		*	*			⧆	*	
9	ECONOMIC ASSESSMENT SERVICE			*		*			*			*			*	*			⧆	*	
10	WORLD COAL RESERVES & RESOURCES DATA BANK		*	*		*			*										⧆	*	
11	MINING TECHNOLOGY CLEARING HOUSE		*	*		*			*				*		*				⧆	*	
12	FLUIDISED BED COMBUSTION					*													⧆	*	
13	LOW BTU COAL GASIFICATION[1]					⧆														*	
14	COAL PYROLYSIS					⧆										*			*		
15	TREATMENT OF COAL GASIFIER EFFLUENT LIQUORS											*							⧆	*	
	NUCLEAR POWER																				
16	NUCLEAR REACTOR SAFETY EXPERIMENTS	*			*	⧆				⧆		*		*		⧆			⧆	⧆	
	GEOTHERMAL ENERGY																				
17	MAN-MADE GEOTHERMAL ENERGY SYSTEMS					⧆										*	*		*	*	
	SOLAR ENERGY																				
18	PERFORMANCE OF SYSTEMS FOR HEATING & COOLING[2]		*		⧆	*	*		*	*		*	*		*	*	*		*	*	*
19	DEVELOPMENT OF COMPONENTS FOR HEATING & COOLING[2]	*	*		*	*	*		*	⧆		*	*		*	*	*			*	
20	TESTING COLLECTORS FOR HEATING & COOLING[2]	*	*	*	*	⧆	*		*	*		*	*		*	*	*		*	*	*
21	INSTRUMENTATION PACKAGE[2]		*	*		*			*			*			*		*		*	⧆	*
22	TREATMENT OF METEOROLOGICAL INFORMATION[2]	*	*	*	*	*			*			*			*	⧆	*		*	*	*
23	SMALL SOLAR POWER DEMONSTRATION	*	*			⧆	*		*						*	*	*		*	*	
	BIOMASS CONVERSION																				
24	TECHNICAL INFORMATION SERVICE		*					⧆								*			*	*	
	OCEAN ENERGY																				
25	WAVE POWER			*						⧆									*	*	
	WIND ENERGY																				
26	LARGE SCALE WIND ENERGY DEMONSTRATIONS				*	*										*				*	
27	TECHNOLOGY OF WIND ENERGY CONVERSION SYSTEMS	*		*	*	⧆		*		*		*	*			⧆				⧆	
	FUSION ENERGY																				
28	SUPERCONDUCTING MAGNETS									*						*	*			⧆	*
29	PLASMA/WALL INTERACTIONS (TEXTOR)			*		*				*						*	*	*		*	⧆
30	INTENSE NEUTRON SOURCE			*						*						*	*			⧆	*
	HYDROGEN																				
31	HYDROGEN PRODUCTION FROM WATER		*	*		⧆			*	*		*				*	*			*	⧆
	OTHER ACTIVITIES																				
	CO-ORDINATED PLANNING OF COAL HYDROGENATION PROGRAMMES					*														*	
	CO-ORDINATED PLANNING OF FORESTRY ENERGY (BIOMASS) PROGRAMMES		*	*				*								*				*	

[1] This project is not yet in an Implementing Agreement, and is covered by a Statement of Intent.

[2] These five projects are combined in the same Implementing Agreement.

* Participation in Project

⧆ Operating Agent

Figure 33

Germany. It doesn't go that way very often but it could if they needed it, and with very little modification to it, they could probably even make it economic.

Presently, people from Sweden, Belgium, The Netherlands, and Germany are becoming more and more convinced that if they can they should convince the people in southern Italy and southern Spain that they should become the source of electrical energy for Europe. They are becoming more and more convinced that one can build these systems and make them economical and provide for the energy needs of Europe.

That's an interesting concept and it's one that's causing, as an example, the German budget for solar energy to go up even faster than ours.

Thank you.

SECTION V - SOLAR HIGH-TEMPERATURE FACILITIES

OPERATION OF THE CENTRAL RECEIVER SOLAR THERMAL TEST FACILITY

Billy W. Marshall
Sandia Laboratories
Albuquerque, NM

SUMMARY

The Central Receiver Solar Thermal Test Facility (CR-STTF) at Albuquerque, New Mexico, has been constructed to test components and subsystems for the Department of Energy (DOE) Large Solar Central Power Systems Program. Facility construction was started in the summer of 1976 and construction activities, exclusive of an office/laboratory addition to the control building and an assembly/warehouse building, are presently being completed. The first phase of the formal facility acceptance tests was completed by a DOE/Sandia team in July and the final phase is scheduled for early October. During June and July, extensive solar operations designed to characterize the heliostat field were conducted using the $1MW_t$ Working Receiver (WR) as the target. In addition the Real Time Aperture Flux (RTAF) system, a diagnostic tool to be used in the tower to measure the flux pattern incident on receivers during a test, was tested and the data correlated with those from the WR. Other ongoing activities include reflectivity characterization and maintenance of the CR-STTF heliostats; development of a system for evaluating prototype heliostats; installation of the first two receivers to be tested at the facility; and design of a flux reconcentrator to be used for very high flux density ($>10MW/m^2$) materials tests.

FACILITY STATUS

All portions of the facility which are essential to operation of the facility have been completed. Two remaining buildings, the assembly/warehouse building and an office/laboratory addition to the control building, have been approved and are in final design or initial construction. Status of the three major elements of the facility is discussed in the following.

Heliostats

Installation of the 222 heliostats which were authorized in the project was completed in November, 1977. Presently, 66 of the 78 heliostats in Zone A (nearest the tower) are aligned to the 42.7m test bay location for the EPRI/Boeing tests and

122 of the 144 in Zone B are aligned to the tower top for the McDonnell Douglas (MDAC) test. Alignment of the remaining heliostats which have been disassembled for repair or aligned for other locations to the elevation appropriate to that zone is underway. Following this interim alignment and completion of the first phase of the EPRI/Boeing tests, all Zone A heliostats will be realigned to the 61m level for use with the MDAC receiver panel tests. Figure 1 is an overall view of the facility which shows all heliostats installed and oriented in the vertical off-set position used for mirror washing.

Master Control and Data Systems

All computer hardware for the Master Control System (MCS) and Data Acquisition System (DAS) has been installed in the control room. Figure 2 presents a view of the system control and data display station. The control software in the minicomputers was completed in May 1978, and the associated documentation completed in August. The MCS and DAS systems both performed as expected during the recent working receiver tests. The systems are now functioning as intended and the specific control, data acquisition, and display requirements for each test program can be programmed into the computers.

Tower

The final major element of the facility includes not only the concrete tower but also the heat rejection system (HRS) and the elevating module. The HRS was modified from the original concept to include high pressure air and steam capabilities specifically to accommodate the first two receiver test programs. All of the capabilities of the HRS including low temperature cooling water, high temperature-high pressure feedwater, and high pressure air are now available at all test locations.

The tower has been completed to its 61m height. Heat protection panels completely around the tower top and on the north side of the tower near the test bays have been installed. The 100-ton elevating module in the center of the tower was completed and raised to the tower top without load (only the module weight on the cables) in June. Load tests, consisting of raising and lowering the module with 100 tons placed first on the east side and then again with the load placed on the west side of the module, were also performed in June. Subsequent inspection of the module revealed damage to the structural members to which the module guide rollers were attached and

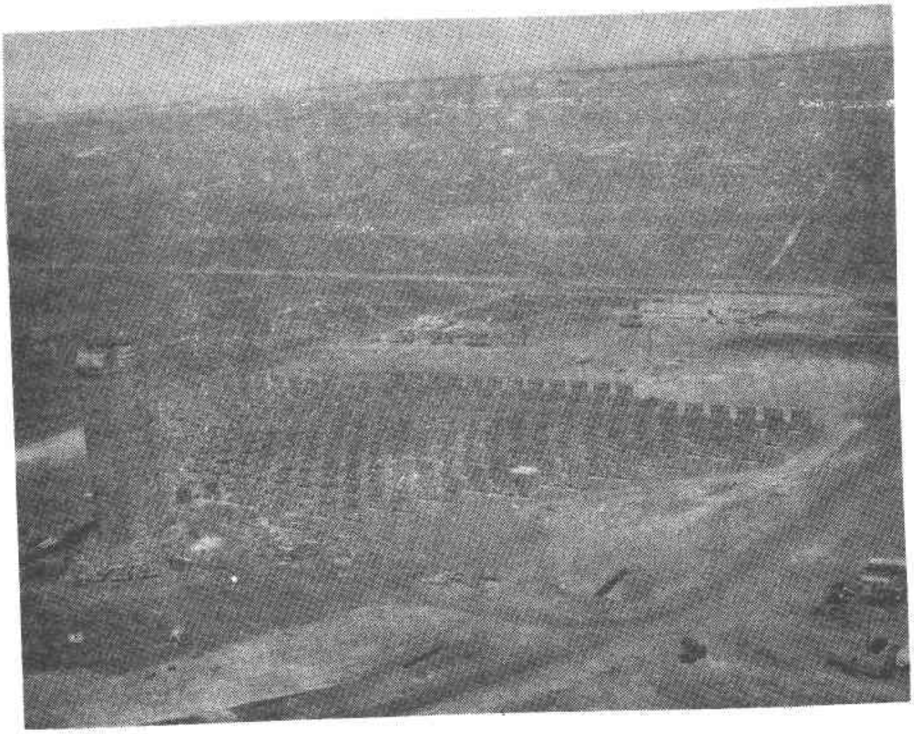


Figure 1
Central Receiver Solar Thermal Test Facility

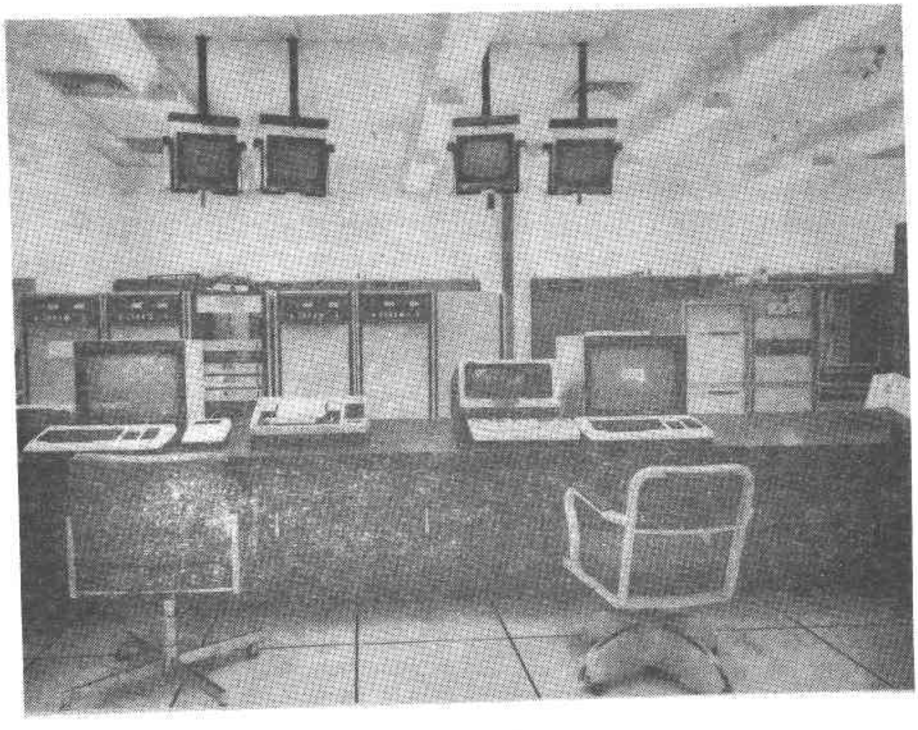


Figure 2
CR-STTF Control and Data System

repair was necessary. During the repair period, the module was raised to the 42.7m level with 20 tons to certify its use with the EPRI/Boeing receiver. The damaged members were repaired and strengthened and the module was successfully raised to the tower top with 50 tons positioned at the location where the MDAC receiver will be attached. On September 20 an accident involving the failure of a contractor supplied hoist caused damage to the elevating module. The module is presently undergoing repair and load testing will be repeated when the repair has been completed.

Acceptance Tests

A team comprised of representatives from DOE/Headquarters, DOE/Albuquerque Operations, Sandia Livermore, and Sandia Albuquerque was formed to conduct and review facility acceptance tests. Phase I of these tests, related to operation of the heliostats, MCS, DAS and the working receiver, was satisfactorily completed in mid-July. Phase II, primarily related to operation of the steam heat rejection system using MCS and to operation of the elevating module, will be performed in October. Although general cleanup, touch-up, painting, and several minor repair items must still be completed, the facility is essentially complete.

FACILITY OPERATIONS

Working Receiver Tests

Figure 3 is a schematic of the water cooled 3m x 3m test receiver which was designed for use in characterizing the flux density and distribution from the heliostat field. This Working Receiver (WR) is populated with 81 symmetrically spaced heat flux gages to measure the flux distribution and a number of thermocouples and flow meters to measure the total power absorbed by each of the nine 1m x 1m panels which make up the receiver. From April through July numerous different combinations of heliostats were targeted onto the WR. A photograph of the illuminated WR located in the 42.7m test bay is shown in Figure 4.

Data from the flux gages and thermocouples were obtained, recorded, and subsequently analyzed using DAS. A typical example of the data resulting from these operations is shown in Figure 5. During this particular test, 49 heliostats were pointed to a single location on the WR and the measured

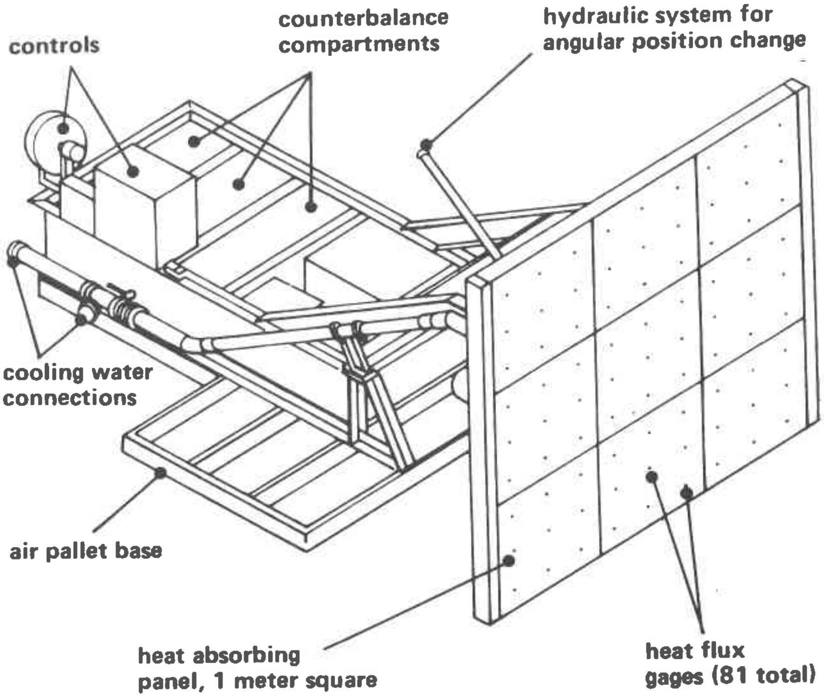


Figure 3
Schematic of Working Receiver

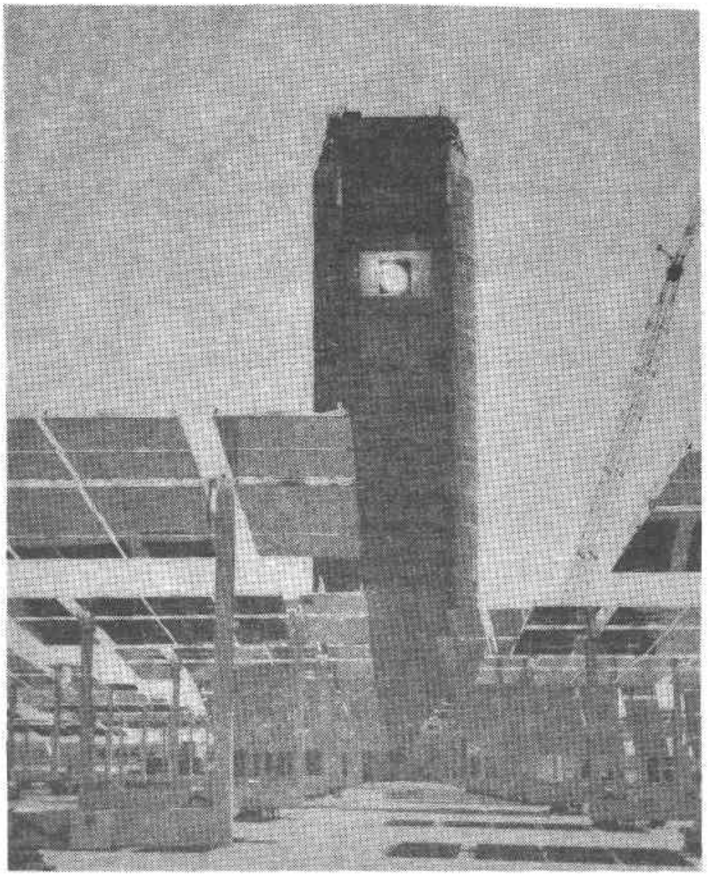


Figure 4
Working Receiver During Tests

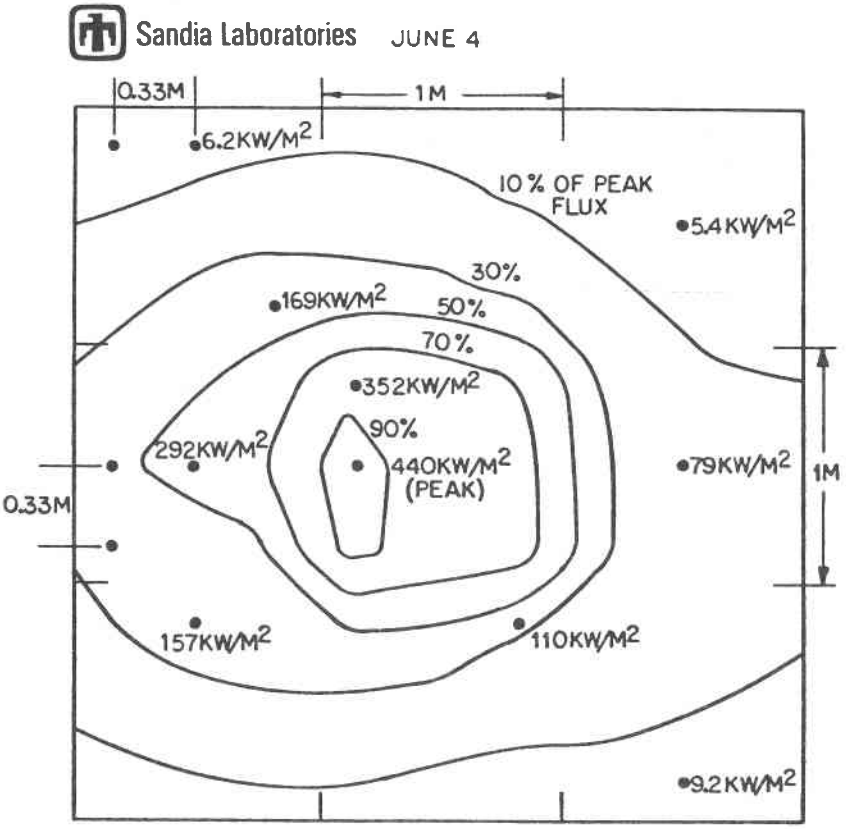
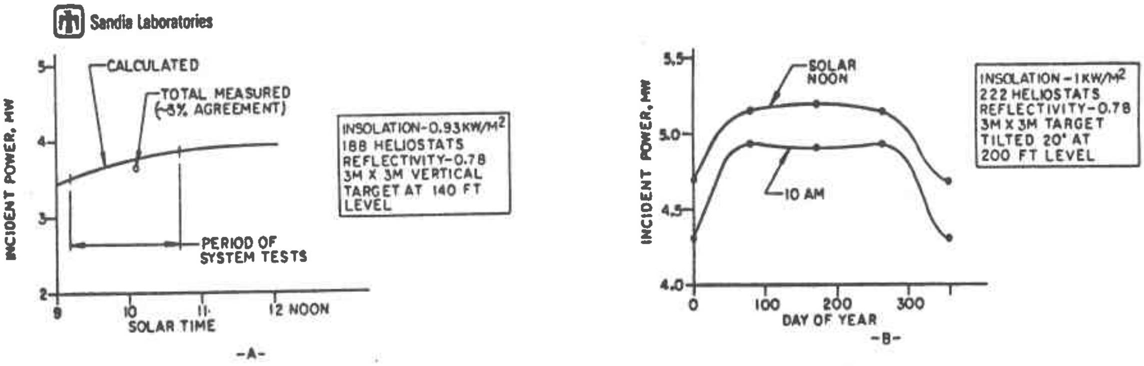


FIGURE 5

FLUX DISTRIBUTION ON WORKING RECEIVER

power was 930 kilowatts. The flux contours were constructed by the DAS computer using data from the flux gages. To illustrate the data, selected measured flux values are shown on the figure. The peak flux density measured near the center of the WR was 440kW/m^2.

During Phase I of the acceptance tests, 210 of the 222 heliostats (all that were operable) were brought to the standby position just east of the 42.7m level of the tower. Seven groups of heliostats, totaling the entire 188 which were optically aligned, were brought onto the WR during an approximate 2-hour period prior to solar noon. The maximum power incident on the WR from any of the groups was 1.06MW$_t$ and the total from the 188 heliostats was 3.64MW$_t$. Data from these tests were compared with the results from calculations made using the computer program HELIOS for the given heliostat alignment and test receiver. Figure 6-A shows good agreement between the measured total incident power and the calculated incident power. Figure 6-B presents results from the latest HELIOS calculations of the maximum flux incident



-A- -B-

FIGURE 6

MEASURED AND CALCULATED POWER

on a 3m x 3m target located at the tower top with all 222 heliostats in operation and properly aligned. These results include effects of shadowing, blocking, heliostat surface and tracking errors, and incorporate the measured mirror reflectivity values. The good agreement between the measured and calculated values shown in Figure 6-A, together with the calculated results shown in Figure 6-B, indicate the peak incident power from the facility should exceed $5MW_t$ at the tower top.

During the final period of operation with the WR, the Real Time Aperture Flux (RTAF) system was placed in position in front of the WR. The RTAF will be used with a number of the receivers to be tested at the CR-STTF and operates by sweeping a bar populated with photon and heat flux gages across the solar beam incident on the receiver. The purpose of these tests was to check out operation of and data acquisition from the RTAF and to correlate the RTAF data with those from the WR. The system worked as planned and the RTAF data, although not completely reduced at this time, agreed generally within 8 to 10% of that from the WR. All of the control and data display functions of the RTAF worked as planned and the system is being fitted with additional photon gages. It is scheduled to be placed in position for the EPRI/Boeing receiver about October 1.

Heliostat Operation and Maintenance

In the past six months greater operation of the heliostat field has revealed several operational characteristics and resulted in certain O & M requirements. As a result of this operation and the exposure of the heliostats to the wide range of weather conditions, several activities were initiated. Figure 7 is a summary of the operational status of the field and the accumulation of total heliostat operating hours since January. At the end of August, over 39,000 heliostat hours of operation had been accumulated. During that period an average of over 10% of the field was inoperable for a variety of reasons. Figure 8 presents a summary of the heliostat repairs since January. The curves show the number of failures for the azimuth and elevation drives, for the heliostat control electronics (HCE), and for other failures such as motors, cabling and power boxes.

Repair of azimuth drives requires complete removal of the heliostat from its foundation. Figure 9-a shows the operation to lift the heliostat from the azimuth drive unit and Figure 9-b shows removal of the azimuth drive from the foundation. A summary of the general causes of failure is shown in Figure 10. To help reduce the moisture problem in the drive system, two actions have been taken. First, the interior surfaces of the drives are being cleaned and painted with zinc chromate to reduce rust. Second, a cover with a built-in, reusable dessicant has been designed and will be installed on the drives. For the HCE's a careful, more precise adjustment of certain components together with the replacement of selected other components with higher performance devices is underway. The continued reduction of the number of heliostats inoperable indicates these and other corrective actions will result in availability of the number of heliostats required to perform the receiver tests.

Reflectivity Measurements

Weekly reflectivity measurements on samples of the heliostat mirrors have continued since March. The test samples are attached to the heliostats and stored in one of three orientations; surface up, surface down, or surface vertical facing south.

The data, including general notations of precipitation and weather, are presented in Figure 11. Effects of dust and rain are particularly evident for the samples stowed surface up. For the other two orientations, a gradual drop in reflectivity has been observed until recently when a heavy rain accompanied by wind caused reflectivity values for all stowage orientations to increase. In the future these measurements will be incorporated with a systematic mirror washing program using a high pressure, mirror wash vehicle which was recently delivered to the CR-STTF.

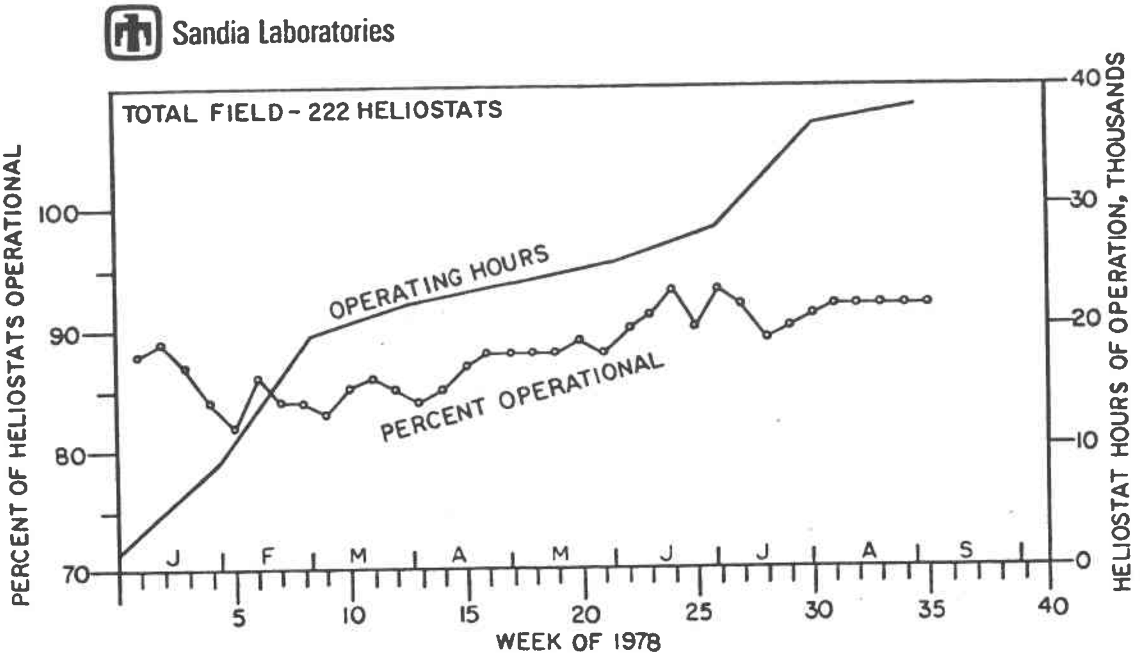


FIGURE 7

HELIOSTAT FIELD STATUS

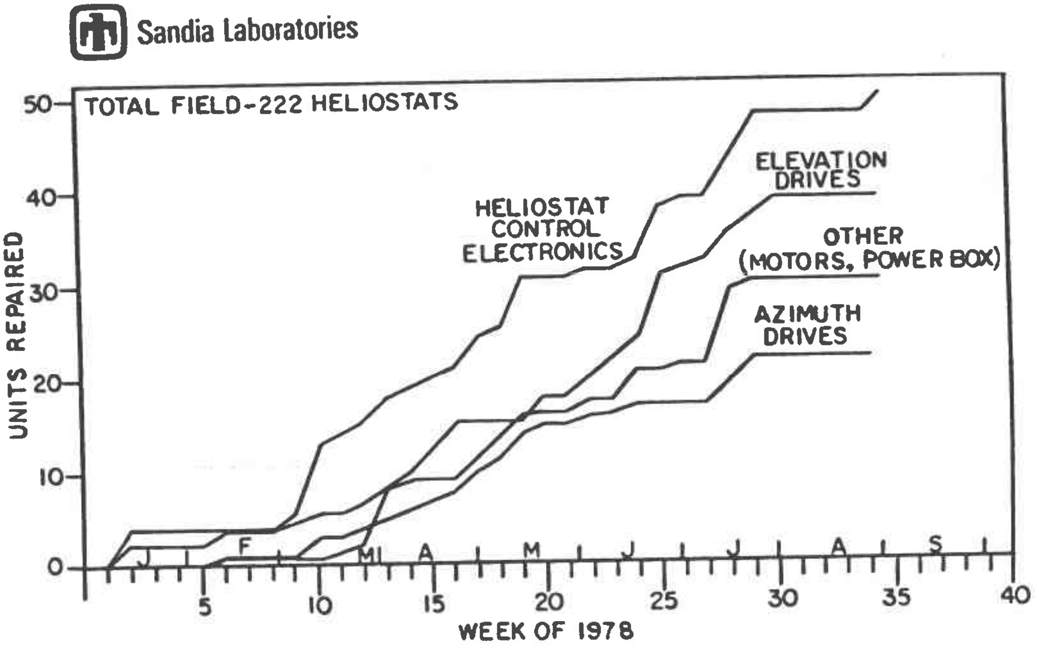
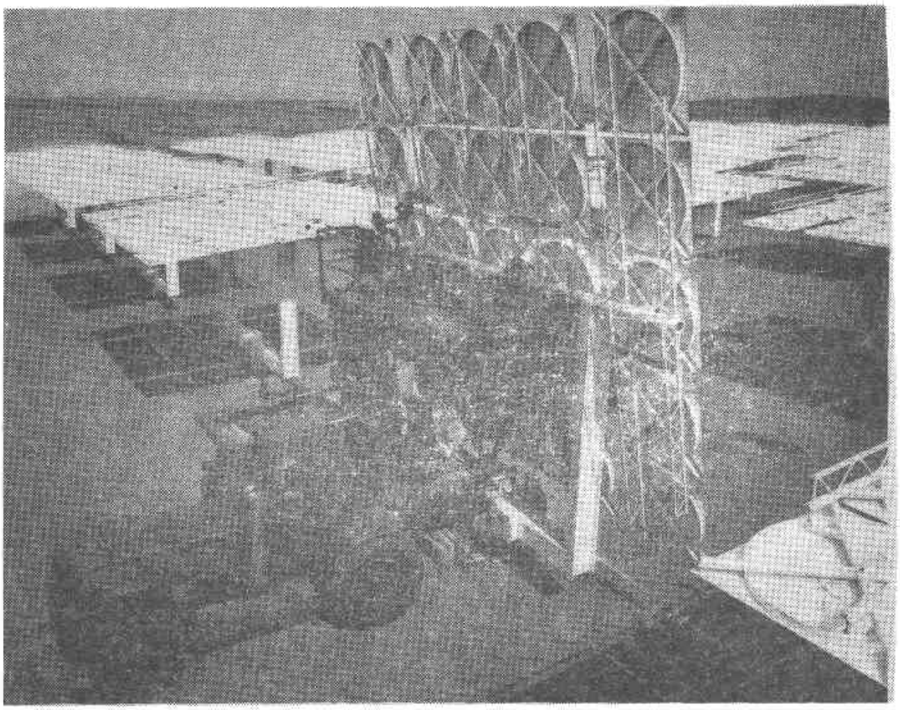


FIGURE 8

REPAIR HISTORY FOR HELIOSTATS



-a-

-b-

Figure 9
Removal of Heliostat Azimuth Drives

- DRIVE SYSTEMS
  - MOISTURE DAMAGE
  - IMPROPER 'POT' ADJUSTMENT IN ENCODER
  - WEAK SENSOR BLOCK IN ENCODER
  - BROKEN COMMUTATOR
  - CORROSION (RUST) CONTAMINATION
- HELIOSTAT CONTROL ELECTRONICS
  - MOISTURE AND CORROSION EFFECTS
  - COMPONENT FAILURE DUE TO TEMPERATURE VARIATION
  - DELAMINATION OF PC BOARDS
  - CONTROL RELAY FAILURE

FIGURE 10

MAJOR FACTORS IN CR-STTF HELIOSTAT MAINTENANCE

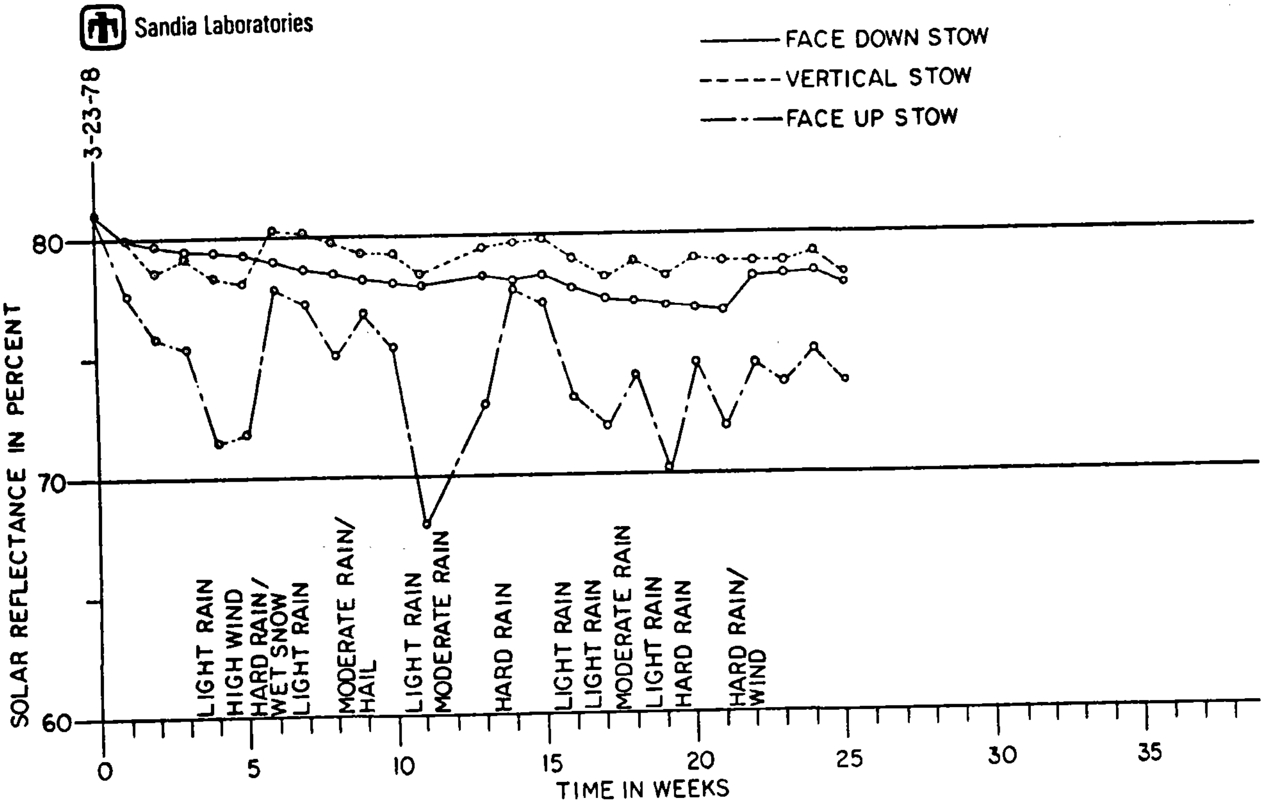


FIGURE 11

REFLECTANCE VS. TIME

FOR

DIFFERENT STORAGE ORIENTATIONS

Heliostat Prototype Evaluation

A program is underway to equip the CR-STTF with the capability to provide systematic and comparable evaluation of prototype heliostats as they are developed. The central element of this capability is a system to measure the quality of the beam reflected from the heliostat. This system, called the Beam Characterization System (BCS), consists of a video camera, an image analyzer, a digitizer and other computer equipment necessary to record and analyze images reflected onto a tower mounted target from the heliostat under test. The target will be equipped with flux measuring gages and pyrheliometers to provide absolute flux values. The system, scheduled for checkout operation in January, will be capable of measuring the beam shape, providing flux contour maps, and calculating the beam centroid. The equipment has been ordered and the main computer system has been delivered. Activities are underway to design and construct both the target and the foundations on which the test heliostats will be placed. The heliostats will be located to provide approximately 365m slant ranges for the evaluation. Other parameters to be considered include pointing and tracking accuracy, heliostat response under simulated wind and/or ice loading, heliostat frequency response, and possibly an evaluation of the effects of vortex shedding.

TEST SCHEDULE

Figure 12 presents the projected test schedule for FY79 and FY80. Phase II of the facility acceptance tests will be performed early in FY79. At that time the emphasis in facility operations will be directed to conducting the scheduled tests and to implementing any required facility additions and improvements. Specific activities include implementation of the controls necessary to perform two separate tests concurrently; design and installation of a secondary concentrator in the tower to provide high flux levels for materials tests; implementation of any heat rejection system modifications necessary for advanced receiver tests; implementation of a permanent heliostat alignment system; and checkout and use of the heliostat BCS.

The planned test activities are shown in Figure 12. Three receiver tests are scheduled in FY79 - two at the 42.7m level and one at the tower top. In addition, two photovoltaic tests are scheduled for FY79.

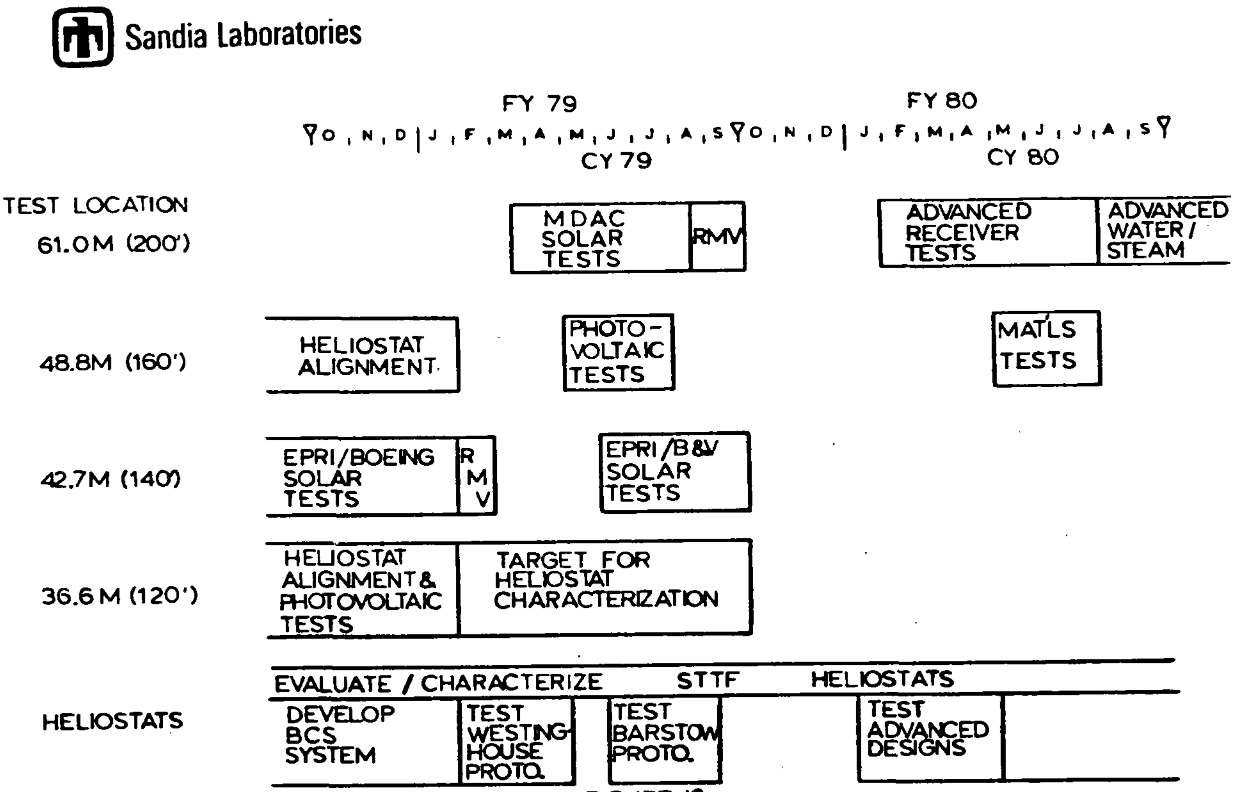


FIGURE 12

TENTATIVE TESTING SCHEDULE (9/15/78)

Two receivers are presently in the final stages of installation and checkout. The EPRI/Boeing receiver is mechanically connected and checkouts of the control and data systems, including the RTAF, are underway. Solar tests are expected to begin by the first week of October and continue for 2 to 4 months - depending on the installation and checkout requirements during the same period for the MDAC panel. The MDAC panel arrived on-site on September 21. While the elevating module is undergoing repair, insulation of the panel and installation of instrumentation is being performed at ground level. Present schedules call for the panel to be elevated to the tower top in the latter part of February. The first solar tests for the panel are expected to occur near the middle of March and to continue for up to five months. Secondary concentrators necessary to provide the high flux conditions required for a portion of the tests have been designed and are scheduled to be completed in February. A second series of receiver tests will involve the EPRI/Black & Veatch receiver. This receiver, a 1MW$_t$ bench model, is expected in early June and will occupy the 42.7m level for up to four months.

Two series of photovoltaic tests are also planned for FY79. The first is a 0.23m x 0.23m panel of single crystal silicon cells which will be placed at the 36.6m level in early 1979. Flux densities up to 200kW/m^2 will be required. The other photovoltaic tests will require flux levels up to 1500kW/m^2 on an approximate 0.4m x 0.4m panel of gallium arsenide cells. The gallium arsenide tests are scheduled for late FY79 and will likely be placed at the 48.8m level. Both tests are a part of the DOE National Photovoltaic Program and will be supported through the Photovoltaic Concentrator Program managed by Sandia.

In anticipation of materials tests which require very high flux densities, a secondary concentrator is being designed and will be fabricated and installed in the tower. Concentration ratios of 7 to 10 will be required. It is anticipated that the concentrator will be conical in shape and provide a test area about 0.3m in diameter. Testing of a prototype will be conducted in the White Sands Solar Furnace in October and design of the full scale will start following those tests.

Two series of heliostat prototypes are expected for tests in FY79. The first, an independent Westinghouse design provided to the CR-STTF by Sandia/Livermore, is scheduled for tests from February through April. These tests will be followed by evaluation of prototypes from the Barstow 10MW$_e$ project. Two heliostats from each of the two contractors will be delivered and the tests are scheduled for the June to August time period. The two series will be identical to allow comparisons of the performance of the different designs.

In summary, during the preceding six months the CR-STTF construction has essentially been completed and a number of limited operational checkouts have been completed. Presently two receivers are undergoing installation at the site with solar tests to begin in the near future. During the next six months the facility will begin operation in a test mode to evaluate not only these receivers but also to provide evaluation of prototype heliostats.

U. S. DEPARTMENT OF ENERGY ADVANCED COMPONENTS TEST FACILITY[†]

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ABSTRACT

Installation of the U. S. Department of Energy's Advanced Components Test Facility has been completed. The facility is operated by Georgia Tech's Engineering Experiment Station and is located on the Georgia Tech campus in Atlanta, Georgia. The principle feature of the facility is a hexagonal array of 550 mirrors or heliostats that are mechanically driven so that they focus sunlight at a point 21.3 meters above the center of the field. A tower for test apparatus stands in the center of the field and a computerized data acquisition system is housed in the control building adjacent to the field. The mirrors are capable of delivering a total flux of 400 kW to the focal zone with a peak flux density of approximately 220 W cm^{-2}.

The facility is designed to serve as a test-bed for solar components that require concentrated solar energy for their operation. New systems and components can be tested at the facility on a moderate scale. It is particularly well suited for the testing of high temperature solar receivers and components, photovoltaic conversion systems, and total energy systems. This paper describes the facility, its intended uses and capabilities. A report on the current goals and accomplishments is included.

[†] This work supported by the Division of Solar Technology of the Department of Energy.

I. INTRODUCTION

The Advanced Components Test Facility, which is located on the Georgia Tech campus in Atlanta, Georgia, is a solar energy concentrator design by Professor Giovanni Francia of Genoa, Italy. A photograph of the facility is contained in Figure 1. Concentration is achieved by aiming sunlight reflected from 550 mirrors at a point located above the center of the field. The mirrors are arranged in a hexagonal array and are mechanically driven so that the sunlight reflected from each mirror passes through the stationary point or focal zone throughout the day.

The facility is operated for the U. S. Department of Energy by the Georgia Tech Engineering Experiment Station. It is designed to serve as a test bed for promising high temperature solar components and materials. It is a flexible and convenient test facility accessible to all research

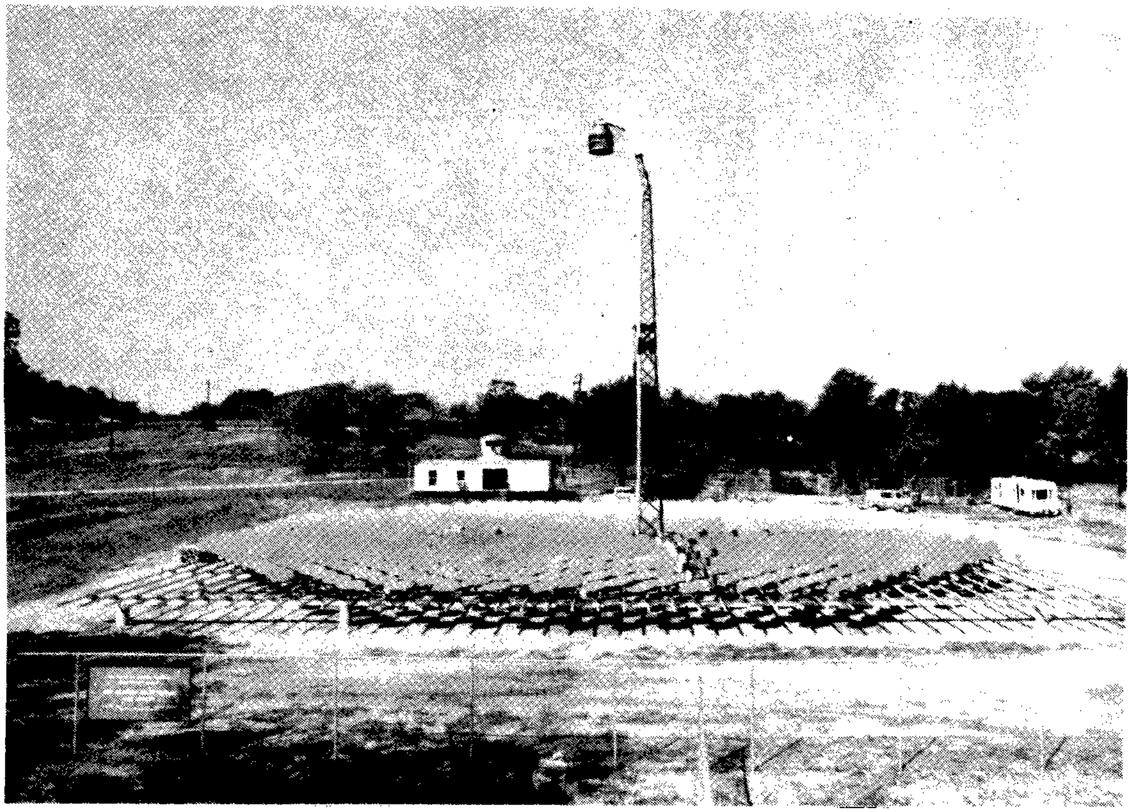

Figure 1. Photograph of the Advanced Components Test Facility.

and development organizations -- large and small, public and private. The facility is particularly well suited for the testing of solar heat receivers and components, high temperature materials and high temperature chemical reaction system components.

II. BACKGROUND

In 1965, Francia built and operated the first of several solar powered steam generators in Italy (1). The solar collector was a tracking mirror field that focused sunlight into a cone shaped receiver located above the center of the mirror field. The mirror tracking mechanism was a unique feature of the field. This mechanical coupling, which Francia called a kinematic motion, moved the mirror it supported in such a way that sunlight reflected from the mirror passed through a stationary focal zone throughout the day. The tracking system required no feedback, either mechanical or electrical, in order to operate. A second unique feature of the system was the antiradiating structure located in the receiver. This structure was constructed of pyrex tubes, closed at the top and open at the bottom, mounted vertically in the lower portion of the receiver.

Since the operation of this first system, Francia has refined and enlarged the design through three generations of systems. The largest and latest test system was first operated at St. Ilario, Italy, in 1972 (2). The mirror field contained 271 tracking mirrors with a total surface area of 135 m^2 (1450 ft^2). The mirrors were round, second surface reflectors with a diameter of 78 cm (30.7 in.). The receiver for the system has generated 150 atm (2200 psi), 600^o C (1110^o F) steam with an overall collection efficiency of 78 percent.

In 1975, the Energy Research and Development Administration purchased a solar powered steam generator of the Francia design through the Italian firm of Ansaldo, SpA,[†] with the intent of installing and operating the system in the U. S. The operation of the facility would accomplish two objectives. The first objective was the transfer of the technology that Francia has developed in Italy. This objective would be accomplished by

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[†] Ansaldo, Societia Generale Elettrromeccanica S.p.A., Divisione Impianti Elettrici, 16152 Genova-Cornigliano, Via N. Lorenzi, 8 ITALY.

installing and operating the mirror field and central receiver and documenting their performance. The second objective, to provide a place to test innovative solar receivers and systems on a moderate scale, would be accomplished following the system characterization by converting the system to a general purpose test facility. Georgia Tech's Engineering Experiment Station would be responsible for the characterization of the original facility, the conversion to a test facility and the operation of the facility after conversion.

III. CHARACTERIZATION PROGRAM

The solar steam plant was installed at Georgia Tech in 1977 and became operational in November 1977. Figure 1 shows the facility in the "steam plant" configuration. The mirror field contains 550 Francia type heliostats or kinematic motions. These devices are mechanically interconnected by torque tubes, and the entire field is driven by one 1.1 kW (1½ hp) electric motor. Each kinematic motion supports and manipulates a 111 cm diameter circular, second surface, low iron glass mirror which can be operated either flat or focused. The receiver shown in Figure 1 is a once-through steam generator. It is located at the geometric center of the field at an elevation of 21.46 meters above the mirror plane. This height combined with the extent of the field, gives a nominal rim angle for the field of 45 degrees.

The principle of operation of a kinematic motion is diagrammed in Figure 2. Point A is the center of a sphere of fixed radius. Point B is the point at which the extension of a line drawn from the sun through Point A intersects the sphere. Line RA is a line drawn from the center of the sphere to the receiver and Point C is the intersection of this line with the sphere. Lines CA and AB are of equal length and form the equal sides of the equilateral triangle ACB. A mirror is placed at point M perpendicular to line MCB. Since line MCB is parallel to the bisector of angle SAR, the mirror surface will reflect the light from the sun (point S) onto the receiver (point R). Point B rotates about axis TA, (parallel to the earth's axis) at 15^{o}/hr and MCB rotates around the fixed point C. This rotation forces point B to follow the sun throughout the day, and keeps the sunlight reflected by the mirror centered in the receiver.

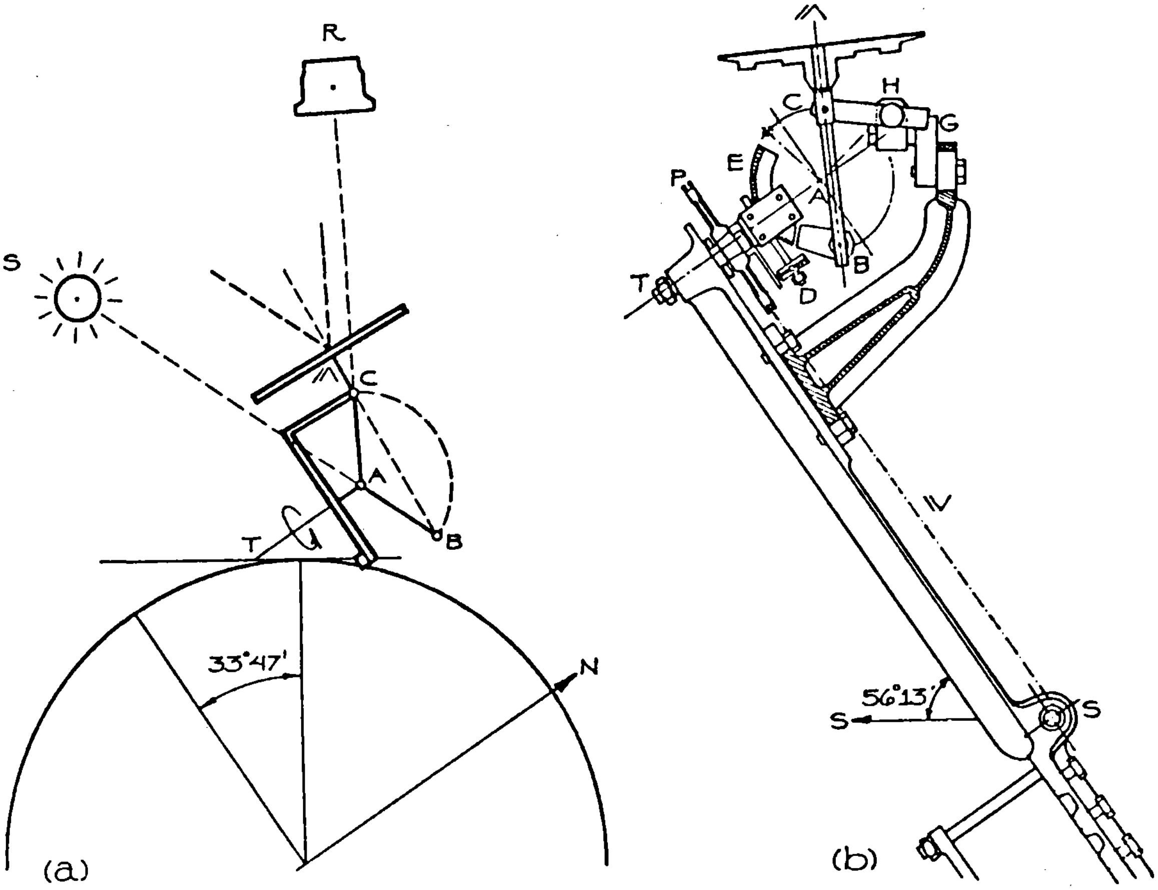


Figure 2. Principle of Operation of Kinematic Motion.

A drawing of an Advanced Components Test Facility kinematic motion is also shown in Figure 2. The relevant points are indicated on the drawing of the kinematic motion. The axis of rotation is shown by line AT which is located parallel to the earth's axis. Rotation is provided by a cable W around the pulley at P and driven through the shaft S. Alignment with the sun (line AB) is provided by a worm gear at D acting on the circumferential gear arm F. Declination adjustments also are provided through D. Alignment with the receiver (line AC) is provided through point H attached to a movable collar on the fixed rod G.

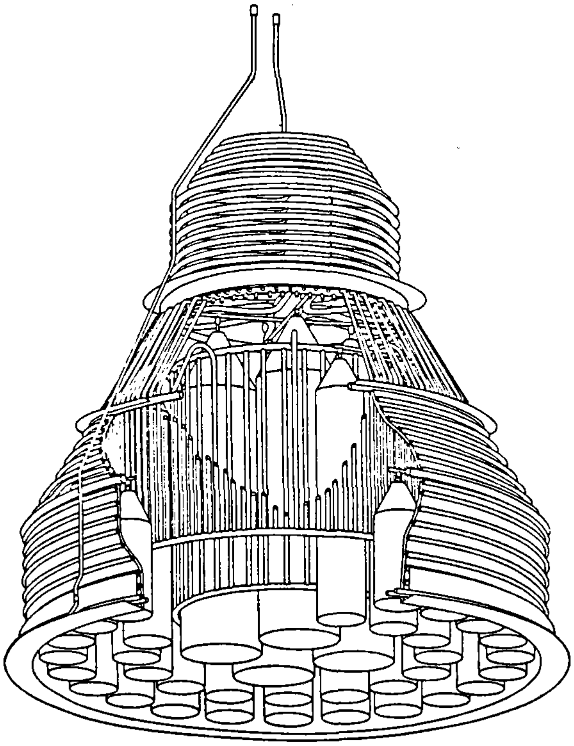


Figure 3. Francia Once-Through Steam Generator.

The receiver supplied with the system is depicted in Figure 3. It is a once-through steam generator constructed entirely of stainless steel. Chemically treated water is first circulated through the tubes that curl around the shell of the receiver. The preheated water then flows into the inner ring of boiling tubes. The boiling sections are in the middle of the receiver. Steam leaving the last boiling section flows through the serpentine superheater tube in the top section of the receiver. The receiver is designed to generate 600^{0} C (1110^{0} F) steam at 120 atm (1700 psi). The large cylinders shown in Figure 3 are the pyrex tubes that make up the antiradiating structure.

The characterization of the basic Francia type facility has been partially completed. The focusing capability of individual mirrors has been determined and the tracking errors of the kinematic motions have been measured. The steam generator has been operated at its design temperature and pressure. The tests to date have been of a preliminary or shake-down nature. Flux measurements in the focal zone are scheduled to take place in July 1978, and the performance of the receiver will be determined in late 1978.

IV. FACILITY CONVERSION

The conversion of the Francia steam plant to a general purpose test facility is proceeding while the characterization tasks are being completed. The conversion process started in December 1977, with the design of a new central tower to replace the articulating tower supplied as part of the Francia solar steam plant. An artist's concept of the new tower appears in Figure 4. The new tower provides an increased load capability and better access to the experimental area. The old tower had a capacity of approximately 680 kg (1500 lb). The new tower has a capacity of 9072 kg (20,000 lb). The focal point for the mirror field is centered on the tower legs and located at the floor level of the experiment platform. Access to the top of the platform is provided by ladder and man/material work hoist; access to the area below the platform is by scissors lift. The scissors list can be withdrawn to the 15.2 m (50 ft) level during a test so as to minimize the blocking of radiation incident on the focal plane. The cantilevered part of the platform will house an instrument building. The facility in its present configuration is shown in Figure 5.

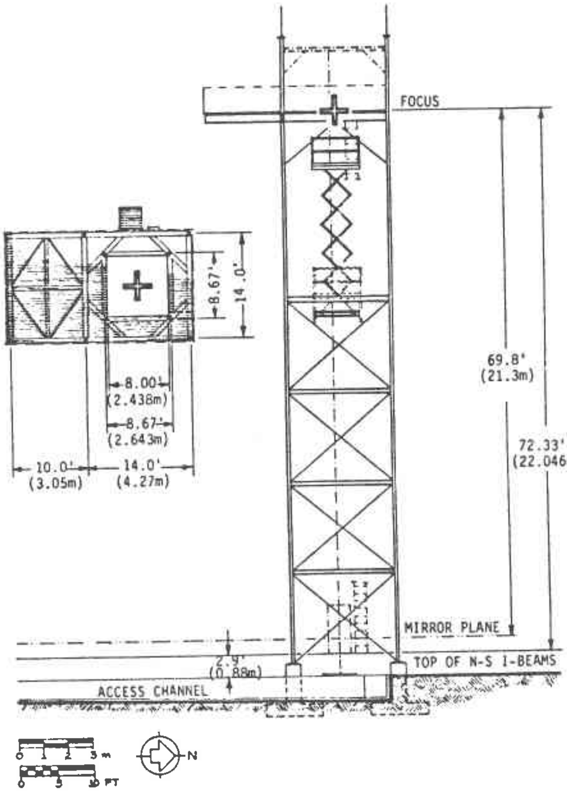


Figure 4. Drawing of New Central Tower.

Support equipment at the DOE Advanced Components Test Facility includes a computerized data acquisition system, a scanning flux calorimeter, pyrheliometers, a pyrometer, and a solar blind infrared TV camera system. The computerized data acquisition system consists of two minicomputers.

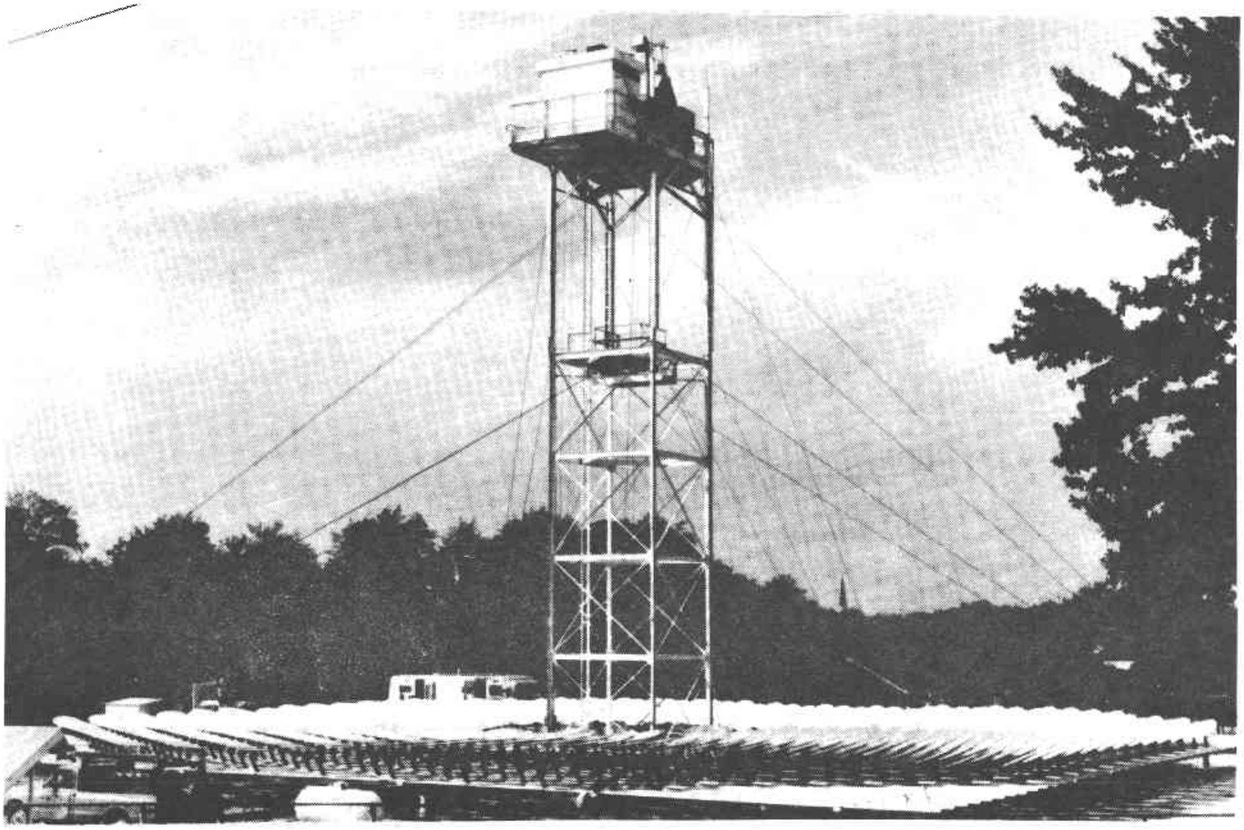


Figure 5. Photograph of ACTF Central Test Stand.

One will be located atop the tower and will control a 120 channel multiplexed A-to-D system. The second computer will be located in a control room adjacent to the mirror field. This processor manages the tower top computer and also manipulates, stores and displays data according to the needs of the experimenter. Data output from the system includes strip chart recorder type displays on a video terminal, line printer listings of selected channels, magnetic tape copies of both raw and processed data, and diskette copies of data. Data input to the computerized data acquisition system can be from virtually any type of analog output transducer.

A scanning flux calorimeter will be used in the characterization experiment and will be available for use by the experimenter. This device is a water cooled bar housing 37 Gardon gage type calorimeters on 5.08 cm (2 in.)

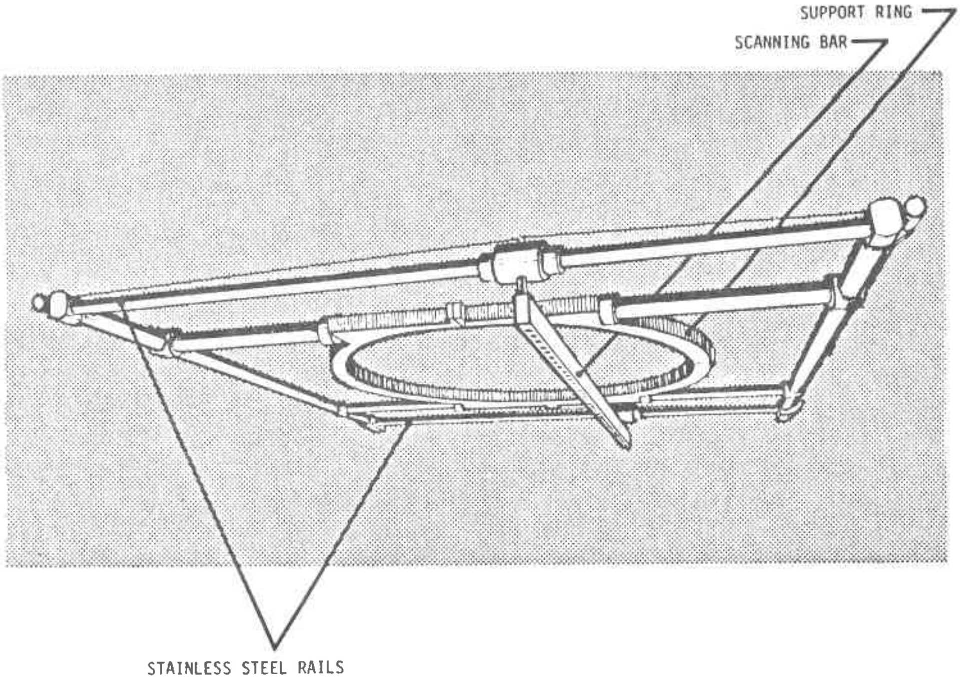


Figure 6. Perspective of the Scanning Flux Calorimeter.

centers. The bar is mounted on a water cooled structure that can in turn be mounted to the tower or an experiment. The device operates under computer control in such a manner that a 5.08 cm x 5.08 cm (2 in. x 2 in.) grid of the incident flux distribution can be produced by scanning the bar through the distribution. The output of the calorimeter is stored by the data acquisition system. A drawing of the flux scanner is contained in Figure 6. The central support ring in Figure 6 was designed to attach the flux scanner to a specific experimental receiver. This ring can be modified or replaced to adapt the scanner to other experiments, or the scanning flux calorimeter can be mounted directly to the central tower.

Presently, two major Department of Energy contractors have tests scheduled at the Advanced Components Test Facility. In the first series of experiments, a prototype of a high temperature ceramic air cooled receiver will be tested. This receiver is designed to be used in an open Brayton cycle to produce electricity. Testing will begin in July 1978. A sodium heat pipe receiver is scheduled for testing in 1979. It is anticipated that additional tests of new receiver concepts or experiments will be added to the facility's schedule in the near future. A manual that contains a detailed description of the Advanced Components Test Facility, its policies and procedures is available. Copies of this Users Manual can be obtained by writing or calling:

Director, Advanced Components Test Facility
SEMTD/EES
Georgia Institute of Technology
Atlanta, Georgia 30332

(404) 894-3650 (Commercial).

V. REFERENCES

1. G. Francia, "Pilot Plants of Solar Steam Generating Stations," Solar Energy 12, No. 1, p 51-64 (September 1968).

2. G. Francia, "The University of Genoa Solar Furnace," Presented at the NSF International Seminar on Large Scale Solar Energy Test Facilities, New Mexico State University, Las Cruces, November 18-20, 1974.

WHITE SANDS MISSILE RANGE SOLAR FURNACE TEST FACILITY

Richard Hays

Abstract

A description of the 30,000-watt thermal White Sands Solar Furnace Test Facility located at the Nuclear Weapon Effects Laboratory, White Sands Missile Range, New Mexico. The White Sands Solar Furnace (WSSF) is primarily used for nuclear weapon thermal effects testing, but is also used for solar energy research. The WSSF is capable of providing a maximum solar flux in excess of 80 cal/cm^2 sec over an exposure area of approximately 5 cm in diameter. The solar flux of the WSSF can be modulated to provide thermal pulse shaping, such as rectangular and nuclear, or operated in a steady-state exposure mode.

Introduction

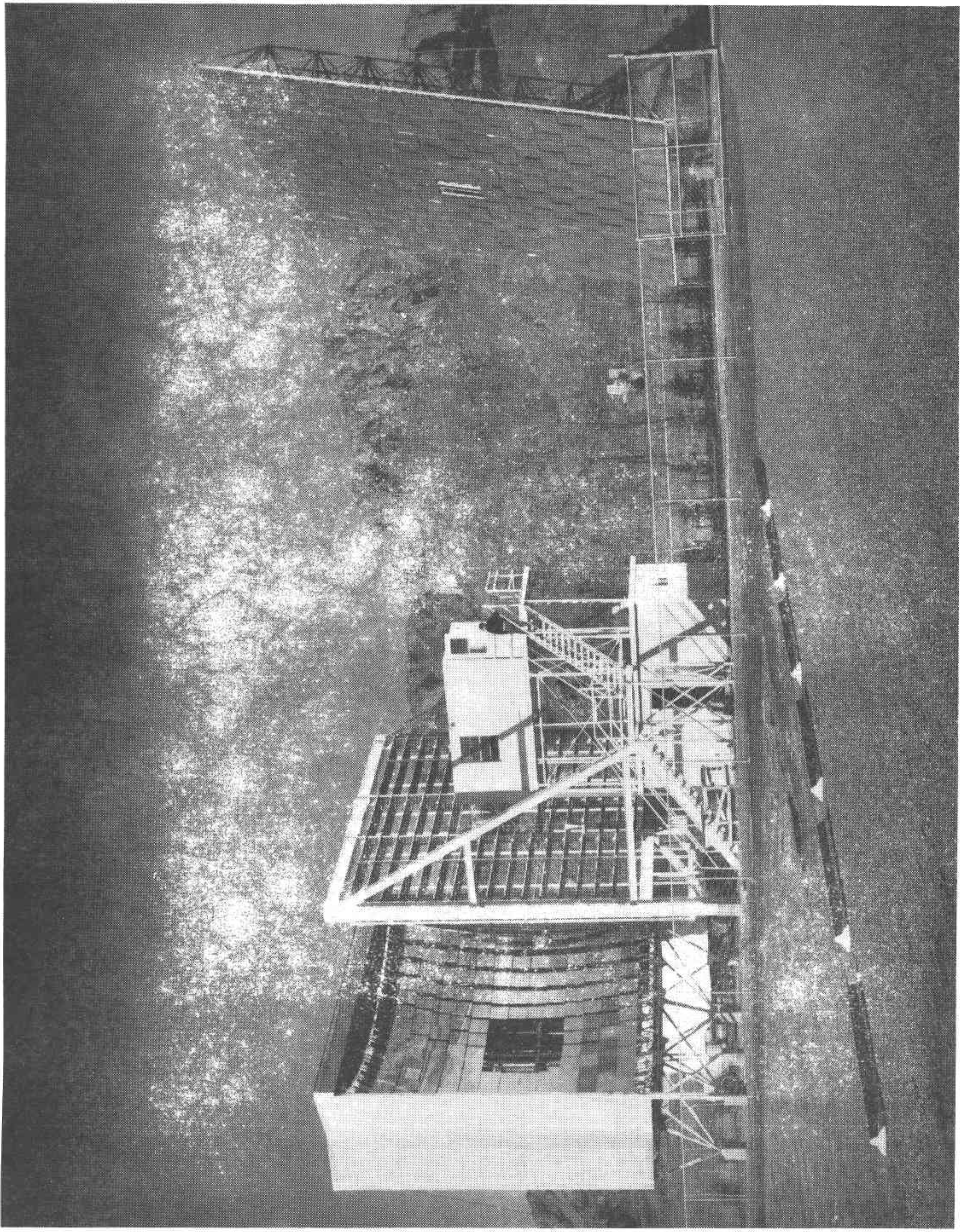
The WSSF was originally constructed in 1958 and operated by the Quartermaster Research and Engineering Center at Natick, Massachusetts. In 1973 the WSSF was relocated at the White Sands Missile Range, New Mexico. The WSSF is available for use by the Department of Defense and its contractors, or other Government agencies and private industry.

The facility is operated by the Army's Nuclear Weapon Effects Laboratory primarily for nuclear weapon thermal effects testing but is also used for solar energy research by numerous Government agencies and universities.

Description of the WSSF

The WSSF is comprised of four main parts: the Heliostat, Attenuator, Concentrator and Test and Control Chamber, see Figure 1.

The Heliostat consists of 356 flat plate mirrors, each 0.635 cm in thickness and 62 x 62 cm square, mounted on a steel framework 1.2 meters wide and 11 meters high. The heliostat moves in azimuth ± 60 degrees and about 180 degrees north-south orientation and 0 to 90 degrees in elevation. The heliostat is an elevation over azimuth mounting with the drive systems located in the vertical and horizontal turret sections. The heliostat mirrors are front-surfaced standard



flat plate glass. The reflective surface consists of vacuum-deposited aluminum with an overcoating of silicon monoxide. Each mirror is mounted on three compression springs with stainless steel bolts through the mirror and spring and attached to the heliostat framework.

There are three modes of movement of the heliostat: slew, manual track and auto track. In the slew mode, two 1/2-hp AC motors (one AZ., one EL.), operating at 1725 rpm, are used to move the heliostat at rates of 7.2 degrees per minute in azimuth and 6.5 degrees per minute in elevation. The slew mode is used to bring the heliostat from the stow position to sun acquisition. In the manual mode, the same mechanical drive systems are used as in the slew mode. The difference between the slew and manual track modes being a further gear reduction and a variable-speed, 1/15-hp, 0-1725-rpm, DC motor coupled to the drive system through an electro-mechanical clutch. In the manual track mode, the heliostat is moved in azimuth at a maximum rate of 11.6 degrees per hour and in elevation at a maximum rate of 7.8 degrees per hour. The third mode of movement is auto track, which is the same as the manual track mode with the exception that the motor speed is controlled by position feedback from a photo detector. In this mode the heliostat automatically tracks the sun, keeping the heliostat positioned within 30 seconds of arc. The auto track system keeps the solar image at the focal plane positioned within 0.25 cm. Gusty winds above 15 knots and clouds passing between the sun and the heliostat can cause tracking instabilities with up to 1.25 cm of movement of the solar image or loss of track. If required, moon tracking can be accomplished with the same auto track system. By using the moon as a source, precise alignment of optical experiments can be performed without the intense concentrated solar heat and light associated with the sun.

The Concentrator consists of 180 spherical mirrors mounted on aluminum rings 59.7 cm in diameter, which are attached to the 9.1-meter square concentrator framework so that a solar image is positioned at the WSSF focal plane 10.7 meters away. All the concentrator mirrors are front-surfaced with vacuum-deposited aluminum and overcoated with silicon monoxide.

The Attenuator controls the useable thermal power of the WSSF, varying the power from zero to maximum within two minutes. The attenuator consists of 17 rows of rotatable horizontal blades. The blade angle is controlled by the solar furnace operator and varies from 45 to 90 degrees from vertical for complete to minimum attenuation of the solar energy. If a hazardous condition occurs during testing, automatic safety circuits are coordinated with the attenuator drive circuits so that the attenuator may be closed within 0.5 second. The attenuator can operate in an auto control mode, compensating for changing atmospheric conditions, and thus keeping a constant flux level at the focal plane during long steady-state exposures. See Figure 2 for attenuator transmission characteristic. The test and control chamber is 2.4 by 2.4 meters in cross section presented to the solar energy reflected from the heliostat and 4.8 meters in the direction of the optical axis and houses the experimental area, the control console and the fast shutter system. Cooling water and high-pressure air supplies are available in the test and control chamber.

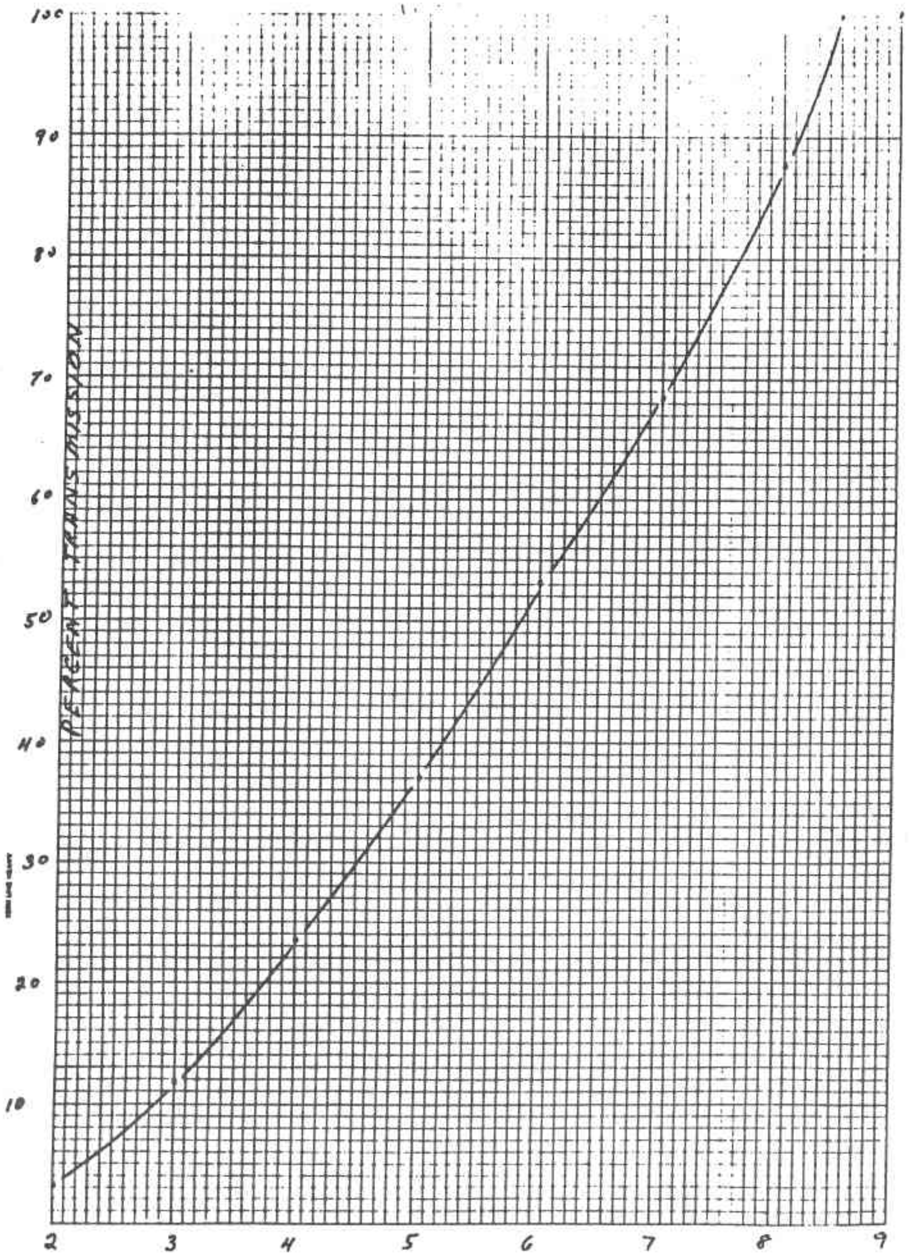


Figure 2

The Fast Shutter System consists of a water-cooled shutter, exposure shutter, and a limit shutter. The water-cooled aluminum shutter is 45.7 cm in diameter and protects the fast shutters and experiment from the 30,000 watts of thermal energy during nonexposure. The exposure and limit shutters have rise and fall times of 25 milliseconds and are mounted 5.1 cm in front of the focal plane. These two shutters produce a rectangular pulse duration as short as 100 milliseconds. The thermal pulse shaper for nuclear weapon simulation is mounted behind the fast shutters and can be for steady-state operation. Also, a wind tunnel which will accommodate 7.6 by 10-cm test specimens can be used in conjunction with the WSSF to provide air flow with velocities up to a maximum of 40,000 feet per minute.

Exposure Characteristics

The thermal exposure area is approximately 16 cm in diameter at the focal plane located 81.25 cm from the south wall of the test chamber and 1.06 meters above the test chamber floor. Larger exposure areas can be obtained by moving out of the focal plane but with reduced flux levels. The maximum available flux at the focal plane to date is 100 cal/cm^2 sec (90 cal/cm^2 sec readily obtainable), with a total available power of 30,000 watts thermal. Maximum flux levels with a 10% uniformity are obtained over an exposure diameter of 5 cm. The thermal flux profile at the focal plane has the 50% flux points occurring at a 5-cm radius from the center of the solar image as shown in Figure 3. Table I gives some of the important exposure characteristics of the WSSF.

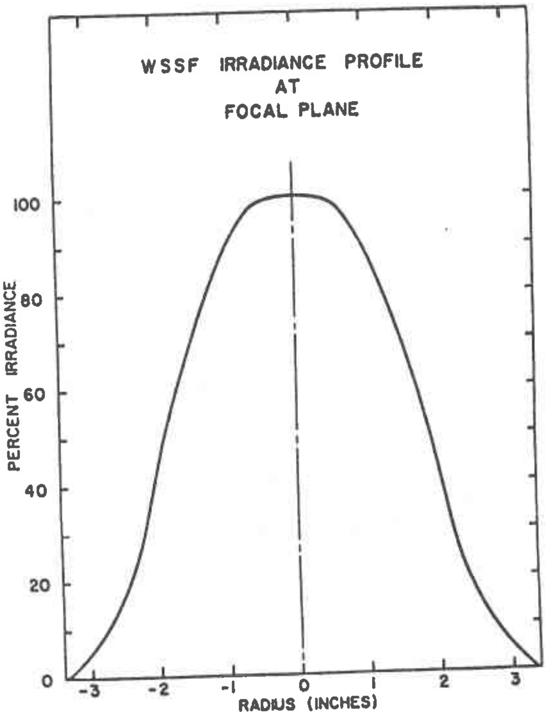


Figure 3

Table I

Diameter (in.)	1	2	3	4	5	6	6.5
Percent Total Power	6.5	24.6	49.5	74.5	91.5	99.1	100.0
Power, kilowatts	1.89	7.21	14.56	21.91	26.97	29.17	29.47
Min. Flux, cal/cm^2 sec	88.2	79.2	59.4	39.7	14.4	4.5	0
Mean Flux, cal/cm^2 sec	89.1	83.7	69.3	49.1	26.6	9.4	2.2

Operational Characteristics

Since the WSSF is dependent upon weather conditions for operations, the following weather data is used to help schedule experiments to be conducted at the WSSF. Wind and cloud cover data taken over a period of 22 years, by the Atmospheric Sciences Laboratory, indicates WSMR is a good location for the WSSF in regard to availability of usable operational hours. Information on wind and cloud cover by month and hour indicates an average of 1200 hours of operation time per year is available at the WSSF. This is based on a 2080-hour work year, 5-day work week, and an 0800 to 1600-hour work day, see Tables II and III. It must be remembered that the WSSF has two operational constraints, cloud cover and wind, when planning thermal tests.

Table II

Category	Cloud Cover	Winds	Available Hours
I	Clear	< 5 knots	395
II	Clear	< 14 knots	666
III	< 50%	< 5 knots	666
IV	< 50%	< 14 knots	1200

Table III lists the month of the year according to percent operational time available for that month in Category IV of Table II.

Table III

Month	% Operational Time
September	71
October	70
June	70
May	61
November	60
August	59
July	57
December	53
April	51
January	50
February	50
March	48

Question - What's the diameter of that dish?

Mr. Hays - It's 84 feet.

Question - What would be the diameter of the secondary mirror?

Mr. Hays - Right now, somewhere between 20 and 30 feet; approximately the same size as our existing facilities.

Question - What kind of thermal readings will you pick up?

Mr. Hays - We'll have roughly a quarter of a megawatt useable power at the focal plane of the facility. The minimum exposure area right at the focal plane will be something on the order of 6-1/2 to 7 inches.

Question - What temperature?

Mr. Hays - Whatever the equilibrium temperature would be at 400 cal/cm^2. That's roughly the temperature of the fringe facility, maybe a little higher.

FRENCH 1000-KW THERMAL SOLAR FURNACE

Claude Royere, operator of the French facility at Odeillo, was unable to attend the workshop; however, we are including a brief description of the facility and further information and photos may be found in the papers by C. S. Selvage on Page 43 and R. L. Skaggs on Page 422.

The CNRS 1000-kW_t Solar Furnace is located in the Pyrenees at Odeillo, Font-Romeu (altitude, 5900 ft), about 40 miles east of Andorra, and consists of 63 heliostats (each 6 x 7-1/2 m) which follow the sun and reflect the sun's rays onto a parabolic reflector. The parabolic concentrator (20,000 ft^2) concentrates 1 MW of thermal energy into an area of about 40 cm in diameter at the focal point of the parabola. At the center of the focal point, in an area 4 cm in diameter, the heat flux is 1600 W/cm^2 and the temperature reaches 4100 K.

Anyone requiring further information on this facility may contact the Users Association or Claude Royere at the following address:

CNRS
Solar Energy Laboratory
BP No. 5, Odeillo, 66120
Font-Romeu, France

Phone: 33-68-30-10-24

SECTION VI - SOLAR CENTRAL TECHNOLOGY STATUS AND PLANS

BARSTOW, CA, 10-MW SOLAR ELECTRIC PILOT PLANT

L. A. Hiles
Sandia Laboratories

Shown in Figure 1 is a McDonnell Douglas central receiver solar electric power plant concept. The term "central receiver" is used to describe those concepts which locate a boiler on top of a tower which is surrounded by a field of multifaceted heliostats. The heliostats are controlled to reflect the sun onto the boiler.

Figure 2 gives a simplified version of how the system can be broken down. The field of heliostats is called the collector subsystem. The receiver subsystem consists of the boiler (called the receiver) and tower. The EPGS in the lower right-hand corner denotes the typical steam turbine, dynamo, and all equipment associated with Rankine steam cycles. The thermal storage subsystem is included to partially desensitize the system to transients such as clouds, as well as provide some flexibility to meet night power demand.

Not shown here is the master control system. This is a digital computer system which serves to control and coordinate the various subsystems in a stable and responsive manner. The requirement for digital control is evident when one considers the problem of controlling large numbers of heliostats. For instance, a 100-megawatt power plant will have approximately 17,000 heliostats (39 square meters each). A staggering number when one considers that each heliostat must track in both elevation and azimuth as well as respond to commands such as emergency devocus, stow and standby!

The system goals are outlined in Figure 3. The key word in the first bullet is technical feasibility. The Barstow design does not represent advanced or sophisticated state-of-the-art technology, but since it applies solar power to a boiler, it is a unique application and, as such, must be demonstrated to potential utility users. The second key word is retrofit. Gerry Braun talked earlier about repowering and that is what this key word addresses. We believe that solar is a natural candidate for many repowering applications.

In the second bullet in Figure 3, the key word is cost. Sandia has been doing studies for three years and many of them indicate what the cost should be and what the design should be, but no one is going to believe that until the utilities actually see a plan of operation--what the cost will be to build, operate and maintain it. This is probably the most critical item on the objectives list.

Finally, we must determine the environmental impact of such a system. Two years ago DOE solicited proposals for design concepts for a solar electric plant. The winners of the contracts were McDonnell Douglas, Martin Marietta and Honeywell. They completed system designs including heliostats. The fourth winner was Boeing, who restricted themselves to design of heliostats. DOE also solicited sites and chose the Southern California Edison site at Barstow. Southern Cal Edison has a small fossil fuel plant at Barstow.

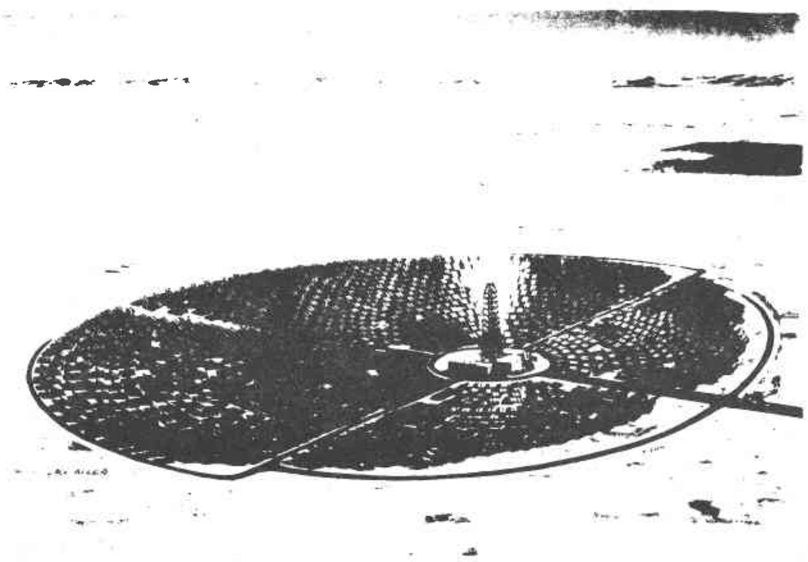


Figure 1

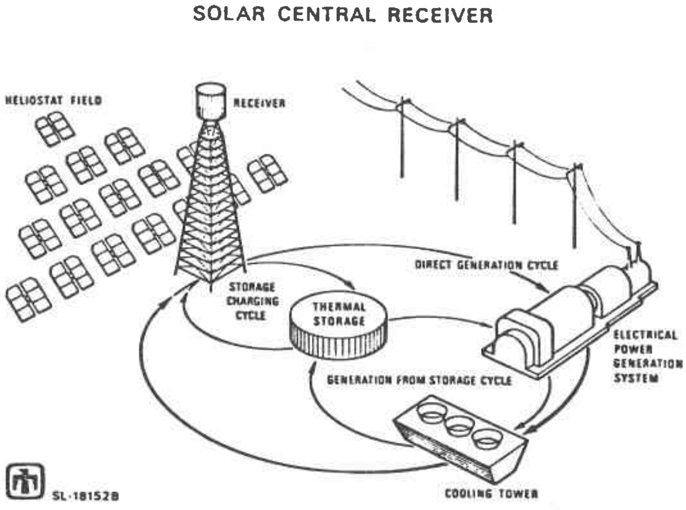


Figure 2

PROJECT OBJECTIVES

PRINCIPAL OBJECTIVES

Figure 3

- ESTABLISH TECHNICAL FEASIBILITY OF SOLAR THERMAL POWER PLANTS OF THE CENTRAL RECEIVER TYPE, PARTICULARLY FOR RETROFIT APPLICATIONS OF SOLAR BOILERS TO EXISTING POWER PLANTS FUELED BY OIL OR NATURAL GAS.
- OBTAIN SUFFICIENT DEVELOPMENT, PRODUCTION, OPERATING AND MAINTENANCE COST DATA TO IDENTIFY POTENTIAL ECONOMICS OF COMMERCIAL SOLAR PLANTS OF SIMILAR DESIGN, ESPECIALLY RETROFIT APPLICATIONS ON A COMPARABLE SCALE.
- DETERMINE ENVIRONMENTAL IMPACT.

It is now common knowledge that the McDonnell Douglas concept was selected for the Barstow facility. What is not generally known are the considerations that led to this choice. The next couple of vugraphs illustrate some of the differences among the three competitive designs, and they show some pretty dramatic results. Figure 4 shows the McDonnell Douglas system. It's about half the size of the other two designs. Also, consider the weight, which is a big driver in terms of tower cost for a 100-MW commercial plant. The tower would be approximately 800-1200 feet high. That's an expensive structure to build and, when it is required to support heavy receivers, it drives the cost even higher.

Some interesting characteristics of the various heliostat designs are shown and compared in Figure 5. It is interesting to note the low weight of Boeing's plastic heliostats. These low weights indicate very low rotational inertias, which means they can accelerate to high slew rates with comparatively little driving horsepower. Unfortunately, one pays a price for this in terms of low net reflectivity.

Some of the losses encountered before the receiver even sees insolation are shown in Figure 6. There are large cosine losses, 13-17 percent, due to the fact that the sun doesn't see the whole area. It sees the only the cosine projection of the heliostat. There are shadows from mirrors blocking each other and, of course, there is spillage, which means some of the energy is going by the receiver.

A simplified schematic of a water/steam system is shown in Figure 7. The primary loop drives the turbine with steam. If one added extra heliostats, the thermal storage unit could also be charged with this loop. However, a heat exchanger is required to charge and discharge the storage unit and results in a significant temperature loss. This inefficient transfer of energy pinpoints the weakness of Barstow design technology. It should be emphasized at this point in the discussion that the technology chosen for Barstow was selected because it was well developed, reliable, and we thought the utilities would be comfortable with it.

Figure 8 is a breakdown and is interesting in the sense that it shows that heliostats constitute about one half the total costs. Obviously this is a key word to concentrate on and that is exactly what Sandia is working on. The cost of the receiver and tower are also an appreciable slide of the pie. Thermal storage costs are strictly a function of just how much storage one chooses. The lower pie in Figure 8 shows the heliostat cost breakdown. It is interesting in that the reflective surface dominates the cost.

One of the 24 panels that will be used in the Barstow power plant design is shown in Figure 9. The panel, 1 meter by 17 meters, was designed and built at Rocketdyne. It was tested at the Rockwell Radiant Land Facility. The next test was to be run at the STTF in Albuquerque, shown in Figure 10 as an artist's concept, and was scheduled to begin next month, but that was before the STTF tower elevator accident. Figure 11 shows the objectives of that test. One could summarize these objectives by stating that it is a scale model verification of the pilot plant. Although it considers many aspects of the design, it reduces to that of dynamics and the stability of the two-phase once-through boiler.

PILOT PLANT RECEIVER CHARACTERISTICS

	Honeywell	Martin Marietta	McDonnell Douglas
1. Tower Height (m)	159.0	122.0	86.3
2. Weight on Top of the Tower (x 10^3 kg)	602	419	160
3. Receiver Type	Downward Opening Cavity	Northward Side Opening Cavity	External Absorber
4. Boiler Type	Forced Circulation Drum	Natural Circulation Drum	Forced Flow Once-Through
5. Working Areas (m^2)			
Aperture	218	36	Not Applicable
Boiler	344	144	267
Superheater	375	48	
6. Max. Absorber Flux (MW/m^2)			
Commercial Plant	0.26	0.68	0.85[0.60/0.30][a]
Pilot Plant	0.26	0.60	0.31
7. Annual Average Efficiency (%) (receiver only)			
Commercial Plant	84.4	91.6	89.8[@ 0.85 MW/m^2]
Pilot Plant	84.1	91.6	84.1[@ 0.31 MW/m^2]

[a] Due to Sandia's concern for the life of the McDonnell Douglas commercial receiver at 0.85 MW/m^2, commercial receivers operating at peak fluxes of 0.30 and 0.60 MW/m^2 were parameterically evaluated in the cost/performance studies.

Figure 4

COLLECTOR CHARACTERISTICS

	Boeing	Honeywell	Martin Marietta	McDonnell Douglas
Orientation Method	AZ-EL	Tilt-Tilt	AZ-EL	AZ-EL
Control System	Open Loop	Open Loop	Open Loop	Closed Loop 10 MW Open Loop 100 MW
Mirror Area (m^2)	48.5	40	41	38
Net Reflectivity (%)	67	91	91	91
Peak Stress in Glass (psi)*	--	2000	500	100
Weight (kg/m^2)	5.3	60	57.6	41.5
Cost/Performance* (\$/kW)				
Commercial Plant	334	383	247	226
Pilot Plant	644	691	498	415

*Calculated by Sandia

Figure 5

YEARLY* OPTICAL COMPARISON OF PROPOSED PILOT PLANTS

	McDonnell Douglas	Martin Marietta	Honeywell
Cosine	0.823	0.866	0.862
Optical Losses			
Tower Shadow (%)	0.2	0.7	1.3
Mirror Shadow (%)	4.2	4.9	3.1
Blocking (%)	0.9	1.5	0.7
Spillage (%)	1.0	3.3	2.6
Mirror Effectiveness** (W/m^2)	672	692	703

*Collection of energy above 15° sun elevations
**Average yearly power input to receiver per m^2 of heliostat

Figure 6

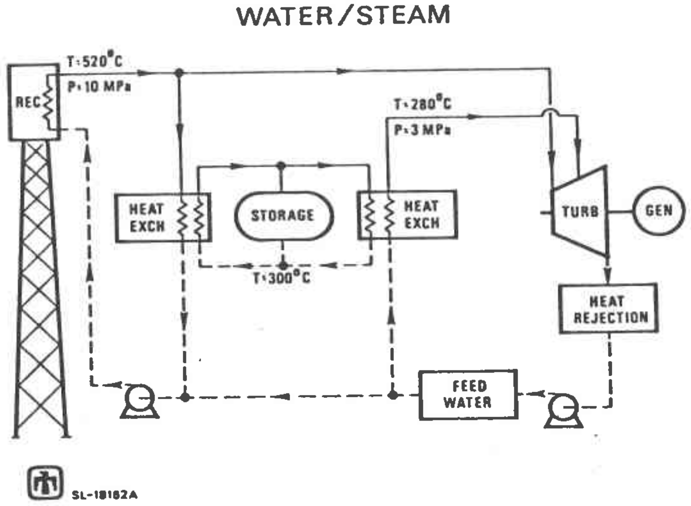


Figure 7

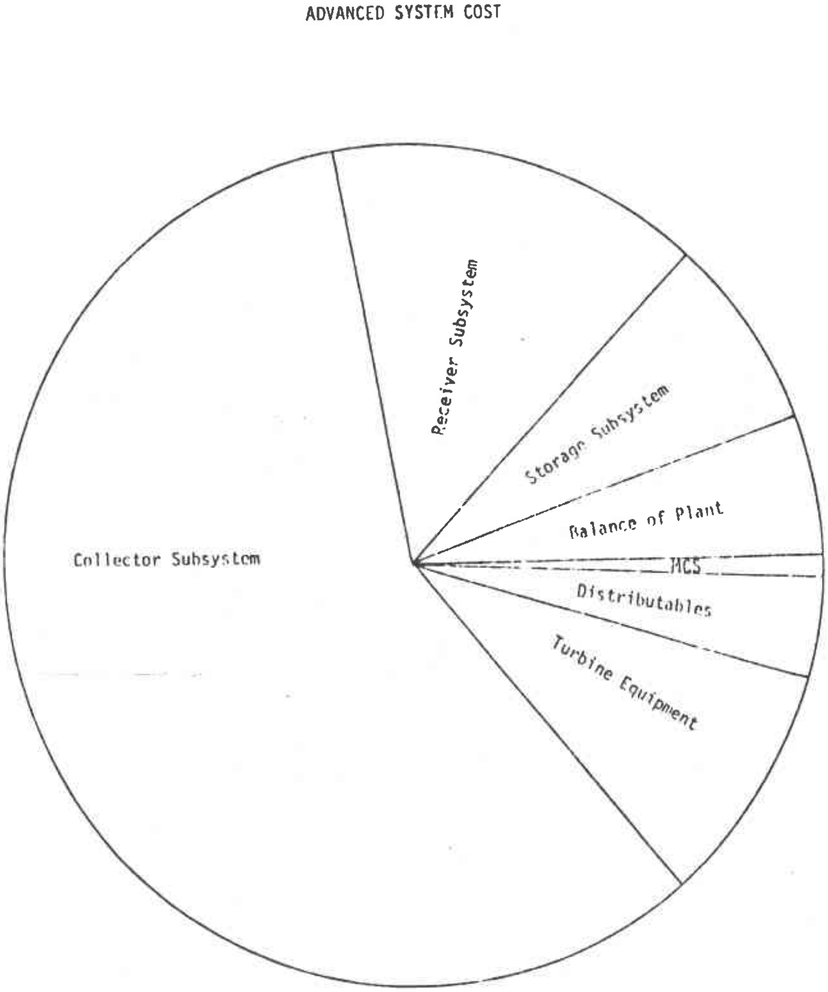


Figure 8

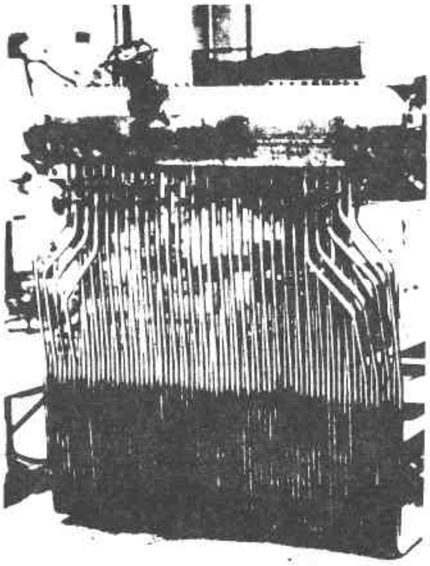


Figure 9

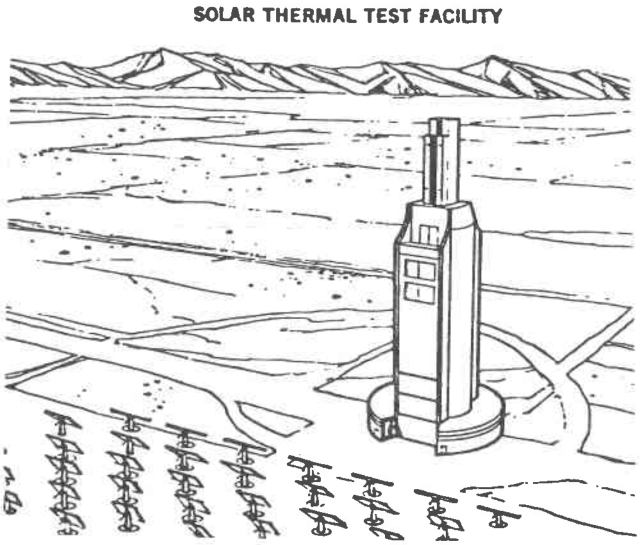


Figure 10

STTF/RECEIVER TEST OBJECTIVES

VALIDATE FULL-SCALE PILOT PLANT RECEIVER PANEL AND CONTROLS

- VERIFY RECEIVER THERMODYNAMIC PERFORMANCE UP TO 125% OF PILOT PLANT FLUX AND POWER
- DEMONSTRATE RECEIVER TEMPERATURES COMPATIBLE WITH A 30-YR LIFE
- VERIFY RECEIVER CONTROL SYSTEM PERFORMANCE
  - FLOW STABILITY AND UNIFORMITY
  - STEAM QUALITY
  - SEQUENCING
  - INTERMITTENT CLOUDS
  - FEEDWATER TRANSIENTS
  - DISCHARGE TRANSIENTS
  - SET POINT CHANGES
  - EMERGENCY CONDITIONS
- VERIFY PILOT PLANT PREHEATER PANEL PERFORMANCE
- VERIFY RECEIVER THERMAL EXPANSION AND CONTRACTION DESIGN
- INVESTIGATE RECEIVER LOSSES
- INVESTIGATE PANEL LATERAL HEAT FLUX GRADIENTS
- INVESTIGATE RECEIVER SURFACE COATING PERFORMANCE AND DURABILITY
- INVESTIGATE BOILER PANEL TUBE WALL FOULING

Figure 11

Consider now the Advanced Central Receiver Program. We are now in the completion stage of what we call the conceptual design phase. Approximately one year ago DOE let four contracts for 12-month conceptual design studies. Three of these contractors chose similar receiver concepts, as shown in Figure 12. Atomics International and General Electric designs both use liquid sodium. Sodium technology is well established and characterized. The sodium enters the receivers at 550°F and exits at about 1100-1200°F. The Martin Marietta design uses a nitrate salt, i.e., a mix of potassium and sodium nitrates. Similar to the liquid sodium systems, the nitrates enter the receiver at 550°F and exit at 1050°F. Since the nitrate salts are corrosive, a significant amount of effort, both at Martin and Sandia, has been directed toward understanding and quantifying the compatibility of structural steels and stainless alloys with nitrate salts.

Figure 13 shows a sodium/salt schematic and demonstrates why we tend to categorize salt and sodium as one type. The significant difference between these technologies and the water/steam technology is that a heat exchange is not required to charge and discharge storage. There is, however, an exchanger in the salt-sodium-to-steam generator interface. Therefore, we have an efficient means of storage and the only performance penalty is that heat is lost during the storage period.

The fundamental difference between the salt and sodium technologies is, of course, their properties. Sodium, like most metals, has excellent heat transfer properties. In fact, sodium transfers heat approximately 20 times better than salt. Unfortunately, fatigue consideration of the sodium-filled receiver tubes does not allow one to make full use of this property. Although salt's poorer heat transfer coefficient does not allow its use in the higher receiver fluxes characteristic of sodium designs, salt has superior heat transport properties which allow it to transport 2-3 times more heat per pound than sodium. These property differences also have their effect on the method and cost of the storage subsystem.

Boeing Engineering and Construction has the fourth advanced central receiver conceptual design contract (Figure 14). It is a very large Brayton cycle cavity receiver. A Brayton cycle uses a gas as a working fluid, see schematic in Figure 15. The Boeing design is a four-aperture cavity. The interior walls of the cavity are lined with tubes containing pressurized air. The solar radiation heats the tubes directly, or is reflected off the interior walls onto the tubes that in turn heat the air that is passing through them. Brayton designs have a potential for higher efficiencies than Rankine designs. This higher efficiency is due to higher upgrading temperatures of Brayton systems--1500°F to 2000°F typically, compared to the 100°F to 1200°F Rankine designs. There are fewer components associated with the Brayton designs, which also tend to lead to higher efficiencies. On the negative side, the Brayton designs are heavy! The Rankine receivers (GE, Martin, and Atomics International) are at or under a million pounds in in weight. This Boeing receiver is in excess of 5 million pounds. These larger weights not only cost more to build, they also drive the design of the supporting tower and become a substantial cost component. The other two Brayton receivers pictured in Figure 14 (Dynatherm and Sanders) are independent receiver studies that Sandia has been pursuing for some time.

SODIUM OR SALT RECEIVERS

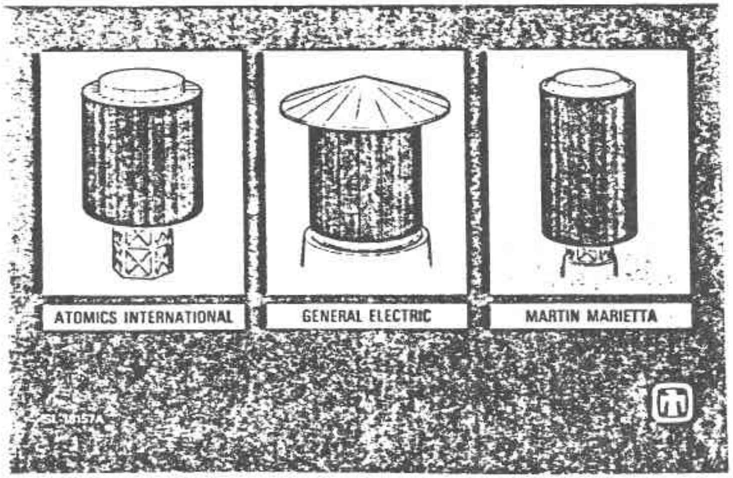


Figure 12

SODIUM/SALT

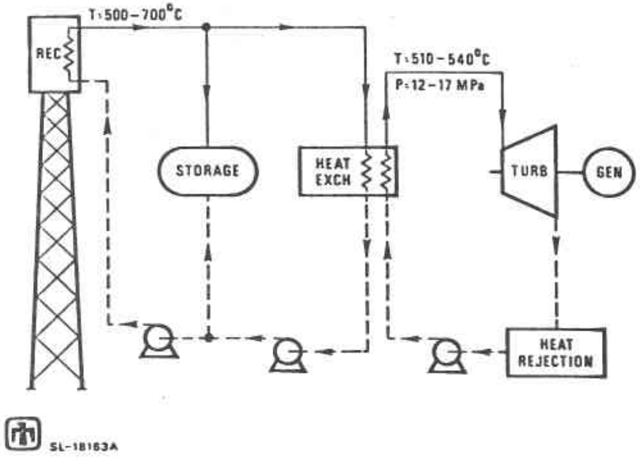


Figure 13

BRAYTON HOT GAS RECEIVERS

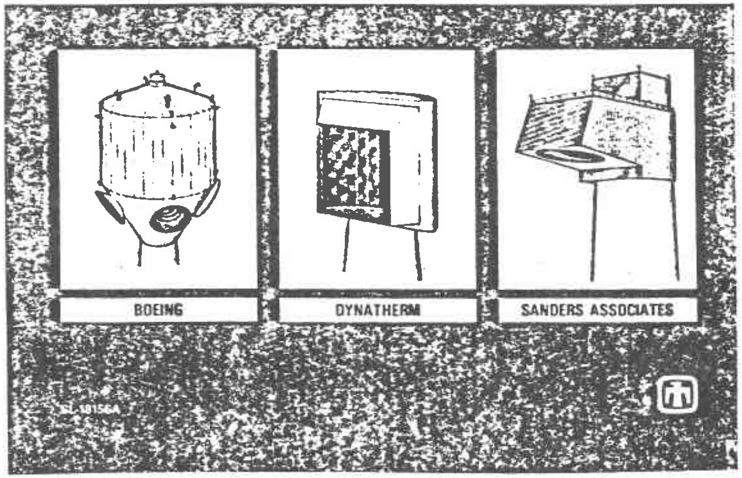


Figure 14

BRAYTON

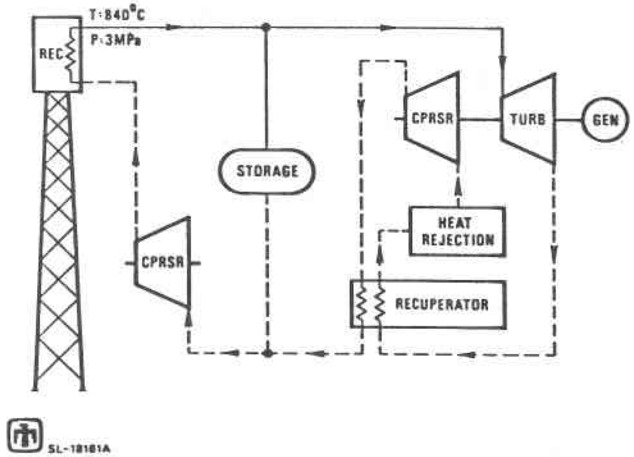


Figure 15

The Sanders Associates concept study has been going on for about three years, and the Dynatherm for at least a year.

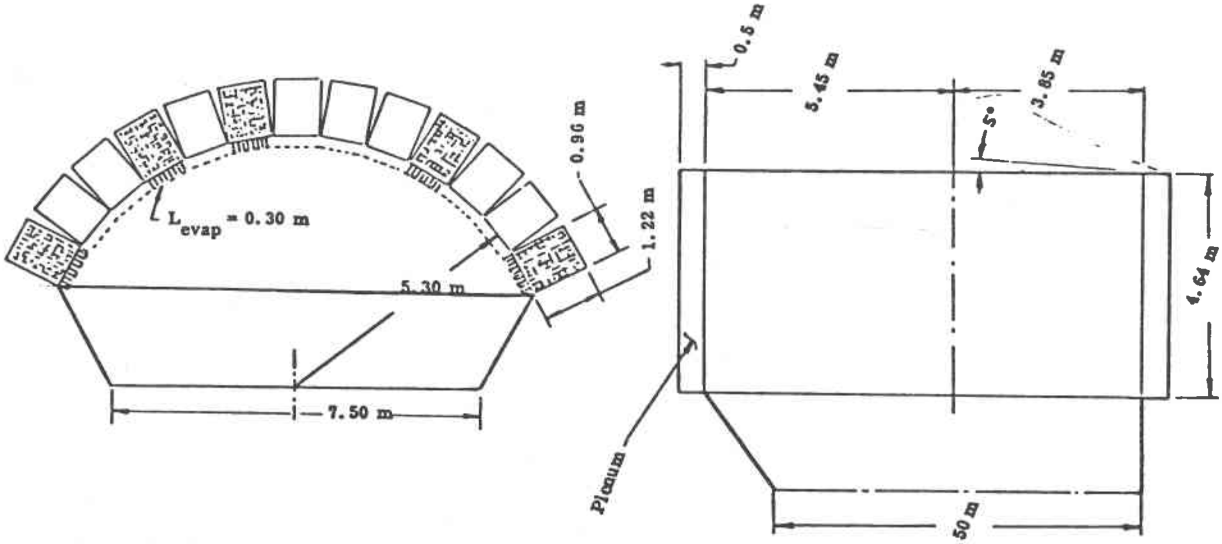
Figure 16 shows the top view of the Dynatherm receiver. The thing to note is that the interior of the cavity is lined with long, rectangular plenum-like chambers with stake-like projections from the interior walls. These projections are heat pipes, Figure 17. Figure 18 shows how the heat pipes interface with the plenum. The tapered ends of the heat pipes receive the insulation. This heat is transferred to the liquid sodium working fluid inside the heat pipe. The sodium vaporizes and travels to the end inside the plenum chamber where passing air removes the heat and condenses the sodium back to the liquid phase. The liquid sodium then returns via a wick at the interior circumference of the tube. This process promises high efficiencies because it uses the excellent heat transfer properties of sodium and couples it with a heat pipe, heat exchanger that allows one to place large surface areas on the media side with the poorest heat transfer properties. This particular design generates temperatures around 1500°F at about 4 atmospheres.

The Sanders receiver is shown in Figure 19. In this design, air is forced through a solar-heated ceramic honeycomb structure of silicon carbide. The heated air is then ducted through a storage stove filled with fire clay brick (magnesium oxide). After the stove is brought to temperature, it is switched out of the circuit and is available to generate steam or drive a turbine. A modification to the one in Figure 19 is now being tested at the GIT Solar Facility and is shown schematically in Figure 20. Figure 21 shows a cross section of the silicon carbide honeycomb. Figure 22 shows the GIT test configuration as it sits on top of the test tower.

The White Sands Solar Facility, where the first Sanders receiver was tested, is shown in Figure 23. Figures 24 and 25 are photographs taken inside the building and show the 20 kW_t Sanders receiver. This was a small-scale experiment that was completed almost 2-1/2 years ago.

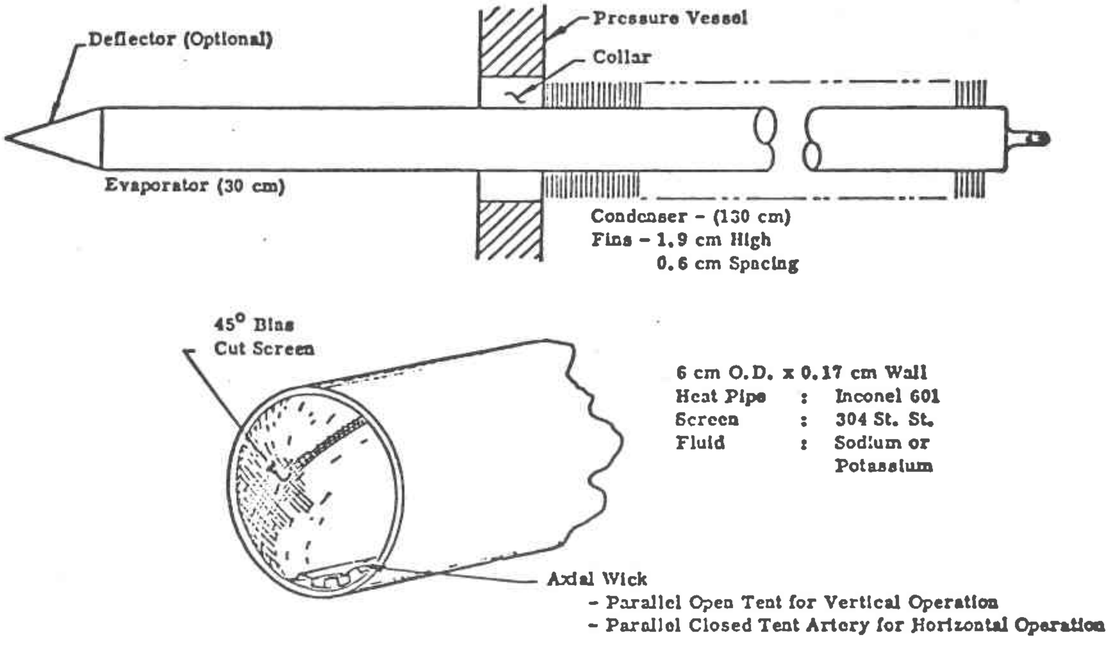
There is one troublesome area in the design of cavity receivers. To date, no one can accurately calculate the convective losses of these cavities, and so one has to resort to experiments. One such experiment was completed for the Sanders receiver. The concern was that air moving in and out of the honeycomb structure would entrain passing cold air and drop the efficiency. To assess this effect, the Sanders' people placed a receiver on a narrow-guage train and measured heat loss as a function of ground speed. The test set-up and results are shown in Figures 26 and 27.

Finally, Figure 28 shows a list of other related receiver work being sponsored by Sandia Livermore. Art Clausing, at the University of Illinois, is doing small-scale convective loss measurements in a cryogenic wind tunnel. A study at the University of Minnesota will characterize two-phase flow and flow stability. The boiler standards that exist for nuclear and fossil-fueled boilers do not apply very well to solar boilers. Therefore, we need to develop these standards and include them in a new ASME code. Materials testing needs to be continued. Characterization of metal and salt materials is currently underway at Sandia at at Martin. The tower



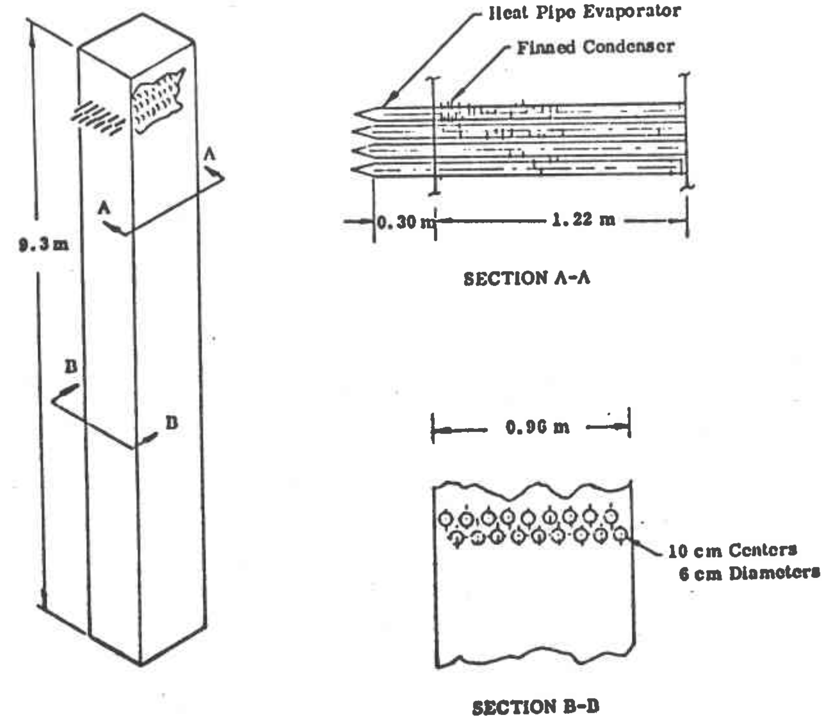
BASELINE RECEIVER DESIGN
(DESIGN THERMAL INPUT: 48.8 MW)

Figure 16



BASELINE DESIGN OF THERMAL DIFFUSER HEAT PIPE

Figure 17



TYPICAL RECEIVER PANEL

Figure 18

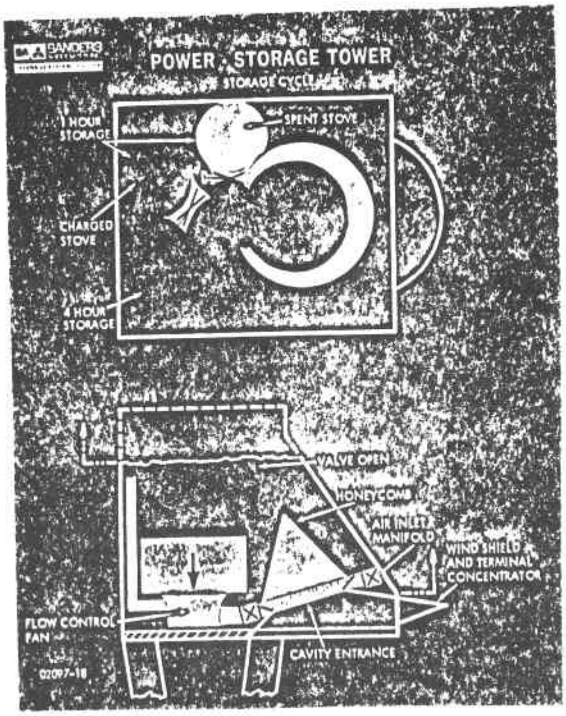
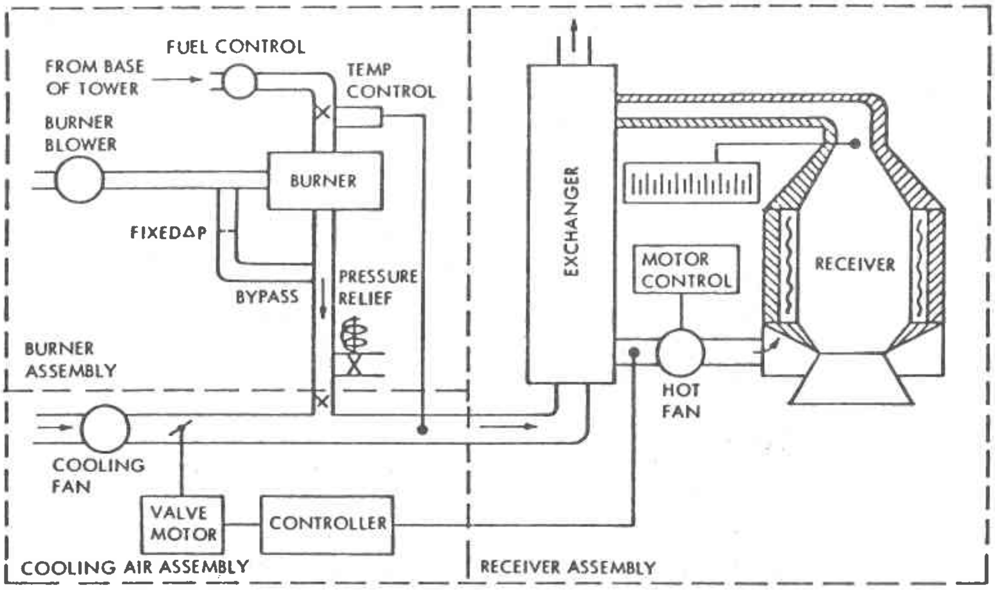


Figure 19



1/4 MWt Receiver Block Diagram

Figure 20

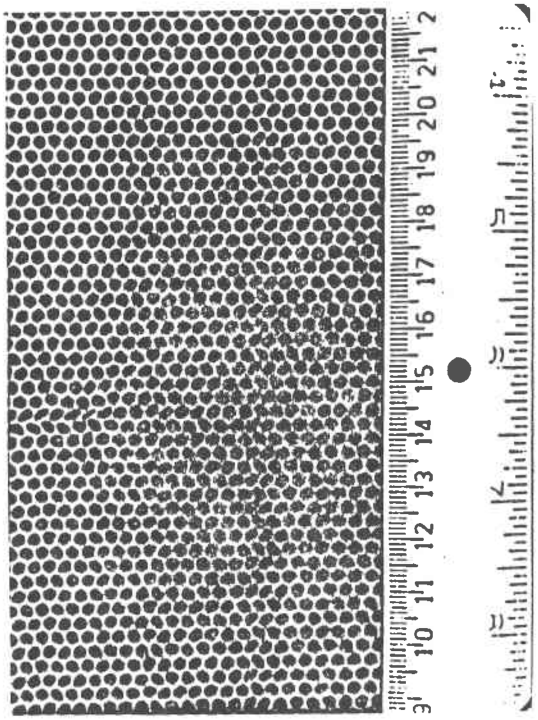
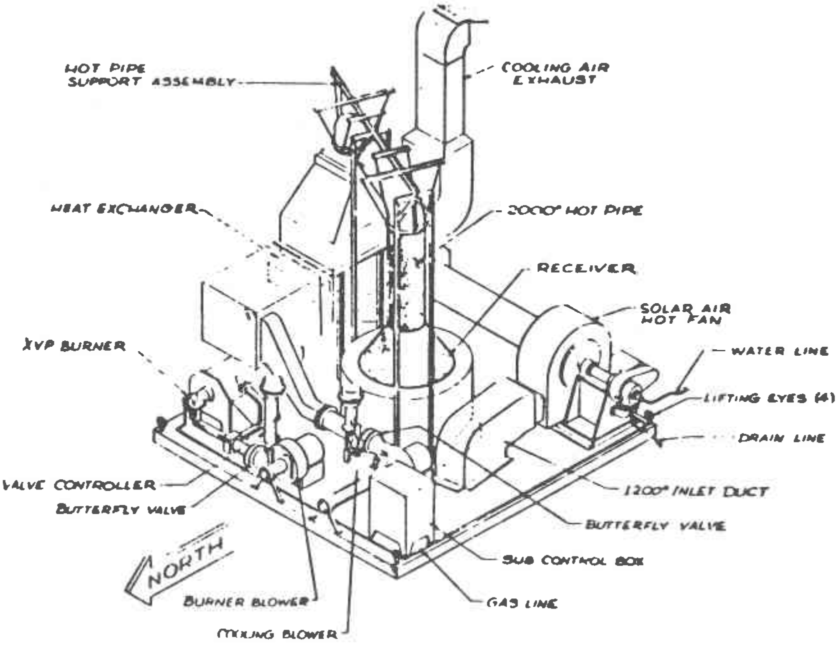


Figure 21



Platform

Figure 22

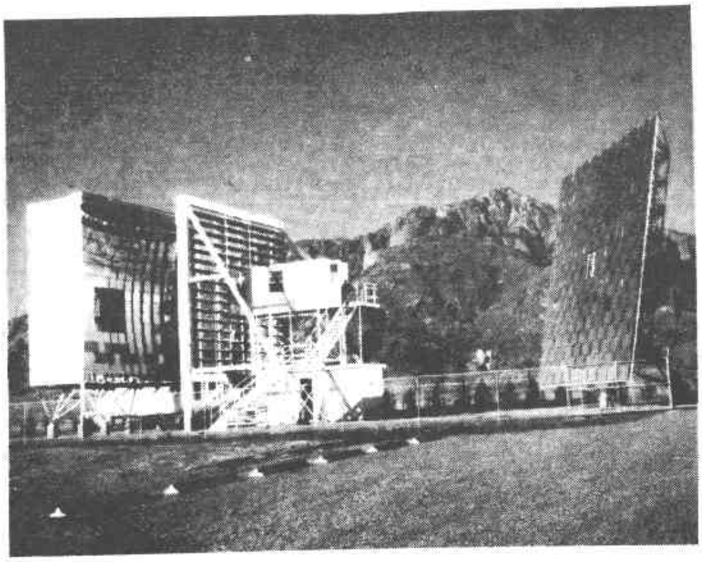
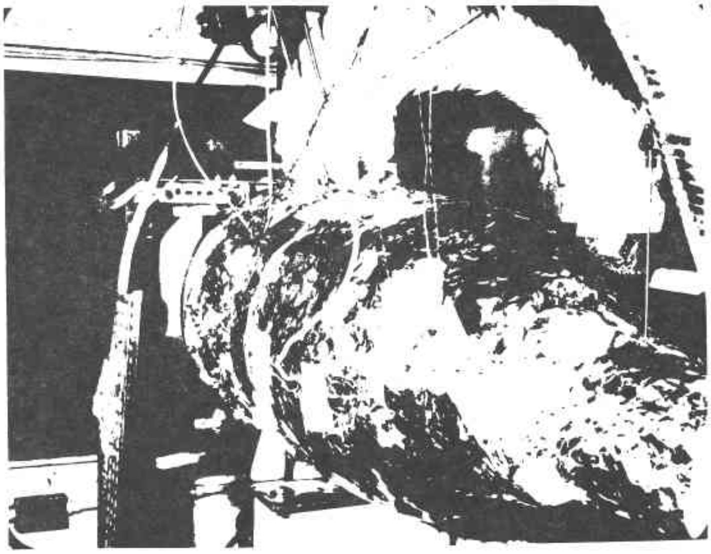


Figure 23

Figure 24



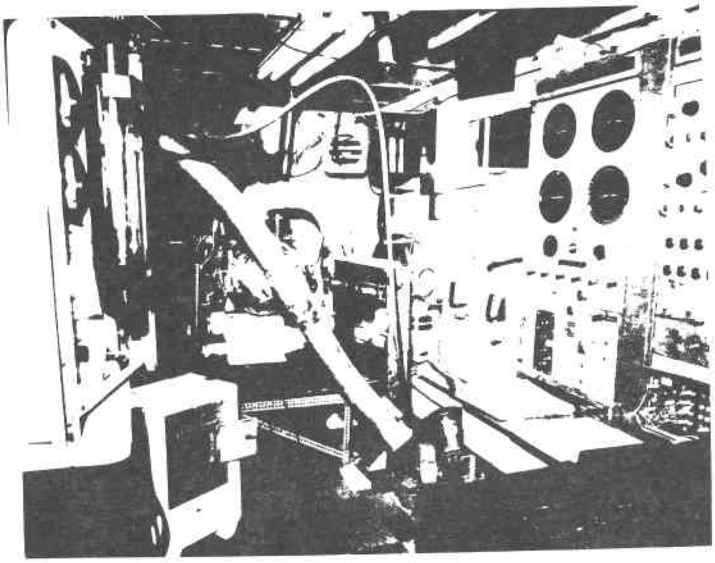


Figure 25

CONVECTIVE LOSS APPARATUS

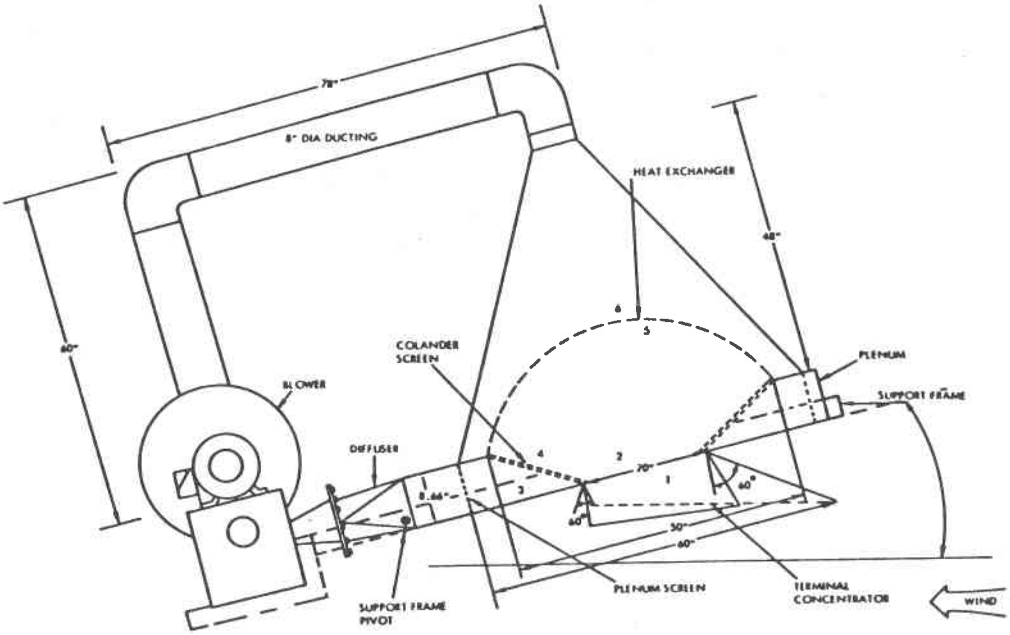


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Figure 26

CONVECTIVE LOSS EXPERIMENT
SUMMARY OF TEST RESULTS

SYSTEM	CONFIGURATION			% ENERGY LEAKAGE
	TERMINAL CONCENTRATOR	α (DEG)	WIND SPEED (MPH)	
1	YES	0	0	0.06
2	YES	14	0	0.06
3	NO	0	0	0.06
4	NO	14	0	0.09
5	YES	0	15	0.96
6	YES	14	15	1.09
7	NO	0	15	0.63
8	NO	14	15	0.43
9	YES	0	25	1.23
10	YES	14	25	2.46
11	NO	0	25	0.95

Figure 27

RECEIVER SPECIAL STUDIES

CONVECTIVE LOSSES - UNIVERSITY OF ILLINOIS

TWO PHASE FLOW - UNIVERSITY OF MINNESOTA

DESIGN STANDARDS FOR RECEIVERS - FOSTER WHEELER

MATERIALS TESTING - ARGONNE LABORATORIES

MATERIALS CHARACTERIZATION - SANDIA LABORATORIES

DIRECT ABSORPTION - SANDIA LABORATORIES

TOWER COST STUDY - STEARNS ROGER

Figure 28

study was necessitated by the discovery of large tower cost discrepancies amongst the various contractors involved in conceptual design studies.

The last entry is a pet project of Tom Brumleve at Sandia (Figure 29). Instead of having salt run inside a tube, Tom's idea is to allow uncontained molten salt to run down the surface of a flat panel. The salt is doped with cobalt oxide to increase its absorptivity. The elimination of the salt containment tubes allows the solar flux density to be increased by a factor of six, which raises the thermal efficiency. It also means that the receiver is lighter and less costly.

Figure 30 shows some of the comparisons between the various technologies related to receivers. The comparison between salt and sodium systems are often made because they employ similar components and have many of the same considerations and constraints. Salt stability is not the problem that it was thought to be. Both Sandia and Martin Marietta are continuing to work with these investigations. Both types of systems still share problems such as development costs, effects of freezing, pump seals, and high-temperature limitations. Sodium is relatively expensive, 37 cents a pound, while salt is projected to be 10-14 cents a pound (depending on where the number comes from). In spite of these differences, salt and sodium systems are both competitive and viable technologies.

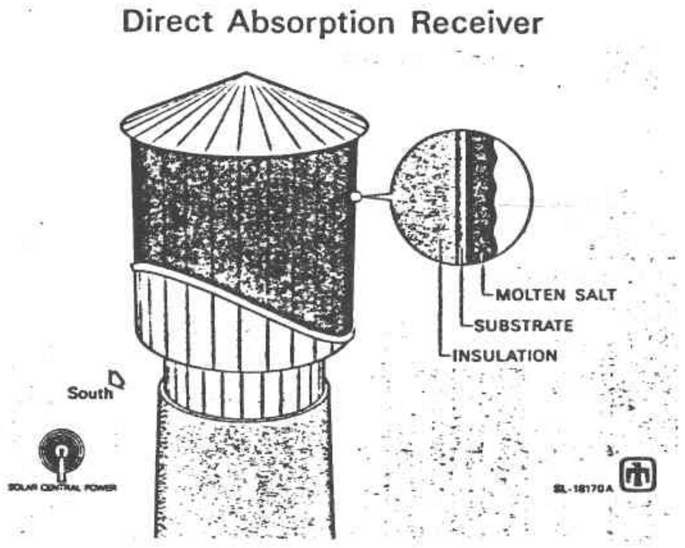

Figure 29

QUALITATIVE COMPARISON OF TECHNOLOGIES

Technology	Advantages	Disadvantages
Water/Steam	Developed technology	Requires dual admission turbine (storage) cost
Brayton	High efficiency EPGS Minimal safety concerns	High temperature desirable Development cost Limited utility experience in United States
Salt	Reheat turbine can be used Heat transport properties Minimal safety concerns High boiler efficiency Thermocline storage Low salt cost	Salt stability Limited compatibility data at maximum operating temperature Freezing Development cost Pumps/seals
Sodium	Reheat turbine can be used Heat transfer properties High boiler efficiency	Limited compatibility data at maximum operating temperature Pumps/seals Safety Freezing Development cost May not be possible to use thermocline Sodium cost

Figure 30

Ceramic, Solar Receivers for the Production of High Temperature Fluids

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913-967-2163

Introduction

Black & Veatch, under the sponsorship of the Electric Power Research Institute in programs RP 475-1 and 475-2, has developed a conceptual design for a solar/electric power plant intended for intermediate load range utility applications; Figure 1 is an artist's rendering of the plant. The conceptual design, which was based upon the use of an open cycle gas turbine as the prime mover, included a central solar receiver that was capable of producing high temperature, pressurized air (~135 psia, ~1900 F) as required for efficient gas turbine performance. This solar plant design offers the promise of high efficiency, as well as the capability to operate in a hybrid mode as illustrated in the process schematic shown on Figure 2. That is, the gas turbine can be powered by solar generated heat from the receiver/heat exchanger and/or by the combustion of fuel to heat the air as in a conventional gas turbine. This hybrid capability enables the solar power plant to be a reliable source of electricity regardless of weather conditions or time-of-day. Hybrid operation represents the most practical and economic approach to high temperature energy storage currently available and, because plant availability is assured through hybrid operation, utility demand capacity credit for the plant is feasible.

Among the many components of the plant, the least conventional and most critical is the high temperature receiver. The high air temperatures and pressures, coupled with the asymmetric heating of surfaces located within the cavity, required that the heat exchanger material exhibit high temperature strength properties beyond those available in current or developmental superalloys. Therefore, a ceramic material, silicon carbide, was selected for use in the receiver because it offered the necessary high temperature strength and heat transfer properties. The receiver concept, which is applicable to processes requiring hot and uncontaminated fluids, has been developed to the bench model stage and will undergo testing and evaluation during 1979. A discussion of that receiver and its development follows.

Receiver Cavity and Heat Exchanger Design. The solar receiver/heat exchanger was designed to meet the following requirements.

- Production of outlet air temperature in the range of 1800 to 1950 F.
- Minimum pressure drop between compressor and turbine.
- Materials selection to withstand internal gas pressure of ~135 psia and thermal stresses of 10,000 to 15,000 psi at the working temperature of 2100 F.
- Configuration to minimize losses by reradiation, reflection, and convection.

A tube-type geometry for the high temperature heat exchange surface was chosen because it offered advantages in fabricability, commercial availability of components, efficiency, and cost over other candidate geometries. The tube-type geometry is shown schematically on Figure 3. The tubes are separated from each other and are located in front of a diffusely reflecting surface. This arrangement minimizes the circumferential variation of tube temperature, and therefore the thermal stress in the tubes.

Silicon carbide was chosen as the heat exchanger tube material. The logic which led to the selection of this material is shown in Figure 4. The critical design parameters are identified in the upper left hand corner. Typical conditions within the heat exchanger cavity which determine the tube wall temperature and the stress are then illustrated on the right hand side of the figure. The important results are that tube wall temperatures will run at approximately 2100 F when the tube contains flowing 1900 F air, and that thermal stresses between 10-15 ksi are anticipated due to the asymmetric heating of heat exchanger tubes by the incident solar flux.

These values for the critical design parameters can then be used to enter the material strength-temperature diagram shown on the lower left hand portion of the figure. The two candidate materials were Inconel 617, a high-temperature super alloy, and Norton 430 silicon carbide. The 100,000 hour creep-rupture stress is shown for Inconel 617, and the modulus of rupture is shown for N430 silicon carbide. The location of the required design point clearly indicates the selection of silicon carbide as the heat exchanger tube material.

Placement of the heat exchanger tubes within a cavity to form the solar receiver is necessary to maximize heat transfer efficiency and to minimize losses due to reflection and reradiation of solar thermal energy. The cavity heat transfer surface was designed as a series of vertical U-tubes because of ease of erection, simple component replacement and low operating stresses. The concept of the U-tube cavity receiver is shown in Figure 5. Both inlet and outlet headers are located beneath the cavity floor. The U-bend (made of metal) is located above the cavity ceiling. Constant load springs, located above the U-bends, keep each U-tube in compression so that mechanical joints at the U-bends and at the headers may be properly sealed.

The design calculations for receiver operating temperatures and stresses, while within the predicted allowable limits, represent an extrapolation of the operating conditions that have been proven in commercial processes. Therefore, during the conceptual design activity, a number of tests were conducted for Black & Veatch at the Engineering Experiment Station of the Georgia Institute of Technology. These tests can be divided into the following two broad categories.

- Single-tube tests. In these tests, compressed preheated air was passed through a short length of silicon carbide tube, which was externally heated with radiant flux from quartz lamps. For a range of air pressures, temperatures, and flow rates, and for a range of incident flux levels, the air temperatures and tube surface temperatures were recorded. The experimental results, as shown in Figure 6, agreed with the analytic predictions of the material temperatures and temperature distribution and with the predicted material and air heat transfer properties.

- U-tube Tests. In these tests, a U-tube was assembled from two, four-foot lengths of silicon carbide tubing and a metal U-bend. Each of the silicon carbide tubes had been cut into two shorter lengths and rejoined with a silicon carbide "weld". The entire U-tube assembly was subjected to an axial compressive load in order to form an effective seal between the U-bend and the tubes and between the tubes and the inlet and outlet ducts. Compressed, preheated air flowed through the compressively loaded U-tube assembly, which was externally heated with radiant flux from a quartz lamp bank. The flux level was varied cyclically to induce severe thermal cycling stresses within the tubes. Although the stress levels and material temperatures under the test conditions shown in Figure 7 were significantly higher than had been analytically predicted for the commercial scale receiver tubes, no material failure or degradation was observed.

Bench Model Solar Receiver. The design and test activities previously described were sufficiently encouraging that EPRI funded Black & Veatch to proceed with the detailed design, fabrication and test of a 1 MWt Bench Model Solar Receiver (BMSR). The primary technological development addressed during the BMSR detail design was the design of the joints at the ends of the silicon carbide tubes shown located within the cavity on Figure 8. The temperature requirements of those joints are as follow.

• Inlet Header:	500 C (950 F)
• U-Bend:	840 C (1550 F)
• Hot Header:	1070 C (1950 F)

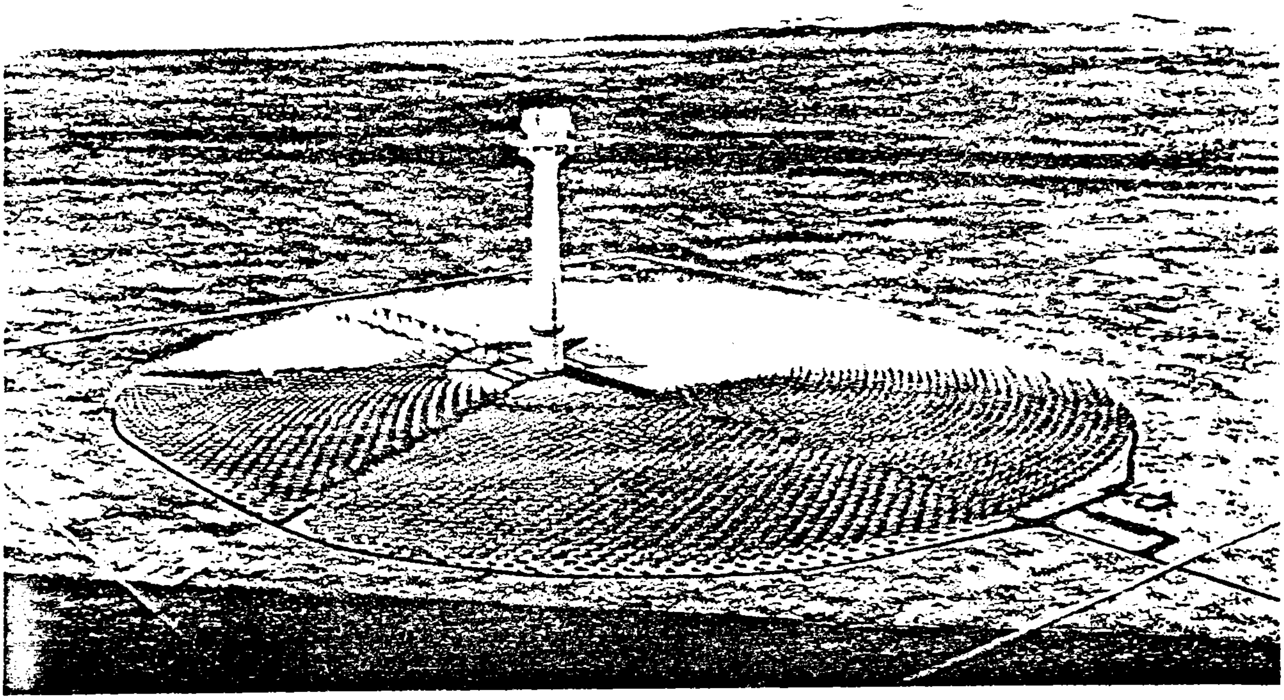
Because the tubes are not perfectly straight, and they are under a compressive load, and they are radiantly heated more on one side than the other, the tubes will tend to deflect into a bowed configuration. If the joints were rigid, the tube material would experience significant tensile stresses; while the predicted level of these stresses is below that which the tubes are expected to withstand, it appeared prudent to permit the joints to articulate, thereby significantly reducing the ceramic tube material stresses. Therefore, in addition to withstanding the internal temperatures previously discussed, the joints must permit a rotation of the centerline axis of the tube; since the conditions which impose this rotation will occur at least on a daily basis, the joint must withstand repeated cycles of this rotation.

In order to design and experimentally qualify joints of this type, Black & Veatch developed a program plan, selected a suitable subcontractor, and directed the joint development program. During this test program, which was conducted by Atlantic Research Corporation in Alexandria, Virginia, a number of joint designs and alternative materials were considered and tested. The fundamental concept for all the candidate joints was a ball-and-seat geometry which had previously been tested at Georgia Tech. In this geometry, the end of the tube is machined to a spherical surface, which rests on a conical seat machined into the mating surface. The sphere is free to rotate within the cone while preserving a pressure seal with a line contact. Two fundamentally different joints were designed and successfully tested. The testing of each joint included three thousand rotational cycles with compressed heated air flowing through the joints; the air temperature was higher than is expected to occur in the commerical receiver joints.

- High-temperature Joint. For the joint between the hot end of the hot tube leg and the internally-insulated stainless-steel high-temperature heater, a transition-type joint was developed. In this design shown diagrammatically on Figure 9, the tube seat cone is machined into a flat circular ceramic disk. The disk rests on an internally-insulated right circular metal cylinder which is fastened to the header envelope using conventional technology. The seal between the ceramic disk and the metal cylinder is a high-temperature O-ring in a bolted-flange configuration. The internal insulation and the cooling from the top side of the disk reduce the flange temperature to an acceptable level. This joint was successfully qualified with three ceramic disk materials: hot-pressed silicon carbide, hot-pressed silicon nitride, and slip-cast silicon carbide. In addition to the three thousand cycles previously described, an additional five hundred overtest cycles were imposed without failure; during these overtest cycles, both the air temperature and tube rotation were more severe than will occur in operation.
- Lower-temperature Joints. For the low- and intermediate-temperature joints, the design is similar, but less complex. The conical seat is machined directly into the mating metal surface and the seat area is coated with a wear-resistant material. Three different wear-resistant materials were successfully qualified: detonation-gun-applied alumina, flame-sprayed chromium carbide, and triballoy.

Conclusion

The joint development program, the last of the BMSR component tests, was successful in qualifying designs for use in the BMSR. Detailed designs of the BMSR have been completed by Black & Veatch and their fabrication subcontractor, Thermal Transfer Corporation. Material procurements are underway and fabrication of the BMSR, shown pictorially on Figure 10, will be completed in January of 1979. Testing and evaluation of the receiver is scheduled to be completed by the end of 1979.



60 MWe OPEN CYCLE GAS TURBINE SOLAR ELECTRIC PLANT
ELECTRIC POWER RESEARCH INSTITUTE
BLACK & VEATCH · DESIGN ENGINEER

Figure 1: Artist's Rendering of the Plant Concept.

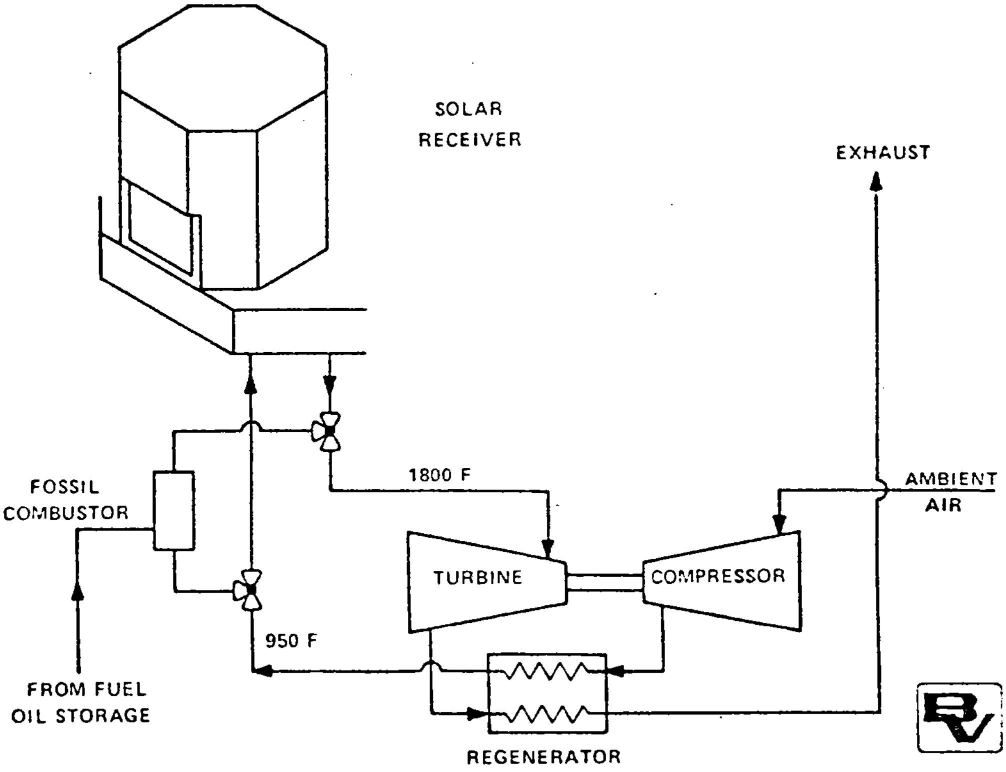


Figure 2: Process Schematic of a Hybrid, Open Brayton Cycle Central Receiver System.

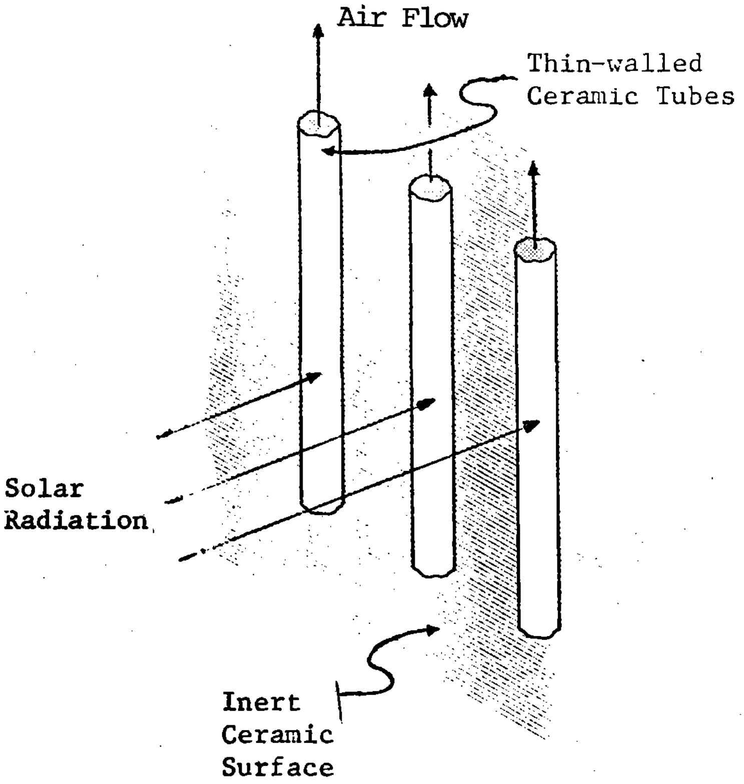


Figure 3: Tube-Type Heat Transfer Surface Geometry.

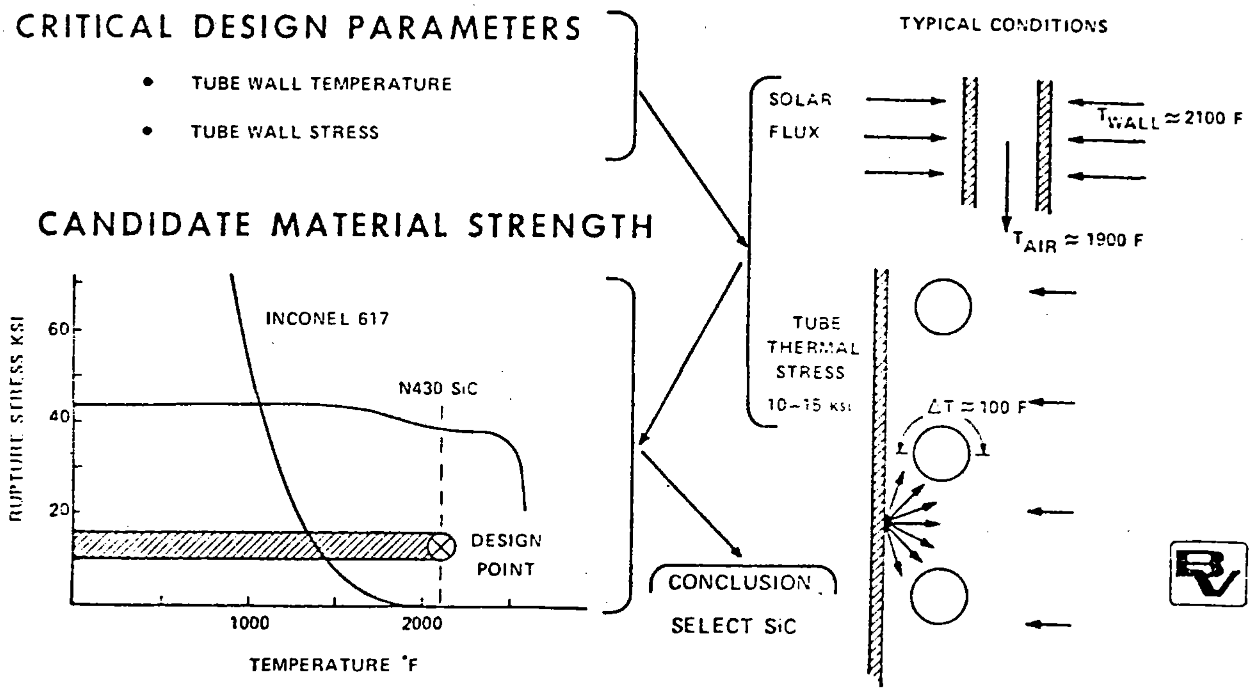


Figure 4: Selection of Heat Exchanger Tube Material.

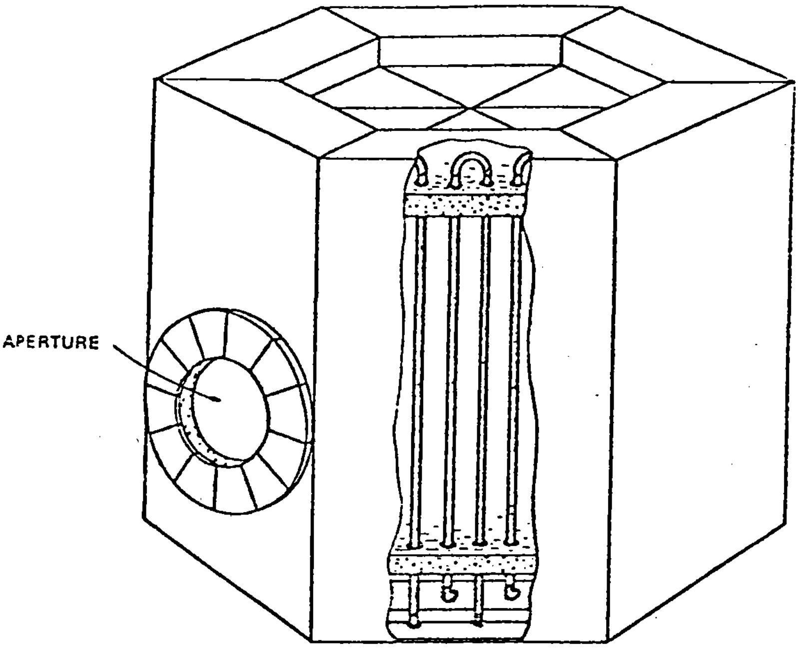


Figure 5: High Temperature Receiver Cavity With U-Tube Configuration.

TEMPERATURE °F	HEMISPHERICAL EMITTANCE $\epsilon = \alpha$
85	0.67
1600	0.83
2000	0.85

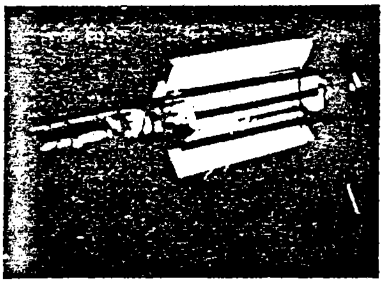
CONVECTIVE COOLING COEFFICIENT

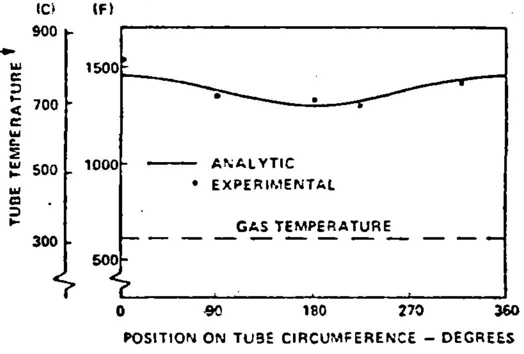
$\frac{W}{M^2-C}\left(\frac{BTU}{HR-FT^2-F}\right)$

CASE	EXPERIMENTAL RESULTS		ANALYTIC RESULTS	
1	210	(37)	199	(35)
2	295	(52)	278	(49)
3	420	(74)	386	(68)
4	698	(123)	534	(94)

CALCULATED AND EXPERIMENTAL TUBE CONVECTIVE COOLING COEFFICIENT – SILICON CARBIDE

SINGLE TUBE TESTS

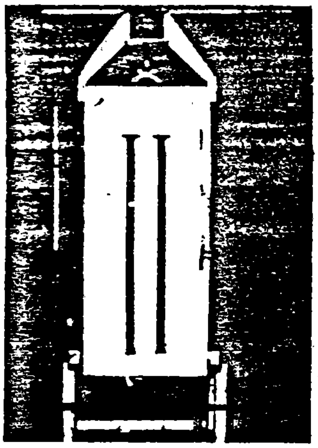




CALCULATED AND EXPERIMENTAL TUBE WALL TEMPERATURES – SILICON CARBIDE

Figure 6: Silicon Carbide Thermo-Optical Properties and Heat Transfer Behavior.

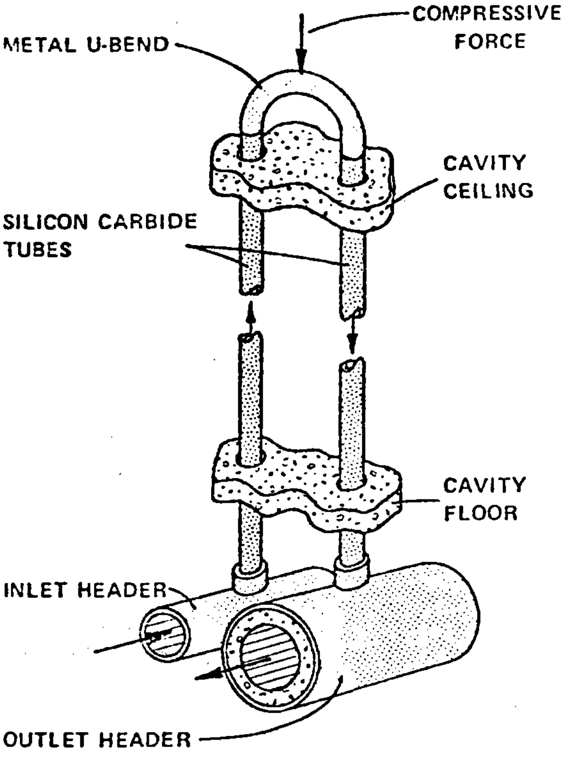
100 KWT RADIANT
HEAT TEST SETUP



CUMULATIVE CYCLES	INLET AIR TEMPERATURE F	MIN/MAX TUBE TEMPERATURE F
245	160	405/1385
270	300	525/1405
341	750	970/1820
500	950	1020/1865
600	STATIC	990/2210
603	STATIC	995/2430

CONCLUSION: JOINED, 2 IN OD SiC TUBES CAN WITHSTAND REPEATED THERMAL CYCLING AT DESIGN TEMPERATURES WITHOUT DAMAGE

Figure 7: Thermal Cycling Tests for 2 Inch OD, Joined SiC U-Tube Configuration.



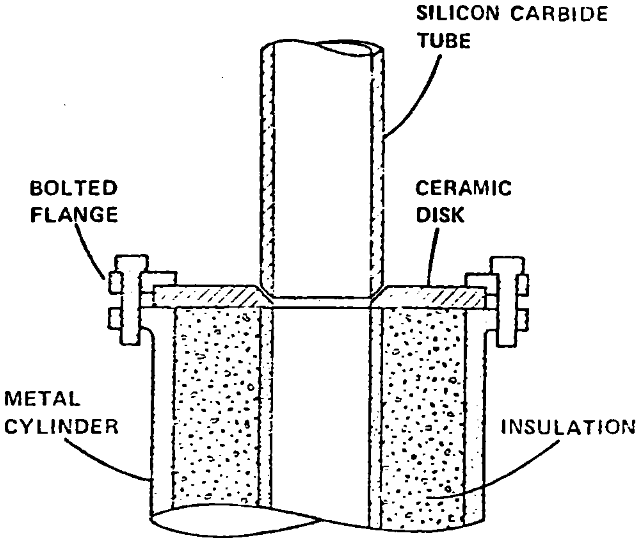


Figure 9: Hot Joint Geometry.

Figure 8: U-Tube Arrangement.

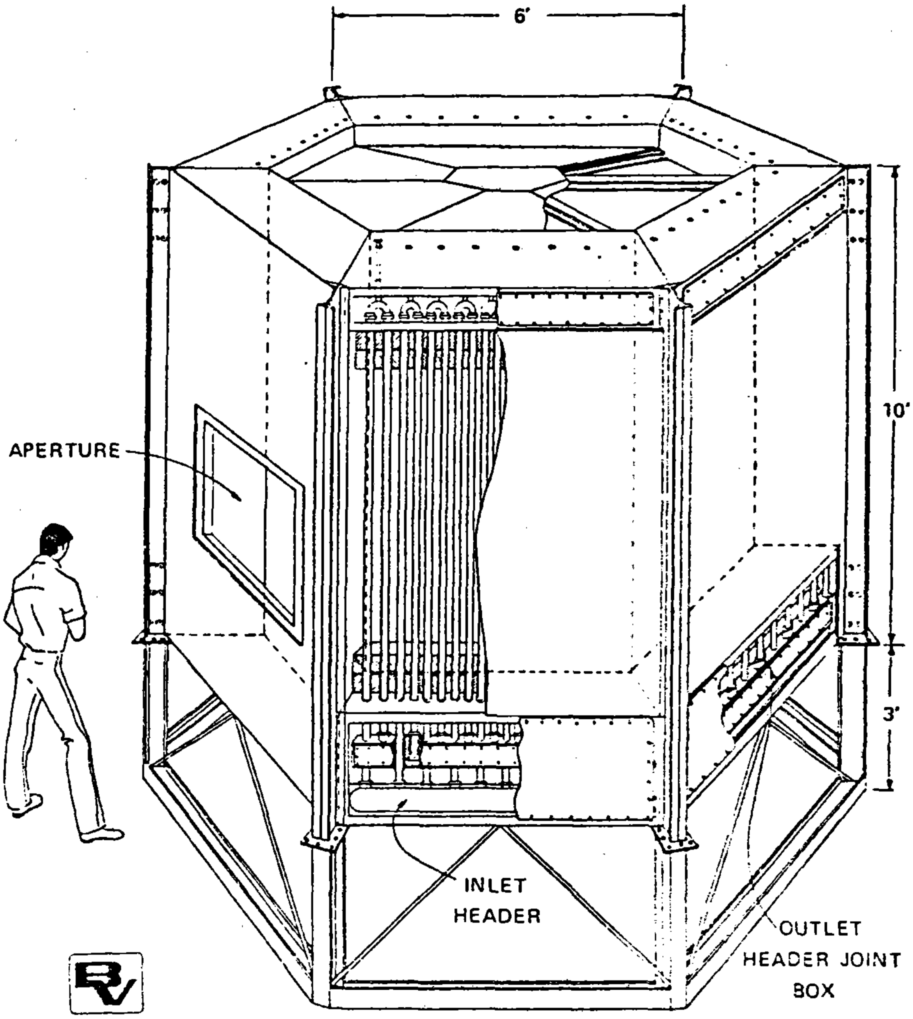


Figure 10: Perspective of the 1 MWt Bench Model Solar Receiver.

HELIOSTAT DEVELOPMENT AND COSTS

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Livermore, California 94550

I'm going to describe to you the DOE heliostat development program in a very cursory fashion, talk about some of the cost projections that have been made and try to give you a feel for why I think we can get there from here.

Figure 1 shows the four heliostat design concepts involved in the Barstow Pilot Plant competition about 18 months ago. It is common knowledge that the McDonnell Douglas concept won that competition. At this time two contractors (Martin Marietta and McDonnell Douglas) are performing detail design studies of that concept in competition for the one-time build of about 2000 units of this first generation technology.

Figure 2 presents a line drawing of the second generation heliostats that we have been pursuing for about six months with DOE funding. The Boeing second generation design is basically an improved version of the enclosed heliostat design they had in the pilot plant competition. General Electric has also been working on an enclosed plastic bubble heliostat design. GE has been concentrating heavily on mass production and automated approaches to the fabrication and installation of the design.

The McDonnell Douglas design shown in Figure 2 is basically a take-off from their winning approach to the pilot plant design. They have increased the reflective area and made several improvements to the mirror modules, foundation and drive system. The Solaramics approach has been to use new and novel materials. They have designed a heliostat using foamed glass and ceramics for structural components.

In addition to the four federally funded second generation heliostat designs shown in Figure 2, a fifth design is being developed by Westinghouse with their internal funds. In exchange for our providing Westinghouse with design critiques and evaluation testing of a prototype, they have agreed to release design details and cost estimates to DOE. In essence then, five different design teams are formulating second generation heliostat studies.

The design cost goals for these efforts have been generated based on the cost projections for competing electricity producing technologies. Figure 3 illustrates the reduction in busbar energy costs for electricity producing plants as the heliostat costs drop. As the heliostat costs are reduced to the \$72 per square meter DOE goal, the production of electricity will be about 60 mils per kilowatt hour. Even though these cost goals have been associated with the production of electricity, the components being developed are also applicable to process heat applications.

Figure 4 shows the DOE heliostat cost goal plotted against reflectivity. Obviously, a heliostat design with high reflectivity is worth more to a buyer because he will have to buy fewer units to generate a given amount of thermal energy. Stated another way, a design with lower reflectivity must be correspondingly cheaper to be competitive. Hence, the $72 per square meter refers to a perfect reflector--100 percent reflectivity. Real world designs must come in at costs below the solid line that drops as it goes to the right.

Also plotted on this chart are the cost estimates supplied by the various second generation heliostat contractors. The two data points shown for each design are for 25,000 and 250,000 units per year. As shown, the various contractors are projecting either close to or below the DOE cost goals for their designs. I've also shown one data point for a mass production estimate of the Barstow Pilot Plant design at $95 per square meter. The reason for including that data point is to give you a feel for the cost reductions that have been made in the last year.

Initial capital costs are only one factor in the determination of the viability of heliostats to compete with other sources of thermal energy. Total life cycle costs and annual performance are the quantities that a user must consider. Sandia has performed these evaluations for each of the four designs and will be making recommendations for hardware development based on these calculations. At this time, however, the contractors have not been debriefed as to Sandia's evaluations and thus I cannot give you any details as to the overall ranking of the designs.

We have gotten some very good design work and detailed cost estimates from the second generation contractors. One of the questions that often comes up is: How much credibility can you put in these numbers? While we have not double checked every number, we have spot checked the data provided and estimated costs for items overlooked. But the fact remains, that no mass produced item is precisely the same as a heliostat and hence our "credibility checks" have been made by drawing analogies to commercially produced hardware.

One of the simplest comparisons can be made with the automobile industry. Here mass production techniques have been employed with such efficiency that several models can be produced simultaneously and many buyer options such as equipment installed, materials used and colors desired can be accommodated. Even with all these complications, it is possible to buy small automobiles and pick-up trucks for under one dollar per pound. This number includes overhead for substantial advertising budgets and middleman profits.

By contrast, heliostats are very simple structures using common building materials, standard fabrication techniques and essentially no buyer selected variations. Figure 5 tabulates several of the pertinent parameters for the four second generation designs at production rates of 250,000 per year. From this data, it can be seen that the contractor cost projections correlate to between 50 cents and roughly $3 per pound.

Figure 6 presents a collage of the costs of mass produced items versus an assumed complexity scale. On the left side of the figure are very simple items like plastic swimming pools and wall mirrors. On the right side are standard automobiles and pick-up trucks while in the middle of the complexity scale are items such as refrigerators and washing machines. The purpose of presenting this data with the cost per pound of the heliostat designs superimposed is to calibrate your intuition as to the believability of the heliostat costs estimated by the various contractors. From this kind of a comparison we have concluded that the costs are credible.

If these are the goals, and the mass production numbers look reasonable, what has been the experience with buying heliostats? Figure 7 plots the heliostat costs in dollars per square meter versus the quantity produced. These numbers are for heliostats of roughly 40 square meters in size and the data shown are both estimates and recorded purchase prices. There have been only two substantial buys of heliostats and both were for the Central Receiver Solar Thermal Test Facility in Albuquerque. For the first buy we had estimates of over $800 per square meter. The first delivery of 78 units actually recorded at $610 per square meter. The second buy was for 144 additional units and the order recorded $420 per square meter.

The data shown in the middle of the chart refers to the Barstow Pilot Plant and at this time is based only on estimates made two years ago and last year. From current information we expect to end up paying somewhere between $200 and $300 per square meter for the under 2000 units planned. In the lower right hand corner is the DOE goal of $72 per square meter. We anticipate reaching that cost after several hundred thousand units have been purchased.

Let me summarize in Figure 8 where we stand with the heliostat development program. We have had a variety of companies, with a variety of design approaches, independently estimating the cost of mass produced heliostats. The cost estimates include fabrication, delivery, installation, check-out, calibration, fees and contingency. Even though I haven't discussed it much here, we have also estimated the operations and maintenance costs for a full 30 years of a plant's life. We have not considered any of a variety of government incentives that could substantially reduce the costs of purchasing these components for the user. In addition, comparison with other mass produced items has indicated that the cost projections are credible and, finally, the trend in purchased heliostats is encouraging.

From this information we have concluded that the $72 per square meter DOE goal for heliostats is attainable. It is attainable but it is not available today. It is going to take relatively large buys of heliostats to create the market conditions to involve the mass producers. But there is one message I want to leave with you. The number I have shown are influenced by learning curve reductions but primarily the achievement of the cost goals will be met by efficient mass production oriented designs. Thank you.

Question: What year dollars were those costs in?

Mr. Wilson: 1978 dollars.

Question: Where did the magic $72 come from?

Mr. Wilson: It was generated by looking at a power plant with advanced technology, and allocating costs to the various components, as Len Hiles showed you earlier. Knowing that the competition in the 1990 time frame will be roughly $1700 per installed kilowatt for electricity production we have allocated cost goals for each of the subsystems. That's how the $72 was arrived at.

Question: You hope that mass-production will bring these costs closer to the DOE cost goals. Are you looking into what factors will increase the economic sale of mass-production techniques?

Mr. Wilson: Yes. We're not relying on mass production to bring the cost down. The costs are coming down because of efficient designs and the designs are being optimized. As a matter of fact, if you look at them in detail, each unit heliostat is getting much larger. There is an economy of scale with these things and there is effective selection of materials. If you look at the McDonnell Douglas heliostat, they're planning on using glass with a reflectivity of about .92 to .93 percent. The heliostats of the STTF have a net reflectivity of .78 percent. It's just because of the glass that was selected for the two and its thickness. I think the design itself is really the big factor in driving these costs down. The mass production and the amount of automation are decisions that a producer will have to make. That's not the major factor in dropping the costs.

Question: One of the major cost factors on heliostats is the drive mechanism. Have you looked at a tradeoff of the precision tracking you can get as opposed to a larger aperture or target space?

Mr. Wilson: Yes, we've used many interrelated parameters. We've been doing something called the floppy heliostat. In terms of the drive mechanism, we specify to the heliostat designer a restriction in total slop factor. He can allocate that wherever he wants to in his design. He can have lousy mirrors and very efficient drives, or the other way around--there are a lot of tradeoffs. We're not trying to push anybody in any given direction. We figure the best answer will come from somebody who really wants to be competitive and that will drive the design cost down.

Question: With respect to the cost of electricity, I believe your figure was 60 mils per kilowatt hour. At what point will that become competitive with other methods of generating electricity?

Mr. Wilson: That's a difficult question to answer. The number you mentioned, 60 mils per kilowatt hour, depends on the assumptions made about the cost of money and various other things; it can vary anywhere from 40 to 80 mils easily. As to when it will be competitive, depends on where you are in the country. Some people are paying that kind of money for electricity now. These numbers are generally 1990 estimates.

Question: Do you have wind loading figured into this? Such as the differences, how they figure, and what kinds of wind loads they will take, or are you not specifying that?

Mr. Wilson: We specify that heliostats have to be able to operate in 30-mile an hour winds. They have to withstand gusts from 50 to 60 miles an hour. In the stow position, they have to survive 90-mile an hour winds. We do specify those kinds of things. Everybody is working to the same set of specs.

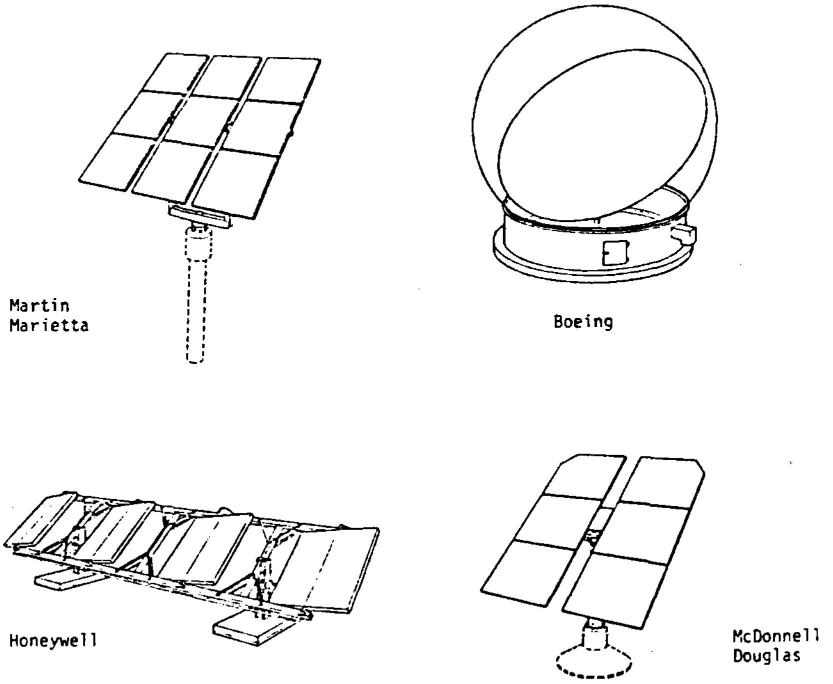
Question: What about shipping and the breaking of those large units?

Mr. Wilson: The tendency is to keep making the things larger because the receiver targets are really pretty large, at least in the external receivers. What has become a constraint is putting them in a truck for shipping to the site, and doing as much in the factory as possible. In most of the designs that are efficient, every bit of work that can possibly be done at the factory is done there. You minimize labor in the field because that labor is very expensive.

Smith: Cost is the name of the game here, the thing that will determine whether this whole technology is really going to fly and make a big impression on our energy shortage. In turn, that cost is very heavily dependent on the cost of the heliostats. As I believe Leonard's slide showed, some 40 percent of the total cost is heliostats. The cost is $200 or more per square meter. Those prices have got to come down to less than $100 per square meter before we get really competitive with coal, oil, etc. DOE is well aware of that, and is intensively pursuing studies with several contractors aimed at lower manufacturing costs and I'm becoming more and more convinced that that program will be successful.

Part of the heliostat cost, in turn, hinges upon the future demand for them. For instance, the 10-MW electric Barstow plant you heard about will use 2000 heliostats. If we're thinking of 100-MW electric plants, then we're talking about something like 20,000 heliostats. If we are serious about this business, and build maybe ten a year, we're talking about a quarter million heliostats per year. The heliostat manufacturing people with whom we've discussed this assure us that if we get demand for heliostats up to those levels, somewhere between a quarter and a half million per year, the cost will, indeed come down because they will be mass produced and there will be a lot of competition. I personally feel that will be true.

Up to now, we've talked almost entirely about operation of electricity. However, there may be an equally large market, if we can identify the potential applications for industrial processes, which would increase the demand for those heliostats, and bring the prices down just that much faster.



First Generation Pilot Plant Heliostats

FIGURE 1

Large Power Systems SECOND GENERATION HELIOSTATS

OBJECTIVES

- **Low Cost Mass Production Design**
- **Detail Cost Estimates**
- **Broad Industry Participation**
- **Identify Required R&D**

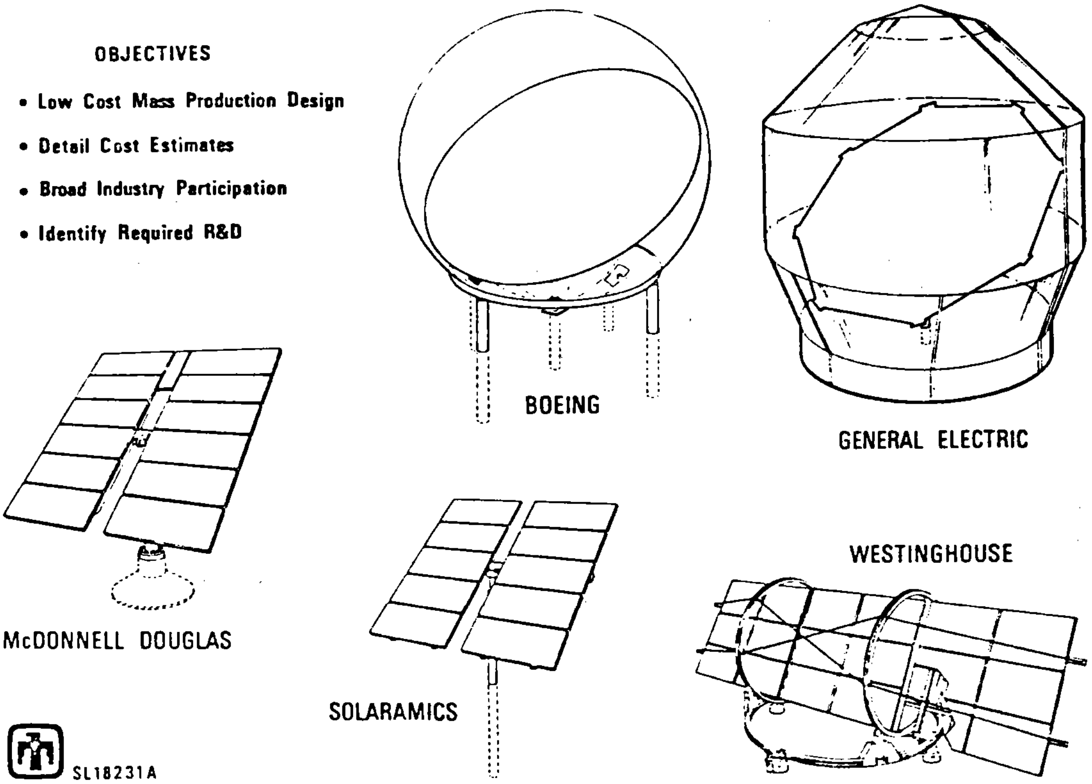


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FIGURE 2

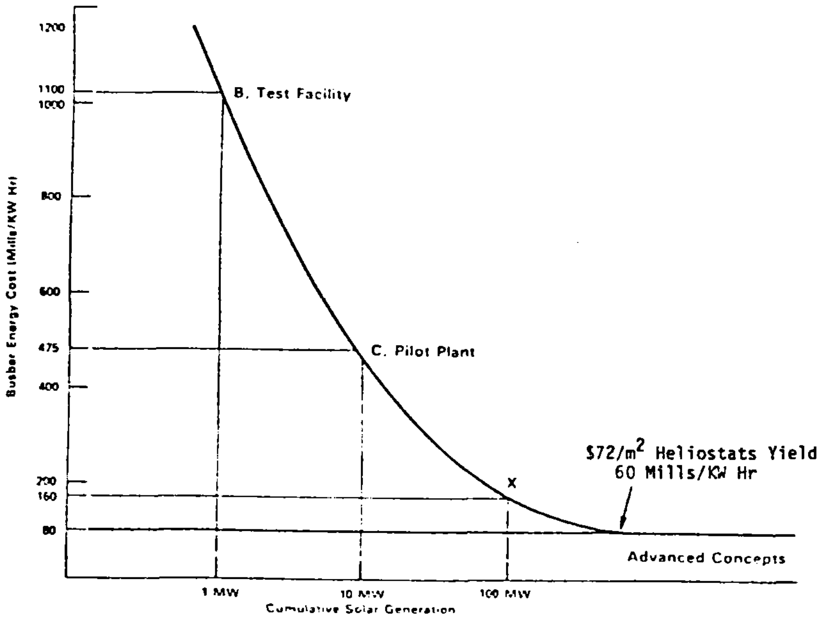


FIGURE 3

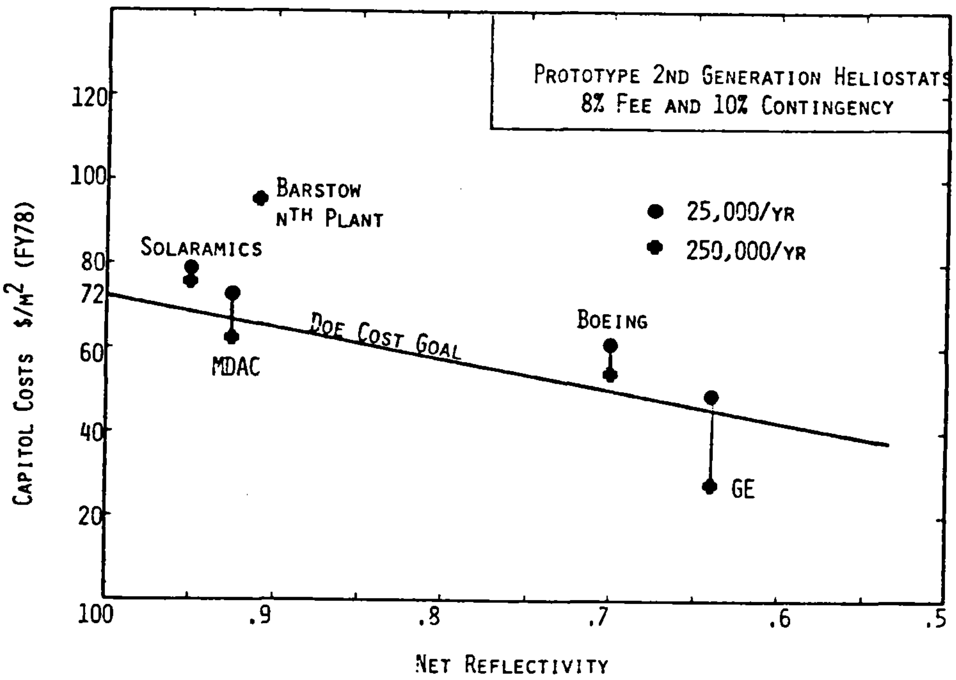


FIGURE 4

SECOND GENERATION HELIOSTAT COMPARISON*
(1978 DOLLARS)

	MDAC	SOL.	BEC	GE
REFLECTIVE AREA (M2)	49.1	38.6	65.7	55
UNIT COST ($)	2999	2934	2825	1443
WEIGHT (LB)**	4041	5995	2390	468
$/LB	0.74	0.49	1.18	3.08

*CONTRACTOR ESTIMATES BASED ON 250,000/YR
**NOT INCLUDING CONCRETE

FIGURE 5

COMPARATIVE COSTS FOR MASS-PRODUCED ITEMS

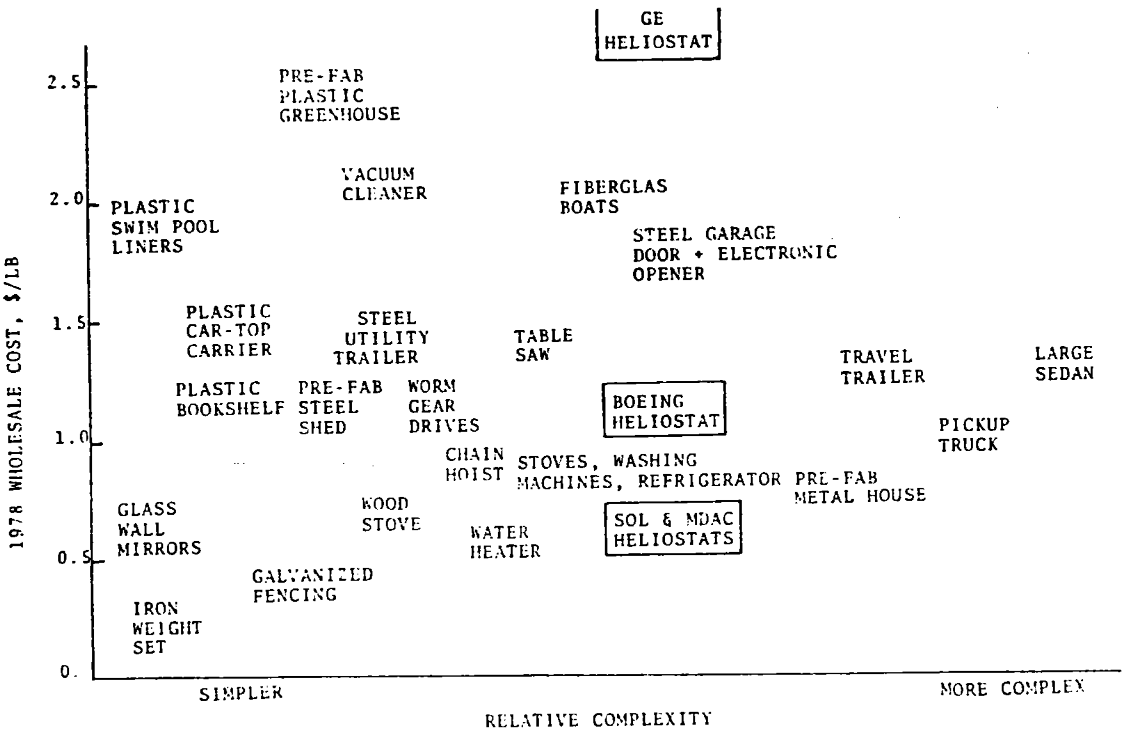
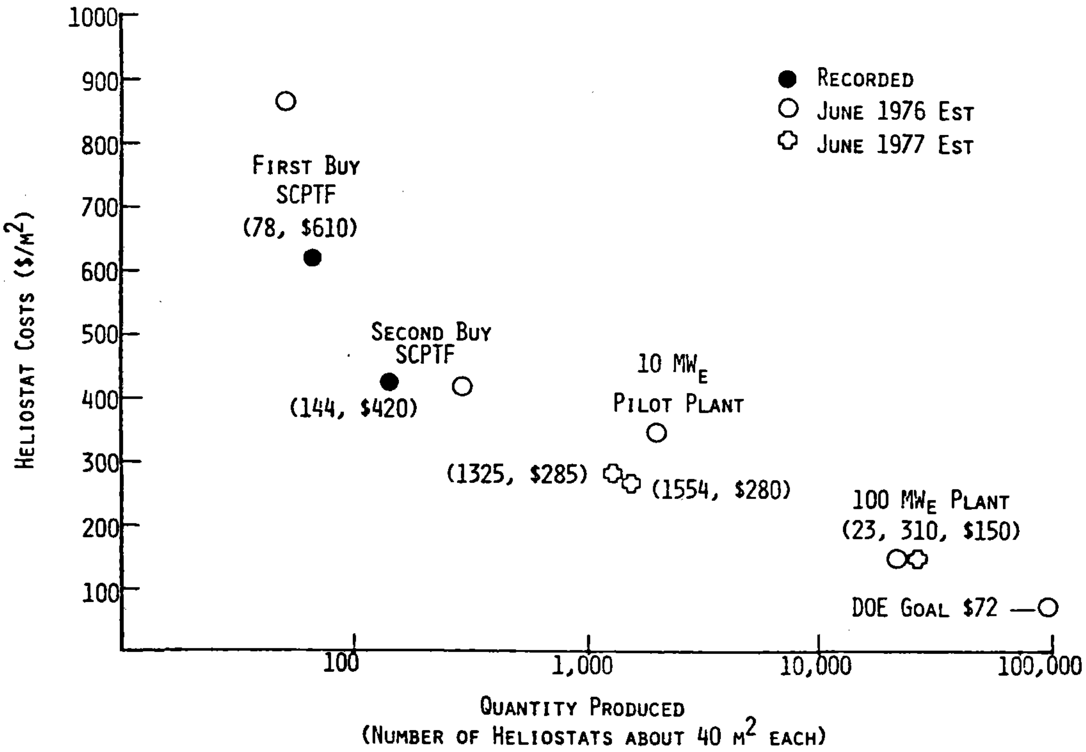


FIGURE 6



SUMMARY

- Several Large Companies Have Supplied Independent Design and Costing Studies.
- The Cost Estimates Include Fabrication, Delivery, Installation, Checkout, Calibration, Fees and Contingency. In addition, the Operations and Maintenance Costs for 30 Years Have Been Estimated.
- Government Incentives Have Not Been Considered.
- Competitive Market Prices (Expressed in $/lb) of Items Currently in Mass Production Suggest that Volume Production Cost Projections of Heliostats are Credible.
- The Trend in "Purchased" Heliostats is Encouraging.

FIGURE 8

SECTION VII

MARKET ANALYSIS OF HIGH-TEMPERATURE SOLAR PROCESS HEAT

By

PAUL A. CURTO
MITRE/Metrek
McLean, Virginia

ABSTRACT

Studies conducted here at MITRE over the last three years have indicated an extremely large market performance potential for solar industrial process heat systems. Engineering analyses optimized several generic configurations of solar process heat systems based on fuel prices, equipment costs and performance criteria. These generic designs were modelled in simulations of markets, competing with oil, gas, coal, synfuels, direct use of electricity and electric heat pumps, over the period 1978 to 2000. The yearly simulations indicated that three generic solar thermal power systems will dominate the solar process heat market: the parabolic trough utilizing evacuated tubes, the parabolic dish and the central receiver. More than 80 percent of projected sales are for concentrators designed to deliver heat between 150° and 800°C. These sales may reach 10 billion square feet (one billion square meters) cumulative by 2000. However, several caveats must be offered as qualifiers: (1) an investment tax credit in excess of 40 percent is needed to make solar equipment cost-effective; (2) fuel prices must be deregulated or taxed to reflect true worth; (3) industrial use of energy must continue to increase 2 to 3 percent per year; (4) the average retirement rate in the market is 5 to 6 percent per year; (5) the end-use efficiency will improve due to conservation practices from roughly 50 percent to about 70 percent by 2000; and (6) the use of electricity for process heat will not increase except for industrial heat pumps. It is further assumed that solar

equipment costs and performance will be achieved as assumed in the study. Installed prices of $400 per kilowatt (thermal) are projected ($\pm$ 20 percent) for the central receiver with an expected performance of 50 to 60 percent sunlight-to-heat efficiency at 500° to $800^{\circ}C$, over a range of 3 MW (thermal) to 300 MW in size. At this cost, a payback of 4 to 7 years may be expected by the turn of the century in any part of the country with the 40 percent tax credit, 6 to 10 years without the additional credit. Considering that industry investors will not be attracted by 10 year payback investments, but are fully interested in the 4 to 7 year range, the tax credits may make a significant impact. A similar effect could be achieved by halving solar cost/performance ratio. but this is not likely (if not impossible).

Considering all market factors, a reasonable expectation for high temperature solar process heat is for energy savings of 0.5 to 3 quads per year by the year 2000. Detailed simulation results indicate good market potential in Texas and California on the near term, with penetration into textile, food processing and industrial chemicals. Longer-term penetration is expected throughout the Nation into the heavier industries as solar equipment becomes more competitive. The expected implementation sequence for industry will be: first, conservation; second, solar fuel saver/hybrids; and third, add storage capacity to displace more fuel. Industry will probably continue its trend of expansion to the South and West, which should improve solar markets. With such scenarios, one might expect a multi-billion dollar per year industry to be formed over the next few decades solely to support high temperature solar process heat.

MARKET ANALYSIS OF HIGH-TEMPERATURE SOLAR PROCESS HEAT

BY
PAUL A. CURTO

MITRE/METREK
McLEAN, VIRGINIA

SEPTEMBER, 1978

STTF USERS ASSOCIATION
SOLAR HIGH TEMPERATURE INDUSTRIAL
PROCESSES WORKSHOP
ATLANTA, GEORGIA

PROJECT SUMMARY

TITLE: "SOLAR PROGRAM ALTERNATIVES AND IMPACTS ASSESSMENTS"

CONTRACT NO.: ET-78-C-01-2854

SUBTASK: 3.2 "SOLAR THERMAL OPTIONS ANALYSIS"

PERIOD OF PERFORMANCE: 15 NOVEMBER 1977 - 15 MARCH 1979

PRINCIPAL INVESTIGATOR: P. A. CURTO

AMOUNT OF CONTRACT: $1.1 MILLION
FOR SUBTASK 3.2: $190K

MARKET FACTORS

- INDUSTRY EXPENSES FUEL
- INDUSTRY WANTS LESS THAN SEVEN YEAR PAYBACK ON CAPITAL
- WE USE 23 QUADS OF PRIMARY ENERGY TO PRODUCE ELECTRICITY
- INDUSTRY USES 15 QUADS OF PRIMARY ENERGY FOR "PROCESS HEAT," 8 FOR ELECTRICITY, 5 FOR FEEDSTOCKS, 2 FOR BUILDING LOADS
- PROCESS HEAT DEMAND IS 8 TO 10 QUADS OF "SERVICE DEMAND," I.E., HEAT DELIVERED TO THE "WORKPIECE"
- ABOUT 75% (6 TO 7.5 QUADS) IS DELIVERED ABOVE 150°C
- ABOUT 25% (2 TO 2.5 QUADS) IS DIRECT HEAT OR RADIATIVE

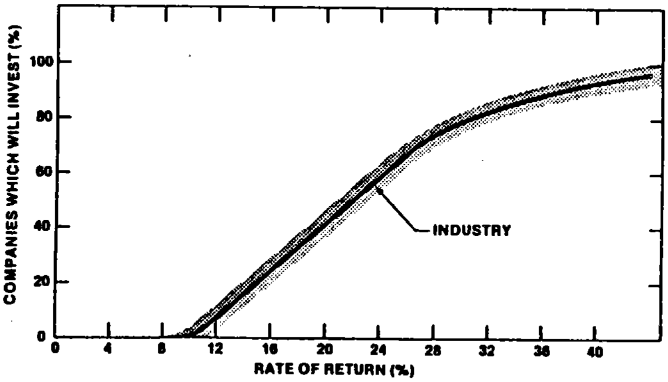
MARKET FACTORS

- THUS, ABOUT 75% (4.5 TO 5.6 QUADS) IS CONVECTIVE AT TEMPERATURES BETWEEN 150°C AND 800°C
- HISTORICALLY, SERVICE DEMAND INCREASES 2% TO 2.5% ANNUALLY
- SERVICE LIFE OF EQUIPMENT RANGES FROM 3 TO 30 YEARS, AVERAGING 15 TO 20 YEARS
- EFFICIENCY (SERVICE DEMAND/PRIMARY ENERGY) REDUCES WITH HIGHER TEMPERATURES
- INDUSTRIAL SITES ARE USUALLY "LAND-LOCKED," BUT MAY HAVE SUFFICIENT LAND FOR 5 TO 10 BILLION SQUARE FEET OF CONCENTRATORS OR COLLECTORS
- INDUSTRY IS EXPANDING TO THE SOUTH AND WEST
- TEXAS IS THE KEY HIGH GROWTH, HIGH CAPACITY STATE

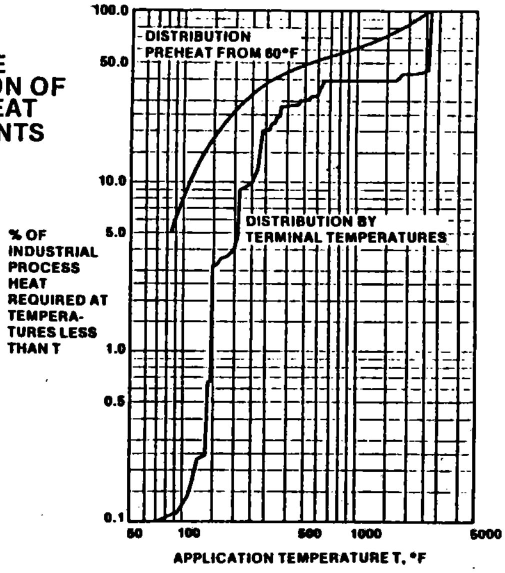
MARKET FACTORS (CONTINUED)

- NATURAL GAS ACCOUNTS FOR MORE THAN HALF OF ENERGY USE
- GAS IS GETTING CUT-OFF
- COAL USE IS INCREASING WHERE UNITS ARE 100MMBTU/HR OR LARGER
- BOTH GAS AND COAL ARE ALREADY EXPENSIVE (>$2/MMBTU)
- GAS MAY GO TO $6/MMBTU, COAL TO $4/MMBTU BY 2000 FOR INDUSTRY USERS (1978 DOLLARS FOR PRIMARY FUEL)
- TOTAL SOLAR MARKET POTENTIAL SHOULD BE 5 TO 12 QUADS/YR BY 2000

ACCUMULATIVE DISTRIBUTION OF INDUSTRY AND UTILITIES WILLING TO INVEST VERSUS RATE OF RETURN



CUMULATIVE DISTRIBUTION OF PROCESS HEAT REQUIREMENTS



THE NATIONAL ENERGY PLAN

IF IT EVER GETS PASSED, THE NEA WILL:

- PROVIDE FOR A 20 PERCENT INVESTMENT TAX CREDIT FOR INDUSTRY SOLAR PROCESS HEAT EQUIPMENT
- BAN OIL OR GAS USE IN BOILERS LARGER THAN 100 MMBTU/HR
- PLACE A TAX ON OIL AND GAS TO BRING IT TO PARITY WITH WORLD PRICE
- PROVIDE TAX CREDITS FOR CONSERVATION EQUIPMENT AND EQUIPMENT TO BURN "ALTERNATIVE FUELS"— OTHER THAN OIL AND GAS
- ALLOW USE OF OIL OR GAS WHERE IT IS NEEDED TO "MAINTAIN THE RELIABILITY" OF THE SYSTEM (AS A BACKUP)
- REFUND OIL/GAS PARITY TAXES AGAINST CAPITAL COST OF "ALTERNATIVE FUEL" EQUIPMENT

PHYSICAL CHARACTERISTICS OF HIGH-TEMPERATURE SOLAR PROCESS HEAT SYSTEMS

- MOST LIKELY CANDIDATE: CENTRAL RECEIVER
- RANGE OF PROBABLE EFFICIENCY: 50% TO 60%
- RANGE OF LIKELY SYSTEM COST: \$320 TO 480/KW$_{TH}$
- RANGE OF LIKELY SYSTEM SIZES: 3 MW$_{TH}$ TO 300 MW$_{TH}$
- TEMPERATURE RANGE: 150°C TO 800°C
- WORKING FLUIDS: STEAM, MOLTEN SALT, LIQUID METALS, HYDROCARBON FLUIDS, THERMOCHEMICAL MIXTURES
- COLLECTOR MODULE: 20-60 M^2
  DUAL-AXIS TRACKING
  FOCUSING (300 M FOCUS)
- RECEIVER MODULE: PLANAR (3 - 10 MW$_{TH}$) TO 500°C
  CAVITY (3 - 300 MW$_{TH}$) TO 800°C
- STORAGE: 0.3 TO 1.5 HRS. AT FULL RATING (EARLY YEARS)
  1.5 TO 12 HRS. (LATER YEARS)
- MOST LIKELY APPLICATION: FUEL SAVER AS HYBRID

TABLE II

AVERAGE PROJECTED ANNUAL OUTPUT FOR SOLAR PROCESS HEAT SYSTEMS

(MMBtu/FT^2/YR)*

City	Annual Collectable Energy**		
	Parabolic Dish	Central Receiver	Evacuated Tube or Parabolic Trough
Albuquerque, NM	.49 - .66	.42 - .56	.33 - .45
Appalachicola, FL	.30 - .40	.26 - .34	.19 - .29
Bismark, ND	.31 - .42	.27 - .36	.20 - .30
Blue Hill, MA	.23 - .30	.20 - .26	.16 - .23
Boston, MA	.23 - .30	.20 - .26	.16 - .23
Brownsville, TX	.30 - .41	.25 - .33	.20 - .30
Cape Hatteras, NC	.29 - .40	.24 - .32	.19 - .29
Charleston, SC	.26 - .36	.22 - .29	.17 - .26
Columbia, MO	.30 - .40	.26 - .34	.19 - .29
Dodge City, KS	.40 - .54	.33 - .44	.24 - .38
El Paso, TX	.50 - .67	.43 - .57	.34 - .46
Ely, NV	.46 - .61	.39 - .52	.23 - .36
Fort Worth, TX	.32 - .43	.28 - .37	.21 - .32
Great Falls, MT	.30 - .40	.26 - .34	.19 - .30
Lake Charles, LA	.25 - .34	.22 - .28	.17 - .25
Madison, WI	.26 - .36	.22 - .29	.17 - .26
Medford, OR	.30 - .40	.26 - .34	.19 - .30
Miami, FL	.26 - .36	.22 - .29	.17 - .25
Nashville, TN	.25 - .34	.22 - .28	.17 - .24
New York, NY	.21 - .28	.17 - .22	.15 - .22
Omaha, NB	.31 - .42	.27 - .36	.20 - .29
Phoenix, AZ	.48 - .64	.39 - .51	.32 - .44
Santa Maria, CA	.38 - .51	.30 - .41	.24 - .32
Washington, DC	.24 - .32	.19 - .26	.16 - .24

*1 MMBtu/FT^2/YR = 3154 kWh/m^2/yr; Average for 20 year life

**Temperature Range:
100°C to 800°C for Parabolic Dish and Central Receiver
50°C to 150°C for Evacuated Tubular Collector
150° to 450°C for Parabolic Trough

PRELIMINARY ESTIMATES FOR ULTIMATE PRICES FOR CENTRAL RECEIVER HIGH-TEMPERATURE PROCESS HEAT SYSTEM CONCEPTS

	60% EFFICIENCY	50% EFFICIENCY
	INSTALLED PRICE ($/M^2)	INSTALLED PRICE ($/M^2)
HELIOSTATS	102 - 153	90 - 135
TOWER	10 - 15	10 - 15
RECEIVER	30 - 45	20 - 30
PIPING	20 - 30	10 - 15
BALANCE OF PLANT	10 - 15	10 - 15
MARKUP/CONTINGENCY	20 - 30	20 - 30
TOTAL	192 - 288 ($/M^2) 320 - 480 ($/KW$_{TH}$)	160 - 240 ($/M^2)* 320 - 480 ($/KW$_{TH}$)

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*LOWEST COST: 300 MW$_{TH}$ SCALE
HIGHEST COST: 3 MW$_{TH}$ SCALE

GOAL PRICES AND PERFORMANCE

- USE 20% FIXED CHARGE RATE ON NET INVESTMENT (NET OF LAND, SALVAGE VALUE, AND INVESTMENT TAX CREDITS)
- MUST HAVE COMPARABLE ENERGY VALUE ($6 TO 10/MMBTU)
- MUST HAVE REASONABLE SERVICE LIFE (>10 YEARS)
- MUST BE "IDIOT-PROOF," EASILY MAINTAINED (<5%/YR O&M)
- RESULTING TARGET INSTALLED SYSTEM PRICES —

  FOR 50% EFFICIENCY SYSTEM:

  96 - 144 $/M² WITH 10% INVESTMENT TAX CREDIT

  104 - 155 $/M² WITH 20%

  124 - 185 $/M² WITH 40%

RELATIVE REGIONAL ECONOMICS OF SOLAR PROCESS HEAT

LOCATION	CAPITAL* COST ($/MMBTU/YR)	COMPETING FUEL COST ($/MMBTU)	PAYBACK (YRS)			
			10%	20%	40%	ITC
ALBUQUERQUE, N. M.	41-55	6	6-8	5-7	4-6	
OMAHA, NB	65-86	8	7-10	6-9	5-7	
BOSTON, MA	89-116	10	8-10	7-9	5-7	

*$250/M² OR ≈$400/KW$_{TH}$

MARKET PROSPECTS

CONCLUSIONS REACHED TO DATE

(1) CENTRAL RECEIVER IS PROBABLY MOST COST-EFFECTIVE SOLAR CONCEPT

(2) NEA DOES NOT GO FAR ENOUGH—AT LEAST 40% INVESTMENT TAX CREDIT IS NEEDED

(3) FUEL PRICES ARE HIGHER IN MORE POPULATED AREAS, THUS SOLAR ECONOMICS TEND TO BE NEARLY UNIFORM IN U.S.

(4) FIRST MARKETS ARE IN TEXAS AND CALIFORNIA (HIGH PRICES, GOOD INSOLATION, LARGE DEMANDS)

(5) LARGEST SALES IN MIDWEST AND TEXAS

MARKET PROSPECTS (CONTINUED)

(6) BEST NEAR TERM TARGET INDUSTRIES: FOOD PROCESSING, TEXTILES, INDUSTRIAL CHEMICALS

(7) BEST LONG TERM TARGET INDUSTRIES: PETROLEUM REFINING, PRIMARY METALS

(8) MOST LIKELY INDUSTRIAL IMPLEMENTATION SEQUENCE IS:
  (A) INSTALL CONSERVATION EQUIPMENT
  (B) INSTALL SOLAR FUEL SAVERS AS HYBRIDS
  (C) ADD MORE STORAGE CAPACITY

(9) CUMULATIVE SOLAR SALES COULD BE UP TO 10 BILLION SQUARE FEET BY 2000

(10) YEARLY REVENUES OF SOLAR INDUSTRY MAY REACH $10 BILLION PER YEAR BY 2000

Question - You said a 40-percent tax credit is necessary?

Mr. Curto - Yes. I thought the amount of the subsidy wouild probably be on the order of 3 or 4 billion dollars a year. The subsidy to industry today for expensing fuel is about 70 billion dollars a year, as an example.

Question - Do you have a number for converting to a million Btu's?

Mr. Curto - I think about 2 dollars per million Btu's.

Comment - I was surprised to hear you say a 7-year pay-back as the objective. I would have thought it would have been more like 3 years.

Mr. Curto - Seven years is the upper limit.

Question - Less than 7 years?

Mr. Curto - Less than 7.

Question - One of your market factors is gas getting cut off. Last year I don't think there were any allocations. As availability of of natural gas goes up, as reserves seem to grow and deplete--because I presume we are going to find new reserves from time to time--the cost will rise because of the National Energy Act. Will that have any strong affect on your projections?

Mr. Curto - Certainly. If gas prices peak at some level, like 3 or 4 dollars or so per, then at that price a lot of marginal price production schemes come in. If that happens, we'll have a very tough competitor in gas. It's clear that it will be a wash. It depends on whether you can get the gas in the particular place you're located in.

Question - The system costs will be $380 or $400 per kilowatt hour, and that's without storage, is that correct?

Mr. Curto - It includes a small amount of storage.

Question - How would those figures compare to the cost per kilowatt electric?

Mr. Curto - Three times that value, maybe three and a quarter. It would be about three or four times that value in 1978 dollars.

Comment - It seems to be higher than that by about 50 percent. You're saying three because of the efficiency.

Mr. Curto - This is kilowatts thermal produced at the work place. That would be at the inlet of the turbine. At that point, your efficiency would be on the order of 35 to 37 percent. There is an additional effect because, as I said, there is a turbogenerator installed. If you're going to generate electricity, you have to add that.

Comment - The repowering, I thought, was like 850 or 900 and if you divide that figure by 850 you come out with something much lower.

Mr. Curto - It was around 320 for that scale. It would be around 900 kilowatt electricity, effectively. Of course, the power doesn't include the cost of the turbogenerator.

Question - I'd like to ask if somebody in one of these government projects studying the cost of solar energy is making an attempt to take all the costs that are being projected and rationalize it to come out with some sort of uniform cost? Already today we've heard a projection from, I think, Leonard Hiles, that the cost of this installation would be $72 per square meter.

Mr. Curto - That's just for the heliostats, not for the whole thing.

Comment - Your projected heliostat costs were about twice that.

Mr. Curto - They start at about $90, corresponding to his $72. We're not quite as optimistic. That is the installed price. Again, the higher cost that I had was for the smaller installations, where you don't have automated equipment available to put the thing on. Those installations range in size from 3 megawatts to 300 megawatts, thermal, so there's a slight economy of scale as you get up there.

Question - You have projected a cost for coal of $4 a ton (per million Btu's) by the year 2000. What do you base that on?

Mr. Curto - That is delivered price at the industrial fence. They're paying between 2 and 3 dollars now for coal, typically. TVA just signed a contract for 3 billion dollars, at 50 dollars a ton, for utilities, but it depends on where you are.

Question - Have you ever done any more analysis on that cost?

Mr. Curto - We have an analysis that gives a breakdown, i.e., a range of the value we might expect, where the industry is located. The cost of coal in the West will be much lower. We've seen costs as low as 50 cents a million Btu's.

Question - These costs you're talking about are initial capital. Is there any data available about repair and maintenance of solar systems as compared to thermal?

Mr. Curto - There is no really good data available. We estimate it about 5 percent on small systems; large systems, 1 or 2 percent, but those are estimates. The numbers sound small compared to the large installations that run around 5 or 10 percent. The reason is that the capital costs are so high. The percentage doesn't mean anything. It's about the same value if you look at how many men have got to be there to operate the facility.

SECTION VIII

SOLAR POSSIBILITIES FOR 500-2500°F

H. M. Webb
The Aerospace Corporation

Chart 1 Good morning. The work that I will cover this morning was undertaken by The Aerospace Corporation for the Division of Solar Technology under the direction of Marty Gutstein and covered the period from March '77 until June '78. Aerospace worked with industry to identify industrial process heat applications that could utilize the higher temperature solar electric technology. At the time the study was initiated the industrial process heat branch was only pursuing solar applications up to 350°F. Therefore, applications requiring process heat as low as 350°F were studied while the upper temperature was limited by the developing solar electric technology.

Chart 2 This presentation should be considered an overview of the studies that will follow in the next couple of days. I'm going to cover quickly the performance of the various solar systems under development, compare the performance with the test facility capabilities, and then categorize and review the high-temperature industrial solar energy uses. I classify industrial process heat as systems where the process heat using plant is co-located at the site of the solar plant. Energy transport is defined as systems where solar energy is produced at one site and converted to chemical energy before being transported by pipe some distance to the using industrial plant where the chemical energy is converted to thermal energy. Finally, in fuels and chemicals production, the production occurs at the solar plant site and the fuels and chemical product is transportable by mobile vehicles and can be used anywhere.

Chart 3 Aerospace compared the capabilities of developing solar energy systems in a simple fashion. Cavity receivers were examined as a function of receiver efficiency, solar concentration ratio and working fluid temperature. The analysis assumes a receiver absorbtivity and emissivity of nine-tenths and insolation of 1000 watts per square meter. Entering the chart (solid lines) with a concentration ratio of 1000, a temperature of 1700°K is obtainable at the receiver stagnation temperature (0% efficiency, no working fluid circulating in the receiver); then as the working fluid is circulated through the receiver, the temperature will drop from 1700 to 1500°K with a 60% receiver efficiency and as more fluid is circulated the temperature will drop further to 1170°K with 90% receiver efficiency. Next, the average yearly efficiencies of the balance of the system was estimated including cosine losses, reflectivity losses, pump losses, etc. By multiplying the receiver efficiency times the balance of system efficiency a total system efficiency is obtained. The broken line curve running from lower right to the upper left of the chart is an envelop of the achievable system performance. Down at the lower temperatures and concentration ratios the technology is available to make some performance improvements but in the higher temperature higher solar concentration ratio range the technology has yet to be developed.

The performance of the solar systems under development is currently bounded by the Sanders receiver at high temperatures and the linear distributed collector at the low end.

The horizontal broken lines at the top of the chart show the high temperature test capability of each of the four solar test facilities. However, keep in mind that each facility has a different size test aperture and power level. The STTF has the most power, next Odiello, then the Georgia Tech facility, and finally the White Sands facility. The advertised high temperature test capability of each facility is the stagnation temperature.

When you test a solar industrial process heat system, you will be required to process a large volume of material and operate at a high efficiency. The available test temperature drops from 4000°F down to about 1600°F when going from a system efficiency of 0% to 95%. You now have a general perspective of solar energy system performance and test facility capabilities.

Chart 4 The next subject is the discussion of the high-temperature industrial energy uses and the first of these is process heat.

Chart 5 Most of the process heat information presented was derived from Battelle and Intertechnology studies for the Industrial Process Heat Branch. In 1971 40% of the energy consumed, purchased fuels and electrical power, was used by the industrial sector. According to the two studies, about 70% of the energy was used in process steam and direct process heat with 75% of the process heat and steam used at temperatures above the 350°F.

Chart 6 The next chart summarizes the process heat energy consumption, temperature requirements, and capital spending patterns of the various industrial sectors. Five industrial sectors consume 90% of the energy. These are primary metals; chemicals; paper and pulp; petroleum; and stone, clay, and glass industries. The industries with the highest temperature needs are primary metals and stone, clay, and glass.

Chart 7 Next, industrial energy consumption was examined by fuel type and region. In the south and southwestern portions of the United States, the primary source of fuel is natural gas and oil. The southwest region also has the best insolation so to maximize further the economic potential of solar industrial process heat systems. Further studies were limited to the south and southwestern regions of the country to obtain the lowest price solar energy and compete with the more precious fuels.

Chart 8 Major process heat users in the Southwest are identical to the total U.S. The chemical, petroleum, and cement industries were contacted. The solar thermal systems were described and the industries were asked to recommend potential applications for these solar equipments in their industry, and the economic criteria the industry would use to evaluate the potential market for solar systems.

Aerospace talked with Shell, Exxon, Continental Oil and Dow Chemical in the petroleum and petrochemical fields and to several of the cement industries including Gibler Hill of Texas, California Portland Cement, and the American Portland Cement Association. The next several charts cover recommended solar process heat applications from 350°F to 3500°F.

Chart 9 One interesting application of the parabolic trough was recommended by the cement industry for preheating oil for efficient combustion and also by the oil industry for heating the more viscous oils for efficient transport. The oil storage tanks are roughly 100 feet in diameter and 30 feet high and the oil in the tank provides the thermal energy storage medium; therefore, separate thermal storage is not required. A minimum of equipment is required, just solar collectors. Steam lines which already run from the steam plant to the oil tanks can easily accommodate a solar system. In the case where we have a new oil tank storage field, it may cost $20,000 to $30,000 to run steam lines for the half mile from the tank farm to the existing control steam plant. For new solar installations the steam line will not be required and this steam line cost can be used to offset the additional cost of solar equipment.

Two tank farm temperature regimes were examined. One where the solar system supplies 350°F steam and the crude oil is heated to about 200°F before leaving the tank. For this application, the crude oil in the tank can store a full month of summer insolation only raising the crude oil 100°F above the oil temperature at the start of the month. The oil companies found this acceptable thus providing adequate thermal storage for the non-solar periods later in the year.

A higher temperature is required to handle the more viscous asphalt. Currently, 485°F steam is used to heat the asphalt to 350°F.

Chart 10 The next solar system recommended for potential use by industry was the solar central receiver steam plant. The petroleum, petrochemical, and chemical industries use central steam plants with relatively low temperatures and pressures and augment the central steam with local heaters as required when higher temperatures are required. Low temperature pressure steam is used for safety and for cost. The central steam plants distribute 500-700° steam staying below the autoignition temperatures of the products and allowing the use of inexpensive pipe..

The 10 MWe solar pilot plant at Barstow will produce 960° steam at the receiver and 570° steam from storage. Industry believes this solar central receiver steam plant could be used in the hybrid retrofit made to save oil and gas.

<u>Chart 11</u> Aerospace talked with the California Portland Cement and Gibler-Hill in Texas and North Carolina and with the American Portland Cement Association, and each had slightly different recommendations which are all depicted on this chart.

The Portland Cement or hydraulic cement industry has two types of plants; a wet plant that typically uses a wet clay out of lake bottoms and then a dry plant where the material moisture content is very low. The oldest wet plant in the United States uses about 12 million Btus per ton of cement and a very modern dry plant uses about 3½ million. The average U.S. plant uses somewhere between 5 and 7 million Btus per ton. There are many applications for solar energy in a cement plant that will allow you to expand the capacity without modifying the basic plant.

The recommended solar applications are shown by the dotted lines. First, there is predrying and stockpiling the dried material so thermal storage is not required. Then, there are the other applications where the output of the plant can be increased by supplying solar heat in a hybrid fashion to the dryer crusher, or by the addition of a solar fired precalcinator. Calcining occurs at 1562°F and the Sanders and EPRI-DOE solar Brayton Cycle systems now under development could have a good application for calcining in either the cement industry or the lime industry.

<u>Chart 12</u> Above the 2000°F temperatures now available with the developing Brayton Cycle systems, there are additional applications that

also appear attractive. In the 1850's and 1860's the Germans developed a high temperature process for reduction of aluminum ore. When electricity became cheap and plentiful the German process was no longer used. However, Alcoa is now considering adopting the original high-temperature method. Solar probably has good potential for this application but more technology development is required.

There is another advantage in using solar in the aluminum industry. Most of the aluminum ores are imported in the United States for the electrolysis process. However, some of the cheaper ores that are plentiful in the U.S. can be used with the high temperature process.

There are other direct cycles for the reduction of metals that could be equally attractive as DOE develops the higher temperature technologies.

<u>Chart 13</u> The next high temperature industrial solar energy use to be covered is energy transport. There are five papers covering energy transport during the Workshop, so I will only briefly cover this subject.

<u>Chart 14</u> An energy transport system combines an endothermic reaction that takes place at the solar receiver and an exothermic reaction that takes place many miles downstream at an industrial site. To select an appropriate energy transport system that best fits our needs one must consider the temperature and pressure requirements of the industrial site, the Btu content of the reaction, the liquid or gas to be transported through the pipes, and finally, selection of a reaction that goes as far as possible to 100% completion and stays within the existing technology. I think you'll hear a good treatment of this subject later on, so we'll just go on to the next subject.

<u>Chart 15</u> The last high temperature industrial solar energy use I will cover today is the production of transportable fuels and organic chemicals. This is one of the areas currently getting very little DOE attention or funding, so some additional background is necessary to obtain a proper perspective.

Chart 16 An examination of the U.S. transportable fuels and chemical feedstock consumption shows about 25% of the U.S. fuel is used in the transportation sector, and when combined with chemical feedstock use in the industrial sector, this totals 30% of the U.S. energy.

The only current solar related program supporting this sector is the biomass program. However, it appears that solar-thermal could provide an attractive alternative to biomass.

Chart 17 In fuels and chemical production there are many approaches, but there exist two fundamental approaches to the production of the two organic chemical feedstocks, hydrogen and carbon monoxide. There are several options for each approach depicted by the arrows on the right. Hydrogen can be produced either by electrolysis or thermal decomposition or by reactant decomposition or a combination of electrolysis and decomposition. As you proceed from left to right across the chart, the processes become more efficient. That's desired in obtaining more economic systems. Similarly, carbon dioxide can be reduced with carbon or by thermal decomposition or by reaction decomposition.

Chart 18 This chart shows a solar energy/hydrogen based fuels and chemicals approach. Electricity is produced with solar energy - like the Barstow pilot plant. Hydrogen and oxygen are produced by electrolysis and the hydrogen and oxygen are combined with coal to obtain hydrocarbon products, using carbon monoxide and hydrogen as feedstocks. These are conventional existing hydrocarbon synthesis processes using different catalysts to produce gasoline, methane and many other organic chemicals.

If you examine the hydrogen production column on the left you will note that reactive decomposition is a function of the selected reducing metal. The temperature required for the decomposition is also a function of the metal while the theoretical efficiency will be approximately 60%. These are theoretical efficiencies, not actual achieved efficiencies.

The next type of hydrogen production is by thermal decomposition. When decomposition occurs above 2500°K, the theoretical efficiency is approximately 100% but other breakdown products occur at those temperatures. This requires hydrogen production by thermal decomposition at lower temperatures and lower efficiencies

Finally, at the bottom of the column we have hydrogen production by common water gas shift reaction which everyone is well aware of.

Chart 19 In reviewing the hydrogen economy and reduction of the oxide of hydrogen to produce hydrogen, Dr. Martin at Aerospace wondered why carbon dioxide, the pollutant, could not be reduced to produce carbon monoxide as a fuel or feedstock. Then, the CO could be used as a power plant fuel or used as a feedstock to stay with the present hydrocarbon transportable fuel economy.

The flue gas of a power plant is roughly 12-18% CO_2 and there are several commercial amine and carbonate processes for extraction of carbon dioxide from flue gas for the production of a dry ice and liquid carbon dioxide for medical and industrial purposes. This carbon dioxide when combined with carbon gives two units of CO, and the energy available when the two units of CO are burned is theoretically 98% of solar energy that was used to produce the CO.

The CO production takes place at roughly 1000°K so the CO can be produced with existing solar technology. Next, also with existing technology, using the water gas shift process the CO can be used as a feedstock producing hydrogen.

The original work by Dr. Martin at Aerospace is depicted by the closed loop production box at the lower left. Patent applications have been made for six closed loop cycles for the production of carbon to feed the CO production cycle. Theoretically, one molecule of carbon is required to start the cycle and then you switch to the closed loop system.

The lower right hand portion of the chart lists some of the hydrocarbon products that can be produced by existing industrial processes using this carbon cycle concept. At this point in time the hydrogen cycle work is far ahead of the carbon cycle. However, much of the hydrogen effort may be adaptable for carbon cycles.

Mr. Smith: Any questions?

A Voice: What is CoO?

Mr. Webb: That's cobalt oxide. Larry Sitney is in the audience. He is responsible for the Aerospace fuels and chemicals work, and can describe carbon cycles in more detail. So, if you want to talk with him during the coffee break, he will be available.

(Applause).

A Voice: It seems to me that when you derate these plans for radiation loss, there is a possibility, I mean, some of the radiation derating could be reduced through the use of the Francia-type windows.

Mr. Webb That is correct. For simplicity's sake - I was trying to compare the systems on a common basis, and the performance of each solar system can shift slightly if one considers options like the one you mentioned.

A Voice: Because that is a substantial suppressor for radiation at intermediate pressures. I think it could make a big difference in the efficiencies which you would get with some of these concentration ratios of 500 to 1000 compared to what you were showing.

Mr. Webb: Is Marty Gutstein here? Well, ask Marty. Marty had a separate study conducted on the use of windows, and I have seen the study. I don't remember the details; however, at lower temperatures the window has an advantage. At the higher temperatures, and I don't remember the exact crossover point, the advantage ceases.

A Voice: Did this include the Francia windows, the tubes, basically, rather than just sheets because there's a big difference?

Mr. Webb: I don't know the answer. I can't answer this because I'm not aware of the work.

A Voice: I have another brief question. At 2300°K, if you're going to use solar energy for mass production and you do probably have a window problem for getting the heat in, what is the vapor pressure of those systems? Are any of them near atamospheric or below atmospheric, or do they require a container at 2350°?

Mr. Webb: I didn't examine that aspect.

Mr. Smith: One more question.

A Voice: Howard, have you looked at the cost of hydrogen - well, first, of the cost of the CO_2 that you might get from power station stacks and how it would affect the cost of the hydrogen that you would make if you made that estimate?

Mr. Webb: We have made the estimate by getting the cost of the commercially produced carbon dioxide at the source, and it looks like it is low enough that it may be attractive. We have gone to two sources, and I don't remember the price but the concept is potentially viable using existing processes.

High-Temperature Industrial Solar Energy Uses
Presentation to the Solar High-Temperature Industrial Processes Workshop

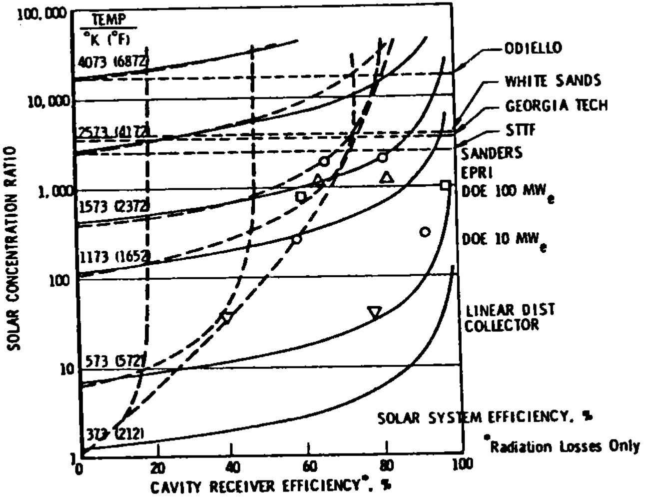
Atlanta, Georgia
27-29 September 1978

by
Howard Webb
The Aerospace Corporation

High-Temperature Industrial Solar Energy Uses

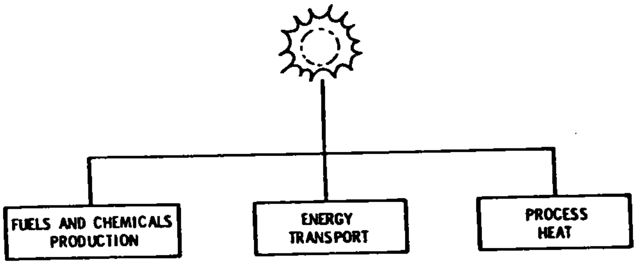
- SOLAR RECEIVER/SYSTEM AND TEST FACILITY CAPABILITIES
- INDUSTRIAL PROCESS HEAT
- ENERGY TRANSPORT
- FUELS AND CHEMICALS PRODUCTION

Solar Receiver/System and Test Facility Capabilities



*Radiation Losses Only

High-Temperature Industrial Solar Energy Uses



FUELS AND CHEMICALS PRODUCTION

ENERGY TRANSPORT

PROCESS HEAT

Industrial Energy Consumption

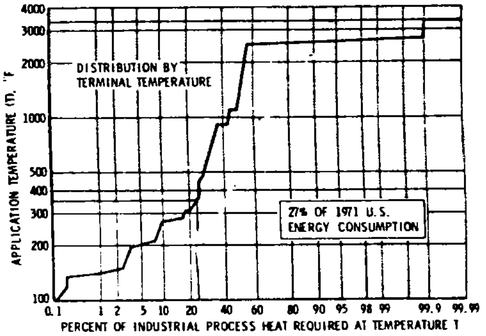
DISTRIBUTION OF ENERGY CONSUMPTION BY SECTOR - 1971

MARKET SECTOR	PURCHASED FUELS		PURCHASED FUELS & ELEC	
	QUADS	%	QUADS	%
HOUSEHOLD/COMM	14.3	20.7	17.4	30.6
TRANSPORT	17.0	24.6	17.0	29.8
INDUSTRIAL	20.3	29.6	22.6	39.7
ELEC GEN	17.4	25.3	--	--
TOTAL	69.0	100.0	57.0*	100.0

INDUSTRIAL ENERGY USE (percent)

PROCESS STEAM	40.6	68.4
DIRECT PROCESS HEAT	27.8	
ELECTRIC DRIVE	19.2	
ELECTRIC PROCESS	2.8	
FEED STOCK	8.8	
OTHER	0.8	
TOTAL	100.00	

CUMULATIVE DISTRIBUTION OF PROCESS HEAT REQUIREMENTS



Industrial Process Heat Requirements and Capital Spending Patterns

INDUSTRY	PROCESS HEAT DATA BASE 10^{12} Btu	TYPICAL TERMINAL TEMP REQ-°F	1978 PLANNED CAPITAL SPENDING (billions of dollars)
IRON AND STEEL	3772	2700-900	4.28
NON-FERROUS METALS			2.48
ELECTRICAL MACHINERY	2	1700-350	2.98
MACHINERY	0	—	5.78
AUTOS, TRUCKS AND PARTS	23	2650-250	
AEROSPACE			0.90
OTHER TRANS EQUIP			0.32
FAB METALS AND INSTRUMENTS	0	—	3.69
STONE, CLAY AND GLASS	991	3300-1500	1.72
OTHER DURABLES	15	150-70	2.64
TOTAL DURABLES	4803	—	27.32
CHEMICALS	534	2200-300	7.94
PAPER AND PULP	1093	1900-280	3.08
RUBBER	10	450-280	1.66
PETROLEUM	2637	1600-250	12.56
FOOD AND BEVERAGES	319	1110-100	4.72
TEXTILES	116	300-200	0.72
OTHER NONDURABLES	173	300-212	1.49
TOTAL NONDURABLES	4882	—	32.17
ALL MANUFACTURING	9685	—	59.49
MINING	129	2500-150	5.07
RAILROADS	—	—	3.30
AIRLINES	—	—	0.88
OTHER TRANSPORTATION	—	—	2.52
COMMUNICATIONS	—	—	15.31
ELECTRIC UTILITIES	—	—	25.84
GAS UTILITIES	—	—	4.20
COMMERCIAL	—	—	22.45
ALL NONMANUFACTURING	129	—	79.57
ALL BUSINESS	9814	—	139.06

Industrial Energy Consumption

BY REGION AND FUEL - 1972

REGION	10^{12} Btu			
	COAL	OIL	N. GAS	TOTAL
NORTHEAST	1067	487	774	2248
NORTHCENTRAL	1993	372	2281	4646
NORTHWEST	21	112	352	485
SOUTHEAST	361	219	544	1124
SOUTHCENTRAL	382	317	2163	2862
SOUTHWEST	134	818	3950	4902
NONCONTIGUOUS STATES	11	14	38	63
TOTAL	3970	2260	10120	16332
PERCENT	24.3	13.9	62.8	100

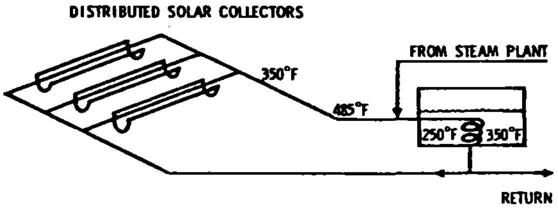
Solar Process Heat

IDENTIFICATION OF INDUSTRIAL APPLICATIONS
MAJOR ENERGY USERS – SOUTHWEST

- CHEMICAL
- PETROLEUM AND PETROCHEMICAL
- CEMENT
  IRON AND STEEL
  COPPER
  PULP AND PAPER

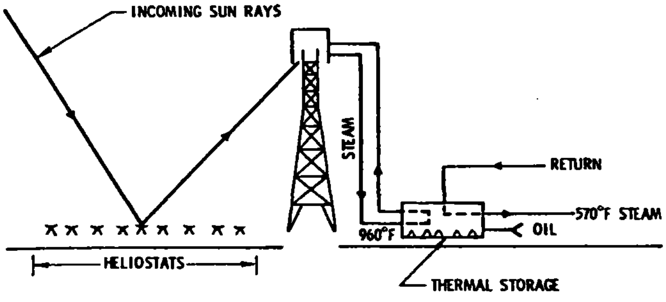
Supplemental Solar Steam

TANK FARM - CRUDE OIL
ASPHALT STORAGE



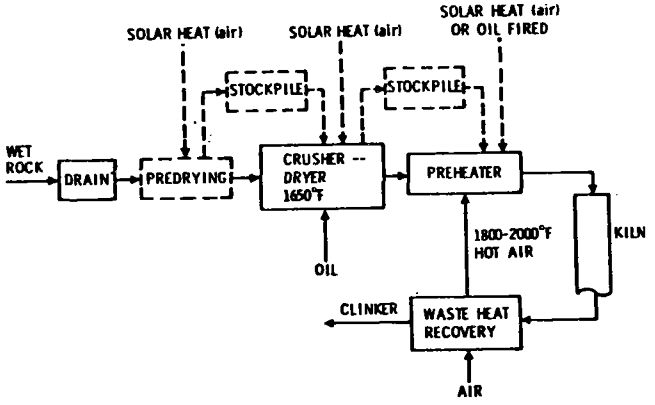
Hybrid Steam Plant

CENTRAL TOWER



Cement Manufacture

DRY PROCESS



New Metals Reduction Concepts

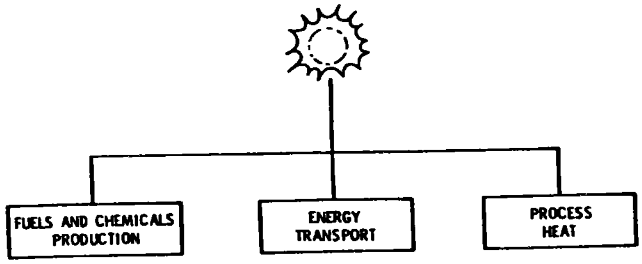
- HIGH TEMPERATURE REDUCTION OF METALS

$Al_2O_3 + 3C = 2Al + 3CO$ T = 2350 K

- DIRECT CYCLES FOR METALS

$NiO = Ni + 1/2\ O_2$ T = 2850 K

High-Temperature Industrial Solar Energy Uses



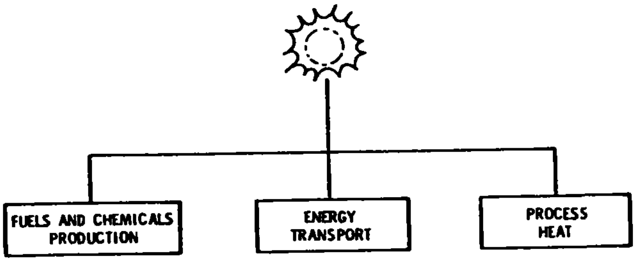
Energy Content of Chemical Energy Storage Reactions

LIQUID/GAS CANDIDATES

REACTION EXOTHERMIC $\longrightarrow$ $\longleftarrow$ ENDOTHERMIC	REACTION ENTHALPY AT 298°K (77°F)		TEMPERATURE (°K) AT WHICH	
	Ws/g	Btu/lb	90% FORMED	90% DISSOCIATED
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(L)$	7345	3160	--	--
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(G)$	6053	2604	754	1466
$C_2H_4(G) + H_2(G) \rightleftharpoons C_2H_6(G)$	4561	1962	841	1205
$2CO(G) + 2H_2(G) \rightleftharpoons CH_4(G) + CO_2(G)$	4118	1772	778	1152
$CO(G) + 2H_2(G) \rightleftharpoons CH_3OH(L)$	3996	1718	345	434
$N_2(G) + 3H_2(G) \rightleftharpoons 2NH_3(L)$	3861	1661	--	--
$N_2(G) + 3H_2(G) \rightleftharpoons 2NH_3(G)$	2695	1159	346	528
$2NO(G) + O_2(G) \rightleftharpoons N_2O_4(L)$	1750	753	549	930
$SO_2(G) + AIR \rightleftharpoons SO_3(G)^*$	1544	644	806	1270
$SO_2(L) + 1/2O_2(G) \rightleftharpoons SO_3(L)$	1517	652	792	1235
$SO_2(G) + 1/2O_2(G) \rightleftharpoons SO_3(G)$	1235	531	792	1235
$NO(G) + 1/2O_2(G) \rightleftharpoons NO_2(G)$	1243	535	549	930
$CO(G) + Cl_2(L) \rightleftharpoons CO\ Cl_2(L)$	1172	504	628	881

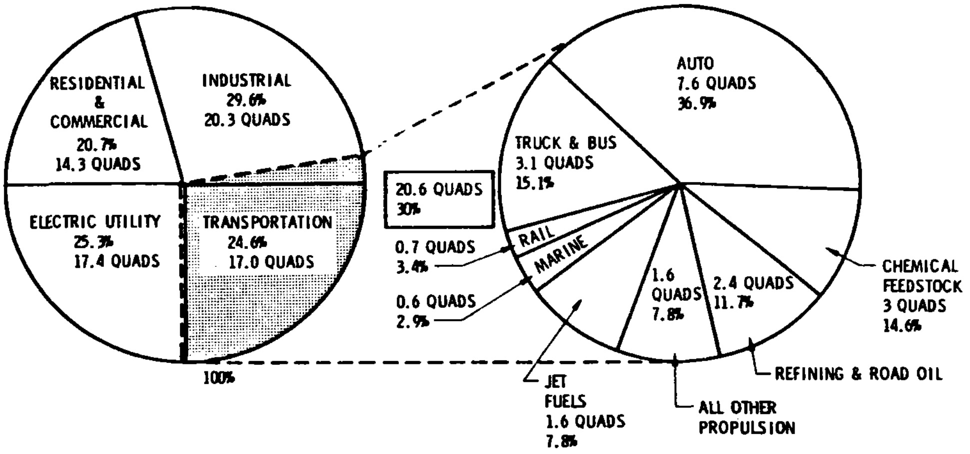
*Based on SO_2 Weight Only. Air Open Cycle

High-Temperature Industrial Solar Energy Uses



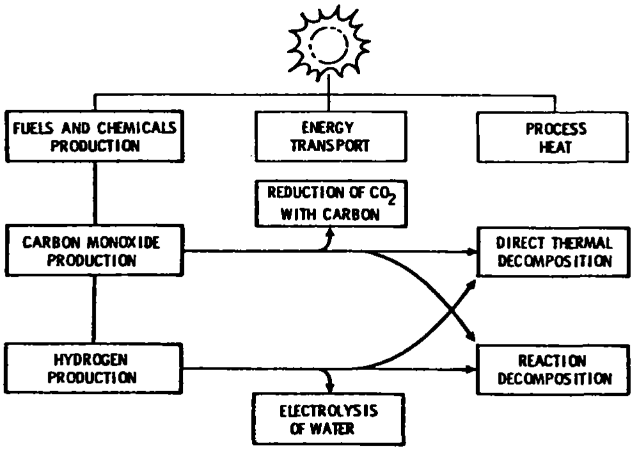
SOLAR FUELS AND CHEMICALS

Transportable Fuels and Chemical Feedstock Consumption



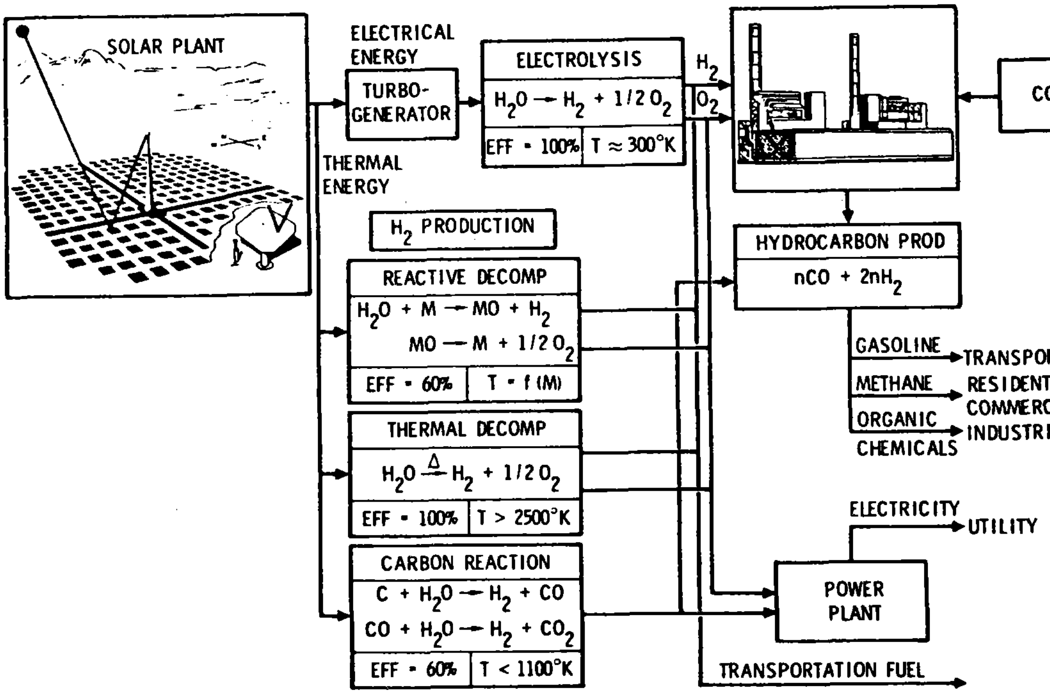
SOLAR FUELS AND CHEMICALS

Alternative Solar Energy Uses



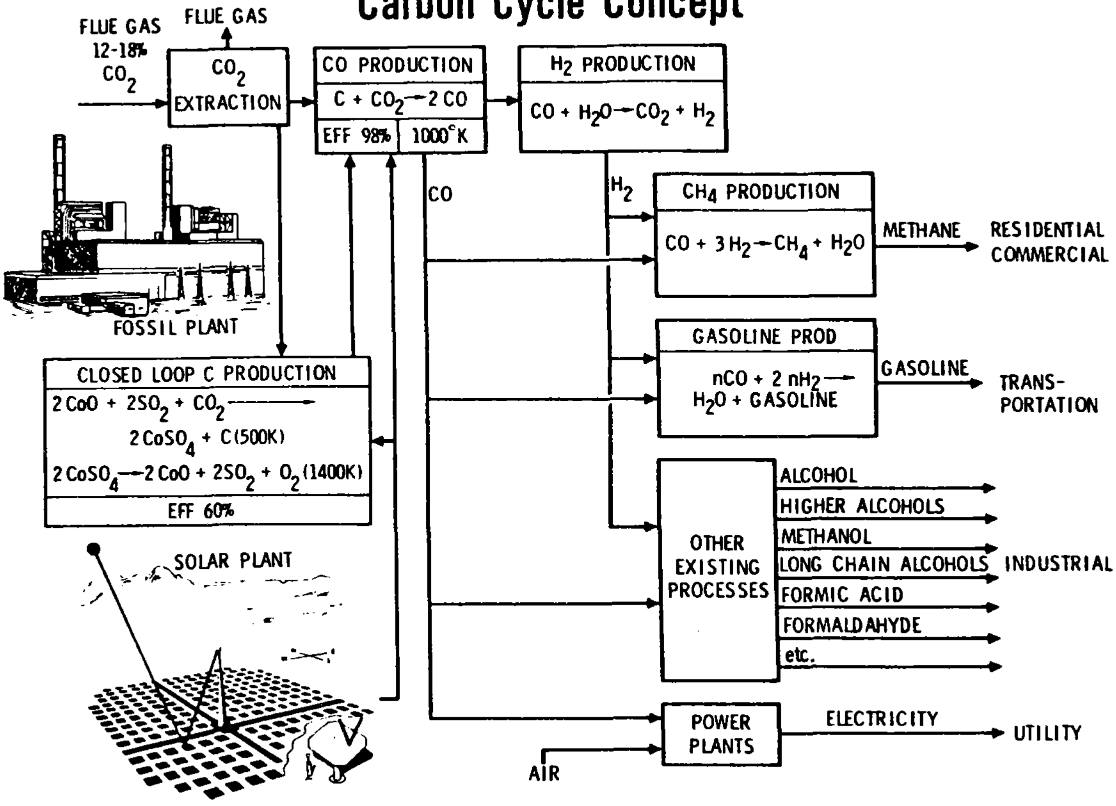
SOLAR FUELS AND CHEMICALS

Hydrogen Cycle Concept



SOLAR FUELS AND CHEMICALS

Carbon Cycle Concept



Question - What is CoO?

Mr. Webb - That is cobalt oxide. Larry Sitney, who is in the audience, handles our fuels and chemicals work and he can describe those cycles in more detail and the work we're doing in that area.

Comment - It seems to me that there is a possibility some of the radiation derating could be reduced through the use of Francia-type windows.

Mr. Webb - That is correct. Just for simplicity's sake, I was trying to compare the systems on a common basis and each one is a little different.

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Mr. Webb - Is a Marty Gutstein had a separate study conducted on the use of windows, as I remember, at the lower temperatures the window has an advantage. At the higher temperatures, and I don't remember the exact crossover point, it doesn't have the same advantage.

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Question - At 2350 K, if you're going to use solar energy for mass production and you do have a window problem for getting the heat in, what is the vapor pressure of those systems? Are any of them near or below atmospheric, or do they require a container at 2350 K?

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Question - Have you looked at the cost CO_2 that you might get from power station stats and how it would affect the cost of hydrogen that you would make if you made that estimate?

Mr. Webb - We have the estimate by getting the cost of the commercially produced carbon dioxide at the source, and it looks like it is low enough to be attractive. We have gone to two sources to find out, but I don't remember the price. However, it is low enough that it can be attractive using existing amine processes.

SECTION IX - CHEMICAL CONVERSION & TRANSMISSION OF SOLAR THERMAL ENERGY

DOE CHEMICAL STORAGE AND TRANSMISSION PROGRAMS

W. G. Wilson
Sandia Laboratories
Livermore, California 94550

Introduction:

Under the DOE's program to decentralize the implementation of its Energy Technology policy to field offices and national laboratories, Sandia Laboratories, Livermore, has been assigned program management responsibilities for the Thermochemical Energy Storage and Transport (TEST) Program. The TEST Program investigates reversible thermochemical reaction technologies as they apply to the storage and movement of thermal energy. All classes of reactions are considered with the exception of hydrogen generating and photochemical reactions. The objective of the program is to initiate and develop those concepts and reactions couples which can provide commercially viable solutions to energy storage and transport problems at the earliest possible date.

Program Structure

The TEST Program has been divided into four technology elements according to a Technical Breakdown Structure (Figure 1). The four TBS elements are: (1) thermal energy storage, (2.0) thermochemical pipelines, (3.0) chemical heat pump storage, and (4.0) generic research. Each of these major elements has been futher divided into subelements which represent specific concepts or applications being pursued.

Thermochemical energy technology (TBS 1.0) is being considered for both solar and nonsolar electric utility applications. Activities to date have consisted of both: (1) systems studies to establish the technical and economic viability of proposed concepts, and (2) parallel laboratory investigations of promising reactions for which more information is required to enable more detailed evaluations to be made.

Emphasis for the thermochemical pipelines portion of the program (TBS 2.0) have been on systems studies and component development. Studies of both open-loop and closed-loop pipelines have been conducted for a variety of energy sources including nuclear, fossil energy and solar. Promising reactions have been identified and applications requiring additional study have been noted. In one case where the reaction technology was well understood (methane steam reforming) a major hardware development activity has been initiated.

Following a preliminary analysis of the potential of chemical heat pump storage systems (TBS 3.0), experimental investigations of several attractive concepts were initiated. Closed-loop operation of a prototype configuration has been demonstrated for one concept, and laboratory results to date suggest the other concepts are viable alternatives.

Generic research (TBS 4.0) consists of catalyst development, heat transfer investigations, and laboratory investigations of promising reaction systems.

Project Activity

In this section, the objectives of each TBS subelement are discussed and the projects and schedules required to meet these objectives are described.

TES for Solar Utilities (TBS 1.1) -- The objectives of this subelement are to assess and develop thermochemical storage technologies on a schedule compatible with the development schedules for solar thermal electric conversion systems. Because the solar thermal electric conversion systems actually chosen for large scale demonstration will depend upon the results of a number of ongoing solar programs, it is essential to carry on a number of parallel investigations of promising thermal energy storage concepts. The coordination, interaction, and anticipated results of these various activities are depicted in Figure 2.

The systems analysis (1.1.1) of selected solar thermal electric power plants, and investigations of several first generation chemical reactions (1.1.4, 4.3, 4.5 and 1.1.9) will continue in FY79. New programs in FY79 are a systems analysis of more advanced solar thermal electric power plants (1.1.12) and initial laboratory investigations (1.1.3) of promising additional chemical reaction systems. Results from these two activities may lead to the initiation of a development activity for a second generation TES system (1.1.10) in mid FY80. In late FY80 results from (1.1.9, 1.1.4, 4.3 and 4.5) will be assessed (1.1.3), leading to a decision by mid FY81 of whether to proceed to a Subsystem Development and Test activity (1.1.9) for the first generation TES system. This activity will be completed in FY84. The schedule for second generation system lags behind the first generation program by approximately 1-1/2 years.

TES for Non-Solar Electric Utilities (TBS 1.2) -- The objectives of this subelement are to assess and develop energy storage and transport technologies for use in nonsolar electric utilities. The second phase of a systems study (1.2.1) which is identifying potential energy source/chemical reaction/end user combinations will continue in FY79. Depending upon the outcome of that study, development of appropriate concepts may be initiated in FY80. At that time, long-range plans consistent with the schedules of the selected users will be developed.

Open-Loop Thermochemical Pipelines (TBS 2.1) -- This subelement is concerned with the development of open-loop energy transport systems. Initial work in FY79 will be conducted as part of the Sandia in-house research program, and will consist of a reassessment of previous work (2.1.1) in light of current DOE guidelines. Research and technology development of a coal gasification based system (2.1.3) could be demonstrated on a large scale by late FY83, as indicated in Figure 3, in ample time to provide an alternative to other coal gasification schemes.

In mid FY79 to early FY80 a study (2.1.4) to determine the possibility of interfacing open-loop thermochemical pipelines and advanced solar systems will be initiated. System identification and development could begin in early FY81 with large scale demonstration by late FY84.

High Temperature Thermochemical Pipelines (TBS 2.2) -- FY79 activities in this subelement are addressing two areas. The first of these is the development of a duplex steam reformer (2.2.2) for interfacing a thermochemical pipeline with a high temperature gas cooled reactor. This activity, which is being supported jointly by the United States and Germany, will be completed in FY80.

The second activity (2.2.5), which will be addressed initially in the Sandia in-house research program will assess the feasibility and desirability of interfacing a high temperature thermochemical pipeline with a solar central receiver energy source. Assuming positive results from this study, an RFQ will be prepared in FY80. Although development is feasible by FY84, (see Figure 4) the actual schedule will be established following the completion of 2.2.5. This program will be in parallel with the development of the solar interfaced open-loop thermochemical pipeline (2.1.4). Depending on the systems identified, the two programs could be combined into one.

Low-Temperature Thermochemical Pipelines (TBS 2.3) -- The objective of this subelement is to develop low-temperature technologies for energy transport systems which may be interfaced with nuclear or solar energy sources. Activities in FY79 and 80 will establish the feasibility of using the benzene/cyclohexane reaction (2.3.1) for energy transport. In FY80, a detailed characterization of the potential market will be initiated (2.3.4), and preliminary investigations of alternate reactions will begin (2.3.5). A critical reassessment of the concept will be conducted in FY80, and this, in conjunction with the results from (2.3.1), (2.3.4), and (2.3.5) will provide the information required to reach a decision regarding large scale system development and test (2.3.2). The target for large scale demonstration is FY83, subject to re-evaluation as the early studies are completed (see Figure 5).

Transmission in Distributed Solar Systems (TBS 2.4) -- The objective of this subelement is to develop energy transport systems for distributed solar systems. Activities in FY79 will be conducted in-house, and will consist of a preliminary analysis of the concept, the identification of required research, and the preparation of an RFQ for a more detailed systems analysis (2.4.1). In FY80, a more detailed analysis (2.4.1) will be performed in parallel with laboratory investigations of potential reaction systems (2.4.2). In FY81, a comparison of the various concepts will be made (2.4.3) and, if warranted, the project will proceed to the System Development and Test stage (2.4.4). Figure 6 presents the schedule for this TBS. This schedule is quite tentative, with considerable interaction between Sandia, JPL and SERI envisioned.

Chemical Heat Pump Storage (TBS 3.1) -- The objective of the subelement is to develop chemical reaction systems for use as chemical heat pump storage systems. In FY79, experimental activities will concentrate on the sulfuric acid (3.1.1), methanolate (3.1.2), and ammoniate (3.1.4, 4.4) systems. Systems analyses conducted in FY79 (3.1.4) will assess the potential of the sulfuric acid system and, coupled with the initial results of (3.1.6), will determine whether (3.1.6) is carried to the large scale development phase. Also part of (3.1.5) will be an evaluation of 3.1.2 and 3.1.4 which may lead to a demonstration project (3.1.8). The results of a workshop held in the first quarter of FY79 will be used to formulate an RFQ for advanced systems (3.1.7). This work will be conducted in FY80 and 81, and examined in detail in later FY80 (3.1.9). If warranted, closed loop demonstration will be conducted in FY82 and analyzed in FY82 (3.1.10). Figure 7 presents the schedule for this activity.

Generic Research (TBS 4.0) -- Long range activities in the program subelement depend upon the evolution of the program. In FY79, they consist of a study of the fundamental processes occurring in gas/solid TGS systems (4.12), SO_2/SO_3 catalyst development (4.3), and research on ammoniated salts (4.4).

Project Status:

Table I gives a brief description of each of the current TEST projects and provides a listing of the contractors and documentation status. Activities summarized include systems studies, basic research, and large scale component development projects for a number of chemical reaction systems and a variety of energy sources and applications. It is anticipated that as more information is obtained regarding the reaction systems, energy sources, and applications, the emphasis of the TEST program will shift from studies of this type to the large scale demonstration of the more promising concepts.

Question: You talked about your materials work with the sulfur oxides--do you have any promising metals?

Mr. Wilson: I don't think we do, but we have accumulated quite a bit of data. Bob Bradshaw at Sandia Livermore has been doing that work and could give you more details.

Comment: Considering some of the environmental health and safety acts, benzine is pretty bad.

Mr. Wilson: Of course, the chemicals with high energy densities are usually nasty rascals. If, for example, there were suggestions for using phosgine, we wouldn't get involved. But we've taken the approach on benzine saying, "Let's understand the technical feasibility before we get hung up really spending a lot of time on environmental impacts. But keeping in mind that we've got to do that." For sure, we don't want to develop a technology that nobody is willing to use.

THERMOCHEMICAL ENERGY STORAGE AND TRANSPORT PROGRAM

TECHNOLOGY BREAKDOWN STRUCTURE

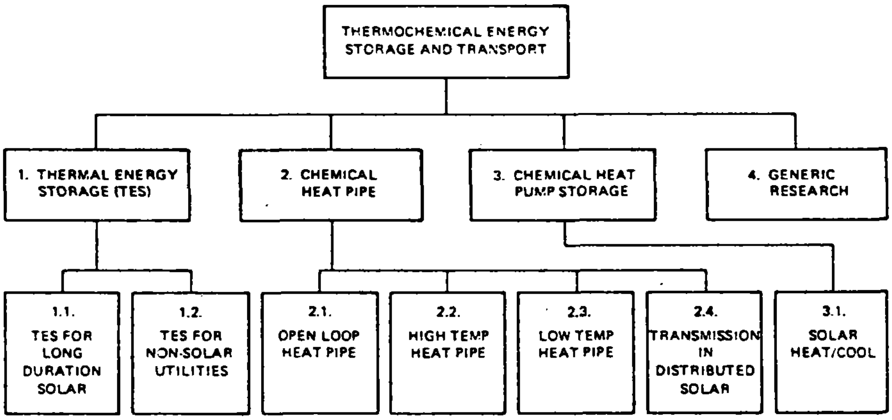
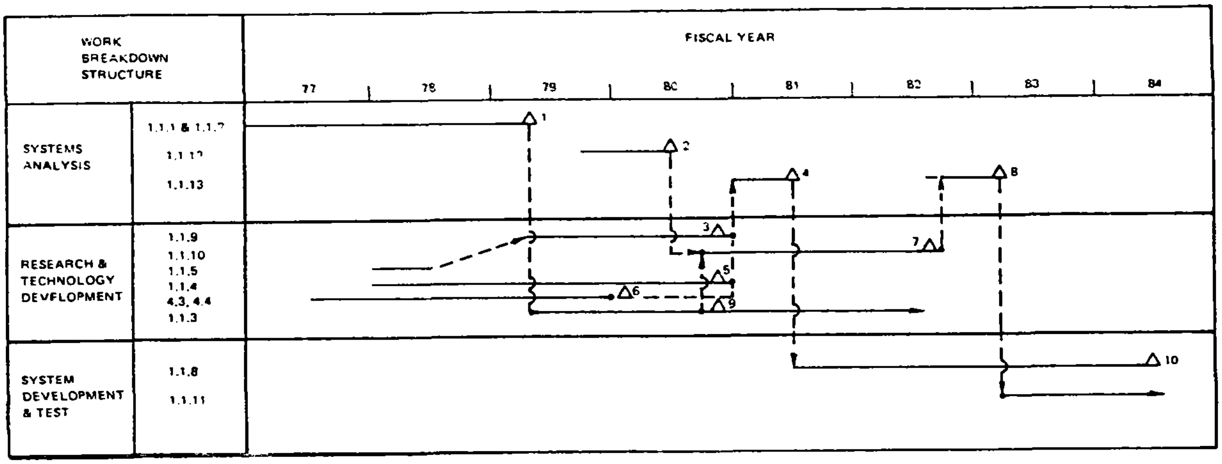


FIGURE 1

TES FOR SOLAR UTILITIES TBS 1.1

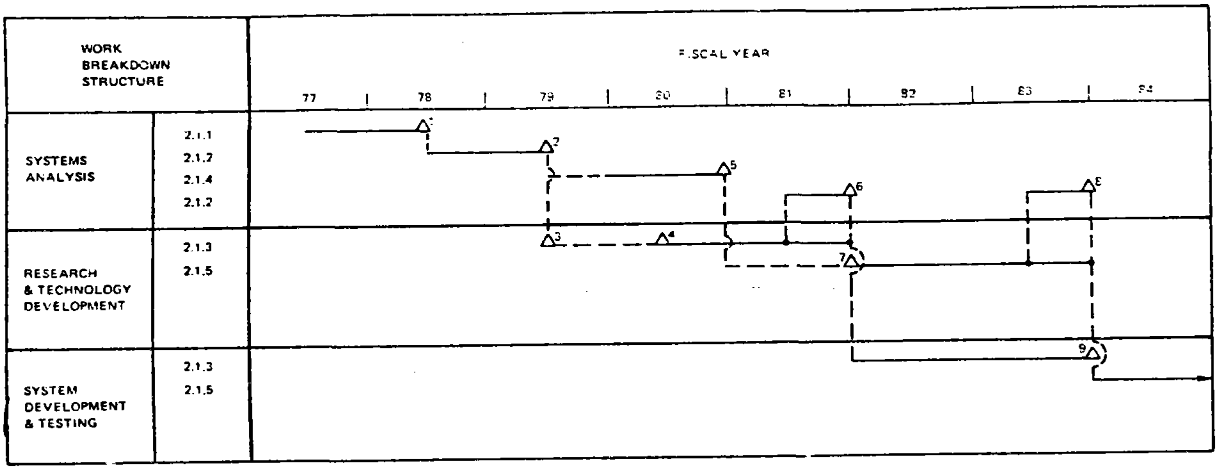


MILESTONES

1 – TECHNICAL & ECONOMIC FEASIBILITY OF TES FOR 3 SOLAR THERMAL SYSTEMS; IDENTIFICATION OF 1 OR MORE REACTIONS FOR FURTHER INVEST
2 – SAME AS 1, BUT FOR ADVANCED SOLAR THERMAL SYSTEMS
3 – LAB SCALE INVESTIGATIONS COMPLETED FOR SELECTED REACTIONS, INFORMATION REQUIRED FOR MORE REFINED SYSTEMS MODELING AVAILABLE
4 – DETAILED ANALYSES COMPLETE; DECISION TO PROCEED TO SYS. DEV. & TEST
5 – LAB SCALE INVESTIGATIONS FOR AHS COMPLETE
6 – SO_2/SO_3 CATALYST DEVELOPMENT COMPLETE
7 – LAB SCALE INVESTIGATIONS FOR SECOND GENERATION TES SYSTEMS COMPLETE
8 – MORE DETAILED SYSTEMS MODELING, DECISION TO PROCEED TO SYS. DEV. & TEST
9 – POTENTIAL REACTIONS IDENTIFIED FOR SECOND GENERATION SYSTEMS

Figure 2

OPEN LOOP THERMOCHEMICAL PIPELINES TBS 2.1

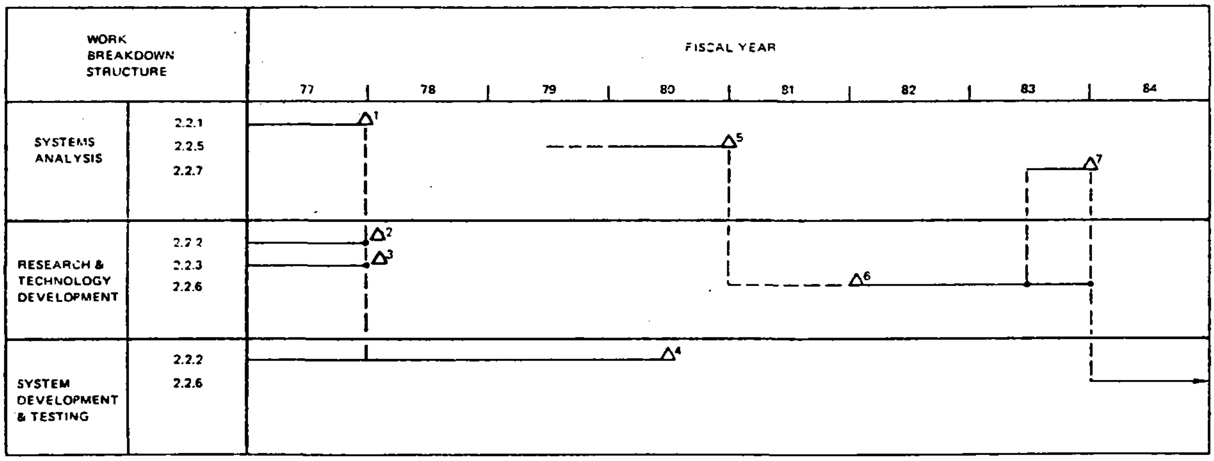


MILESTONES

1 – TECHNICAL AND ECONOMIC FEASIBILITY OF OPEN-LOOP THERMOCHEMICAL PIPELINE CONCEPT ESTABLISHED
2 – 2.1.1 REASSESSED, AND, IF WARRANTED, RFQ PREPARED
3 – RFQ ISSUED
4 – CONTRACT AWARDED FOR RESEARCH AND TECHNICAL DEVELOPMENT OF METHANE-BASED SYSTEM
5 – INTERFACE OF OPEN-LOOP THERMOCHEMICAL PIPELINES AND SOLAR SYSTEMS EVALUATED, RFQ ISSUED, IF WARRANTED
6 – RE-EVALUATION OF METHANE-BASED SYSTEM AND DECISION TO PROCEED WITH SYSTEM DEVELOPMENT
7 – CONTRACT AWARDED FOR SOLAR INTERFACED SYSTEM TECHNOLOGY DEVELOPMENT
8 – RE-EVALUATION OF SOLAR INTERFACED SYSTEM AND DECISION TO PROCEED WITH SYSTEM DEVELOPMENT
9 – METHANE-BASED OPEN-LOOP THERMOCHEMICAL PIPELINE CONCEPT READY FOR COMMERCIALIZATION

Figure 3

HIGH TEMPERATURE THERMOCHEMICAL PIPELINES TBS 2.2

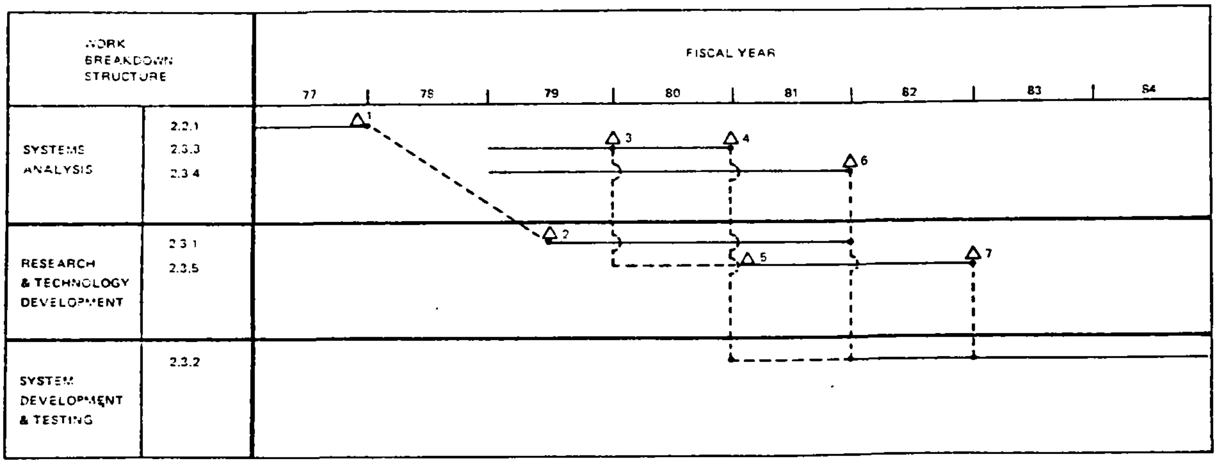


MILESTONES

1 – FEASIBILITY OF THERMOCHEMICAL PIPELINE ESTABLISHED
2 – DECISION TO PROCEED WITH SYSTEM DEVELOPMENT
3 – ALTERNATE CATALYST DESIGN COMPLETED AND EVALUATED
4 – TEST EVALUATION REPORT ISSUED
5 – SOLAR INTERFACED HIGH TEMPERATURE THERMOCHEMICAL PIPELINE EVALUATED, RFQ ISSUED, IF WARRENTED
6 – CONTRACT AWARDED FOR SOLAR INTERFACED HIGH TEMPERATURE THERMOCHEMICAL PIPELINE TECHNOLOGY DEVELOPMENT
7 – RE-EVALUATION OF SOLAR INTERFACED SYSTEM AND DECISION TO PROCEED WITH SYSTEM DEVELOPMENT

Figure 4

LOW TEMPERATURE THERMOCHEMICAL PIPELINES TBS 2.3

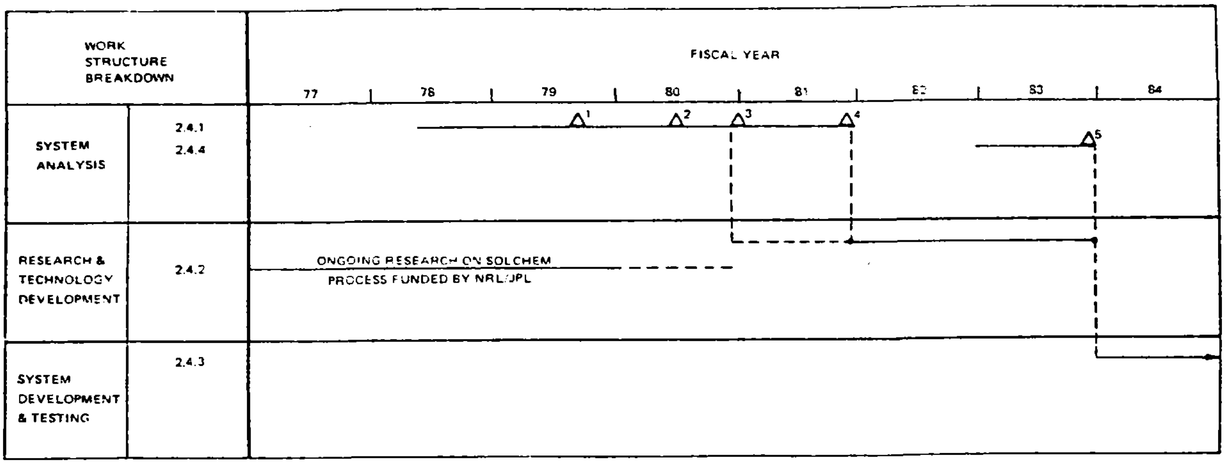


MILESTONES

1 – TECHNICAL AND ECONOMIC FEASIBILITY OF THERMOCHEMICAL PIPELINE ESTABLISHED
2 – CONTRACT AWARDED FOR BENZENE/CYCLOHEXANE TECHNOLOGY DEVELOPMENT
3 – RFQ ISSUED FOR ALTERNATE REACTION(S) TECHNOLOGY DEVELOPMENT
4 – RFQ ISSUED FOR LOW TEMPERATURE THERMOCHEMICAL PIPELINE SYSTEM DEVELOPMENT
5 – CONTRACT AWARDED FOR ALTERNATE REACTION(S) TECHNOLOGY DEVELOPMENT
6 – MARKET ANALYSIS COMPLETE, DECISION TO PROCEED WITH SYSTEM DEVELOPMENT
7 – ALTERNATE REACTION(S) ASSESSED AND FINAL SYSTEM FOR DEVELOPMENT SELECTED

Figure 5

TRANSPORT IN DISTRIBUTED SOLAR SYSTEMS TBS 2.4

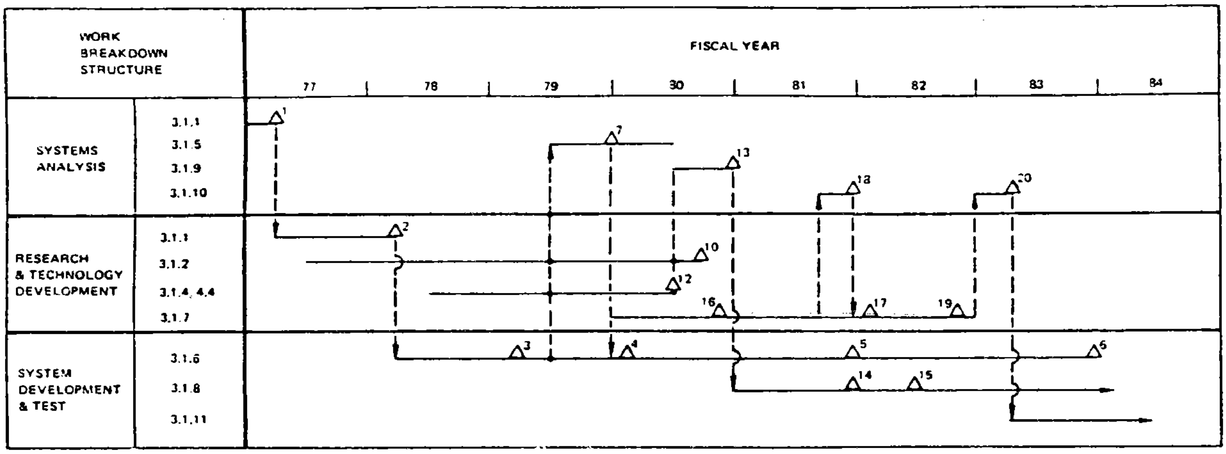


MILESTONES

1 – RFQ ISSUED FOR DETAILED SYSTEMS ANALYSIS AND REACTION(S) IDENTIFICATION
2 – CONTRACT AWARDED FOR SYSTEMS ANALYSIS
3 – RFQ ISSUED FOR RESEARCH AND TECHNOLOGY DEVELOPMENT OF ALTERNATE REACTION SYSTEMS
4 – CONTRACT AWARDED
5 – DECISION TO PROCEED WITH SYSTEM DEVELOPMENT TO PROTOTYPE STAGE

Figure 6

CHEMICAL HEAT PUMP STORAGE TBS 3.1



MILESTONES

1 – H_2SO_4 CHEMICAL HEAT PUMP CONCEPT IDENTIFIED
2 – COMPONENT DEVELOPMENT COMPLETE, CLOSED-LOOP OPERATION DEMONSTRATED
3 – COMP. OPTIMIZATION & TRANSIENT TESTING COMPLETE
4 – PROTOTYPE DESIGN COMPLETE
5 – PROTOTYPE FABRICATION & TEST COMPLETE, SECOND GENERATION SYSTEM DESIGNED
6 – SECOND GEN. FAB. & TEST COMPLETE
7 – MARKET POTENTIAL FOR H_2SO_4 ESTAB. TECH. EVALUATION OF GAS/SOLID SYSTEMS COMPLETE
8 – CANDIDATE METHANOLATES IDENTIFIED
9 – METHANOLATE CHARACTERIZATION & HEAT TRANSFER EXPMTS. COMPLETE
10 – CLOSED-LOOP SYSTEM DEMONSTRATION
11 – AMMONIATE CHARACTERIZATION & HEAT TRANSFER EXPMTS. COMPLETE
12 – CLOSED-LOOP DEMONSTRATION
13 – COMPARATIVE EVALUATION OF GAS/SOLID HEAT PUMPS
14 – COMPONENT OPTIMIZATION COMPLETE
15 – DETAILED PROTOTYPE DESIGN COMPLETE
16 – ALTERNATIVE CHEMICAL SYSTEMS IDENTIFIED
17 – CHEMISTRY OF ALTERNATIVE SYSTEMS CHARACTERIZED
18 – SELECTION OF ADVANCED SYSTEMS FOR CLOSED-LOOP DEMONSTRATION
19 – CLOSED-LOOP DEMONSTRATION COMPLETE
20 – SELECTION OF ADVANCED SYSTEM FOR SYSTEM DEV. & TEST

Figure 7

Table I TEST Project Status

TBS	Project	Contractor	Documentation
1.1.1	Extended Storage Feasibility - a system study to evaluate the technoeconomic feasibility of thermochemical storage concepts in solar energy systems	RRC	Several technical papers; final report due January 1979
1.1.2	Extended Storage Feasibility - an activity complementary to activity 1.1.1	SLL	Several technical papers
1.1.4	Ammonium Hydrogen Sulfate Decomposition - to develop an energy storage concept based upon the decomposition of ammonium hyrogen sulfate	U of H	Several technical papers; draft final report due
1.1.5	$Ca(OH)_2/CaO$ Reaction - to develop an energy storage concept based upon the hydration and dehydration of CaO and Ca(OH) respectively	AI	Draft report received February 78
1.1.6	High Temperature Storage and Heat Pipe Analysis - system studies to formulate and evaluate operational chemical cycles	LBL	Final draft report expected October 78
1.2.1	TES for Non-Solar Electric Utilities - a system study to evaluate the technoeconomic potential of thermochemical storage concepts in current and near near electric utilities	Gilbert Associates	Draft final report received and reviewed August 78

Table I TEST Project Status (Con't)

TBS	Project	Contractor	Documentation
2.1.1	Open Heat Pipe Feasibility - a system study to determine the technoeconomic feasibility of the open-loop methane-based heat pipe	IGT	Final report approved August 78
2.2.1	Heat Pipe Feasibility - a systems study to determine the technical and economic feasibility of chemical heat pipes	GE/CRD	Final report approved August 78
2.2.2	Duplex Steam Reformer - to test and evaluate the duplex steam reformer concept at the very high temperature reactor at the Kernforschungsanlage facility in Germany	GE/ESPD	Several interim reports
2.2.4	CH_4/CO Heat Pipe Solar - a system study to assess the potential of using solar central receivers as the thermal energy source for a methane based heat pipe	U of H	Draft final report past due
3.1.1	Sulfuric Acid Concentration/Dilution - a chemical heat pump system based on the concentration/dilution of sulfuric acid will be developed	RRC	Draft final report for Phase 2 received and reviewed March 78. Revision expected November 78
3.1.2	Methanol-Salt System - a chemical heat pump storage system using methanolated salt reactions will be developed	EIC	Draft final report for Phase I received and reviewed August 78. Revision expected November 78
3.1.3	Hydrated Salt Heat Pump - a chemical heat pump storage system based on hydrated salts, $MgCL_2 \cdot XH_2O$ in particular will be pursued	CES	Final report received January 78
3.1.4	Ammoniated Salt Heat Pump - to develop a chemical heat pump system based upon the use of coupled ammoniated salt reactions	MM	---
4.1	Heat Transfer - experimentally obtain heat transfer correlations in packed beds	MM/CSU	Final report received and approved
4.2	Thermal Decomposition Kinetic Studies - an investigation of fundamental processes occurring in gas/solid systems	UCD	Interim report past due
4.3	SO_3/SO_2 Catalyst Development - assess the applicability of current catalysts for use in the SO_3/SO_2 system, and develop new catalyst if required	RRC	--
4.8	In-House R&D	SLL	--

Thermochemical Cycles and Distribution of Process Heat

by K. Kugeler, Nuclear Research Centre Jülich, Germany

1. Principle of nuclear heat pipe system

The transportation of chemically bound energy (see fig. 1) represents a potential application for process heat plants, in which the endothermic reaction takes place at the heat source (for instance a high-temperature reactor combined with a steam reformer), whereas the exothermic back-reaction occurs at the region of heat utilization (a methanation which delivers steam, electricity and hot water for supply of district heat systems).
The system can be designed either to be a closed system only to transport heat or to be an open system from which CO and H_2 can be given off for different users (see fig. 2). Fig. 3 and 4 show the more detailed flow sheet and the main data for a closed system which is connected to a high-temperature reactor as the heat source.

In the conversion of methane in a steam-reforming plant heated by helium at 950 °C from a high temperature reactor, the gases H_2, CO and CO_2 are mainly formed according to the following reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2, \quad \Delta H = +205.2\ kJ/mol,$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2, \quad \Delta H = +163.3.\ kJ/mol.$$

The cooled product gas (reformer gas) is compressed to a pressure of 60-70 bar, usual nowadays for long-distance transportation, and is then transported as 'cold gas' to a consumer situated far away. At the end of this long-distance transport line, i.e. at the consumer centre, the reformer gas can be led via a district distribution network to different methanation plants where a catalytic conversion occurs into methane and steam. Heat, which was utilized form the nuclear reactor for the steam reforming of methane, is thereby nearly completely recovered. According to today's technology, gas temperatures of 450 °C can be attained by methanation. By means of the reaction heat set free, hot water can be produced which is supplied to consumers. Furthermore, the production of steam at low pressure is possible. In a subsequent development step, it is aimed at attaining gas temperatures of above 600 °C. This would render the following possibility. On the one hand, the production of high-pressure turbine steam for the generation of electricity

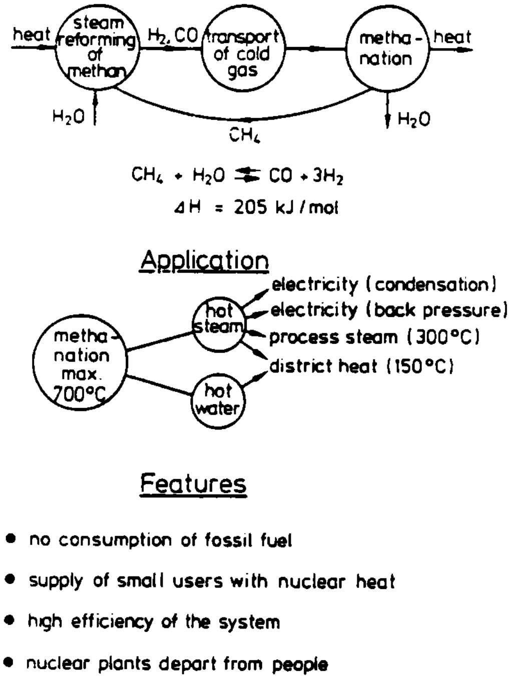


Fig. 1: Principle of transport of chemical energy (chemical heat pipe system ≙ NFE-System)

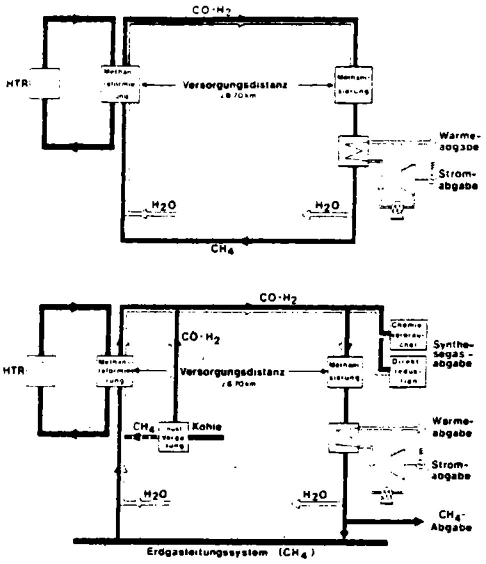


Fig. 2: Principle flow sheets of chemical energy transport of HTR-heat (a): closed system b): open system)

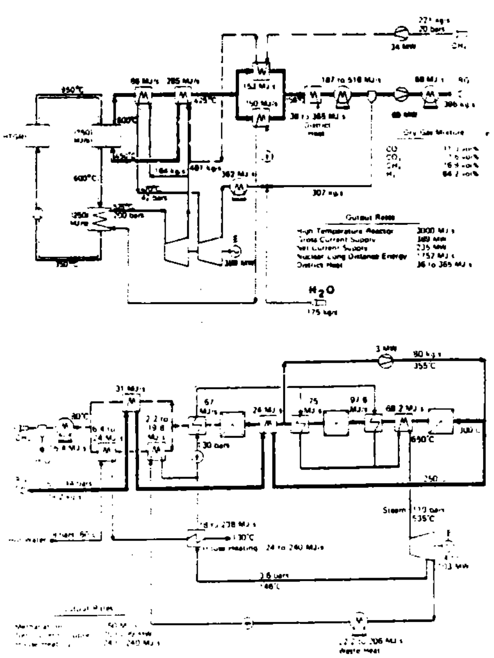


Fig. 3: Detailed flow sheet of a closed NFE-system

DATA OF A CLOSED NUCLEAR HEAT-PIPE-SYSTEM

POWER OF NUCLEAR REACTOR	3000 MW
POWER FROM METHANATION (535 °C / 110 BAR)	1752 MW
NET ELECTRIC POWER	235 MW
DISTRICT HEAT (FROM REACTOR)	MAX 365 MW
USE FACTOR FOR NUCLEAR HEAT	65 ... 80 %
HEAT PRODUCTION (700 H/A)	$1.5 \cdot 10^6$ T $\frac{SKE}{A}$

Fig. 4: Data of a closed NFE-system

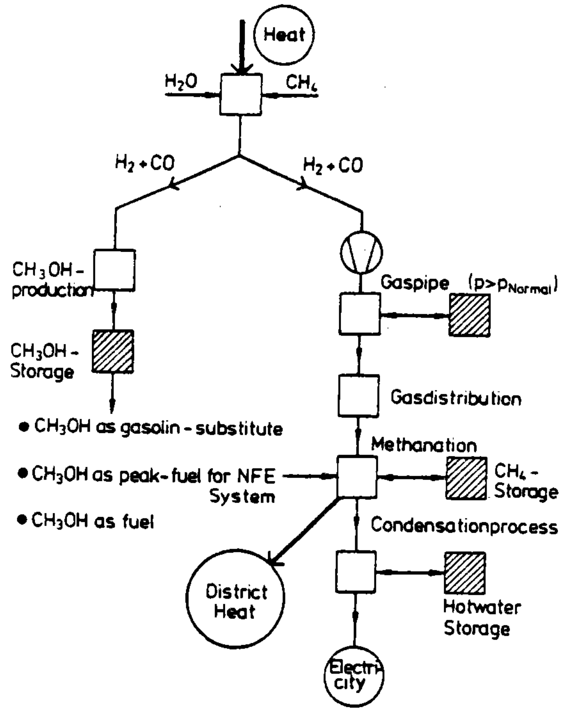


Fig. 5: Possibilities of heat storage in the NFE-system

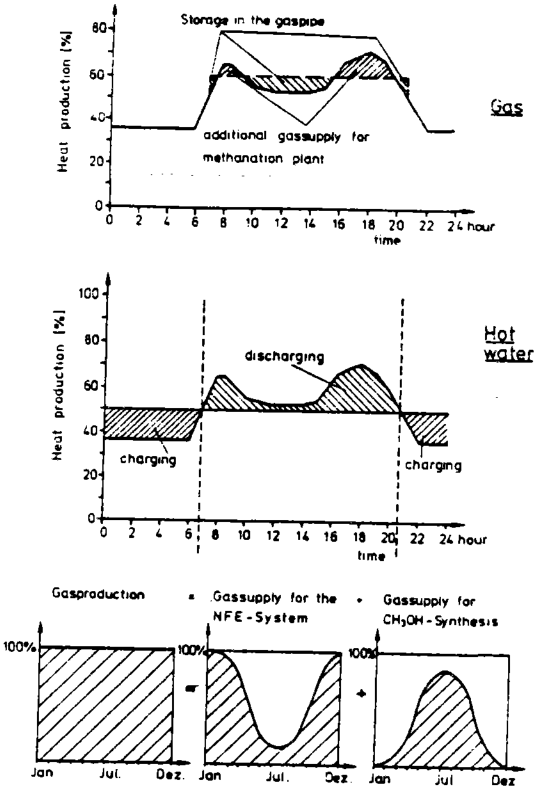


Fig. 6: Load distribution

with a favourable net efficiency, and on the other, the production of process steam at high temperature for industrial consumers. The methane formed in methanation is fed back via second long-distance transport gas line to the steam-reforming plant, after condensation and separation of the water formed.

Apart from extensive application possibilities of the system described and additionally of advantageously substituting fossil raw materials by nuclear heat with a view of providing for long-term energy planning, the nuclear long-distance energy displays the following additional advantageous features considering the limiting conditions known today:

(a) known and surveyable technology;
(b) considerable lessening of contamination emission in the production and consumption of energy;
(c) the energy production costs are only slightly increased by an increment in raw material prices, because these form only a small percentage of the total costs;

(d) a smaller amount of foreign exchange requirements for uranium and thorium as compared to crude oil; also a smaller dependence on the fluctuation in exchange rates due to economically more favourable storage possibilities of nuclear fuel;

(e) by means of gas interconnecting system it is possible to ensure supplies and reserves;

(f) possibility of covering demands of day-time peaks by pipelines (see fig. 5 and 6);

(g) already existing distribution systems (infrastructure of district heating systems, heating systems in buildings) can be utilized;

(h) heat provision known and tested at the consumer;

(i) system easily expandible; and

(j) by utilization of the system for electricity production in the vicinity of consumers, no need of transformation at high voltage level.

2. Technology of steam reformer and methanation

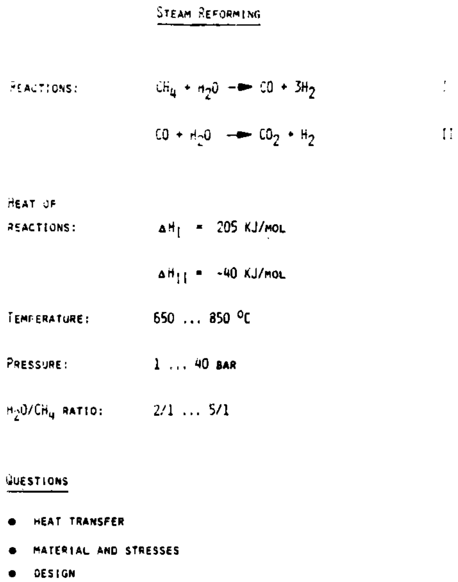
Following the industrial experience with steam reformers and the result which we have obtained from the operation of the helium-heated pilot plant EVA in Jülich (see fig. 15 and 16) from kinetic experiments, and from laboratory work concerning the hydrogen and tritium permeation and from many studies on a large pilot plant (30 tubes), the following idea is obtained about helium-heated steam reformers:

Due to the large reaction velocity of the steam reforming reaction the process is only limited by the heat transfer possibilities and the theoretical equilibria are fulfilled.

A maximum temperature of the helium of 950 °C is sufficient to obtain heat fluxes through the wall of the tubes similar to that in conventional plants (in the order of 70 kW/m^2). The reason is the good convective heat transfer by helium at 40 bar (see fig. 8).

If the process parameters are in the order of $p \sim 40$ bar, $T \sim 800$-850 °C, H_2O/CH_4: 2/1-4/1 then the methane conversion is sufficiently high (60-65 %).

With the materials (cast or rolled) available today for 100,000 h of operation, stress values of 0.5-1 kp/mm^2 can be tolerated. For a tube design with $\Delta p \sim 1$ bar, across the wall, and a wall temof max. ~ 900 °C, a conservative design is possible (see fig. 9, 10, 11).



STEAM REFORMING

REACTIONS: $CH_4 + H_2O \rightarrow CO + 3H_2$ I

$CO + H_2O \rightarrow CO_2 + H_2$ II

HEAT OF REACTIONS: ΔH_I = 205 KJ/MOL

ΔH_{II} = -40 KJ/MOL

TEMPERATURE: 650 ... 850 °C

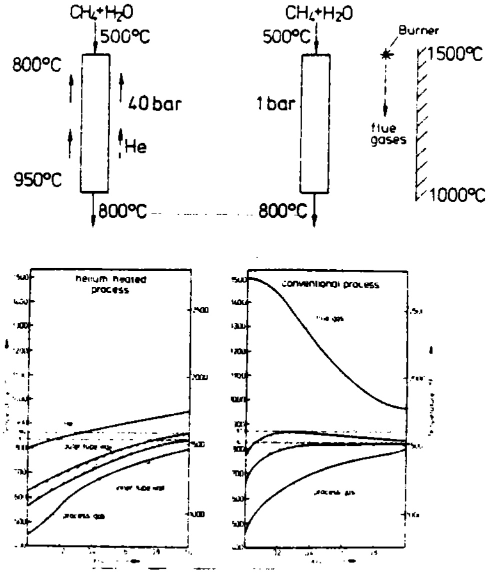
PRESSURE: 1 ... 40 BAR

H_2O/CH_4 RATIO: 2/1 ... 5/1

QUESTIONS

- HEAT TRANSFER
- MATERIAL AND STRESSES
- DESIGN

Fig. 7: Main data of steam reforming



	dimension	helium heated process	conventional process
$\alpha_{process}$	W/m²°K	1000	1000
$\alpha_{heating}$	..	1000	150
k	..	350	120
ΔT	°C	200	500
q	kW/m²	70	60

Fig. 8: Heat transfer in steam reforming system (heating by helium, heating by flue gases)

Because of the heat transfer to the reformer tubes is made by convection, these tubes must be arranged in a very compact heat exchanger. Following the different possibilities of gas ducting (helium) inside bundle, 30-40 tubes/m^2 can be accommodated. This corresponds to a columetric power density of 1-1.5 MW/m^3 for the steam reformer.Fig. 12 shows such a design.
Tests for understanding the behaviour of materials in helium with impurities (H_2, CO, CO_2, H_2O, CH_4) have been started.
The materials for the reformer tubes must be qualified in a very broad material program including creep tests, burst tests, low and high cycle fatigue tests and manufacture and quality control

While the work done until now has shown that the process is feasible, we now have to demonstrate the feasibility of the bundle. This will be done in a 30 tube bundel experiment (10 MW) (see fig. 17), which will be heated by helium and is in construction in Jülich. We hope that from the operation of this plant adequate technical know-how can be gained.

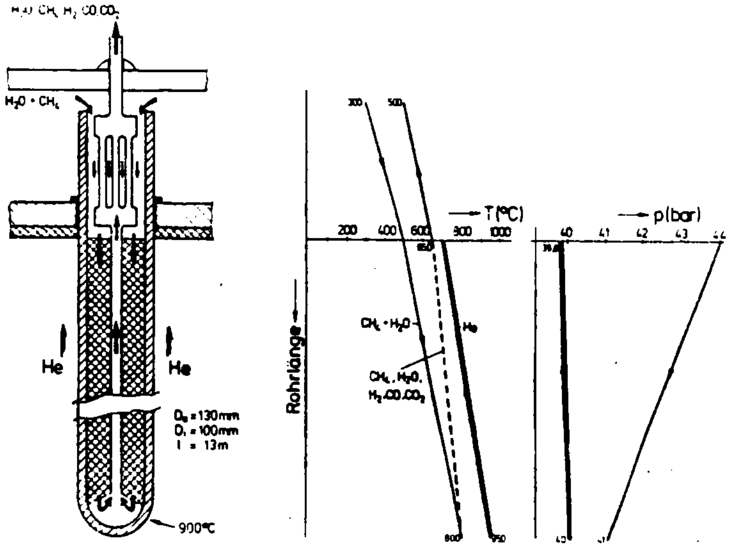
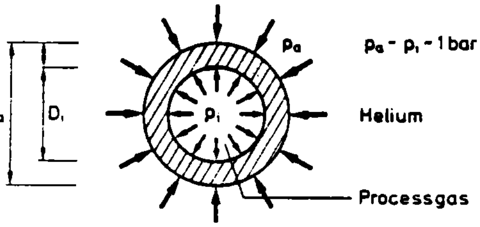


Fig. 9: Tube for steam reforming with temperature and pressure distribution



$$\Delta p_{allowable} = \frac{s \cdot 200 \cdot \sigma_B}{D_i}$$

s = wall thickness (15mm)

D_i = inner diameter (100mm)

σ_B = rupture strength for 900°C/10^5h (0,5kp/mm^2)

$\Delta p_{allowable}$ = 15 bar, i.e. safety factor 15

	inner side of wall	outer side of wall
σ_{tang}	- 0,27	- 0,3
σ_{radial}	- 0,42	- 0,39
σ_{axial}	- 0,35	- 0,35
σ_{total}	1,3	0,08

stresses in wall (kp/mm^2)

Fig. 10: Stresses in reformer tubes

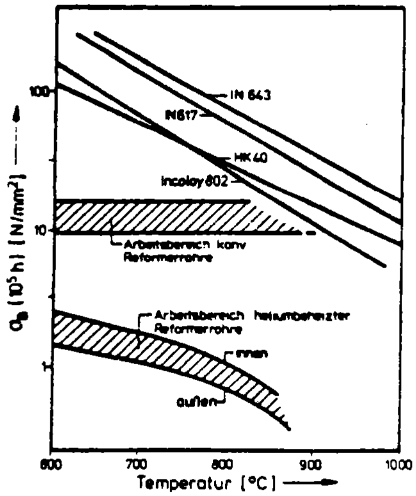


Fig. 11: Strength of materials for reformer tubes

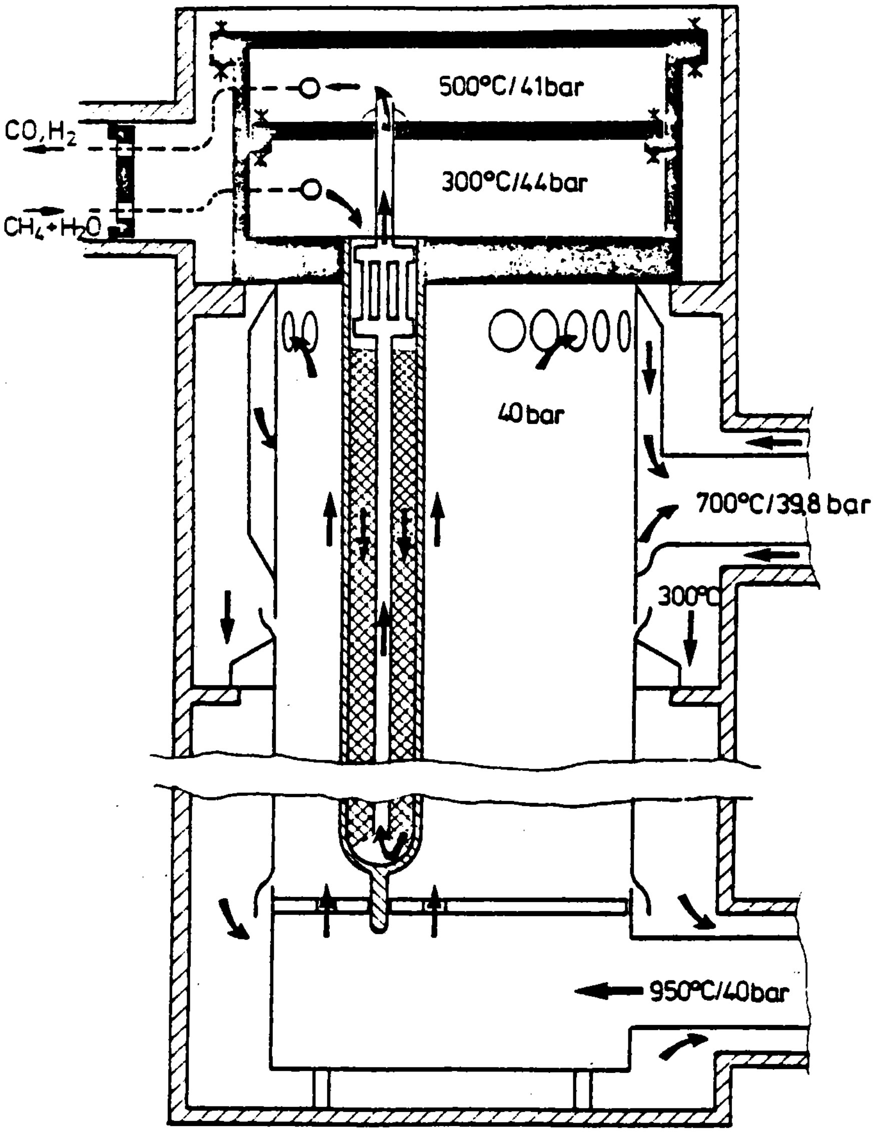


Fig. 12: Steam reformer for nuclear application

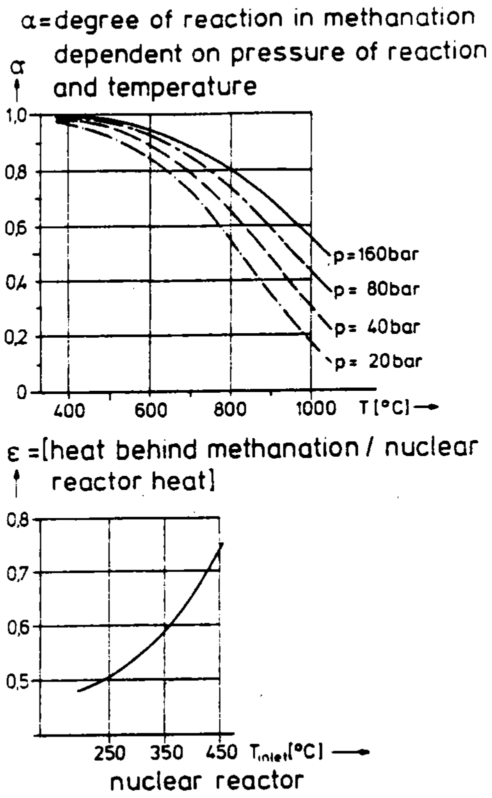


Fig. 13: Aspects of methanation

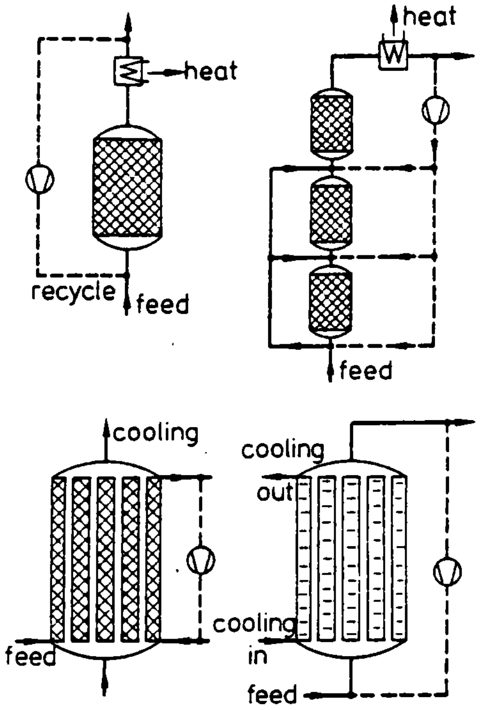
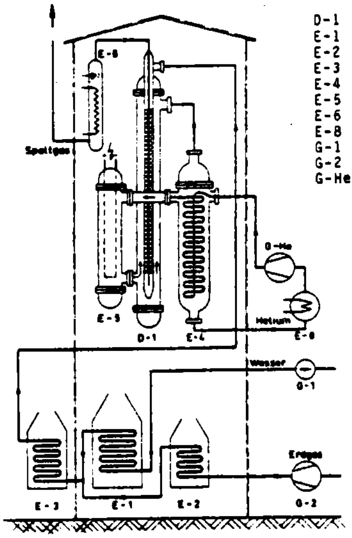


Fig. 14: Aspects of methanation

The catalytic methanation of gaseous mitures containing CO and H_2 is a process applied and proven for a long time on the industrial scale. It is applied in cleaning town gas from toxix CO contents. A methanation stage is also planned in the production of SNG by coal gasification to convert the remaining CO and H_2. For this application, technical plants have been successfully tested with a maximum reaction temperature of ∿500 °C.

For the design of methanation plants to deliver hot steam (500 °C) there are different technical possibilties as fig. 14 shows. According to fig. 13 several steps must be realised to design a methanation with nearly 100 % conversion.



D-1	Reforming reactor
E-1	Evaporator/Superheater
E-2	Natural gas heater
E-3	Steam/Natural gas superheater
E-4	Helium heat exchanger
E-5	Helium heater
E-6	Product gas cooler
E-8	Heat exchanger
G-1	Feed water pump
G-2	Natural gas compressor
G-He	Helium compressor

Main design data

Electrical power ~ 1 MW

Helium side

Maximum temperature	1000 °C
Maximum pressure	50 b
Maximum mass rate of flow	0.4 kg/sec

Process side

Inlet temperature	550 °C
Maximum pressure	35 b
Maximum CH_4 input	200 Nm^3/h
Maximum steam input	500 kg/h

Fig. 15: Schematic and data of EVA 1-plant

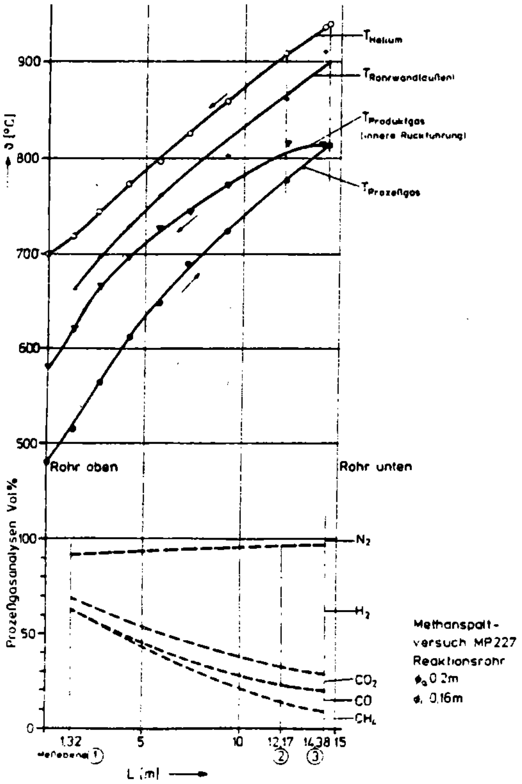
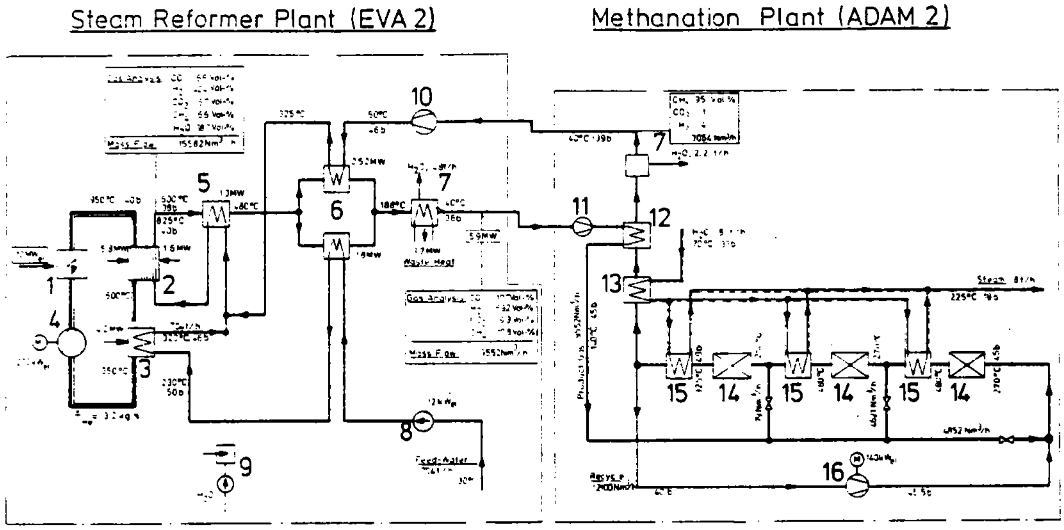


Fig. 16: Main results for EVA 1-plant
(Temperature and gas-analysis-destribution)



1 Electrical Heater
2 Steam Reformer
3 Steam Generator
4 Helium Circulator
5 Waste Heat Utilization 1
6 Waste Heat Utilization 2
7 Cooler and Water Separation
8 Feed-Water Pump
9 Auxiliary Steam Generator
10 Methane Compressor
11 Product Gas Compressor
12 Gas Preheater
13 Feed-Water Preheater
14 Methanation
15 Heat Exchanger
16 Recycle Compressor

Fig. 17: Flow sheet of EVA-2 and ADAM-2 plant

3. Development and cost estimates

The development of the above mentioned technology requires different steps as fig. 18 shows:

- Baisc investigations and tests of the catalyst to increase the reaction temperature of the methanation process to ∿650 °C. The experiments have been conducted since 1975.
- Investigation and test of single components in a technical scale in the EVA (steam reforming) and ADAM I (methanation) experimental facilities. The EVA I experimental facility has operated since 1972, while the ADAM I experimental facility will be erected and begin operation in 1978.
- The last step before building a nuclear prototype plant is the test and demonstration unit on a technical scale, whith a power of 10 MW (the EVA II and ADAM II pilot plants). EVA II is the designation for a bundle of 30 reformer tubes heated by helium of 40 bars and 950 °C. The power is transferred to the helium

Steam Reforming

Step	Nr. of Tubes	Power	Time
differential reactor	section of 1 tube	10 kW	ready since 1976
EVA 1	1	0,5...1 MW	in operation since 1973
EVA 2	30	10 MW	ready 1979
prototype (nuclear)	300	100 MW	start of construction 1985
commercial plant	600	200 MW	after 1990

Methanation

Step	Temperature	Power	Time
differential reactor	700 °C	10 kW	since 1977
ADAM 1	600 °C	0,3 kW	ready 1978
ADAM 2	600 °C	6 MW	ready 1979
prototype (nuclear)	600 °C	30 MW	start of construction 1985
commercial plant	600 °C	100 MW	after 1990

Fig. 18: Development of steam reforming and methanation

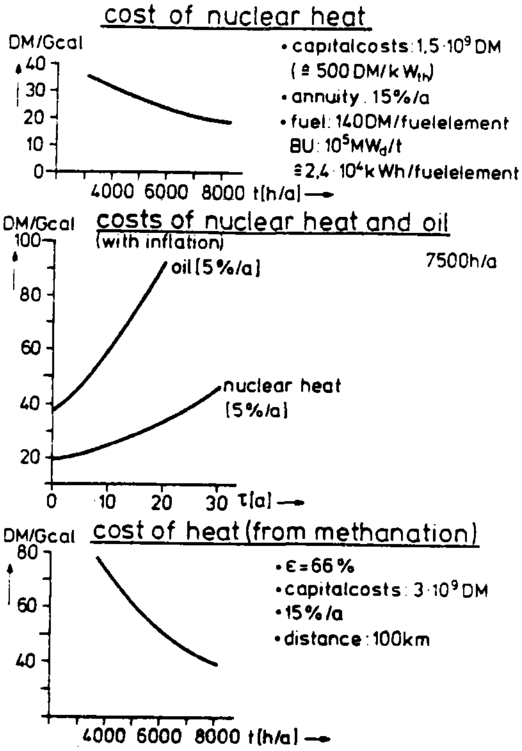


Fig. 19: Cost estimates

by an electrical heater. In this pilot plant, the behaviour of a complete reformer tube bundle and some components in connection with it are tested in a closed helium circuit under various conditions (see fig. 17).

The ADAM II methanation plant is joined to the steam reforming part of EVA II to form a closed-loop system. In ADAM II, a maximum amount of 10 000 m^3/h at N.T.P. of synthesis gas will be converted. The maximum reaction temperature planned is 650 °C. By this, a complete loop system of both energy conversion processes can be demonstrated, and the mutual influence of both processes can be determined. The pilot plant will begin operation in the second half of 1979.

If the above-mentioned steps are successful, the construction of a nuclear prototype plant for process heat will start in 1985. After the year 1990 there should be a commercialization of this technology.

Cost estimates of plants which have not been build are difficult. Fig. 19 shows some numbers on this important point.

One thing which is very attractive for such a system is that the costs during operation time will be relatively stable compared to the costs of fossil fuel, for instance oil, because the cost of nuclear energy are more dependent on capital. In any case the cost of heat behind methanation are for long time considerations small compared to the costs of fossil fuel (oil). Studies about the distribution of district heat (behind methanation) in towns have shown that the system is attractive for Germany.

4. Outlook on possible applications of solar heat for the system

In principle solar energy can be used to fulfill the demands of the above mentioned process. In this case the nuclear reactor would be substituted by the receiver of a heliostate system.

The tower would contain a steam reformer, a steam generator, a helium circulator and the helium pipes. Fig. 20 and 21 show possible flow sheets. The easiest way would be perhaps to heat a heat exchanger for helium by solar energy and to use the helium

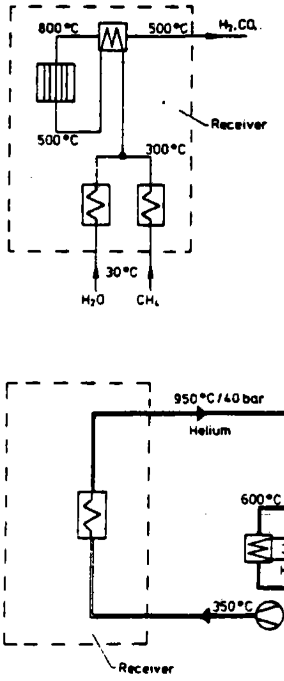


Fig. 20: Principle proposals for steam reforming using solar energ

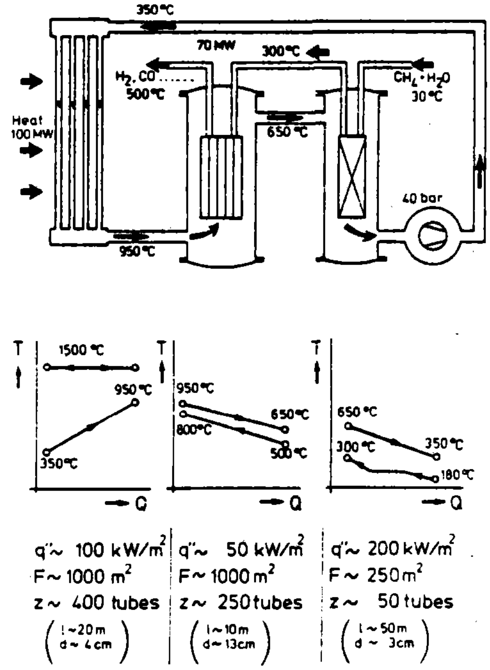


Fig. 21: Flow sheet and maian data for a 100 MW_{th}-facility

circuit as an intermediate circuit. This method could help to reduce the additional stresses in the heat exchangers during start-up and shut-down procedures following the intensity of solar energy. For normal steam reformer tubes with 1,5 cm wall thickness the velocity of temperature change is limited to 100 ... 200 °C/h depending on the allowable additional stress level (see fig. 22). To reduce the importance of this question alternative solutions for the steam reformer are possible (see fig. 23). The inner diameter of the tubes and therefore the wall thickness can be reduced if helium is flowing through the tubes and the catalyst is outside. An other alternative is to use tubes with small diameter with catalytic acting walls.

Taking into account these possibilities there is some hope to overcome the question of changing load of steam reformers, which would be a typical condition of solar heat application. The other essential component would be the heater to produce hot helium. The status of technology today is as following: In Germany there is an helium heater (power: 50 MW, T_{He} = 750 °C, p_{He} ∿ 30 bars)

$$\sigma_T = \frac{E\cdot a\cdot c_p\cdot\gamma}{(1-\mu)\cdot 3\lambda}\left[s^2\left(0{,}43\cdot\frac{r_a}{r_i}+0{,}57\right)\right]v_T$$

E = E-modul
a = thermal expansion
c_p = specific heat
γ = specific weight
λ = heat conductivity
s = wall thickness
v_T = velocity of temperature change

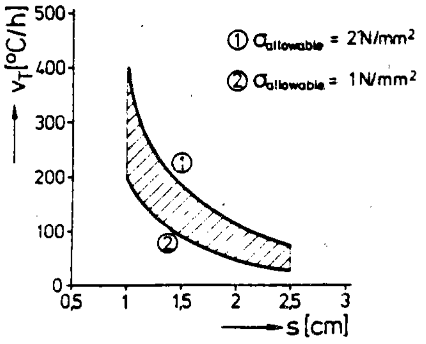


Fig. 22: Stresses in reformer tubes due to temperature change

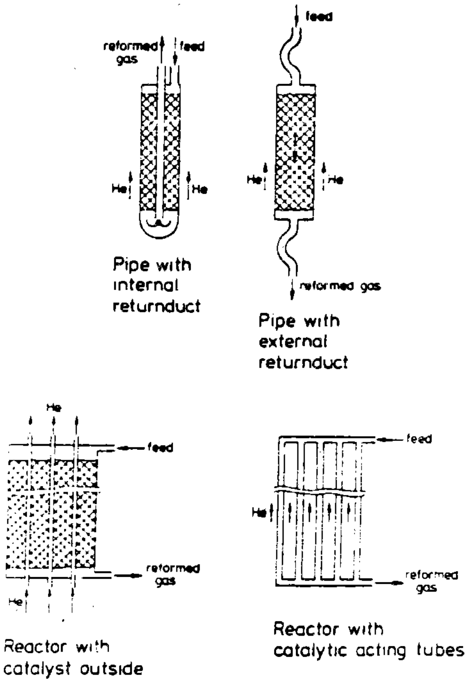


Fig. 23: Types of tubes for steam reforming

which is heated by burning light hydrocarbons in successful operation. This heater uses Incoloy 807 tubes (50 mm diameter), which are sampled to collecting tubes. A similar design, however for 950 °C should be feasible for solar heat applications. Additionally a helium/helium-heat exchanger (125 MW, 950/900 °C, 40 bars) for the German Nuclear Process Heat-Prototype Plant is in development, testing is in preparation.

There seems to be some hope, that the proposal could be realised from the technical point of view, the economical conditions of such a process using solar energy must be analysed in more detail.

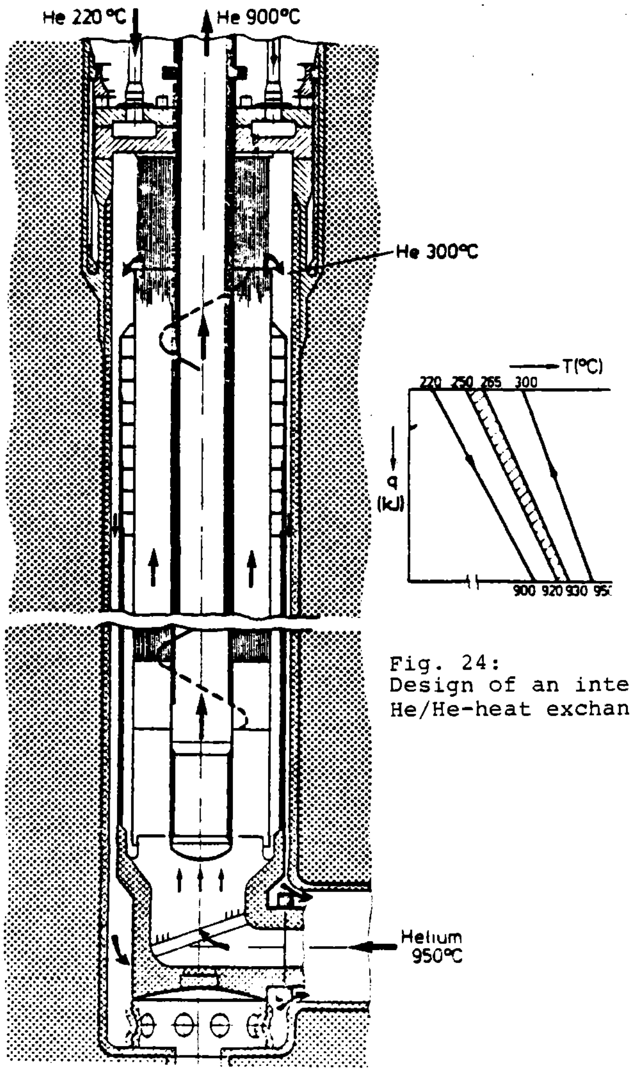


Fig. 24:
Design of an intermediate
He/He-heat exchanger (125 MW)

Question - Do you operate the loop with a stoichiometric operation?

Dr. Kugeler - You cannot operate the steam reformer with a stoichiometric operation because you get a common distribution. We are always using a ratio of steam to methane on the order of 2 to 1 to 4 to 1. It depends on the process. For nuclear heat purposes, I think more on the 2 to 1, and for coal gasification, 4 to 1.

Question - What is the catalyst you use in the recombination reaction?

Dr. Kugeler - That's one of the things which is private information. We take a catalyst from what the normal catalytic companies sell, test it, but I'm not allowed to say which it is. However, they are normal catalysts which you can buy. They are similar to reforming catalysts, with special things.

Dr. Hildebrandt - You didn't mention the transportation cost. If you have delivery near the reactor, and then consider that you deliver the heat, say, 100 kilometers away, what does this add to the cost?

Dr. Kugeler - That is a very important thing and, of course, varies greatly depending on distance. What I have shown was for a distance of 100 kilometers and the cost for the piping is nearly 10 percent of the overall operating cost. That means if we use existing facilities, we save 10 percent. If the distance is 200 kilometers, we have 10 to 15 percent added to the total cost. At a distance of 200 kilometers we must add a little extra because of the higher pumping power.

Question - Does that cost include nuclear reformer heat?

Dr. Kugeler - Yes. This cost includes the nuclear reactors, steam reformers, and there is the waste utilization. We have done very careful studies on these things, but you know how exact cost estimations are. At the moment a study is being carried on with a special run between Cologne and Frankfurt and many companies are engaged in trying to remove uncertainties. The only thing that is really uncertain is the reactor because it has not been built in this size, but the cost of the piping for methanation is relative. But the nuclear reactor capital costs are on the order of 35 percent, I think. That means if you have 20 percent uncertainty, it means 5 percent more.

INTERFACING METHANE-CARBON MONOXIDE CHEMICAL HEAT PIPES WITH SOLAR TOWERS: PRELIMINARY DESIGN AND ECONOMIC STUDY

by
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The solar tower is a potential source of energy for chemical heat pipe storage and transmission. Of all the chemical reactions proposed, the steam reforming-methanation sequence is the most advanced. This paper reports the feasibility and economics for the application of the process to solar energy.

The methane-carbon monoxide chemical heat-pipe is best illustrated by the EVA-ADAM process described in the previous paper. Advantages in using EVA-ADAM for solar applications are as follows: (1) high heats of reaction with potentially large efficiencies per mole of carbon in the cycle, (2) high equilibrium conversions for reforming and methanation, (3) no side reactions other than carbon formation, which is controllable, (4) proven technology from steam reforming, methanation and the pipeline industries, and (5) the advanced state of development of the EVA-ADAM project, necessitating only adaptations to solar usage. Disadvantages are: (1) high input and low output temperatures, causing design problems at the solar receiver and limiting the product heat to the 300-500°C range, (2) gaseous reactants and products, with subsequent large-vessel reactors or storage and low heat-transfer coefficients, (3) heat transfer limitations at the reforming reactor, which will require some form of flux transformer (heat exchanger or heat-pipe) in order to interface with the solar receiver, and (4) reactor tube materials and catalysts designed for continuous operations.

We have designed a solar process, called SOLTHERM, based on the existing EVA-ADAM with the following exceptions: (1) Heat is delivered to the steam reformer from the solar collector via some as-yet unspecified means. Possibilities are the use of a heat exchange medium (helium-as in EVA-ADAM-or air) or the design of reactors in the receiver itself, using sodium heat-pipe exchange. (2) The methanation stage is designed to operate continuously 800 hours/year and the reformer in daily cycles for 3000 hours/year. Steam reforming reactors are thus three times as large as for EVA-ADAM and storage between the reformer and the pipeline is necessary. Figure (1) shows the unit features of SOLTHERM. Both reactors are assumed to operate isothermally and compression takes place prior to methanation, with all other units experiencing lower values due to unit pressure drops.

Using a computer model of SOLTHERM, we have analyzed the response of both efficiency and economics to the process parameters of temperatures, steam to carbon ratios, pressures and pipe-line lengths.

Figures 2 through 5 demonstrate the significant results, in each case two thermal efficiencies are given. The first is the theoretical or maximum efficiency, i.e., the total amount of heat extracted for the heat input at all stages. The second efficiency is the fraction of heat delivered assuming the usual losses in heat-exchangers, pipes, etc. and also non-utilization of low-grade heat from air-coolers used to condense the steam. Actual efficiencies will be between these limits depending upon the success of energy conservation measures. Also in Figures 2 through 5 is the quantity Q_R, which is the amount of heat absorbed at the reformer per mole of carbon in the system and is a measure of the effectiveness of the cycle.

The higher the reformer temperature the more efficient the process (Figure 2). Also, the large difference of about 30% between the two efficiencies emphasizes the need for energy conservation. Increasing the H_2O/C ratio (Figure 3) improves Q_R by about 20%, but the efficiency is lower due to the extra steam load. Low pressures at the reformer are very definitely preferred (Figure 4) although it will be shown that economics is more important in this consideration. Pipeline distance (Figure 5) has no appreciable effect on efficiencies. The small increase in Q_R is due to the larger pressure drop in the longer pipeline so that the reformer operates at a lower, and more efficient, pressure.

Figures (6) through (8) give the effect of temperature, pressure and distance on the economics of the process. Standard industrial cost factors were used to calculate the capital cost in 1978 dollars. Annual operating costs were taken as twenty percent of capital with no further refinement attempted at this time. These were used to estimate the cost of delivery of process steam at the methanation plant. These studies indicate that (1) the reformer costs are six to seven times those of the methanation and approximately one-third of total costs, (2) storage cost is very critical to pressure, (3) large distances are not feasible, and (4) optimization of the system through the use of different pressures is necessary.

Figure (9) gives the "best case" conditions. Higher reformer temperatures are better but 850°C is a practical value. A reformer pressure of ten atmospheres is an absolute lower limit in order to compromise between efficiency and size.

The heat cost for this case is 2.67 $/MMBTU (as steam at 350°C). In Figure (10) this is compared with delivery costs to on-site storage at the solar plant and with the EVA-ADAM nuclear mode. The SOLTHERM is also compared in Figure (11) to the current process of steam raised by conventional fuels. Thus the cost of delivered steam via SOLTHERM is not unreasonable!

However, the cost of the original solar energy is a key figure in practical estimates.

Figure (12) gives estimates of costs of several receiver alternatives using current factors. Four modes were considered but details are not given here. The first two utilize helium and air as a heat-exchange medium. The SOLTHERM then operates much as a modified EVA-ADAM. Cavity receivers are necessary for heat flux considerations. With heat exchange transfer at the reformer, temperature differentials in the reactor will make the assumed isothermal operation difficult to attain and the heat value in Figure (11) may be too low. However, isothermal operation can be achieved using a sodium heat-pipe to modify the flux of either a cavity or external receiver. In this case the extra cost of the sodium heat-pipe (e.g. Dynatherm) is offset by incorporating the reformer in the receiver and saving the cost of external units. Details of this design are now being considered in our program.

The two best alternatives have been combined with delivery costs to calculate the overall cost of delivered steam (Figure 13). The current cost from natural gas is 3.75 \$/MMBTU which does not compare favorably with 11-12 \$/MMBTU estimated for SOLTHERM. However, projections tell a different story. In Figure (14) the cost of steam (in 1978 dollars) is given through 2000. The escalation is due to the increase in cost of natural gas (if available) and the lesser increase due to energy related construction costs. If we assume, with some optimism, that the energy related costs and other increases in SOLTHERM are compensated by the decrease in solar costs due to scale-up, larger applications and learning-experiences (e.g. with heliostat production) so that the SOLTHERM cost does not change, then the two processes become competitive about 1995.

The problems that must be solved before these predictions are realized can be seen from much of the preceding discussion. Process energy conservation is vital. Recovery and utilization of low grade heat must be maximized through appropriate process optimization. The question of daily cycles in the reformer must be answered. This will depend upon the design of both reformer tubes and the catalyst. Innovations such as wall-sprayed catalysts or honeycomb ceramics may be necessary. In addition, the chemical nature of the catalyst will have to be modified with promoters to avoid coking problems during cooling periods. If these problems can not be solved then thermal blanketing of the reformer bed will be necessary with subsequent loss of efficiency.

Alternatively, the design of cavity-reformer reactors is a potential area for development. The use of sodium heat-pipes with catalytic combinations must parallel the design of various types of receivers.

The SOLTHERM process is feasible and potentially competitive if these problems are addressed and solved.

SOLTHERM PROCESS FLOW DIAGRAM FIGURE 1

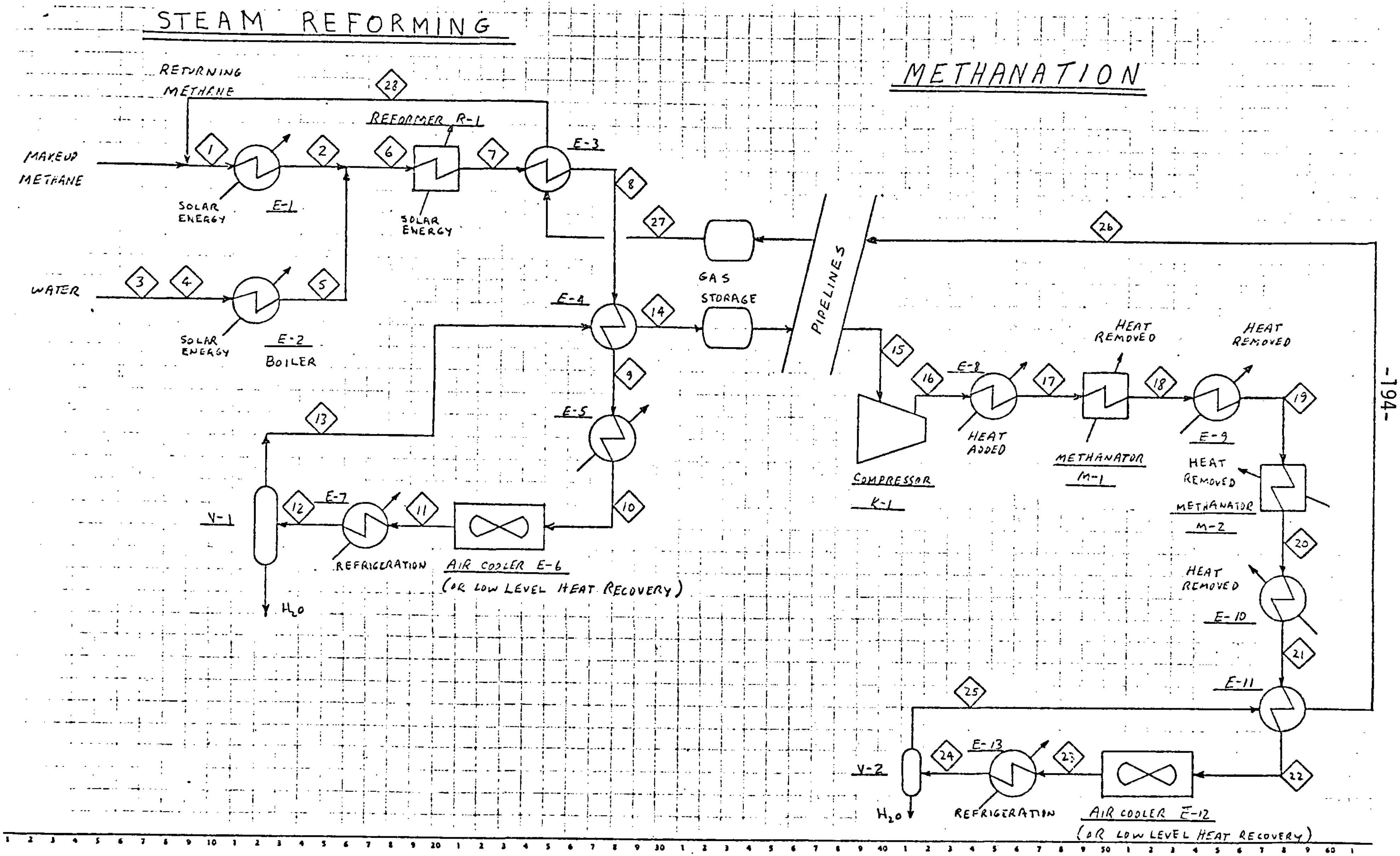

Figure (2)

EFFECT OF TEMPERATURE

$H_2O/C = 3$

$T_{M1} = 510°C$

$T_{M2} = 350°C$

$P_{M1} = 50$ atm

$L_P = 100$ miles

T_R, °C	Efficiency (1)	Efficiency (2)	Q_R
1000	.94	.64	48.7
850	.94	.62	34.4
700	.94	.53	15.2

Figure (3)

EFFECT OF H_2O/C RATIOS

$T_R = 1000°C$

H_2O/C	Efficiency (1)	Efficiency (2)	Q_R
2.0	.99	.75	41.3
2.5	.94	.69	46.9
3.0	.94	.67	48.7
3.5	.95	.66	49.4

Figure (4)

EFFECT OF PRESSURE

H_2O/C = 3

T_R = 850°C

T_{M1} = 510°C

T_{M2} = 350°C

L_P = 100 miles

P_M, atm	Efficiency (1)	Efficiency (2)	Q_R
50	.93	.62	34.4
35	.95	.65	38.5
20	.93	.65	45.2

Figure (5)

EFFECT OF PIPELINE DISTANCE

T_R = 1000°C

T_{M1} = 510°C

T_{M2} = 350°C

P_{M1} = 50 atm

H_2O/C = 3

D_P = 12 inches

L_P, miles	Efficiency (1)	Efficiency (2)	Q_R
0	.94	.69	48.7
100	.94	.67	48.7
200	.95	.68	48.7
500	.94	.67	49.7

Figure (6).

EFFECT OF REFORMER TEMPERATURE

Cost[*], 10^6 \$, 1978

Unit	T_R °C 700	850	1000
Reformer	1.46	2.10	2.60
Storage	0.94	0.87	0.84
Pipeline	1.64	1.64	1.64
Compressors	0.03	0.03	0.03
Methanators	0.18	0.31	0.39
Total	4.26	4.98	5.53
Heat cost[**]	5.67	3.49	2.85

* 25 MMSCFD to methanation

** cost of steam delivery, \$/MMBTU

Figure (7)

EFFECT OF PRESSURE

Cost, 10^6 \$, 1978

Unit	P_M, atm 20	35	50
Reformer	2.39	2.23	2.10
Storage	3.06	1.33	0.87
Pipeline	1.64	1.64	1.64
Compressor	0.10	0.04	0.03
Methanator	0.39	0.35	0.31
Total	7.48	5.57	4.95
Heat cost	4.02	3.38	3.49

Figure (8)

EFFECT OF PIPELINE DISTANCE

L_P miles	Heat cost
0	1.98
100	2.85
200	3.63
500	5.97
1000	12.97

Figure (9)

OPTIMIZED PROCESS PARAMETERS

Reformer:	850°C average, 3000 hrs/yr, 10 atm., 40 MW_{th} input
Storage:	60 atm., sufficient for 15 hrs
Pipeline:	100 miles, 12" and 6" diameter to and from the methanator, 60 atm.
Methanator:	350°C, 8000 hrs/yr, 60 atm., delivers 1,120 MMBTUD of steam

Unit	Capital Cost, 10^6 \$, 1978
Reformer	2.63
Storage	0.48
Pipeline	1.74
Methanation	0.45
Total	5.30
Steam delivery cost, \$/MMBTU	2.67

Figure (10)

COMPARISON OF CH_4/CO CHEMICAL HEAT PIPE MODES

	Steam Delivery Cost $/MMBTU
EVA-ADAM (Nuclear)	1.76
SOLTHERM	2.67
Storage (on-site)	1.71

Figure (11)

COMPARISON OF STEAM DELIVERY COSTS

(less fuel costs)

Heat Source	Cost of steam delivery $/MMBTU, 1978
Electricity	0.11
Gas	1.50
Coal (low sulfur)	1.58
EVA-ADAM	1.76
SOLTHERM	2.67
Fuel oil (high sulfur)	3.17

Figure (12)

SOLAR RECEIVER COSTS

40 MW_{th} delivered to the reformer

	He, 1000°C	Air, 1000°C	Heat-Pipe	Heat-Pipe
Receiver	3.21	4.84	7.53	7.53
Tower	0.86	0.86	0.86	0.32
Heliostats (101 $/$M^2$)	8.71	8.71	8.71	8.16
Compressors	2.80	2.80	2.80	2.80
Land, etc	1.84	2.02	2.32	1.91
Total	17.42	19.23	22.22	20.72
Heat cost, 1989 $/MMBTU	8.51	9.39	10.85	10.12

Figure (13)

BEST CASE, TOTAL DELIVERED STEAM COST

	1978 $/MMBTU
Cavity, He, 1000°C	11.17
External, heat-pipe reformer	11.50

Figure (14)

STEAM COST PROJECTIONS

1978 $/MMBTU, Gulf Coast

Year	Total Cost	
1978	3.75	
1980	4.84	
1985	6.46	
1990	11.04	
2000	13.80	← SOLTHERM

PROCESS STEAM END USE FOR SOLAR ENERGY USING CHEMICAL HEAT PIPES

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The Chemical Heat Pipe is a novel concept for the transport and storage of thermal energy via closed loop chemical systems (Figure 1). In this concept, the primary thermal energy is converted to a chemical form by a catalyzed endothermic chemical reaction at a centrally located energy source. The products of this reaction are heat exchanged down to ambient temperature and transported to distant user sites where the reverse exothermic reaction takes place to recover the thermal energy. The products of the exothermic reaction are returned, in ambient temperature pipelines, to the original site, thus completing the closed loop. The pipelines can be used in conjunction with liquid tanks to provide energy storage as well as transport and may provide energy to small scale users on a one or two shift basis.

In a study recently completed[1], GE has identified two chemical systems as best candidates for the CHP concept. The first system utilizes the steam reforming of methane as the endothermic reaction and requires temperature of the order of 1100K to drive it; thus, it has been designated the High Temperature Chemical Heat Pipe (HTCHP). The second system employs the dehydrogenation of cyclohexane as the endothermic reaction, operates at 600 to 800K, and is termed the Low Temperature Chemical Heat Pipe (LTCHP).

A preliminary market analysis has shown that if these technologies could be applied in the US at the present time, up to $12\text{x}10^6$ BBL of oil equivalent per day of prime fossil fuels could be substituted by solar, coal, or nuclear sources and a maximum conservation potential of $5\text{x}10^6$ BBL/day by using conservation technology could be realized. An estimate of the prime industrial process steam market showed a potential of $1.1\text{x}10^6$ BBL/day for prime fuel substitution.

A convenient method of comparing the CHP concept with other proposed energy conversion and transport systems is that based on exergy analysis. The "exergy ratio" for any form of energy is defined as the amount of work available per unit of heat and is a measure of the quality of the energy. For thermal energy this is simply the Carnot factor $(1 - T_o/T)$ for reversible processes. For chemical energy the exergy ratio is $(1 - \frac{T_o \Delta S^o}{\Delta H})$ where ΔS and ΔH are the entropy and enthalpy changes of the reaction. This exergy ratio ranges from 0.50 to 0.75 for thermal sources ranging in temperature from 600K to 1200K. Exergy ratios for such secondary energy carriers as electricity, hydrogen, the HTCHP and the LTCHP are 1.0, 0.83, 0.70 and 0.61. Process steam exergy ratios range from 0.37 to 0.47 for saturated steam ranging from 471K (15b) to 559K (70b). Thus, for electricity and hydrogen, an uphill thermodynamic climb must be made to convert the primary energy into a higher quality secondary form. A combination of the first and second laws of thermodynamics shows that this uphill climb results in an inherent first law loss of energy during the conversion and an inherent second law loss at the user site when process steam is generated at a low exergy ratio. The chemical heat pipe systems avoid this uphill climb, and thus have a much higher first law efficiency. In addition, a large decrease in exergy ratio is avoided at the process steam generation site and as a result these systems also have a much higher second law efficiency. Of course, process irreversibilities and design limitations must be considered in a final comparison of conversion systems but generally, the arguments presented here will still apply in actual conversion processes.

These inherent thermodynamic advantages of CHP systems make them prime candidates for use in Solar Central Receiver energy conversion schemes where it is desirable to utilize as much of the collected energy as possible. In combining these technologies, some type of intermediate heat exchange loop (IHX) would be required. This intermediate loop would serve to damp out short and long term fluctuations in the solar intensity, alleviate the flux mismatch between the solar incident energy on the outside of the reactor tubes and the chemical reaction on the inside of the tubes of a reactor, and minimize the weight of the apparatus located at the top of the central receiver. The design limitations on the reactor tubes tend to favor the LTCHP system in which thermal stress on the tubes and corrosion problems in the IHX would be significantly reduced when compared to the HTCHP. Also important is the cost of the endothermic reactor since it must be oversized by roughly a factor of 3 to account for the periodicity of the solar energy. Again, the LTCHP system is favored since the reactor system is less expensive than the methane based system.

The estimated costs for a solar/LTCHP/process steam system are detailed in Table 1 for a transmission rate of 1000 MW and distance of 160 km. The cost of the primary solar energy is assumed to be \$6.00/GJ and the incremental LTCHP cost is \$3.09/GT resulting in a delivered heat cost of \$9.09/GJ. The endothermic reactor accounts for 65% of the capital cost and the capital cost contributes 60% of the LTCHP cost to the cost of delivered heat. The incremental LTCHP cost is a function of the primary heat cost since the heat losses and power requirements must be accounted for. The effect of variation in the primary energy cost on the LTCHP incremental cost and the total cost for delivered heat is shown in Figure 2. Here the LTCHP cost ranges from \$1.80/GJ to \$4.00/GJ for primary heat cost ranging from \$0.00/GJ to \$10.00/GJ. The \$1.80/GJ represents the minimum cost for the CHP system resulting from the capital charges only. It should be noted that no attempt was made to optimize the system for this economic evaluation.

The real incentive for the solar/LTCHP system becomes apparent when the economics of the cogeneration option are investigated. As shown in Figure 3, if electricity were generated from the primary solar energy only 36% of the collected energy could be utilized while the remainder would be lost to dry cooling towers and transmission losses. For the LTCHP system, approximately 82% of the collected energy could be delivered to users and the cooling towers eliminated. Assuming that the electricity from both systems is sold at the same price, the generated process steam could be sold at \$5.75/GJ, a price below that assumed for the primary thermal energy (\$6.00/GJ) and the revenues would be equivalent to the electricity only case with no credit taken for the elimination of the cooling towers in the LTCHP case. In addition, by using the LTCHP transportation and storage system, one and two shift process steam end users could be served or peaking electricity generated.

Thus, there is ample reason to argue that a solar/LTCHP/process steam/cogeneration scheme could have a significant place in solar thermal technology. The major solar developments which must take place before the system becomes a reality are the development of an economical solar central receiver and LTCHP/receiver interface, the proof of the technical feasibility of the cyclohexane/benzene chemistry to be repeatedly cycled without uneconomical side product formation, and the solution to institutional barriers such as the nucleation of chemical pipeline grid to supply heat to a variety of users.

GE will be attacking the proof of the chemical feasibility problem in a proposed multi-year program to test catalysts that will provide the desired selectivity for the cyclohexane dehydrogenation/benzene hydrogenation reactors. UOP, Inc., Des Plaines, Illinois is the proposed subcontractor who will provide the catalyst testing facilities while GE will provide a closely coupled reactor and process design program. The major goal of this contract will be to demonstrate the existance of selective hydrogenation/dehydrogenation catalysts that will function in the LTCHP system.

Mr. Flock - I will give you the contract number of this report we have written because many things are discussed there in more detail--it is Contract Number EY-76-6-02-2676.

Question - You had a graph that showed the endothermic reactor cost at 64.8 percent and storage at 0.8, was that correct?

Mr. Flock - Yes. We were storing benzene and cyclohexane and hydrogen and the hydrogen was based on 8 hours of storage in the pipeline, in that case, pressurized.

Comment - I thought you might have thermal storage integrated that way and get that factor of 3 down on your shift.

Mr. Flock - Yes. I think that's an important consideration in the short term thermal storage. For a small incremental cost you might go to somewhat longer thermal storage times.

REFERENCES

1. "Closed Loop Chemical Systems for Energy Storage and Transmission (Chemical Heat Pipe)", H. B. Vakil and J. W. Flock, Final Report on ERDA Contract EY-76-C-02-2676, (February 1978).

Table 1
SUMMARY OF COST ANALYSIS
FOR SOLAR/LTCHP TRANSMISSION OF HEAT

Capital Costs	10^6\$	% of Total
Dehydrogenation Reactor and Heat Exchangers	166.5	64.2
Storage Tanks	2.0	0.8
Transmission Line	54.2	20.9
Hydrogenation Reactors	36.5	14.1
TOTAL CAPITAL COST	259.2	100.0
Operating Cost	10^6 \$/yr	
Yearly Capital Cost (@ 20%/yr)	51.8	59.5
Power and Losses (28.3 MW x 2.5 = 70.8 MW_{th})	12.2	14.0
Undelivered heat (at 132.8 MW_{th})	23.0	26.5
TOTAL YEARLY COST	87.0	100.0
Incremental LTCHP Transportation Cost (at 2.81 x 10^7 GJ/yr)	\$3.09/GJ	
Total Cost of Delivered Heat	\$9.09/GJ	

Figure 1 CHP CONCEPT

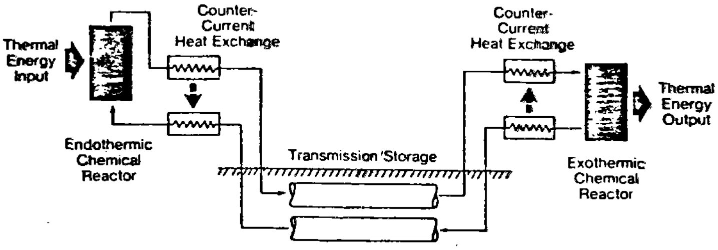


Figure 2 Cost of LTCHP Transportation and Cost of Delivered Heat as a Function of the Cost of Solar Heat

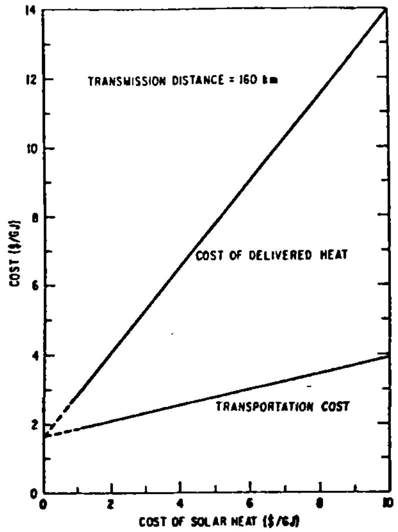
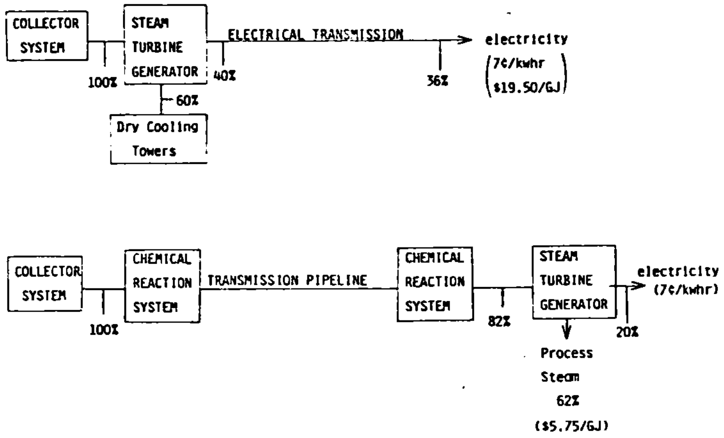
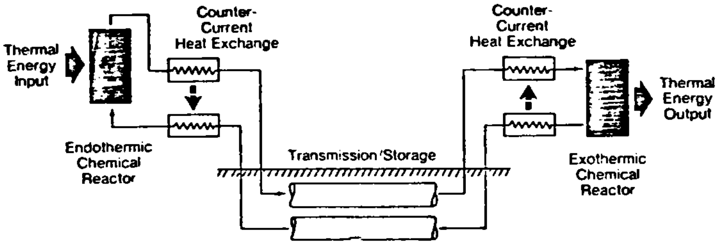


Figure 3 SOLAR THERMAL SOURCE



MAJOR FEATURES



- AMBIENT TEMPERATURE THERMAL TRANSPORT
- STORAGE
- HIGH EFFICIENCY OF THERMAL DELIVERY
- DISTRIBUTED GENERATION AND COGENERATION

MARKET POTENTIAL

- APPLICATIONS
  - INDUSTRIAL PROCESS STEAM
  - PEAK ELECTRICITY
  - RESIDENTIAL/COMMERCIAL SPACE HEAT
  - COGENERATION
- PRIME FUEL DISPLACEMENT
  (TO COAL, NUCLEAR, SOLAR)
  - $12\text{x}10^6$ BBL/DAY (MAXIMUM)
  - $1.1\text{x}10^6$ BBL/DAY (CONSERVATIVE)
- CONSERVATION POTENTIAL
  (OF COAL, NUCLEAR, SOLAR)
  - $5\text{x}10^6$ BBL/DAY

SOLAR CHEMICAL HEAT PIPE FOR PROCESS STEAM APPLICATIONS

- THE CHEMICAL HEAT PIPE CONCEPT
- MARKET POTENTIAL FOR CHP
- WHY CHP FOR PROCESS STEAM
- ECONOMICS OF SOLAR APPLICATIONS
- FUTURE PROGRAM AT GE

CHEMICAL HEAT PIPE CHEMISTRY

- HTCHP ($T > 875K$)
  - BEST CHEMISTRY - METHANE/STEAM

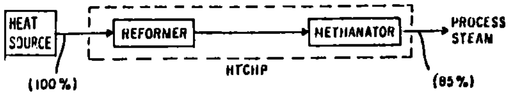
$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$

- LTCHP ($T < 875K$)
  - BEST CHEMISTRY - BENZENE/CYCLOHEXANE

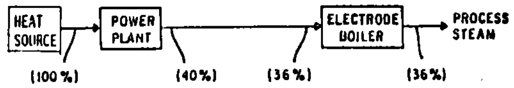
$$C_6H_{12} \rightleftharpoons C_6H_6 + 3H_2$$

ENERGY CONVERSION EFFICIENCIES

a) HTCHP CASE



b) ELECTRICAL TRANSMISSION

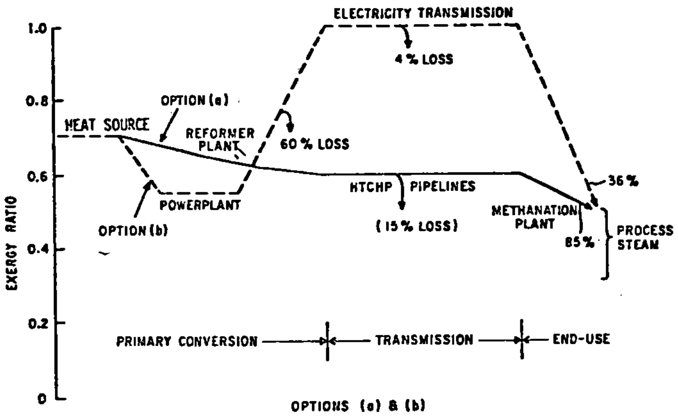


COMPARISON OF ENERGY FORMS

$$\text{EXERGY RATIO} = 1 - \frac{T_0 \Delta S}{\Delta H} \quad \text{CHEMICAL}$$

$$= 1 - \frac{T_0}{T} \quad \text{THERMAL}$$

PRIMARY THERMAL SOURCE TEMPERATURE, K	EXERGY RATIO
1200	0.75
900	0.67
811 (1000F)	0.63
600	0.50
SECONDARY ENERGY CARRIERS	
ELECTRICITY	1.00
HYDROGEN	0.83
HTCHP	0.70
LTCHP	0.61
PROCESS STEAM	
70B, 559K	0.47
35B, 515K	0.42
15B, 471K	0.57



EXERGY ANALYSIS CONCLUSIONS

- CHP CONCEPT OFFERS THERMODYNAMIC ADVANTAGES
  - AVOIDS EXERGY UPGRADING
  - CONVERSIONS AVOID LARGE CHANGES IN ENERGY RATIO
- DESIRABLE TO MATCH CHEMISTRY/SOURCE EXERGY RATIO
- MAXIMIZE HEAT TRANSFERRED IN A FORM AT OR ABOVE THE EXERGY RATIO OF THE FINAL USE
- MUST CONSIDER
  - PROCESS IRREVERSIBILITIES
  - MATERIAL LIMITATIONS AND OTHER PROCESS DESIGN CONSTRAINTS

Solar Economics

- Important considerations
    - Economy of Scale
        - ..Backyard vs central receiver
    - Moderate to high concentration receivers required
    - One shift endothermic reactor
        - ..3x cost
        - ..optimize for source
    - Intermediate heat exchange loop required
        - ..thermal stress
        - ..flux mismatch
        - ..weight limitations
    - LTCHP offers reduced
        - ..thermal cycling problems
        - ..corrosion problems
- Promising Option for Solar Distributed Cogeneration (vs On-site generation)
    - Conservation
    - Economics

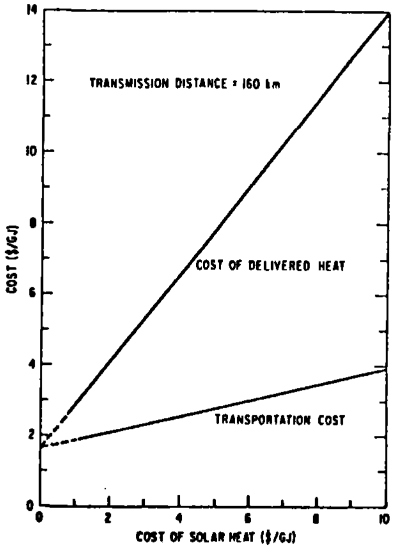
SUMMARY OF COST ANALYSIS
FOR SOLAR/LTCHP TRANSMISSION OF HEAT

<u>Capital Costs</u>	<u>10^6\$</u>	<u>% of Total</u>
Dehydrogenation Reactor and Heat Exchangers	166.5	64.2
Storage Tanks	2.0	0.8
Transmission Line	54.2	20.9
Hydrogenation Reactors	36.5	14.1
TOTAL CAPITAL COST	259.2	100.0
<u>Operating Cost</u>	<u>10^6 \$/yr</u>	
Yearly Capital Cost (@ 20%/yr)	51.8	59.5
Power and Losses (28.3 MW x 2.5 = 70.8 MW_{TH})	12.2	14.0
Undelivered Heat (at 132.8 MW_{TH})	23.0	26.5
TOTAL YEARLY COST	87.0	100.0

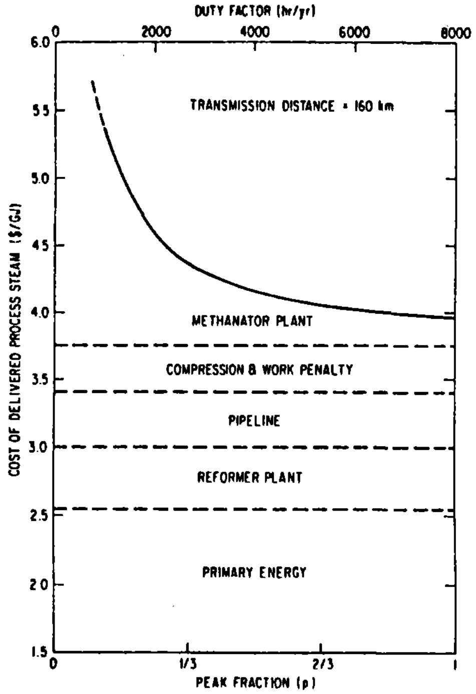
<u>Incremental LTCHP Transportation Cost</u>
(at 2.81 x 10^7 GJ/yr) \$3.09/GJ

<u>Total Cost of Delivered Heat</u> \$9.09/GJ

Cost of LTCHP Transportation and Cost of Delivered Heat as a Function of the Cost of Solar Heat



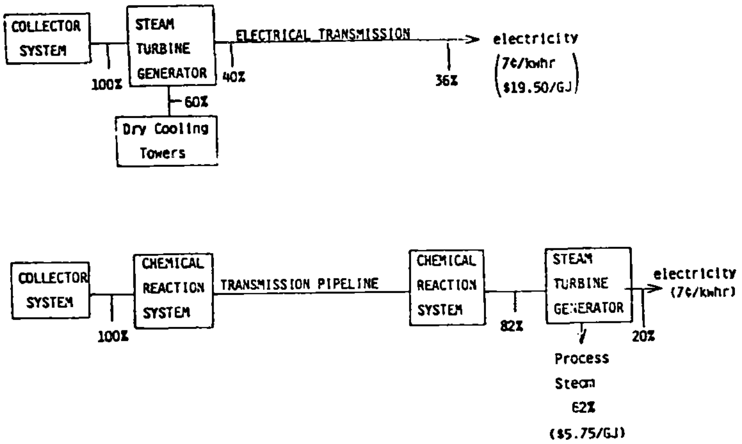
HTCHP Applications
Distributed Process Steam



CHP SOLAR APPLICATIONS SUMMARY

- BEST APPLICATION--CENTRAL RECEIVERS
- CHP COST--$2 TO$4/GJ
- TO BE COMPETITIVE WITH $5/GJ SNG
  - PRIMARY SOLAR HEAT MUST BE SUPPLIED @ $1 TO $3/GJ

SOLAR THERMAL SOURCE



SOLAR CHP DEVELOPMENT REQUIREMENTS

- ECONOMICAL PRIMARY SOURCE TECHNOLOGY
- SOLAR/CHP INTERFACE
- PROOF OF CHEMISTRY
- OVERCOME INSTITUTIONAL BARRIERS

PROPOSED FOLLOW ON LTCHP CONTRACT

- PROPOSED DOE CONTRACT (SWET)/SANDIA MONITORING (WILSON, BRAMLETTE, HAALAND)
- 30 MONTHS
- PRIMARY GOAL--ESTABLISH TECHNICAL FEASIBILITY OF CYCLOHEXANE/BENZENE CHEMISTRY
- PROPOSED SUBCONTRACTOR--UOP, INC.--CATALYST TESTING
- GE/CRD--REACTOR DESIGN, ECONOMIC EVALUATION

ENERGY COLLECTION AND TRANSPORT USING THE SO_3/SO_2-O_2 THERMOCHEMICAL CYCLE; PF_3H_2 AS A POSSIBLE THERMOCHEMICAL FLUID

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5 OCTOBER 1978

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ENERGY COLLECTION AND TRANSPORT USING THE SO_3/SO_2-O_2 THERMOCHEMICAL CYCLE; PF_3H_2 AS A POSSIBLE THERMOCHEMICAL FLUID

INTRODUCTION

This paper addresses three topics: (1) the use of the gas phase SO_3/SO_2-O_2 reaction for thermochemical collection and transport of solar energy; (2) the use of the $SO_3(\ell)/SO_2(\ell)$, $O_2(g)$ chemical system for intermediate distance energy transport; and (3) an initial examination of the PF_3H_2/PF_3-H_2 system as a possible gas phase thermochemical cycle.

THE SO_3/SO_2-O_2 THERMOCHEMICAL CYCLE

Our group at the Naval Research Laboratory is exploring the applicability of thermochemical methods for collecting solar energy. Thermochemical collection of solar energy makes use of the temperature shift in chemical equilibrium that occurs in reversible chemical reactions. Thermochemical energy collection requires reactions that are catalytically controllable and that do not have irreversible side chains. These requirements are met in the SO_3 dissociation reaction.

Figure 1 shows dissociation equilibrium curves for SO_3 for pressures over the range of 1 to 40 atmospheres. These curves show that the SO_3, SO_2, O_2 system shifts from being predominantly SO_3 below 600°C to being predominantly SO_2 above 950°C. Selection of operating pressure determines the position of the dissociation curve; the pressure shift effect is about 175°C for a 40-fold change in pressure. In Figure 2 we show at each pressure the temperatures corresponding to 10%, 40%, and 70% dissociation. We prefer to design an SO_3 energy collection system to receive 10% dissociated gas as feedstock at the solar collectors and to produce 70% dissociated gas as exiting flow. The arrows on the bottom of the Figure mark temperatures at which low-cost energy storage can be provided. These arrows mark the melt points of potentially low-cost nonoxidizing salt eutectics. An SO_3 system operating at 10 atmospheres between 10% and 70% dissociation points can deliver 50% of the collected energy at 680°C. A 680°C delivery temperature is suitable for energy storage at 638°C. The balance of the delivered energy can be stored at 500°C or 385°C. The dotted line on the Figure is the condensation temperature of SO_3. This condensation temperature determines the pipeline temperature required for circulation of gas to solar energy receivers. Thus an SO_3 system operating at 10 atm requires feedstock lines at 104°C. Return chemical product lines will operate at slightly higher temperature.

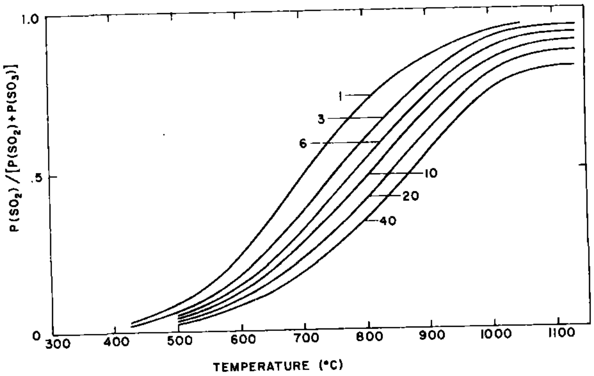

FIGURE 1
Equilibrium SO_2 sulfur oxide fraction as function of temperature, for pressures of 1, 3, 6, 10, 20, and 40 atm.

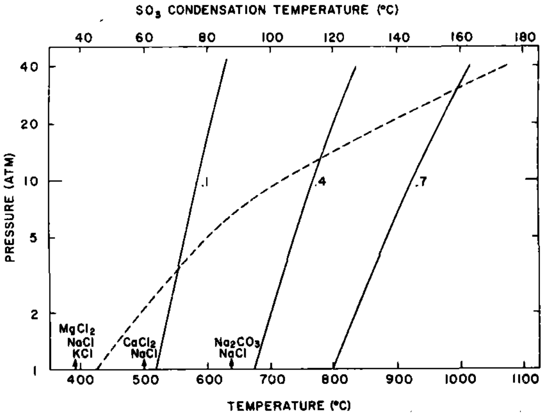

FIGURE 2
Solid lines show pressure vs. temperature curves corresponding to 0.1, 0.4, and 0.7 sulfur oxide equilibrium fractions for the $SO_3 \rightleftharpoons SO_2 + 1/2\ O_2$ system. Dotted line shows vapor pressure vs. temperature for pure SO_3.

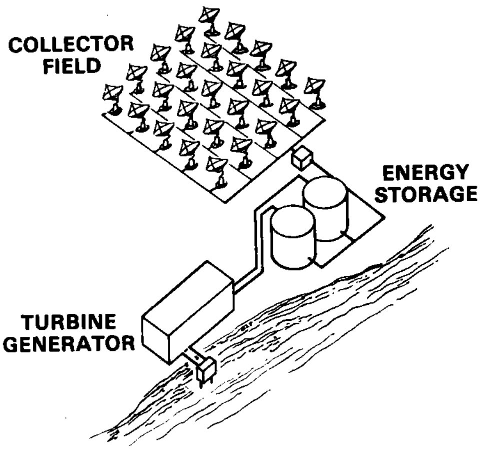

FIGURE 3 A Solchem power plant consists of a solar energy collection field, an energy storage field, and a Rankine cycle power plant. Solar energy is captured at each solar collector by thermochemical conversion of high temperature heat into chemical energy. Energy is carried to the energy storage area by a thermochemical cycle using a gas phase working fluid. Energy is stored as heat-of-fusion in containerized eutectic salts. The storage tanks contain boilers and superheaters and provide on-demand steam (or other vapor) for operation of load-following turbine-generators.

SOLCHEM POWER PLANTS

We call the NRL approach to using thermochemistry for collection of solar energy, Solchem. The Solchem concept is shown in Figure 3. It envisages solar electric power plants built up from three components: a solar collector field employing a multiplicity of thermochemical receivers; an energy storage field in which energy is stored as heat-of-fusion in containerized salt eutectics and a conventional steam, or other Rankine cycle, power plant. In Solchem, all collected energy is delivered into storage and all energy is generated from storage. Boilers within the storage tanks provide on-demand steam as required for generation of load-following power. Energy is delivered to the energy storage tanks by delivering to the storage medium the heat produced by SO_3 synthesis. Circulation piping connects the collection field to the salt tank field. This piping operates at relatively low temperature, as dictated by the SO_3 condensation temperature. Counter current heat exchangers at each receiver and a big regenerator at the storage field capture the sensible heat that would otherwise be lost. The circulating fluid is always in gas phase.

Figure 4 shows one concept for constructing a thermochemical receiver. The receiver shown is a cavity receiver. The inflowing and outflowing gas streams are confined to spiral passages within a ceramic body. Most of the receiver consists of heat exchange surfaces. The innermost passage, however, contains catalyst and receives heat through the cavity-facing ceramic wall. In this passage heat is absorbed in dissociating SO_3, producing the energy rich $SO_2 + O_2$ output stream. The relatively low temperature of the exiting $SO_2 + O_2$ permits use of gaskets to couple the ceramic receiver to the external metal pipeline network.

We have examined the operation of Solchem-type systems analytically for several scales of system size. The solid line in Figure 5 shows the losses that occur for one such system. The individual losses are described in the Figure caption. This particular study was for a system providing a peak energy delivery to storage of 5.1 MW thermal (based on 804 $W\ M^{-2}$ direct beam sunlight). The system used 240 collectors of 23-foot diameter, arranged in subfields of 96 collectors. The layout is shown in Figure 6. The piping leading to the collectors was made up of 12" header lines, 3" feeder lines, and 1" hose lines. The system operates at 3 atm absolute. Returning to Figure 6, note specifically the losses associated with the circulation system. There are losses associated with pumping the gas through the lines, and losses due to heat flow through the insulating blankets covering the lines. These losses were calculated to be 4.9% for pumping power required to drive the gas circulation, and 5.9% for

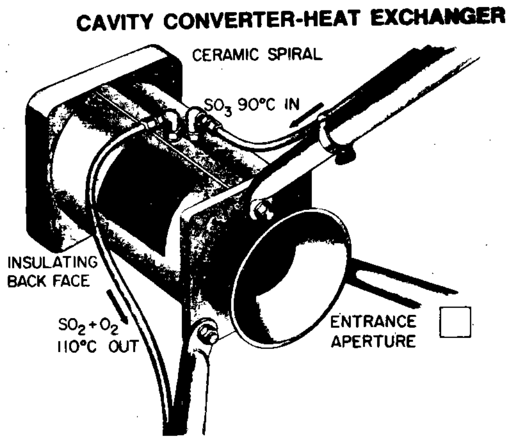

FIGURE 4

Cavity-type thermochemical receiver for SO_3 dissociation. An SO_3 rich chemical feedstock enters passages in a spirally configured ceramic extrusion. Inflowing gas is heated to near cavity temperature by exiting hot gas in a counter current heat exchanger. In the gas layer adjacent to the hot cavity, heat flowing through the extrusion wall heats a catalytic surface on which SO_3 is dissociated into SO_2 $+O_2$ with conversion of heat into chemical energy. Most of the extrusion serves as heat exchanger, permitting outflowing gas to exit at a sufficiently low temperature that gasketing can be used to provide connection to an external, medium-temperature pipeline network.

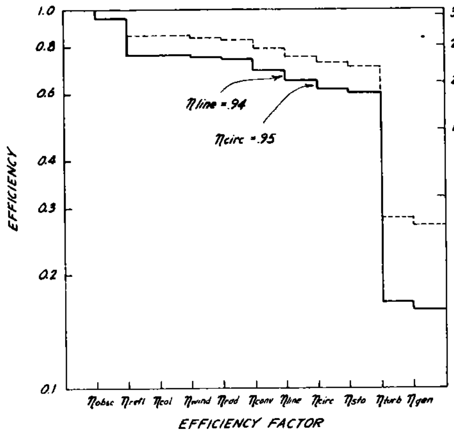

FIGURE 5

Losses calculated for a Solchem power plant. Sequential losses are due to: (1) mirror obscuration and gaps between mirror gores, (2) mirror reflectivity, (3) solar image spillover relative to receiver aperture, (4) reflection loss from Francia window, (5) radiation loss from hot cavity, attenuated by Francia window, (6) conduction loss through receiver walls, (7) heat loss through insulation covering chemical circulation lines, (8) pumping power required for chemical circulation ÷ efficiency of pumps and efficiency of heat-to-electricity conversion, (9) conduction loss through insulation surrounding the energy storage tanks, (10) Rankine cycle turbine efficiency, and (11) generator efficiency. Solid line is for 1 MW(e) power plant with toluene Rankine cycle operating from 385°C storage; dotted line is for 100 MW(e) power plant using both 385°C and 638°C storage tanks feeding high pressure steam re-heat turbines, and using low iron, dust controlled mirrors.

heat loss from the insulated circulation lines. The pumping losses assumed a 70% pump efficiency and a 26% conversion efficiency for converting heat into electricity. These losses are quite tolerable for a Solchem-type system.

INTERMEDIATE DISTANCE ENERGY TRANSPORT USING THE $SO_3(\ell)/SO_2(\ell)$-$O_2(g)$ THERMOCHEMICAL CYCLE

Let us now consider the problem of intermediate distance energy transport. For distances exceeding a few miles, the gas phase SO_3/SO_2-O_2 thermochemical cycle requires excessive pumping power. The question arises: can one transport energy over significant distances using the SO_3/SO_2, O_2 system, if one transports the sulphur chemicals as liquids and the O_2 as a compressed gas? The picture we wish to examine is the following: Consider two sites--Site A and Site B. Site A contains a solar collection field fitted with thermochemical receivers, gas compressors, liquifiers, separators, and storage tanks; Site B contains an industrial park, SO_3 heat generating synthesizers for production of process heat, and SO_2 vaporizers for extraction of air-conditioning cooling values or other low temperature cooling values as needed for the support of industrial processes. We assume that Sites A and B are separated by 100 miles and that the sites are connected by 3 pipelines: a 1200 psi pipeline for carrying O_2 from Site A to Site B; a medium pressure liquid pipeline for carrying liquid SO_2 from Site A to Site B; and a medium pressure liquid pipeline for carrying liquid SO_3 from Site B to Site A. We assume that the heat process needs of the industrial park are 100 MW(th). We also assume that no elevation difference exists between A and B. The arrangement is shown in Figure 7.

Our analysis shows that the fluid transport can be carried out using three 8" ID pipelines. The results of our analysis are given in Table 1. The pressure drops for the three lines are: O_2, 11.7 psi mi^{-1}; SO_2, 19 psi mi^{-1}; and SO_3, 28 psi mi^{-1}. Pumping powers are: O_2, 1.2 MW; SO_2, 0.6 MW; SO_3, 0.8 MW. The total pumping work required is 2.6 MW. Assuming that the pumps operate at 50% efficiency and that pumping power is worth 3X thermal power, the thermal energy cost of fluid transport is 16 MW. The required flow rates are: O_2, 1550 tons/D^{-1} (1.53 million std cu.ft. per hr); SO_2, 6200 tons/D^{-1}; SO_3, 7750 tons/D^{-1}. Mass inventories in the lines are: O_2, 625 tons; SO_2, 8250 tons; SO_3, 10,530 tons. The SO_3 and SO_2 inventories represent 83 and 105 R.R. tank cars of chemicals. Energy storage time represented by these inventories are: O_2, 0.4 D; SO_2, 1.3 D; and SO_3, 1.4 D. The energy transport system looks acceptable, although a larger O_2 line should be used to reduce pumping power demands.

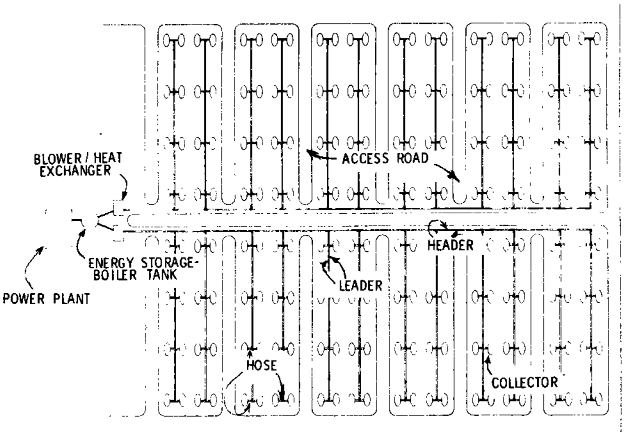

FIGURE 6

Collector layout for 1 MW(e) power plant. Collectors are arranged in 96-collector subfields, serviced by 12" headers, 3" leaders, and 1" hoses. Heat loss calculations are based on 4" of urethane foam insulation on the headers, 3" of foam on the leaders, and 2" of foam on the hoses.

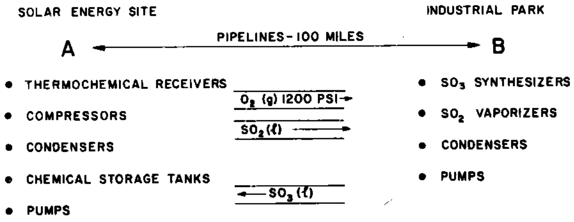

FIGURE 7

Configuration for intermediate distance energy transport.

TABLE 1

100 MW(th), 100-Mile Energy Transport System Using 8" Lines

Items	O_2	SO_2	SO_3
Direction	A B	A B	B A
Phase/Pressure	1200 psi gas	Liquid	Liquid
Line Temperature	20^oC	20^oC	40^oC
Pressure Gradient	11.7 psi mi^{-1}	19 psi mi^{-1}	28 psi mi^{-1}
Pumping Power	1.2 MW	0.6 MW	0.8 MW
Air-Conditioning Provided	------	6450 tons	------
Flow Rates	1550 Ton/ D^{-1}	6200 Ton/ D^{-1}	7750 Ton/D^{-1}
Inventory	625 Tons	8250 Tons	10530 Tons
Line Energy Storage	0.4 Day	1.3 Day	1.4 Day

A most interesting aspect of the $SO_3(\ell)/SO_2(\ell)-O_2(g)$ energy delivery system is the cooling power delivered to Site B in the form of liquid SO_2. This cooling power is delivered as heat of vaporization. The heat of vaporization of liquid SO_2 at 0°C, minus the cooling needed to lower the temperature of liquid SO_2 from a 20°C line temperature to a 0°C pressurized boiling point is 5.31 kcal mol^{-1}. This compares with 23.5 kcal mol^{-1} SO_3 synthesis heat delivered by the fluid stream. For 100 MW of SO_3 synthesis heat delivered, a cooling capacity corresponding to 6450 tons of air-conditioning is automatically provided.

There are problems that must be considered with regard to transport and storage of liquid SO_3. These problems are illustrated in Figure 8, which shows a vapor pressure diagram for liquid and solid SO_3. The Figure shows that SO_3 exists in three solid phases, which must be avoided in a liquid transport system. On the Figure, the heavy line shows the vapor pressure of the liquid. The liquid boils at 44.6°C. The liquid can be cooled to 16.8°C before freezing, if thoroughly dry and properly stabilized. At this point it has a vapor pressure of 160 Tor. However, if not stabilized, or if kept for a very long time, the liquid will solidify to a fibrous mass below 32.2°C. For long-term storage, tanks should be kept between 35°C and 41°C to avoid fibre build-up and to keep the liquid subatmospheric. Formation of solids should be avoided not only because of line plugging, but also because the SO_3 solids, once formed, convert into an asbestos-like αSO_3 polymer which can be melted at 62.2°C, but only if sufficient time for heat transfer and internal equilibration is provided. On heating, αSO_3 easily fractionates, creating metastable higher melting fractions. These metastable higher melting fractions when heated to their melting points can convert to normal liquid and gas with an almost explosive rate of pressure increase. The dotted line on Figure 8 is the locus of melting points of these metastable higher cross-linked polymers.

It is important to contain any liquid SO_3 leaks which occur. SO_3 leaks produce a dense acid mist which is quite persistent and readily apparent. Wherever line rupture could occur, it is essential to provide fluid drain-down reservoir volume for collection of outpouring SO_3. Dry diatomaceous earth should be available for soaking up any surface spills and water spray trucks should be available for treating fuming surfaces.

PF_3H_2 AS A POTENTIAL THERMOCHEMICAL ENERGY TRANSPORT FLUID

Let us now consider our third topic, PF_3H_2. PF_3H_2 is a stable inorganic vapor with a liquid boiling point of about 3.8°C. PF_3H_2 is believed to dissociate mainly into

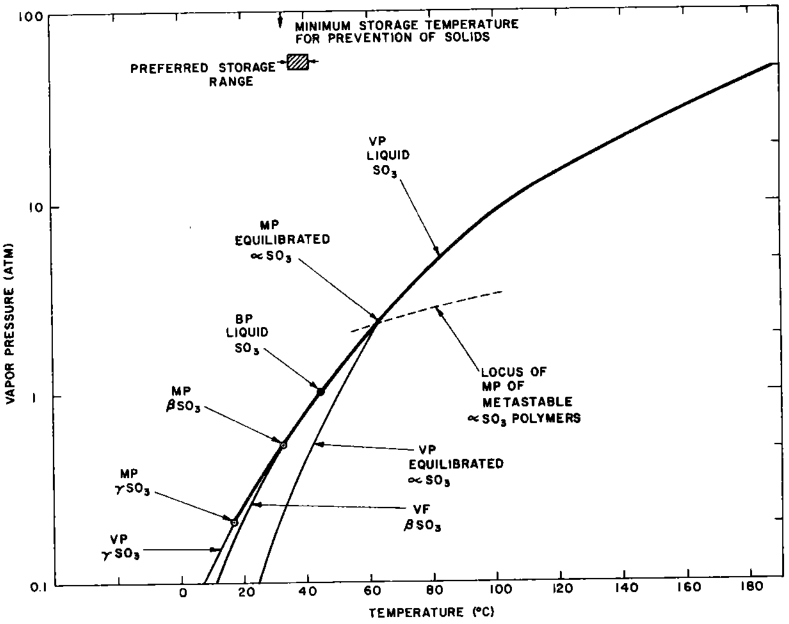

FIGURE 8

Vapor pressure curves for liquid and solid SO_3. Heavy line marks vapor pressure of liquid SO_3. Unstabilized SO_3 freezes after a time at a temperature of 32.6°C, forming βSO_3. Stabilized SO_3 remains liquid down to 16.8°C, freezing at 16.8°C into γSO_3, an ice-like solid. Both solid forms convert slowly to high melting asbestos-like αSO_3. Under equilibrium conditions, αSO_3 melts at 62.2°C. However, if αSO_3 is heated under conditions such that high vapor pressure fractions are withdrawn, fractionation occurs producing metastable, low vapor pressure solids that melt above 62.2°C. The dotted line shows the locus of melting points that can occur. When the higher melting point metastable solids melt, they can almost explosively convert to normal liquid/gaseous SO_3, as represented by the heavy solid line.

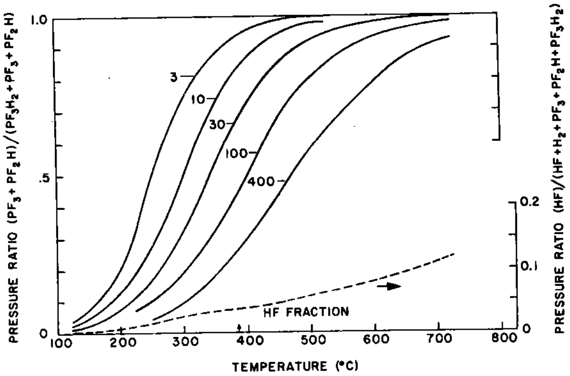

FIGURE 9

Equilibrium fraction of phosphorus containing molecules in the form of PF_3 or PF_2H as a function of temperature, for pressures of 3, 10, 30, 100, 400 atm. The dotted curve shows the 10 atm HF molar fraction. These curves are calculated from unpublished thermodynamic data calculated by Wagman. Since no experimental heat of formation or dissociation data is available on which to anchor Wagman's calculations, the positions of the curves could be in substantial error. The calculations indicate that PF_3H_2 could be a useful low-temperature Solchem gas.

PF_3 and H_2 at elevated temperature. To a lesser degree dissociation into PF_2H and HF will occur. PF_3H_2 is basically a reducing agent, and has been used as a source of hydrogen for an HCl chemical laser. Its structure is known. It is a bipyramid with two hydrogens on the equatorial plane.

What is not known about PF_3H_2 is almost everything else, including heats of formation and Gibbs free energies. Similarly, little is known about PF_2H, whose properties determine the partition between PF_3H_2 dissociation routes. However, based on PH and PF bond strengths, D.D. Wagman, of the Bureau of Standards, has estimated heats of formation and free energies. Using his values, I have calculated dissociation equilibrium values and HF content vs. temperature for various pressures. These results are shown in Figure 9. They indicate that dissociation will likely occur over an interesting temperature range. The dissociation temperatures are much lower than those for SO_3, but nonetheless are high enough for operation of an efficient Rankine cycle power plant. HF concentrations are below 10% for practical cycles; hence, HF condensation is not likely to be a problem. The PF_3H_2 condensation temperature at 10 atm is estimated to be $68^{\circ}C$. Hence, a PF_3H_2 system would likely operate with relatively low temperature lines.

Two big unknowns regarding PF_3H_2 are a complete lack of knowledge on direct synthesis catalysis possibilities and a similar lack of knowledge on toxicity. My purpose in presenting this material is to stimulate further work on this interesting chemical system.

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CONVERSION OF SOLAR ENERGY TO CHEMICAL ENERGY THROUGH AMMONIA DISSOCIATION

Dr. Terry G. Lenz
Colorado State University

PROPOSAL FOR ENGINEERING DESIGN STUDY OF CONVERSION OF SOLAR ENERGY TO CHEMICAL ENERGY THROUGH AMMONIA DISSOCIATION

Abstract

It is proposed that an experiment be designed to investigate key components of a system for collection of solar energy utilizing reversible chemical reactions in a closed cycle gaseous working fluid. Concentrated solar energy would thermally dissociate ammonia in the presence of a catalyst into nitrogen and hydrogen. The gases are recombined at a central plant to yield ammonia plus high quality heat. Countercurrent heat exchangers at each chemical reactor allow the collection lines to operate at near ambient temperature to minimize transport losses. The key component to be investigated is the solar absorber-chemical reactor-heat exchanger. The project has broad applicability to general energy transport and energy storage solutions as well as solar applications.

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INTRODUCTION

Solar power plant concepts which have received considerable attention include flat plate absorbers and concentrating collectors utilizing thermal transport of the collected energy by means of a hot circulating fluid to a central station. Energy losses resulting from the collection and transport of the high temperature heat for such systems have limited their consideration to fairly small plants (<150MW) and/or low temperature operations (<200° to 300°C).(1,2) Higher temperature operation at a larger scale is offered by a tower heliostat system in which the energy corradiation is performed optically between the collectors (heliostats) and a central absorber.

Recently, an alternate scheme for collection of solar energy using a distributed collector system has been proposed.(3,4) The energy transport system between the individual collectors and the central power plant utilizes reversible chemical reactions in a closed-cycle gaseous working fluid. The studies have indicated that by transporting the chemical energy in low temperature lines, the production of electrical energy at efficiencies of 25-30% (electrical output ÷ solar input) are achievable. Too, the system may lend itself to desirable energy storage techniques, either as chemical storage or intermediate temperature thermal storage.

The specific system which we propose to experimentally investigate utilizes ammonia as the working fluid. Carden(4) describes such a system which is shown schematically in Figure 1. Solar energy is

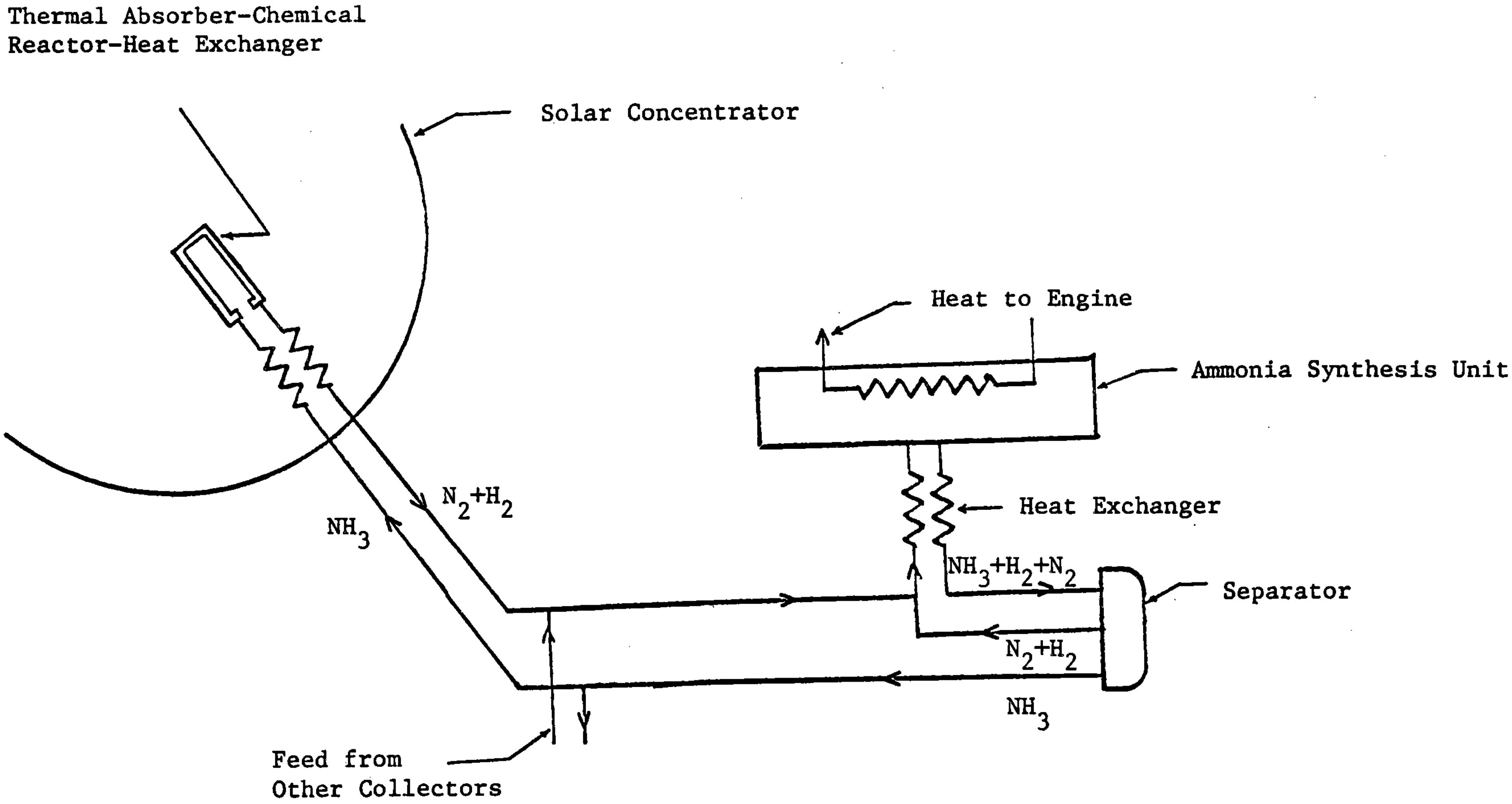


Figure 1. Schematic Diagram of Chemical Solar Power Plant

collected at the focus of a paraboloidal mirror in a thermal absorber-chemical reactor. The thermal energy is used to dissociate ammonia at high temperatures in the presence of a catalyst. The hot dissociated gas mixture is cooled by the incoming ammonia in a counter-current heat exchanger. The mixture is then piped to a common generating plant which accepts the feed of many identical solar collector units. The gas is reheated in another heat exchanger utilizing heat from the outflowing gases. In the power plant the nitrogen and hydrogen is recombined in a synthesis unit to yield ammonia plus heat. The heat is extracted to produce power, and the ammonia (and unreacted nitrogen and hydrogen) is cooled in the heat exchanger mentioned above, and returned to the solar collector units for another cycle through the system. Carden also includes a separator as shown in the figure, to recycle the unreacted H_2 and N_2 back to the synthesis reactor and feed pure NH_3 back to the collectors.

CHARACTERISTICS OF THE AMMONIA CYCLE

The reversible chemical reaction to be investigated is:

$$2NH_3 + \Delta H \rightleftharpoons N_2 + 3H_2$$

where ΔH is the enthalpy of ammonia gas formation. Figure 2 shows some values for the ΔH of the synthesis reaction. The values are for 100% conversion into NH_3, whereas in industrial practice conversion is rarely greater than 20%. The corrected values, obtained by taking into account the heat of mixing of $NH_3(g)$ with $N_2 + H_2$ are appreciably different only for pressures above 300 atm.(6)

The total heat absorbed by 2 mol of dissociating ammonia is given as 31.5 kcal. This value is independent of the temperature at which the actual dissociation reaction occurs.(4)

The reversible ammonia reaction always tends toward an equilibrium condition, characterized by the percentage of ammonia in the mixture, which is a function of temperature and pressure. As can be seen from the data in Table 1,(7) high pressures and low temperatures favor large ammonia yields (high equilibrium yields of ammonia are desirable in the synthesis reactor) whereas low pressures and high temperatures favor large percentage yields of N_2 and H_2 (desirable in the dissociation reactor). However, before choosing a temperature and pressure at which to operate the system, the reaction rate must also be examined.

Reaction rate of a chemical system is dependent upon three factors: how close the mixture is to equilibrium for the mixture's temperature and pressure, the temperature, and the presence of a catalyst. Large departures from equilibrium, high temperatures, and the presence of a catalyst tend to favor high reaction rates.

TABLE 1. Equilibrium yields (in %) of NH_3 at different pressures and temperatures (as determined after expansion up to ambient pressure)

Temperature (°C)	Pressures (atm)				
	10	100	300	600	1000
200	50.66	81.54	89.94	95.37	98.29
300	14.73	52.04	70.96	84.21	92.55
400	3.85	25.37	48.18	66.17	79.82
450	2.11	16.40	35.87	54.00	69.69
500	1.21	10.51	25.80	42.32	57.47
550	0.76	6.82	18.23	32.18	41.16
600	0.49	4.53	12.84	24.04	31.43
700	0.23	2.18	7.28	12.60	12.87

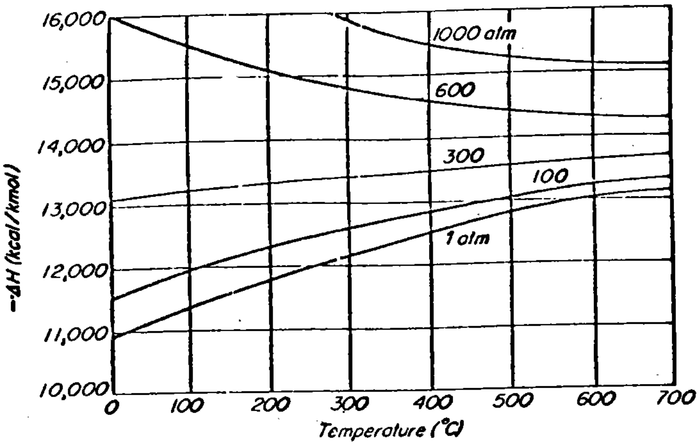


Figure 2. Enthalpy of ammonia gas formation at various pressures and temperatures (not taking into account the mixing heat of NH_3 and $N_2 + 3H_2$).(4)

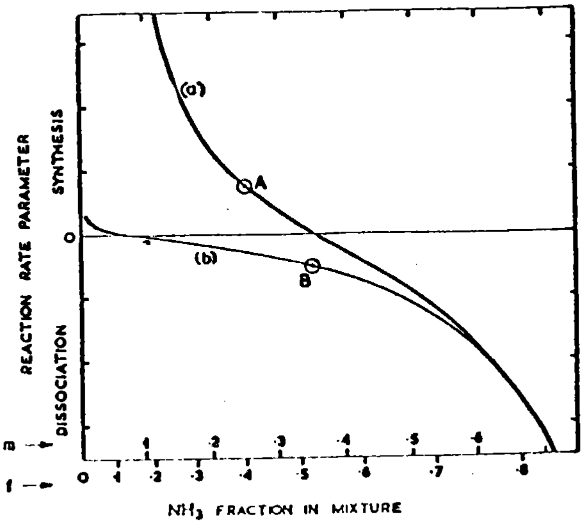


Figure 3. Reaction rate parameter vs. ammonia fraction. The parameter excludes temperature effects. The ammonia fraction scale is given both as mole fraction m and fraction by weight f. (a) Curve based on equilibrium point appropriate for 450°C and 300 atm. (b) Curve based on equilibrium point appropriate for 700°C and 300 atm. A, End point for typical synthesis process. B, End point for a typical dissociation process.(4)

Carden$^{(4)}$ has summarized the reaction kinetics considerations as follows. The Temkin-Pyzhev reaction rate equation$^{(8)}$

$$W = K_2\left[K_P P_{N_2}\left(\frac{P^3_{H_2}}{P^2_{NH_3}}\right)^{\alpha} - \left(\frac{P^2_{NH_3}}{P^3_{H_2}}\right)^{1-\alpha}\right] ,$$

where K_P is the equilibrium constant, yields the synthesis reaction rate based on the generally accepted assumption that nitrogen chemisorption is the rate limiting step of the reaction. Vancini$^{(8)}$ gives evidence that this equation is also applicable to the decomposition of ammonia (more precisely fugacities should replace the partial pressures employed above). Taking $\alpha = 0.5$ and known values of K_P , Carden has evaluated the expression in square brackets in the equation. His results are plotted in Figure 3 vs m, the ammonia mole fraction. The two curves shown are for 700° and 450°C, and in each case the total pressure is 300 atm.

The parameter K_2 varies with temperature T (Bridger and Snowdon)$^{(9)}$ according to

$$K_2 = K_{2(0)} \exp\{-\left[\frac{\Delta E}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)\right]\}$$

and ΔE , the activation energy is 38 kcal/mole.

K_2 at 700°C is thus 854 times $K_{2(0)}$ at 450°C.

Point A on curve (a), Figure 3, corresponds to common commercial synthesis practice whereas point B represents the dissociation of ammonia to approximately 50% by mass. The ratio of the two reaction rates when the effect of temperature is included is Rate B/Rate A = 569.

It follows that approximately 569 times less catalyst should be required for conditions of point B compared to those of point A. Carden points out that since commercial synthesis plants employ about 4 tonnes/MW$_{\text{thermal}}$ we might therefore expect approximately 7g/KW of similar catalyst to be required in the dissociation chamber.$^{(4)}$

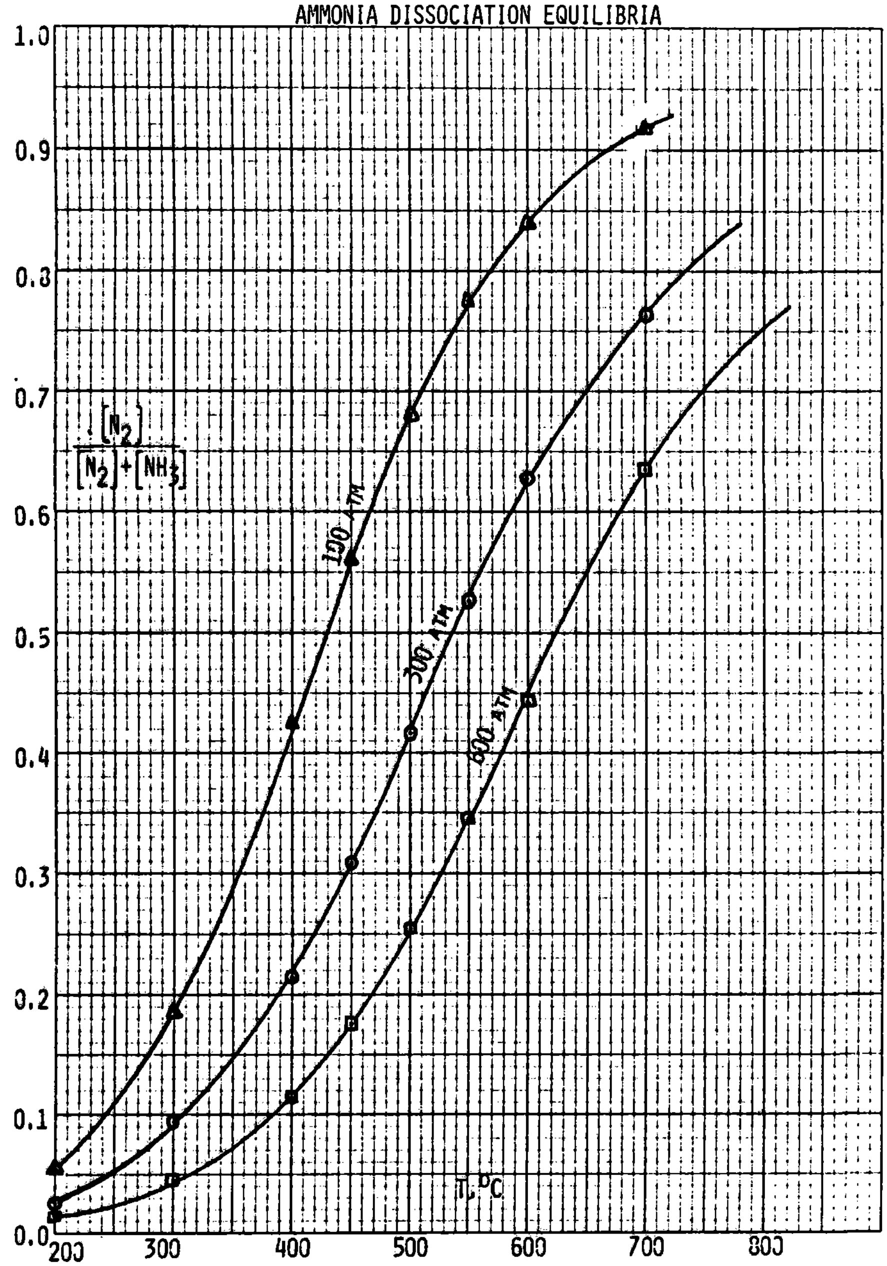
TABLE 1

REACTION	ΔH KCAL/MOLE	KCAL/G
$SO_3 \rightleftharpoons SO_2 + \frac{1}{2}O_2$	+24*	0.29
$\frac{1}{2}H_2O + \frac{1}{2}CH_4 \rightleftharpoons \frac{1}{2}CO + 3/2H_2$	+24.5**	1.44
$COCl_2 \rightleftharpoons CO + Cl_2$	+26	0.26
$2NF_3 \rightleftharpoons N_2 + 3F_2$	+31	0.43
$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2$	+59	0.98
$CH_3OH \rightleftharpoons 2H_2 + CO$	+25	0.78
$2NH_3 \rightleftharpoons N_2 + 3H_2$	+25	0.79

* FROM CHUBB

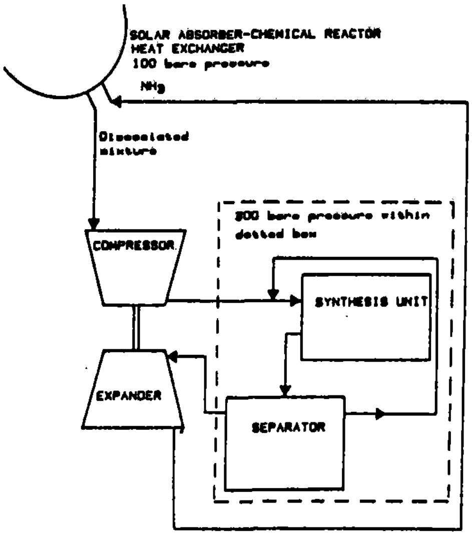
** FROM HILDEBRANDT

AMMONIA DISSOCIATION EQUILIBRIA



AMMONIA SYSTEM CHARACTERISTICS

ADVANTAGEOUS POINTS	:	A. WELL-KNOWN LARGE SCALE TECHNOLOGY B. NON-CORROSIVE & LESS TOXIC THAN MANY SYSTEMS C. GOOD HEAT TRANSFER D. COMPACT CONSTRUCTION POSSIBLE BECAUSE OF HIGHER FLUID ENERGY/UNIT VOL., AND EFFECTIVE HEAT TRANSFER E. REASONABLE CATALYST COST LIKELY
TEMP'S.	:	700°C ⟶ 450°C
PRESS.	:	100 ⟶ 600 ATM (300 ATM DESIGN POINT)
EFFICIENCY	:	20-25% SOLAR ⟶ POWER
NH_3 CIRC. RATE	:	4 TONS/H - MW_E
ENERGY DENSITY	:	5600 BTU/FT^3



SCHEMATIC OF ENERGY COLLECTION LOOP OPERATED AT TWO PRESSURES

DESIGN OF AN EXPERIMENTAL
NH_3 DISSOCIATION REACTOR

FUNDAMENTAL MECHANISMS OPERATIVE

- HEAT TRANSFER
  - radiative (cavity and reaction zone)
  - conductive (through reactor and heat exchanger tube walls)
  - convective (within cavity and tubes)
- MASS TRANSFER
  - NH_3, N_2, H_2 to and from catalyst
- CHEMICAL REACTION

$$\text{Heat} + 2NH_3 \rightleftharpoons N_2 + 3H_2$$

  - kinetics
  - thermodynamics
  - catalysis

The above occurring simultaneously

PRACTICAL ASPECTS OF THE DESIGN

- MATERIALS OF CONSTRUCTION
  - strength
  - corrosion (nitride formation and hydrogen embrittlement)
  - ease of fabrication
  - allowance for thermal expansion
- CATALYST
  - composition (Ni, Ru, Fe-Ru alloys)
  - form (metal on Al_2O_3 spheres)
  - reverse reaction possible in heat exchanger
- PRESSURE DROP
  - reactor Δp controlling (manifold flow)
  - phase behavior in heat exchanger
- RELATED AUXILIARIES
  - optical design considerations
  - sampling
  - control and instrumentation

Table 6.4

COMPOSITIONS OF NICKEL-BASE SUPERALLOYS

Alloy	Percent by weight*															
	C	Mn	Si	Cr	Fe	Co	Ni	Mo	W	Cb	V	Ti	Al	Zr	B	Cu
Group 1: high-molybdenum grades																
Hastelloy B	0.05 max	1.00 max	1.00 max	1.00 max	4.00/7.00	2.50 max	bal.	26.0/30.0	—	—	0.20/0.60	—	—	—	—	—
Hastelloy C (Wrought)	0.08 max	1.00 max	1.00 max	14.5/16.5	4.00/7.00	2.50 max	bal.	15.0/17.0	3.00/4.50	—	0.35 max	—	—	—	—	—
Hastelloy C (Cast)	0.12 max	1.00 max	1.00 max	15.5/17.5	4.50/7.00	2.50 max	bal.	16.0/18.0	3.75/5.25	—	0.20/0.40	—	—	—	—	—
Group 2: 75 nickel - 15 chromium grades																
Inconel 600 (formerly Inconel)	0.15 max	1.00 max	0.50 max	14.0/17.0	6.00/10.0	—	72.0 min	—	—	—	—	—	—	—	—	0.50 max
Inconel 702	0.10 max	1.00 max	0.70 max	14.0/17.0	2.00 max	—	oal.	—	—	—	—	0.25/1.00	2.75/3.75	—	—	0.50 max
Inconel 721	0.07 max	2.00/2.50	0.15 max	15.0/17.0	8.00 max	—	bal.	—	—	—	—	2.75/3.35	0.10 max	—	—	0.20 max
Inconel 722 (formerly Inconel W)	0.08 max	1.00 max	0.70 max	14.0/17.0	5.00/9.00	—	70.0 min.	—	—	—	—	2.00/2.75	0.40/1.00	—	—	0.50 max
Inconel X-750 (formerly X)	0.08 max	1.00 max	0.50 max	14.0/17.0	5.00/9.00	—	70.0 min.	—	—	0.70/1.20	—	2.25/2.75	0.40/1.00	—	—	0.50 max
Inconel 751 (formerly X, Type 550)	0.10 max	1.00 max	0.50 max	14.0/17.0	5.00/9.00	—	70.0 min.	—	—	0.70/1.20	—	2.00/2.60	0.90/1.50	—	—	0.50 max

COBALT- AND NICKEL-BASE SUPERALLOYS

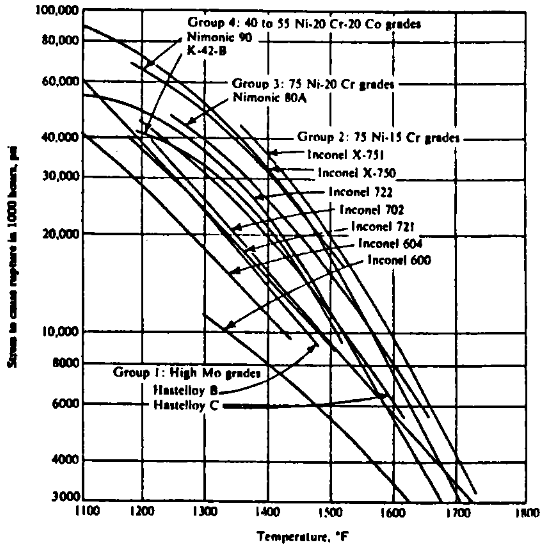
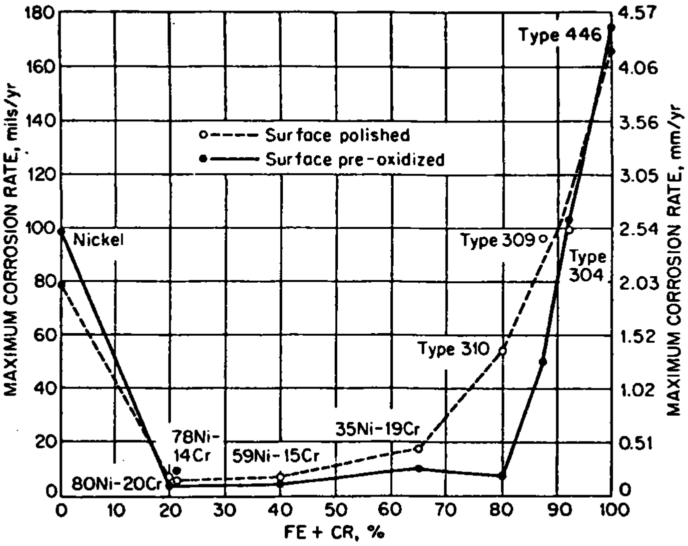


Figure 6.3. 1000-hr rupture strengths of typical nickel-base superalloys in Groups 1, 2, 3, and 4.



Corrosion of Fe-Cr-Ni alloys by anhydrous ammonia at 932°F (500°C). (Based on 1540-h exposure.) *(Adapted from Krebs.[28])*

AMMONIA REACTION KINETICS

$$2(-r_N) = r_A = 2k\eta\left[K^2\left(\frac{a_N a_H^{\frac{3}{2}}}{a_A}\right) - \left(\frac{a_A}{a_H^{\frac{3}{2}}}\right)\right], \quad \frac{\text{kg moles NH}_3}{(\text{m}^3\text{cat.})(\text{hr})}$$

$$2k = 1.7698 \times 10^{15} \exp\ (-40{,}765/R'T)$$

$$\log_{10} K = -2.691122 \log_{10} T - 5.519265 \times 10^{-5}\ T$$

$$+ 1.848863 \times 10^{-7}\ T^2 + \frac{2001.6}{T} + 2.6899$$

$$\eta = b_0 + b_1T + b_2X + b_3T^2 + b_4X^2 + b_5T^3 + b_6X^3$$

$$\nu_H = \exp\ \{e^{(-3.840T^{0.125} + 0.541)}P - e^{(-0.1263T^{0.5} - 15.980)}P^2$$
$$+ 300\left[e^{(-0.011901T - 5.941)}\right](e^{-P/300} - 1)\}$$

$$\nu_N = 0.93431737 + 0.3101804 \times 10^{-3}T + 0.295896 \times 10^{-3}P$$
$$-0.2707279 \times 10^{-6}T^2 + 0.4775207 \times 10^{-6}P^2$$

$$\nu_A = 0.1438996 + 0.2028538 \times 10^{-2}T - 0.4487672 \times 10^{-3}P$$
$$-0.1142945 \times 10^{-5}T^2 + 0.2761216 \times 10^{-6}P^2$$

$$r_A = \eta 1.7698 \times 10^{15} \exp\left(-\frac{40{,}765}{R'T}\right)\left[K^2P^{\frac{1}{2}}\left(\frac{\nu_N y_N \nu_H^{\frac{3}{2}} y_H^{\frac{3}{2}}}{\nu_A y_A}\right) - \frac{1}{P^{\frac{1}{2}}}\left(\frac{\nu_A y_A}{\nu_H^{\frac{3}{2}} y_H^{\frac{3}{2}}}\right)\right]$$

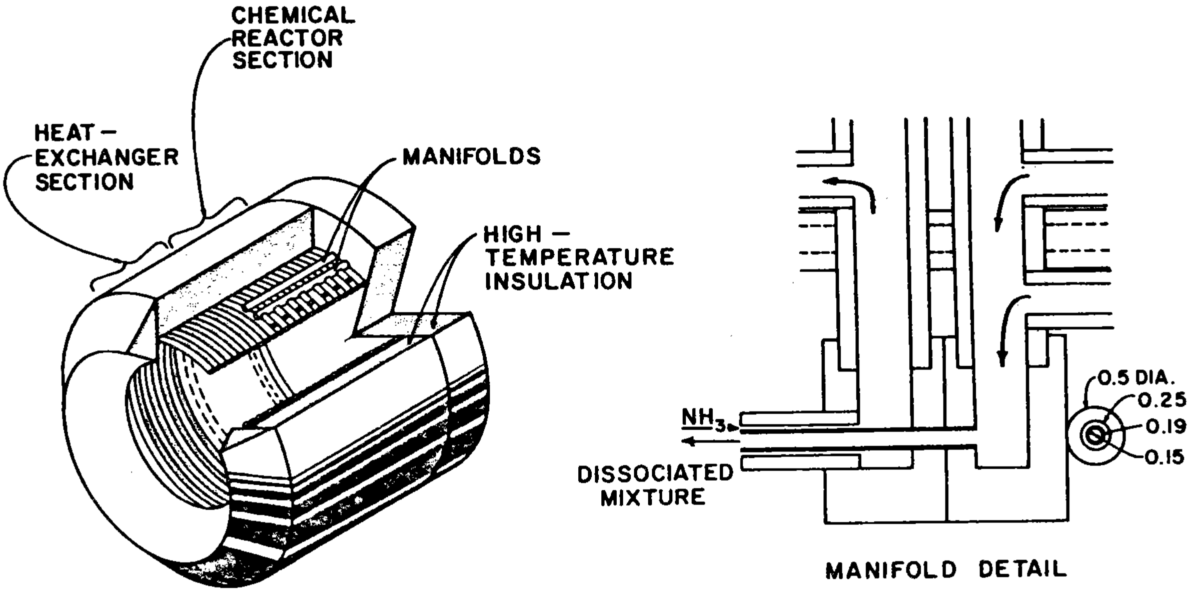
FIRST ESTIMATES FOR NH_3 DISSOCIATION REACTOR DESIGN PARAMETERS

REACTOR SIZE	6.25 KW	10 KW	25 KW
MIRROR SIZE (100% η)	2.8 M DIA	3.5 M DIA	5.64 M DIA
APERTURE SIZE	10 CM DIA	12.5 CM DIA	20 CM DIA
MASS FLOW (90% CONV.)	106 G/MIN	170 G/MIN	425 G/MIN
MEAN VOLUME FLOW (@ 700°C AND 300ATM)	2500 CM³/MIN	4000 CM³/MIN	10000 CM³/MIN
CATALYST VOLUME (BASED ON SPACE VELOCITY = 1000/HR)	150 CM³	240 CM³	600 CM³

REACTOR-HEAT EXCHANGER
CONCEPTUAL DESIGN CHARACTERISTICS

RATING	:	10 KW
CAVITY DIMENSIONS	:	12" DIA X 13" LENGTH
NH_3 FLOW RATE	:	$0.356 \frac{LB}{MIN}$ (171 GR/MIN)

REACTOR FLOW ARRANGEMENT	:	8 PARALLEL FLOW TUBES FILLED WITH CATALYST, WITH EACH TUBE CIRCLING THE CAVITY TWICE.
HEAT EXCHANGER FLOW ARRANGEMENT	:	ANNULAR COUNTERFLOW HEAT EXCHANGER WITH FIVE SPRIALS INSIDE CAVITY.
REACTOR MATERIAL	:	TENTATIVELY INCONEL/600 OR 617
REACTOR TUBE SIZE	:	0.50 "O.D. X 0.25" I.D. X 50' LENGTH
CATALYST	:	NI ON Al_2O_3, 0.0625" DIA SPHERICAL



MANIFOLD DETAIL

SOLAR ABSORBER — REACTOR
HEAT EXCHANGER

Question - If you can only do, let's say, 20 percent efficiency to your end delivery, how can you compete with electricity, which is for many purposes a better energy source and has about the same efficiency?

Dr. Lenz - I mentioned there was the 20-25 percent solar-thermal electric power. There is literature out on that but it is difficult to come by. Dr. Chubb went through some of the more detailed reasoning. I view this as a powerful tool, more so than just generation of electricity. The ammonia is representative of a class of reversible chemical equilibria that can deliver energy at different temperature levels. I will not argue the point that we can and have mismatched, in many cases, the value of the energy. I can't try to fight that.

Comment - You are both talking about distributor systems. There is still this flex mismatch problem--the fact that if clouds come over and your reactor starts cooling down rather rapidly, there are severe problems. In addition, I think one important thing that you saw in my presentation was that for a 1000-MW reactor, the endothermic costs were almost completely dominant. I know from your experience at DuPont, that you know they build big ammonia reactors rather than small ones. The reason they build big ones is that they are most economical. It gives you a gut feeling that it will be very, very expensive to build these little reactors and have them sitting around even if you solve the other problems.

Dr. Lenz - To your first point, I address the fact that the small reactor, stress-wise, is superior to the larger one. I have been around ammonia reformers, I've emptied the tubes and have been around them when they've been emptied. There is a distinct advantage in the arrangement we showed here for the small particle size reactor. I should emphasize that not only do I keep my mind flexible to the temperature level at which these systems can deliver, but also that this concept can be amenable to different size reactors on each end. That is, I could do this eventually going to a central receiver, or that type reactor as well, and still be useful.

Comment - I would like to comment briefly on the statement that a large-size reactor is necessarily cheaper than a small one; and I am not sure that point has been cleared up yet. But if you will go back to the fuel cell technology and look at some of United Technology's cost estimates on the Marsh system, it is not at all clear that the small system is necessarily more expensive. In fact, they show it as less expensive.

Comment - On this scale, you've got 600 miles of piping, which is totally ridiculous. It won't work; it's too expensive. It will not be cost effective. By comparison to the central receiver, on a small scale, you may be right.

Dr. Lenz - The type reactor, whether it be distributor or central, may well be tied to the size of the end user. Again, I want to emphasize that this is a powerful concept in variation of size.

AMMONIUM HYDROGEN SULFATE STORAGE CYCLE

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The ammonium hydrogen sulfate (AHS) storage cycle is intended to store concentrated thermal solar energy, such as that received by the tower in a heliostat field. The stored energy should generate heat in the range 400-500°C for efficient electrical power generation. The solar thermal energy is stored through a two-step dissociation into the products NH_3, H_2O, and SO_3. The products can be conveniently stored as liquids at moderate pressures, thus reducing the required storage volume compared to the storage of gases. This fact, combined with the relatively large H of reaction (80 kcal/mole) leads to a high-energy density for the system in the range 740-980 kcal/ℓ, depending upon the use of ambient or waste heat for vaporization of the liquid products prior to the heat-regeneration reaction. Furthermore, AHS has a reasonably low melting point (147°C) and can be conveniently transferred in the liquid state.

Two chemical separation schemes are being investigated. In both schemes NH_3 and H_2O are first released in the temperature range 400-500°C and SO_3 (or $SO_2 + 1/2O_2$) in a second reaction at 850-1000°C. One reaction scheme involves the reaction of AHS with a metal sulfate to form an intermediate metal pyrosulfate as shown in Figure 1. In the other reaction scheme AHS is reacted with a metal oxide to form a metal sulfate or mixed metal oxide-metal sulfate intermediate, also shown in Figure 1. In order to screen different metal sulfates or metal oxides that may be used for these separations, we have obtained thermogravimetric and differntial thermal analysis of the reaction mixture. The thermogravimetric results for some of the more promising candidates are shown in Figures 2 and 3. In these experiments the samples were heated in a furnace at the specified temperature for one hour, cooled in a dessicator and weighed. This procedure was repeated for each increasing temperature. A loss in mass of $\approx 31\%$ would correspond to the loss of NH_3 and H_2O. A good separation would be indicated by a plateau region at $\approx 31\%$ weight loss where NH_3 and H_2O have evolved prior to the evolution of SO_3 or ($SO_2 + 1/2O_2$).

The reaction with the Group IA alkali metal sulfates is shown in Figure 2. Only K_2SO_4, Rb_2SO_4, and Cs_2SO_4 appear to give a separation. The reaction with some metal oxides is given in Figure 3. Of these metal oxides, ZnO, Cu_2O, and MnO appear to be the most promising and NiO is also a possibility. PbO apparently forms the sulfate which is too stable for this separation, requiring an exceedingly high temperature to release the sulfur oxide. On the other hand Al_2O_3 does not form a sufficiently stable sulfate to accomplish the separation.

In order to further investigate the more promising candidates for these separation schemes we have constructed a very simple reactor where the gaseous products are continuously swept away and collected in a test solution which is analyzed for NH_3 and SO_3 evolved from the reaction. The apparatus is shown in Figure 4. At the completion of the reaction, the reaction mixture is analyzed for residual NH_3 and SO_3. Likewise the reactor itself, primarily the transfer line, is washed and this solution is analyzed for NH_3 and SO_3. In these studies the effects of mole ratio M_2 SO_4:AHS or MO:AHS and temperature on the reaction yield were investigated. The results for the reaction with Rb_2SO_4 are shown in Figures 5 and 6. Note that a maximum yield is obtained at a mole ratio of ~1.1 Rb_2SO_4:AHS and a temperature of 415°C. Simultaneous variations in mole ratio and temperature are being carried out to obtain the optimum conditions based upon a Simplex Technique.(1) Similar studies are being carried out for the separations with K_2SO_4 and Cs_2SO_4. The effects of mole ratio and temperature on the yield in the reaction with ZnO are given in Figures 7 and 8. Note the maximum yield at a mole ratio of 1.5 ZnO:AHS and a temperature of 390°C. The effect of water vapor in the carrier gas (He) has also been investigated. The separation with K_2SO_4 was chosen since it gives a poorer separation and any effect of H_2O vapor may be more apparent. The results are given in Figure 9, where the He gas was saturated with H_2O vapor at room temperature (21 torr). The effect on the yield is quite apparent as well as the effect on the total recovery of NH_3 and SO_3. Apparently the H_2O vapor, even at 21 torr, reduces the decomposition of the AHS, giving essentially complete recovery. The effect of H_2O vapor as well as mole ratio and temperature will be included in subsequent optimization studies.

In order to study the kinetics and thermodynamics of the reaction, we have followed the progress of the reaction by the pressure of NH_3 produced. The reaction vessel was attached to an evacuated glass manifold as shown in Figure 10. The furnace was preheated to the desired temperature and the reaction vessel was inserted directly into the furnace. Warm-up of the reaction vessel was only a few minutes and the temperature was re-equilibrated in 8-10 min. The pressure of NH_3 as a function of reaction time is shown in Figure 11 for the reaction with Rb_2SO_4. Note that the rate of increase increases with temperature as well as the reaction yield. Analysis of the data is the range 25 t 5 minutes reveals that the reaction is first order with respect to NH_4HSO_4 and the reverse reaction appears to be second order with respect to product formation. The rate expression analyzed is

$$\frac{dx}{dt} = k_f(a_o - x) - k_r x^2$$

where x = moles of NH_3 produced, a_o = initial moles of NH_4HSO_4, k_f = forward rate constant, k_r = reverse rate constant. The integrated expression is

$$A(x) = \frac{x_e}{(2a_o - x_e)} \; n \; \frac{a_o x_e + x(a_o - x_e)}{a_o(x_e - x)} = k_f t$$

where x_e = moles of NH_3 at equilibrium. A graph of A(x) versus time is given in Figure 12 for the reaction with Rb_2SO_4. Reasonably straight lines result, as expected from the above equation. Similar data for the reaction with Cs_2SO_4 is shown in Figures 13 and 14. The half-life for the reaction with Rb_2SO_4 is 6.4 minutes at 431°C.

Some initial studies on the back reaction

$$NH_{3(g)} + H_2O_{(g)} + SO_{3(g)} \rightarrow NH_4HSO_{4(\ell)}$$

have been carried out. A reaction vessel was fabricated from glass and mixes the SO_3 with H_2O prior to the addition of NH_3, as shown to form a finely divided mist of H_2SO_4. This provides a large surface area for the reaction with NH_3 and NH_4HSO_4 appears to form immediately upon mixing with the $SO_3 + H_2O$ mixture. The temperature generated depends upon the stoichiometric ratio of NH_3 to the SO_3. With an excess of NHJ_3 forming a mole ratio of $NH_4HSO_4:(NH_4)_2SO_4$ of 2:1, a temperature of 355°C was attained. Decreasing the amount of NH_3 to give a mole ratio of 6:1 in the molten product gave a temperature in the range 394-405°C. These results are consistent with the thermodynamic data and the calculated equilibrium constant at a total pressure ~ 1 atmosphere. Subsequent studies will establish the reaction temperature and the pressure of the reactants.

In conclusion the results obtained thus far are encouraging for the use of the AHS cycle for energy storage. In the final stages of our investigation the separation reactions will be run at higher pressures to condense the products of the reaction directly. The energy regeneration reaction will also be studied at higher pressures.

Thank you.

Question - Have you reflected on the energy cost of separations in this scheme?

Dr. Wentworth - Once we had decided on the scheme itself, preliminary estimates there were arrived at, assuming the sulfates would work, indicated it did not seem to be costly in terms of energy but in terms of efficiency. I think probably the biggest disadvantage in the separations scheme that we have is the temperatures requiring 900 to 1000°C. This is the second loss of efficiency. This concerns me more than anything else. This is the reason we are interested in looking at physical methods where we hope to keep that temperature down, maybe down to 500 or 600°C.

Comment - The thing about SO_3 is that you only have to quench; you don't have to do any separation.

Dr. Wentworth - Are you talking about SO_3 or SO_2?

Answer - I mean as a heat pipe technique. If you have these separations, it seems to me you take a big penalty.

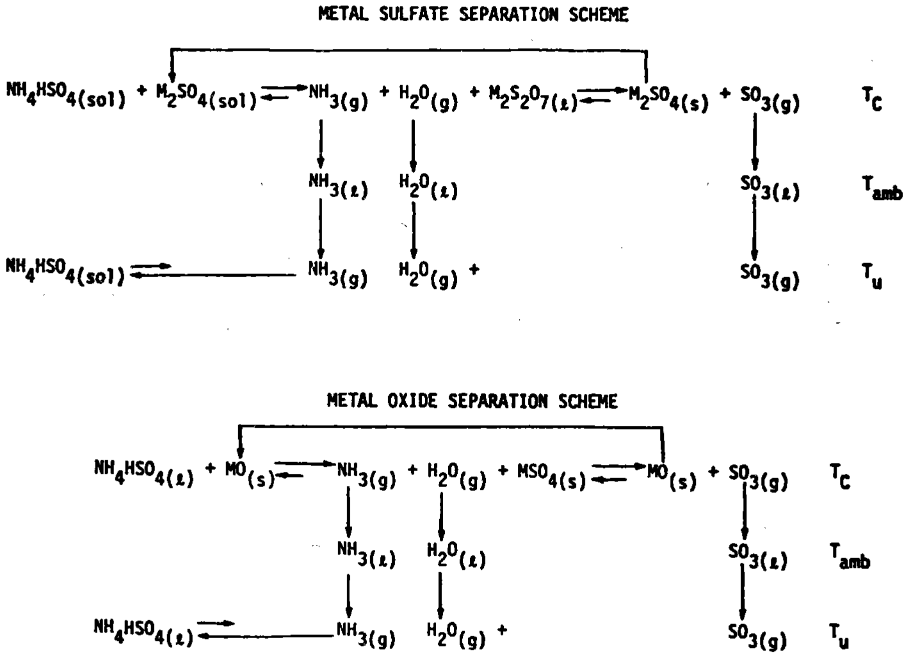
Dr. Wentworth - You could; that's possible. Of course, you must take a big penalty. Professor Gibbs has worked that out for us.

Reference

1. S. N. Deming and S. L. Morgan, Anal. Chem., 45, 278A (1973).

FIGURE 1

THE AHS REACTION


METAL SULFATE SEPARATION SCHEME

METAL OXIDE SEPARATION SCHEME

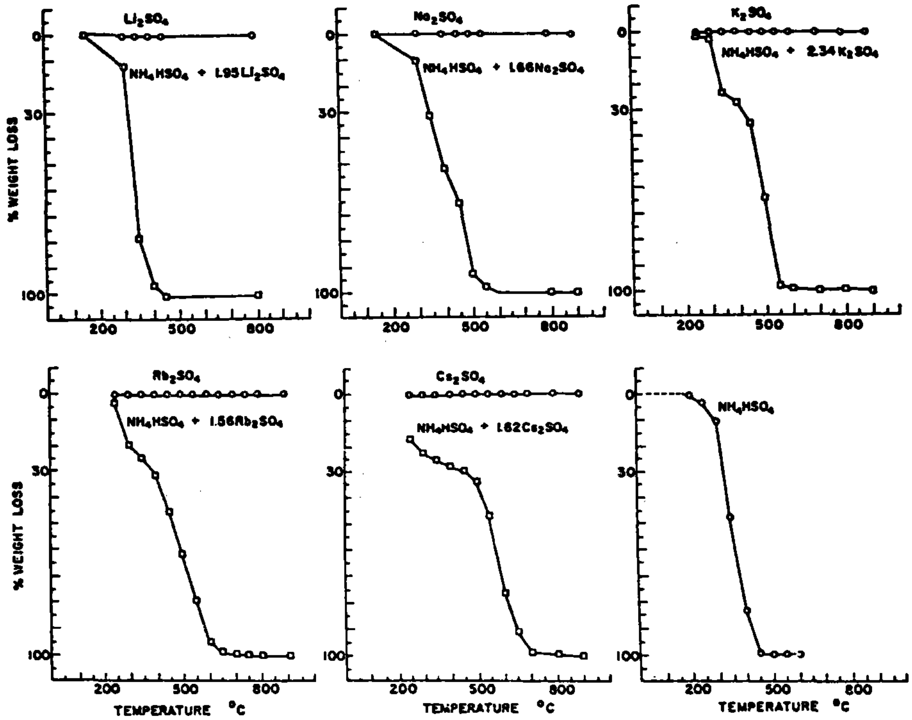


FIGURE 2

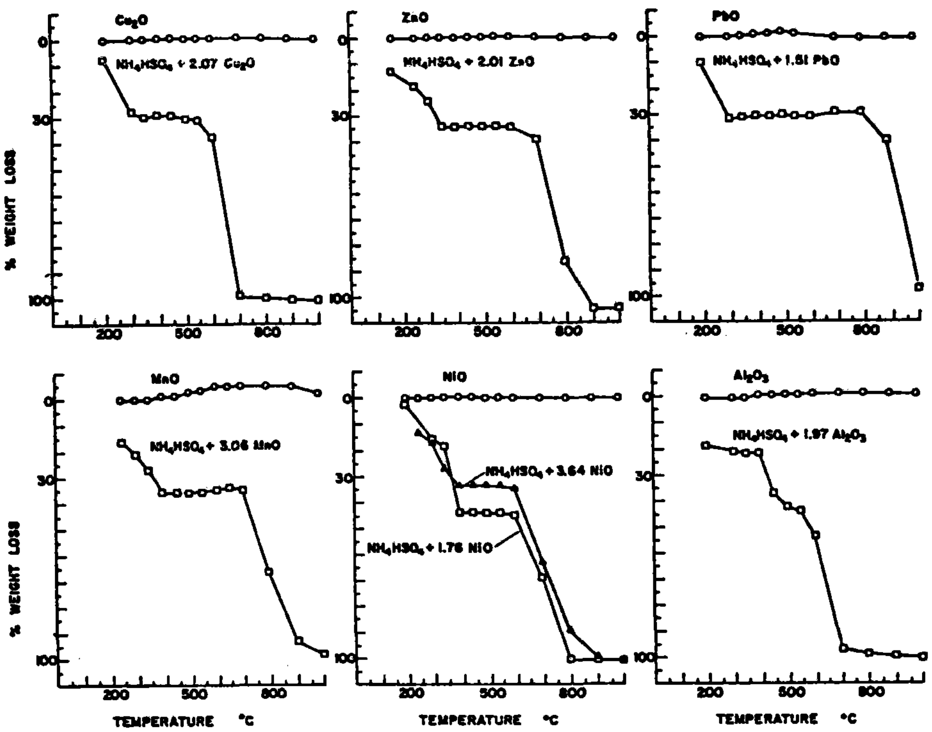


FIGURE 3

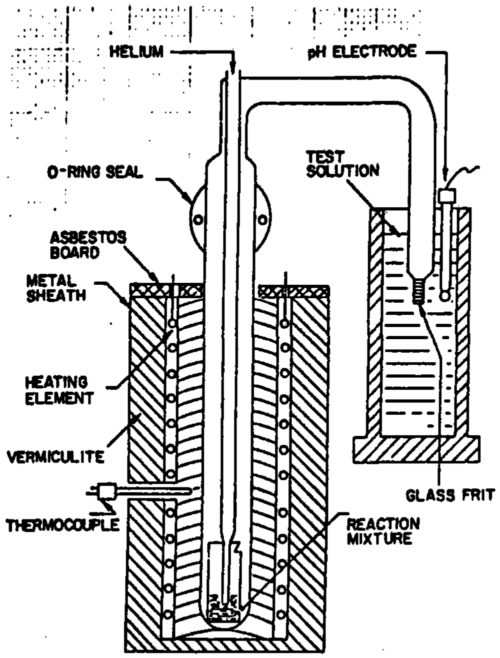


FIGURE 4

FIGURE 5

PERCENT YIELD AS A FUNCTION OF MOLE RATIO[a] FOR THE REACTION OF NH_4HSO_4[b] + nRb_2SO_4[c]

	NH_3 Yield As A Function of Mole Ratio Complete Reaction							SO_3 Yield As A Function of Mole Ratio Complete Reaction						
Mole Ratio	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Rb_2SO_4:AHS	0.85:1	1.04:1	1.13:1	1.2:1	1.4:1	1.5:1	2.5:1	0.85:1	1.04:1	1.13:1	1.2:1	1.4:1	1.5:1	2.5:1
Trapped Gases[d]	78.8	96.5	97.3	95.7	90.7	91.2	82.0	0.1	-.7	-.5	-.2	-.7	-1.2	-.8
Other Volatiles in Transfer Line	12.5	1.9	1.1	1.9	2.0	2.4	3.8	9.4	1.0	0.7	0.95	1.0	1.1	2.0
Residue	5.7	1.8	1.7	2.8	5.4	5.2	13.8	86.3	99.9	99.9	99.7	98.5	99.2	97.2
Total Recovery	97.0	100.2	100.2	100.4	98.1	98.7	99.6	95.8	100.9	100.6	100.6	99.5	100.3	99.2

(a) Mole Ratio is the Rb_2SO_4:(NH_4HSO_4 + H_2SO_4) mole ratio.

(b) · NH_4HSO_4 was Cerac/Pure dried by vacuum dessication. Analysis showed 93.5 mole % NH_4HSO_4, 4.7 mole % H_2SO_4 and 1.8% H_2O

(c) Samples were heated directly to 415°C.
All samples held at 415°C for 6 hours.

(d) Carrier gas was He at 20 cc/min for entire heating period.

FIGURE 6

PERCENT YIELD AS A FUNCTION OF TEMPERATURE[a] FOR THE REACTION OF NH_4HSO_4[b] + 1.2 M_2SO_4

	NH_3 Yield As A Function of Temperature Complete Reaction						SO_3 Yield As A Function of Temperature Complete Reaction					
Temperature °C	375	385	400	415	425	450	375	385	400	415	425	450
Trapped Gases[c]	79.3	84.2	93.5	95.7	93.9	92.0	0	0	0	0	0	0
Other Volatiles in Transfer Line	1.0	1.8	0.6	1.9	2.0	4.6	0.5	0.8	0.4	0.95	1.1	2.6
Residue	14.1	10.5	2.6	2.8	2.3	2.0	98.0	96.5	98.2	99.7	99.3	97.5
Total Recovery	94.4	96.5	96.7	100.4	98.2	98.6	98.5	97.3	98.6	100.6	100.4	100.1

(a) Samples were heated directly to setpoint temperatures.

(b) NH_4HSO_4 was Cerac/Pure dried by vacuum dessication. Analysis showed 93.5 mole % NH_4HSO_4, 4.7 mole % H_2SO_4 and 1.8% H_2O

(c) Carrier gas was helium at 20 cc/min for entire heating period.

FIGURE 7
PERCENT YIELD AS A FUNCTION OF MIXTURE MOLE RATIO AT 409°C FOR THE REACTION OF
$NH_4HSO_4 + nZnO$

409°C	NH_3 Yield As A Function of Mole Ratio Complete Reaction					SO_3 Yield As A Function of Mole Ratio Complete Reaction				
	(a)	(b)	(c)	(d)	(e)	(a)	(b)	(c)	(d)	(e)
Mole Ratio	1.09	1.29	1.49	1.97	2.47	1.09	1.29	1.49	1.97	2.47
Trapped Gases	95.33	97.74	98.52	98.40	95.86	0	0	0	0	0
Other Volatiles in Transfer Line	2.95	.41	.75	.52	.59	2.26	.18	.34	.26	.27

Notes: NH_4HSO_4 was Cerac/Pure dried by vacuum dessication. Analysis showed 94.1% NH_4HSO_4 and 5.9% H_2SO_4.
Samples were heated directly to 163°C, held at this temperature for one hour, and then heated directly to 409°C.
All samples held at 409°C until pH change in test solution became negligible.
Reaction time was measured only after sample reached 409°C.
Carrier gas was helium at 20 cc/min. for entire heating period.

FIGURE 8
PERCENT YIELD AS A FUNCTION OF TEMPERATURE FOR THE REACTION OF
$NH_4HSO_4 + 1.3\ ZnO$

n = 1.3	NH_3 Yield As A Function of Temperature Complete Reaction						SO_3 Yield As A Function of Temperature Complete Reaction					
	(a)	(b)	(c)	(d)	(e)	(f)	(a)	(b)	(c)	(d)	(e)	(f)
Temperature °C	365	380	390	399	409	419	365	380	390	399	409	419
Trapped Gases	90.22	95.95	98.13	97.46	97.74	95.09	0	.02	0	0	0	0
Other Volatiles in Transfer Line	.87	.68	.86	.72	.41	.46	.41	.31	.42	.34	.18	.22

Notes: NH_4HSO_4 was Cerac/Pure dried by vacuum dessication. Analysis showed 94.1% NH_4HSO_4 and 5.9% H_2SO_4.
Samples were heated directly to 163°C, held at this temperature for one hour, and heated directly to the setpoint temperature.
All samples were held at setpoint temperature until pH change in test solution became negligible.
Reaction time was measured only after sample reached setpoint temperature.
Carrier gas was heium at 20 cc/min. for entire heating period.

FIGURE 9

T_1/P_{H_2O}	NH_3 Yield 400°C/0 torr	NH_3 Yield 400°C/21 torr	SO_3 Yield 400°C/0 torr	SO_3 Yield 400°C/21 torr
Trapped Gases	85.7	94.0	0	0
Volatiles in Transfer Line	2.1	1.7	3.1	2.6
Residue	4.4	3.5	91.0	98.4
Total Recovery	92.3	99.2	94.1	100.9

Notes: NH_4HSO_4 was Fisher Reagent dried in vacuum. Analysis gave 99.2 mole % NH_4HSO_4, 0.5 mole % H_2SO_4 and 0.3 mole % H_2O.

Flow rate 22 cm^3/min.

Samples were heated directly to set point.

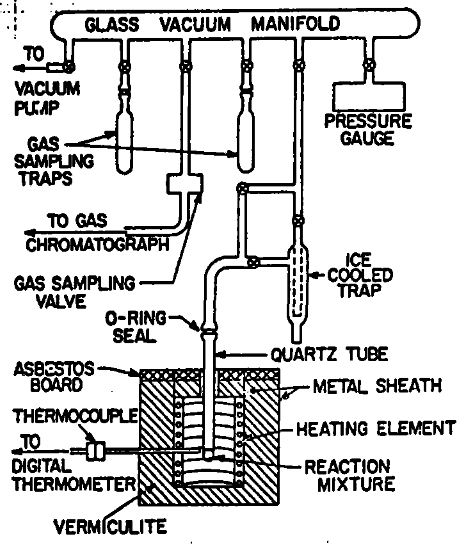
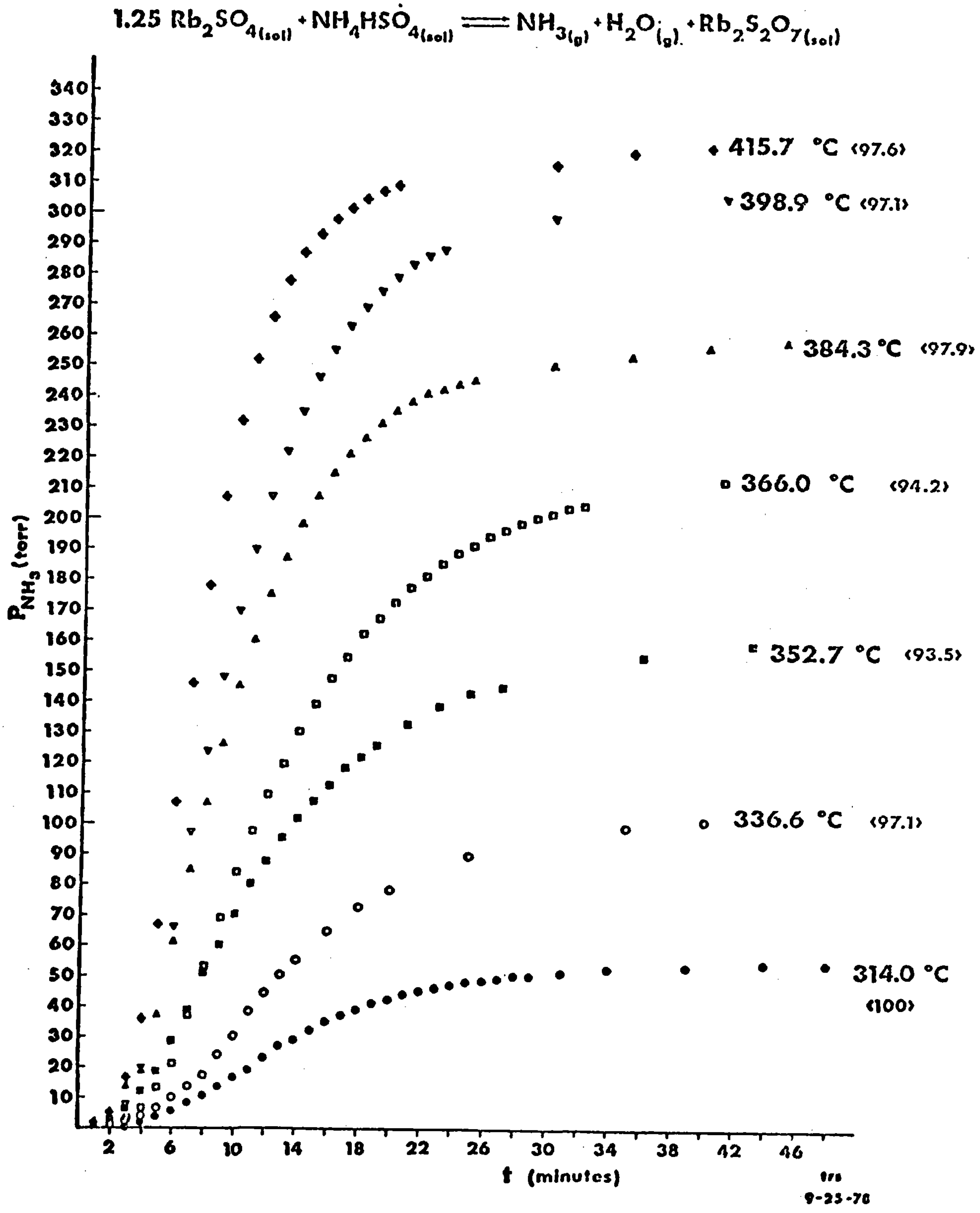


FIGURE 10



$1.25\ Rb_2SO_{4(sol)} + NH_4HSO_{4(sol)} \rightleftharpoons NH_{3(g)} + H_2O_{(g)} + Rb_2S_2O_{7(sol)}$

FIGURE 11

$$1.25\ Rb_2SO_{4\,(sol)} + NH_4HSO_{4\,(sol)} \rightleftharpoons NH_{3\,(g)} + H_2O_{(g)} + Rb_2S_2O_{7\,(sol)}$$

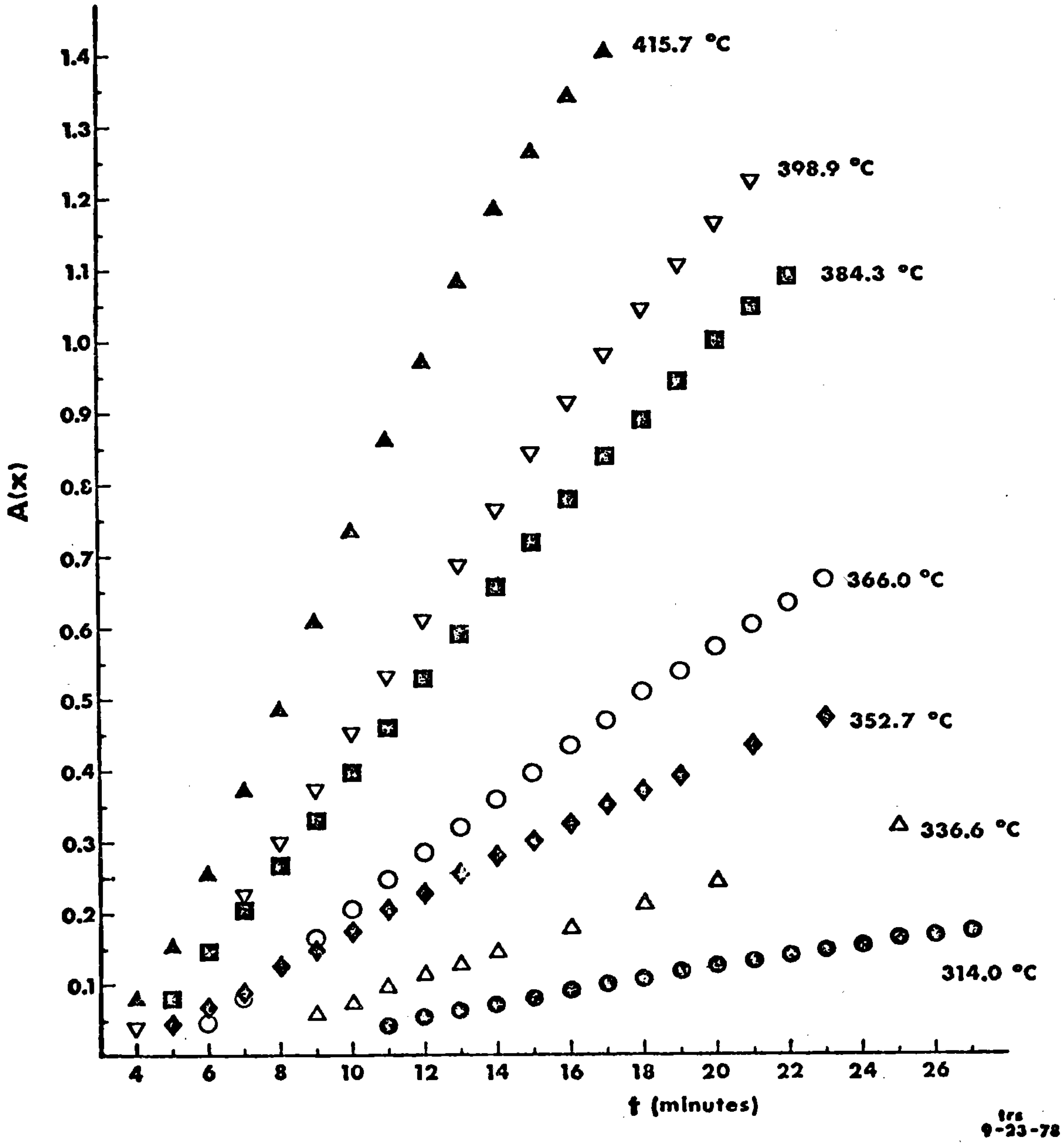


FIGURE 12

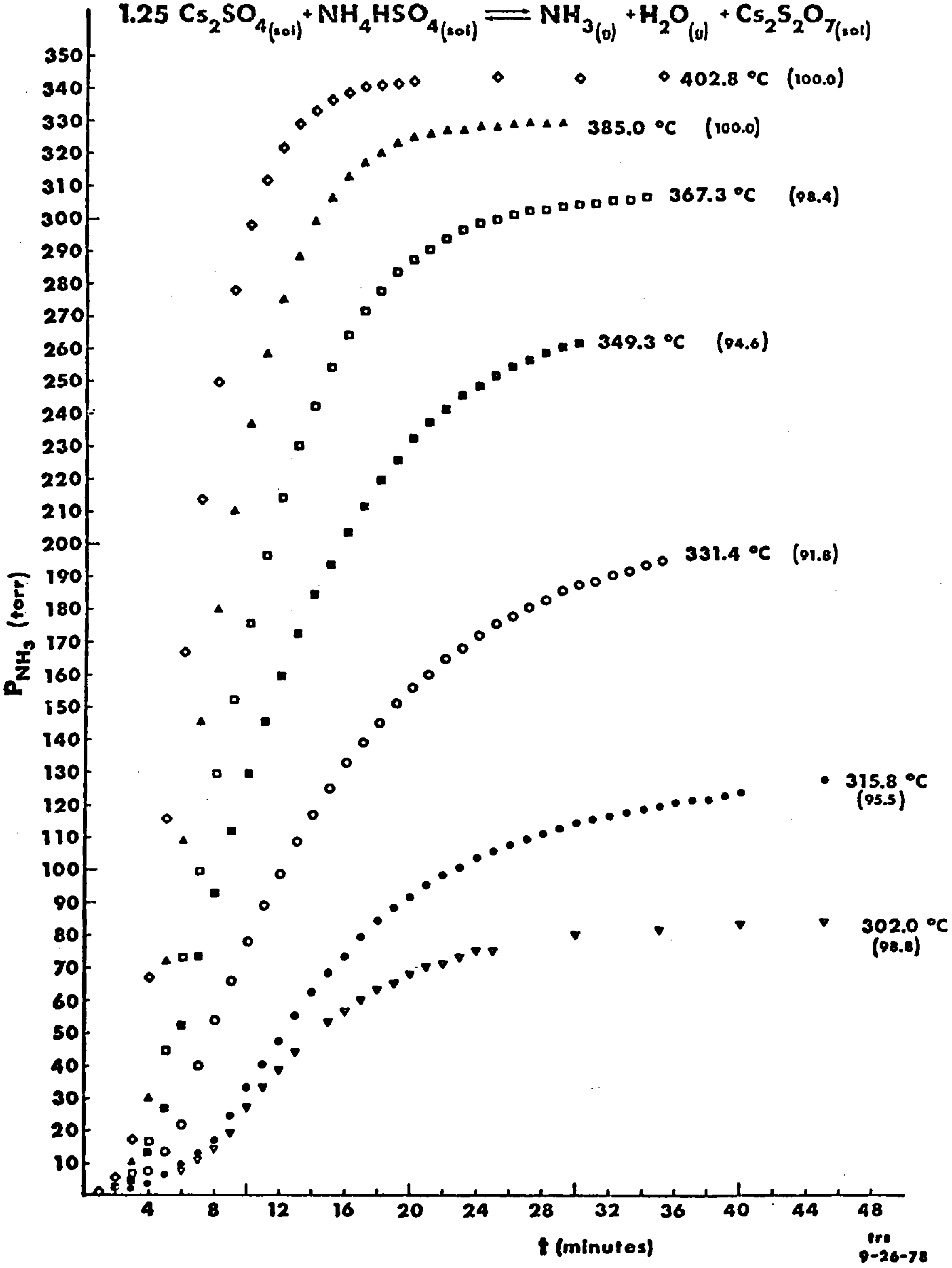

$1.25\ Cs_2SO_{4(sol)} + NH_4HSO_{4(sol)} \rightleftharpoons NH_{3(g)} + H_2O_{(g)} + Cs_2S_2O_{7(sol)}$
P_{NH_3} (torr)
350
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
4
8
12
16
20
24
28
32
36
40
44
48
t (minutes)
◇ 402.8 °C (100.0)
385.0 °C (100.0)
367.3 °C (98.4)
349.3 °C (94.6)
331.4 °C (91.8)
• 315.8 °C (95.5)
302.0 °C (98.8)
trs
9-26-78

FIGURE 13

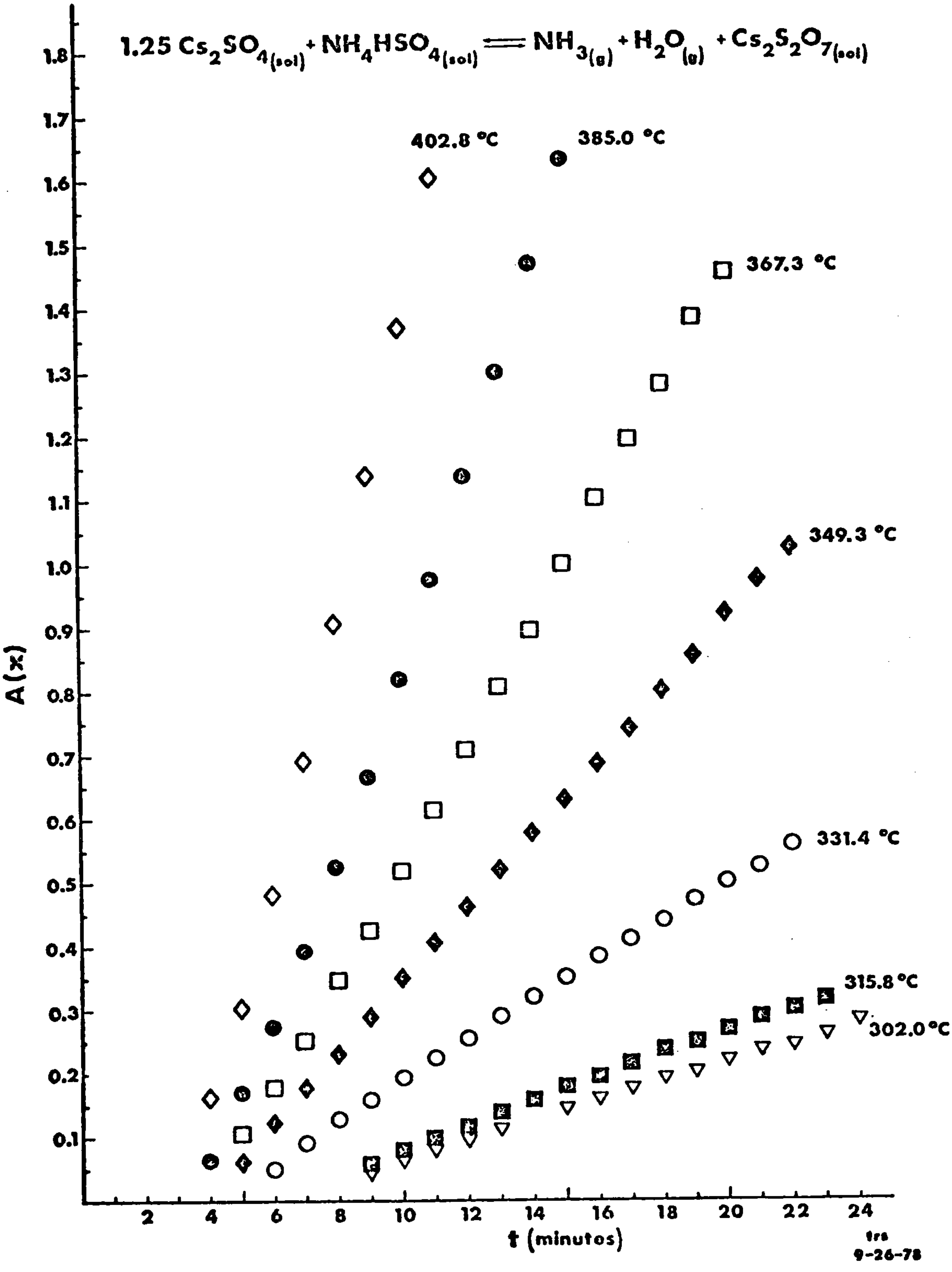

$1.25\ Cs_2SO_{4(sol)} + NH_4HSO_{4(sol)} \rightleftharpoons NH_{3(g)} + H_2O_{(g)} + Cs_2S_2O_{7(sol)}$
402.8 °C
385.0 °C
367.3 °C
349.3 °C
331.4 °C
315.8 °C
302.0 °C
A(x)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
2
4
6
8
10
12
14
16
18
20
22
24
t (minutos)
trs
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FIGURE 14

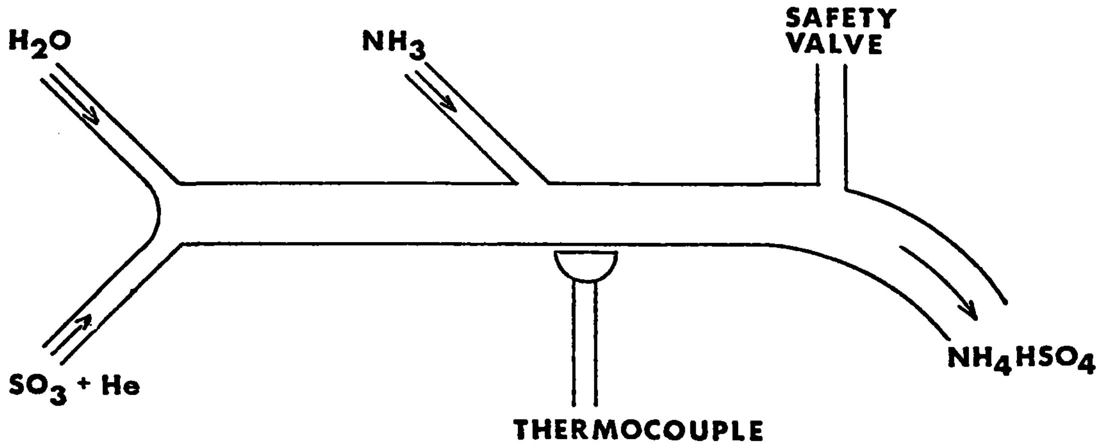

FIGURE 15

CHEMICAL CONVERSION AND TRANSMISSION OF SOLAR THERMAL ENERGY SUMMARY AND DISCUSSION

A. F. Hildebrandt
University of Houston

Interfacing Solar Towers with Power and Thermochemical Cycles

In the following I will outline a brief summary of receiver considerations made jointly with Surajit Das Gupta. Table 1 is a partial listing of central receiver power concepts with types of receivers and exit temperatures. Table 2 is a tabulation of tower/receiver characteristics of two optimized advanced receiver systems. The $C_{AV,N}$ is the average normal solar concentration on the receiver aperture. Since thermochemical cycles are expected to require receiver temperatures of $900^{o}C$, liquid metal compatibility is shown in Table 3. The temperature of $900^{o}C$ is required for the AHS cycles under study at UH as well as the German EVA-ADAM. If low temperature chemical heat pipe cycles as proposed by Flock of General Electric are proven, then temperatures of $600\text{-}700^{o}C$ with sodium as a heat transfer fluid will prove much simpler and more efficient. In Table 4 is shown the flux compatibility requirements for various candidate chemical reactions. Solar beam radiation is given to us in dilute form ($\simeq 1$ Kw/m^2), which needs to be concentrated as much as possible to minimize reradiation and consistent with the best heat transfer fluid available. The chemical reactors themselves are slow, requiring lower power densities or a flux density transform. The flux density transformation required is from the order of 1 MW/m^2 solar at the receiver to the order of 0.1 - 0.01 MW/m^2 in a chemical reaction. This can in principle be accomplished with an external cavity reactor shown in Fig. 1 where the chemical reaction would take place in tubes similar to the steam tubes in the original Martin Marietta steam cavity design. A second means would be an external receiver (Fig. 2) with internal cavity reactor with liquid metal as a heat transfer fluid. The choice of external cavity implies the solar radiation is incident on the reactor tubes, whereas in the internal reactor cavity no optical radiation is incident. Heat transfer is via a liquid metal. The advantage of either system must be evaluated in terms of thermal loss as indicated in Table 5, which shows the thermal loss equations as well as the loss estimates for external cylinders and cavities operating under similar conditions.

In conclusion, it should be noted that an external cavity receiver compared to cylindrical receiver coupled with internal cavity results in (1) a higher tower (2) has a lower averaged field efficiency, and (3) requires equal to or greater C_{AV} for comparable thermal loss. Obviously, lower operating temperatures permit less loss. It should be noted that the estimates indicate that a cavity does not necessarily always have the lowest thermal loss.

Industrial Process Heat Delivery

Industrial process heat from solar energy requires development of a reliable utility. Certain process heat requirements can be supplied with 1-2 towers such as for shale oil heating or salt cavern solution mining. If two towers are available, one has more reliability and is moving toward a utility mode. A single unit is unsuitable for supply to a capital intensive use such as a chemical plant. Furthermore, it is not always easy to match a 30 year lifetime plant with a 30 year requirement. Solar thermal electric is getting support from utilities because first units will be a small pertubation on a stable system. Therefore, a solar tower park is proposed, with at least two units, supplying users with a chemical transmission utility line. This requires pipeline or cavern storage to overcome the intermittent nature of solar of the 24 hour day, as shown in Fig. 3. Through EVA-ADAM or a chemical system as described by Dr. Chubb, solar energy could be transmitted several hundred km and greater and supply 400^{o}C steam at costs competitive for the 1985 period and beyond. The AHS system described by Dr. Wentworth can supply process heat locally on a daily basis. For longer periods such as cloudy days, fossil fuel backup may be required.

Developing a large system probably will have to be an overt effort of government and industry. However, the addition of chemical transmission considerations and electrical repowering efforts on rapid lowering of heliostat costs and associated reduction of the 100 MW_e Barstow type plants should not be overlooked.

Table 1

CENTRAL RECEIVER POWER CONCEPTS

Name	Type	Exit Temp. (^oC)
MDAC/UH	Cylinder (Steam)	516
Rocketdyne	Cylinder (Sodium)	593
Martin-Marietta	Cavity (Steam)	516
Honeywell	Cavity (Steam)	516
Boeing	Cavity (Helium)	816
Black and Veatch	Cavity (Air)	1066
Sanders	Ceramic Cavity (Air)	1100
M.I.T.	Ceramic Cavity (Air)	1100
Dynatherm	Heat Pipe Cavity (Air)	816

Table 2

TOWER/RECEIVER CHARACTERISTICS *
(FOR STEAM)

Type	Cylinder	Cavity
Receiver Exit Temp.	593^{o}C	593^{o}C
Size	16·15m x 16·15m	19m x 19m x 19m
Aperture	———	19m x 19m
$C_{(AV,N)}$	726	1250
ηth	90.0%	94.2%
Tower Ht. (M)	211	264
Receiver Wt. (Kg)	225,000	520,000
Th. Power (MW)	514.1	406.4
Mirror Cost	\$96.6 x 10^6	\$74.6 x 10^6
Cost Index $\left(\frac{\$}{BTUA}\right)$	107.3	127.0

* Walzel, Vant-Hull, "A Comparison of Central Receiver Systems Optimized for Advanced Receivers," Proc. 1978 Annual Meeting, AS-ISES, Denver, Aug. 1978.

Table 3

LIQUID METAL COMPATIBILITY

	18-8 SS	Ni and Ni alloys	Mo,Cb,Ta,W (refractory metals)
Hg	POOR >700^{0}C	POOR >500^{0}C	GOOD To 800^{0}C
Na/Na-K	MASS TRANS. >700^{0}C	>800^{0}C	GOOD To 900^{0}C
Li	POOR >500^{0}C	NR	GOOD To 900^{0}C
Pb	POOR >600^{0}C	POOR >300^{0}C	GOOD To 800^{0}C
Bi	NO DATA >300^{0}C	POOR >300^{0}C	GOOD To 800^{0}C

Table 4

FLUX COMPATIBILITY

Chemical Reaction Fluxes	Receiver Fluxes
Steam - Methane Reforming ~64 Kw/m^2 (German Data)	External Receiver (Sodium) 0.7 MW/m^2 (avg.), 1.7 MW/m^2 (peak)
Ammonium Hydrogen Sulphate ~45 Kw/m^2 (Present Estimate)	Cavity Receiver 0.2 - 0.5 MW/m^2

Table 5

THERMAL LOSS EQUATIONS*

RADIATION: $$\eta = \frac{1 - \sigma T^4/C_{AV}I_s}{1 - R_a(1-1/\alpha)}$$

CONV'N: $$\eta = \frac{h\,\Delta\,T}{C_{AV}I_S R_A}$$

R_A = APERTURE AREA/CAVITY AREA

C_{AV} = AVG. CONCENTRATION RATIO AT APERTURE

h = HEAT TRANSFER COEFFICIENTS

NOTE: FOR EXTERNAL CYLINDERS, $R_A = 1$

h = 4 - 6 BTU/HR FT^2 F FOR CYLINDERS

h = 1 - 2 BTU/HR FT^2 F FOR CAVITIES

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* Das Gupta, Mauk, Hildebrandt, "Flux Distributions Inside and Thermal Efficiencies of Solar Cavities Heated by Parabolic Dishes," Proc. 1978 Annual Meeting, AS-ISES, Denver, Aug. 1978.

LOSS FACTORS (%)

RECV'R	REFL'N	EM'SN	CONV'N	TOTAL
CYLINDER (593°C, C_{AV} = 726)	5	3.5 (α = ε = 0.95)	1.5	10
CAVITY (593°C, C_{AV} = 1250, R_A = 0.2)	3.1	(α = ε = 0.95)	2.4	5.5
HYPOTHETICAL CYLINDER	12	9.5 (α = ε = 0.88)	3.3	24.8
(900°C, C_{AV} = 726)	5	10.3 (α = ε = 0.95)	3.3	18.6
CAVITY (900°C, C_{AV} = 1250, R_A = 0.041)	6.8	(α = ε = 0.8)	13.0	19.8

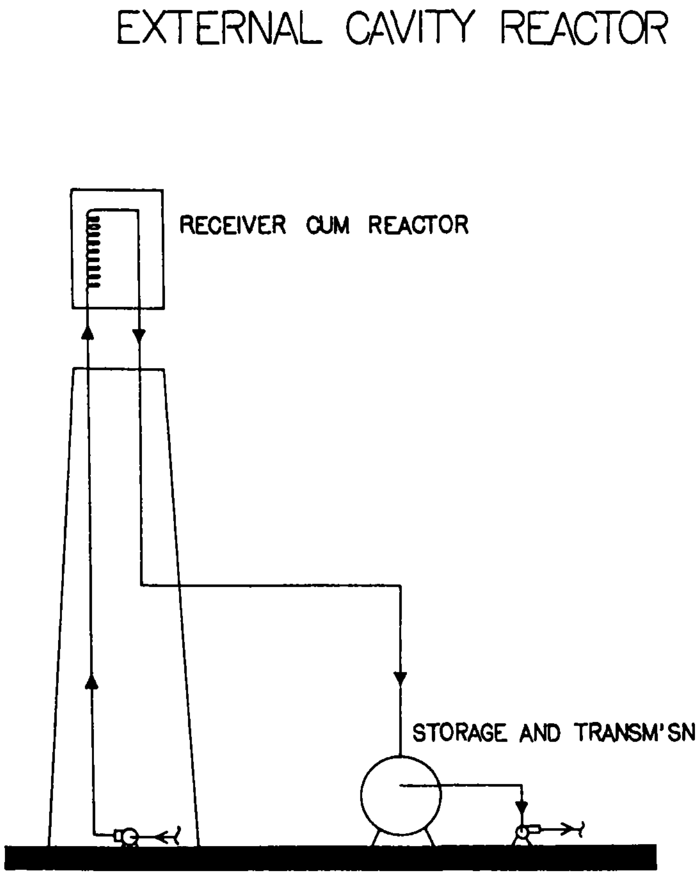


Figure 1

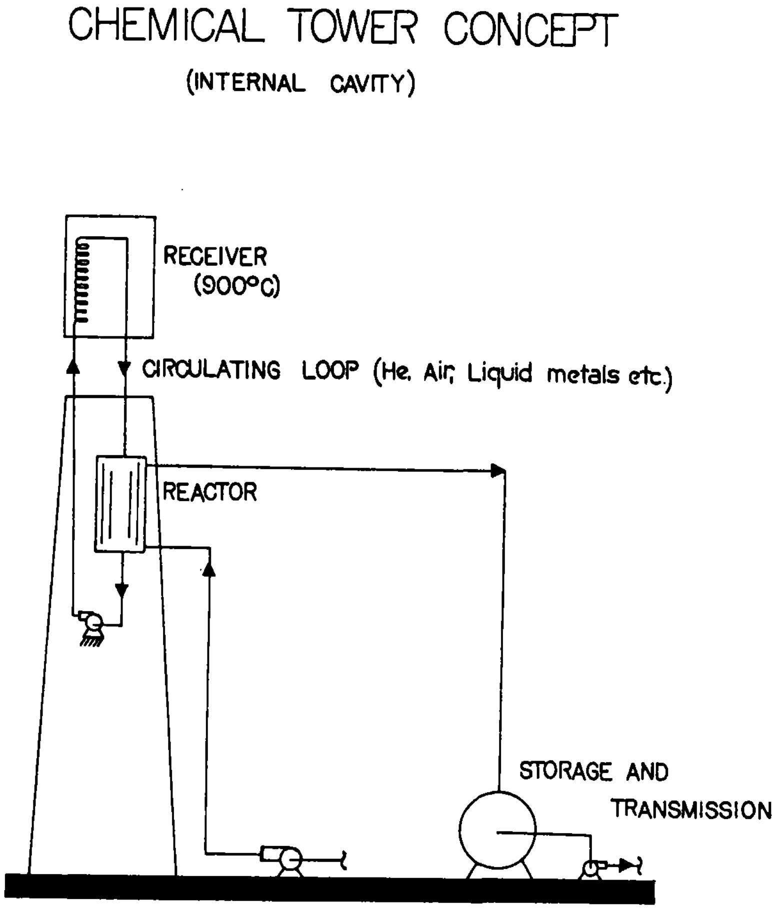


Figure 2

SOLAR TOWER PARK

CHEMICAL TRANSMISSION AND STORAGE

FOR INDUSTRIAL PROCESS HEAT

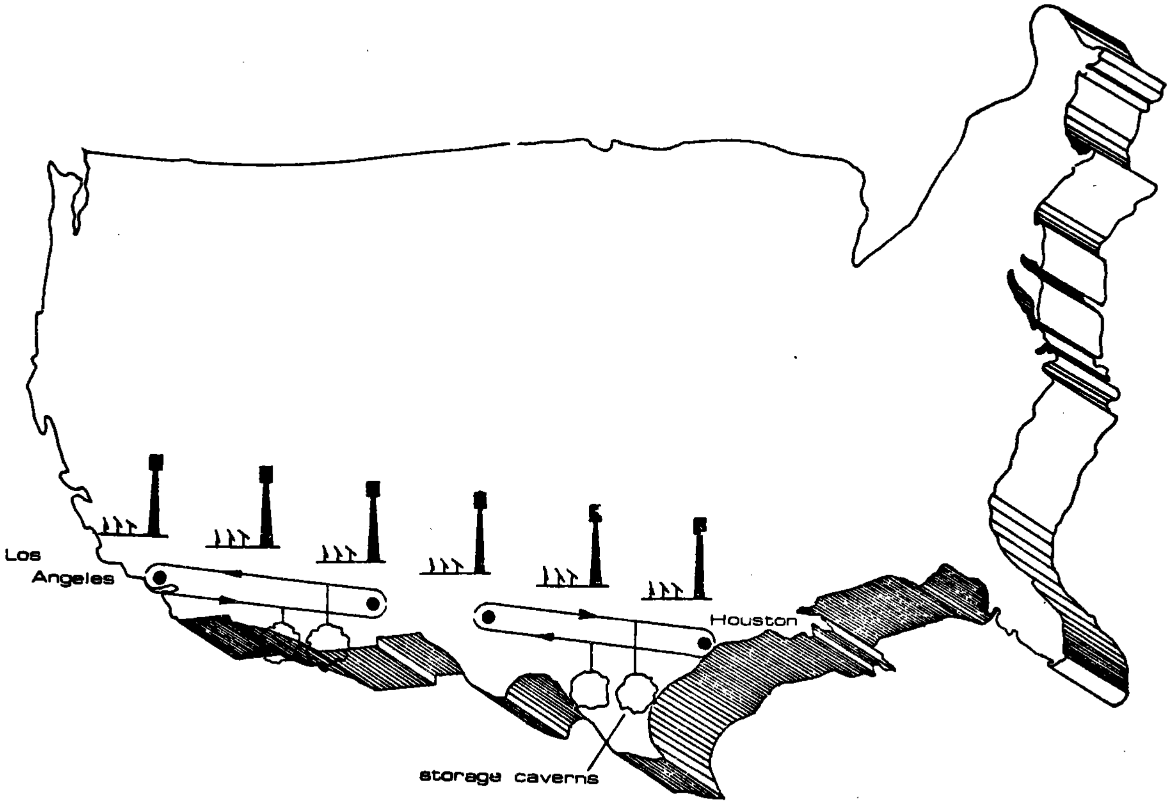


Figure 3

SECTION X - CHEMICALS, FUELS AND PROCESS HEAT

PROFILE OF THE CHEMICAL INDUSTRY

T. P. Whaley
Institute of Gas Technology

One of the major process industries that potentially could utilize high-temperature thermal energy from a central receiver solar installation is the chemical industry. As a way of leading into the workshop session on "Fuels, Chemicals, and Process Heat", I would like to give a brief profile of the industrial chemicals field, based largely on observations from my lengthy association with this important industry.

In 1977, the top 50 industrial chemicals represented an aggregate production of 483 billion lbs. The top 50 producers had total chemical sales of $63.7 billion; this includes the chemical sales of oil companies as well as chemical companies.

The top 50 products in 1977 included 21 inorganic products (excluding minerals) that represented 325.8 billion lbs and 29 organic products (excluding pharmaceuticals and light hydrocarbon fuels such as propane and butane) that represented 156.9 billion lbs. Although the organic chemicals production was only about half the production of inorganic chemicals in tonnage, the organic chemicals were generally higher priced products. It is probably safe to say that the organic chemicals segment is also less energy-intensive.

Historically, the most important parameters for chemical process consideration have been technology and feedstock availability. These have been the means by which a proprietary position could be established in producing a given chemical, either by developing a new product or process for which patent protection could be obtained or by establishing a raw material/feedstock position that would provide a competitive edge over other producers. Research and development efforts have been directed largely toward the goal of establishing such a proprietary position or circumventing adverse positions by competitors.

Although the chemical industry has always been energy-conscious, energy costs have not been generally as important as raw materials costs and generally not considered as a major item. Such items as transportation, water for cooling towers, etc., have generally been more important than energy availability in selecting sites for plants, although certain of the more energy-intensive plants such as those involving electric furnaces were obviously sited near sources of low-cost electrical power.

In keeping with the risk factor associated with products or processes that could be rendered obsolete by a competitor's technological breakthrough, the pay-back time requirements for new plants has historically been relatively short for the chemical industry--in most cases, less than five years. With the relatively inexpensive energy available in this country during previous years and the relatively low contribution of energy costs to overall costs of most chemical processes, the greater importance attached to technology and raw materials positions than to energy costs is understandable.

In recent years, however, energy costs have risen and many companies in the chemical process industry have formed special departments to spearhead their effort in erergy conservation; from all reports, these efforts have been quite successful. Although feedstock availability and technology are undoubtedly still the most significant factors, future energy cost and availability will probably assume an increasingly important role in future plans. For this reason, we would hope that workshop sessions such as this can initiate a dialogue to determine what role high-temperature solar energy might be able to play in future activities of the chemical process industry.

FUELS AND CHEMICALS FROM SOLAR ENERGY

James R. Dafler
Institute of Gas Technology

I'm going to talk specifically about a program we've recently completed at the Institute of Gas Technology.

We were a subcontractor to Oak Ridge National Laboratory in a program to develop assessments of fuels and chemicals manufactured using solar high-temperature heat.

I think the primary motivation for a program of this kind can be seen if we look at the division of thermal energy use in the US (Figure 1). About 46 or 47 percent is used in space heating and for private sector electricity generation; 53 percent is used in the industrial sector for utility generation and industrial heat. The whole thing adds up to about the 41 percent that Marty discussed in his address at lunchtime.

Figure 2 shows this broken down a little bit more, and you see that there is quite a percentage of the national energy, or primary fuel burning that goes into process heat, either as direct heat or steam, or as part of the small amount of electricity that's used in processes. Some of the primary energy is also used as feedstock, of course.

The program that we had was a three-task effort, which was aimed at selecting processes, evaluating them in terms of market, feedstock futures--things of that kind; basically all techno-economic assessments--to provide an alternative to electricity. I think we've heard enough about why we want to do that: To provide also a transmittable commodity for fuel, and to provide for conservation of the natural resource base in hand.

This was a fairly tightly disciplined study. We had rather close guidelines to follow. We wanted only to identify conventional processes--technology in being. We also identified some innovative processes as a small part of this program. I will not discuss these today.

We assessed capacities, the demand, present and future, and estimated the prices we might expect, present and future.

The assessment guidelines were, of course, for technology in hand using conventional feedstocks. We wished to operate conventional plants with fossil fuels, with solar displacement of fossil fuels, with solar displacement of fossil fuels for a part of the day, the part of the day in which we had insolation. It's kind of a partial retrofit, if you like--solar energy into a conventional process, so that the process can operate on a 24-hour-a-day chemical industry basis.

There was another assessment guideline: Direct use of feedstocks as cooling, where feasible. That guideline was not addressed in this study to a great degree. The selection guidelines were: primary temperatures above 400°F, energy use of 10^{12} Btu's per year, and electricity only through utility purchase. We've put together a kind of techno-economic assessment network, that began with Task 1, which was process selection. We selected a large number of processes based on the guidelines of energy use. We also looked at processes in which large tonnages were manufactured each year. We did market research on the processes.

If we network together the market research and characterization of processes to define the solar technology interface, we've identified the solar technology insolation characteristics. We come finally to an integrated economics picture for the processes we selected, the ones that looked as if they had the most potential for partial or displacement-type retrofit to solar energy heat, and eventually made it a comparison including an economics assessment.

Those of the conventional processes we finally selected are shown in Figure 3. The selection process was basically a paper assessment of the fuel futures, the kind of feedstocks, and the capacity and demand projections. They were methanol, styrene, vinyl chloride monomer, and terephthalic acid.

If we look at the overall package, you'll see we divided chemicals into what one might call inorganic and petroleum, or organic, chemicals. IGT constrained itself almost exclusively to the investigation of high-energy organic chemicals.

We characterized each process and I'll go through these very quickly. Styrene was the conventional process that was highest in our ranking process. We based our work on a plant size of 2.5×10^5 tons per year. It has ordinary feedstocks: ethylene, the most widely used feedstock in the world, and benzene. It has a fuel, or heat, demand per pound of product of 2780 Btu's, and a rather small electricity requirement.

Vinyl chloride monomer is the primary basis of the American plastics industry and its techno-economic assessment made it second in the ranking. Again, very ordinary feedstocks are used: ethylene, chlorine, rather a smaller heat requirement per pound of material, and a larger electricity requirement. The price runs to about 14 cents per pound, and demand is expected to go up almost 100 percent between now and 1985.

Terephthalic acid is now enjoying a lot of use in engineering plastics although it seems to be the bane of environmentalists because a lot of plastic bottles are being made out of it that the sellers like. They're trying to make them put deposits on these as well as glass bottles. It's going to enjoy a demand increase of about 60 percent between now and 1985. It has rather more exotic feedstocks: p-xylene, methyl-ethyl ketone and oxygen.

The fourth process turned out to be the lowest ranked of the processes that we selected for final assessment and integration in our program. The reasons for that are complex and a little difficult to work with in this short time. Methanol is made in quantities far in excess of a billion pounds per year. It is the chemical that's made in the largest amount--of the organic chemicals--in the country; in the world, for that matter. More methanol is made than just about any other organic chemical except ethylene. It uses a synthesis gas feedstock, which is very common, and has a fairly high fuel requirement and a small electricity requirement. That is a little bit false because a lot of our exported steam from the exothermic process of manufacturing methanol is used to drive compressors for these very high-pressure processes. Something that a solar-driven methanol plant might give us is more of a choice about where we manufacture methanol.

Figure 8 is a chart based on 1975 locations of methanol synthesis plants. There are, I think, about 18 very large methanol synthesis plants in the US and they are all located, or locked into hydro-cracker capacities, or hydro-cracker plants on the Gulf Coast.

Methanol is also the kind of material that enjoys a kind of gray area whether it's a fuel or a chemical; whether it's going to be used a lot in transportation in the near future isn't very clear right now. But, if we wish to make a lot of methanol, we might be able to use large installation areas in the Southwest to put up a solar process heat utility for making a very valuable, easily transmittable chemical such as methanol.

Just as an excerise, we looked at the possible conservation of natural gas from one-third, or 10-hour-a-day, operation in a small, 360,000 pound per day, methanol plant. For 1978 it was 370,000 standard cubic feet per day, or 111 million standard cubic feet a year. In 1985, it would represent 12.3 billion standard cubic feet a year of natural gas conserved.

If we took the fuel requirements for all four of the processes we reviewed and we converted them to solar energy on a 10-hour-a-day basis, and if all of the fuel was otherwise supplied by natural gas, the conservation in 1985 for the four processes at the 1985 demand levels would be 2×10^{11} standard cubic feet per year.

Just to put this into a kind of perspective, the 1975 reserves of natural gas were 23,000 trillion cubic feet, so it's a part of a percent of the total of the reserves in 1975 that could be conserved by converting these four industries.

We did one other exercise, a small sensitivity analysis on the steam generating plant, based on fossil fuel, or a central receiver for a styrene plant. The sensitivity analysis was done in terms of the 1978 conventional fuel costs. The costs for solar heat don't escalate with time. Figure 11 shows the return on investment relationship for the central receiver steam plant for styrene. We don't begin to see a positive rate of return on investment for the solar plant until the 1978 conventional energy costs run to about 3.8 dollars per million Btu's. I've seen studies that seem to indicate that the problem was a lot more severe than that, but I think it's not entirely unencouraging.

The program was, as I said, rather tightly disciplined in its outlook, and I think what it did, for us at least, is show that we needed to probe a little bit deeper into the economics problems, and in the next six months at IGT we will finish a program funded out of Marty Gutstein's branch for conceptual economics of solar chemicals and fuels using solar hear. I think that study will allow us to put into better perspective the problems that Figures 10 and 11 illustrate. Thank you.

Comment - I might point out that the choice of location for modern organic chemicals plants is more complicated than you imply. For example, in the Texas Gulf Coast you find companies with plants adjacent to each other and they feed by-products and products back and forth. One reason some of those plants are there is that they have the source of raw materials from their neighbors.

Mr. Dafler - That's certainly the reason why so many methanol companies are on the Gulf Coast. But suppose somebody in Southern California wanted, for example, to generate electricity with methyl fuel. You'd have to pipeline it from the Gulf Coast.

Comment - If there's an extraordinary reason for building an isolated plant, it might be done for reasons such as that, but it's not normally done any more.

Mr. Dafler - All I want to do is kind of wave the flag that this kind of processing might give you the opportunity to end this wedding, so to speak, without losing too much.

Question - Why divorce them?

Mr. Dafler - You might want to generate electricity in Southern California. That's not so far-fetched, of course.

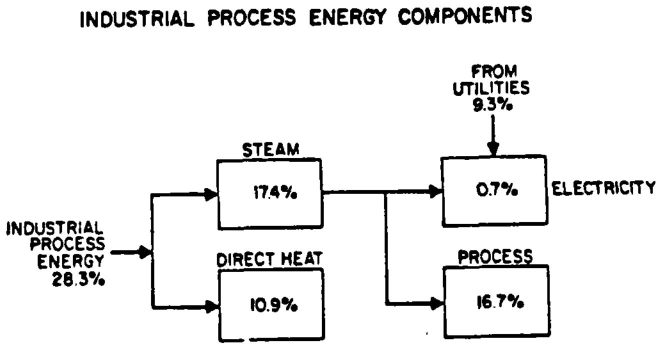


Figure 1

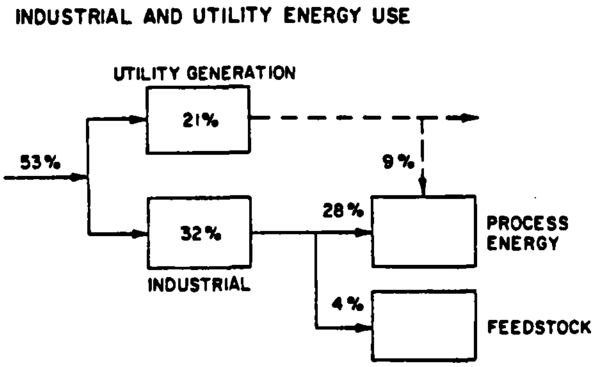


Figure 2

PROCESSES SELECTED

- METHANOL
- STYRENE
- VINYL CHLORIDE MONOMER
- TEREPHTHALIC ACID

- STYRENE/METHANOL
- SOLAR THERMOCHEMICAL H_2/AMMONIA

Figure 3

STYRENE	6.6×10^9 lb/yr
PLANT SIZE:	2.5×10^5 ton/yr
FEEDSTOCK:	
ETHYLENE	0.31
BENZENE	0.82
FUEL:	2780 Btu
ELECTRICITY:	0.04 KWh
PRICE (1977):	0.18 TO 0.21
1985 DEMAND	9.4×10^9 lb

Figure 4

VCM	5.6×10^9 lb/yr
PLANT SIZE:	10^5 ton/yr
FEEDSTOCK:	
ETHYLENE	0.47
CHLORINE	0.62
FUEL:	1545 Btu
ELECTRICITY:	0.09 KWh
PRICE (1977):	0.145 TO 0.15
1985 DEMAND	10^{10} lb

Figure 5

TEREPHTHALIC ACID	10.2×10^9 lb/yr
PLANT SIZE:	5.5×10^5 ton/yr
FEEDSTOCK:	
p-XYLENE	0.68
MEK	0.24
O_2	0.90
FUEL:	5500 Btu
ELECTRICITY:	0.11 KWh
PRICE (1977):	0.19
1985 DEMAND	15.9×10^9 lb

Figure 6

METHANOL	6.4×10^9 lb/yr
PLANT SIZE:	360,000 lb/day (ICI) 250,000 lb/day (Lurgi)
FEEDSTOCK:	
SYNTHESIS GAS	13.6 SCF
CO_2	3.4 SCF
FUEL:	2570 Btu
ELECTRICITY:	0.05 KWh
PRICE (1977):	0.071
1985 DEMAND	13.3×10^9 lb

Figure 7

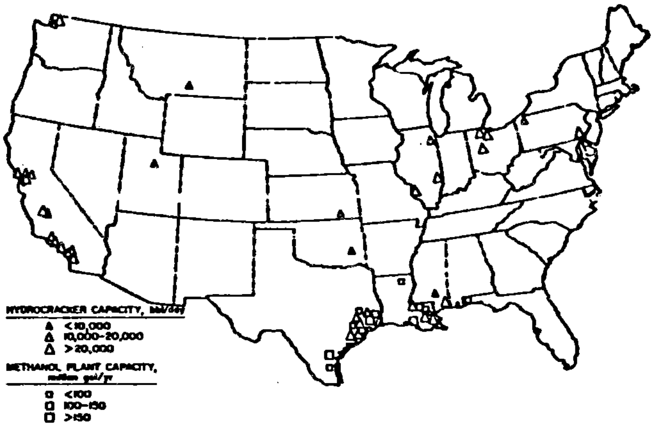


Figure 8

CONSERVING NATURAL GAS

Methanol (1978)	3.7×10^5 scfd 1.11×10^8 scfy
(1985)	12.3×10^9 scfy

over-all : 1985

2×10^{11} scfy

1975 proved reserves: 23,000 Tcf

Figure 9

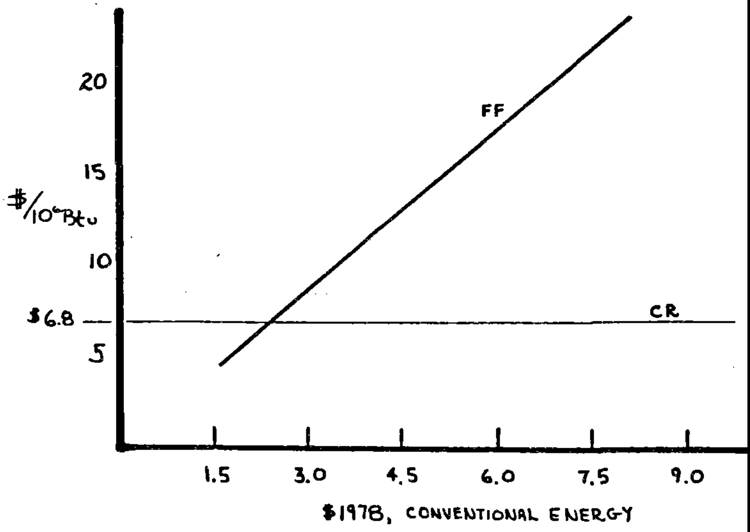


Figure 10

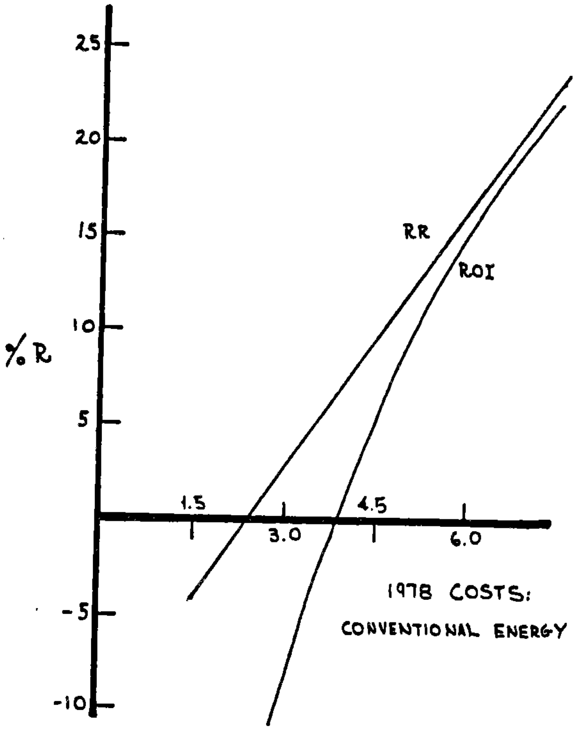


Figure 11

England:

Comment - I noticed that you talked about efficiencies of 109 percent.

Question - On the slide of the hydrogen-iodine cycle you had lines for the 1977 performance; what was the reason?

Dr. England - That particular effort is being handled by Westinghouse and the goals are a little less specific. I think the status is that that experimental effort is in a state of flux and the purpose of closing the cycle was to solve that problem.

Question - Several of the cycles, including this one, have SO_2 and oxygen is produced. What do you propose for separation?

Dr. England - You can use any of the acid gas scrubbing methods. Some people use straight refrigeration.

Comment - Being from General Atomic, I would like to say that the process we are working on is all thermochemical. We have been working for a few years on the chemistry of separation of the various constituents and the chemistry of reaction. Of the various reactions, we have put together something like three different flow sheets. The last one is different from the previous two because we have demonstrated in the laboratory all the separation techniques. We have used experimental parameters for all of the chemistry that went into the last flow sheet. So we feel like where we stand now is that we have a very credible chemical system defined which could be built. It would work as designed. The catch is that because it is a complex chemical system we feel that by working on it and getting more information about some of the ranges of chemical parameters, etc., we would be able to improve the efficiency and reduce capital costs. This is the objective of the program, actually in a few years.

SOLAR APPLICATIONS AND COST FACTORS IN THE PROCESS INDUSTRY

K. T. Geoca
Shell Development Company

Good afternoon. It is both a pleasure and an honor to be here with some of the most knowledgeable people in the field of solar high-temperature technology. You members and officers of the Solar Thermal Test Facilities Users Association and its Executive Director, Frank Smith, are to be complimented for organizing a fine meeting.

I have been actively involved in the solar energy field for only about a year. Therefore, I cannot contribute much to this group in high-temperature solar technology. However, perhaps my insight in the petroleum and chemical industries (which I will henceforth refer to as the process industry) would be useful to you in your studies of the process industry as a market for solar high-temperature technology.

The process industry is the largest user of energy in the industrial sector (see Figure 1). Although fuel consumption of the process industry is predominantly natural gas, use of this fuel has decreased since 1972, as shown in Figures 2 and 3. Forecasts by the process industry indicate continued decline in the use of this environmentally desirable fuel by the process industry in the foreseeable future. Residual fuel oil, purchased electricity and refinery gases have replaced natural gas as its use is phased down because of conservation measures and curtailments. Indications are that coal will increasingly replace gas and oil as conservation measures and gas curtailments increase in the future. Coal will be the fuel which will show the largest increase in usage through the turn of the century. This is a logical step when one considers that most other fuels used are readily saleable products by these industries. It is interesting to note on Figure 4 the difference in usage of fuel in the refinery industry versus the chemical industry. The refinery industry uses a much higher percentage of fuel for process heat, a use where alternate fuels are more difficult to substitute, than it does for steam production.

Because of the relatively large use of energy in these industries, energy conservation has always been an important factor in plant design and operation. The cost of energy is constantly being weighed against the capital cost of conservation equipment in a delicate balance to achieve cost reductions in these highly competitive industries. Figure 5 lists methods of conservation which have been used to reduce energy consumption. Conservation efforts have been successful in the process industry--resulting in a reduction of about 16.5 percent in the industry's energy requirements since 1972 (see Figure 6).

We hear considerable discussion today concerning "cogeneration," especially in reference to integrating power generation with process industry heat requirements. The process industry, especially the petroleum industry, has been practicing this method of optimization of fuel usage from its early days. Figure 7 illustrates a typical refinery system in which steam is generated at higher pressures and cascaded to lower pressures as required. I guess it is safe to say that today some form of cogeneration is used in very large process plant.

What I am trying to illustrate is that the petroleum and chemical industries are energy conscious industries and have been energy conscious throughout their history. Therefore, I feel that these industries are always receptive to the consideration of any energy saving new technology--such as solar.

However, because of the nature of the process industry (continuous operation at constant conditions, 24 hrs/day, 365 days/year), any new technology must either meet these operating criteria or be flexible enough to mesh with the process without disrupting its operation.

Since I noticed some smiles in the audience, let me elaborate. Although "on-stream-time" for large utility boilers and nuclear reactors average out to about 65 percent, individual oil refinery and petrochemical units usually operate at "on-stream" factors greater than 85 percent. I do not want to imply that any solar unit must meet these high operating rates to be acceptable; however, like a utility boiler, a solar-derived energy system must be able to be removed from the system without disrupting the system. Unlike the utility boiler, however, when a solar collector system is not operating, it is not supplying energy and thus reducing its payout.

Controllability and reliability are essential factors in the process industry--most oil refinery and chemical processes operate under very exacting operating conditions, such as temperature and pressure. Loss of or erratic control of the process heat or energy (steam or electricity) source can result in process upsets or even plant shutdowns, either of which can be very costly and if uncontrolled, even dangerous. Therefore, any solar collector system used in a process plant must be sufficiently controllable to be compatible with the system. This suggests that any solar system providing energy to a process plant must be well instrumented and must be adequately backed up by fossil fueled facilities.

Availability of land for installation of an adequate solar collector system could be a problem. Most process plants are clustered together and tightly integrated to take advantage of feed availability, sequential processing of feed streams and optimization of heat exchange. As a result, land is not always available, especially in older plants, for a solar system and what is available is expensive. Land rapidly becomes a limiting fctor when considering that a solar-powered plant supplying one million pounds of steam per hour would require about 950 acres of collectors.

Assuming that land is available and the solar collector systems can be made compatible with process plants, there remains a third and, in my opinion, more difficult obstacle to be overcome--cost. As mentioned earlier, there is a delicate balance in most process plants between the cost of energy and the cost of capital investments to conserve it. Since any solar facility supplying energy to a process plant will require full backups by a fossil-fueled system, the only credit which can be used in determining payout is fuel savings. This presents quite a paradox since predicting fuel costs is probably riskier than predicting future solar collector system costs.

Figure 8 illustrates the cost of liquid hydrocarbon fuels to the industrial market as projected by Intertechnology Corporation's "Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat" in a study for the US Department of Commerce. Most studies I have seen generally agree on the cost of oil (in constant 1976 dollars) up through 1985. This consensus is based on the assumption that the average US price will equilibrate with the world market price in that period. However, from 1985 on, estimates diverge radically. The ITC report uses an 8 percent average annual increase (AAI) of oil and gas prices in constant 1976 dollars through 2020. There is some serious question that either gas or liquid hydrocarbon prices will increase at that rate when the alternates are considered:

1. Coal production and consumption (particularly in the industrial sector) as shown in Figure 9, will continue rising through the turn of the century, and indications are that the ability of markets to absorb the "production potential" will be limited by air quality regulations and the economics of converting boilers to coal. If this is true, coal, therefore, will be demand limited, thus tending to hold prices down. This is reflected in the ITC report which estimates that coal prices increase at substantially lower rates (5 percent AAI) than ITC used for oil and gas (8 percent AAI). Beginning from a lower base, coal prices are estimated to reach a national average to industrial users of only \$2.14 per MM Btu's (constant 1976 dollars) in the year 2000. This is a substantial difference from the \$9.20 per MM Btu's projected by ITC for oil in the year 2000.

2. Electricity: the Shell "National Energy Outlook 1980-1990" shows the use of electricity in the industrial sector increasing through 1990 (Figure 10). There

appears to be no reason to believe its use will moderate thereafter. Figure 11 shows coal and nuclear increasing their share of the electric generation market through 1990 and the trend is likely to continue through the turn of the century. Generation of the electricity by these two low cost fuels should restrain electricity price increases, thus adding downward pressure to oil and gas prices.

3. Other alternate fuels are shown in Figure 12, taken from th, June 1977, ERDA Presidential Briefing on Alternate Energy Technologies. This chart shows estimated timing and pricing of various technologies. Note an overlay of estimated fuel prices at 4 percent AAI from 1985 onward. Figure 13 is a Shell estimate of unconventional oil and gas supplies through 1990.

Since it is important to have a baseline forecast from which various assumptions are developed, I have chosen to use the ITC forecast for oil prices through 1985 and then escalated the price of oil at a more conservative 4 percent AAI (in constant 1976 dollars) through the year 2000. This is somewhat of a compromise between the ITTC and EPRI forecasts.

Using values from this fuel cost forecast, economic installed costs for solar facilities were developed in accordance with the parameters set out in Figure 14 and in the calculations shown in Figure 15. The results of these calculations are shown in Figure 16. These economic installed costs for solar thermal systems are plotted in Figure 17.

There are circumstances one can envision which can drastically alter the justification for installing solar thermal collector facilities, circumstances which would overshadow economics. What I have tried to show in Figure 17 is the installed costs which would make solar thermal collector systems economically viable relative to alternate energy sources which they will supplement or replace.

Gentlemen, to summarize; the Petroleum and Chemical Industries:

1. Are large energy consumers.

2. Are energy conscious industries--especially when one considers that the energy they consume usually represents products not available for sale.

3. Have demonstrated a willingness to spend capital to conserve energy.

4. Would be receptive to new energy saving technology such as solar thermal.

However, for solar thermal to win a place in this (or any other) industry, it must:

1. Demonstrate reliability.
2. Demonstrate controllability.
3. Fit into space constraints.
4. Be economically viable against the energy source it replaces.

Thank you.

Question - What year dollars are these?

Mr. Geoca - All in 1976 dollars.

Comment - But that's break-even at the year. You're talking about 1990 rather than levelized over the period to 1990.

Mr. Geoca - No, that's break-even in that year.

Question - Concerning your basic assumption on the square footage, or square acres, of solar collectors needed for a certain process, it seems prevalent throughout this whole conference that everyone overlooks the fact that there is hardly one industrial process, at least above 500°, that is going to 100 percent solar. It disturbs me very much that for industrial process heat, we should be looking to solar to assist with from 30-70 percent, but certainly not base any studies on a full 100 percent because the economics just go right out. I'd certainly like to see a computer analysis taking the percentage of solar and the land required--whether it's high-temperature trough concentrators, or point-focus, small heliostat systems--to come up with a very cost effective solar system within the next three years on something less than 70 percent. One thing about the conference that has bothered me is that everything is based on 100 percent and not on the most cost effective less capital uses of solar energy.

Comment - Those process sequences you are presently using are based on the available cost of cheap fuel, aren't they?

Mr. Geoca - That's true but what has happened is they're being upgraded constantly.

Question - I guess we're saying now that if you started with solar energy, could you develop a new set of process sequences that would give you the same products using solar as input? That's a long-range problem.

Mr. Geoca - To get reliability, I think we'd have to do pretty much what the gentleman said and you can see it if you have a plant using 5 million pounds of steam per hour. To install a thousand acres of solar collectors to provide 20 percent of your energy is quite a sizeable solar market. You don't have to do the whole process. There's a gigantic market.

Comment - In your analysis, you indicated you had assumed a collector of around 250,000 Btu's per square foot per year of solar energy. I think that figure is probably a little low. There are parts of the country, particularly in the Southwest, where that figure might be as high as 700,000, 800,000 or even 900,000. So, it might very well be that you could figure on collecting at least twice the figure you were talking about. In which case, I would assume your investments will probably go up accordingly.

Mr. Geoca - Right. If you can double that amount of solar delivered to the processor, it would help appreciably. It would double the economic justification. One of the surprising things is the 950 acres needed; we don't have plants with that much room.

Comment - You don't have to put the solar collectors on open land; you can plut them above present facilities.

SUMMARY OF INDUSTRIAL PROCESS HEAT CONSUMPTION BY SEVEN MAJOR INDUSTRIAL GROUPS IN 1974

		1976 **
PRIMARY METALS	3.772 quads*	2.8
PETROLEUM & COAL PRODUCTS	2.637	2.98
PAPER AND ALLIED PRODUCTS	1.093	0.98
STONE, CLAY & GLASS	0.991	-
CHEMICALS	0.534	3.25
FOOD & KINDRED PRODUCTS	0.319	-
TEXTILES	0.116	0.168
TOTAL	9.462 quads (10^{15} Btu)	

* PURCHASED POWER ONLY

** TOTAL ENERGY CONSUMPTION AS REPORTED TO DOE

Figure 1

CHEMICAL INDUSTRY FUEL COMPOSITION PERCENT

	1972	1977
DISTILLATE	0.8	2.3
RESIDUAL	5.6	7.3
LPG	0.6	0.4
NATURAL GAS	47.3	39.5
PROCESS GAS	8.6	8.7
PROCESS LIQUID	1.7	3.5
PROCESS SOLIDS	0.4	0.2
COKE	0.2	0.2
COAL	9.4	8.7
PURCHASED STEAM	3.9	3.6
PURCHASED ELECTRICITY	21.5	25.6

SOURCE: MCA

Figure 3

REFINING INDUSTRY FUEL COMPOSITION PERCENT

	1972	1977
CRUDE	0.1	0.1
DISTILLATE	0.5	0.9
RESIDUAL	8.6	10.1
LPG	1.4	0.9
NATURAL GAS	31.4	24.9
REFY GAS	35.5	39.7
COKE	14.6	14.2
COAL	0.1	0.1
PURCHASED STEAM	1.1	1.3
PURCHASED ELECTRICITY	6.7	7.8

SOURCE: API
EHM P&A-0 6/13/78

Figure 2

REFINERY/CHEMICAL ENERGY CONSUMPTION-PROCESS HEAT, STEAM GENERATION, AND PURCHASED ELECTRICITY

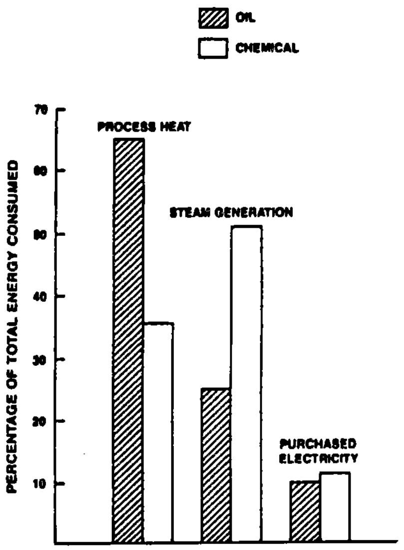


Figure 4

ENERGY CONSERVATION MEASURES

1. PROCEDURAL CHANGES
2. ADDITIONAL HEAT EXCHANGE
3. REVISION OF EXISTING PLANT DESIGN AND INSTRUMENTATION
4. IMPROVED FURNACE/BOILER FIRING
5. FLARE GAS AND VAPOR RECOVERY
6. STEAM & CONDENSATE RECOVERY
7. INSULATION
8. MECHANICAL EQUIPMENT MODIFICATION
9. OTHER

Figure 5

ENERGY CONSERVATION
OIL INDUSTRY
API SYSTEM — 1972 BASE
REFINERIES

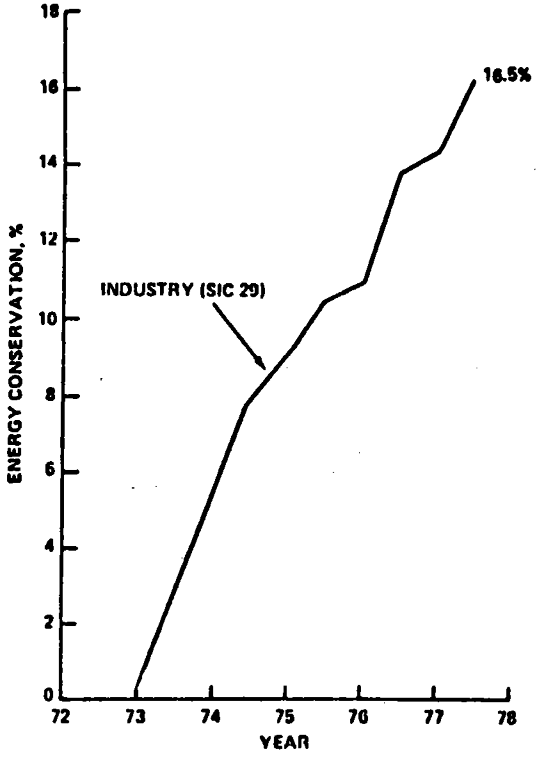


Figure 6

TYPICAL REFINERY STEAM SYSTEM

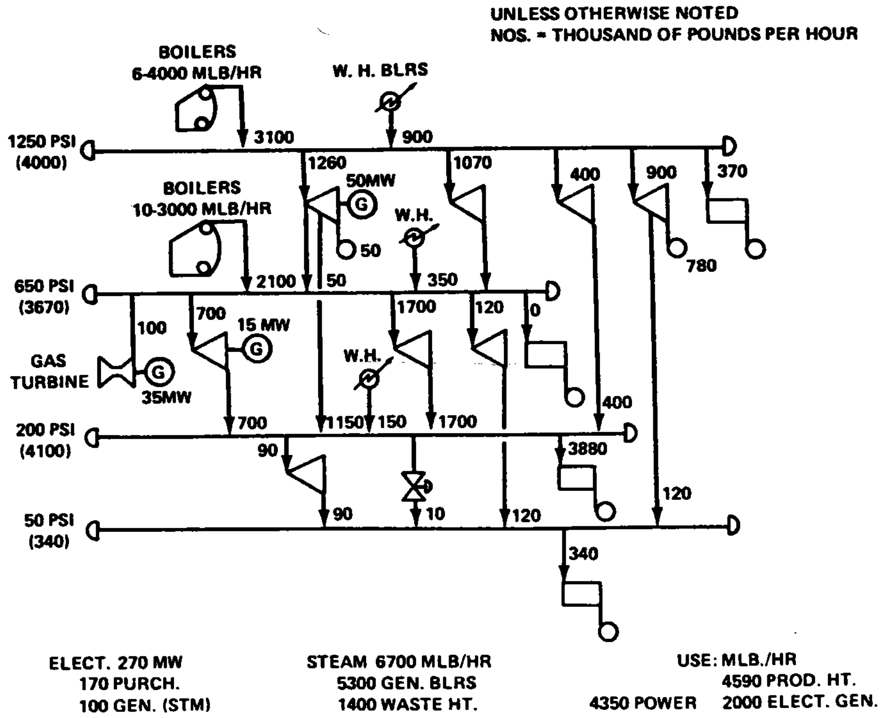


Figure 7

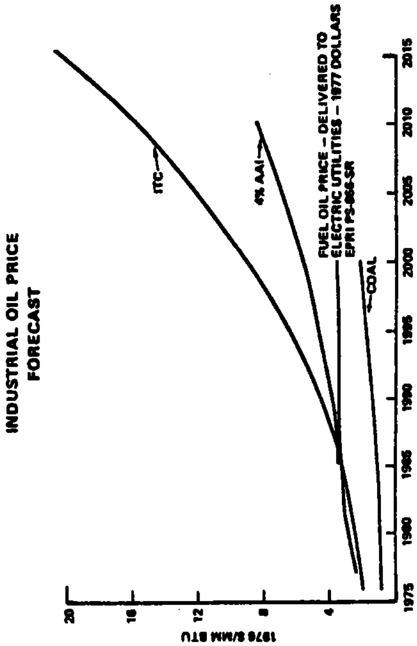


Figure 8

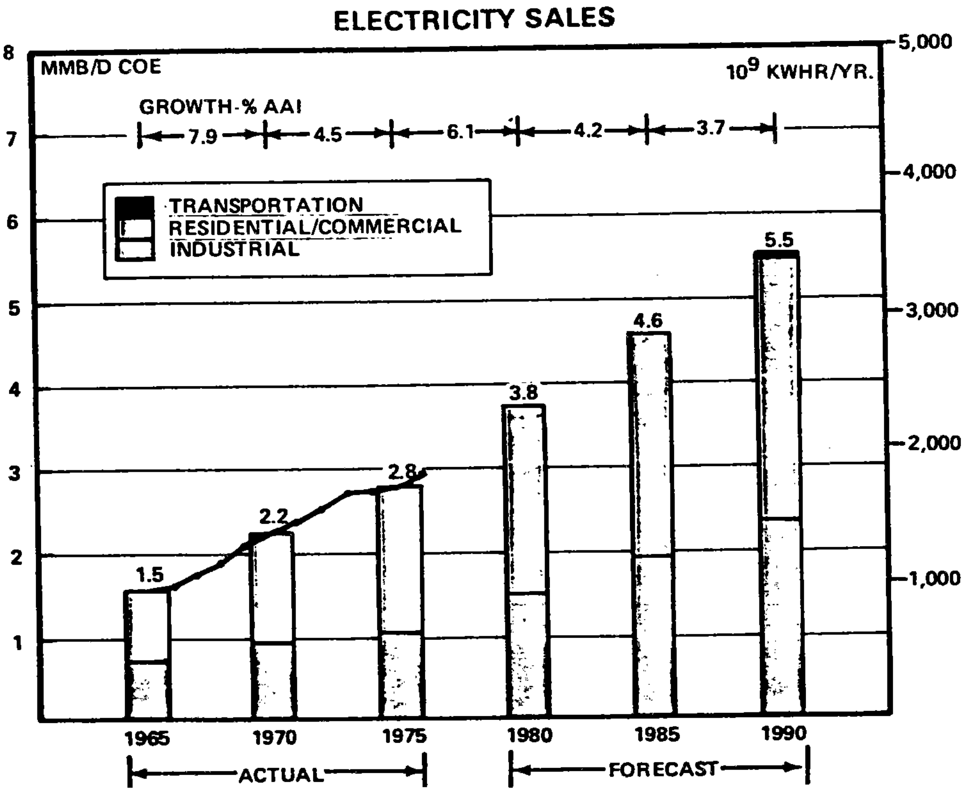
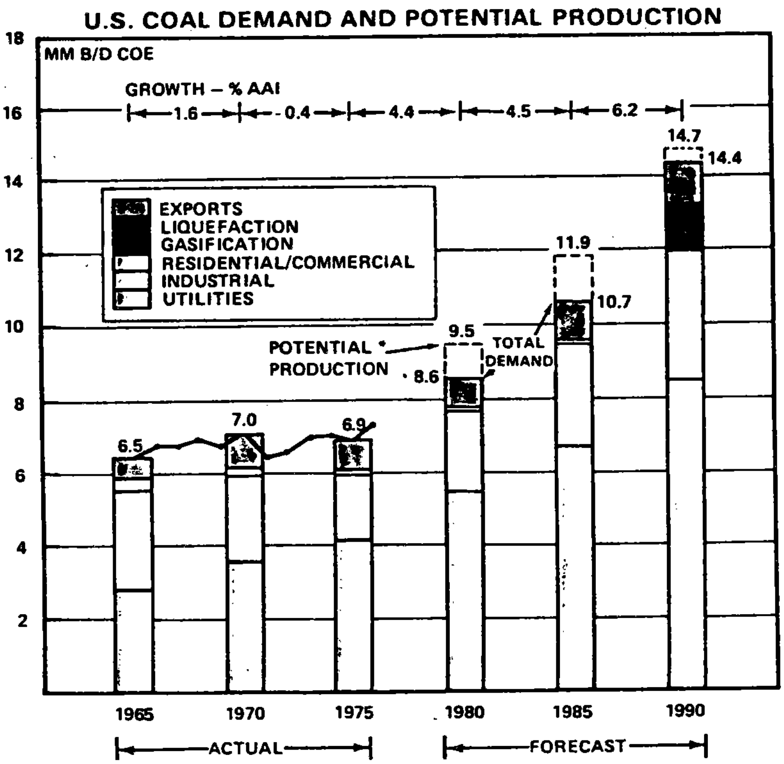


Figure 9



*POTENTIAL COAL PRODUCTION CONSIDERING MINING, TRANSPORTATION AND OTHER CONSTRAINTS

Figure 10

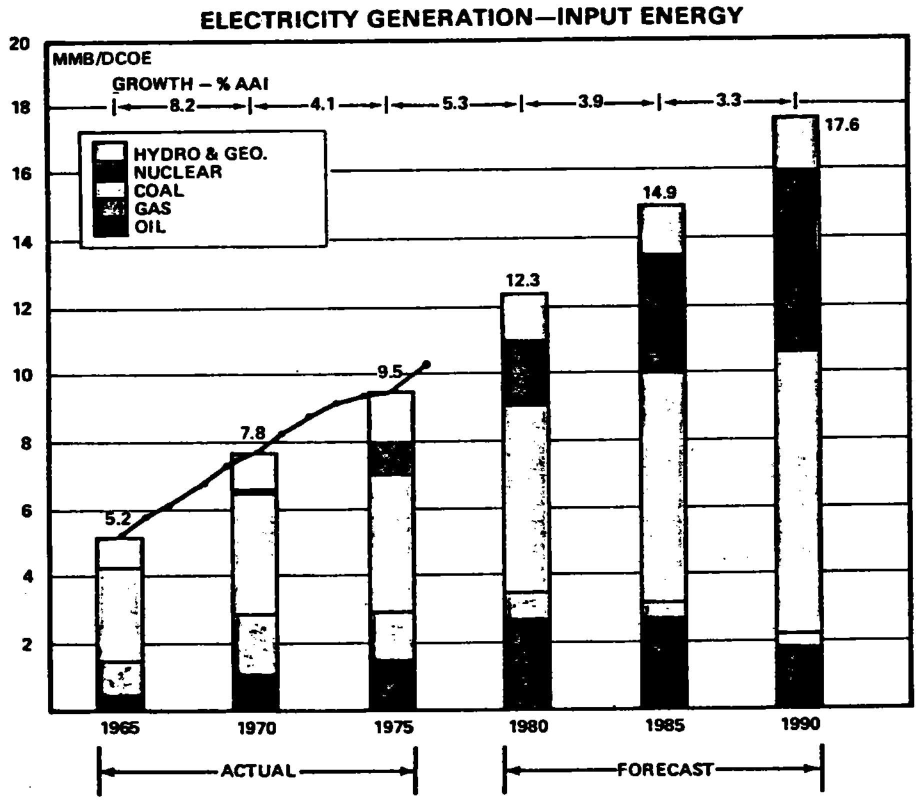


Figure 11

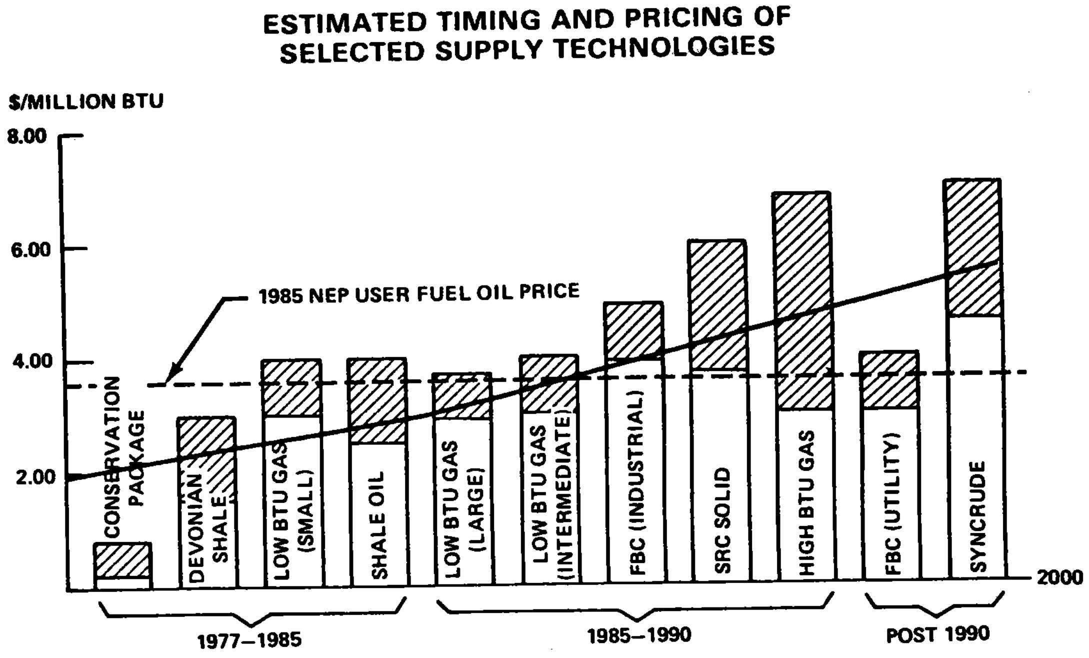


Figure 12

UNCONVENTIONAL OIL & GAS SUPPLY

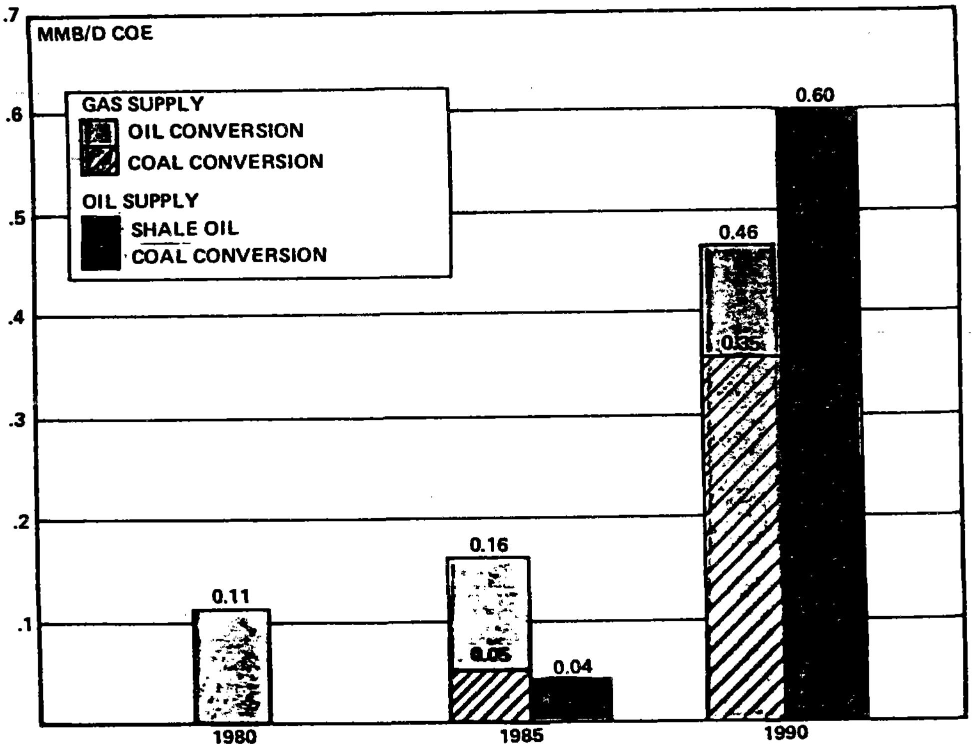


Figure 13

PARAMETERS USED TO DEVELOP ECONOMIC INSTALLED COSTS

6% DISCOUNT RATE

48% TAX RATE

10% INVESTMENT TAX CREDIT

2.2%/YR. MAINTENANCE }
1.5%/YR. TAX & INSURANCE } DISCOUNTED @ 6

SUM OF DIGITS METHOD OF DEPRECIATION OVER NINE YEARS – DISCOUNTED @ 6%

SOLAR COLLECTORS WILL COLLECT 250,000 BTU/SQ. FT./YEAR

Figure 14

ECONOMIC INSTALLED COST CALCULATIONS

FUEL SAVINGS*	$8.82
P V OF $1 CAPITAL EXPENDITURE	1.00
INVESTMENT CREDIT	– .10
MAINTENANCE	.23
DEPRECIATION CREDIT	– .40
NET	.73

ALLOWABLE CAPITAL INVESTMENT (ACI)/$ OF FUEL SAVINGS $= \frac{8.82}{.73} = \$12.08$

ECONOMIC INSTALLED COST (EIC) $= \frac{\text{FUEL COST/MM BTU X (ACI)}}{\text{4 SQ. FT. OF COLLECTOR/MM BTU}}$

EIC $/SQ. FT. IN 1990 $= \frac{3.80 \times 12.08}{4} = 11.48$

*NET PRESENT VALUE OF $1 FUEL SAVINGS EACH YEAR DISCOUNTED AT 6% EACH YEAR FOR 20 YEARS AFTER 4% GEOMETRIC INCREASE/YEAR AND TAX RATE OF 48%.

Figure 15

ECONOMIC INSTALLED COST CALCULATIONS

FUEL SAVINGS, PV OF $1/YEAR @ AAI OF FUEL PRICE	7.33 2%	8.03 3%	8.82 4%	9.71 5%
ALLOWABLE CAPITAL INVESTMENT / DOLLAR OF FUEL SAVINGS =	10.04	11.00	12.08	13.30

ECONOMIC INSTALLED COST

	1976	1985	1990	1995	2000
FUEL COST	1.99	3.12	3.80	4.62	5.62
@ 2% AAI	4.99	7.83	9.54	11.60	14.11
@ 3% AAI	5.47	8.58	10.45	12.71	15.46
@ 4% AAI	6.01	9.42	11.48	13.95	16.97
@ 5% AAI	6.62	10.37	12.64	15.36	18.69

Figure 16

ECONOMIC INSTALLED COST OF SOLAR THERMAL FACILITIES

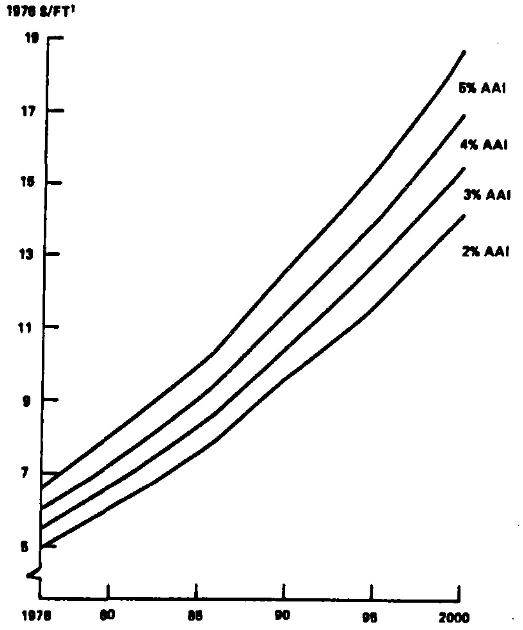


Figure 17

NITROGEN FERTILIZER PRODUCTION BY SOLAR THERMAL ENERGY

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Abstract

Nitrogen and oxygen in the air can be combined to produce nitrogen oxides at elevated temperatures (>2000°C). The temperatures necessary to produce nitric oxide, which is then air oxidized to nigrogen dioxide, can be obtained by focusing solar energy. Nitrogen dioxide can be trapped in water containing lime, limestone or rock phosphate to produce calcium nitrate fertilizer. The possibility exists, therefore, for developing a system that produces nitrogen fertilizer from air and solar energy. The economics for such a process today appear faborable for use on certain types of farm sites.

Background

Over thirty years ago, F. Trombe, et al (1947), demonstrated the synthesis of nitric acid by concentrating the irradiation of the sun on a quartz tube containing air and a thorium oxide catalyst. Trombe, et al (1951), later, described an improved system and Guilemont and Frixon (1952) also reported similar findings. For both technical and economic reasons at that time, these observations were not vigorously pursued. The highest product yield reported was 25 grams of nitric acid per kilowatt-hour of input energy (Trombe, et al, 1951). This yield was less than one-fourth of the yield obtained by the older electric arc process used commercially but abandoned about 1930. A modified version of the arc process system currently is being developed in our Laboratory (Treharne, et al, 1978).

At the time of the original investigations into the solar thermal process for the fixation of nitrogen, there was little economic incentive to conduct research and development into the solar thermal process for nitrogen fixation. Today, however, with the marked increased cost of nitrogen fertilizers derived from our declining natural gas reserves and continuously rising energy costs, the solar thermal process warrants further investigation.

Proposed System

This paper recommends that two modifications of the original solar thermal nitrogen fixation experiments be investigated.

The first modification we propose is that a complete system be developed for the on-site production of nitrogen fertilizer at the farm site where the fertilizer is to be used. On-site production of nitrogen fertilizer would eliminate the distribution and transportation costs responsible for a large percentage of the delivered cost. On-site production also would permit use of some of the waste heat of the process for other farm needs such as crop drying, space heating, etc. Thus, we believe that the economics of a complete system for the production of nitrogen fertilizer at the farm site could be more favorable than a large-scale, central processing system for the production of nitrogen fertilizer.

The second modification that we plan to study is the effect of recently developed catalytic materials on the over-all efficiency of the system. In particular, a study of the effect of catalytic materials exhibiting pyroelectric properties appears important. Pyroelectric materials have the capability of generating high voltages under thermal stress (e.g., Mattes and Perls, 1961, Treharne and McKibben, 1968). Thus it appears possible to combine some of the known advantages of the electric arc process for nitrogen fixation with the solar thermal process to produce a more efficient system for the production of nitrogen fertilizer.

The proposed system is shown in a flow diagram form in Figure 1 and a general outline of one version of the reaction chamber is shown in Figure 2. The flow diagram shows the basic input and output products of the proposed system for the on-site production of nitrogen fertilizer in calcium nitrate form. The reaction chamger shown is a lens-type system but, in actual practice, a parabolic mirror (or heliostat) system may be preferred. The reaction chamber will be designed to track the sun by one of several standard procedures. The pulsed air input may be found desirable if a pyroelectric material-type catalyst is used since the voltages generated by a pyroelectric material are proportional to the rate of change of temperature sensed by the pyroelectric crystals.

As described below, the reaction of combining nitrogen and oxygen to form nitrogen dioxide is a two-step reaction with the first step being an endothermic reaction and the second step an exothermic reaction. From our arc process research, we have evidence that the pulsed air approach also may improve the efficiency of the over-all reaction kinetics of the process.

The pyrolysis support material and the catalyst material, of course, must be chosen to withstand the high temperatures (>2000°C) involved. Materials such as magnesium oxide, tantalum oxide and tantalum carbide are a few of the materials that may be investigated as pyrolysis support and/or catalytic materials. Materials such as tourmaline or quartz may serve as pyroelectric-type catalytic materials.

Energy Requirements

The energy requirements for the formation of nitrogen oxides in the proposed system are given by one or more of the following reactions:

$$N_2+O_2 \longrightarrow 2\ NO, \quad \Delta G = +41.4\ \mathrm{Kcal/mol}$$

$$2NO+O_2 \longrightarrow 2NO_2 \quad \Delta G = -16.6\ \mathrm{Kcal/mol}$$

or by combining the above equations

$$N_2 + 2O_2 \longrightarrow 2NO_2, \Delta G = +24.8\ \mathrm{Kcal/mol}$$

The energy requirements in electrical units per gram or pound of nitrogen oxide are:

$$2.88 \times 10^{-2}\ \mathrm{KWH/92\ gms}\ NO_2$$

PROPOSED NITROGEN FERTILIZER PRODUCTION SYSTEM FLOW DIAGRAM

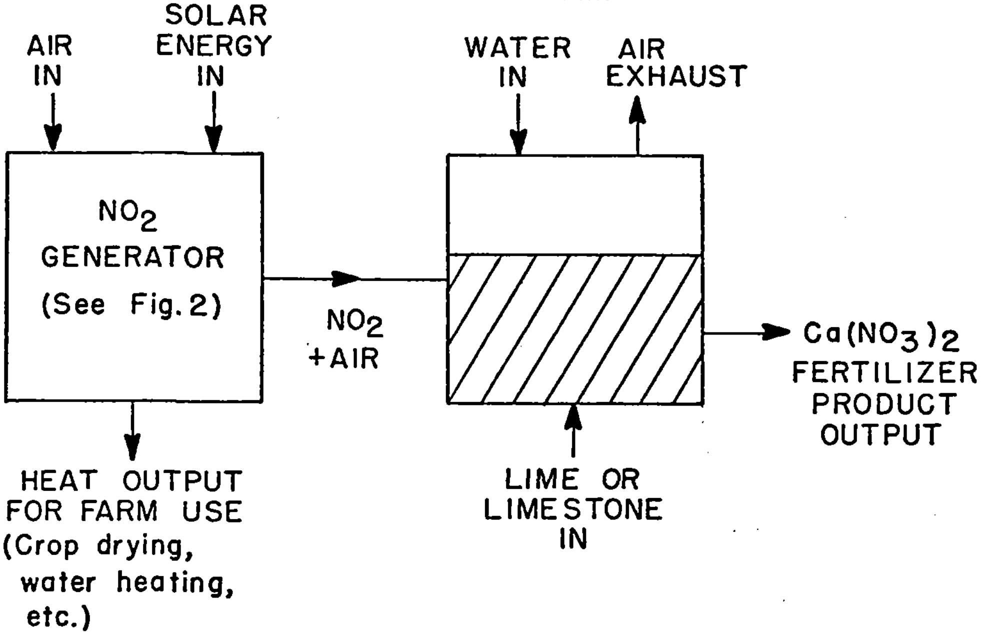
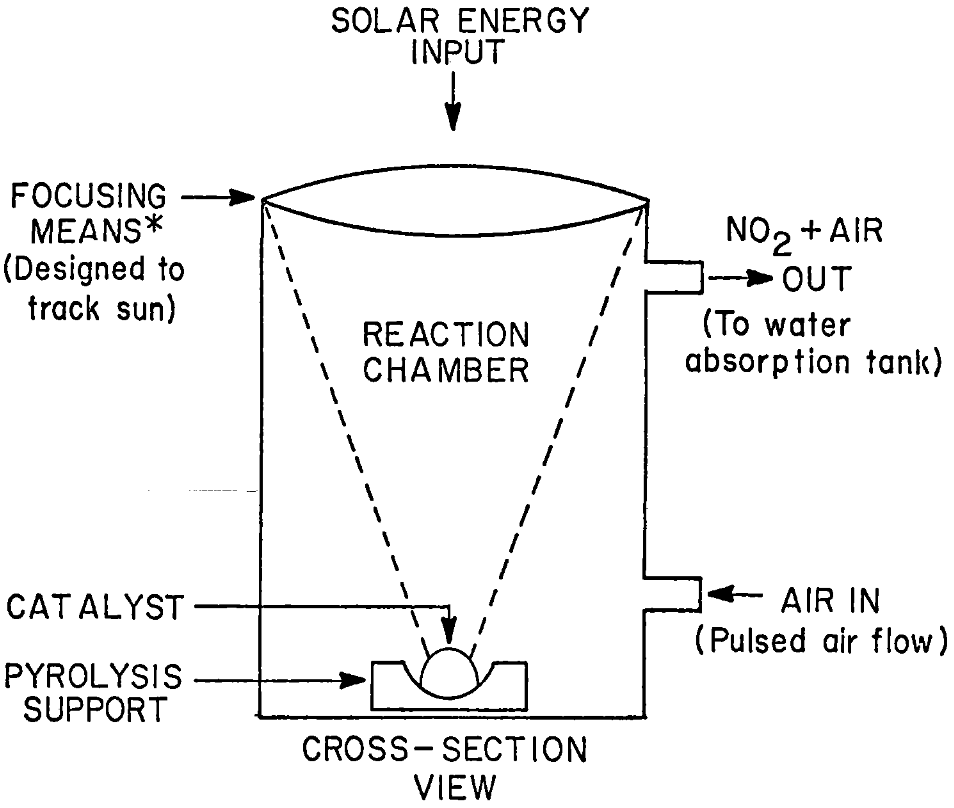


Figure 1

PROPOSED SOLAR-POWERED NITROGEN FERTILIZER GENERATOR



*Parabolic mirror (heliostat) focusing means may be preferred.

Figure 2

or 0.143 KWH/lb NO_2

or 0.469 KWH/lb fixed nitrogen

(theoretical minimum energy required)

The above are theoretical minimum energy requirements. In actual practice, from electrical arc systems currently being developed at our Laboratory, we have found that, in a practical system, the energy requirement is one kilowatt-hour to produce about 22 grams of fixed nitrogen product. (This corresponds to approximately 99 grams of product in the form of nitric acid). Or, conversely, about 42,000 kilowatt-hours are required to fix one ton of nitrogen. We believe that a solar thermal system of at least comparable efficiency is feasible.

To provide the energy required to fix one ton of nitrogen per year (i.e., 42,000 kilowatt-hours per year), an effective solar energy collecting area of 20 square meters would be required. This area requirement is based on an average insolation energy of 0.7 kilowatt per square meter in an area receiving 3000 hours of sunlight per year.

Economic Estimates

Using the above energy requirement estimates, equipment cost estimates for a system to produce one ton of fixed nitrogen per year are given in Table I. Amortizing the equipment cost estimates for a twenty-year period at 8 percent interest, we project that the cost per ton of nitrogen fertilizer (based on 100 percent nitrogen content alone) will range from \$250 to \$750 per ton. At the higher cost figures, the system would be economically feasible in only a few areas of the world where fertilizer costs presently exceed \$750 per ton. At the lower cost projection (\$250 per ton), the system could be competitive worldwide.

An increase in efficiency over the 2.2 percent over-all system efficiency assumed, or an increase in the present-day costs of nitrogen fertilizer could make the economics of the proposed system even more attractive. Also, effective use of some of the waste heat of the process could improve the economic projections summarized in Table I.

Proposed Solar Thermal Nitrogen Fertilizer Generator

(Projected Cost Estimates)

Assumptions

1. Energy requirement to "fix" 1 ton of nitrogen in nitrate form is 42,000 Kilowatt hours per ton of fixed nitrogen--based on a system efficiency as low as 2.2 percent (see text).

2. A 20-square meter tracking heliostat, providing temperatures to 2000°C, will supply enough energy to fix 1 ton of nitrogen per year--based on an average sunlight energy of 0.7 KW/sq. meter/hour in a location providing 3000 hours of sunlight per year.[A]

Capital Equipment Cost Estimates

(To produce 1 ton of nitrogen fertilizer per year)

		Today	Projected
1.	20 sq. meter heliostat and tracking mechanism, installed	\$5000[A]	\$1200[A]
2.	reaction chamber and product collecting system	3000	1500
	Total	\$8000	\$2700
	Total cost amortized over 20 years $\cong$	\$ 750/yr[B]	\$ 250/yr[B]

Conclusions

1. In certain areas, such as less developed countries, where nitrogen fertilizer costs exceed \$700 per ton of <u>fixed</u> nitrogen, a solar-powered nitrogen fertilizer generator could be economically feasible today.

2. If projected costs are realized, or greater than 2.2 percent efficiency is obtained, a solar-powered nitrogen fertilizer generator could find wide use.[C]

   A. The heliostat energy collection and cost estimates have been kindly supplied by Mr. George Kaplan, Chief, Central Power Branch, Division of Solar Energy, DOE

   B. Present-day costs of fixed nitrogen fertilizer, in anhydrous ammonia form, are \$200 to \$300 per ton of fixed nitrogen to the United States and >\$700 per ton in some areas of the world. An increase in natural gas prices will increase the above quoted prices for ammonia since natural gas is a feestock for the production of ammonia.

   C. The 2.2 percent efficiency assumed is considered to be conservative. This conservative estimate, plus the probability that effective use of the waste heat of the system can be developed, may result in a more economically attractive system than presented.

Table I

Question - Do you have any thoughts about that catalyst?

Mr. Treharne - In the arc process we found that certain types of additives work best, particularly molybdenum. The catalyst is all-important and I want to emphasize that. It's not just a matter of focusing the energy. In order to extract you have to have some form of catalyst. We know that in the arc process it's more involved than simply temperature. The ionization takes place and that's important but another thing we are proposing is to look at some of the newly developed pyroelectric materials. These materials have the characteristic of generating very high voltages under different tunnel stresses. It's possible that one could combine both solar and electrical in the solar system. This is another variation on what was done in the late 1940's and early 1950's.

Question - Would you say anything about any of the schemes you tried that did not work in the three years you were trying?

Mr. Treharne - One was the model I showed you of the electrode system that got us the money originally. Although it looks nice, it's very inefficient. We went through many types of cell designs. We have tried many fuels to spread out the arc. We have tried rotating electrodes. We have tried many different types of cell configurations like cone-shaped and double cone-shaped. The trick is to get the gas expanded rapidly after you make the NO in order to cool it. The type of cell design one uses is very important as well as the materials in the cell because the electrodes act more than just like electrodes--they are catalytic.

Comment - I think you will find that at 2000 degrees the reaction is extremely high and is limited by the thermodynamics but I'm not sure the catalyst is the real priority in this system.

Mr. Treharne - We know it has been done before.

Question - What catalyst will stand up under 2000 degrees?

Mr. Treharne - Magnesium bauxite. I wouldn't call it a catalyst necessarily but that is one thing that has been used.

References

F. Trombe, M. Foex, and C. H. LaBlanchetais, "Synthesis of Nitric Acid by Concentrating the Irradiation of the Sun," Compt. rend. 225, 1073-5 (1947)

F. Trombe, M. Foex and C. H. LaBlanchetais, "New Tests on the Synthesis of Nitric Acid with the Help of Solar Energy," Compt. rent. 233, 311-13 (1951)

A. Guilemonat and L. Frixon, "Nitric Acid Synthesis by Solar Rays," Compt. rend. 234, 1371-3 (1952)

S. B. Lang, "Use of Pyroelectric Devices for Measuring Temperature Changes," Temperature, Its Measurement and Control in Science and Industry, Vol. 3, Part 2, Reinhold Publ. (1962)

R. W. Treharne and C. K. McKibben, "Direct Reading, Wavelength Independent Radiometer Employing a Pyroelectric Crystal Detector," US Patent No. 3,398,281 (1966)

R. W. Treharne, D. R. Moles, M. R. Bruce and C. K. McKibben, "A Nitrogen Fertilizer Generator for Farm Use," C. F. Kettering Research Laboratory Technical Note 1 (1978)

AMMONIA AND NITROGEN FERTILIZERS

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Feedstocks for Ammonia

Last year, we in the United States used 60 percent more natural gas and 100 percent more oil than we discovered.(1) This situation is having a serious impact on the chemical industry which is already faced with dwindling supplies of natural gas and is heavily dependent on imported oil. Both industry and government experts are attempting to answer the question of just how long supplies of these two important resources will last. Although there are wide differences of opinion, all agree that the US is short on known reserves and rapid development of additional reserves must take place. In order to maintain the 1975 demand for natural gas, reserves must be added at the rate of 17 trillion cubic feet/year, when in reality additions to the reserves have dropped from a high of 21.1 trillion cubic feet in 1967 to only 8 trillion cubic feet in 1975.(2) This translates to future development of serious natural gas shortages even with declining usage as shown in Figure 1.

Gas reserves at the end of 1976 were estimated to be about 216 trillion cubic feet and total annual consumption to be about 20 trillion cubic feet.(3) Considering increased production from known reserves plus gas likely to be discovered in the future, most experts predict that our gas will be depleted in the next few decades.(4) As a result, substantial increases in gas prices are expected.

How is all of this likely to affect the nitrogen fixation industry? About 95 percent of current ammonia capacity is based on natural gas which is used both as fuel and the hydrocarbon feedstock. Practically all nitrogen fertilizer is produced from ammonia. In order to assure adequate supplies of food and fiber, our agricultural industry must have nitrogen fertilizer. Therefore, development of alternate feedstocks for ammonia production as well as alternate nitrogen sources deserves our highest priority efforts.

Much valuable research work is in progress on alternate methods of nitrogen fixation. Parallel efforts are also being carried out to develop alternate energy sources, such as solar energy, nuclear fusion, energy derived from thermal differences in seawater and biomass conversion. Although all these efforts will help in the future to provide nitrogen to our agricultural industry, they will not solve the immediate need to develop an alternate feedstock for the existing ammonia producing industry. Gas curtailments in recent years have already resulted in significant production losses.

For the short run, major programs are already underway for conversion to oil or coal for fuel.(5) Naphtha and heavy fuel oils can be used as feedstock for producing ammonia, but because of high cost, scarcity, and large capital investments required for conversion, they are not attractive alternatives. It appears that coal is the only viable alternative for the foreseeable future.

Coal reserves in the US recoverable by current technology have been estimated to be sufficient for 700 years at current use rates and for approximately 100 years assuming a six percent per year increase in consumption. Sizeable portions of these reserves are located in or near the large agricultural regions of the nation.

Coal as a Feedstock

The basic technology for producing ammonia from coal is now available but is in need of further development particularly in the areas of improved reliability and definition of the economics. Existing technology was developed in Germany prior to World War II and has been used in about 20 plants including two large plants in India which are in the commissioning phase and one large plant in South Africa which is performing satisfactorily following a two-year period beset by difficulties. There is a need for research, development, and demonstration of coal-based technology in the US to provide the information and confidence needed for the industry to embark on a multibillion dollar conversion and expansion program.

In 1975, the Tennessee Valley Authority (TVA) and the Fertilizer Institute (TFI) identified the need to develop highly visible, efficient US technology for production of ammonia from coal as the top priority for the nation's fertilizer R&D. This conclusion was also reached independently by the Agricultural Research Policy Advisory Committee and the National Academy of Science. TVA has responded to this need by establishing an Ammonia from Coal Project at its National Fertilizer Development Center at Muscle Shoals, Alabama.

An investigative study(6) showed that the quickest and lowest cost approach to the problem would be to retrofit coal gasification facilities to TVA's small, but modern, ammonia plant at Muscle Shoals. The TVA plant, completed in 1972, uses steam reforming of natural gas to produce 225 tons per day of ammonia. It can be operated at a minimum capacity of 60 percent of 135 tons per day. The least cost installation would be one that would gasify enough coal to produce 135 tons per day of ammonia and would make maximum use of the equipment in the existing plant. The new facility would produce a gas to match the composition, temperature, and pressure at the inlet of the existing low-temperature shift converter, Figure 2. This would allow flexibility to operate with 60 percent of the synthesis gas from coal and 40 percent from natural gas or at 60 percent capacity using coal only.

The gasification process to be used was chosen on the basis that it should accept a wide variety of coals, produce a gas at a composition, temperature, and pressure compatible with ammonia processes, and with a minimum of undesirable contaminants, and be of reliable, modern US technology with a sufficiently advanced state of the art and competitive economics.

After a thorough review of all available processes, the Texaco Development Corporation process was selected for the project because it best met the above criteria and has been commercially proven with oil as a feedstock. The process will be used to partially oxidize and gasify about 170 tons of coal per day.

There are about 100 natural gas-steam reforming ammonia plants in the US, of which about 30 are 1000-ton-per-day capacity. The TVA demonstration facility should provide a basis for retrofitting these existing plants. In addition, much of the technology developed will be applicable to new grass roots facilities designed to produce ammonia from coal. Besides the TVA Ammonia from Coal Project, the US Department of Energy (DOE) is conducting two projects for production of synthesis gas from coal.(7) These complement the TVA project in that they involve grass roots facilities while the TVA plant is primarily a retrofit project.

Four basic steps are required to produce ammonia from any feedstock; gas preparation, shift conversion, gas purification, and ammonia synthesis, Figure 3. The shift conversion, gas purification, and ammonia synthesis steps are similar in most commercial processes. Significant variations occur when pure hydrogen is available (e.g., electrolysis of water) or when byproduct gases such as refinery gas or cokeoven gas are used.

For the natural gas plant, Figure 3, methane is reacted with water (steam) at about 900-1000°C and moderate pressure to produce carbon monixide, carbon dioxide, and hydrogen. Air is introduced into the process to provide the nitrogen for ammonia synthesis. From the reforming section the gas passes to the shift section where the remaining carbon monoxide is reacted with water to produce carbon dioxide and hydrogen. The carbon dioxide is removed in an acid gas-removal system and the remaining trace quantities of carbon monoxide and carbon dioxide are converted back into methane. The synthesis gas containing hydrogen, nitrogen and trace quantities of methane and argon is introduced into the high-pressure synthesis section for conversion to ammonia. The process described above is very energy intensive.

Energy Requirements for Ammonia Production

Energy required for the various types of processes is given in Table I. Production of one ton of ammonia by partial oxidation of coal requires about 41 million Btu's. About 35 million Btu's per ton are required for the natural gas reforming process. The first step in the ammonia process, reforming, uses most of the energy required by the process. About 60 percent of the gas requirement in natural gas reforming is necessary to produce hydrogen for ammonia synthesis and the remaining 40 percent is used as fuel in the reforming section. Of the gas used as fuel, only about 50 percent provides heat for endothermic reforming reaction and the remainder is recovered in the furnace convection section. Of the 60 percent for the process, about 76 percent of the hydrogen potential of the gas is necessary for ammonia synthesis. About 15 percent of the remaining 24 percent of the hydrogen potential is used for combustion with the oxygen in the air introduced in the reforming section, Table II. Burning of this hydrogen also provides the heat necessary to complete the endothermic reforming reaction. The remaining 9 percent of the hydrogen potential of the process gas is lost through purging from the synthesis loop and process losses.

In summary, about 30 percent of the total energy required for ammonia production is used to supply heat to the endothermic reforming reaction at 800-950°C. This high-temperature energy could be supplied from another source such as solar energy.

The overall thermal efficiency of a conventional, natural gas ammonia plant ranges from approximately 75 to 85 percent depending on the design. This efficiency can be increased to 90 to 93 percent by reducing purge losses and improving recovery of low level heat primarily from the flue gases. Many producers are already working at improving heat recovery because of the increasing cost of energy. Therefore, there is not much potential for use of solar energy to supply low level heat for ammonia plants.

Supply and Demand Situation-Nitrogen Fertilizers

Ammonia is the building block for essentially all of the nitrogen fertilizer used in the world. The primary products are ammonium nitrate and urea and solutions containing these materials. In 1968, the world capacity for producing ammonia was about 35 million tons, Figure 4. Presently the capacity is about 85 million tons. In the early 1980's, it is expected that the capacity will surpass 100 million tons which means that growth is taking place at a rapid rate. Capacity in the United States in the early 1970's was about 13 million tons and the current capacity is about 17 million tons, Figure 5. Capacity is expected to increase to about 25 million tons in the early 1980's.

Planning for this expansion in the US is already beginning which means that decisions about feedstocks for the plants will be made in the near future. Uncertainties about natural gas and oil supplies are complicating the decisions. Results of much of the research being done today, such as solar energy, will not be available in time to affect the new capacity. Therefore we at TVA think that the primary feedstock for some of the new plants will be coal.

There is currently an oversupply of fertilizer nitrogen in this country, Figure 6. By the early 1980's this situation should begin to reverse which means that additional capacity will be necessary. Figure 7 shows where the growth is likely to take place. In recent years ammonium nitrate production has been decreasing and the trend is expected to continue. Production of nitrogen solutions and urea are expected to continue to increase. Nitrogen solutions are becoming more and more popular because of the convenience of use. Urea is increasingly replacing ammonium nitrate as a solid fertilizer because it is cheaper to produce and is more concentrated than ammonium nitrate.

Economics of Ammonia from Alternate Feedstocks

Those engaged in research and development need some idea of how the economics of the new developments compare with current practices. For this reason, the following discussion of costs of producing ammonia has been included.

Conceptual designs and cost estimates were prepared for 1000 short-ton-per-day newly constructed ammonia plants for the following processes:

1. Natural gas - steam reforming
2. Naphtha - steam reforming
3. Fuel oil - partial oxidation
4. Coal - partial oxidation
5. Electrolytic hydrogen

Estimates of the capital required for each of the processes are shown in Table III. Each of the plants has a capacity of 1000 tons per day and is rated at 330,000 tons annually. The working capital is based on 60 days' production cost. The capital investment and the production cost estimates are for mid-1978.

The equivalent energy requirements per ton of ammonia for fuel and process feedstocks range from 34.5 MM Btu's for natural gas to 41 MM Btu's for partial oxidation of coal as shown in Table I.(8,9,10) Thus, ammonia synthesis is an energy-intensive process, not only in terms of the heat energy (fuel) required, but also in terms of the chemical process feed required.

Requirements per ton of ammonia for the fuel, feedstock, and cooling water for natural gas, naphtha, and fuel oil processes were cited by Buividas.(11) The data for the electrolytic production of hydrogen was developed from information presented by Norsk Hydro(12) except for the electricity requirement which is from Smith and Hatfield.(9) The other process requirements such as boiler feedwater, labor, maintenance, etc., are from Nichols and Blouin.(13)

Costs assigned to feedstock and fuel, labor, utilities, materials, and maintenance are shown in Table IV. Capital charges were taken as 19.7 percent of the total capital investment, Table V. The plant life was assumed to be 15 years, with straight-line depreciation.

Calculations were made for the revenue requirements for each of the processes. Data for the natural gas plant are shown in Table VI. Similar calculations were made for the other processes. The revenue requirements represent the average price that would have to be charged under the assumptions of the base case to recover the full costs including a normal return on investment. Operation at less than the assumed efficiency and/or rate could significantly increase the revenue requirements per ton of ammonia.

Revenue requirements ranged from a low of $147/t for ammonia from the natural gas reforming process to a high of $417/t from the electrolytic process, Figure 8. Ammonia at $180/t from a coal-based plant was second to natural gas followed closely by ammonia at $184/t from fuel oil and at $191/t from naphtha.

Although this study shows the revenue requirements for the base case for coal to be lower than either fuel oil or naphtha, circumstances different from the base case could cause any one of these three feedstocks to be selected for a specific plant. Even ammonia from electrolytic hydrogen should be considered under special circumstances. Electrolytic hydrogen plants have been used for ammonia production for many years where inexpensive electricity is available.

The major components of the revenue requirements, representing 80 percent of the cost of ammonia from natural gas-steam reforming, are energy costs (feedstock and fuel) and capital charges. The effect of variation in the cost of energy, for both fuel and feedstock, on revenue requirements per ton of ammonia is also shown in Figure 3. Minor inputs of heat (steam) or electrical energy are held constant. It can be seen that if natural gas rises to around $3.60 MCF, coal (10,800 Btu/lb) would be competitive at the base case price of $27/t. Naphtha (19,000 Btu/lb) at the base case price of $125/t would be competitive with natural gas at $3.90/MCF. Similarly, heavy oil at $13/bbl would be competitive with natural gas at $3.70/MCF.

This study indicates that:

1. If the cost for coal, naphtha, and fuel oil remain near the levels of the base cases and the cost of natural gas increases to around $3.50-$4/million Btu, ammonia from these alternate feedstocks would be competitive with ammonia produced from natural gas.

2. Coal, naphtha, and fuel oil should be considered as alternative feedstocks to meet the demand for ammonia if the supply of natural gas becomes too restricted.

3. With the assumptions of the base cases, electrolytic hydrogen is not competitive with the other processes considered. To become competitive, the cost for electricity would need to be greatly reduced and/or marketable byproducts would have to be produced.

In summary, production of nitrogen fertilizer is a very energy-intensive process. As cost of energy increases and natural gas availability decreases, producers will be looking at substitute energy sources. Research to develop these alternate sources deserves our highest priority efforts.

References

1. American Gas Association, Committee on Natural Gas Reserves, "News Release," April 10, 1978.

2. Mayfield, R. R., "Natural Gas Supply and Pricing on the Gulf Coast." Chemical Engineering Progress, 25-31, October 1977.

3. Meyer, Richard F., "A Look at Natural Gas Resources," Oil and Gas Journal, 334-346, May 8, 1978.

4. Schanz, J. J., Jr., "Oil and Gas Resources--Welcome to Uncertainty," Resources, No. 58, March 1978.

5. Friedman, Jack, "US Chemical Industry to Invest in Fuel Change," Chemical Age, March 17, 1978.

6. Tennessee Valley Authority (TVA). "Investigative Phase Report, Ammonia from Coal Project," November 1976 (Unpublished).

7. ERDA, "Information from ERDA--Weekly Announcements," Volume 3, No. 36, No. 77-151 and No. 77-117, July 18, 1977.

8. Slack, A. V. and James, G. R., Ammonia--Part 1, Marcel Dekker, Inc., New York, 1973, page 341.

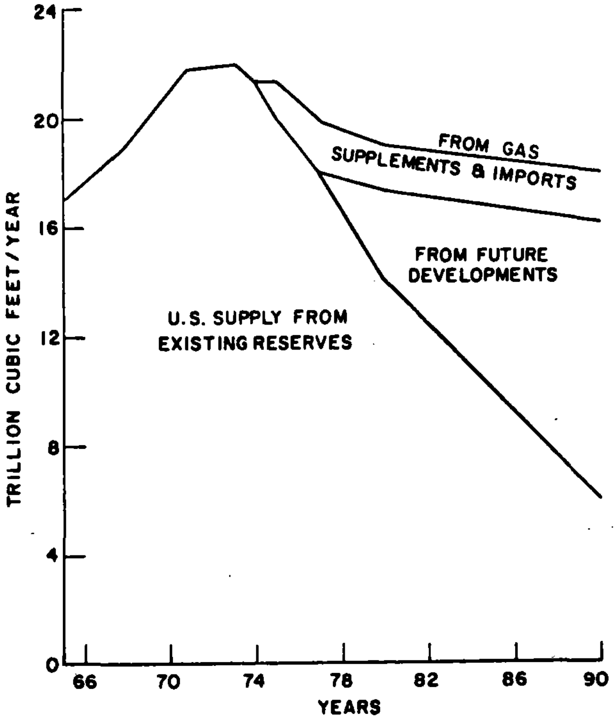
9. Smith, A. J. and Hatfield, J. D., "A New Look at the Electrolytic Production of Hydrogen for the Manufacture of Ammonia." Tennessee Valley Authority, Muscle Shoals, Alabama, May 1978.

10. Quartulli, O. J. and Turner, A., Nitrogen, No. 80, 2834 (November-December 1972).

11. Buividas, L. J., Finneran, J. A., and Quartulli, O. J., "Alternate Ammonia Feedstocks," Chemical Engineering Progress, 21-35, October 1974.

12. Grundt, T., "Water Electrolysis and Its Possibilities as Basis for Ammonia Production." Norak Hydro Fertilizer Technology Seminar, Sao Paulo, Brazil, January 26 and 27, 1977.

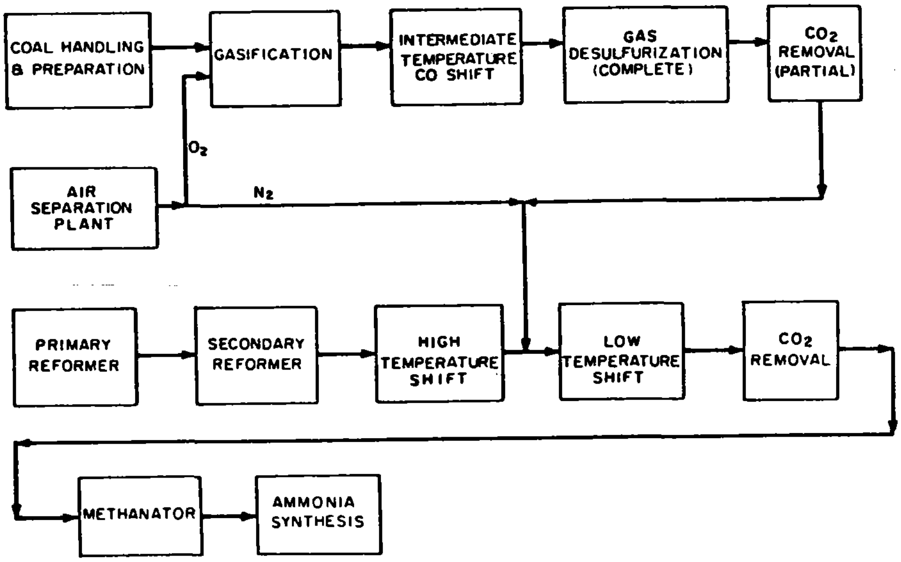
13. Blouin, Glenn M. and Nichols, David E., "Economic Considerations of Chemical Nitrogen Fixation." Tennessee Valley Authority, Muscle Shoals, Alabama, August 1977.

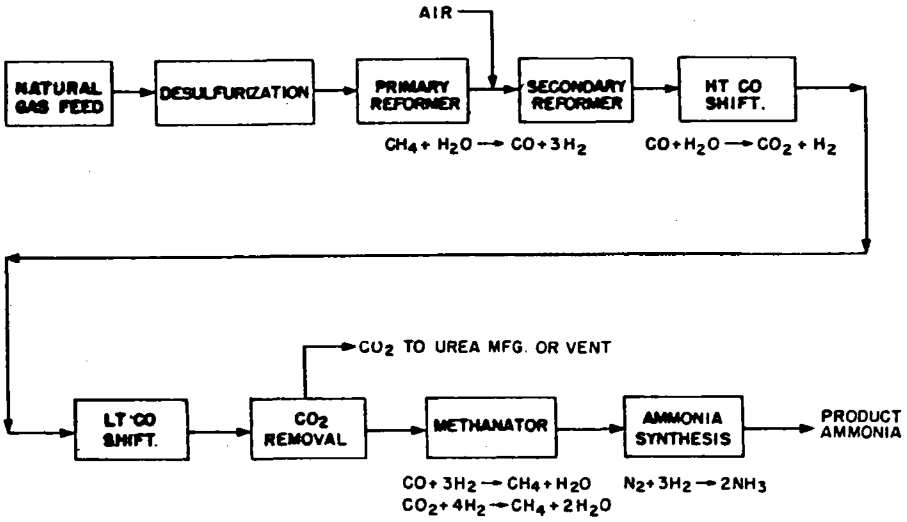


Source: Mayfield, R.R., 1977

FIGURE 1
U.S. NATURAL GAS SUPPLY

FIGURE 2
COAL GASIFICATION RETROFIT TO EXISTING NH_3 PLANT





NATURAL GAS ROUTE TO AMMONIA PRODUCTION
FIGURE 3

Table I

ENERGY REQUIREMENTS FOR ONE TON OF AMMONIA

Fuel/Feedstock	Process	Energy consumption Btu x 10^6/t NH_3
Natural gas	Reforming	34.5
Naphtha	Reforming	37
Fuel oil	Partial oxidation	38
Coal	Partial oxidation	41
Electricity/water	Electrolysis	36

List of abbreviations:

Btu - British thermal unit

t - ton

TABLE II

FEED LOSS IN STEAM REFORMING PROCESS

Item	Type of Loss	% of Potential Hydrogen
Secondary Reforming	Combustion of H_2, CH_4 with O_2	15
Purge from Syn-Loop and other losses	Loss of H_2, N_2, and NH_3	9
Total		24

Source: Reference 3

FIGURE 4

OWNERSHIP OF WORLD AMMONIA CAPACITY

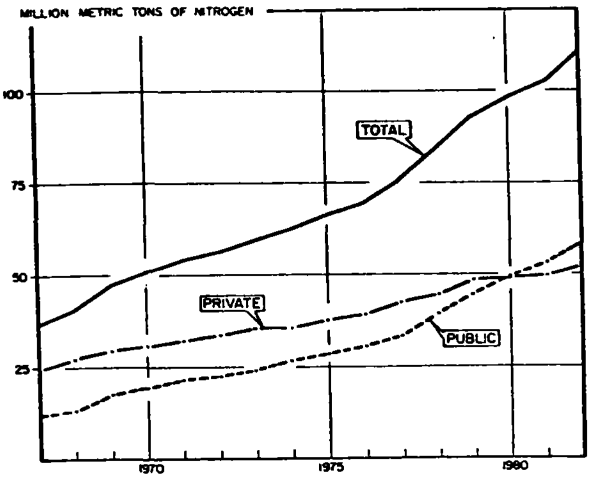


FIGURE 5

ANHYDROUS AMMONIA PRODUCTION

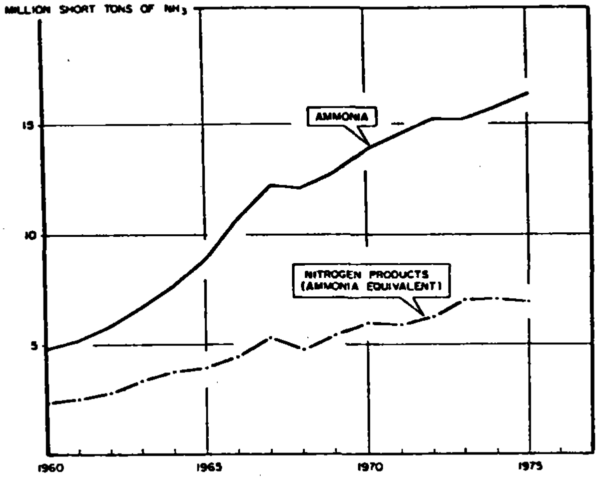


FIGURE 6

U.S. NITROGEN SUPPLY-DEMAND OUTLOOK

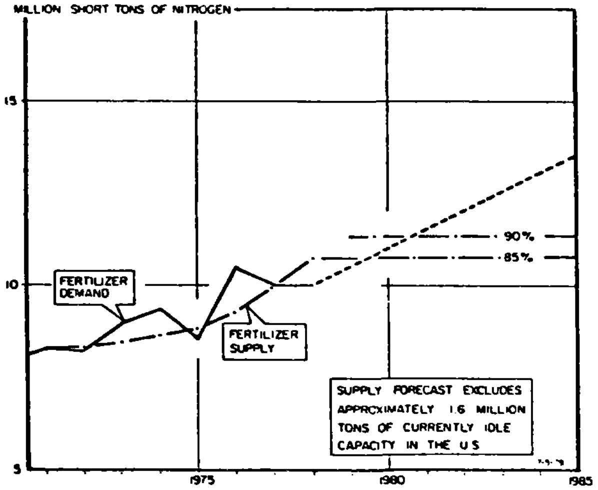


FIGURE 7

CONSUMPTION OF NITROGEN FERTILIZER MATERIALS

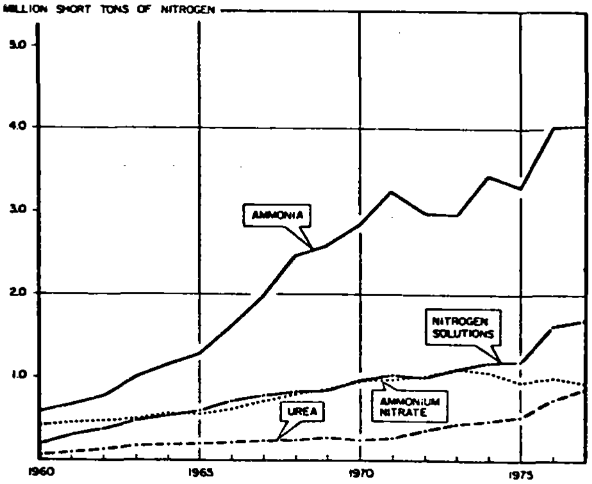


TABLE 3

CAPITAL INVESTMENT REQUIREMENTS FOR 1000 TPD AMMONIA PLANTS

	Investment[a], $ million (1000 t/day plant)				
	Natural Gas	Naphtha	Partial Oxidation		Electrolytic
Investment Item	Reforming	Reforming	Oil	Coal	(Conventional)
Battery limits NH_3	50.0	57.1	94.5	99.9	74.3
Site preparation	1.8	1.8	1.8	2.7	1.8
Auxiliary facilities	7.5	8.5	10.2	15.0	7.5
Support facilities	7.5	8.5	10.2	15.0	7.5
Subtotal	66.8	75.9	116.7	132.6	91.1
Product storage	3.6	3.6	3.6	3.6	3.6
Total depreciable investment	70.4	79.5	120.3	136.2	94.7
Land	0.1	0.1	0.1	0.1	0.1
Working capital	5.1	7.2	5.4	4.5	18.8
Total capital investment	75.6	86.8	125.8	140.8	113.6

[a] Chemical Engineering Plant Index = 218.4

List of abbreviations:

t - ton

TPD - tons per day

TABLE IV

Unit Rates for Base Cases

Energy	Units	Price/Unit,$	$/MM Btu
Natural gas (1,000 But/scf)	1,000 MCF	2.50	2.50
Naptha (19,000 Btu/lb)	t	126.00	3.31
Fuel Oil (19,000 Btu/lb)	Bbl	13.00	2.21
Coal (10,800 LHV Btu/lb)	t	27.00	1.25
Electricity	kWh	0.027	7.91
Labor			
Operating labor and supervision	manhours	8.00	
Utilities			
Cooling water makeup	M gal	0.25	
Boiler feedwater	M gal	1.00	
Materials - Intermediates, catalysts, and chemicals			
			$ton/$NH_3$
Natural gas - steam reforming			0.75
Naptha - steam reforming			1.00
Fuel oil - partial oxidation			0.50
Coal - partial oxidation			0.50
Electrolysis			0.50
Maintenance			
50% material and 50% labor (chemical processes)		5% of depreciable investment	
50% material and 50% labor (electrolytic)		2.5% of depreciable investment	
Indirect Costs			
Average capital charges		19.7 of total plant investment	
Administrative and plant overhead		75% operating & maintenance labor	
Marketing		3.00/ton NH_3	
Working Capital		60 days' direct production cost	

List of abbreviations:

Bbl - barrel

Btu - British thermal unit

gal - gallon

kWh - kilowatt hour

lb - pound

LVH - lower heating value

M - thousand

MM - million

mcf - thousand cubic feet

scf - standard cubic feet

TABLE V

Capital Charges for Base Case

	Percentage of total depreciable capital investment
Depreciation (15-year life)	6.7
Insurance	0.5
Property taxes	1.5
	8.7
	Percentage of unrecovered capital investment[a]
Cost of Capital (capital structure assumed to be 40% of debt and 60% equity).	
Debt at 10% interest	4.0
Equity[b] at 15% return on investment	9.0
Income taxes (Federal and State)	9.0[c]
total rate applied to depreciation base	22.0
	Percentage of total capital investment
Total annual capital charge rate	19.7[d]

---

[a] Original investment yet to be recovered or "written off."

[b] Contains retained earnings and dividends.

[c] Since income taxes are approximately 50% of gross return, the amount of taxes is the same as the return on equity.

[d] Applied on an average basis, the total annual percentage of original investment for new (15-year) plants would be 8.7 + 1/2 (22.0%) = 19.7%.

TABLE VI

Natural Gas-Steam-Reforming/Ammonia Production[a]

Total Average Revenue Requirements

	No. units/t product	Unit cost, $	Cost/t product $	Total annual cost, $
Direct Costs				
Materials				
Feedstock, natural gas				
(1,000 Btu/scf)	20.40 MCF	2.50/MCF	51.00	16,830,000
Intermediates, catalysts, and chemicals			0.75	248,000
Utilities				
Fuel, natural gas	10.60 MCF	2.50/MCF	26.50	8,745,000
Electricity	30.00 kWh	0.027/kWh	0.81	267,000
Cooling water	2.00 M gal	0.25/M gal	0.50	165,000
Boiler feedwater	0.60 M gal	1.00/M gal	0.60	198,000
Labor				
Operating labor and supervision	0.18 man-hr	8.00/man hr	1.44	475,000
Maintenance labor and material				
(5% of depreciable plant investment)			10.70	3,531,000
General expense			1.00	330,000
Subtotal direct costs			93.30	30,789,000
Indirect Costs				
Capital charges, 19.7% total				
capital investment			45.13	14,893,000
Administrative and plant overhead			5.09	1,680,000
Marketing			3.00	990,000
Subtotal indirect costs			53.22	17,563,000
Total revenue requirement			146.52	48,352,000

---

[a] Basis:

Plant capacity 1,000 t/day, 330,000 t/year

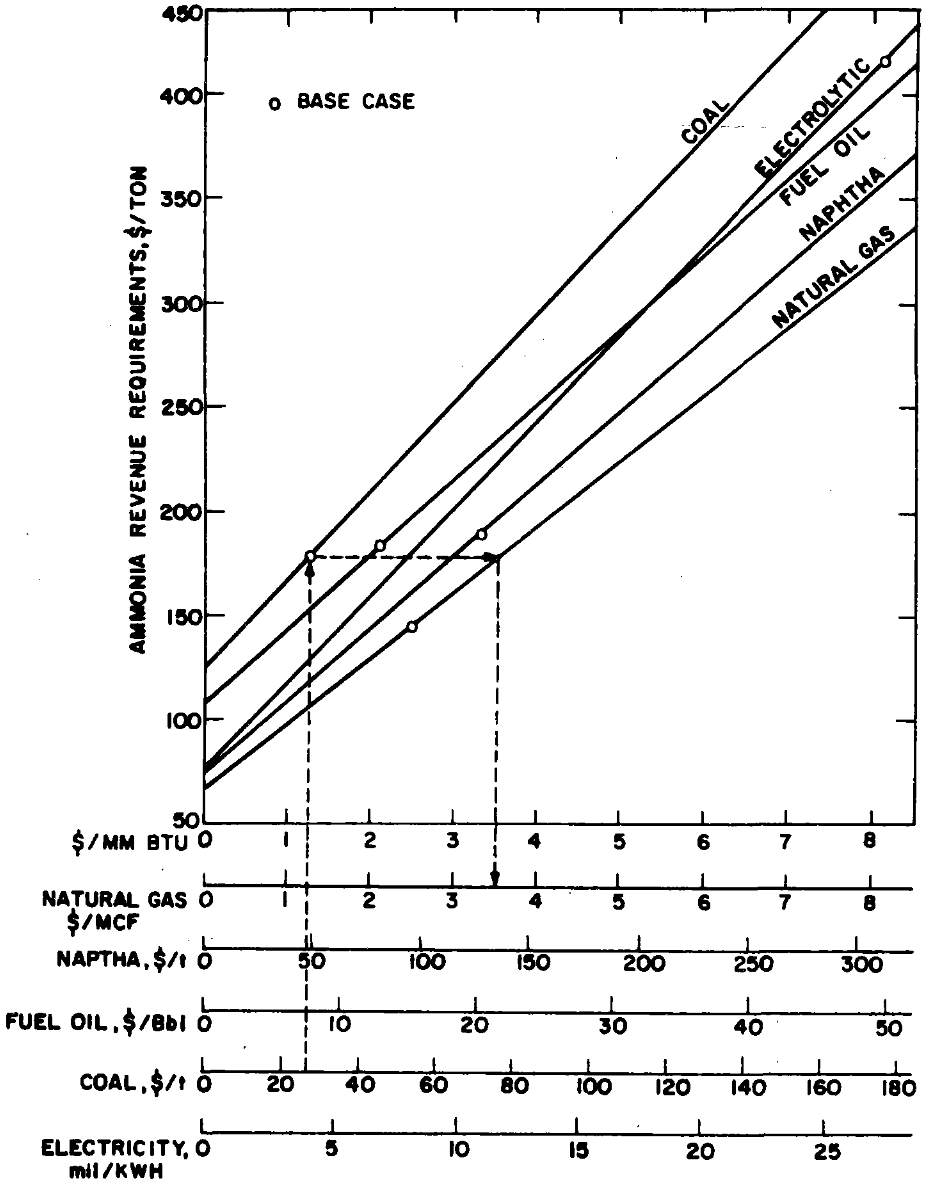
Life of plant, 15 years

Depreciable plant investment, $70,400,000

Total capital investment, $75,600,000

List of Abbreviations:

Btu - British thermal unit
gal - gallon
kWh - kilowatt
lb - pound
M - thousand
man-hr - man-hour
mcf - thousand cubic feet
scf - standard cubic foot
t - ton



LIST OF ABBREVIATIONS:

Bbl	BARREL
KWH	KILOWATT HOUR
Mil	ONE-THOUSANDTH OF A DOLLAR
MCF	THOUSAND CUBIC FEET
MMBTU	MILLION BRITISH THERMAL UNIT
t	TON

REVENUE REQUIREMENTS VERSUS FEEDSTOCK COSTS

Figure 8

DEPARTMENT OF ENERGY/HYDROGEN ENERGY STORAGE PROGRAM

Christopher England
Jet Propulsion Laboratory

Introduction

The US Department of Energy/Division of Energy Storage Systems (DOE-STOR) supports research and development of energy storage systems based on the utilization of hydrogen as the storage medium and energy carrier. The Hydrogen Energy Storage Program is jointly managed by the Brookhaven National Laboratory (BNL) and by the Jet Propulsion Laboratory (JPL) with overall program management at DOE-STOR. Dr. Beverly J. Berger is currently the program manager.

Among the areas of interest at BNL are:

1. electrolytic hydrogen production
2. hydride storage subsystems
3. utilization technology
4. system analysis engineering

Project management at JPL includes:

- thermochemical cycles
- advanced production concepts
- containment materials
- transmission, distribution and storage of hydrogen

Electrolysis is the major competition of fuels and chemicals from solar heat, and it may be advantageous to discuss the state of this technology. A full discussion of this and other programs in the Hydrogen Energy Storage Program may be obtained in the proceedings of the annual contracts review which is available from DOE or by contacting the author at JPL.

Electrolysis

The major program supported by DOE-STOR in electrolysis is the development of the solid polymer electrolyte (SPE) electrolyzer under contract with the General Electric Company. The SPE electrolyzer uses a polymeric acid ion-exchange membrane as the electrolyte instead of a conventional aqueous solution of acid or base. The advantage of the SPE electrolyzer is its high output of hydrogen and oxygen per unit of electrolyzer area. The program status is shown in the vugraph at the end of the paper. The high output gives the promise of both efficient electrolysis and low electrolyzer costs. The present technical effort centers on reducing costs by reducing the noble metal content of the current collectors.

DOE-STOR also supports work on advanced alkaline water electrolysis technology. The two major areas of work are (1) separators stable to the alkaline environment above 80°C and (2) improved electrocatalysts for oxygen evolution. In the former case, asbestos separators deteriorate at the higher temperatures required to accelerate electrode reactions and increase electrolyzer efficiency. In the latter case, investigations on reducing the oxygen over-voltage by inexpensive electrocatalysts such as perovskite structures are underway.

Exploratory studies being considered for high-temperature electrolysis coupled with a fusion heat source (HOT ELLY).

Thermochemical Cycles

DOE-STOR supports development of chemical processes (termed thermochemical cycles) that decompose water using high-temperature heat. The major processes being studied center on the chemistry of sulfur compounds. The high-temperature reaction is the decomposition of sulfuric acid to produce oxygen and sulfur dioxide.

$$H_2SO_4 \longrightarrow H_2O + SO_2 + \frac{1}{2} O_2 \; . \qquad (1)$$

The heat may be supplied from nuclear or solar sources, but must be supplied at 850°C or above. The major emphasis thus far has been on coupling the above reaction with a high-temperature gas-cooled reactor such as the General Atomic Company graphite reactor or the Federal Republic of Germany's pebble bed reactor.

Hydrogen is produced from the overall reaction

$$SO_2 + 2H_2O \longrightarrow H_2SO_4 + H_2 \qquad (2)$$

which recycles the sulfuric acid decomposed earlier. Reaction (2) cannot be driven thermally, and, as a result, several means have been devised to produce hydrogen from sulfur dioxide. These include the sulfur-electrochemical cycle (see vugraph), the sulfur-iodine cycle (see vugraph) and the sulfur-bromine process.

Sulfur-Electrochemical Cycle

In this cycle, under development by Westinghouse Electric Corporation, reaction (2) is driven electrochemically, i.e., a voltage is applied to a solution of sulfurous acid in sulfuric acid. Hydrogen is evolved at the negative electrode, and sulfur dioxide is oxidized to sulfuric acid at the positive electrode. The voltage at which electrolysis takes place largely determines the cost of hydrogen produced. As a result, the DOE-STOR effort is centered on the design and operation of low-cost, low-voltage electrolytic cells. As with all hydrogen-producing methods, it is desirable to evolve hydrogen at pressures of about 2 MPa. The overall efficiency of the sulfur electrochemical process is estimated as about 45-50% if the cell can be maintained at a potential of 0.6 volts.

DOE-SOLAR is funding related work on the high-temperature aspects of sulfuric acid decomposition including materials of construction and high-temperature catalysis.

Sulfur-Iodine Cycle

In this cycle, under development by General Atomic Company, reaction (2) is driven by means of iodine chemistry by the overall reactions,

$$SO_2 + 2H_2O + I_2 \xrightarrow{AQ} H_2SO_4 + HI \qquad (3)$$

$$2HI \xrightarrow[CAT]{570°} I_2 + H_2 \qquad (4)$$

These reactions sum to reaction (2). Since reaction (4) can be driven thermally, there is no need for an electrolytic step, and the overall process is similar to an ordinary chemical process. Present estimates set the process efficiency at about 45%.

Sulfur-Bromine Cycle

This cycle is under development at the Joint Research Center of the Commission of the European Communities, and also utilizes the decomposition of sulfuric acid as the oxygen-producing step. Reaction (2) is conducted by means of two reactions including an electrolytic step:

$$SO_2 + 2H_2O + Br_2 \xrightarrow{AQ} H_2SO_4 + 2HBr \qquad (5)$$

$$2HBr \xrightarrow{ELEC.} Br_2 + H_2 \qquad (6)$$

Reaction (6) is operated electrolytically at higher voltage than if reaction (2) were run electrolytically. The European researchers consider reaction (6) as easier to accomplish in a commercial system.

Other Research on Thermochemical Cycles

DOE-STOR supports research on materials and catalysts for sulfuric acid decomposition at the Los Alamos Scientific Laboratory (Dr. M. G. Bowman), on materials for boiling sulfuric acid at Lawrence Livermore Laboratory (Dr. O. Krikorian), and on high-temperature cycles for use with solar energy at the Institute of Gas Technology (Dr. J. Pangborn). In addition, an evaluation panel is supported to assess the progress of the various cycles (Dr. J. E. Funk, University of Kentucky, Chairman).

Open Thermochemical Processes

Open thermochemical processes are thermally-driven processes which accept feedstocks other than water, and produce hydrogen and other products. The feedstocks contain some residual energy value that can be converted into hydrogen by thermochemical means. An example is the conversion of sulfur dioxide and water to sulfuric acid and hydrogen, thus recovering the substantial fuel value of sulfur dioxide. DOE-STOR is considering support of theoretical and experimental studies on the recovery of hydrogen from wastes in this manner. The accompanying heat source may be fossil, nuclear or solar in origin.

Advanced Concepts for Hydrogen Production

DOE-STOR supports studies of an applied nature on the production of hydrogen by unconventional and advanced means. Many of these involve the use of solar energy in both thermal and photolytic forms. On-going work includes work on photoelectrolytic hydrogen production on polycrystalline substrates, photocatalytic decomposition of water using bridged inorganic compounds, and the direct thermal water decomposition using very high-temperature solar heat. Further information on advanced concepts can be obtained from D. D. Lawson at JPL.

Photoelectrolytic hydrogen production involves the irradiation of semiconductors in contact with aqueous electrolytes. Potentials built up on the semiconductor can be used to reduce or eliminate the need for applied voltage to electrolyze water. This concept was originally demonstrated on titanium dioxide (Fujishima and Honda) but effort now centers on materials with lower band gaps to provide greater efficiency.

The photocatalytic production of hydrogen involves the photolysis of water in the presence of inorganic complexes which have the ability to store energy. Experiments have been centered on bridged complexes of rhodium and bromine.

Summary

The DOE-STOR program in hydrogen systems centers on production and distribution. End uses such as fuel cells are not emphasized in this program since the emphasis is on conservation of fossil fuels using hydrogen as a buffer between primary energy production and consumption. For solar energy, the concept of an energy buffer is attractive because of the transient nature of the source on both a diurnal and seasonal basis. Thus, it is perceived that hydrogen can serve as an expedient to the use of solar energy in all forms.

DOE PROGRAM IN HYDROGEN ENERGY STORAGE SYSTEMS

PRESENTED BY

Dr. Christopher England

JET PROPULSION LABORATORY

DOE-STOR HYDROGEN ENERGY STORAGE PROGRAM

- PURPOSE

  DEVELOP TECHNOLOGY FOR UTILIZING HYDROGEN IN ENERGY STORAGE AND ENERGY CONSERVATION SYSTEMS

- APPROACH

  APPLIED RESEARCH AND DEVELOPMENT IN NON-FOSSIL PRODUCTION OF HYDROGEN, STORAGE OF HYDROGEN, TRANSMISSION, DISTRIBUTION AND USE

DOE-STOR HYDROGEN ENERGY STORAGE PROGRAM ORGANIZATION

- OVERALL PROGRAM MANAGEMENT AT DOE-STOR
- PROJECT MANAGEMENT AT DOE-BROOKHAVEN NATIONAL LABORATORY
  - ELECTROLYTIC HYDROGEN PRODUCTION
  - HYDRIDE STORAGE SUBSYSTEMS
  - UTILIZATION TECHNOLOGY
  - SYSTEM ANALYSIS ENGINEERING STUDIES
- PROJECT MANAGEMENT AT NASA-JET PROPULSION LABORATORY
  - THERMOCHEMCIAL CYCLES
  - ADVANCED PRODUCTION CONCEPTS
  - CONTAINMENT MATERIALS
  - TRANSMISSION, DISTRIBUTION AND STORAGE
  - SYSTEMS STUDIES AND ASSESSMENTS

ELECTROLYSIS

- SOLID POLYMER ELECTROLYTE TECHNOLOGY
  - USES POLYMERIC ACID ION-EXCHANGE MEMBRANE AS THE ELECTROLYTE
  - PROGRAM GOALS

PROGRAM GOALS	GOAL	1975 EST.
INSTALLED ELECTROLYSIS SYSTEM	\$82/KWe	\$188/KWe
CELL VOLTAGE AT 10,000 A/M^2	1.63V	1.85V
OPERATING TEMPERATURE	150^{o}C	82^{o}C
OPERATING PRESSURE	2 MPa	2 MPa
ACTIVE CELL AREA	1.0 M^2	0.23 M^2
COST OF HYDROGEN	75% DEPENDENT ON COST OF POWER	
EFFICIENCY	90%	80%

- ADVANCED ALKALINE WATER ELECTROLYSIS TECHNOLOGY
  - PRESENT SYSTEM LIMITED TO 80^{o}C BECAUSE OF ASBESTOS SEPARATOR
  - ACTIVITIES ON THERMOPLASTIC SEPARATORS STABLE TO ALKALINE SYSTEMS
  - ACTIVITIES ON IMPROVED OXYGEN ELECTROCATALYSTS
- HIGH-TEMPERATURE ELECTROLYSIS (HOT ELLY)

THERMOCHEMICAL CYCLES

- DEFINITIONS
  - A "THERMOCHEMICAL CYCLE" IS A CHEMICAL PROCESS WHICH ACCEPTS WATER AND HEAT AS THE ONLY FEEDSTOCKS AND PRODUCES HYDROGEN AND OXYGEN
  - A "HYBRID-THERMOCHEMICAL CYCLE" IS A THERMOCHEMICAL CYCLE IN WHICH ONE OR MORE STEPS ARE ACCOMPLISHED ELECTROLYTICALLY
- DOE-STOR PROGRAM
  - DEVELOPMENT OF THE "SULFUR CYCLE" HYBRID THERMOCHEMICAL CYCLE
  - DEVELOPMENT OF THE "SULFUR-IODINE" THERMOCHEMICAL CYCLE
  - TECHNICAL SUPPORT STUDIES ON MATERIALS AND CHEMISTRY
  - HIGH-TEMPERATURE CYCLES FOR USE WITH SOLAR ENERGY

WESTINGHOUSE SULFUR CYCLE

- CHEMISTRY
  - $H_2SO_4 \xrightarrow[CAT]{1100^{o}K} SO_2 + H_2O + \boxed{\frac{1}{2} O_2}$ $\Delta F^{o}_{298} = +38551$ cal/mol
  - $SO_2 + 2H_2O \xrightarrow{ELECTRO} H_2SO_4 + \boxed{H_2}$ $\Delta F^{o}_{298} = +16085$ cal/mol
- TECHNOLOGY
  - REQUIRES INTERFACING OF SULFURIC ACID DECOMPOSITION WITH A HEAT SOURCE AT 1100°K
  - REQUIRES SPECIALLY-DESIGNED ELECTROCHEMICAL CELLS
- GOALS

	GOAL	1977
● ELECTROCHEMICAL CELL VOLTAGE	−0.600V	−0.800V
● CELL ACID CONCENTRATION	60%	50%
● CELL TEMPERATURE	50°C	90°C
● CELL PRESSURE	2 MPa	0.1 MPa
● OVERALL PROCESS THERMAL EFFICIENCY	45-50%	——
● COST OF HYDROGEN	~ $6.00/GJ	
● CLOSED CYCLE DEMONSTRATION	DEC 1978	

SULFUR-IODINE CYCLE

GENERAL ATOMIC COMPANY

- CHEMISTRY
  - $H_2SO_4 \xrightarrow[CAT]{1100^{o}K} SO_2 + H_2O + \boxed{\frac{1}{2} O_2}$
  - $SO_2 + 2H_2O + I_2 \xrightarrow{AQ} H_2SO_4 + 2HI$
  - $2HI \xrightarrow[CAT]{570^{o}K} I_2 + \boxed{H_2}$
- TECHNOLOGY
  - REQUIRES SPECIALIZED PHYSICAL CHEMISTRY TO ECONOMICALLY SEPARATE ACID MIXTURE
  - REQUIRES INTERFACING OF SULFURIC ACID DECOMPOSITION WITH A HEAT SOURCE AT 1100°K
  - REQUIRES MATERIALS RESISTANT TO HYDROGEN IODIDE
- GOALS

	GOAL	1977
● OVERALL PROCESS THERMAL EFFICIENCY	45-50%	——
● COST OF HYDROGEN	$6.00/GJ	——
● CLOSED CYCLE DEMONSTRATION	DEC 1980	——

"OPEN" THERMOCHEMICAL PROCESSES

- AN OPEN THERMOCHEMICAL CYCLE PRODUCES HYDROGEN FROM HEAT AND A CHEMICAL FEEDSTOCK

- EXAMPLE:

$$SO_2 + 2H_2O + HEAT \xrightarrow[\text{SULFUR-IODINE CYCLE}]{\text{SULFUR CYCLE}} H_2SO_4 + H_2$$

$$H_2S + HEAT \xrightarrow{?} H_2 + S$$

ADVANCED CONCEPTS FOR HYDROGEN PRODUCTION

- PHOTOASSISTED HYDROGEN PRODUCTION
  - PHOTOELECTROLYTIC HYDROGEN PRODUCTION ON POLYCRYSTALLINE SUBSTRATES
  - PHOTOCATALYTIC DECOMPOSITION OF WATER USING BRIDGED RHODIUM COMPLEXES
  - DIRECT THERMAL WATER DECOMPOSITION BY EFFUSION

- ADVANCED THERMOCHEMICAL CONCEPTS TASK
  - DECOMPOSITION OF HYDROGEN SULFIDE
  - SOLAR HYDROGEN INTERFACE

Hydrogen by Thermochemical Reactions*

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Everybody agrees that the demand for hydrogen will continue to grow in the future; furthermore the most abundant source for hydrogen is water, which is a very stable compound. The problem is not the feasibility of splitting water into its components but rather how to do it using a primary source of energy efficiently so that the hydrogen is produced at a low price. Water electrolysis is a well known technique but it suffers from the drawback that the conversion of heat to electricity is not very efficient ($\lesssim$ 40%). The coupling of several chemical reactions, performed at different temperatures, in such a way that the products of some constitute the reagents of others, while the net effect is the consumption of mainly thermal energy, is known as a thermochemical cycle. If water is the only chemical allowed to be consumed, the cycle will produce hydrogen and oxygen at separate reactions. Presently thermochemical cycles hold the promise of decomposing water with higher efficiency than electrolysis because the thermal energy is used directly, this can be visualized as a conversion to chemical energy. It is from this fact that interest in such cycles started. Although a British patent originated in 1924[1] disclosed a thermochemical cycle for water decomposition, it did not kindle any interest at that time. There was a large supply of hydrogen contained in abundant natural gas and the fact that the cycle was inoperative seems not to have effected that lack of interest. It was only recently, in 1966,[2] that the possibility of using thermochemical cycles was critically examined on a scientific basis by J. Funk at

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*Research sponsored by the Division of Solar Energy, U. S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

the University of Kentucky in a study for the U. S. Army. Later,[3] C. Marchetti and coworkers, at the European Communities Joint Research Center in Ispra, Italy begun, with their Mark I cycle, an experimental program for developing thermochemical cycles to be used in hydrogen production by splitting water. The energy crisis accentuated by the oil embargo in 1973 finally produced an awareness in the versatility of hydrogen for alleviating energy problems and many countries around the world initiated research programs in this field. Because hydrogen is not a primary source of energy, such a source is required for accomplishing the decomposition of water by thermochemical or any other means. Up to the last couple of years the source of energy considered for fueling thermochemical cycles has been nuclear energy, in the form of High Temperature Gas Cooled Reactors (HTGR). The uncertainty of public acceptance of nuclear energy, namely in this country and also abroad, has led us at ORNL and elsewhere to look for other thermal energy sources more acceptable to the general public. Many people agree that solar thermal energy is a good candidate for such a task, based on its availability and the proven capability of delivering heat at practically every temperature range. Although the cycles which are presently being developed were conceived with the use of nuclear energy in mind and this has established their upper limits of temperature, about 900°C, this does not exclude the use of solar energy. On the contrary such maximum temperatures could hasten the application of solar energy because they could be provided by presently available solar collectors. The problems affecting the coupling of solar energy to hydrogen producing cycles are mainly of two kinds: (1) economical, which is presently common to all high temperature solar processes and (2) material compatibilities of the chemical species with container-heat exchanger walls, which is common to most thermochemical cycles. Both may be eventually solved, respectively, by governmental action and by technological advances.

There are three thermochemical cycles which are presently at a more advanced developmental stage than all the other numerous cycles[4] which have been identified. It is expected that some or all three may become the first generation cycles to be demonstrated on a large production scale.

Because these cycles are being studied and developed in several institutions around the world, each using their own designation, their basic chemical reactions, will be described here using our own chemical notation.* Two of the cycles are hybrids, that is, they involve one reaction which is not thermally driven. In these cases it is electrolytic. The key to a successful electrolytic hybrid cycle being that the voltage required to drive the reaction has to be significantly lower than the voltage required to electrolyze water.

S/S Cycle*[5]

$$SO_2 + 2H_2O \xrightarrow{\text{elect.}} H_2SO_4 + H_2 \tag{1}$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2 \tag{2}$$

Presently, the voltage required to drive reaction (1) is approximately 0.7 V, depending somewhat on the temperature and mainly of concentration of H_2SO_4 produced, about 55 w/o. Reaction (2) is carried out catalytically at about 850°C after thermally dehydrating the H_2SO_4 solution obtained in (1). An alternative to the latter is being studied and evaluated at LASL in which instead of concentrating the H_2SO_4, insoluble bismuth sulfates are precipitated and subsequently thermally decomposed.

The Westinghouse Corp. is in the process of building a laboratory scale of the full cycle to operate continuously.

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*The first element represents the one which is oxidized in the hydrogen evolution reaction, the second that which is reduced in the oxygen evolution reaction, and those in parenthesis are auxiliary if any. (Water and its components are not listed).

I/S Cycle[6]

$$SO_2 + I_2 + 2H_2O \rightarrow H_2SO_4 + 2HI \quad (3)$$

$$2HI \rightarrow I_2 + H_2 \quad (4)$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2 \quad (5)$$

Reaction (3) is run at about 90°C in the presence of excess iodine which binds to the HI forming HI_x species. Their solution is only partially miscible in H_2SO_4 solution allowing thus for a bulk separation of both streams. This reaction produces solutions of H_2SO_4 of higher concentration than the previous cycle. After purifying both solutions they are thermally decomposed in separate reactions; HI is decomposed at about 450°C. General Atomic Company is building a laboratory model for continuous operation.

Br/S Cycle[7]

$$SO_2 + Br_2 + 2H_2O \rightarrow H_2SO_4 + 2HBr \quad (6)$$

$$2HBr \xrightarrow{elect} Br_2 + H_2 \quad (7)$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2 \quad (8)$$

Reaction (6) is carried out at temperatures between 20 and 120°C in the presence of excess bromine, thus forming HBr_x species whose solution is easily separated from the H_2SO_4 solution. Reaction (7) is performed between 80 and 250°C; it is presently being further developed to permit working at high current densities, around 5 K amp/cm^2. Reaction (8) is common to the two previous cycles.

This cycle is presently being carried out on a laboratory scale at the European Communities Joint Research Center at Ispra, Italy and it is the first in the world that has reached this stage.

Many laboratories around the world are presently conducting compatibility tests to select materials which will survive corrosive environments for a long time and thus allow for scaling up the processes. Several institutions have started, by means of design studies, to give consideration to the interfacing of cycles, such as the above, to solar collectors and concentrators.

Because of the proven capabilities of solar energy to deliver heat at very high temperatures, consideration has also been given lately to cycles which would operate at temperatures up to about 2500°C. Such high temperatures would have the advantage of allowing for simpler cycles with fewer reactions, fewer separation operations and very fast kinetics, thus promising a high efficiency. A serious disadvantage is containment problems arising from reaction of reagents and/or products with the walls. The solution to this problem may require the development of new materials and ingenious techniques.

Our own experimental program at ORNL is presently geared to finding and developing thermochemical cycles with maximum temperatures up to 1500°C.[9]

Several higher temperature cycles are currently being studied at the Laboratoire des Ultra-Refractaires at Odeillo, France, one example follows:

Fe/Fe Cycle[8]

$$Fe_3O_4 \rightarrow 3FeO + 1/2\ O_2 \qquad (9)$$

$$3FeO + H_2O \rightarrow Fe_3O_4 + H_2 \qquad (10)$$

Reaction (9) has been tested at temperatures above 2000°C in various gaseous environments and 100% conversion was obtained. Reaction (10) has been tested at about 700°C and studies continue in order to raise the presently low yield of hydrogen. Because from a chemical engineering point of view the higher temperature of the Fe/Fe cycle is an attractive feature, we have developed for it some very preliminary flowsheets and material and heat balances. These are shown in Figs. 1 and 2 for a plant producing 48 tons H_2/day.

Two methods were considered for engineering the process. In the first, a continuous process shown in Fig. 1, the iron oxide would be contained in a solar heated bed and only the gases (steam, and generated hydrogen and oxygen) would be moved. In this method the bed would be solar heated during the day and cooled at night with steam, resulting in a 24-hr cycle. The approximate 5000 tons of iron oxides would occupy 29,000 cubic feet as molten FeO, and 50,000 cubic feet as solid Fe_3O_4 with a bulk density of ∿70%. The latter volume is equivalent to a cube 37 ft on a side. Although this method avoids moving solids it may have some problems in keeping the iron oxides from agglomerating and in promoting sufficiently rapid heat transfer in heating and cooling. It would probably be difficult to obtain good thermal efficiency because the heat generated during the day would have to be stored during the night cooling cycle for subsequent reuse where feasible. Further,it requires a large inventory of iron oxides, but these oxides are a relatively inexpensive material. On the other hand, this method would probably have lower attrition and losses.

In the second method, a batch process shown in Fig. 2, both the iron oxides and the gases would be moved countercurrent to each other. Both reactions would be carried out at the same time in different equipment and the process could be run only 10-12 hr a day; however, assuming about a 1-hr cycle for material, the solids inventory could be reduced by about 90%.

In this method Fe_3O_4 would be lifted to a steam heated preheater and would drop from there to a solar heated moving bed or dropped through a solar heated "falling curtain" if solids heating and melting could be made sufficiently rapid. The released oxygen would pass countercurrent to the falling solids and provide a small amount of heat (<1%) for final preheating of the solids. After collection the produced FeO would be cooled countercurrently with steam in a second moving bed or falling curtain. The heated steam would then pass to the Fe_3O_4 preheater as already noted. Finally the cooled FeO would drop to the FeO oxidizer bed where hydrogen would be released and the FeO reconverted to Fe_3O_4, completing the cycle. In this scheme the plant would only operate 10 to 12 hr/day but no heat storage would be needed. For safety reasons the two reactors would have to be physically isolated from each other to prevent mixing of oxygen and hydrogen. This method would undoubtedly have better heat conservation characteristics and would probably suffer less from solids agglomeration.

CONCLUSIONS

The use of high temperature solar energy for the production of hydrogen from water is feasible from a strictly chemical point of view and desirable from an environmental point of view. Since there are no objectionable institutional problems to its application the main factor in deciding whether or not it will become an established system is the cost of its implementation. This will be regarded in competition with other advanced systems being also presently developed for the production of hydrogen, i.e. electrolysis at elevated temperatures.

Thank you.

Question - Was any work done with the alkaloid oxide produced from the metal and, of course, the metal going on to produce hydrogen?

Dr. Bamberger - Yes. I have shown you only three or four cycles that look interesting; the first three look as if they probably would suceed in the future as a first generation. Looking at the literature I have compiled, there are something like three cycles, of which at least two use alkaline oxide decomposition. The other is based on potassium oxide decomposition. They were envisioned as running at relatively high temperatures, like 200°C, in that range. For the time being nothing is being done about these cycles.

I should say as a point of philosophy that the way I read DOE, is that they are interested in seeing a quick demonstration of cycles and therethere a large effort is put into demonstrating these and in trying to come up with a pilot plan, maybe a demonstration plan, in the future. In my opinion, that has taken away a little of the effort from finding new cycles.

Comment - I found your coupling of solar and the iron process very interesting, but the second step of it, the steam iron, which is old technology, is a very difficult process to pull off successfully.

Dr. Bamberger - Yes, I agree. We haven't done any experimental work on this. That's why Odeillo is finding difficulties there. I talked to a student who was there, who was seeing a yield on the order of 10-15 percent. One of the problems was that after the FeO melted, it had to be ground and it was probably the main stumbling block for the reaction.

Question - What kind of yield do you get from any of these processes-- energy input versus the energy?

Dr. Bamberger - That's what I mentioned as the efficiency for the first three cycle calculations, which have indicated in the range of 45-55 percent. This would be heat put into the cycle related to the heat you get when you burn the hydrogen you obtain from the cycle.

Question - What refraction from solar energy do you anticipate would be reradiated?

Dr. Bamberger - Probably Sam Beall or Al Hildebrandt would want to comment on that.

Mr. Beall - It can't be very large at those temperatures.

Dr. Bamberger - Maybe 90 percent at 4000°. That's one of the problems.

Question - The problem with the alkaline metal which I think you ought to bring out is that you can't operate it at that temperature. You have this huge free energy penalty to pay if you hydrolize alkaline metal. I think that's something that works against those kinds of cycles. Is there no way to make that more efficient?

Dr. Bamberger - Anybody here like to comment? The problem with alkaline metals is that you have to hydrolize them and you pay a penalty for this that you cannot get back.

Question - Isn't that the problem with any metal reaction, the ratio of molecular waste is such that the materials problem becomes tremendous. You have to physically handle 200-300 pounds of metal, and the energy requirement just to move it makes it impossible.

Dr. Bamberger - We don't have time to get into that; it's debatable.

Question - One of the problems involving gas solids is going to be whether the product will cover up the reaction on the surface of the solid. Do you have any simple way of getting around that problem?

Dr. Bamberger - Not necessarily. There are two ways of looking at this. The way you asked the question appears to be like in the iron steam where you have to steam with a solid. The way I like to look at them is to find solids which would only involve a gas and therefore I won't have that much trouble. Fluid beds may be one way of solving it.

Question - The FeO is still covering the particle?

Dr. Bamberger - I don't know. Again, we don't have enough time, but there may be a diffusion problem. There are people in the Chemical Engineering Department at the University of Pennsylvania, who are looking at these processes in general to see how one can solve them or how one can improve them. One name I can give you is Don Parmetter.

References

1. British Patent No. 232,431 (1924).
2. Funk, J. E. and Reinstrom, R. M., I&EC Process Design and Devel. 5 (1966), 336.
3. De Beni, G. and Marchetti, C., Eurospectra 9, 2 (1970), 40.
4. Bamberger, C. E. and Richardson, D. M., Cryogenics, April (1976), 197 and Bamberger, C. E., Cryogenics, March (1978), 170.
5. Brecher, L. E., Spewock, S. and Warde, C. J., Intl J. Hydrogen Energy 2, #1 (1977), 7.
6. Russell Jr., J. L., McCorkle, K. H., Norman, J. H., Porter II, J. T., Roemer, T. S., Schuster, J. R., and Sharp, R. S., Proceedings 1st World Hydrogen Energy Conf., Miami Beach, Florida, Vol 1 (1976), p. 1A-105.
7. Schuetz, G. H., Intl J. Hydrogen Energy 1, #4 (1977), 379.
8. Bilgen, E., Ducarroir, M., Foex, M., Sibieude, F. and Trombe, F., Intl J. Hydrogen Energy 2, #3 (1977), 251.
9. Bamberger, C. E. and Richardson, D. M., Proceedings 2nd World Hydrogen Energy Conf., Zurich, Switzerland (1978).

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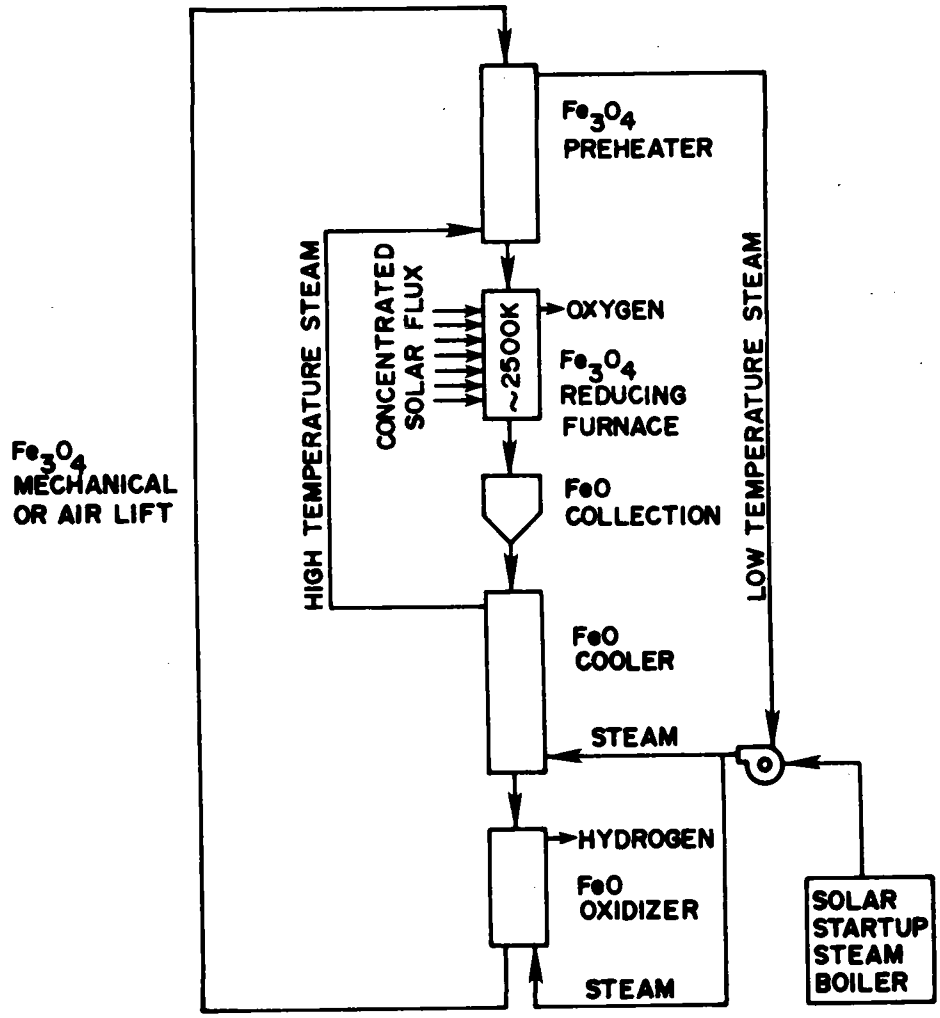

FIGURE 1. SCHEMATIC ENGINEERING FLOWSHEET FOR 2-STEP CONTINUOUS IRON OXIDE PROCESS

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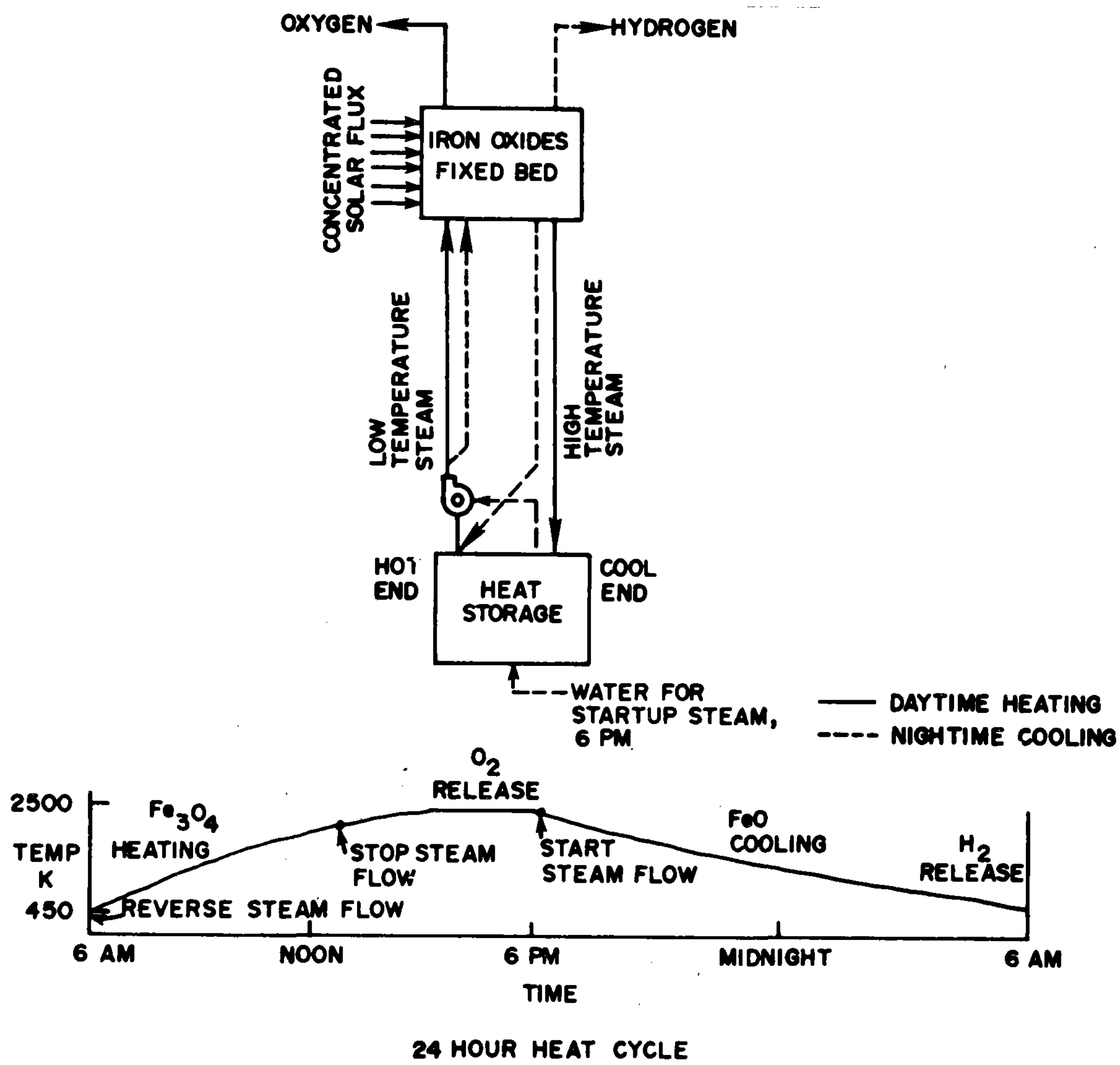

FIGURE 2. SCHEMATIC ENGINEERING FLOWSHEET FOR 2-STEP CONTINUOUS IRON OXIDE PROCESS

FUELS AND CHEMICALS FROM SOLAR-PRODUCED HYDROGEN

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Significant quantities of conventional fossil fuels are required in the production of many energy-intensive chemicals, fuels, and metals. Several methods are presently under study to adapt solar energy, mainly as process heat, as a substitute energy source. In certain applications, the solar energy can be used to decompose water into hydrogen and oxygen, and the resultant hydrogen used as a feedstock to the end-product process. The objective of the work described in this paper is the identification of specific solar/hydrogen/chemical and/or fuel processes which appear to have the greatest promise with respect to technical and economic feasibility and ultimate market acceptance.

The basis used for solar-hydrogen production is the Westinghouse Sulfur Cycle Hydrogen Generation Process. The Sulfur Cycle, shown schematically in Figure 1, is a two-step hybrid electrochemical/thermochemical cycle for decomposing water. It involves the use of sulfur oxides as recycling intermediates. The energy needs of the process are thermal energy, for the acid vaporization and sulfur trioxide reduction steps, and electrical energy for the electrolysis and auxiliary power. The temperature levels desired for the thermal inputs are compatible with the capabilities of solar collectors.

The integration of the Sulfur Cycle with a solar heat source, and with an end-product process, is shown in Figure 2. Energy storage subsystems permit 24-hour operation of the electrolyzer and a continuous hydrogen feed to the end-product process. An alternate design, employing H_2/O_2 fuel cells, is shown in Figure 3. This design eliminates the need for thermal energy storage. Other design options, including the use of purchased electrical power, are also being studied.

The most promising processes identified to date are shown in Table I. Capacities are based on a 350 MW_t solar heat input and a nine-hour solar day. The solar heat input was based on recent studies of commercially-sized solar thermal electric systems (100 MW_e).

Schematics of two of the identified processes, a solar/hydrogen/ammonia complex and a solar/hydrogen/methanol-lime complex, are shown in Figures 4 and 5, respectively. In each case the solar/hydrogen plant provides hydrogen feedstock, as well as auxiliary electrical power. The ammonia complex requires only water, air, and solar energy as inputs, while the methanol complex requires carbon dioxide, in addition to water and solar energy. In the proposed scheme, the CO_2 is recovered from the exhaust of a limestone calciner. Thermal energy required for the calcining operation may be obtained from solar, conventional fossil fuels, or part of the product methanol.

Thank you.

Question - What fraction of hydrogen are you using now?

Dr. Summers - It looks like we are defying the second law of thermodynamics but that is not really the case. Apparently, half the hydrogen produced is required to operate the fuel cells and to charge the energy storage system. The reason is that we are inputting a lot of energy in the acid decomposition system.

Question - In your environmentally designed system to produce ammonia, what was the quantity of thermal energy required to produce a ton of hydrogen from the solar plant?

Dr. Summers - The conversion efficiency of the hydrogen depends on the method we use for electrical power conversion. It's in the range of 40-45 percent. That is, in terms of the energy content of the hydrogen, based on the higher heating value of 40-45 percent of the total thermal energy input into the system, that's energy input to both create electrical power and to operate the acid decomposition system.

Question - I'm talking about the ammonia system, the air-water-solar heat. What was the quantity of solar heat per ton of ammonia?

Dr. Summers - The ammonia synthesis is an electrothermic reaction. There is no other thermal input into the ammonia plant. So, it's twice the heating value of the hydrogen, or 325 Btu's per cubic foot. So, you have 650 Btu's per cubic foot of hydrogen.

Question - In the last example where you used a calciner to get CO_2, can you identify the geographic location of the country which has abundant limestone, water, and solar. And, secondly, if you found that, would you probably have a lot of biomass around?

Dr. Summers - Arizona has a lot of input with the biomass.

Comment - You need very high temperatures for calcining, 2000°F, which we can't generate now with the ceramic central receivers.

Dr. Summers - No, we haven't looked at the total country in trying to locate such a facility. I thought that this complex would be located in the Southwest. As far as the temperatures required for the calciner, it would be nice if we had a calciner being driven by solar energy. That is not a requirement of the process. We need a CO_2 source is what it amounts to.

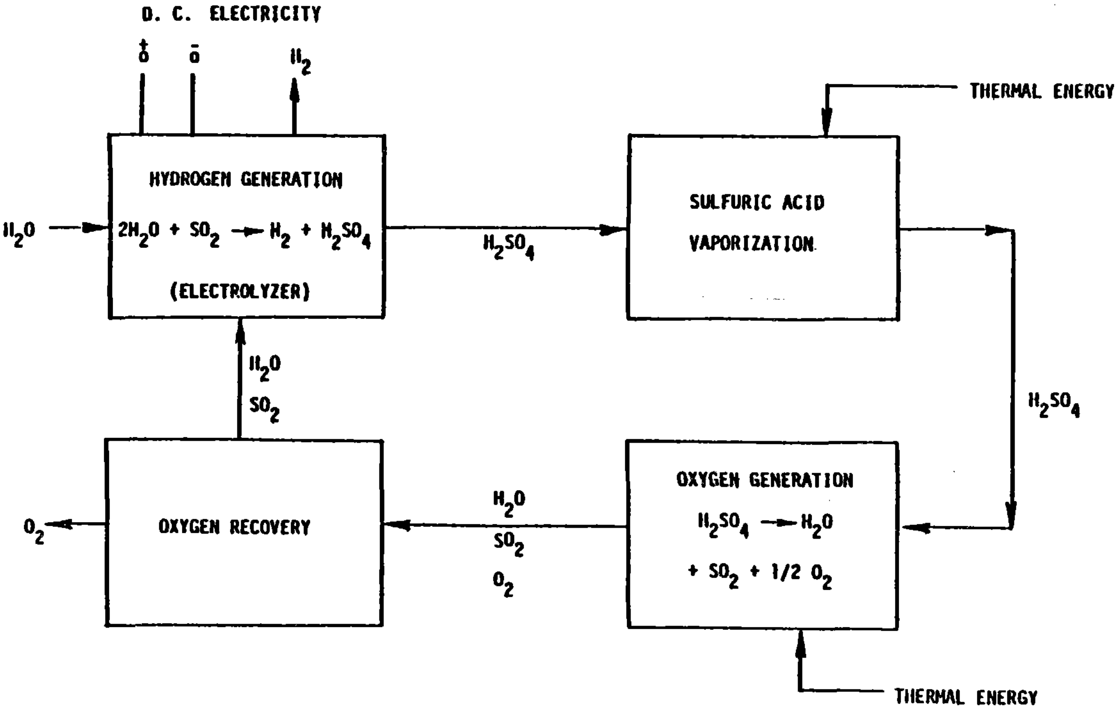

Figure 1. Sulfur Cycle Hydrogen Generation Process

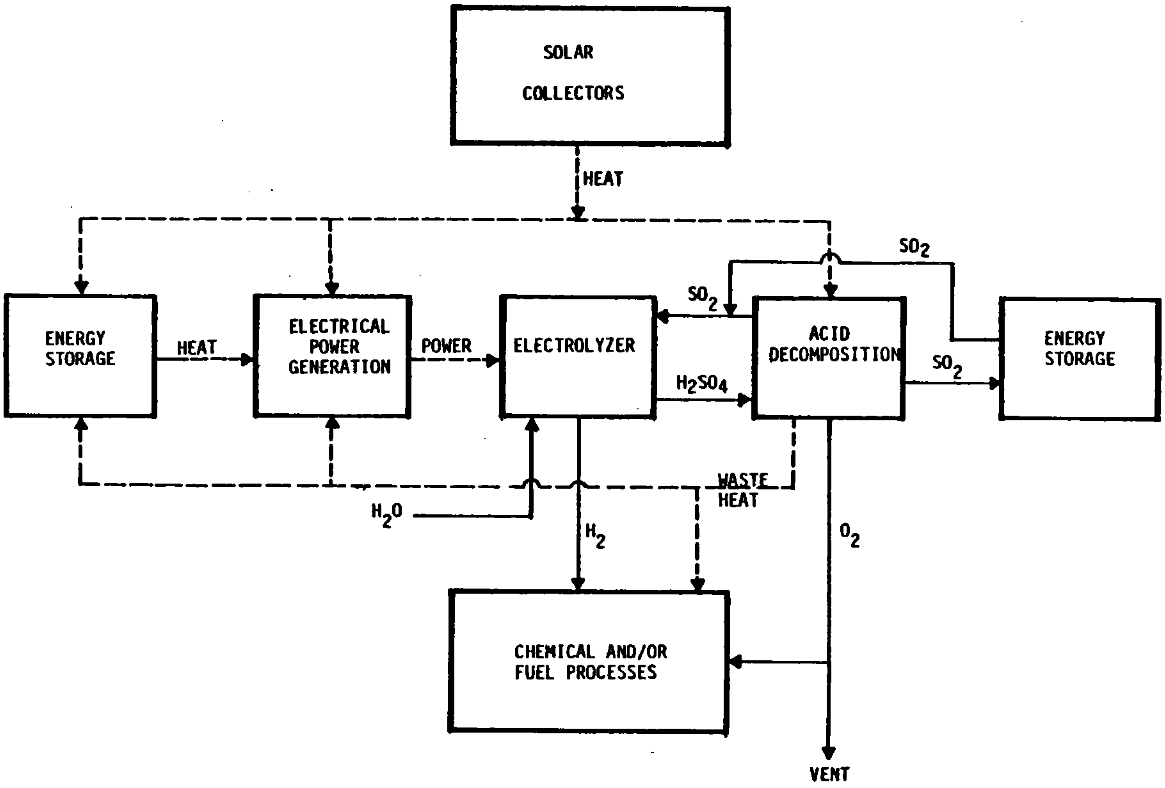

Figure 2. Integrated Solar/Hydrogen/Chemical Plant

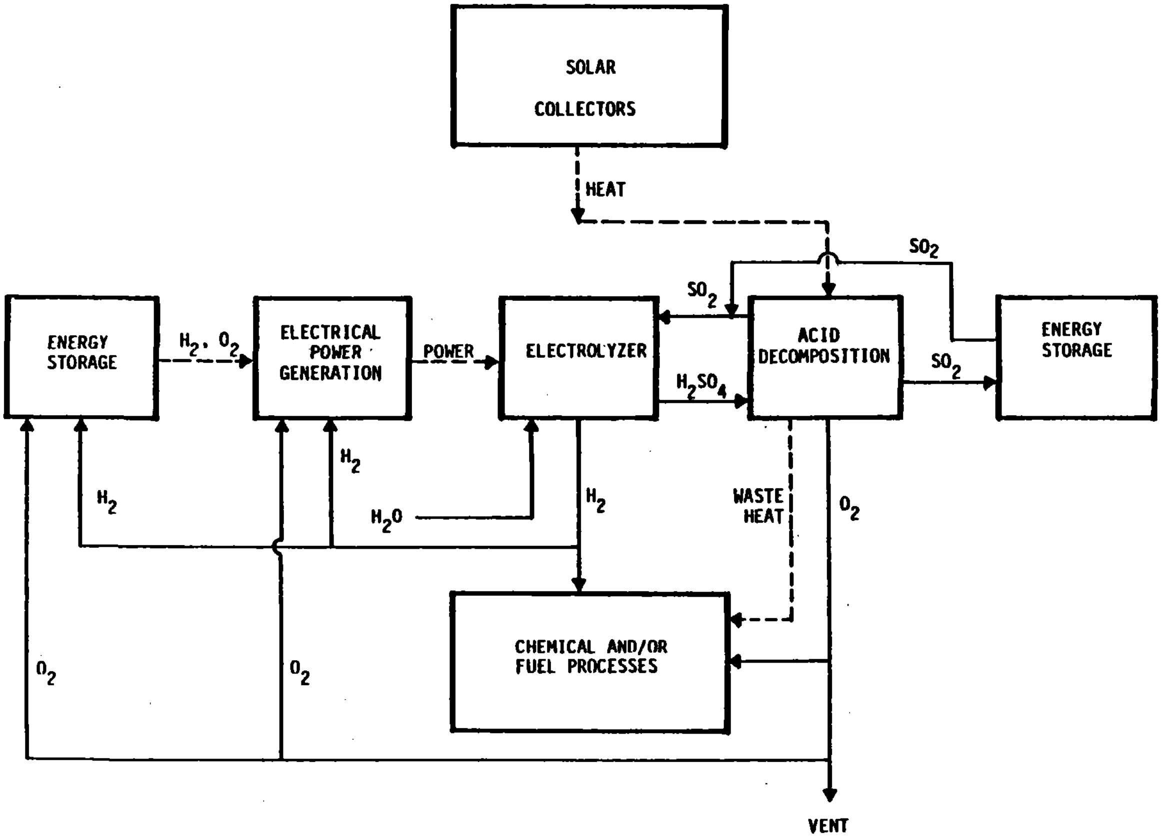

Figure 3. Integrated Solar/Hydrogen/Chemical Plant With Fuel Cells

TABLE I

CANDIDATE SOLAR/HYDROGEN/CHEMICAL OR FUEL PROCESSES

PLANT DESCRIPTION	END-PRODUCT	APPROX. PLANT CAPACITY
1. AMMONIA SYNTHESIS	ANHYDROUS NH_3	150-380 TPD
2. NON-ELECTROLYTIC H_2O_2 MANUFACTURE	35% H_2O_2	250-650 MILLION LBS. PER YEAR (100% H_2O_2)
3. LIME/METHANOL SYNTHESIS	CaO AND CH_3OH	250-650 TPD CaO 125-300 TPD CH_3OH
4. H-IRON REDUCTION	Fe POWDER	600-1500 TPD
5. COAL LIQUEFACTION	SYNTHETIC OIL	700-1700 TPD COAL

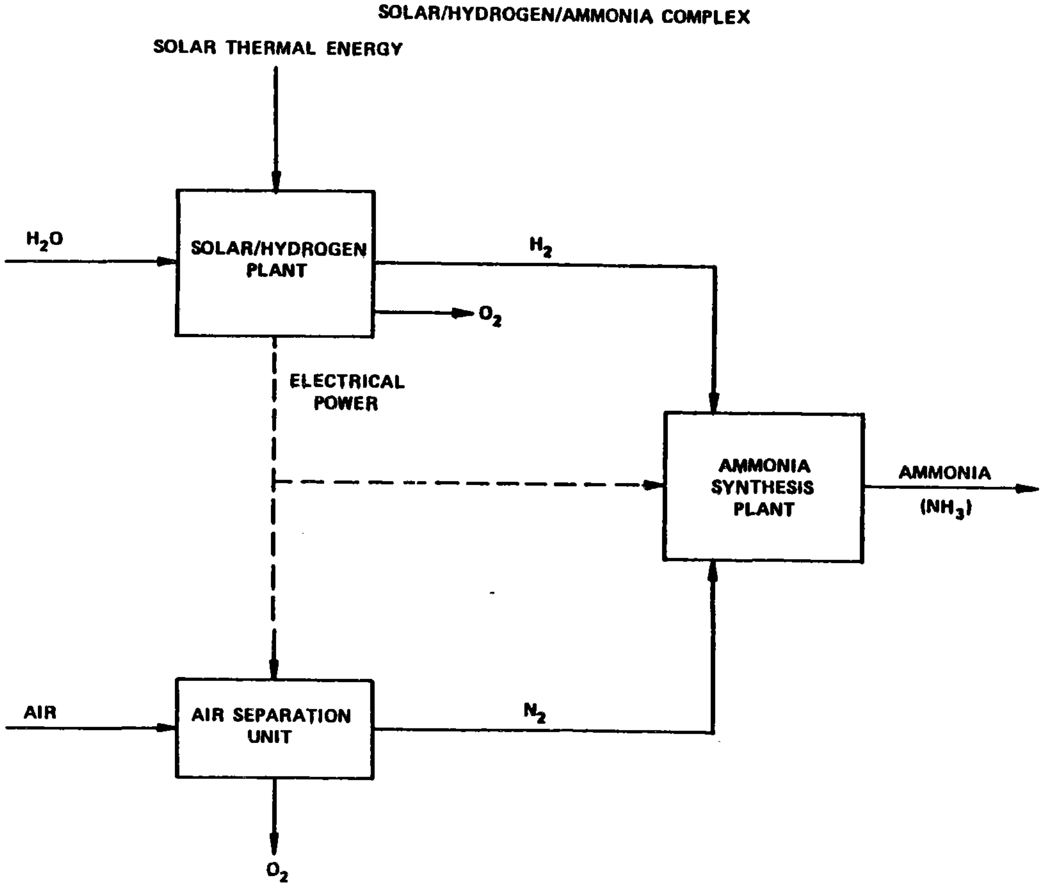

Figure 4. Solar/Hydrogen/Ammonia Complex

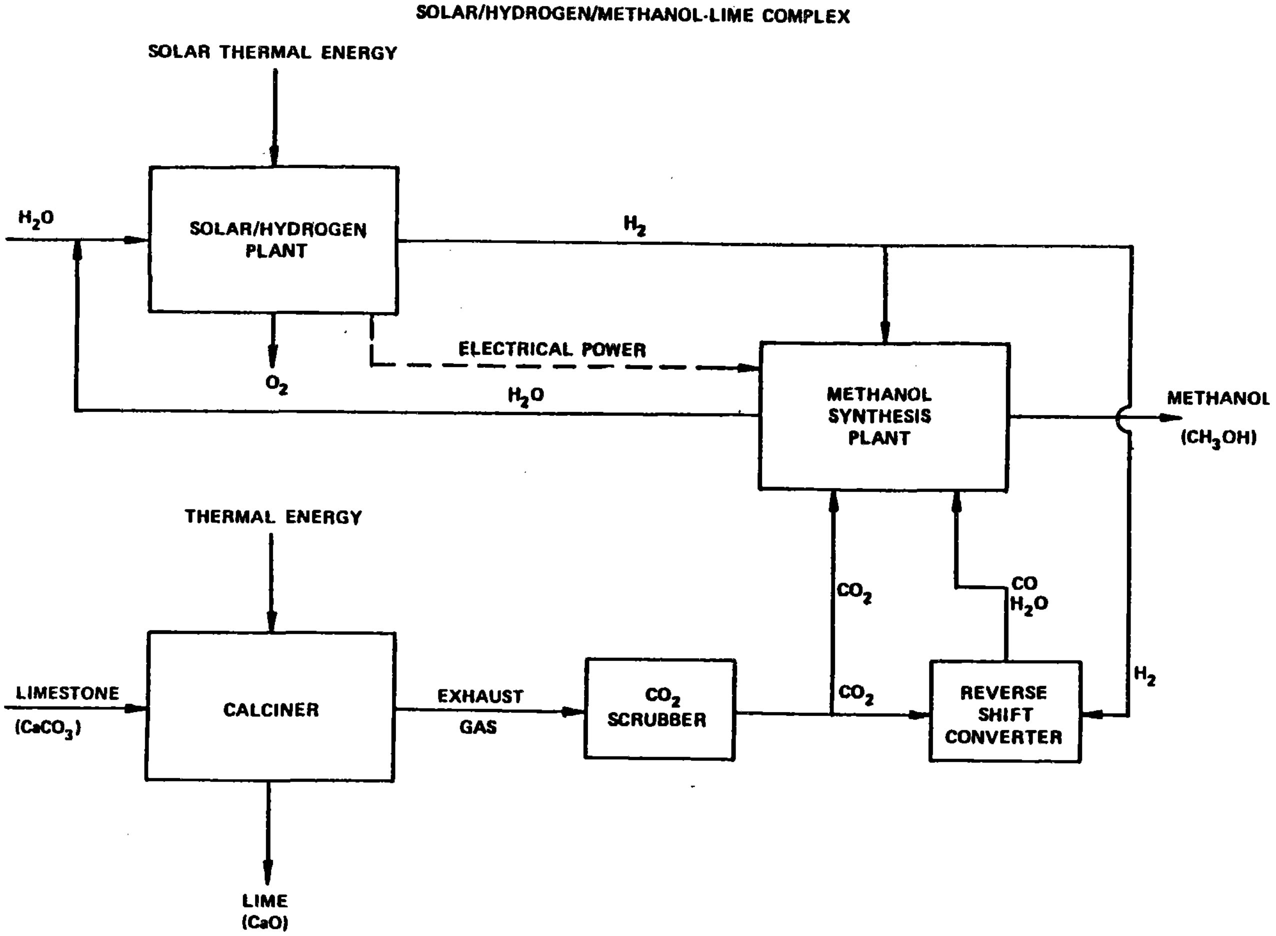

Figure 5. Solar/Hydrogen/Methanol-Lime Complex

A CENTRAL RECEIVER FOR THE PRODUCTION OF MONOXIDES OF CARBON AND NITROGEN*

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*Research sponsored by the U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

The purpose of this paper is to stimulate your thinking about two long-range applications of central receiver technology. Both are somewhat speculative but the reward for successful development would be very great. Consider, for example, the possibility that the thermal energy collected by central receiver systems could "fix" nitrogen in large quantities; or produce unlimited stocks of liquid and gaseous hydrocarbons by using carbon dioxide as the carbon source and water as the hydrogen source.

Nitrogen Fixation

In today's chemical industry, nitrogen is fixed by combining nitrogen and hydrogen gases to form ammonia. The nitrogen is obtained from air and the hydrogen from methane. Much of the ammonia is used to manufacture nitric acid, from which nitrate fertilizers are made. The complete series of reactions is shown in Fig. 1. World production of ammonia is approximately 50 million tons annually, and each ton requires an input of 40 million Btu,(1) so that world consumption of energy, mostly natural gas, for ammonia production is about 2×10^{15} Btu/yr. Roughly half of this energy is feedstock and half is needed for process heat.

The important point is that the half represented by hydrogen is lost (as water) (see Eq. 3, Fig. 1) in converting ammonia to nitric acid.

Such "waste" of hydrogen does not occur if the NO can be made by directly combining atmospheric nitrogen and oxygen, as in the electric arc process:

$$1/2\ N_2 + 1/2\ O_2 \xrightarrow{\text{Elec. Arc}} NO$$

Although the arc process has been used successfully for many years, the high

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(1) G. C. Sweeney, "Technology and Economics of Ammonia Production," Arthur D. Little, Inc., Cambridge, Mass.

Fig. 1. Chemical Reactions for the Manufacture of Nitric Acid via Ammonia Synthesis

$$2\ CH_4 + 2\ H_2O \longrightarrow 6\ H_2 + 2\ CO_2 \qquad (1)$$

$$2\ N_2 + 6\ H_2 \longrightarrow 4\ NH_3 \qquad (2)$$

$$4\ NH_3 + 5\ O_2 \longrightarrow 4\ NO + 6\ H_2O \qquad (3)$$

$$4\ NO + 2\ O_2 \longrightarrow 4\ NO_2 \qquad (4)$$

$$3\ NO_2 + H_2O \longrightarrow 2\ HNO_3 + NO \qquad (5)$$

cost of electricity and low thermal efficiency has made it non-competitive with the synthetic ammonia route to nitric acid in most countries.(2)

The Hydrogen Economy

Of course, hydrogen has many uses other than ammonia manufacturing and could have more if it were available economically from non-petroleum and gas sources. Those who envision the "Hydrogen Economy" propose that hydrogen will eventually provide most of our "pipeline" energy, replacing both natural gas and petroleum. For this to occur, the annual supply in 2000 A.D. would have to be in the range of 30 to 60 x 10^{15} Btu.

Although nearly all of the present-day hydrogen is supplied from methane (or light hydrocarbon liquids) (see Eq. 1, Fig. 1), hydrogen can be made in other ways which may not consume natural gas or petroleum.

Production of hydrogen by electrolysis of water with uranium, coal, solar, or any other electrical energy sources is one possibility. Another is hydrogen from the carbon-water reaction.(3) The carbon can be in coal or coke, or it can come from the dissociation of carbon dioxide, as will be discussed later in this paper. Finally, hydrogen can be released in a series of chemical reactions which dissociate water and recycle various reactant chemicals. Some of these thermochemical methods will be discussed by Bamberger in another paper in this session.

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(2) Iceland, with plentiful hydro and geothermal resources, still uses the arc process.

(3) Bosch and Haber developed their ammonia synthesis process in the early 1900's with hydrogen from "water-gas," obtained by reacting steam with red-hot coke. Beginning in the 30's, methane became the principal source of hydrogen.

The Wisconsin Process for Nitrogen Fixation

As mentioned already, nitrogen can be fixed directly from air in an electric arc. The electric arc, per se, is not crucial; it is one way of attaining the very high temperature (∿ 2500 K) required by the reaction. In 1939, Frederick Cottrell suggested that a natural-gas fired furnace might be another way to achieve such temperatures and fix nitrogen directly. He also recognized that rapid quenching with a heat recovery device (a bed of magnesium oxide [MgO] pebbles) would save much of the energy lost in the arc process. His ideas were developed in more detail at the University of Wisconsin over the next decade, and in 1952, the Food Machinery and Chemical Corporation constructed a demonstration plant to produce enough NO to make 40 ton/day nitric acid. The plant was operated from April 1953 to October 1954 and was a remarkable accomplishment, considering the fact that it successfully achieved the 40 ton/day HNO_3 production rate by generating NO in two pebble-bed reactors at temperatures measured as high as 2480 K (4000°F).(4)

A Solar-Fired Wisconsin Process

We believe that there are reasonable prospects for adapting the Wisconsin process to a solar furnace. Our conception of the solar-fired process is to combine the essential features of a ceramic central receiver (such as those designed by Sanders Associates(5) for DOE, or Black and Veatch(6) for EPRI) with the Wisconsin pebble-bed arrangement. Both Sanders and Black and Veatch

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(4) E. D. Ermenc, "Wisconsin Process Pebble-Bed Furnace Fixes Atmosphere Nitrogen," Chemical Engineering Progress, April 1956.

(5) Unpublished report #01287, personal communication, April 1978, Sanders Associates, Inc., Nashua, N.H.

(6) "Solar Thermal Conversion to Electricity Utilizing a Central Receiver Open Cycle Gas Turbine," EPRI-ER-652, Black & Veatch Consulting Engineers, March 1978.

have based their designs on silicon carbide as the receiver material, but it is unsuitable for temperatures above 1525 K (2200°F). A screening of several candidate ceramics for higher temperatures found several possibilities. Although the data characterizing their high temperature properties is presently insufficient to make a choice, we believe that either zirconium oxide (ZrO_2) or magnesium oxide (MgO) will prove to be suitable for temperatures above 2500 K. Thorium oxide (ThO_2) may be another possibility. The Wisconsin process used MgO bricks and pebbles and reported no serious difficulty except breakage of some pebbles during handling.

To attain the 2480 K (4000°F) temperature required for nitrogen fixation, the central receiver optical system must achieve concentrations greater than 4000, which is an increase of several times present designs of commercial receiver (Fig. 2).

Such concentration ratios can be achieved but the attainment of 2480 K (4000°F) in a cavity large enough for commercial production is probably unrealistic because reradiation losses from present designs would appear to reduce the cavity efficiency to a few percent. A solar heat supply system which has combined losses (from mirrors to the cavity thermal energy output) greater than 75% is not likely to be economical. The reason is that solar electric heat at about 20% efficiency from the same central receiver system would be a cheaper source of high temperature energy.

Thus, we must turn to designers (or inventors!) to see if the problem of attaining very high temperatures at reasonable efficiency can be solved. Reconcentration at the aperture, cavity covers with selective coatings and larger cavity-to-aperture area ratios are possible solutions.

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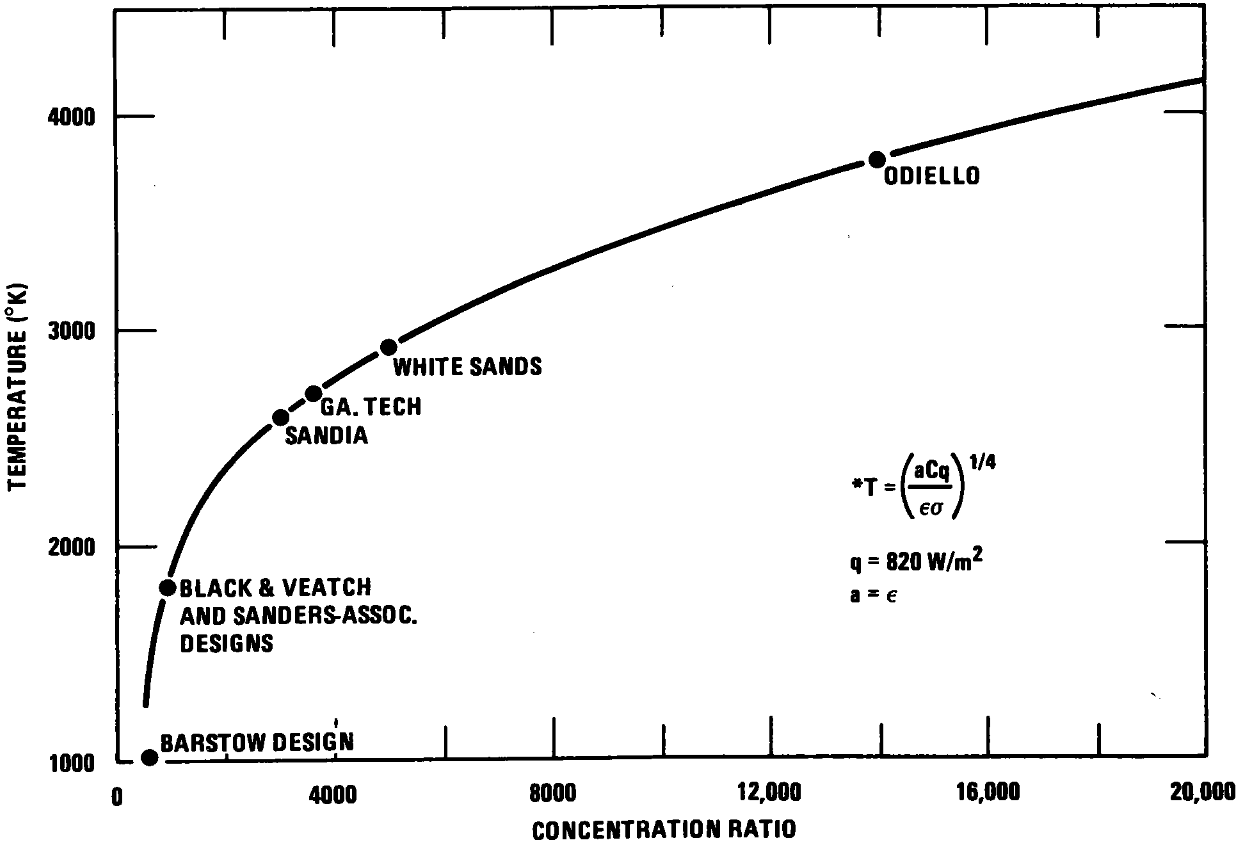
MAXIMUM FURNACE TEMPERATURE* AT VARIOUS CONCENTRATION RATIOS



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Another approach is to seek means of reducing the temperature requirement for a given reaction, or increasing the yield at a given temperature such as the reported(7) possibility that mixtures of nitrogen, oxygen, and carbon dioxide produce much higher yields of NO at a given temperature than does a mixture of nitrogen and oxygen alone.

In any case, no central receiver design is presently available for our proposed applications (NO & CO production) or others requiring temperatures above 1300 K. Of the two proposed designs (Table 1) for electricity generating plants with ceramic (SiC) heat exchangers, we judge the Black & Veatch concept to be a possibility for redesign with MgO or ZrO_2 ceramics, for temperatures in the 1300 K to 2500 K range.

We propose some redesign targets (Table 2), recognizing that all will probably not be achieved. The first target is the maximum temperature of 2500 K (4000°F), already discussed. The second target is the rate of heat input to the process stream. This determines the size of the solar energy system. For a process such as nitric acid manufacture to have much industrial significance, a plant's production tonnage must be high, say hundreds or thousands of tons per day. If the process is energy intensive, a large energy supply must be available. With this reasoning we set a minimum heat input target of 50×10^6 Btu/hr, roughly equivalent to a 15 MW(t) system. A third target is that 20 to 25% of the energy collected be deposited in the process. This was based on the efficiency of solar electricity (20%) as discussed earlier. Another target is that the system be capable of pressurization to around 10 atm, so that the density of the process fluid permits a high through-put and good heat transfer.

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(7) Harry A. Curtis, Ed., Fixed Nitrogen, Chemical Catalog Company, N.Y., 1932.

Table 1. Conceptual Design Data for Solar Heated Open-Cycle Gas Turbine Power Station

	Sanders Associates (1)	Black & Veatch (2)
Design Electrical Capacity	100 MW(e)	60 MW(e)
Avg. Heat Delivered to Receiver	666×10^6 Btu/hr	390×10^6 Btu/hr
Number of Receiver Cavities	1	4
Total Land Area	1,064,000 m^2	643,000 m^2
Total Collector Area	414,000 m^2	260,000 m^2
Tower Height	260 m	213 m
Receiver Aperture	161 m^2	156 m^2
Concentration Ratio	2500	∿1600
Receiver Heat Exchanger Type	Honeycomb	Multiple U-Tube
Air Flow	∿500 kg/sec	∿275 kg/sec
Number of Tubes or Surface Area per Cavity	Honeycomb	70 Tubes, 10 cm diam x 12.2 m long
Tube Material	Silicon Carbide	Silicon Carbide
Outlet Temperature	1384°K	1310°K
Outlet Pressure	∿atm.	130 psia
Capital Cost per 10^6 Btu/hr	\$116,200 (3)	\$110,000 (4)

(1) Based on Personal Communication from Armand Pourier, Sanders Associates.
(2) Extracted from EPRI-ER-652.
(3) Assumes \$100/m^2 heliostats, 5% contingency, 10% indirect costs.
(4) Assumes \$100/m^2 heliostats, 5% contingency and spare parts, 10% indirect costs and 15% interest during construction.

TABLE 2. PROPOSED DESIGN TARGETS FOR A VERY HIGH TEMPERATURE CENTRAL RECEIVER

1. Operating temperature: 2500 K (4000°F).
2. Heat Input to Process Stream: 15 MW(t) (about 50×10^6 Btu/hr.)
3. Overall Efficiency: 20 to 25%.
4. Operating Pressure: 10 atm.

Equipment Layout for NO Process

Assuming that these targets could be met at some time in the future, we postulated a physical concept which could produce tons per hour quantities of NO and CO. A possible arrangement of equipment on the tower is shown in Figs. 3 and 4. Figure 3 is a plan view of the receiver and the pebble-bed reactors, with the U-tube heat exchanger assembly centered between the two ceramic pebble bins. Figure 4 is an elevation view. In this version of the Wisconsin process, air at 10 atm pressure is pumped through one pebble bed which preheats the air to about 1870 K. The air flows at a rate of 275 kg/sec (466,000 SCFM) to the solar heat receiver, consisting of 55 ceramic U-Tubes, 10 cm diam and 12.2 m long, reaching a temperature of 2480 K, and thence to the second pebble bed where the NO mixture is rapidly cooled to 2000 K. In the Wisconsin experience, air leaving the 2480 K zone contained 2.5% NO, but the dissociation reaction ($NO \longrightarrow 1/2\ N_2 + 1/2\ O_2$) reduced the concentration to 1.8% to 1.9% prior to quenching. The quench bed continues to accept heat (about 3 minutes) until its exit gas temperature reaches 600 K (620°F), causing the flow to reverse so that the chilling bed becomes the preheat bed and the former preheat bed becomes the chilling bed. The flow continues to reverse at approximately three-minute intervals while the plant operates.

The theoretical heat energy required per short ton of NO produced is 2.6×10^6 Btu (2.74×10^9 J), and the production rate 275 kg/sec x .019 x 3600 sec/hr = 18,800 kg/hr (∿ 20 tons/hr), so the total heat requirement is $2.74 \times 10^9 \times 20 = 54.8 \times 10^9$ J/hr (52×10^6 Btu/hr). The exit gases, cooled to 600 K and containing the product NO, flow from the tower reactor to the nitric acid plant at ground level. The process flow diagram shown in Fig. 5 is a standard HNO_3 plant.

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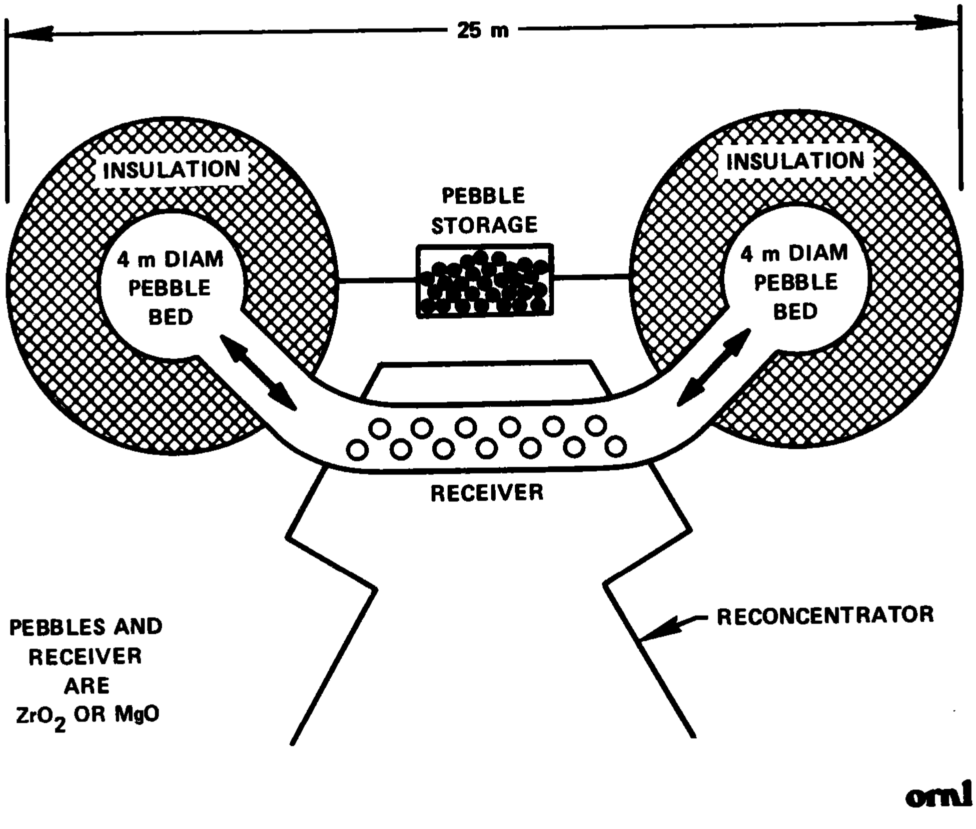
CROSS-SECTION VIEW OF SOLAR-FIRED WISCONSIN PROCESS FOR NO PRODUCTION



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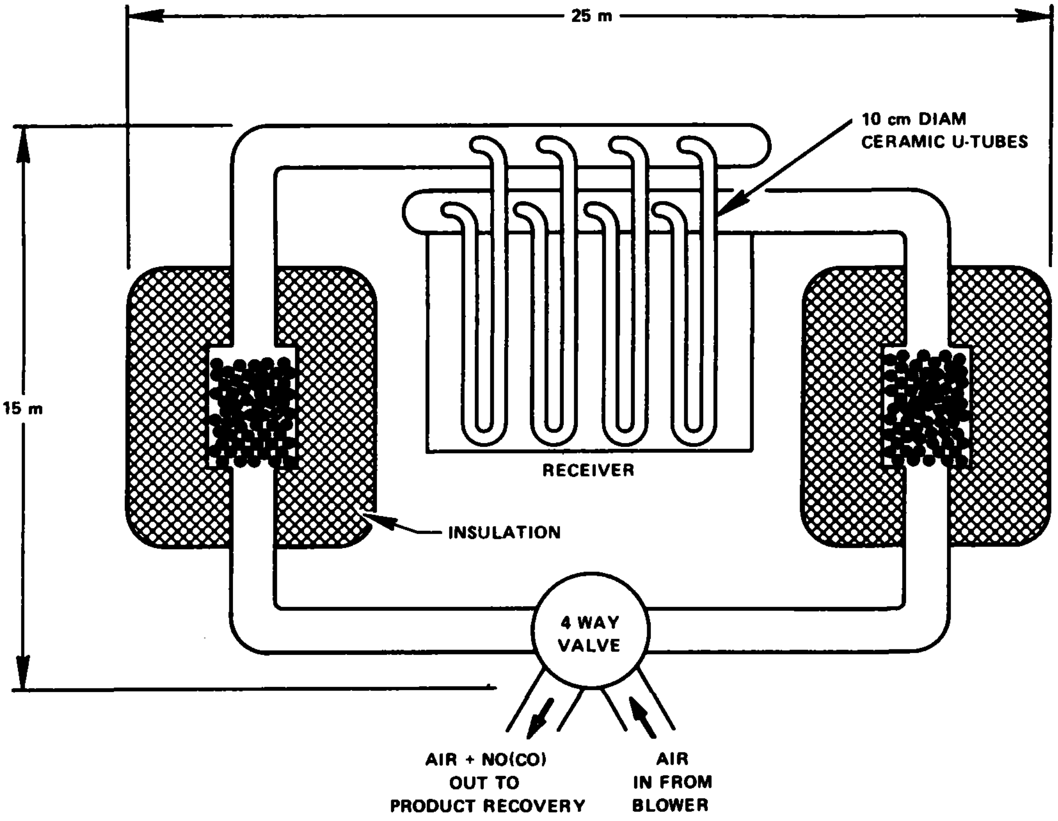
TOP LEVEL ELEVATION

RECEIVER AND PEBBLE BEDS
OF SOLAR FIRED NO PROCESS



Economics of Solar Produced Nitric Acid

Whether the plant described is an economic producer of nitric acid cannot be determined without much more information but we can estimate an allowable cost for the central receiver system. Based on present day energy requirements for the ammonia consumption which this plant would replace (about 42 x 10^6 Btu/ton for feedstock and process heat), and assuming the 1980 cost of natural gas at \$3.15 million Btu,(8) the allowable cost of energy would be 42 x \$3.15 or \$132/ton NH_3 (or for HNO_3, 11.3 million Btu/ton and \$35.60/ton). A central receiver system capable of delivering 52 x 10^6 Btu/hr (15.2 x 10^6 J/sec) at 20% efficiency must collect 260 x 10^6 Btu/hr (76.1 x 10^6 J/sec) to produce 20 tons HNO_3/hr or 80,000 tons/yr, assuming 4000 hours sunshine at Inyokern. The capital charge permitted each year for energy supply would be approximately:

$$\$36 \times 80{,}000 = \$2{,}880{,}000$$

If operating costs for the tower are \$880,000/yr (a guess), leaving \$2 million/yr to cover the annual capital charge (16%), the allowable investment in the central receiver system, including land, collectors, tower, receiver, etc., but not the acid plant, would be:

$$\frac{\$2{,}000{,}000}{0.16} = \$12{,}500{,}000 \text{ (1980 dollars)}$$

Considering that the Black & Veatch-EPRI capital cost totaled \$110,000 per 10^6 Btu/hr (Table 2) without reconcentrators or pebble beds, the 260 x 10^6 Btu/hr heat collection capability would cost \$28,000,000, more than double the allowable cost.

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(8) "Most Likely Price," Conclusion of H. G. Corneil, F. J. Heinzelman, and E.W.S. Nicholson in "Production Economics for Hydrogen, Ammonia and Methanol During the 1980-2000 Period." Exxon Research and Engineering Company, Linden, N.J., April 1977.

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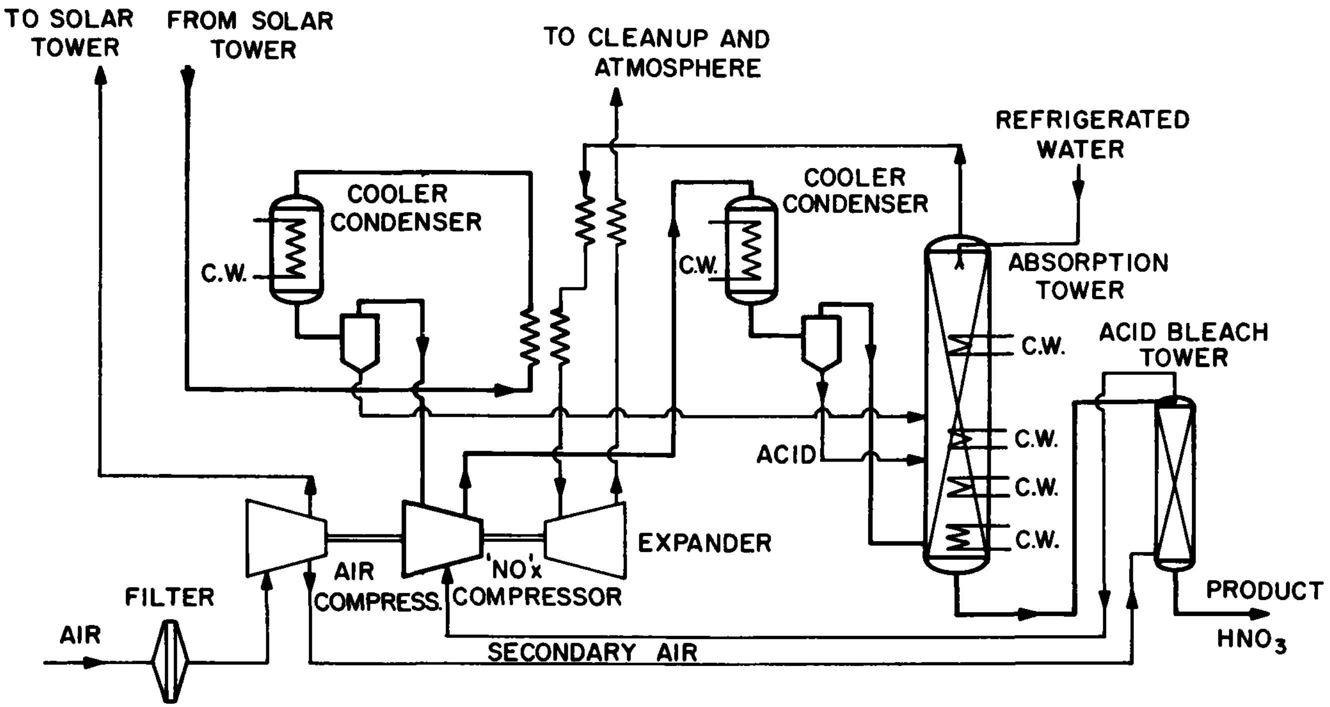


DUAL PRESSURE HNO_3 PLANT FLOWSHEET

(RE, PG 227, "MODERN INORGANIC CHEMICALS INDUSTRY")

CO_2 Dissociation Plant

The possibility of dissociating CO_2 to CO in a solar heated reactor is perhaps more important than fixing nitrogen from air because of its significance to a possible future "hydrogen economy." At 2480 K, the temperature which we assumed for the NO reactor, the fraction of CO in a 1-atm CO_2-CO mixture is 14%. Unfortunately, there is insufficient information available on the kinetics of the back reaction ($CO + 1/2\ O_2 \longrightarrow CO_2$); the allowable quench time and temperature are not presently known. Even so, we considered how the solar central receiver might be adapted for CO_2 dissociation and concluded that the concept of receiver and dual pebble beds already described for the NO process might also be suitable for the $CO_2 \longrightarrow CO + 1/2\ O_2$ reaction. In place of the nitric acid plant in the NO process, the CO rich mixture would then be reacted directly with steam:

$$CO + H_2O \longrightarrow CO_2 + H_2$$

and the CO_2 separated by scrubbing and returned to the reactor, leaving pure hydrogen as the product.

Alternately, part of the CO could be scheduled for reaction with the hydrogen already formed:

$$CO + 3\ H_2 \longrightarrow CH_4 + H_2O$$

or

$$CO + 2\ H_2 \longrightarrow CH_3OH$$

Each kilogram of CO formed would require 9.02×10^6 J/kg (3884 Btu/lb) theoretically. Thus, the central receiver chosen for the NO plant might deliver 15.2×10^6 J/sec (52×10^6 Btu/hr) and produce:

$$\frac{15.2 \times 10^6 \text{ J/sec}}{9.02 \times 10^6 \text{ J/kg}} = 1.65 \text{ kg/sec } (13{,}000 \text{ lbs/hr})$$

or

23.76×10^6 kg/yr (52×10^6 lbs/yr) for 4000 hrs operation

Each kilogram of CO can be converted to 1/14 kg of hydrogen by reaction with steam ($CO + H_2O \longrightarrow CO_2 + H_2$) so the annual hydrogen production rate would be about 2×10^6 kg. The manufacture of one kg of hydrogen from natural gas requires 3.06×10^8 J (132,000 Btu/lb) for feedstock and process energy. A production rate of 2×10^6 kg/yr would require 6.12×10^{14} J ($580{,}000 \times 10^6$ Btu) fossil fuel per year, which is the annual fuel savings possible for the solar CO plant. With natural gas costing \$3.15 (1980 dollars) per million Btu, the dollar savings would amount to $\$2.16 \times 10^6$/yr. Again allowing \$880,000/yr for operating expense, the savings would be reduced to $\$1.28 \times 10^6$/yr. For a 16% annual charge rate, the allowable capital investment for the central receiver system would be only \$8,000,000. This is low, considering that the cost derived from the Balck & Veatch estimate was \$28,000,000.

Thus, it appears presently that the $CO_2 \longrightarrow CO \longrightarrow H_2$ solar route may not become competitive with hydrogen from oil or natural gas, at their projected prices for the 1980's.

Conclusions

The thermal nitrogen fixation process has been demonstrated in the past and the CO_2 splitting process appears technologically feasible. Our crude cost estimates using reasonable assumptions for solar collector costs and projected costs for raw materials indicate that the above processes will not compete favorably with established processes for the production of HNO_3 and of H_2 in the near future. However there are enough uncertainties built-in the simple assumptions made which do not allow for discarding these processes from further consideration. On the contrary, since both chemicals are so important for supporting life under modern agriculture, our cursory analysis suggests avenues of research for upgrading such processes. These areas involve mainly ways of minimizing losses by reradiation and perhaps optimizing designs, and these not only would benefit the production of H_2 and HNO_3 but any other high solar temperature process as well.

Comment - That process is not dead as far as we are concerned. We've been working on it three years. Next year we are going to have two small-scale installations. But I agree that the same process can be extended using solar energy.

Mr. Beall - I think your applications for very small-scale and underdeveloped countries are quite different than the large-scale production I'm talking about. So I don't disagree that you might be able to do it economically.

Question - Is the arc reaction a serious problem in the CO production process?

Mr. Beall - We don't know. We don't have any kinetics on it. We are making optimistic assumptions just to see if everything turned out all right. Whether you are going to have an economic system would certainly have to be determined because the temperature concentrations of CO and CO_2 at 4000°F is 14 percent.

COMMENTS ON THE GYPSUM INDUSTRY

S. E. Beall
Oak Ridge National Laboratory

We have been working with US Gypsum for a year or more. They have a plant at Plaster City, California, one of the best insolation areas in the whole world, and they mine a lot of gypsum, which is calcium sulfate. Mr. Beightol, of US Gypsum, is scheduled to be our next speaker but he was unable to attend.

US Gypsum, through him, is interested in exploring the application of solar energy to plasterboard production at Plaster City. We have visited their plant and observed their operations. After mining the gypsum, it must be calcined to remove the water of hydration. This takes place at something like 200°C. After being mixed with water, the gyp board is formed and then put through a drying process at 650°C. Many of their plants have been based on natural gas and are in isolated locations like Plaster City. They have had enormous problems in obtaining fuel and have had to shift to oil at much greater cost, which accounts for their interest in solar.

A central receiver similar to the Barstow plant might be located there and steam piped to the gypsum process, or the more advanced ceramic receiver (Black & Veatch or Sanders Associates) could supply hot air. The dehydration can be accomplished in two different kinds of equipment. One can be steam fed, the other is a rotary kiln-type in which hot air could be used. So, either the steam-generating central receiver or the ceramic hot-air central receiver is applicable to the gypsum operation. The ceramic hot-air receivers are also applicable to other kinds of calcining operations.

The gypsum plant at Plaster City is a good candidate for a demonstration, which is why we have been working with US Gypsum. Many of the other gypsum plants are in high sun areas, so there are possibilities for expanding solar uses in this industry.

Again, I apologize for Mr. Beightol not being able to come, but I hope our relationship develops into some plans for future action.

SOLAR FLASH PYROLYSIS: SYNGAS FROM BIOMASS

Michael J. Antal, Jr.
Princeton University

Abstract

Processes for thermochemical biomass gasification require a source of high-temperature heat. In addition, if char formation is to be minimized the solids heating rate must be very high. This paper considers the use of point focus solar concentrators to provide heat for the flash pyrolysis of biomass materials. A detailed outline of the thermochemistry of biomass gasification is given, followed by a discussion of the energy demands of the gasification process and their implications for a solar-powered gasifier.

Biomass gasification is a three-step process. At relatively low temperatures biomass pyrolyzes, producing volatiles and char. This phenomenon is illustrated in slides 1 and 2, which give weight loss versus temperature data for various biomass materials. Slide 3 presents the apparent activation energy of red alder wood pyrolysis as a function of fractional conversion. It is known that higher heating rates reduce char formation and lead to greater yields of combustible gas.

Volatiles evolved by the pyrolysis reactions crack at higher temperatures to produce a hydrocarbon-rich syngas. A reactor for studying these gas-phase reactions, currently in use at Princeton, is described in slide 4, and gas yields for cellulose gasification are given in slides 5-7. Slide 8 portrays the carbon, hydrogen and oxygen efficiencies of the process. Generally, 70 percent of the initial energy of the cellulose feedstock was carried by the gaseous conversion products, which possessed a heating value exceeding 500 Btu/scf. It is important to note that at gas-phase temperatures exceeding 700°C the syngas is produced in residence times less than 0.5 sec.

At still higher temperatures char can be made to react with steam using the water-gas reaction. However, the rates are slow and the products (CO and H_2) less desirable. A well designed biomass gasifier should not produce sufficient char to require high-temperature gasification.

Energy requirements for biomass gasification are small. Slide 9 is an energy level diagram for cellulose gasification, and shows that about one million Btu's of heat are needed to gasify one ton of cellulose with a heating value of fifteen million Btu's. Slide 10 compares conventional biomass conversion technologies with a solar-powered gasifier. Solar gasification can double or triple the amount of useful energy obtained from biomass over conventional techniques.

Biomass is one of the world's major renewable resources. But since only a limited quantity is produced each year, conversion efficiency is the most critical concern in the area of biomass utilization. Solar gasification provides conversion efficiencies approaching 100 percent, and stores the solar heat in the form of a valuable gaseous fuel. Research at Princeton has generated sufficient experimental data to begin the design of a solar-powered gasifier. This effort is now underway, and initial results should be available shortly.

Question - When you say one million Btu's, does that involve the steam and oxygen?

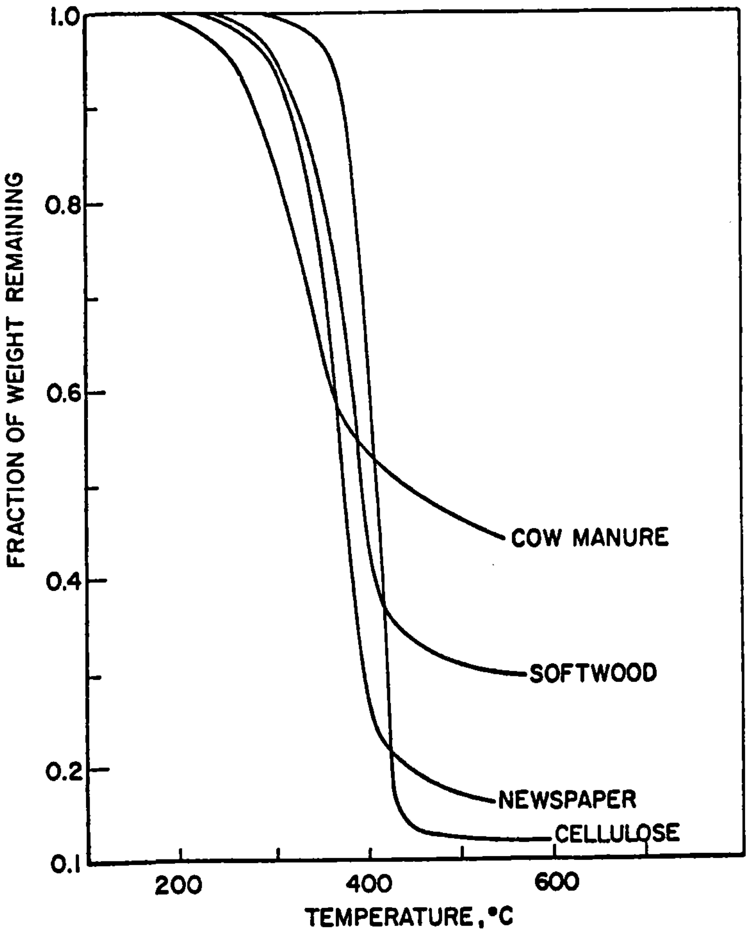
Dr. Antal - That takes care of everything, and that assumes reasonable efficiencies. It doesn't assume that you are recovering all the heat from condensing the steam and it's nominally a million depending on the exact assumption you make. It might be 0.18 or it might be 1.4, but the point is that it's very small.

Comment - You know that in my work we are using 1000 instead of 600 and you need a catalyst.

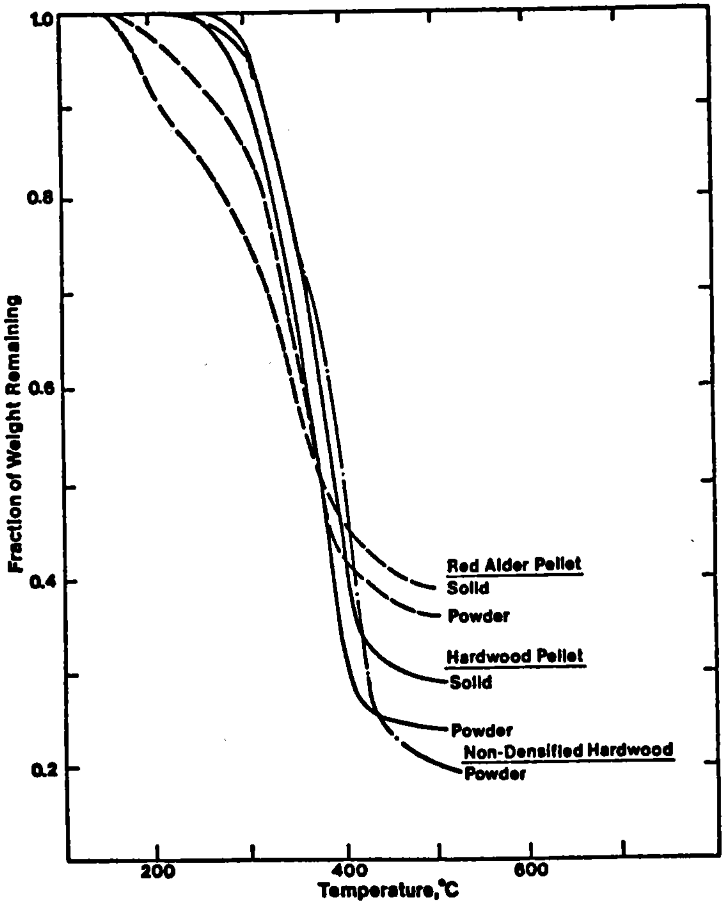
Comment - I think this is the essence of what we are trying to get across. We have solar energy. We have facilities now that are trying to find these potential new thing that solar energy can give us--a clean, highly intense source of heat. I'm aiming this at the industrial people: find ways to do new things and use them to make the products we are making now but in new ways.

Question - Do you care where the million Btu's come from? If you could do it by burning trash, would that be better?

Dr. Antal - That is the pertinent question and I will talk about the economics of that tomorrow.

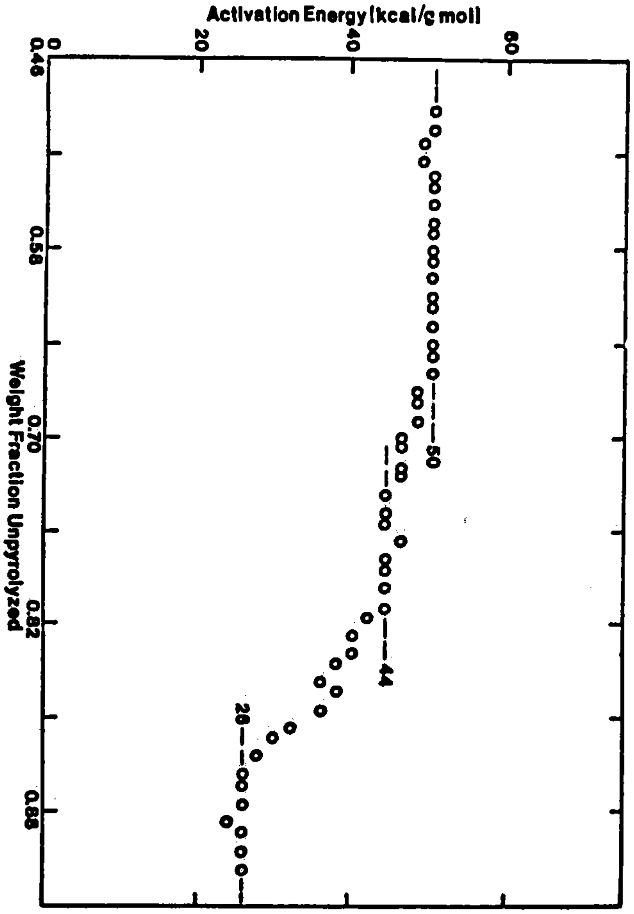


Slide 1 Pyrolytic weight loss (on a mass fraction basis) vs. temperature for various biomass feedstocks.



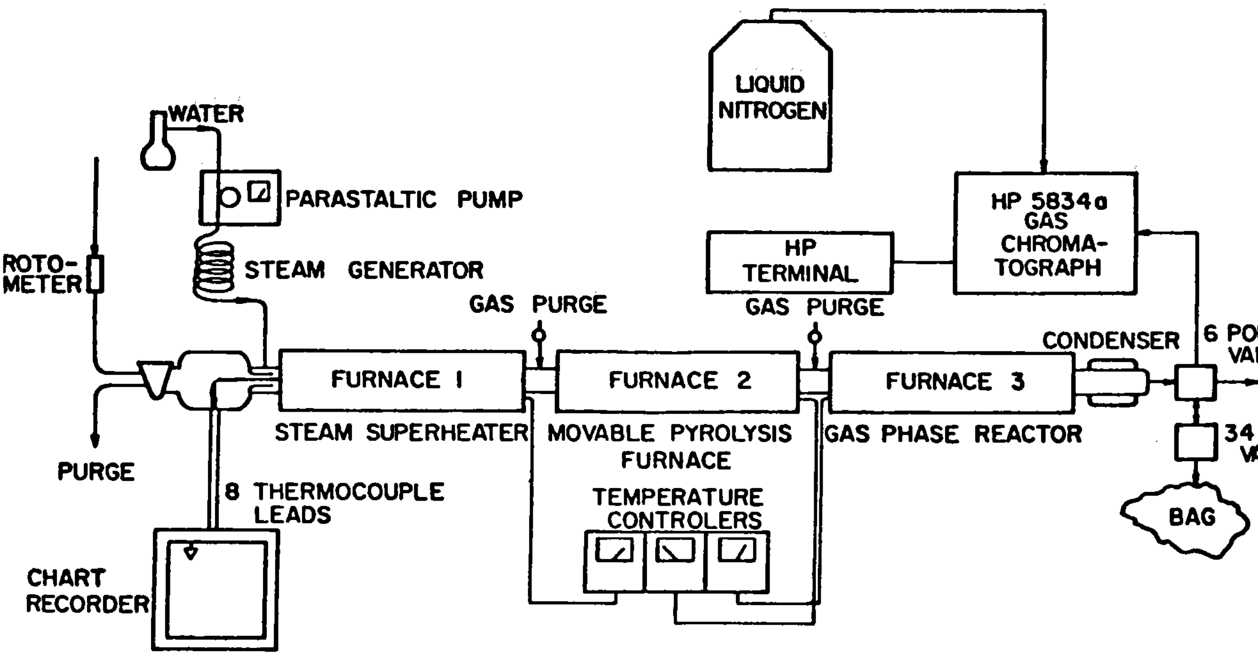
Slide 2

WEIGHT LOSS VS. TEMPERATURE CURVES FOR VARIOUS PELLETIZED AND NON PELLETIZED WOODS



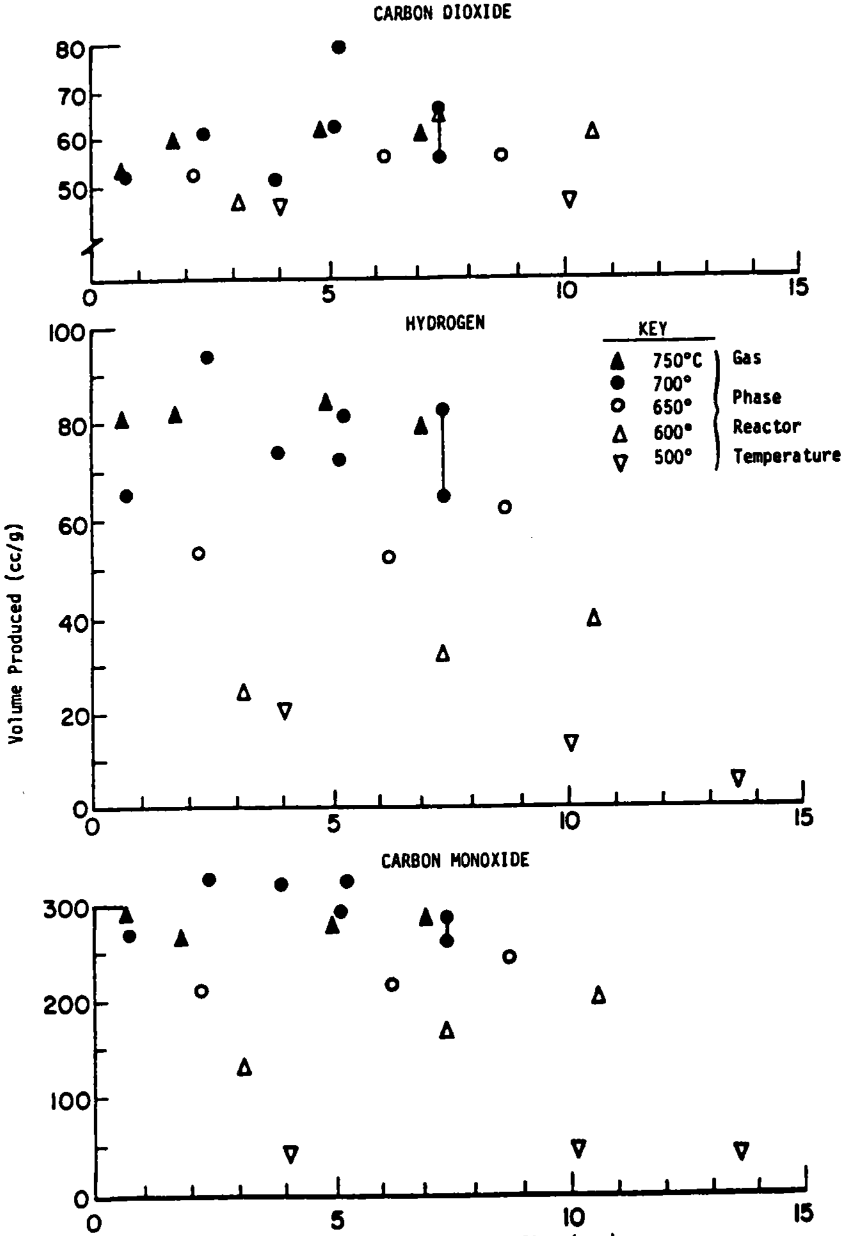
Slide 3

ACTIVATION ENERGY VS, WEIGHT FRACTION REMAINING FOR PULVERIZED RED ALDER PELLETS

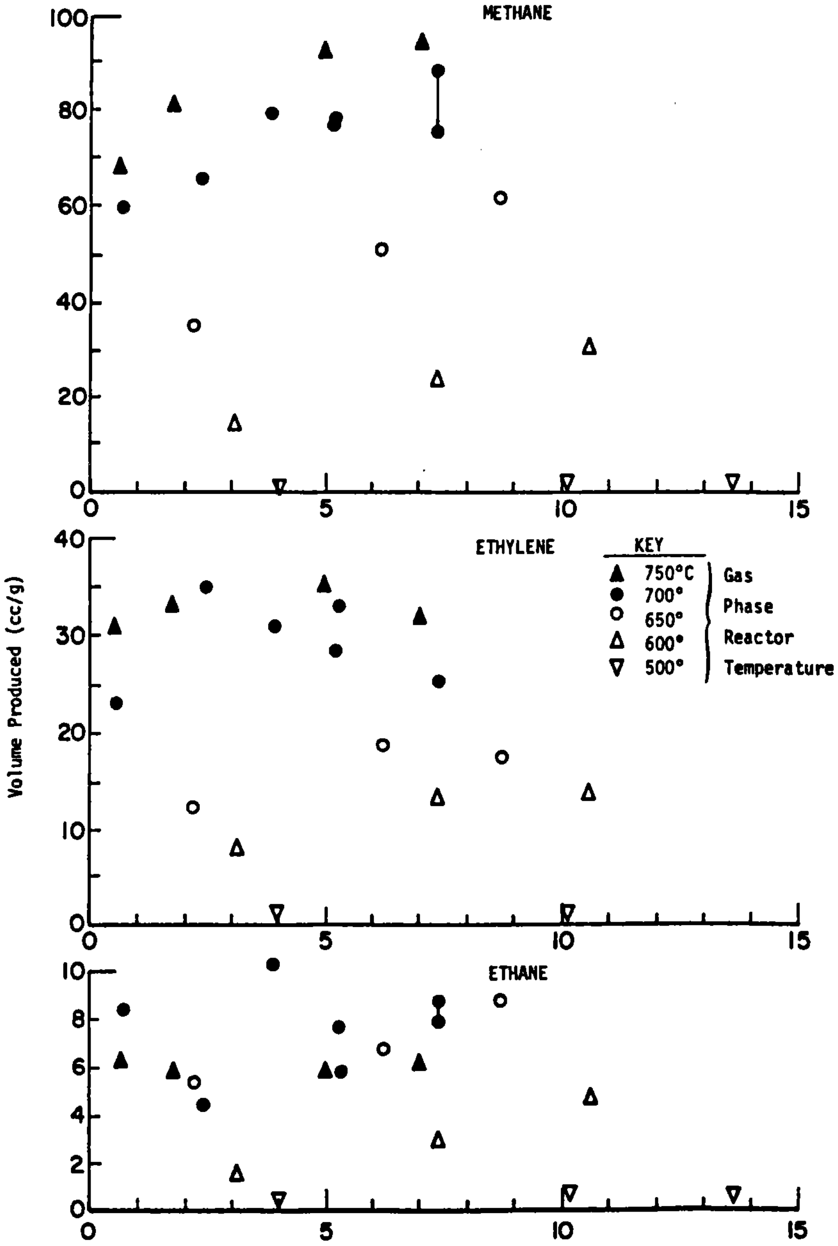


Slide 4

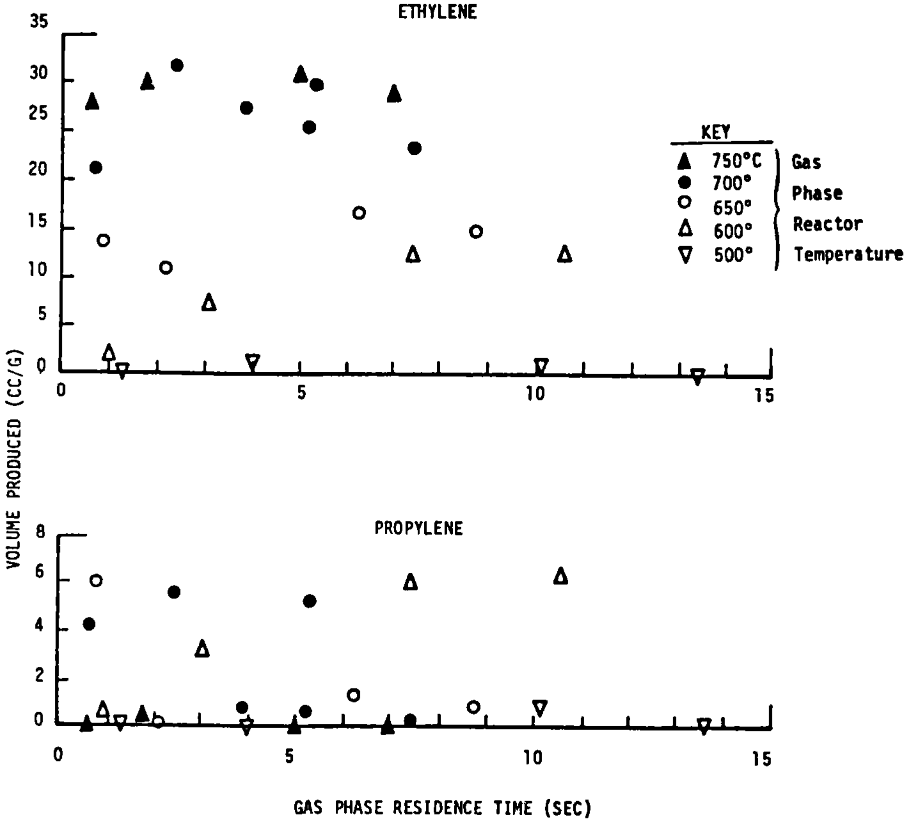
Schematic of Princeton's pyrolysis/steam gasification experiment.



<u>Slide 5</u> Gas Phase Residence Time (sec)

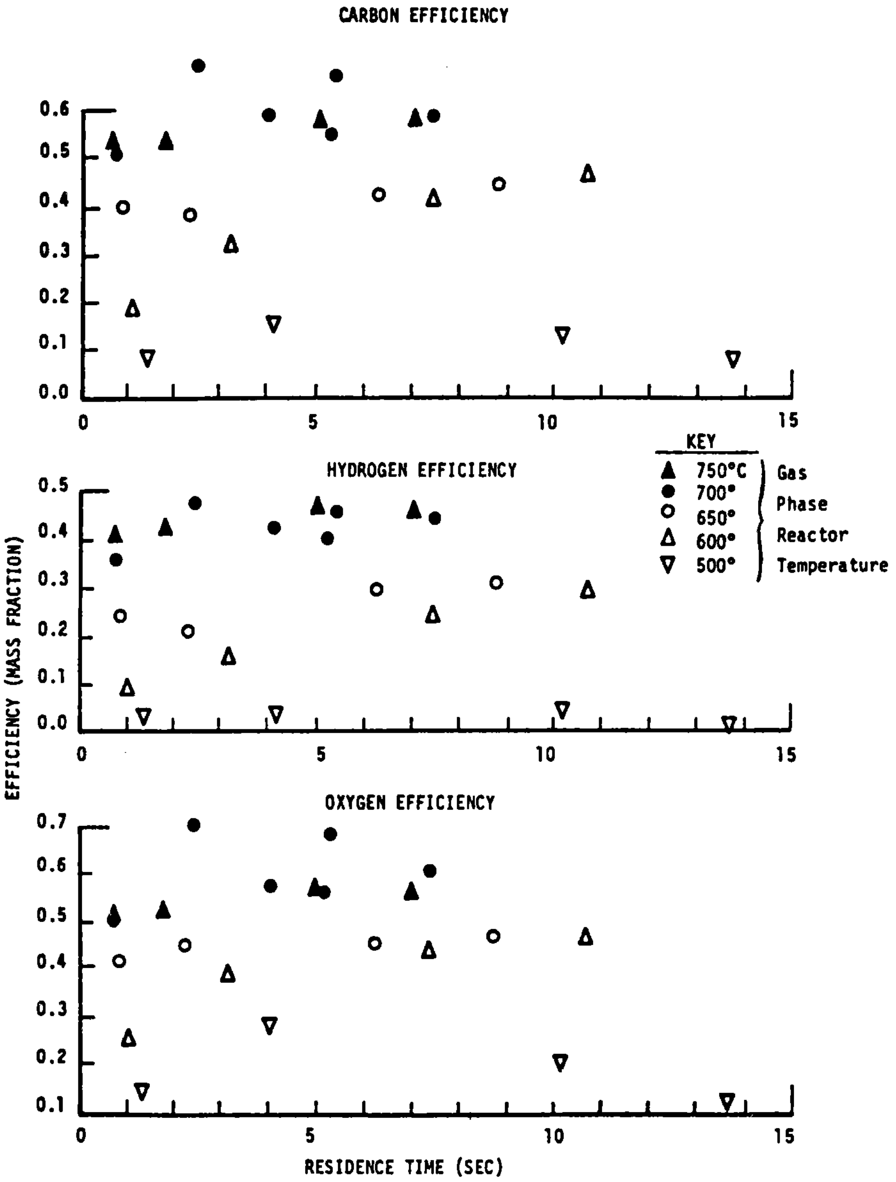


<u>Slide 6</u> Gas Phase Residence Time (sec)



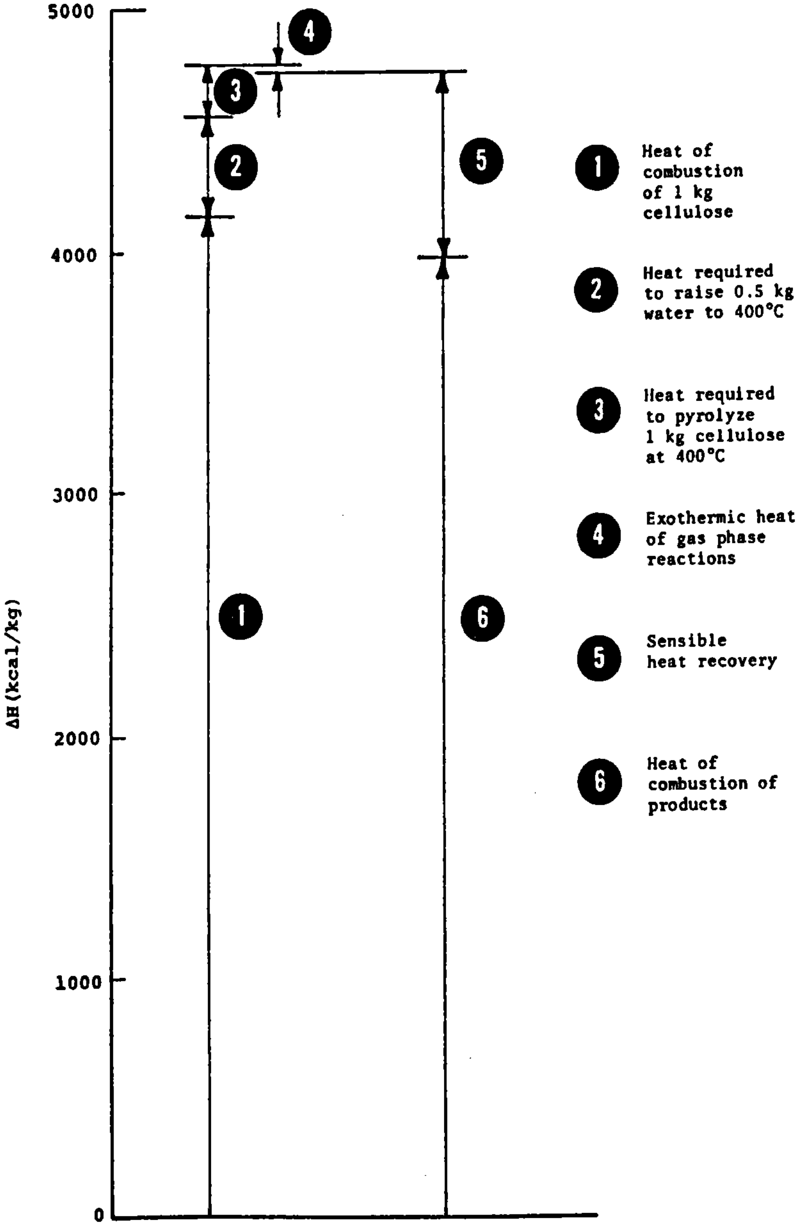
Slide 7

OLEFINIC HYDROCARBON PRODUCTION FROM CELLULOSE

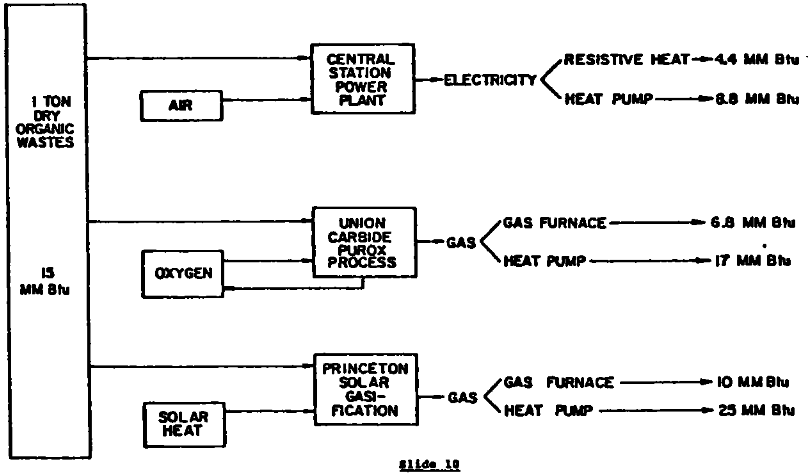


Slide 8

CARBON, HYDROGEN AND OXYGEN EFFICIENCIES OF CELLULOSE GASIFICATION



Slide 9 Enthalpy level diagram for the pyrolysis/steam gasification process at atmospheric pressure.



Slide 10

A comparison of the useful energy derived from selected biomass conversion processes.

SOLAR COAL GASIFICATION

D. W. Gregg, W. R. Aiman, H. H. Otuski,
and C. B. Thorsness
Lawrence Livermore Laboratory

Solar Coal Gasification is potentially an attractive commercial process. The coal can be gasified by reacting it with steam (or CO_2) in the focal zone of a Solar Central Receiver plant. Since the coal-steam reaction is endothermic, the product gas has more heating value than the initial coal. The necessary energy is thus converted into chemical energy at the same time that the coal is gasified. This process has the dual attractions of upgrading coal to a more valuable form of fuel while chemically storing solar energy.

The use of solar energy proportionately improves the efficiency of coal utilization over alternate coal gasification processes, and thus conserves on coal, an exhaustible resource. Such a reduction in coal usage in a gasification process reduces many potential environmental problems associated with the use of coal. In addition, a major cost advantage is achieved by substituting solar energy for the "expensive" oxygen-coal energy normally used in the production of medium Btu (synthesis) gas.

The medium Btu product gas consisting primarily of CO and H_2 is commonly called "synthesis gas" and can be used as a primary feedstock in a multitude of chemical processes. It can be converted to methane (pipeline quality gas), methanol, gasoline, most monomers for plastics, and a source of H_2 for coal liquidification, hydrogination of oil and oil shale, and the production of NH_3. Thus, if Solar Coal Gasification can be shown to be technically and economically feasible, it is a solar-chemical process which could have a very large impact on our energy and chemical economy.

CHEMISTRY

The chemistry of coal gasification involves two basic steps: pyrolysis and char gasification. Pyrolysis chemistry simply describes the manner in which coal decomposes when heated. It can be represented by the following equation:

$$\text{Coal} + \text{heat} \rightarrow \text{char (C)} + CO + CO_2 + H_2 + CH_4 + \text{tars} \qquad (1)$$

The energy required for this reaction is relatively small since these decomposition reactions are only very slightly endothermic. The primary energy requirement is for heating the coal up to pyrolysis temperatures. The mass liberated by pyrolysis can vary from a few percent to as much as 40 percent by weight, depending on the particular coal.

The char gasification chemistry can be represented by the following equation:

$$\text{Char (C)} + H_2O \rightarrow CO + H_2 - 31.4 \text{ kcal/g-mole} \qquad (2)$$

This reaction is highly endothermic and thus is the primary reaction that chemically stores solar energy in product gas. It adds 31.4 kcal/g-mole to the heat of combustion of the product gas. Since the heat of combustion of one g-mole of H_2 + one g-mole of CO is 125.45 kcal, solar energy contributes approximately 25 percent of the heating value of the product gas resulting from the char gasification step. The net contribution of solar energy to the heating value of the product gas will depend on the relative magnitudes of the pyrolysis and char gasification steps and thus on the particular coal being gasified.

The required reaction temperature is 1100 100 K.(1) This temperature requires the use of two-dimensional focusing of sunlight, and thus is well matched to the Solar Central Receiver plant concept.(2,3) The temperature is also low enough so that reradiation can be kept to a few percent of the insolation in the focal region of such plants. Efficient utilization of the focused solar energy is thus feasible.

ECONOMICS

The primary objective of a Solar Coal Gasifier is to use sunlight to replace the oxygen-coal energy source normally employed in the production of a "medium Btu" product gas. Conventional coal gasification plants use the partial combustion of coal with oxygen to provide the energy to drive reactions 1 and 2. Air is used as a source of oxygen for the production of "low Btu" product gas which is diluted with large amounts of nitrogen. A higher heating value "medium Btu" product gas is produced when oxygen is substituted for air to carry out the partial combustion. The primary beneficial effect is to remove the nitrogen from the product gas. This requires the construction and operation of a devoted oxygen plant associated with the coal gasification plant. The Solar Coal Gasification plant will not need such an oxygen plant, and will produce a medium Btu product gas. It is therefore meaningful to compare the cost of solar energy at the focus of a Solar Central Receiver Plant with the cost of energy derived from burning coal with oxygen, since these energy sources are interchanged between the two gasification concepts.

1. Solar Energy Cost

The estimated cost of solar energy made here is based on cost and performance estimates made by the McDonnell Douglas Corporation.(3) Their performance analysis indicated that their design for an individual heliostat (with an area of 49 m^2) will produce approximately 280 kWh_t/day averaged over the year and over the different field positions anticipated in a possible design for a 100-MW plant to be built at Barstow, California. A summary cost analysis presented by the Sandia Corporation estimates that the McDonnell Douglas heliostat field for the Barstow plant would consist of 16,900 heliostats which could be built and operated for a cost of approximately $6,000,000/year (assuming mass production).(4) If one assumes that the field can be operated for 330 days/year, the resultant cost of solar energy focused at a position in space is approximately $1.07/$10^6$ kj ($1.13/$10^6$Btu).

2. Coal-Oxygen Energy Cost

The price of coal was obtained from prices quoted in Coal Week, August 21, 1978. In this issue, quoted steam coal prices ranged from 66.1¢/10^6 Btu to

169.1¢/10^6 Btu with an average of 120¢/10^6 Btu. Estimates for the cost of oxygen using a devoted plant for a coal gasifier range from \$20 to \$30/ton.(5) Using the composition and heat of combustion for a typical Powder River Basin, Wyoming, coal and the above price information, the cost of energy derived from burning coal with oxygen can range from \$2.28/10^6 kj (\$2.41/10^6 Btu) for coal at 66.1¢/10^6 Btu and oxygen at \$20/ton to \$4.08/10^6 kj (\$4.31/10^6 Btu) for coal at 169.1¢/10^6 Btu and oxygen at \$30/ton. Using the average coal cost of 120¢/10^6 Btu and oxygen cost of \$25/ton, the cost of coal-oxygen energy is \$3.22/10^6 kj (\$3.40/10^6 Btu).

It can be seen that the cost of oxygen-coal energy is considerably more expensive than focused solar energy from a Solar Central Receiver plant. Even though the estimated solar energy cost is probably subject to change with improved design information, it must increase considerably before it becomes more expensive than oxygen-coal energy.

3. Product Gas Energy Cost

The proposed Solar Coal Gasification Plant is compared to a Lurgi Coal Gasification Plant because the Lurgi Plant is the most tested and well understood coal gasification plant design and comparatively good cost data are available for it.(5) For this reason, it is commonly used as a standard of comparison for surface coal gasification. A summary of the results is presented in Table 1. For these results it is assumed that coal costs \$1.20/10^6 Btu, solar energy costs \$1.13/10^6 Btu, oxygen costs \$25.00/ton (\$2.20/10^6 Btu when burned with Powder River Basin, Wyoming, coal), both the Solar and the Lurgi Plants have a 70-percent thermal efficiency, and for the Solar Plant, 20 percent of the heating value in the product gas is supplied by solar energy. It is assumed that for the Lurgi Plant, the thermal losses are supplied by coal-oxygen energy, while for the Solar plant thermal losses are supplied by solar energy.

Table 1

Comparison Between a Lurgi and a Solar Coal Gasifier

Product Gas Cost:

Gasifier	Coal Cost	Oxygen Cost	Solar Cost	Plant Cost	Total
Lurgi	1.4(1.20)	+ 0.4(2.20)	+ none	+ 2.40	= \$4.96/10^6Btu
Solar	0.8(1.20)	+ none	+ 0.6(1.13)	+ 2.40	= \$4.03/10^6Btu

Capital Cost:

Solar Coal Gasifier/Lurgi Gasifier = 1.13

Coal Consumption:

Solar Coal Gasifier/Lurgi Gasifier = 0.57

It is difficult to establish the cost of the portion of the Solar Coal Gasification Plant that processes the coal and product gas (everything excluding the heliostat field). An argument could be made that this portion of the plant might be more expensive than a Lurgi Plant since it involves the use of a solar tower. However, approximately 50 percent of the cost of a Lurgi Plant involves the construction of facilities to preprocess coal and clean up the product gas. Since far less coal will be needed for the Solar Plant, one would expect some cost reduction in this area. A quantitative comparison between these costs is not feasible at this time. Therefore, it is assumed that the Solar and Lurgi Plant costs will be the same, approximately $\$2.40/10^6$Btu.(5)

It can be seen from Table 1 that, with the above assumptions, the product gas cost from a Solar Coal Gasifier is considerably less ($\$0.93/10^6$Btu) than that from a Lurgi Gasifier. It is anticipated that this difference will grow as the cost of fossil energy increases, due both to the increase in coal cost and the increase in the cost of oxygen. The cost of oxygen is highly dependent on the cost of energy, being an energy-intensive separation process, and thus is also likely to increase in proportion to the cost of fossil energy. One would thus expect the anticipated economic advantage of Solar Coal Gasification to grow rapidly in the future.

Table 1 also presents a comparison in capital cost between a Solar Coal Gasifier and a Lurgi Gasifier assuming that both plants cost the same, with the Solar Gasifier requiring the additional costs associated with building the heliostat system. The cost of a Lurgi Gasifier was obtained from Reference 5 and the cost of the necessary heliostat field needed to supply sufficient solar energy to such a gasifier was estimated using the cost figures from the McDonnell Douglas and Sandia reports.(3,4) It was thus estimated that a Solar Coal Gasifier will require approximately 1.13 times more capital than a Lurgi Gasifier with the same production capacity.

One of the most significant differences, presented in Table 1, between the two gasification systems is the relative coal consumption. The Solar Coal Gasifier is estimated to require only 57 percent of the coal required for a comparable Lurgi Gasifier. This is a considerable savings on the utilization of coal, which is an exhaustible fossil energy resource.

BASIC DESIGN OPTIONS FOR A SOLAR COAL GASIFICATION PLANT

A basic design component of a Solar Central Receiver Plant is the requirement for a tower needed to position an energy collector in the focal zone of the heliostat field. The tower height is estimated to be as much as 250 m for a nominal 500-MW_t plant built at Barstow, California.(3) The very substantial height of this tower naturally separates Solar Coal Gasification Plant designs into those where the coal and steam are transported to a reactor at the top of the tower and those where the coal-steam reactor is positioned at the base of the tower and heat is transported from the top of the tower to it using a heat transfer fluid. We have identified four promising reactor designs, two at the top of the tower and two at the base. The two reactor concepts for the base of the tower are: a) one which invokes the use of direct heat exchange between solar-heated molten salt and coal, and b) one which uses a closed He loop for heat transfer between the solar tower and the gasifier. The two tower-top reactor concepts are: a) a moving bed reactor with a window, and b) a fluidized bed reactor.

All four reactor concepts are presently under consideration. They are distinctly different from each other and all of them strongly capitalize on the broad base of existing solar and coal gasification technology.

COMPUTER MODELING OF SOLAR COAL GASIFICATION

Lawrence Livermore Laboratory has developed two computer codes for calculating the chemistry of coal gasification. One code assumes equilibrium chemical compositions and is used when quick estimates are needed. The other code takes into account the temperature dependency of the rates of the chemical reactions. It thus gives more accurate predictions in the low-temperature, rate-limited region. However, the rate code is presently structured so that it can be applied only to the moving bed reactor concept. Both codes are presently being used to quantify Solar Coal Gasification reactor designs.

The equilibrium code was modified to simulate the solar fluidized bed reactor, and a number of runs were made to optimize the efficiency of the gasification. The chemical properties of a typical Powder River Basin, Wyoming, coal were assumed. It was also assumed that there was no heat loss from the system except the sensible heat in the product gas, which was exhausted at 500 K. The results are presented in Table 2 as scaled to a 500-MW_t basic heliostat field. The brackets indicate the added energy that would be needed to produce steam. The energy can be added either with additional solar energy or by burning coal.

Table 2

Properties of a Solar Coal Gasifier Matched to a 500-MW_t Basic Heliostat Field

Coal Rate into Reactor	5.03 K-mole/sec
Steam Rate into Reactor	2.84 K-mole/sec
(Coal to Raise Steam)	0.30 K-mole/sec
(Solar Energy to Raise Steam)	150 MW_t
Operating Temperature in Reactor	1049 K
Specific Heat of Combustion for Product Gas	335 kj/mole (377 Btu/scf)
Thermal Efficiency	98%

Question - You're not using heat exchangers but windows. Are you looking at both options or just at solar energy coming in on top?

Dr. Gregg - We're looking essentially at four options: 1) pack bed, or moving bed, 2) fluidized bed, and 3) a multisalt option. Each one has a different way of getting solar energy into the system.

Question - What surface power can you tolerate in this reaction? Can you have chemical reactions taking place in tubes at 45 or 50 kilowatts per square meter? What kind of power density can you tolerate? Is it dramatically different?

Dr. Gregg - One of the attractive features that we hope to be successful in is to absorb light directly onto coal, so your flux density of sunlight is simply limited by the rate at which you can flow steam through the system, which is a very flexible thing, especially if you add pressure to the system. I see no real fundamental limitation there. The other flux density that you're talking about is caused by your ability to conduct heat through materials without melting them. If we can go through a window, and that window could be kept cool, and we really do just absorb sunlight onto the coal, then we have no flux limitations. It's a very good heat transfer system. Flux densitites of a few hundred watts per square centimeter in the laser business is fairly trivial for a window. Window materials are readily available if they're clean. I don't know what the dirt is going to do.

Comment - I would encourage you to do two things. First, consider the cost of compressing gas at atmospheric pressure. I think what you'll find is that the cost of compressors will rival or exceed the cost of the tower--and this is based on calculations Ive done for biomass. The reason for that is that the compressors will have to operate at three times their normal capacity since they are only operating for eight hours a day.

Dr. Gregg - We're aware of that because we ran into it in our other coal gasification. We'll have to crank that in when we relook at the system. I was worried about operating a pressurized reactor with a large window also. So that's why I was saying probably atmospheric. It's a big factor.

Comment - The second thing is: I've done calculations like you've done for biomass two or three years ago and you're exactly right; if you compare the cost of an oxygen plant versus the cost of a solar tower, the solar tower looks good, but what I encourage you to do, rather than using that as a comparison, is to look at a Westinghouse gasifier, where you have two fluidized beds, one where you burn char which transfers the heat to the second, where you gasify the coal.

Dr. Gregg - Or an Exxon process, which you're familiar with, too, where you catalyze the reaction with potassium carbonate. The reason I went to the lurgi gasifier is because it's the accepted standard in the field at this point and it is just beyond this talk to make this comparison.

Comment - I did that to. A Union Carbide gsifier is the accepted standard for biomass, but what I'm telling you is that when I did the comparison which I just described for biomass, solar did not look good, and I'll show that tomorrow.

Comment - I'd like to comment on your window. I've been looking at windows for some time and had some serious discussions with the French in the last two weeks about them and their experience is that the windows get dirty rather rapidly and become very ineffective if you're trying to get sunlight transmitted through them. They are working on some alternate solutions, which have things like silicon carbide--a good absorber for solar energy--which then reradiates into the fluidized bed. There are other techniques besides allowing that solar energy to shine directly on the coal.

Dr. Gregg - In our fluidized bed version, we were thinking of silicon carbide and sodium nitrite. They have high thermal conductivities. That would be a good option but we haven't gotten that far. I'm sorry to hear about the window; I hope we can improve upon that technology.

Question - Can you say how you arrived at the cost of $1.13 per million Btu's for the Barstow plant?

Dr. Gregg - Yes. There is a prototype heliostat report by McDonnell Douglas and I based my calculation on Chapter 7 of thet August 1978 report. What they expected an average heliostat to put out in terms of energy per day, rather than watts, is in the report. I used a Sandia draft report where they state a field of 1690 heliostats at an average cost of $62 a square meter can be built, installed and operated at a cost of 6 million dollars a year net. I didn't make that calculation but it included interest rates, purchase of land, maintenance, write-off of capital--essentially everything. I guess it did not include some of the laying of the wiring to the heliostats. I took those numbers and essentially made a division and came up with a cost. I'm not going to claim that I've done a better job than they have, but that's how the numbers are coming out.

Question - Did you use peak or average fluxes?

Dr. Gregg - I used the technical performance data in the McDonnell Douglas report. I used average fluxes over the year and average fluxes over the day. I assumed a 330-day year of sunlight instead of 365 and it comes out to that number. It's certainly lower than people have been talking about in this conference. I think it needs to be checked out but that's what came out at this point.

Comment - I can confirm those figures. I've gone through those calculations myself and at $7 a square foot, that's just about what you get. You convert that, amortize the cost of the collectors over time and take into account the amount of energy that's incident on the collectors. That's not an unreasonable number.

Dr. Gregg - That's $62 a square meter so that's good confirmation.

Question - I want to ask whether you've taken into account the power that you require to pump coal, in whatever form, up the tower to the reaction chamber? That may turn out to be a problem.

Dr. Gregg - I don't know how to balance that.

Comment - Up the tower you want to use mechanical energy, and down the tower you want to use steam. You lose heat in this process but you're using electrical energy and you're not getting all of the electricity back. It's about half a percent of the energy involved in pumping the water and steam back and forth, so a coal bed would be maybe one or two percent or more.

Dr. Gregg - It's apparent that once those windows come down, you can pick up a little of that on the way down.

Question - Did you say 90 percent?

Dr. Gregg - To clarify that, you assume that the product gas of the heat exchange, or the incoming steam and coal exhausts at 500 K. The only heat loss is the sensible heat in the product gas. It assumes zero other thermal losses in the system, and zero reflective losses and so on.

Comment - It's very difficult to heat exchange product gas in a gasifier because you have tar. You're going to have to bring the tar out sometime.

Dr. Gregg - The packed bed design clearly has a tar problem. The fluidized bed does not. I don't like that problem. Everybody's experience with fluidized gasifiers is that there is very negligible tar. Also, in the molten salt system there are no tars that come off of it, so it depends on which reactor you use. I agree that there's a serious tar problem.

REFERENCES

1. H. H. Lowry, Ed., "Chemistry of Coal Utilization," (Wiley & Sons, Inc.,) New York, (1963), Supplementary Volume.

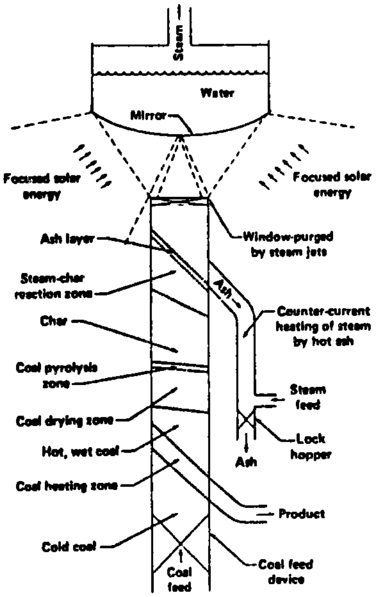
2. "Recommendations for the Conceptual Design of the Barstow, California, Solar Central Receiver Pilot Plant, Sandia Laboratories Report No. SAND77-8035, October 1977.

3. "Solar Central Receiver Prototype Heliostat CDRL ITEM B.d, McDonnell Douglas Report No. MDC G7399, August 1978.

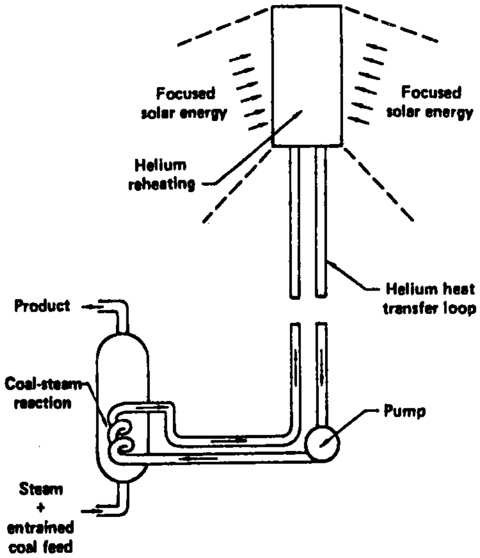
4. "Summary of Prototype Heliostat Evaluation and Recommendations," Sandia Laboratories Report No. SAND-8265, September 1978.

5. Detman, Roger, "Factored Estimates for Western Coal Commercial Concepts," C. F. Braun & Co. Report No. FE-2240-5, October 1976.

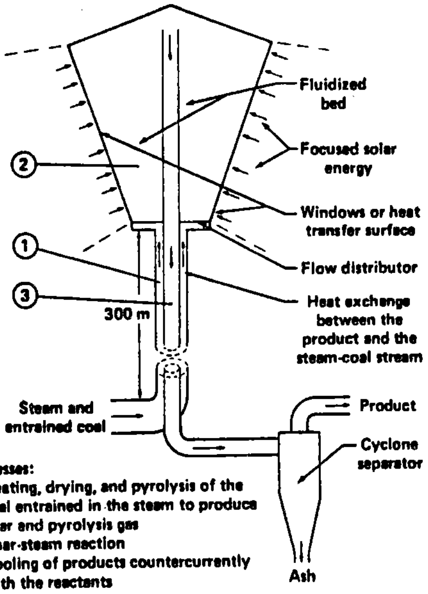
MOVING-BED SOLAR COAL GASIFIER



HELIUM HEAT TRANSFER SOLAR COAL GASIFIER

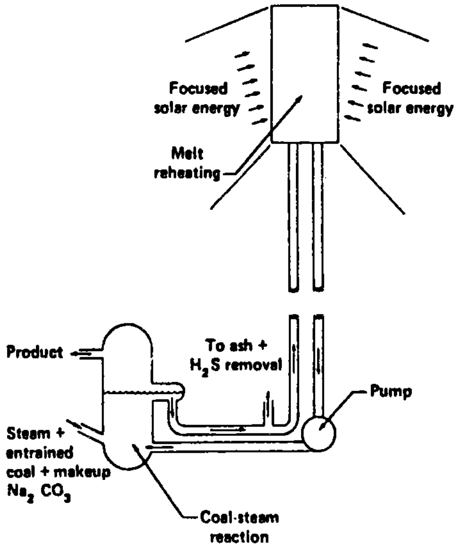


FLUIDIZED-BED SOLAR COAL GASIFIER



Processes:
1. Heating, drying, and pyrolysis of the coal entrained in the steam to produce char and pyrolysis gas
2. Char-steam reaction
3. Cooling of products countercurrently with the reactants

MOLTEN SALT SOLAR COAL GASIFIER



TWO DIMENSIONAL MELTING PHENOMENA
IN SOLAR HIGH-TEMPERATURE PROCESSES

Richard Zito
University of Arizona

Thin metallic films subjected to high temperatures show large changes in reflectivity and electrical resistance because of the formation of hillocks and agglomerations. These latter surface structures grow via surface and grain boundary diffusion. The characteristic temperature at which these diffusive processes and their concomitant effects become important is predicted from the theory of two dimensional melting. No semi-empirical Arrhenius relations are used. It is shown that the ratio of the characteristic temperature to the bulk melting point of the film material is 0.59. This is in good agreement with the value of 0.6 proposed by other researchers.

Introduction

The formation of hillocks and agglomerations on thin metal films has been observed to occur via surface and grain boundary diffusion [1,2]. The thickness of the mobile layer has been estimated to be one atomic layer deep [1]. Andrade [3] has observed agglomeration in Ag and Au films 150Å thick in vacuum. These materials show well developed islands of metal at 623°K and 723°K respectively. However, other researchers [1] report stability for Ag in an inert atmosphere of hydrogen and water vapor up to 753°K. Ag films isolated from the surface diffusion enhancing effect of oxygen by an overcoating of SiO_2 [2] have been successfully used at temperatures of 923°K for 50 hrs with only a 1% loss of reflectivity. Gimpl et al. [4] report agglomeration of Au in vacuum at 873°K. This result is in agreement with the measurements of Langley [5] and Pennebaker [6]. However, a study by Kane et al. [7] is in agreement with Andrade. D'Heurle et al. [8] have observed micron sized rounded hillocks after annealing 5-11000Å films of Al between 723°K and 833°K in an inert N_2 atmosphere. However, Lahiri and Wells [9] report initiation of hillocks at 523°K in vacuum. Sato et al. [10] cite an intermediate temperature of 673°K, and the measurements of Herman et al. [11] are in rough agreement with Lahiri and Wells. Lead films 5000Å thick display hillocks between 323°K and 398°K [9], whereas Ni films show this phenomenon at 1073°K [4]. The initial stages of agglomeration in Sn films have been observed by Scharnhorst [12] between 200°K and 300°K. Copper films heated for 5-20 min at 673°K in a 10% oxygen - 90% hydrogen atmosphere show large holes and hillocks [13]. However, the same films heated to 773°K in pure hydrogen are stable for 1 hr. Experiments by Nielsen et al. [14] have turned up similar changes in Cu films heated to 598°K for 2-3 hrs in the same O_2-H_2 atmosphere. In short, the surface monolayer of atoms of a variety of metals may become quite active at sufficiently high temperatures, resulting in hillocks and agglomeration.

Theory

In this work the theory of two-dimensional (2-D) melting, as developed by Kosterlitz, Thouless, and Feynmann (KTF) [15,16], will be used to predict the temperature at which the surface monolayer of atoms becomes highly mobile. Thus, we will model surface diffusion as a higher order (gradual) phase transition. The characteristic temperature at which changes in surface morphology occur may then be predicted from first principles. KTF have found that an adsorbed monolayer of He^4 (and a variety of other materials) on graphite undergoes a transition to a state of high mobility (called a 2-D liquid) at a temperature, T_{2D}, given by [15]

$$T_{2D} = \frac{1}{(2\pi)^2} \frac{mka^2\Theta_{2D}^2}{8\hbar^2} \qquad (1)$$

where K is the Boltzmann constant, m is the mass of atoms in the film, <u>a</u> is the interatomic distance (for a square lattice of adsorbed atoms), Θ_{2D} is the 2-D Debye temperature, and $\hbar$ is Plank's constant over 2π.

It is convenient to rewrite this last equation in terms of Θ_{3D}, the three dimensional Debye temperature, and r, the radius of the average volume per atom. At the atomic densities occuring in solids, $\Theta^2_{2D} \sim \frac{1}{2}\Theta^2_{2D}$ [16], and by definition $a^3 = \frac{4}{3}\pi r^3$.

Substituting these last two relations in Eq. 1 gives

$$T_{2D} \simeq \frac{1}{243}\ \frac{mkr^2\Theta_{3D}{}^2}{\hbar^2} \qquad (2)$$

We now compare this last result to the Lindemann 3-D melting formula [17] for a simple cubic lattice,

$$T_{3D} = \frac{X^2mkr^2\Theta_{3D}{}^2}{9\hbar^2} \qquad (3)$$

where X is the fraction of r which atoms must be displaced from their lattice sites at 0°K in order for melting to begin. It has been found that X ranges from 0.2 to 0.25 [17]. We will use the larger value since this gives the correct value of T_{2D}/T_{3D} for a variety of rare gases on which detailed 2-D melting studies have been conducted [20, 21]*. Thus, the theoretical temperature at which surface diffusion becomes important is $T_{2D} \simeq (.59)\ T_{3D}$ and is graphed below as a straight line against the bulk melting points of various materials. The bars indicate the temperature region where various experimenters have observed the onset of hillock growth and agglomeration. Hence, surface diffusion (and 2-D melting) should occur at these temperatures.

*Studies on adsorbed monolayers of rare gases on graphite have been cited for two reasons. First, the Debye temperature is well defined for the rare gases. This is not the case with studies on N_2 and a variety of other molecular materials because of internal degrees of freedom. Second, graphite is a "homogeneous" substrate, that is, it produces no lateral fields for adatoms [18,19]. Thus, the monolayers behave "naturally" (i.e. we can ignore the substrate).

Data

The data associated with some of the metals have quite large error bars. This is primarily due to the fact that surface diffusion in some metals is greatly enhanced by the presence of oxygen, even in trace amounts. Hence, experiments performed under laboratory vacuum conditions will have residual air left in the vacuum vessel which may not allow the agglomeration process to proceed "naturally." The consequence of this contamination sensitivity is widely varying results from different experiments. Silver films are particularly bad in this respect as seen from the large error bars. Ideally, the data that should be fit to the KTF theory is agglomeration of unsupported metal films in a perfect vacuum. Unsupported films avoid hillock growth enhancement caused by compressive stress induced via thermal mismatch between the substrate and film. A perfect vacuum is not realizable in the laboratory; however, for best results the film material should be relatively inert to the residual gas left in the vacuum vessel. The measurements of Gimpl on Ni and Au films satisfy both of these requirements. Hence, the error bars for these films are relatively small.

Finally, it should be noted that most researchers used films between 400-13000Å thick. In this range surface diffusion is, at least approximately, independent of film thickness. This is shown clearly by the detailed measurements of Gimpl et al. [4].

Conclusion

Meinel [22] has suggested that diffusive phenomena in metal films become important at a temperature of about 60% of the melting point. A value of T_{2D}/T_{3D} equal to 0.6 is in excellent agreement with the value of 0.59 predicted in this paper. The correspondence is particularly striking when we consider that the detailed nature at the substrate and film material underlying the mobile surface layer has been ignored. We must consider the result to be partially fortuitous; however, it does seem to indicate that the essential physics has been included in the model. Apparently, at the temperatures of interest for surface and grain boundary diffusion in non-cryogenic substances, the underlying film material displays only "weak heterogeneity" [23]. Helium adsorption studies on Cu and Ag seem to support this possibility [24]. The effect of this heterogeneity is to create a more abrupt transition of surface atoms to a state of high mobility [25]. Furthermore, thermal mismatch between the film and substrate may accelerate the rate of film surface change but should not change the temperature at which surface and grain boundary diffusion begins (compare ref's 4 and 6, also 9 and 10). Hence, as a first approximation, it might be permissible to ignore the supporting materials of the mobile surface monolayer.

The theory of two dimensional melting can be extended to take into account more complex situations. For example, surface diffusion involving a mobile layer several atoms deep may be taken into account by a factor M placed on the left side of eq. (1). In that case, $T_{2D} = (.59)\ MT_{3D}$. The value of M may be obtained from observation of melting in He^4 multilayers. Specific heat measurements imply that mobile layers much more than about 12 atoms deep behave much like the bulk material [26]. Thus, $M_{(12)} \sim 1/.59$. Premature 2-D melting in the presence of a non-inert atmosphere may be treated by adjusting the 2-D Debye temperature.

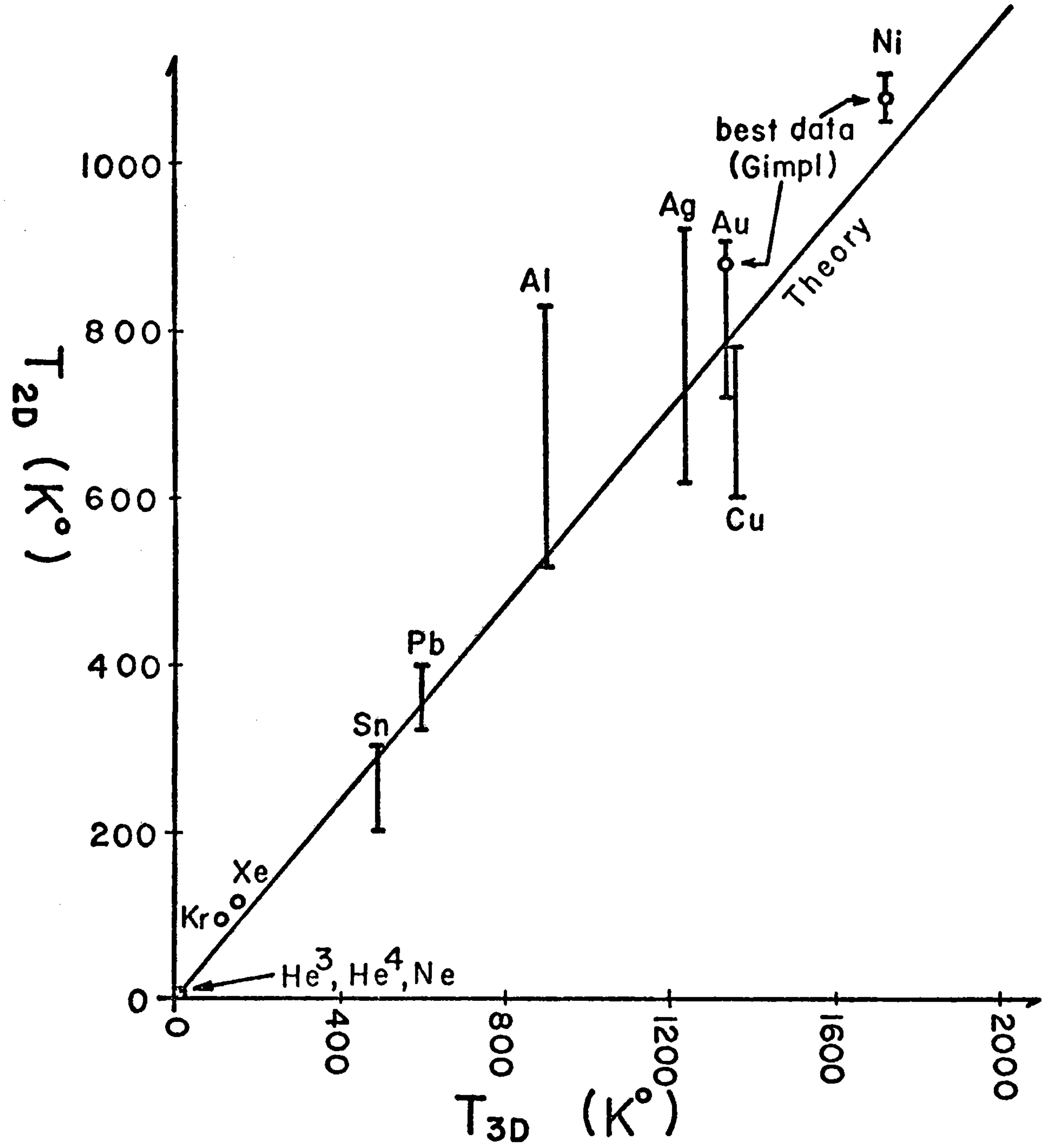
Adsorbed O_2, for example, would change the effective spring constant for harmonically oscillating surface atoms, this would result in a change in Θ_{2D}.

As pointed out in the introduction, grain boundary diffusion has also been cited as an important source of agglomeration damage. This is not hard to understand since a grain boundary may be considered a 2-D adsorbed layer on the well crystalized grain material [27]. Migration may then proceed by the surface diffusion mechanism previously described.

In summary, a method of analysis for surface and grain boundary diffusion has been presented. The onset of these diffusive processes was modeled as a higher order (gradual) phase transition, with a characteristic melting temperature given by the KTF theory. The ratio of this characteristic temperature to the bulk melting point gives a ratio in good agreement with experiment. The method presented follows from first principles and does not depend on the use of semiempirical Arrhenius relations.

Acknowledgement

The author would like to thank Dr. Aden B. Meinel of the Department of Optical Sciences, University of Arizona, and Dr. Richard Young of the Department of Physics, University of Arizona, for their valuable discussions during the work.



The error bars indicate the range of reported temperatures where extensive surface rearrangement may be expected to commence. T_{2D} for He, Xe, and Kr were obtained from precise measurements [16, 19]. The errors are too small to be presented on this graph. T_{2D} for Ne is approximate, and represents the 2-D Ne triple point. Again, the errors are too small to be presented.

Appendix 1

The implications of the simple law $T_{2D} = .59\ T_{3D}$ for the High Temperature Workshop are far reaching. Suppose we wish to operate a selective surface at about 2000° K. There are only four candidate elemental materials which can maintain their surface morphology. These are C, W, Re, and Ta (listed in decending order of their melting point). Carbon surfaces have two big problems. First of all, a carbon surface has a low TIR reflectance, which means low selectivity. The situation can be improved if the carbon is deposited on a reflective substrate. However, carbon particles adhere poorly to a metal surface. A binder would make the carbon stick, but would also increase the TIR emittance. Again, we lose selectivity. In addition heating carbon to high temperatures in air causes it to change to CO_2. Ta surfaces, by our simple law, are very marginal in their refractory properties. Hence, it is clear that W and Re surfaces with a needle-like morphology will provide the only effective selective materials. W needles are preferred because of their lower cost. In addition, such a surface would probably have to operate in a vacuum or an inert atmosphere since the chemically similar metals W, Re, and Ta all have relatively high oxidation rates. Our choices are very limited at 2000° K. If we are willing to operate a selective surface at about 1400° K, our options are much greater. At this temperature the metal surfaces of Os, Mo, Ru, Nb, Ir, Hf, and B should be stable. At an operating temperature of about 1000° K the acceptable elemental materials are <u>Rh</u>, V, <u>Cr</u>, Zr, <u>Pt</u>, Th, <u>Ti</u>, Lu, <u>Pd</u>, Sc, <u>Fe</u>, Tm, Co, Dy, Er, Ho, Y, <u>Si</u>, Tb, and Gd; where underlined materials are of greatest interest and Gd is quite marginal. We might use this list of elements for design purposes. For example, suppose we wish to build a solar collector in space. Considering the cost involved to orbit each pound of material, light Ti might be the best choice for both a substrate and a TIR reflective layer. The Ti might be overcoated with Si to trap visible radiation. This configuration would then be run as part of a concentrating system near 1000° K, since the greatest economic advantage of power plants in general is obtained when materials are used near the limit of their capabilities. If materials costs are the primary concern, an Fe substrate coated with a thin deposit of Cr and then Si might offer the best tradeoff. If great hardness, electrical conductivity, and chemical inertness are required of a reflective coating, then Rh is the preferred material. The point is clear, the "60% rule of thumb" is a useful tool in the design of high temperature devices where surface morphology must be maintained.

Appendix 2

It has been known for some years now that the introduction of certain impurities into films, whose surface morphology is unstable at relatively low temperatures, causes a substantial increase in stability. In the calculations below we assume that added impurities are segregated at the grain boundary [10]. The result is an alloyed grain boundary. Our simple theory still applies to this kind of two dimensional structure since the Debye temperature of an alloy is well defined, thus $T_{2D(A)} = .59\ T_{3D(A)}$. The quantities $T_{2D(A)}$ and $T_{3D(A)}$ are now the liquidus temperatures of the 2-D alloy network and bulk alloy material, respectively. To evaluate the improvement in film performance by doping we divide by the bulk melting point of the pure metal, $T_{3D(P)}$. Thus,

$$\frac{T_{2D(A)}}{T_{3D(P)}} = .59\ \frac{T_{3D(A)}}{T_{3D(P)}} \qquad (4)$$

By knowing the weight percentage of added impurities, and the dimensions of a typical grain (as obtained from electron micrographs), the approximate composition of the alloy at the grain boundary may be determined. The value of $T_{3D(A)}$ may then be obtained from standard metallurgical references. The result of this program of calculation for Mn doped Al [10], Sn doped Al [10], and Rh doped Au [5], are shown in the table below.

Principle Metal	Impurity	$T_{2D(A)}/T_{3D(P)}$ (Theory)	$T_{2D(A)}/T_{3D(P)}$ (Experiment)
Al	Mn	0.82	0.72
Al	Sn	0.55	0.51
Au	Rh	0.64	0.77

Phase diagrams do not exist for many alloy systems. However, if specific heat data are available it is convenient to use eq. (3) to express eq. (4) as

$$\frac{T_{2D(A)}}{T_{3D(P)}} = (0.59)\ \frac{m_A\ r_A^2\ \Theta_{3D(A)}^2}{m_P\ r_P^2\ \Theta_{3D(P)}^2} \qquad (5)$$

The Debye temperature $\Theta_{3D(A)}$ may now be extracted from the "knee" of the specific heat versus temperature plot. From the effective media approximation we interpret m_A and r_A as the average atomic mass and average atomic radius of the alloy, respectively. When the speed of sound for longitudinal and transverse modes of vibration are equal to each other and to some average speed of sound $\bar{u}$, we may write

$$\Theta_{3D}^2 = \left(\frac{2\pi \bar{u} \hbar}{a k}\right)^2 \left(\frac{3}{4\pi}\right)^{2/3} .$$

In addition, we know $a^3 = \frac{4}{3}\pi r^3$. Therefore,

$$\frac{T_{2D(A)}}{T_{3D(P)}} = (0.59) \frac{m_A \bar{u}_A{}^2}{m_P \bar{u}_P{}^2} . \qquad (6)$$

Equation 6 connects $T_{2D(A)}/T_{3D(P)}$ to the dispersion relations for the alloy. Since $\bar{u}^{\,2} = Y/\rho$, where Y is Young's modulus and ρ is density, and since the ratio m_A/m_P is the same as the ratio of the gram atomic weights (GAW), we may write

$$\frac{T_{2D(A)}}{T_{3D(A)}} = (0.59) \frac{(GAW)_A Y_A \rho_P}{(GAW)_P Y_P \rho_A} . \qquad (7)$$

This last formula expresses $T_{2D(A)}/T_{3D(P)}$ in terms of constitutional and macroscopic bulk physical properties.

The numbers presented in the table above should not be taken too strictly for several reasons. First of all, peculiar precipitation patterns of impurities often make the determination of the constitution of the grain boundaries very difficult, and may affect the thermal properties of the film substantially. In addition, severe O_2 contamination was present in all films. Oxygen contamination in Al films may lower the temperature at which hillocks form by about 100°K [10], and diffusion phenomena in gold also begin at temperatures about 100°K lower when heated in air [22]. In addition, it should be noted that a film with $T_{2D(A)}/T_{3D(P)}$ less than 0.59 is not necessarily an inferior material. Inspection of electron micrographs of Sn doped Al [10] show hillocks at 473°K.

However, these hillocks are much smaller and much fewer in number then in pure Al films which were similarly prepared and thermally cycled. This is probably due to the fact that Sn seems to encourage rather large grain growth. With the decrease in area of the grain boundary network comes a concomitant decrease in diffusion and hillock growth.

References

1. A. E. B. Presland, G. L. Price, D. L. Trimm, Surf. Sci., 29, (1972) 424.

2. P. H. Smith, H. Gurev, Thin Solid Films, 45, (1977) 159.

3. E. N. da C. Andrade, Trans. Far. Soc., 31, (1935) 1137.

4. M. L. Gimpl, A. D. McMaster, N. Fuschillo, J. Appl. Phys., 35, (1964) 3572.

5. R. C. Langley, "Proc. of the Symposium on the Material Science Aspects of Thin Film Systems for Solar Energy Conversion," (NSF/RANN GI-43795, Tucson, AZ, May 20-22, 1974).

6. W. B. Pennebaker, J. Appl. Phys., 40, (1969) 394.

7. W. M. Kane, J. P. Spratt, L. W. Hershinger, J. Appl. Phys., 37, (1966) 2085.

8. F. d'Heurle, L. Berenbaum, R. Rosenberg, Trans. Met. Soc. AIME 242 (1968) 502.

9. S. K. Lahiri, O. C. Wells, Appl. Phys. Letters, 15, (1969) 234.

10. K. Sato, T. Oi, H. Matsumaru, T. Okubo, T. Nishimura, 2, (1971) 691.

11. D. S. Herman, M. A. Schuster, R. M. Gerber, J. Voc. Sci. Tech., 9, (1971) 515.

12. P. Scharnhorst, Surface Sci., 15, (1969) 380.

13. T. F. Swank, K. R. Lawless, J. Appl. Phys., 35, (1964) 3574.

14. N. A. Nielsen, K. B. Keating, W. R. Miller, Surface Sci., 8, (1967) 307.

15. J. G. Dash, "Films on Solid Surfaces," (Academic Press, New York, 1975) 81.

16. R. L. Elgin, D. L. Goodstein, Phys. Rev. A, 9, (1974) 2657.

17. J. M. Siman, "Principles of the Theory of Solids," (Cambridge U. Press, London, 1964) 63.

18. Ref. 15, p. 233.

19. K. D. Timmerhaus, W. J. O'Sullivan, E. F. Hammel, "Low Temperature Physics, Vol. 1," (Plenum Press, New York, 1974) 21.

20. Ref. 15, pp. 153, 157.

21. A. Thomy, X. Dural, J. Chem. Phys. - Chem. Biol., 67, (1970) 1101.

22. A. B. Meinel, M. P. Meinel, "Applied Solar Energy," (Addison-Wesley, Reading, Mass., 1977) 270.

23. Ref. 15, pp. 226-7.

24. K. D. Timmerhaus, W. J. O'Sullivan, E. F. Hammel, "Low Temperature Physics, Vol. 1," (Plenum Press, New York, 1974), p. 21.

25. Ref. 15, p. 182.

26. J. R. Rairden, C. A. Neugebauer, R. A. Sigsbee, Met. Trans., 2, (1971) 719.

27. Ref. 15, p. 251.

28. L. H. Van Vlack, "Elements of Materials Sciences," (Addison-Wesley, Reading, Mass., 1964), p. 95.

A VERTICAL HIGH TEMPERATURE SOLAR KILN

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Abstract--A novel method, first applied to water purification by selective absorption of concentrated insolation, is described as a multipurpose device. Its method of operation is then described in a feasibility analysis of an idealized process for which parameters are defined. That such a process could be performed with available energy concentrations is established. The method/device is then evaluated for a similar real world process, the manufacture of Portland cement. Although such an application appears to be feasible, basic research and experimentation are required prior to pilot plant design in order to determine the characteristics of materials as they react in this process. Modularity of the method/device permits sizing the laboratory experimental requirements and techniques.

INTRODUCTION

Veda was organized in 1962 by people whose interests were in total systems, rather than in subsystems or components. Analysis of the mission requirements of a user, in order to optimize a system to satisfy his needs, frequently establishes a requirement for an unusual solution to a conventional problem. Tailoring a fixed design to partially solve a problem, or limiting an investigation to only those problems which can be conveniently solved by conventional systems, is often costly in time and energy, and results in poor performance. The unencumbered systems analysis first establishes the general needs, then optimizes the method to satisfy them. Veda supports DoD by performing analyses of this type in areas such as advanced airborne weapons systems.

Veda's interest in solar energy has developed along this same line: "What are the needs of the community that can be met by appropriately developing solar energy?"

One immediately envisions a modern community, oriented to satisfy all of its energy needs by use of solar energy. This leads to specifying that a cost effective system will incorporate the energy conversion within the local community. Structures to house people and industry become intimately associated. Whenever possible, product development will use solar energy directly. To do this in a manner having wide applicability requires the development of simple, efficient systems having a low life cycle cost.

Our primary emphasis is directed toward developing total systems. A total system, rather than a "total energy" system, applies energy use to develop marketable product lines in addition to marketable energy forms. In this manner, total income is applied toward retiring the investment in solar equipment. Veda's total systems approach results in solar energy systems that are cost competitive for many of society's energy needs.

For solar energy to become a viable alternate energy source, early widespread application must be introduced. To accomplish this, however, we cannot afford to restrict our programs to the current approaches which require the "power tower."

We believe the Central Receiver concept has much more potential than what is currently being considered. We also believe that if the "power tower" is the only Central Receiver approach considered little of this additional potential will ever materialize.

Therefore, an in-depth analysis should be performed which evaluates innovative heliostat arrangements which are more adaptable to the near urban environment with special attention and interest to industrial applications.

The Unified Heliostat Array (UHA) is the only approach that we know of that fits into the near urban community and still provides the energy benefits of the current heliostat fields. The UHA concept is not only modular but has the functional flexibility to permit a direct high density energy input to a user (comparable to a solar furnace) without requiring the prior conversion through the thermal-electric chain. Thus, electric to thermal load ratios are not significant in establishing commercial applicability. Also recognized is the potential use of the structure for a multitude of uses other than merely supporting the heliostats.

The UHA is comprised of closely spaced two-axis steerable heliostat elements mounted on the terraced east-west wall of a single structure. This terraced wall is on the side of the structure pointing towards the equator and sloping upwards toward the pole.

The present designs need large land parcels whose sole function is solar energy conversion. This poses severe obstacles in incorporating the system into urban or suburban areas. Therefore, much consideration has been devoted to providing a heliostat arrangement that can be integrated into a typical community so that land would be available for joint use by the community for various public benefits rather than dedicated only to the conversion of solar energy.

The high central tower required in present concepts demands particular concern for structural rigidity and strength to support a central receiver and maintain its efficiency during wind and possible earthquake conditions. Of necessity, the central receiver aperture must be larger than optimum. This decreases efficiency due to re-radiation and convection losses. An increase in power output under present concepts would require an increase in the tower height to maintain an aperture size having a reasonable efficiency for the central receiver. Present designs for larger systems must guard against creating a hazard to air navigation. Maintaining an elevated central receiver during its life cycle will be more expensive than maintaining boilers in conventional plants, because of its relative inaccessibility atop a tower.

When costs are being considered, special care must be taken to offset the price for one item with the savings achieved by eliminating another. Operating costs must adequately compare the total cost of one system with another. This approach, which substitutes a common prefabricated structure for the individual heliostat foundations of the current designs and increases the collector density, has the following cost-effective advantages:

- The heliostat components including pedestals, mirrors, and a drive mechanism are identical and adaptable to factory line production. Pedestals can be eliminated by designing them into the common structure.
- The common structure is modularized, factory prefabricated, and then assembled on site. Less grading, site preparation, paving, and environmental damage result.
- It eliminates the installation cost of precisely located foundations for each heliostat.
- It reduces the heliostat's exposure to natural hazards due to the protection afforded by the common structure and increased distance from ground level for most heliostats.
- It reduces materials and maintenance of inter-heliostat wiring (no underground requirements).
- It automates heliostat cleaning by recovering and recycling cleaning materials to lessen environmental impacts and life cycle costs.
- It eliminates large mobile support equipment, i.e., cranes and cleaning trucks.
- It eliminates major building construction by housing energy storage, electrical power generating equipment, and central receiver in the common structure.

In order to have an early impact on fuel usage, energy intensive or resource limited processes are high priority candidates for investigation. The production of high-quality water, or even potable water, is such a process. Current methods are expensive, energy and materials intensive, and inefficient.

By eliminating the "power tower," the use of a horizontally directed concentrating heliostat array can be integrated with the receiver conventionally located in or adjacent to an existing facility. With this array as the solar energy source, a basic method was developed to use this available energy directly in a variety of processes.

Although the first process evaluated was production of high-quality water, the method was found to be applicable to other industrial processes of value. Several of these give promise of requiring less energy input per unit of product output when fueled in this manner rather than by the current methods.

BACKGROUND

There is a large body of documentation concerning the properties of water. Based on this information, we have performed comprehensive analyses to apply this method to desalination of sea water. Several references are noted illustrating some of the experimental work done in the study of the absorption properties of water in the visible region of the spectrum. Referenced literature also describes a method of drop formation to produce controlled rainfall. As a result, we have performed a laboratory scaled experiment using approximately an 8 foot high, 3 foot diameter cylindrical tank heated with a 15 Kw arrangement of quartz iodide lamps. Although thermal losses to an uninsulated cold wall occurred, more than 50% of the incoming radiant energy produced recoverable steam. The process is representative of the class of reactions in which selective absorption of radiation occurs. In the solar spectrum which reaches the earth's surface, light water has a much higher absorption coefficient for radiant energy than does heavy water. It is interesting to note that during the experimental process the liquid residue remained essentially at constant temperature.

Conventional distillation carries over both the light and heavy water components of ordinary water. Using this processor, light water evaporates during exposure to the radiant energy. Heavy water and dissolved solids will remain in the residual droplet. The heavy water fraction can then be separated from the dissolved solids by conventional thermal processes.

For most other processes we do not have a correspondingly large body of reference data which may be used to perform a comprehensive analysis.

Definition and performance of experiments are required to verify the necessary design parameters applicable to adaptation of this device to a particular process.

Veda Incorporated recently submitted a design for a small solar power system utilizing a terraced heliostat array to provide the concentrated solar energy. Since detailed energy delivery calculations have been performed for this array, it is used as a candidate energy source in the following discussion.

DESCRIPTION OF THE KILN

The Vertical High Temperature Kiln is a device intended to directly use concentrated solar energy to perform a desired thermal function. In this device, solar energy is absorbed into the material being processed rather than first being converted into sensible heat in another medium prior to being applied to the material. In order to provide a large surface for absorption of the radiant energy, the materials to be processed will be dispersed into the reaction cavity as particles of controlled size. Scattered energy will be intercepted by surrounding particles and the cavity walls. The cavity walls will be controlled as to reflectance and emissivity in order to return that energy to the reaction cavity in a manner which will promote the process. The following is a partial listing of processes that could be performed by a solar kiln:

- Desalination of saline or brackish water
- Separation of agricultural waste to recover fresh water and/or solids
- Drying "wet" solids, such as paint pigments
- Fractional distillation, either by thermal or selective absorption differentiation
- Calcining
- Removal of water of crystallization
- Sterilization

Material processing will take place in a cylinder (Figure 1) in which the cylindrical axis is vertical with respect to the gravitational field. The material to be processed will enter the reaction cavity at the top, and be dispersed in such a manner as to promote the reaction desired. The concentrated solar energy will enter the cylinder through a window in the vertical wall. In general, the window will be closed to the atmosphere by a material transparent to radiant energy in the 0.2-2.8 micron band, and strong enough to withstand whatever internal pressure and other stresses may be encountered, such as structural forces and radiant intensity. Some processes may be such that a closed solar window will not be necessary, effective closure being obtained through use of an "air curtain."

The horizontal section through the reaction cavity will be such that the side walls will be set back somewhat from the expected beam space so the intended reaction will occur without the material being processed coming into contact with the cavity wall. To protect the components inside the kiln from the effects of concentrated sunlight in the absence of sufficient process material to absorb the incident energy, there may be a requirement to either block the entry window, or redirect incoming energy back through the entry window. This may be accomplished in a variety of ways, e.g., by proper curvature of a reflective cavity surface perpendicular to the incident energy. Suitable temperature control treatment of the interior walls may consist of reflectivity/emissivity controlled surfaces, insulation, cooling by radiation to the outside world, or by means of heat exchangers to an external heat sink.

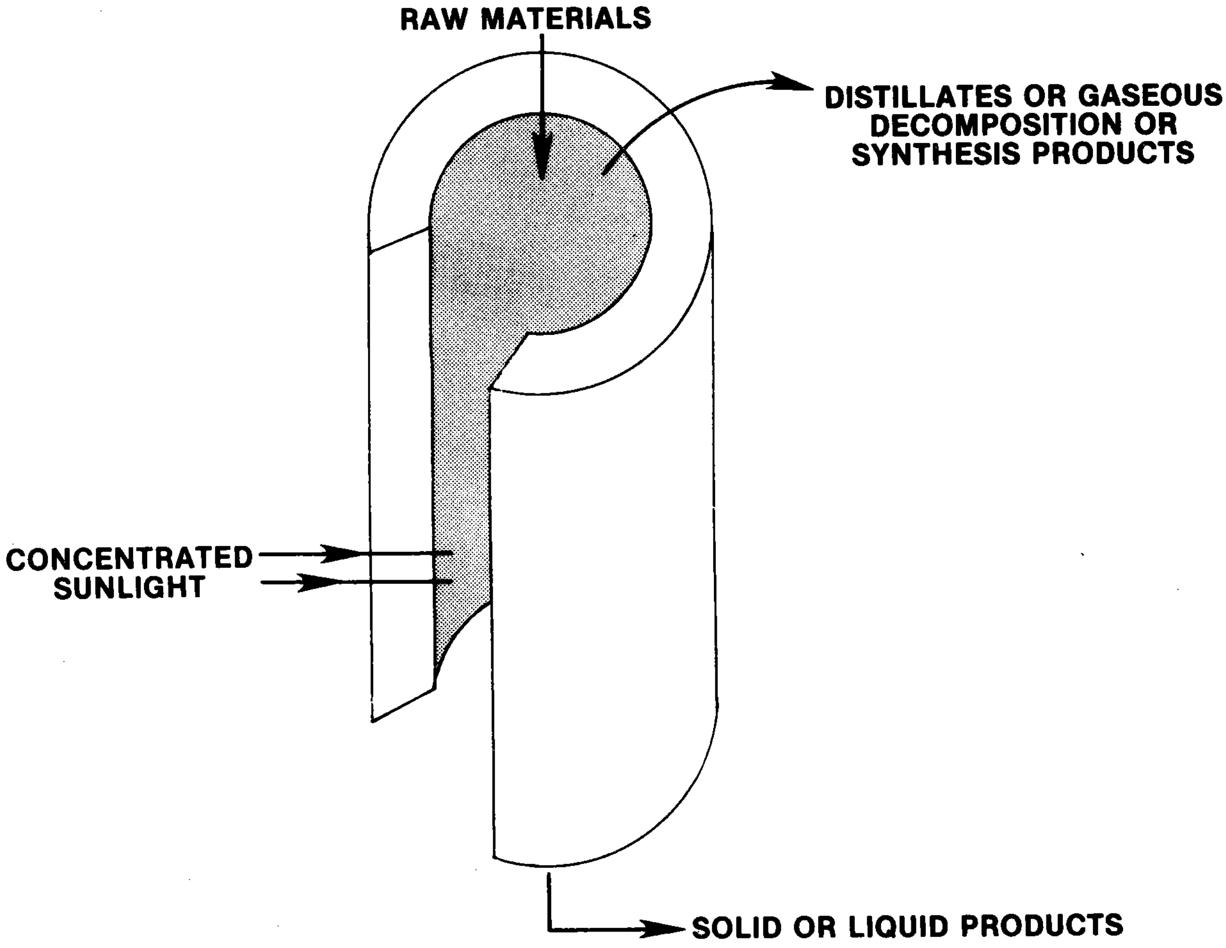


FIGURE 1

EXAMPLE OF APPLICATION METHOD

To illustrate application of this device to a purely thermochemical process we can evaluate the feasibility of heating a material such as round grain sand. In this case, the proposed device becomes a continuous flow, gravity-fed kiln. The raw materials enter the kiln as a finely divided, dispersed particulate and fall through the reaction cavity under gravitational acceleration. The concentrated sunlight enters through a side aperture (window) which may be either open or closed by a heat resistant window transparent to solar radiation. The concentrated radiant energy is both scattered and absorbed by the particles. The interior walls of the chamber are set back from the stream of falling particles. Reflection, absorption, and reradiation phenomena return most of the scattered radiation to the stream of falling particles. (See Figure 2)

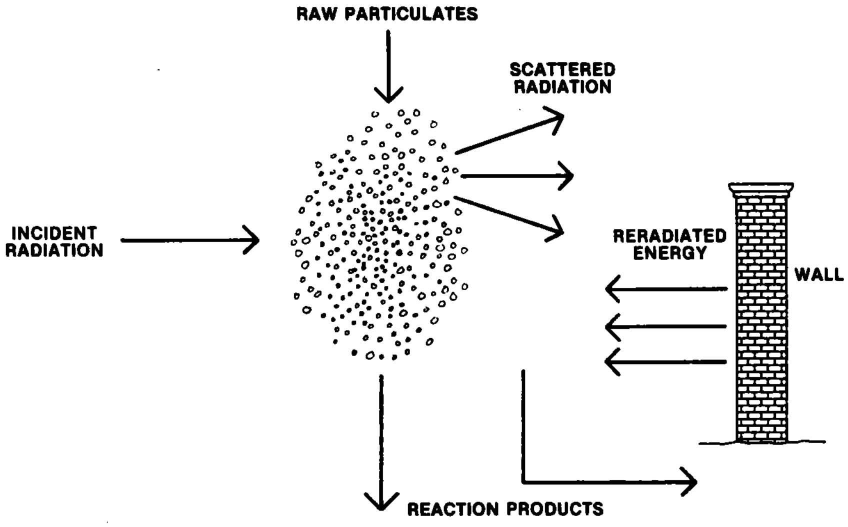


FIGURE 2

For this illustration, the process is designed to permit the particles to attain the required temperature during an exposure time of approximately one second. The relationship of particle size, exposure time, and radiant flux is:

$$F = \frac{EM}{KAt}$$

where:

F = flux density required

K = net absorptance

E = energy required per unit mass

M = mass of one particle

A = effective surface area of one particle

t = exposure time

The quantity K is the least well-defined item in currently available literature, since it must account for particle irregularities as well as incident/scattered/reradiated energy irregularities. The exposure time and particle size can be considered as independent variables if one wishes to determine the flux density requirements. Assume that each particle is spherical and of uniform radius, R, is of uniform density, D, and that the material has a constant specific heat, S, over the desired temperature change, T.

Then:

$E = ST$

$M = 4D\pi R^3/3$

$A = 4\pi R^2$

$F = STDR/3Kt$

Assigning values to the particle of:

$S = 0.2$ BTU/pound °F

$T = 1000°$ F

$D = 0.145$ pounds/cubic inch

$K = 0.5$

Then:

$$F = 1.002 \times 10^7 \frac{R}{t}$$

Where:

$F \sim$ BTU ft^{-2} hr^{-1}
$R \sim$ in
$t \sim$ sec

The question then becomes whether or not a compatible set of particle size, exposure time and flux density are attainable using concentrated solar energy. Since the proposed device is designed to operate in a conventional processing environment, a side entry window, producing a horizontally directed flux is desired. We have addressed this problem in the following manner.

A terraced hillside permits an arrangement of heliostats for directing reflected sunlight horizontally to a central receiver. Since a terraced hillside is not available in many locations, a terraced structure will support the heliostats to direct the radiant flux horizontally. The structure can be designed to be functional, not only for holding heliostats, but also for housing other aspects of the operation. The use of several such structures can stimulate the development of industrial parks where yearly insolation warrants. The arrangement shown in Figure 3 was recently submitted as a design for a power plant.

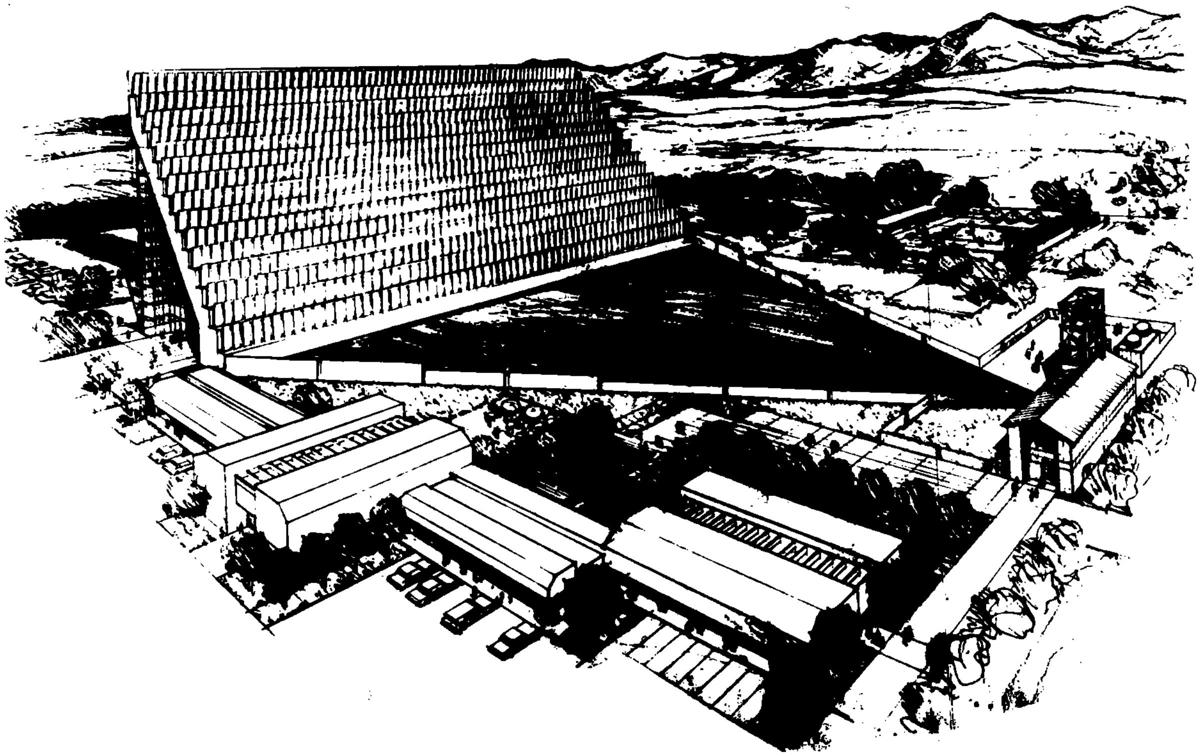
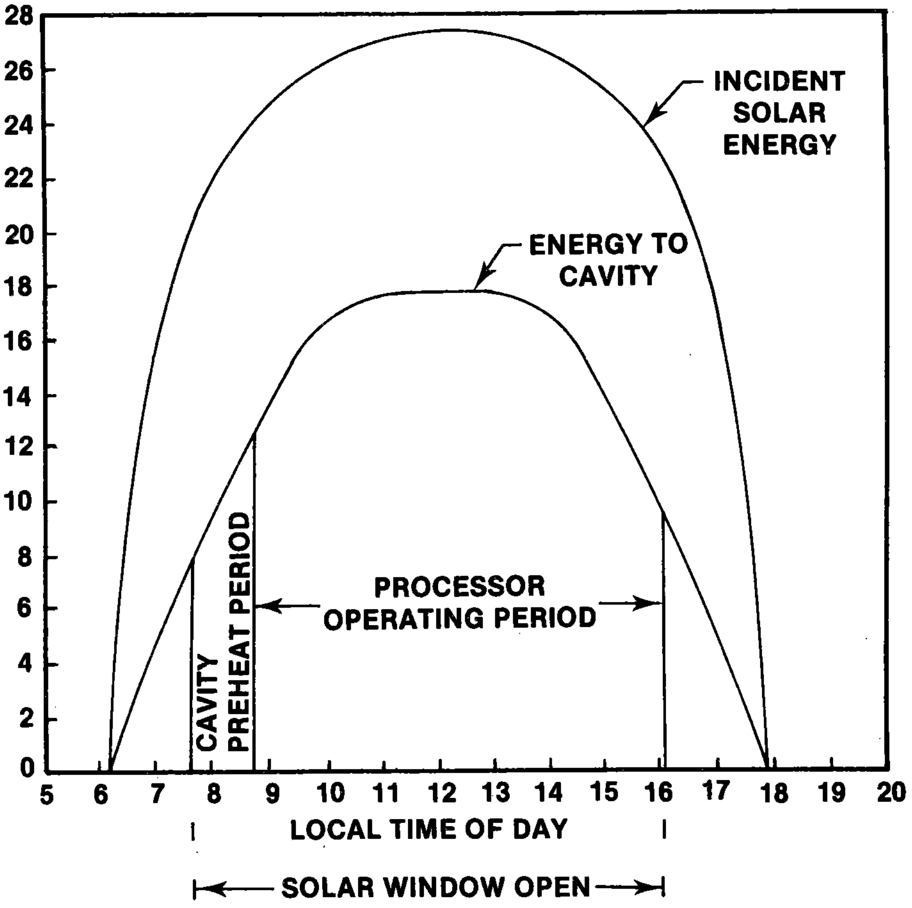


FIGURE 3

Figure 4 shows the energy attainable with this array on an average sunny spring day at Alburquerque, NM.



DAILY POWER HISTORY FOR SUNNY SPRING DAY

FIGURE 4

The smallest cavity aperture which can be used with this particular array of heliostats is about 3 meters high by 3 meters wide. The energy flux attainable in this area will vary throughout the usable sunny part of the day from a minimum value of about

1.106×10^5 BTU ft.$^{-2}$ hr.$^{-1}$ to a maximum value of almost

2.072×10^5 BTU ft.$^{-2}$ hr.$^{-1}$.

For this size cavity aperture, the exposure time for free falling particles of sand will be on the order of 0.5 seconds. This yields a maximum particle radius of 0.0055 inches. The total energy available on this sunny day from this array is about 126×10^6 BTU. For the process of this calculation, this energy would be sufficient to process 315 short tons per day.

CALCINING IN THE MANUFACTURE OF PORTLAND CEMENT

There are several real world processes to which this concept can relate. We have chosen to look at the manufacture of Portland Cement as an energy intensive industry.

The raw materials consist of miscellaneous, naturally occurring substances which are used to supply calcium silicon, aluminum, and iron to the final product. These are ground together to a particle size of less than 0.0029 inch diameter. Raw material enters the kiln in the amount of 3400 pounds for each short ton of output. The energy requirement is 6 - 6.5 x 10^6 BTU/short ton of output material. The decomposition products formed during calcining are driven off primarily as water vapor and carbon dioxide. Most of the external energy is used in this part of the kiln. A large part of that energy is dissipated in the heat of vaporization of the water and the molecular energy of dissociation. The temperature of the residual solids is raised to about 811° K (1000° F). The remainder of the process is exothermic. The eventual maximum temperature attained is about 1755° K (2700° F), the energy being mostly obtained from the exothermic reactions forming tetra-calcium-alumino-ferrite, tricalcium-silicate, and tricalcium-aluminate.

For this process assume:

$E = 1{,}764.71$ BTU/lb. of input

and

$D = 0.16276$ pounds/cubic inch

$R = .00145$ inch

$K = 0.5$

$t = 1$ sec (the exposure time will be longer because the gases will be vented out the top of the kiln, thus slowing the falling particles)

$$F = \frac{EDR}{3Kt}$$

Based on the requirement for approximately 6 x 10^6 BTU/short ton, this particular heliostat array could process about 20 short tons of Portland Cement per day. A somewhat larger heliostat array (approximately 30%) would provide the required flux to at least 8 hours per day, and could produce 28 short tons of Portland Cement per day.

In order to go to a theoretical design stage for such a process we need to know such things as the scattering and absorption coefficients of the raw particulates over the available spectrum and the rate of progress of the reactions in such a suspension state. Another unknown is the relationship between the amount of purely radiant energy required and the energy requirements when the transfer is primarily by conduction of sensible heat. We would also like to investigate ways to use this technique as a supplement to an existing conventional fossil fueled kiln, in order to optimize the location of feed point and rates for introducing the solar processed material into the fossil fueled system.

Veda Incorporated is a systems analysis oriented organization. As such, we offer these services of application analysis and design to persons or organizations who wish to use devices such as those described here.

REFERENCES -

1. Seraphin A. Sullivan: Experimental Study of the Absorption in Distilled Water, Artificial Sea Water, and Heavy Water in the Visible Region of the Spectrum, J. Opt. Soc. Am. 53, 962 (1963)

2. Joseph A. Curio and Charles C. Petty: The Near Infrared Absorption Spectrum of Liquid Water, J. Opt. Soc. Am. 41, 302 (1951)

3. Ven Te Chow and Terence E. Harbough: J. Geophysical Res. 70, 6111 (1965)

CHEMICALS, FUELS AND PROCESS HEAT PANEL DISCUSSION

Chairman: M. U. Gutstein

Highlights

Gutstein: Suggested more materials and window experiments. Makes no sense to use STTF for many of concepts; should be tested in laboratory first and then with much smaller solar facility.

Laxar, Bethlehem Steel: Coal gasification for steel plant where gas may become unavailable.

Gregg, Lawrence Livermore Lab: Acetylene directly from coal by very rapid solar heating.

Sprague, US Borax Research; Laxar: Solar generated hot air could reduce cost for borax by dehydrating before shipping.

Beall, Oak Ridge: Bring 100-lb sample of borax to Georgia Tech for experiment with Sanders hot-air receiver.

Hickman, Lawrence Livermore Lab: Very high temperature solar produces photochemical plasma, which introduces entirely new processes; e.g., air plus water to make fertilizer.

Sprague: Use solar for spray drying of particles; could be intermittent. Also, are interested in process steam from solar central receiver.

Gregg: Use STTF to power king-size 1/2-MW laser.

Panel Discussion

Mr. Gutstein: Let's first introduce the panel members: Sam Beall, Oak Ridge; Jim Dafler, IGT; Frank Laxar, Bethlehem Steel; and Bob Sprague, US Borax Research.

Mr. Gutstein: The whole purpose of this workshop is to identify potential experiments or studies for design of experiments that might go on one of the solar thermal test facilities at Georgia Tech, Albuquerque, White Sands or possibly abroad.

Our purpose here is to see whether we can get started on providing a technology base, via the mechanism of tests or experiments done on the test facilities, that would build up and support the solar thermal fuels and chemicals program, and also support industrial process heat. I think we have to focus on that.

What I would like from the panel is to get some of their viewpoints, some feedback on what they've heard in the past two days as to possibilities, and also to get some feedback from the audience as to ideas for specific experiments. At least they can point the direction in which the Users Association can go in talking to people and encouraging them to think about experiments.

Dr. Bamberger: In Germany it appears to be an accepted fact that the coal industry supports nuclear energy. For instance, and this is more a question, when we look at solar energy, it has to help the coal industry, without even going to coal gasification. I am reminded that the ratio of hydrogen to carbon in coal is about 0.8 to 1, and one of the problems with coal is the sulfur content. I was wondering if, when one heats coal by solar energy, one could extract even a fraction of that hydrogen, which could then be devoted to removing the sulfur, and maybe even end up with excess hydrogen that doesn't have to be burned. One goes through the exercise of how much coal is burned a year, and if you can recover only a fraction of that hydrogen, I think you have made progress.

Dr. Skaggs: I've heard papers all day saying, "Gee, here's a process and we can do it and it will work," and I've only heard a couple of people allude to the materials handling problem. I have come face-to-face with that in the last two or three weeks in addressing the molybdenum process. The process I propose has got to compete with an industry which processes approximately 50,000 tons per day. I think that one of the things people need to think about very seriously in any process they are considering is: how do you handle large quantities of material? In order for these things to be competitive, as the man from Shell Development Company told us, we're going to have to come right down to their level of handling the materials to make solar energy competitive. I want to stand up and ring the bell for that. Be sure that you consider how you're going to handle large quantities of material.

Dr. Antal: Farrington Daniels, in his classic book, devoted about one paragraph to making fuel from high-temperature solar heat. He identified very early on the use of solar heat for flash pyrolysis. I've heard a lot of talk today about using solar heat for its heat virtue alone, but I would like to encourage the group to consider solar heat for its virtue of very high heating rates, which is of supreme importance and interests me greatly.

For example, addressing the refinery industry: all ethylene producers rely on flash pyrolysis and I think this combination of heat plus an interesting chemical effect, through rapid heat transfer, is very difficult to get by burning fuel. The reformer furnace has to be run at fairly high temperatures in order to get these very rapid heating effects. I think that's an area that well bears focusing on.

Dr. Gregg: I'll comment on the rapid heating. Recently AVCO received a contract for, I think, about 5 million dollars for electroheating of coal. This project was initially started for MHD high-temperature exhaust gasses. It was found that if small particles of coal are rapidly heated, you can get acetylene as a direct conversion--hydrogen comes out directly as acetylene, and you get a major part of the coal as acetylene gas. You have almost an equal amount of hydrogen particles in that system. I went through the numbers recently and it appears you need solar fluxes on the order of 500-1000 watts per square centimeter to accomplish this, but the kinetics may not be exactly right. The basic requirement is that you have 40-micron diameter particles that are taken up to a couple thousand degrees in 5 milliseconds. When you go up to that number, it comes within striking distance of making acetylene directly.

Mr. Laxar: In Dr. Kugeler's talk yesterday about direct reduction, he mentioned that about six years ago the American Iron and Steel Institute started a project to look into nuclear steel-making, which was based on the idea of using the heat from the high-temperature gas reactor to reform natural gas, CO and H_2, and use that in direct-reduction processes.

By far the great majority of steel now starts out in the blast furnace and then goes into a basic oxygen furnace. That is, we get pig iron from the basic oxygen furnace where the impurities are oxidized out and we make steel. However, there is a well-developed technology for direct reduction in which one starts with an iron oxide pellet from beneficiated ore, and reduces that directly with CO and hydrogen to form a sponge iron. That goes into the electric furnace to be melted, perhaps with some scrap, to make steel.

It seems to me that what I've heard today about reforming natural gas, and perhaps even more importantly, gasifying coal through solar processes, would have real possibilities in this kind of process. If natural gas prices go up, as they're supposed to do, the use of natural gas may become unattractive. Then, coal gasification through solar processes might be much more interesting to the whole steel industry.

The added advantage of direct reduction is that capital costs of the plants are relatively low. One can have a small plant and make it pay, which one cannot do with a blast furnace. Blast furnaces now run 6 to 8 thousand tons per day. They are huge vessels and that size is required in order to achieve real economical operation.

So, I am encouraged by some of the things I've heard today.

Dr. Kugeler: I want to comment that the costs of all of these processes are very complex. You really have to have continuous operation to judge these things. One of the main problems, and the thing which requires further study, seems to be to find a way to have continuous heat from the solar furnace. For instance, I suppose you cannot equate the coal gasification with solar energy if you cannot solve this problem.

To give you an example, in our project to use nuclear energy for coal gasification, we had to find out that if you interrupt the coal gasification for some hours, it takes some days to come again to operation, and all of these gasification systems require this time. A very important point seems to be how to store energy.

Dr. Sprague: I think the comment that Karl offered on continuous operation is a critical point for industrial processes, particularly in the context of this conference.

The kinds of high-temperature processes that we use at US Borax are fusion processes. We will run somewhere on the order of 800 to 1000°C. We do this on a large scale, but we can't get a furance of this type fired up and at an optimum temperature quickly. It has to be brought up over a period of weeks because if temperatures are changed too quickly the refractories will crack--all kinds of things go bad.

Tom Erickson, who is here from Owens Corning, could probably point out that their problem is even more severe because they're at even higher temperatures. Once the temperature is achieved, it has to be maintained. So far I have not heard anything about heat storage at these elevated temperatures. I've heard about heat generation, but I think this is one area that probably is of critical importance to these high-temperature processes.

The other area on which I've heard some talk, and I've really come as one to learn rather than somebody who knows everything about this field, is the actual method of transferring energy from the solar receiver to the process. I think there has been some work on this and it is, indeed, critical.

I can see hot air being useful to us in dehydrating calcide products. However, one factor that is important when transferring energy from a hot gas to a particulate solid is what happens to the effluent gas. If it has a lot of fine dust in it, the dust will have to be scrubbed. Because of air pollution controls, we find the problem of removal of particulates from the effluent process has now become one of the more important factors in our processing. I think a number of other industries who deal in particulate solids are finding this is now a major factor. Many of these people have gone to electric melting of glass, not because electrical energy is cheaper than gas, but because by using this process, they can reduce particulate emissions, and they save enough on scrubbing costs to more than compensate for the higher cost of energy.

I think solar energy has some potential in this area, but it will depend on the method used to transfer the energy from the receiver to this process. I find it difficult, myself, to envision a process where the particulate solids can be melted directly in a solar receiver and removed from that receiver. Maybe I'm just not imaginative enough to do it, but it seems to me this is going to produce a real problem in that you need something more on the order of a heat exchanger, analogous to an electric heater, to deliver energy into the process stream. But again, if you are operating at the high temperatures on which I understand this conference is focusing, then energy storage at those temperatures will be critical, because a high-temperature process generally has to go on continuously or your equipment length is too short.

Mr. Dafler: There are some gas-fired processes that are used in the metal industry, for example, that operate at close to 1000°, in which they move solids--very efficiently, I might add--but it is done. In the battery industry, we make graphite or carbon pencil-shaped objects in natural gas-fired furnaces that operate at 8000 and 9000°C. To give you an idea of how bad it is, for example, these things are put into mullite saggers and rolled over mullite rolls, which are kept on end and they're just pushed through. Industry has faced up to this problem in an inefficient way. I think we can probably find ways to move solids through radiant energy fields that are as high as this, but the problem has been solved in this way in the battery industry for many years. Now they're suffering because they've never modernized. They're suffering natural gas allocation difficulties in the East, particularly around Lancaster, PA, but perhaps there's a kernel of something in these ideas that we might use in a more efficient way in movement of solids.

Mr. Gutstein: I think that the solar thermal program is about 5 years old, and I think it's a little unfair to expect all the problems to be solved at this moment, particularly high-temperature storage. I don't think at this point anyone in the program would be ready to offer a super high-temperature storage device. I think what we do is suggest that they burn fuel when the sun is not available, at least for now.

Mr. Owen: You mentioned before that we haven't been serious enough in our approach to high-temperature storage and someone mentioned glass. I've had quite a bit of experience in a glass shop and I can see a potential here. I see a problem in using multiglass of 90 something percent sensible heat. There is something I don't think has been addressed yet that could possibly fit into a high flux central receiver or a conentrated type. I think there are several other materials that could be similar to multiglass that could be used for high-temperature storage. Glass melts at 1250°C.

Mr. Gutstein: I think the materials compatibility issues there are considerable

Mr. Owen: They hold glass with no problems. They've done it for centuries. There must be an established technology there.

Mr. Gutstein: I don't know if you could heat exchange it. In other words, if they get the heat out.

Mr. Owen: That process of doing it has just dissipated, as far as I know.

Mr. Beall: As you may know from the description of the Sanders Associates concept, they have an idea for heat storage that's pretty good, I think. They use the so-called checkered stove, of the steel industry, which is really just a vessel of magnesium oxide, I suppose. Sanders proposes that they charge, say, 4 hours of heat into those things and then take it out to continue to run their turbine at about 2000°F.

I want to go back to the question Frank keeps asking about what we can do on these facilities, and suggestions to see what kind of reaction we get, or what other ideas are stimulated. It seems to me that there is an investment, not only in the collecting and energy delivering capability, but also in experiments like Sanders has been doing at Georgia Tech and the 1-MW silicon carbide heat exchanger which Black & Veatch will make, which will provide sizeable quantities of hot air at around 2000°F. Why not bring your 100 lbs of borax down to Georgia Tech and see if they can dry it or whatever. It would be an easy thing to do with the equipment already available, and paid for, if Marty will pay to continue to operate it.

Also, you've got steam--the test steam generators that are fairly small. It seems to me that would be suitable for some of these process applications.

I'd like to go back to the 1950's, when Felix Trombe took a quartz tube and ran some nitrogen and oxygen and air through it--there's your window. I don't see why you can't do a flash pyrolysis test in a sizeable quartz tube to see whether it works. Also, for the coal system, that would tell you whether it would work without building the big window. It seems it could be done on a small scale in either of these facilities.

The window test itself is also one that might be useful--whether you can cool a transparent surface at these high flux densities. I'm reminded that Lavoisier, when he did his famous 3-meter lens experiment, had it filled with fluid, and it would be simple, I think, to circulate a fluid through a sizeable window and keep it cool.

Mr. Dafler: With reference to experiments for the facilities, Carlos Bamberger talked about thermochemical hydrogen production cycles and trying to find more efficient cycles, for example, 2-step cycles with some of the oxides. At IGT we're very interested in trying to get some experiments operating at these higher temperatures. There are some problems, though, that we're not quite prepared for in the use of the facilities. For example, we do a lot of engineering rate measurements with radiatnly heated reactor tubes because this is the only way one can run a 1000° or 1100° experiment in a laboratory. One uses some kind of box furnace in which the heat is supplied radiantly. We're used to doing experiments in tubes 2 or 3 feet long, and making measurements in which we find oftentimes that the heating rate is a little bit too low. The size of the Sandia facility target area is 2 or 3 meters, so there is a real mechanical and hardware problem for people who do thermochemical hydrogen experiments, such as we do at IGT, in interfacing with the Sandia facility, which is not a monster by any means. We need somebody, maybe from STTF or the Users Association, who can help us. We can't work the hardware up, it seems to me, efficiently to take advantage of that solar heat and the experiment.

We'd like to have a high-temperature target area of, maybe, 18 inches or a couple of feet in diameter, rather than 2 or 3 meters. There's a mechanical problem that needs to be overcome for people who are currently doing experimentation, who would like to go up a little bit in temperature and approach the STTF for doing some of these experiments.

Mr. Walton: We do have a smaller size here at Georgia Tech; about 1-1/2 meters in diameter. The spot size can be adjusted, it can be masked and trimmed.

Mr. Dafler: This is the kind of information we need to have about these kinds of things, also the degree to which Association funding is available, and help with the associated hardware problems. We have a number of solid/gas separations and thermochemical cycles, hydrogen production cycles that we would like to investigate at these kinds of temperatures--things of the kind that Carlos Bamberger addressed when he talked about thermochemical cycles.

Mr. Smith: We have published that information several times and can give you a rundown, unless you're suggesting using somebody as an intermediary to design some of them.

Mr. Dafler: We don't need that kind of help. Those who visited the facility at Sandia were stunned by the size of the target.

Mr. Gutstein: But isn't it true also that we're looking at something smaller than that at the 5-MW facility?

Mr. Smith: Yes, but it's not available yet. I would guess it's about six months to a year off. However, we do have a project looking at a reconcentrator, and, of course, there are the Omnium-G facilities--the University of Houston has one. It's about a 3-6 inch target area. I really think we can provide anywhere from 3 inches up the size of the Sandia facility, whichever is more appropriate.

Mr. Dafler: I think that information is not uniformly available.

Mr. Gutstein: I'd like to suggest more materials experiments. There are a number of very specific requirements because of the high flux solar energies. In most cases, a combination of high temperature and high strength is required and then there is a corrosion problem in handling solids, and you also have the problem of thermocycling once a day, and that is too big to be ignored. You have thermal shock, or sudden disappearing of sunshine because of passing clouds, etc., and being a materials engineer, it seems to me that all these requirements at the same time mean some of them are mutually exclusive. I don't know any material that's going to solve all the problems at once. I would suggest some very serious experimentation for each potential application.

Dr. Gregg: When a cloud comes by, we have oxygen on reserve, which we can turn into the system and regulate the temperature. Clearly, this also could be adjusted to overnight operations. We can make this exchange with sunlight, for example oxygen and sunlight, which essentially gets around the thermal shock problem, so it's not insurmountable. There are other kinds of economics, also. Many of the tests we're talking about really don't require large illumination areas. They can be carried out in a centimeter size. That's an interesting, probably low-cost test facility.

Comment: One of the advantages in solar heat is that you can turn to electrical energy at night, and you can get electricity at a reduced rate where you don't want the dilution of the oxygen reaction. In fact, you have to heat it with some other kind of heat. We'll talk about an application like that later, where you simply balance the electrical power off--and the utilities would like that, too.

Mr. McBride: With reference to making synthetic fuels from coal, coal transportation really isn't the key. Whether a gas or a liquid, the key is the hydrogen-carbon ratio because coal doesn't have enough hydrogen in it. It's more a liquid and it's mostly a gas. I've been involved with economic evaluations of a number of complexes and a number of fuels and chemicals from coal. The thing that will make it go or not go is the cost of the hydrogen that you have to insinuate in the coal molecule. If solar energy can produce hydrogen more cheaply than other possible processes, a lot of people will seize upon it and use it, but it has to be competitive. It has to be better than the other means of producing hydrogen. But, I know for sure that the cost of the hydrogen production facility is the key to the economics of making coal gasification practical and economical.

Dr. Aiman: Our current projections on coal gasification are that we need about twice as much hydrogen. Hydrogen comes from water, out of steam, so we're pretty good on hydrogen and carbon.

Mr. Gutstein: I think I'd like to get back to the issue, which is what kinds of experiments and what areas should be emphasized in building this technology base and using the facilities. It seems that a number of the processes postulate using a window, a material window, and there was a suggestion about use of a silicon carbide material, which would then reradiate. Other ideas, such as an aerodynamic window, have been suggested as a way of sealing off and leaving an optical opening.

Dr. Hickman: I was going to suggest an aerodynamic window just before you said the word. Let me take this opportunity to say that the reason we have such high temperatures is because we're working with very high fluxes here. But there is a component of visible light associated with the photon energy which is something between a factor of ten and a hundred higher than the actual thermal temperatures we're talking about. When you talk about flash pyrolysis, particularly in an electric arc, the arc is a fully ionized plasma, which is probably running in the neighborhood of a hundred thousand degrees, and it is possible that the production of acetylene is not so much due to the heating rate of the coal, but perhaps due to what I will loosely describe as the photochemical effects, the high energy effects, of the plasma itself, over and above what we think of as normal thermal effects.

So, if we extend this, most photochemical reactions occur slowly because there is a low flux level. Here we have an opportunity to address, in a very high flux facility, both the chemical and photochemical reactions that might open up enormous new horizons for additional processes that normally would't occur at all. For example, we might use CO_2 to make cycles for air and water, or air and water to make fertilizers. So, I think perhaps the chemical company representatives might review or think about the combination of not only high thermal temperature but also the possibility of taking advantage of the photon energy in the visible light spectrum.

Question: To bring those two ideas together, would you think of using a filter?

Dr. Hickman: I'd rather not filter anything that's useful. I was thinking more along the lines of a plhotoactive catalyst.

Comment: Along those same lines, there was a proposal for using the fluid value and coupling the optical values. We know a lot about infrared. That's the way we use our photon reactors, but we don't know very much--in fact, we don't know anything--about coupling solar energy to a feed bed and, depending on the product in the feed bed, we might have a very high absorptance of visible light, or we might have a very low absorptance of visible light. We don't really know what's going to happen, so we have to look at it. The absorptance of, let' say, coal molecules--a coal particle at high temperature--to visible light, I really don't know what that would be. Your fluid bed might be very efficient, or it might be very inefficient, and I think only the experiment will tell you.

Mr. Gutstein: Would you like to run one?

Mr. Beall: Just a couple of points. I support very much the idea of doing some experiments to check the photochemical effect. Trombe's experiment with nitrogen didn't seem to indicate any. On the other hand, there have been lots of comments that dissociation of carbon dioxide is accelerated if one can introduce visible energy, so the questions still need to be answered. I read of one bed experiment but have forgotten the details. However, it is something that must be fairly easy to do. They use a small quartz tube, I believe. But we're not limited to a 1-inch diameter. We can go higher and have the fluid bed right in one of these facilities. I think that would make a fine experiment.

Mr. Gutstein: Frank, I'd like to ask you a question. Are there any plans to put a sodium-cooled receiver on the tower?

Mr. Smith: Yes, R&D is being done on sodium-cooled receivers, but I don't know the schedule, but presumably it will be tested.

Mr. Webb: There is a series of competitive contracts right now, with the better ones coming through to the top.

Mr. Gutstein: I think at this point it's just a series of design studies, Howard, based on the outcome of those designs. There may be a selection to go forward to hardware, and presumably it would go to one of the facilities, but that selection has not been made as yet. I think there was an indication that there was a sodium-heat receiver being considered in Spain as part of that 500-kW facility.

Mr. Webb: Someone has tested sodium with an arc searchlight at the 6-MW level. This breaks down the wall inside the receiver. It might be suitable to try that on a larger scale.

Mr. Gutstein: It's not sodium, it's salt.

Mr. Zenty: I'd like to make the proposition that some of the questions and problems that seem to be troubling the solar thermal users, be answered by much simpler experiments than going to the tower, which would be extremely useful for purposes of utilizing the tower. I don't want to name specific solar concentrating devices, laboratory or bench scale, which would provide the answers. I think the question of photochemistry coal conversion, or photolytic effect, could be very easily answered by an experiment and would avoid all the problems of material handling, window melt-down and anything else, without having to go to the tower, which involves practically a one-year effort or more. I would like to suggest to the Users Association that if you want to solve your problems in this century, attempt to get some of the answers in the laboratory by simpler systems.

Mr. Smith: I some instances, the Users Association has suggested the same thing to DOE.

Mr. Gutstein: I think it's clear that some experiments probably could be done more conveniently in a laboratory setting rather than up on the tower, but there may be some processes where you just don't know. The best way would be to go directly to the kind of flux that would be present in a real system and get a handle on that problem.

Dr. Bishop: One of the functions of the Users Association is to recommend to the DOE what facilities are required. If these existing facilities don't fit the bill, then they would be utilized a lot more down stream if we had smaller test facilities also available. It might be appropriate to make an investment in smaller test facilities. That's a question that has been raised previously.

Mr. Smith: As a matter of fact, we have funded--and I presume will continue to fund--what we're calling both Phase 1 and Phase 2 experiments. Many experimenters run into the problem that before they really know whether they can run something on the tower, they must spend a some time and effort analyzing and designing the experiment. Therefore, we have funded Phase 1 experiment design efforts with the expectation that we will subsequently expect a Phase 2 proposal, and will decide at that time whether it's worth spending $100,000 or more to build and test it.

Mr. Gutstein: I think there is a risk that the Users Association may become another DOE, or another laboratory. By funding an organized program, for example, I think that if an experiment doesn't make sense to run on a facility, you shouldn't run it. You should run it where it makes sense.

Mr. Laxar: There are a lot of mundane uses for high-temperature heat, heat treatment, annealing, reheating, forging, and they range anywhere from 1300° up to 2500°. Pelletizing is another place where we need 2000° temperatures and these are gas-fired, oil-fired, and some are electrically-heated, and I guess what I would ask is, are there any experiments going along to provide large quantities of hot air? That's all we need for a lot of things and at various temperatures.

Dr. Sprague: I'd like to echo that same feeling. It was said that we could bring our borax down and try it. We already know that hot air will dehydrate, but what we really need to see is the hot air produced from the receiver, or more quantitative date on that. It's what I had in mind when I mentioned the heat transfer from the receiver to the process. We use combustion gasses directly. We can probably save on air pollution if we use hot air, but we don't have to go to the facility to find that out. It's hot air and/or storage in between we to know about. Do we have to go to combustion gas to fill in when solar hot air is unavailable, or is there some high-temperature way of storing it so we have it for 24 hours?

Mr. Gutstein: What temperatures are you talking about--2000° and up?

Dr. Sprague: We dehydrate our borates to save freight, there's no point in shipping water. We presently fuse them in order to completely dehydrate them, but we don't have to dehydrate them completely. We could effect a substantial saving if we merely took them part way down. If we used hot air, we would achieve that. We can use air temperatures of 300°F and up. The fusion temperature of borax is on the order of 850°C. We use 900-1000°C. We're using combustion gasses at a higher temperature--I've forgotten the exact figure--but we're getting this ultimate fuse temperature. It might even be that there are fused borates used as high-temperature heat storage devices. I don't know, it occurred to me.

Mr. Beall: The experiment we saw yesterday was going to produce 1000° or 1200°C air. That would fit your bill.

Dr. Sprague: That's exactly what we would need. We could use lower temperatures also, possibly with modifying our process. Of course, we're like many industries, if we have a capital investment in a given facility, we'd like to continue to use it. On the other hand, we're not locked out of some alternate process if it's going to provide lower cost energy, etc.

Mr. Owen: As far as the different processes are concerned, I've noticed that we've all talked today about coal gasification at large, centralized processes. On the way down here I got the recent Solar Engineering magazine and was very surprised to see the completeness of the list of industrial processes and their attendant temperatures. That one page could generate enough ideas for subsequent testing. I just wanted to mention that. There is more room for heating and reheating than was previously mentioned by the gentlemen up there.

Dr. Bamberger: I'd like to address my comments to Dr. Kugeler, especially. I recognize the problem of coal gasification and the complexity of it, but if one wants to start adapting solar energy to a process, I would think that it is not necessary to go to a complex process. One can, for instance, use as a good example: the dehydration of borax. When we looked at which processes solar energy could be adapted to, we put particular emphasis on those that deal with the decomposition or dehydration of a solid so it wouldn't be necessary to operate on a 24-hour-a-day basis. So, if one starts walking before running, it is conceivable that we can make some inroads into this problem.

Mr. Gutstein: I think another aspect is the very high temperatures that might be achievable in the long run. That might be an area for some new products that have not been available because of the inability to reach those temperatures. You may not get much efficiency out of the solar receiver because of the reradiation, but if the product is really valuable, maybe we can still make it pay off.

Question: What's the borax like? What can you drop? Can it tolerate the high flux densities? What's its outside appearance? It would be a very simple process to test something like that.

Dr. Sprague: It doesn't sound too attractive because it's white, which implies low absorptivity. On the other hand, in our fusing furnaces, we depend very heavily on radiant energy transfer, so it's not necessarily bad. I think this is in the category of the kind of experiment which could be carried out on a laboratory scale to determine absorptivity, etc. You wouldn't have to to go the tower to find that out.

Mr. Smith: Direct solar radiation might be different than the IR you get in a radiant heater.

Dr. Sprague: Oh, yes. There's always a question of scale. I think if it looked attractive on a laboratory scale, you would want to follow it up on a larger scale.

One thought that occurred to me from Rudy Kretchek's talk is that one thing we run at our plant is a spray dryer, to make a different product. Spray drying is a process that's used in many industries. If there is a mixture of materials and what is needed is a fine particulate dry solid, one way to achieve a uniform composition is to spray an atomized spray and dry it at completion--clear the solid before it contacts any particle--and there is a uniform composition. Absorbing radiant energy at high flux density to evaporate the dryness might be a very useful application, and this could be operated on an intermittent process. You could run 8 hours a day and shut the process down without having any big problem about materials cracking, etc.

Mr. Moore: I just wanted to say it is a selected absorption process. If you change the wavelength of the energy by absorption in the walls, and then reradiate it out to IR where you don't have the energy present from sunlight, you can get as much as 100,000 times the dispersion rate from the water molecules.

Mr. Sullivan: I wonder if you're not putting too much emphasis on a complete switch to solar energy. For example, in the Wisconsin process, if you consider using solar to heat your air up to, say, 1200°C, and natural gas to get you on up to the 2500 K that you need, I think that to depend on a complete switch is almost unreasonable for a lot of high-temperature processes.

Mr. Gutstein: At this stage, I agree. We're really going to have to start at much lower temperatures to look at thermal storage. There's some work going on at 500-600°F and some work at 1000°F and up. There was mention of a Sanders concept using the checkered stove concept from the steel industry. That work is just beginning and there has been nothing done on it. At this point, in general, I think it's very reasonable to consider solar at this point as a fuel save, rather than as a base-load kind of operation. In the long term, maybe storage concepts will come along that are economical. Maybe the thermochemical storage concepts might come along that will look attractive. I think it's too early to tell, but right now I think, realistically, we have to look at solar as a fuel saver.

Comment: In certain areas plasma jets are used for high-temperature baking. I don't know what those are, but I know they are used in certain ceramic areas. It may well be that high solar fluxes that are available could be used in areas parallel to the plasma jet high flux temperature baking.

Comment: It might be helpful in developing these ideas to know what the Users Association budget is for such experiments. This would give us a better idea of what level and size experiment would be appropriate within the financial constraints.

Mr. Smith: I'm going to answer that in a roundabout way because when I tell you what our budget is, you might say "Why didn't you tell me that sooner and we wouldn't have bothered to come down here." Our budget isn't very large; however, I think somebody said you've got to walk before you can run, so you propose to us whatever kind of experiment and budget you think makes sense, and if it's larger than our budget, I will nevertheless not hesitate to recommend it to SERI, and SERI will not, I believe, hesitate to recommend it to DOE. Our operating budget for experiments for the next year will probably be around a quarter million dollars. I'm well aware that if we had one really hot experiment, it might take the whole budget, and maybe more. That's one reason I stressed a moment ago the Phase 1 and Phase 2 thing. So far, proposals from people wanting to design experiments are very nominal--like 5 or 10 thousand bucks. For others, where they actually want to get into a more complicated piece of hardware and start building it, it's run up around $25,000 or so. But I say again, none of us--myself, Marty Gutstein or Chuck Bishop--believe for a minute that we can design anything really elaborate for that amount of money. So you go ahead and propose whatever you have in mind and we'll go ahead and look at it.

Question: Is the Sandia experiment, for example, being financed through your organization, or is that independently part of their contract?

Mr. Smith: At the moment, that's independent of the Users Association. Yesterday someone mentioned two experiment tracks. On the larger experiments, a quarter million dollars or more, for instance, the Users Association may recommend but not follow through with detailed technical monitoring. With only three of us in the office, it's kind of unlikely.

Question: What you're looking for right now, then, are relatively small-scale experiments, to determine, basically, the feasibility of things rather than some sort of a large-scale demonstration?

Mr. Smith: That's true, but I'd like to qualify that by saying that if there's something very worthwhile that is going to require a quarter million dollars or more, I surely do not want to discourage someone from putting in that sort of proposal.

Mr. Gutstein: If you can come up with a process that runs on solar energy and makes hydrogen for a dollar, and it's a couple hundred K, and it looked really good, I think we could find the money somehow.

Question: I suggest an awful lot of the experiments have a common interest. For example, testing windows has a common interest to a great number of people. For an experiment that might satisfy a large number of people, will you have a central dissemination of information?

Mr. Smith: Yes. All we have at the moment is a newsletter, which we will be publishing quarterly, when we have something realy worthwhile to report.

Question: So if somebody tests the window, everybody is going to know about it?

Mr. Smith: If we know about it and we know about your interest, you'll certainly know about it.

Mr. Gutstein: I would also like to say that I have the responsibility for the window technology at DOE Headquarters and it certainly is an area of interest. Based on what I've heard at this session, and the workshop that was held previously, the issue of the window will appear in my program on receiver technology development. But if there's a good idea for a window today, by all means come forward with it.

Dr. Schreyer: Regarding your request for experiments, I can't help thinking that it's a little unrealistic, from the point of view of the organization that I represent anyway, to look at it this way. There are too many gaps in your technology--the window, the photochemical effect, the storage. You know that it's going to take a fair amount of money to develop an experiment. You'd have to take people off of other work and put them on this in order to figure out a worthwhile experiment. You have to have some reasonable expectation of success to even bother with it.

I think you would be better advised to spend your money accumulating data on what it's going to cost to clean those mirrors, and how often they are going to get dirty. Is it practical to throw the energy right into the reaction? Do you have to design a secondary heat transfer system which would have limitations as far as transferring heat through a wall-type thing, etc. I think you have to bring it a little closer before you can stimulate a great deal of interest.

Mr. Smith: May I respond to that? I don't have a complete response, but I've thought all along--and I'm even more impressed after these last couple of days--that our approach leaves something to be desired. For instance, listening to Dr. Sprague, I feel certain that there are some areas of common interest between the borax business and the Users Association that we do not have a good mechanism for exploring right now. He needs to know more about our operation, and we need to know more about his. I don't know how we're going to handle that, especially when you multiply it by, I suspect at least ten other similar areas of mutual interest. We need to give that more thought. Does anybody have any ideas?

Question: There is an idea in the sense that this information will accrue. We could have a brain storming session in these areas--like a furnace--and talk back and forth to see how to use this information.

Mr. Gutstein: You've got to have willingness on the part of the organization or company to take a couple people off of their normal business to sit down with the group and that is also an expense.

Comment: After listening to the gentleman from Union Carbide, I'm not sure that the whole audience is aware that only 5 years of work and experiments have gone into the development of these systems, and only 120 million dollars have been invested in these plants. The technology of receivers has pretty well been developed--the mirrors, collector fields--and now we're trying to take the solar electric technology and apply it to industry and other applications, rather than just the utilities. It's going to require different receivers and we have more applications that may be of potential benefit. Initially, we're looking for applications where we can have a qualified system, beyond the 10 hours a day that the sun is up. I was thinking that US Borax might be able to use a solar heating system that doesn't have to go continuously if they can get a receiver that can recycle it off within a reasonable lifetime.

Mr. Beall: It has to recycle every day anyway.

Dr. Sprague: I think, for example, that the Barstow facility will be of intense interest to us because it's going to generate steam. We use a great deal of process steam and our plant is only 40 miles away, so I think the experiences gained there will be of direct benefit. We can find out how much it really is going to cost per pound of steam at temperatures we know we can use. We do a great deal of processing of liquid solutions. That's our major activity, and I didn't touch on that because I didn't think it was really necessary that experiments be direct.

It just occurred to me, however, when the gentleman from Union Carbide made a comment, that one area I haven't heard discussed that would be of interest to us, and I'm sure Union Carbide as well, is possibly the higher temperature processing of high value products like refractory materials. They make a number of refractory materials which we don't have to make, like nickel boride and boron nitrate, although we make some other borides. But these are inherently high-temperature processes and also are expensive end products. These might be worthy of some direct experiments because they are presently made with electric heating and supply a relatively inexpensive heat source. If there is no way solar energy can be transferred directly into, say, the reaction mixture, then this might be a kind of experiment that would be worth doing on the tower. This might afford an economic approach. These are not exactly high tonnage products, but they're high cash products.

Dr. Schreyer: We had an unsolicited approach from one of our company's major contracting firms about putting in a solar facility in our Sebring plant to generate steam and power and process heat for that plant, and putting in some polyethylene facilities. In the course of that presentation, somebody asked the question: What's the fall-back position if the mirrors get dirty, or the sun isn't out?" They said, "Oh, you have to put in your regular steam plant, you know, or fossil fuel as a back-up." That's a pretty expensive facility to put in just as back-up--total duplication. There is no way we can do that now. We have to have more confidence in reliability. You can't double your cost and expect to get anything but a license to lose money.

Mr. Gutstein: You're addressing some of the difficult issues in bringing solar energy into use commercially. Those are not easy issues, and I think it's inappropriate to get into those issues--much as I'd like to--at this time. But I would like to give you something to think about.

I take a broader view than just how the company might view solar energy. It's maybe a little idealistic, but the price of conventional fuels are too low and solar can't compete with artificially low-priced fuel. When the fuel prices come up, and the environmental impacts are put into them as well, then maybe solar will have a chance of competing. It's got a long way to go, because it just started a couple of years ago, and there has been coal, oil, and natural gas technology for a couple hundred years. So, these are the real issues. There may be some overall social benefits to be derived from the use of solar energy as compared to some of the other fuels. Those are difficult concepts to come by, but that's a justification from the point of view of industry.

Dr. Schreyer: I agree with what you're saying. I'm just saying that despite the years you've worked on it, there's still a lot of gaps before it will be ready for commercialization by the private sector without any subsidy.

Mr. Gutstein: This being about 4 or 5 years worth of work, I think we need a few more than that to bring solar into commercial reality. I won't argue that.

Dr. Swartout: Returning to your request for suggestions for experiments, I think you're in a situation very similar to what we were in in the nuclear field about 20 years ago, after we had built several high-test experimental reactors. There is a group of people here who are very familiar with the facilities and know what's available, the type of radiation and so on, but now you're asking industry for suggestions for experiments and maybe industrial people don't know what's there. So, I'd like to suggest that if you don't have it, that you prepare a set of specifications on each facility--the type of radiation characteristics, the windows, space available, etc., so that people have some idea of what sort of an experiment could on on them.

Mr. Gutstein: I believe that information is available.

Mr. Smith: Yes. It's been summarized in the newsletter which was mailed to everyone here and there is a copy in your handouts for this meeting. Also, there are experimenters' manuals available for each of the facilities.

Mr. Gutstein: The Georgia Tech people handed out a brochure on how to fit experiments on their facility. In it I think you'll find the specs on what that facility can do. If anyone does not have that information, see Frank Smith, and will certainly make it available.

Dr. Gregg: I think it's appropriate to close with a semi-insane idea. My background of the laser field, says that actually the solar central receiver station is perhaps the most powerful optical source that's been created in the world today. It's well known that you can take sunlight and pump a laser with efficiencies approaching 10 percent. You're talking about a 5-MW focused solar system, which translates into a 50-MW laser, which is, without a doubt, the most powerful laser the world has ever seen, with a rather modest investment in crystals.

It is a rather fascinating system because the conversion of efficiencies aren't great. I don't know what you can do with fossil energy and fuels and chemicals, but you surely can make an awfully hot focus at the end of that laser. You can shoot down missiles.

Comment: Only in the daytime.

Dr. Gregg: But, technically, it would work.

Mr. Gutstein: I believe that we'll adjourn for today and thank you, gentlemen.

SECTION XI - METALS

ENERGY REQUIREMENTS AND POSSIBLE SOLAR USE IN METALS REDUCTION

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The objectives of this paper are to review United States energy requirements for smelting/reduction of the most important industrial metals; to consider thermodynamic, kinetic and other physical constraints on the invention of metal reducing processes; and very briefly outline some possibilities for use of solar heat for augmenting fossil fuels that are used as reducing agents and to provide heat for smelting/reduction processes. In this paper we will be concerned with primary metal reduction from ores rather than recycling of scrap.

The usual processing steps for metal production are shown in Table 1 along with the type of energy inputs normally required to produce metals by process routes that involve pyrometallurgical treatment. Beneficiation, or ore concentration, and finish operations on metal ingots require primarily mechanical work which is usually supplied by electricity and consequently the use of solar energy to augment these steps is reduced essentially to solar generation of electric power. Any nonferrous metals that exist primarily as sulfide ores may be roasted (oxidized) but this is an exothermic autogenous process that requires little external energy. Refining operations usually involve the removal of impurities from hot liquid metal with relatively little requirement for additional heat input. For example, steel making requires the oxidation of carbon, phosphorous and silicon, all of which occurs exothermically.

One of the major requirements for excess heat is in the smelting/reduction step and consequently we want to concentrate on these processes in determining possible application of solar heat in place of heat provided by fossil fuel either directly or indirectly. Annual consumption of primary or new metal for the major industrial metals in the United States is shown in Table 2 along with the fossil fuel equivalent energy required for smelting or reduction of these metals. Energy requirements for mining, beneficiation, finishing, etc., are not included in these totals which by any standard are very significant indeed. Energy primacy of iron making and aluminum reduction must be recognized. The major energy input in iron making is in the form of coal which is processed to coke and a summary of United States coal consumption is given in Table 3. It indicates that the steel industry alone consumes over 14 percent of the total coal produced in the United States. The energy requirement for aluminum smelting is almost entirely electrical energy used in the fused salt Hall-Heroult process.

Process heat requirements for a general case of smelting/reduction are summarized in Table 4. Sensible heat of the ore, fuel, fluxes and other reactants at the required operating temperatures must be provided. It should be recognized that the reduction of metal oxides are generally endothermic and that the chemical potential required to achieve reduction also requires that fossil fuel be incompletely burned in the process. Sources of the process heat for the smelting/reduction operations are summarized in Table 5.

It is important to emphasize the heterogenous and impure nature of ores and the constraints that result in devising a reduction process. Even after very thorough beneficiation or concentration of ores they will be composed of several minerals and the minerals themselves are not pure compounds. Of the most important industrial metals which are listed in Table 2, iron, aluminum, chromium, and manganese occur primarily as oxides or occasionally as silicates that can be reduced to metal. Copper, lead, zinc, and molybdenum occur almost exclusively as sulfides and nickel occurs both as sulfides and silicates. The ore concentrates are almost always contaminated with silica, which is the most abundant mineral in the earth, and generally they are also contaminated with alumino-silicate minerals. The nonferrous metals are usually contaminated with iron minerals. At the risk of oversimplification, metal oxide ore reduction processes can generally be divided into gas-solid reduction processes in which liquid phases are not formed, and smelting processes in which liquid phases are formed and separation of two or more immiscible phases occur as part of the smelting process. In Figure 1 I have attempted to indicate some of the major constraints in the design of gas-solid reduction processes which are limited by the fact that the processes are kinetically too slow at lower temperatures to be industrially efficient while at higher temperatures the accretion of glass forming silicates, a sticky quasi-slag, prevents the flow of solid materials through the process reactor. In other words, the upper temperature limit is one in which incipient slag formation must be avoided. These are usually the lower and upper limits on a gas-solid reduction process and they tend to also be the upper and lower limits on sulfide roasting processes. Conversely, the ability to have sufficient temperature to produce a fluid slag is mandatory for a smelting process and generally this marks the lower temperature limit on the process. Slags are usually silicate glasses and a slag fluidity is dependent on slag composition and temperature. At good slag-making temperatures almost all processes are kinetically fast. There is usually a gap of about 200°C between strictly gas-solid processes and smelting processes, which is indicated in Figure 1. Common smelting processes involving fossil fuels and air are limited to about 1500°C, and above that temperature it is more efficient to use either electric-arc or other electric furnace smelting, or to substantially augment air with oxygen. The upper limit on high-temperature smelting processes is usually governed by the inability of refractory materials to withstand the temperature combined with the necessity of minimizing chemical reaction between materials being smelted and refractory lining. It is interesting to note that earlier attempts to use solar heating in metallurgical processes conducted in various experiments shortly after World War II tended to concentrate on developing processes to work at very high temperatures using the very high-temperature capability of solar concentrators. At that time there was hope that systems could be developed that were not dependent on use of thermally insulating refractory materials to contain the metal reduction or smelting process. In general this approach has not been successful and in our judgment a better chance for success in use of solar heating is likely to be in the solar augmentation of fossil fuel processes conducted at lower temperatures that can reasonably follow the constraints imposed on either conventional smelting or gas-solid reduction processes.

Figure 2 attempts to indicate heating efficiency as a function of operating temperature for a fossil fuel (methane) and oxygen system compared with electric furnace heating. This figure illustrates the fact that the electric furnace is inefficient at low temperatures because of the loss associated with conversion of fossil fuel energy to electric power but at high temperatures the electric furnace provides very high conversion of electric energy to heat whereas the fuel air system requires most of the heat to be dumped into the heating of the fuel combustion products. In effect, when the process temperature operates at the adiabatic combustion temperature no energy is left for the process. Oxygen enrichment raises the adiabatic combustion temperature and permits a proportionately larger share of the energy to be used for heating the primary reactants. Consequently, high-temperature metallurgical reduction processes usually use either electric furnaces or substantial oxygen enrichment of fossil fuel combustion.

Before proceeding to some of the thermodynamic constraints on metal oxide reduction processes, I would like to briefly discuss the roasting of sulfide ores and matte smelting. Figure 3 shows the standard Gibbs free energy of formation of several oxides including SO_2 and illustrates the two common processes involving sulfides. Roasting is a process in which sufficient oxygen is provided usually simply as air and a sufficient temperature kinetically to convert the metal sulfide to metal oxide and SO_2. This is illustrated by the roasting of MoS_2 to MoO_3 which is then added directly to steel melts to make molybdenum containing steels. Excess air is used and the only constraint in this process is that it be limited to a fairly low temperature because of the high volatility of MoO_3 whose sublimation point is shown in Figure 3. A more interesting case is that of matte smelting which is very important for both copper and nickel sulfide ores which invariably contain large amounts of iron sulfide. At smelting temperatures it is possible to use a limited amount of oxygen sufficient to oxidize all of the sulfur to SO_2 and all of the iron to FeO, which enters the slag phase forming a $FeO \cdot SiO_2$ slag. With a limited amount of oxygen the oxygen potential is controlled at a level sufficient to oxidize sulfur and iron but insufficient to oxidize copper and nickel; hence, a single smelting step can convert sulfides directly to liquid copper and nickel metals without requiring complete oxidation of the copper and nickel with a subsequent metal reduction step. I see little potential for the use of solar heat for augmenting roasting or matte smelting processes.

Let us now turn to the reduction of metal oxides by the most common gaseous reductants: carbon monoxide and hydrogen. In Figure 4 and subsequent figures we will consider the thermodynamic constraints on metal reduction processes but in each figure we are showing temperature zones for gas-solid reduction, for common smelting and for electric furnace or oxygen enriched smelting. These temperature bands are the same ones shown previously in Figure 1. The physical constraints on these bands are very real. It is important to keep them in mind in considering thermodynamic constraints. Figure 4 shows that the oxides of copper, lead and nickel are easily reduced by carbon monoxide, and that copper and nickel could be reduced by gas-solid process leaving solid reduced metal. The black dots in this and subsequent figures indicate the metal melting point. Both copper and nickel also have sufficiently low melting points that they can be subjected to a reductive smelting process and this has been done but has fallen into disuse in modern times because of the efficiency of matte smelting. On the other hand, it would be difficult to kinetically devise a gas-solid reduction process for lead oxide because of the low melting point of lead. Currently the primary method for production of lead is reductive smelting of lead oxide which is produced from a prior total roasting of lead sulfide ores. Significant health and environmental problems in lead smelting are the significant volatility and toxicity of PbO whose sublimation point is shown as the open circle in Figure 4. Condensation of vaporized PbO and collection of the PbO particulate in efficient baghouses is mandatory. In the reduction of these metal oxides using carbon monoxide, the conversion of carbon monoxide to CO_2 can be nearly complete. Various percentage conversions in terms of the thermodynamic potential measured by the negative free energy of formation of carbon monoxide reacting to form carbon dioxide at standard conditions are shown as dashed lines in Figure 4.

The reduction of iron oxides by carbon monoxide is possible but more difficult in terms of the limiting thermodynamic conversion efficiency of CO to CO_2. Data comparing the reaction between CO and oxygen to produce CO_2 and negative free energy of formation of the iron oxides are shown in Figure 5. Inspection of Figure 5 shows that the CO conversion to CO_2 will be less than 50 percent efficient. In fact the reduction efficiency is better in the gas-solid band than it is at smelting temperatures, and both blast furnace iron-making technology and more modern direct iron-making technology involve gaseous reduction of solid iron oxide to metallic iron at oxygen potentials indicated in Figure 5. Again the dashed line shows the thermodynamic potential for conversion of CO to CO_2 at the efficiencies shown.

Figure 6 shows the pertinent thermodynamic potentials for hydrogen reduction of iron oxide wherein the dashed lines indicate the thermodynamic potentials for formation of water from hydrogen and oxygen at various conversion efficiencies. The results with hydrogen reduction of iron oxide are very similar to those for CO reduction and the efficiency of conversion of hydrogen is less than 50 percent to effect reduction.

Figure 7 is a schematic drawing of a blast furnace which is used for reduction of lead and more importantly liquid iron. The blast furnace essentially is a two-compartment furnace consisting of a shaft furnace in which ore solids move down counterflow to the reducing gases containing CO and H_2. Reduction of iron oxide is nearly complete in the shaft portion of the furnace before any melting occurs. In the lower or hearth portion of the furnace the solids are melted forming liquid iron and a silicate slag, which are separated by gravity. Limestone is added to the charge to provide flux for the slag which is essentially a calcium silicate glass. Carbon is present in the solid charge and is oxidized to CO by hot air just above the hearth.

Figure 8 shows the thermodynamic potentials for iron oxides coupled with the thermodynamic potentials for both oxidation of CO to CO_2 and oxidation of carbon to CO. At high temperatures the oxygen potentials at iron-gas and coke-gas interfaces define the upper and lower limits respectively. In the low-temperature shaft part of the furnace the reaction is constrained at the lower oxygen potential by the CO oxidation process. This is shown by the experimental loci for iron blast furnaces. The data actually observed in iron blast furnaces are in very good agreement, as shown in Figure 8, with limits predicted from thermodynamic considerations. Let us now turn to the industrially ferroalloy metals where the thermodynamic constraints are shown in Figure 9. Molybdenum is easily reduced from its oxide but chromium, maganese and vanadium require carbon reduction rather than CO reduction and high smelting temperatures. At the present time the production of ferro-chrome and ferro-manganese invariably involve electric-arc furnaces. There may be considerable potential for a solar concentrator heat augmentation for these processes as a substitute for electric furnace smelting.

The carbothermic reduction of zinc oxide is an interesting case as shown in Figure 10. Zinc has a low melting point and a low boiling point as shown by the closed circle and open circle respectively in Figure 10. High smelting temperatures are required for reasonable efficiency in the use of CO reduction and hence carbon reduction is employed. At smelting temperatures the reduced zinc is a vapor which must subsequently be collected outside the reduction furnace. Pure zinc oxide is made by burning the zinc metal vapor downstream from the reduction furnaces.

Aluminum oxide is such a chemically stable oxide that it cannot be readily reduced at reasonable temperatures by carbothermic reaction. The relevant thermochemical data are shown in Figure 11. This problem is surmounted industrially by finding an alternative electrochemical cycle. Molten fluoride salt, Na_3AlF_6, partially dissolves Al_2O_3 and provides the electrolyte for reduction of alumina. Because of the high electrical energy cost involved in the production of aluminum (an aluminum can really is stored energy), alternative thermochemical cycles usually involving chloride vapor metallurgy and/or electroreduction of fused aluminum chloride salts are under intensive investigation by the aluminum producers.

Solar heat provided through solar concentrators cannot completely replace fossil fuels in reducing metal oxides since part of the fossil fuel is used as a chemical reducing agent, but much larger amounts of fossil fuels are currently required to provide heat and thus it would appear that solar heat via solar concentrators could augment fossil fuels. Consequently, the major impact of solar energy on reduction processes is likely to be through a hybrid system rather than an all-solar energy system. Most previous attempts in using solar concentrators for metal reduction processes have involved a direct coupling of solar energy into the reduction system. However, this is not imperative and it may be technologically easier to decouple the metal reduction step from the solar energy input step, i.e., to involve two separate but connected reactors. Note that each reactor can be optimally designed for its purpose, that is metal reduction in one case and solar energy input in the other case. However, the two systems must be designed to be completely compatible with each other. In our judgment the most probable area for this kind of solar metal reduction synergism is likely to occur in those systems where metal oxide reduction can occur by CO or hydrogen. This reduces the primitive solar heat problem to one of providing solar heat for an endothermic carbon or other fossil fuel gasification step which would provide hot CO and hydrogen for the reduction process. In this context it is interesting to look at the enthalpy requirements for various chemical steps involving the gaseous reduction of iron oxides beginning with Fe_2O_3 and proceeding stepwise to Fe. Reaction enthalpies for a series of reactions and the net reactions are shown in Table 6. Three iron oxide reduction steps have a net small exothermic reaction enthalpy but the gasification of carbon to CO is extremely endothermic. Coupling a coke gasifier with an iron ore shaft reduction furnace is shown schematically in Figure 12. The gasifier needs heat (solar) because it is not efficient in operating as a partial gasifier with sufficient additional oxygen to provide the heat as would be the case in a gasifier used for producing either intermediate or low Btu gas for energy production. There are already several direct reduction processes in which iron ore or iron ore pellets are reduced to "metallized" pellets in a gas-solid reduction step. The metallized pellets are subsequently melted in electric furnaces to produce steel. An example of a specific direct reduction process is shown in Figure 13. The Bethlehem process uses natural gas which is steam reformed to produce CO and hydrogen for reduction of iron oxide pellets. The effluent gas is cooled to partially remove water and recycled through the pebble bed for reforming. Since the reforming reaction is highly endothermic heat must be provided to the pebbles and this is accomplished by having two pebble beds in parallel. They operate on alternate short cycles of gas reforming and preheating of the pebble bed by simple combustion of gas or other fuel. The ceramic pebbles in the pebble bed are a heat exchange media for transferring heat to the endothermic gasification step. Solar heating of a pebble bed or solar heating of a coke or charcoal bed are obvious possibilities of solar augmentation-metal reduction.

Solar concentrators have in the long run great potential for saving fossil fuels not by replacing them in metal reduction processes but by substantially augmenting the use of fossil fuel. The solar concentrator energy can be coupled directly with the reduction step, or perhaps more optimally indirectly via a gasifier step, or use of solar energy to heat a heat exchange media. Even with indirect solar concentrator energy for metal reduction steps, it is important that an overall system be designed that is mutually compatible and optimum. Gasification steps optimum for supporting metal reduction processes are likely to be substantially different chemical engineering processes than those that are otpimum for producing low or intermediate Btu gas for other energy conversion applications.

Question: What company uses the pebble beds?

Dr. Bartlett: ARMCO has a plant that runs that way. They are fired alumina pebbles.

Question: Which industry of primary metals is growing most rapidly in the US?

Dr. Bartlett: Aluminum is probably still the most rapidly growing. I think it's 7 percent a year. The economics experts, along with us, predict it is going to drop to about 3 or 4 percent over the next couple of decades. Copper is growing at maybe 3 percent.

Question: How about titanium?

Dr. Bartlett: Titanium has a negative growth in this country in the sense that we don't even make any titanium any more. We buy it from Japan and Russia. It is considered a strategic metal and we buy it from Russia.

Comment: I think the situation is the same in iron and steel. The use has gone up 2 percent and it's all foreign, or has been.

Dr. Bartlett: Agreed.

Question: You said, when you showed the energy consumption for the ore category, that the primary candidates were maybe aluminum and iron. Would you comment on what the prognosis is?

Dr. Bartlett: That's almost an impossible question to answer in any other way than being highly speculative. Let me state my own gut feeling about it. I think from the point of view of growth, you can say that there is not much hope in any of these. On the other hand, they are extremely large industries. Plants become obsolete and many of them shut down--as you all saw on TV during the coverage of Youngstown. When I said targets, I was speaking primarily from one, the size, and two, the nature of the chemistry. For example, it just doesn't fit the chemistry of copper.

There was quite a bit of work done in this country and probably elsewhere by metallurgists trying to use solar heat after World War II, and the approach at that time was to say, "Gee, this fantastically high temperature--all we've got to do is develop a system where we can do these high-temperature processes directly by focusing solar heat on the processes." They got in all kinds of trouble with refractories and windows and all the other problems that were discussed yesterday. My own guess is that this is not the way to go in using solar heat for metal reduction. The way to go is to probably not work at extremely high temperatures in the process itself, but to work with the gasifier. I guess I support the work that the Livermore people are doing--their contention that we ought to look at the use of solar and the gasifier coupled with iron ore reduction, where the iron ore reduction unit sits right alongside a tower and it provides heat to the gasifier. Even the gasifier may be decoupled. That is why I showed the pebble bed. It's a clean system that way. It's not coke and all the messy tars. With the pebble bed the heat is transferred to a methane reformer or some other kind of gasifier. I think it's probably a hybrid system. We are still going to have to use fossil fuel reductants, and the reductant has got to be there. But there is a lot of excess heat that goes into these systems and that could be augmented by solar if it's cheap enough; whether it will be cheap enough, I have no idea.

MAJOR ENERGY INPUTS IN PRIMARY METAL PRODUCTION

Steps	Temperature	Energy Input
Mining	Cold	Mechanical (Work)
Beneficiation	Cold	Mechanical (Work)
Roasting Sulfides	Hot	Exothermic (Autogenous)
**Smelting/Reduction	Hotter	● Process Heat (Major)
Refining	Hot	● Reagents (Minor)
Finishing (Shapes)	Hot and Cold	Mechanical (Work); Some Reheat

Table 1

U.S. METAL CONSUMPTION (1976) AND SMELTING FFE ENERGY EQUIVALENTS

Metal	Consumption (1000 Tons)	Btu/Ton	Btu Total
Pig Iron	90,000	12.4×10^6	1116 Quad $\times 10^{-3}$
Aluminum, Primary	4,200	187×10^6	785
Copper, Primary	1,600	35×10^6	56
Lead, Primary	610	20×10^6	12
Zinc	480	40×10^6	19
Chromium (Ferroalloy)	410	57×10^6	23
Manganese (Ferroalloy)	1,300	40×10^6	52
Nickel	162	40×10^6	7
Molybdenum	57		

Table 2

USA COAL CONSUMPTION 1976

Electric Utilities	442,000,000	(74%)
**Cokeplants (Steel)	85,000,000	(14.2%)**
All Other Manufacture	64,000,000	
Retail	6,000,000	
Total	597,000,000	(100%)

Table 3

HEAT REQUIREMENTS IN SMELTING/REDUCTION

- Sensible Heat of Ore, Fuel, Air/O_2, Fluxes at Operating Temperature
- Incomplete Oxidation of Fuel Because of Low Oxygen Potential — Lowers Heat Released
- Reduction of Metal Oxide is Endothermic

Table 4

SOURCES OF HEAT FOR SMELTING/REDUCTION

(1) Combustion of Reducing Agent

(2) Combustion of Additional Fuel (Air/O_2)

(3) Electricity (Hydro, Fossil Fuel, Nuclear, Solar)

(4) Solar Concentrator

Table 5

GENERAL PYROMETALLURGY PROCESS CONSTRAINTS: FUEL EFFICIENCY AND SILICATE SLAG VISCOSITY

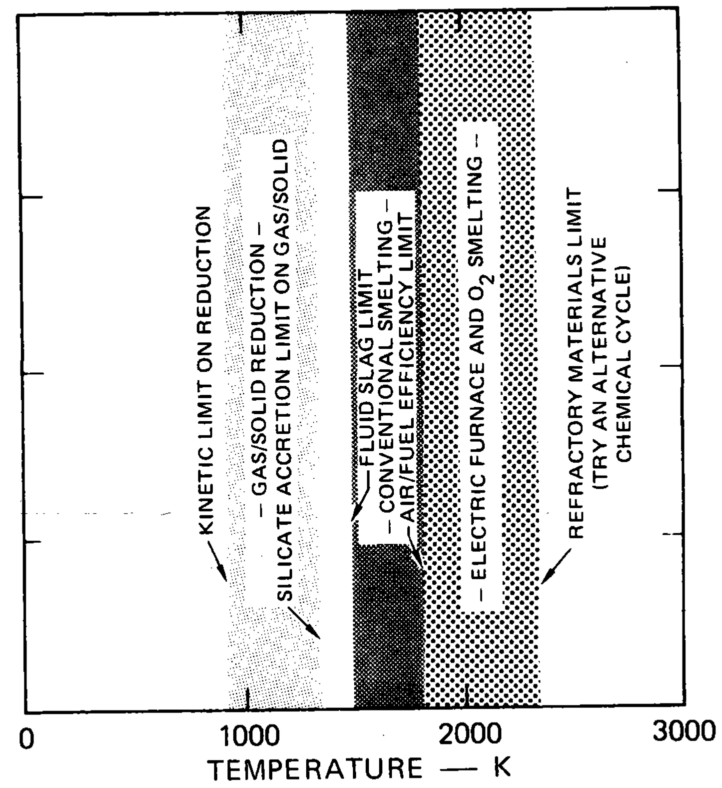

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Figure 1

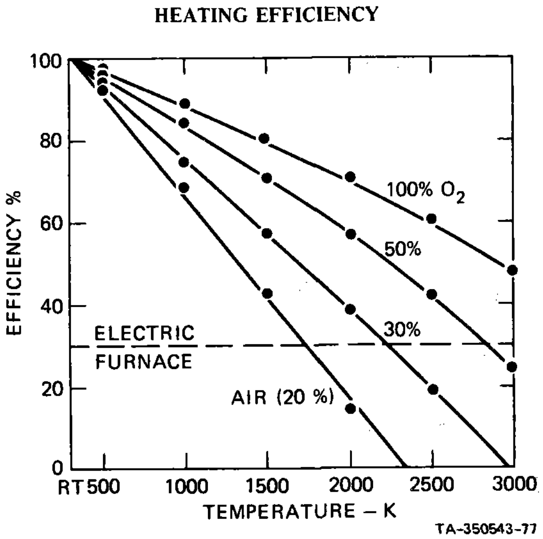

Figure 2

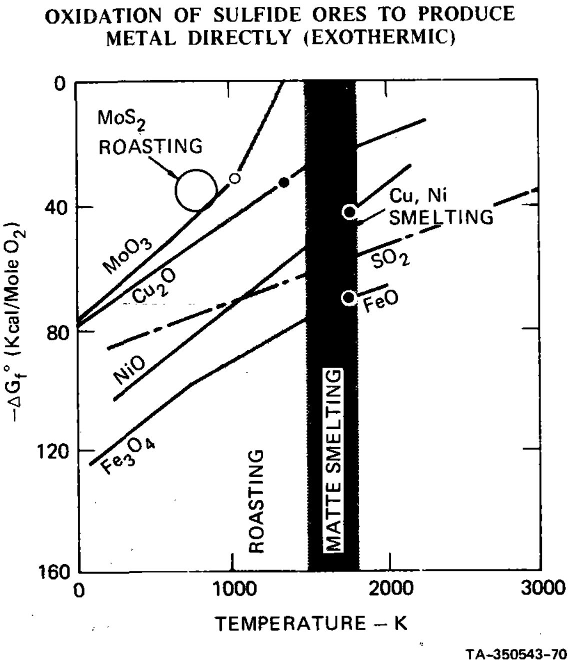

Figure 3

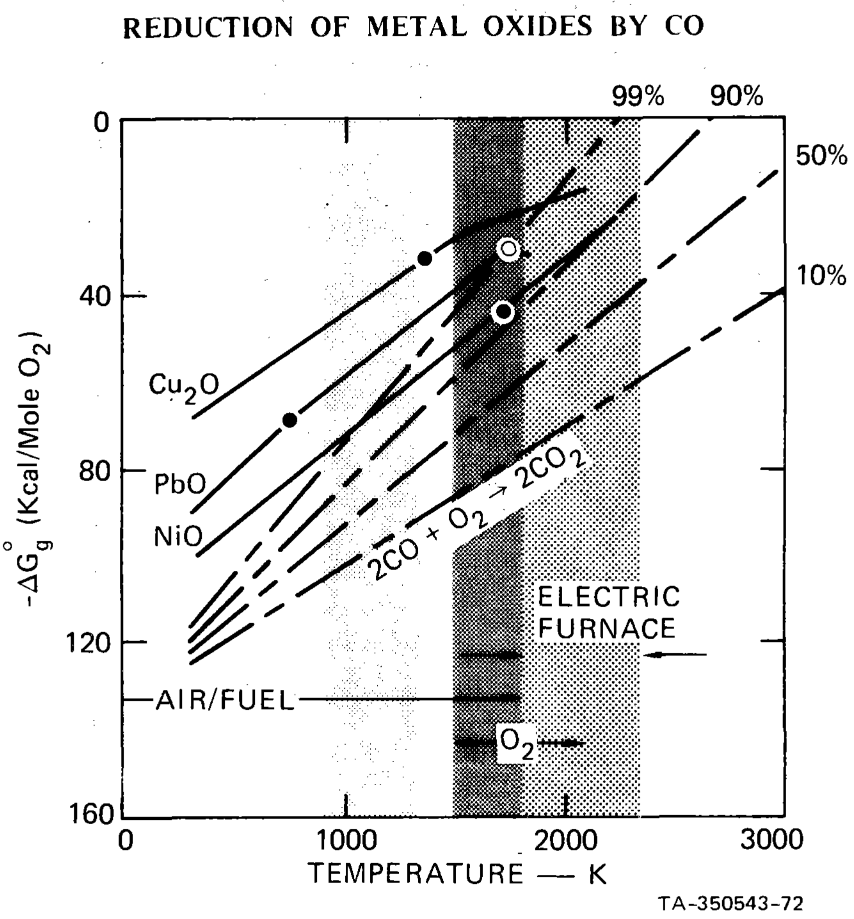

Figure 4

REDUCTION OF IRON OXIDES BY CO (<50% EFFICIENT)

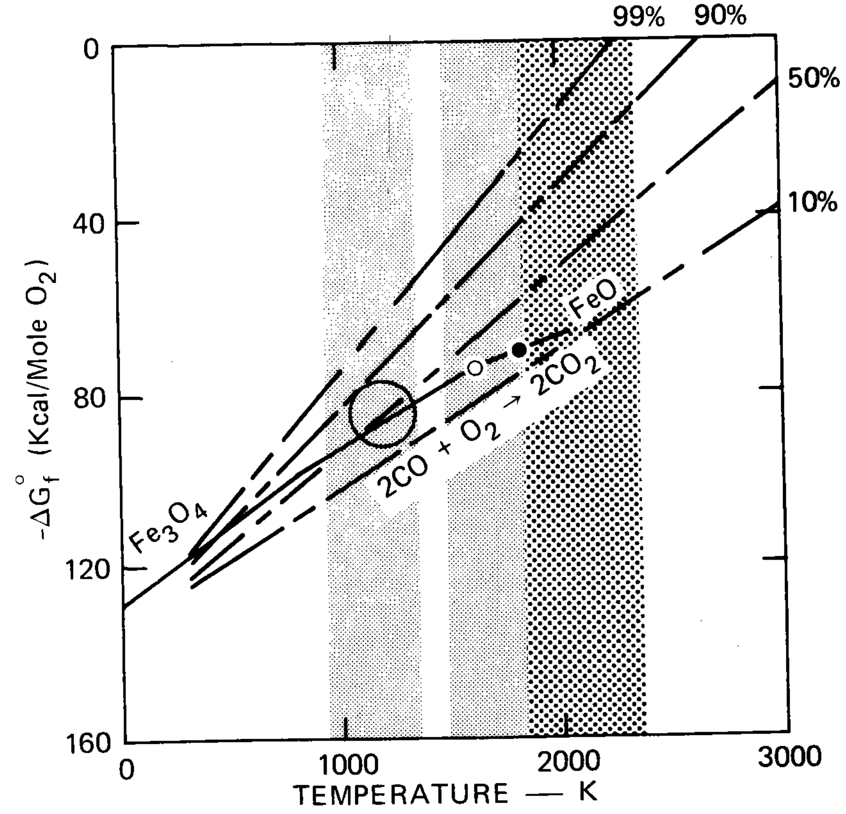

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Figure 5

REDUCTION OF IRON OXIDES BY H_2 (<50% EFFICIENT)

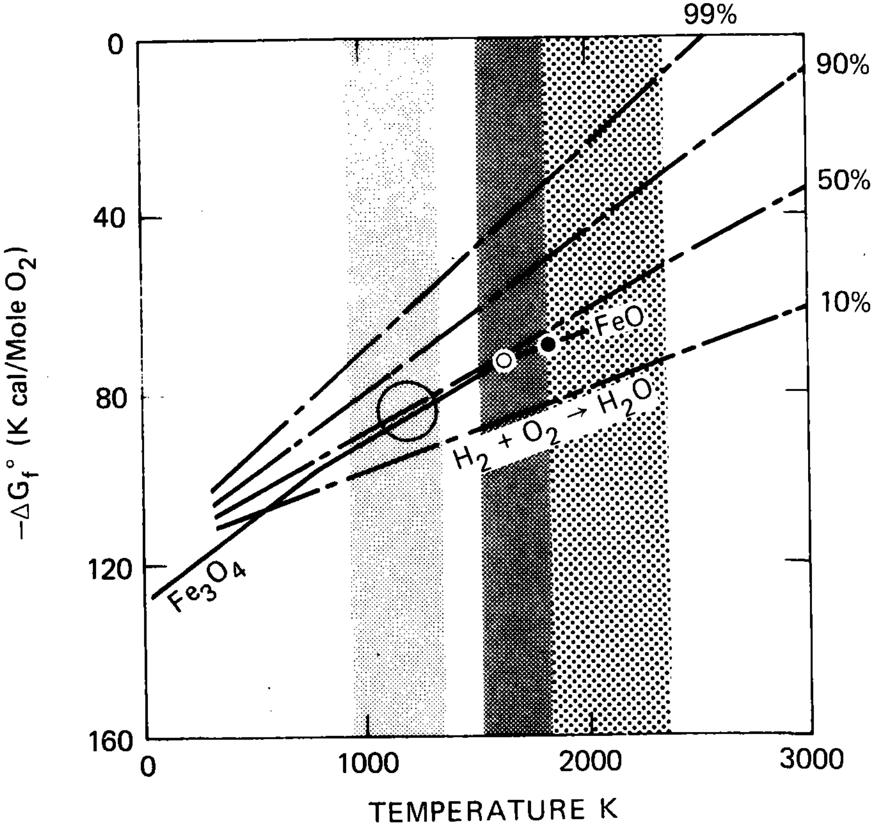

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Figure 6

BLAST FURNACE

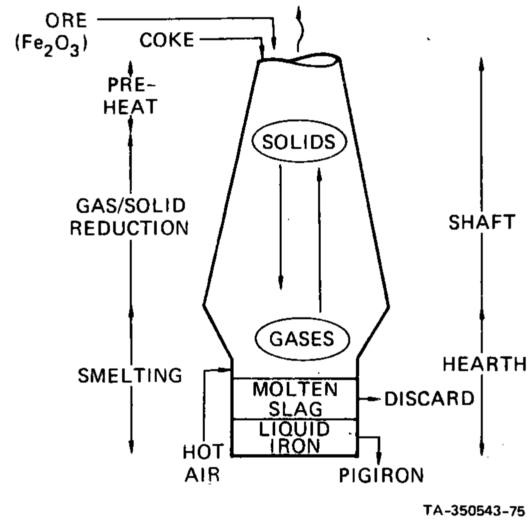

Figure 7

COMBINED GAS (CO) AND CARBON REDUCTION OF IRON OXIDES (BLAST FURNACE PROCESS)

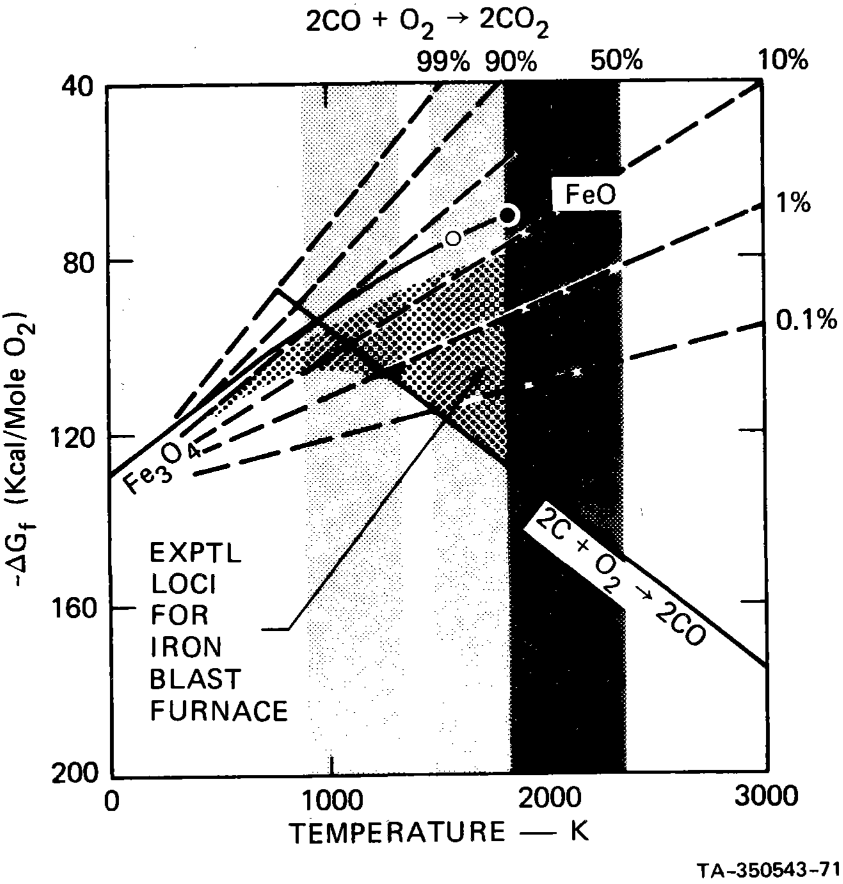

Figure 8

CARBON REDUCTION OF FERROALLOY METALS (USUALLY IN ELECTRIC FURNACES)

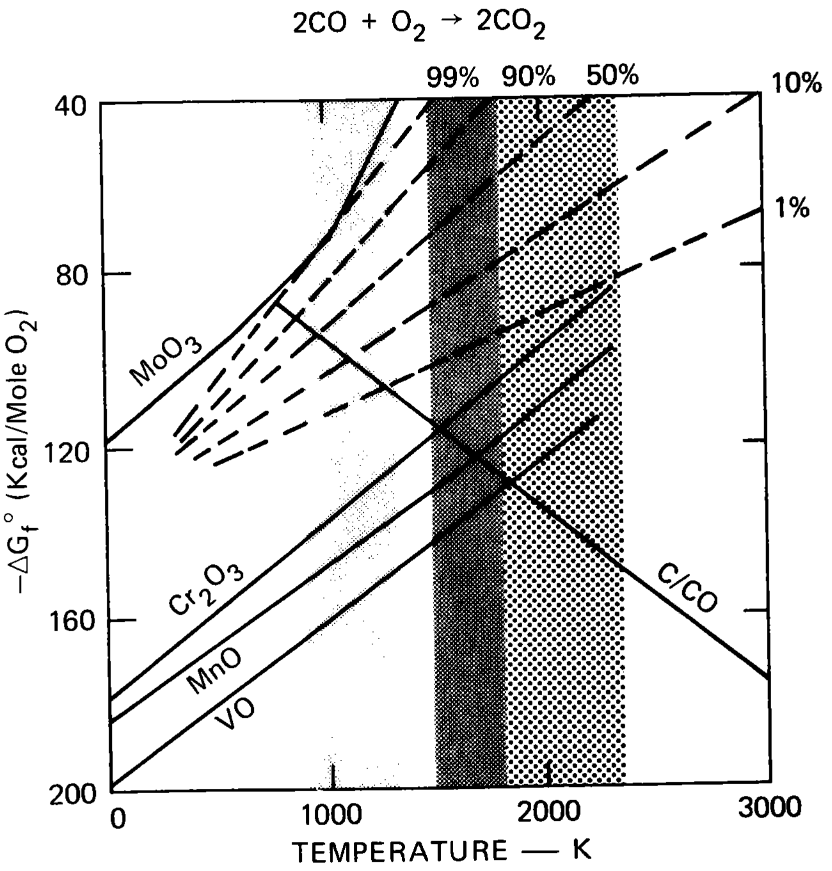

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Figure 9

REDUCTION OF ZINC OXIDE TO PRODUCE ZINC VAPOR

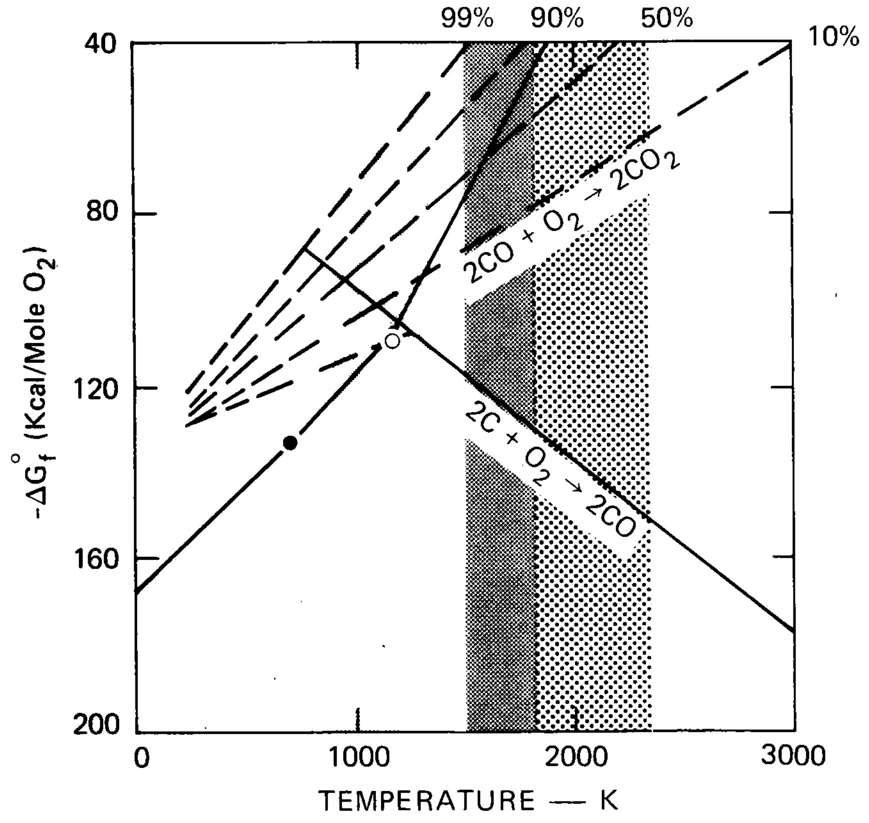

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Figure 10

DIFFICUTLY OF DIRECT ALUMINUM REDUCTION

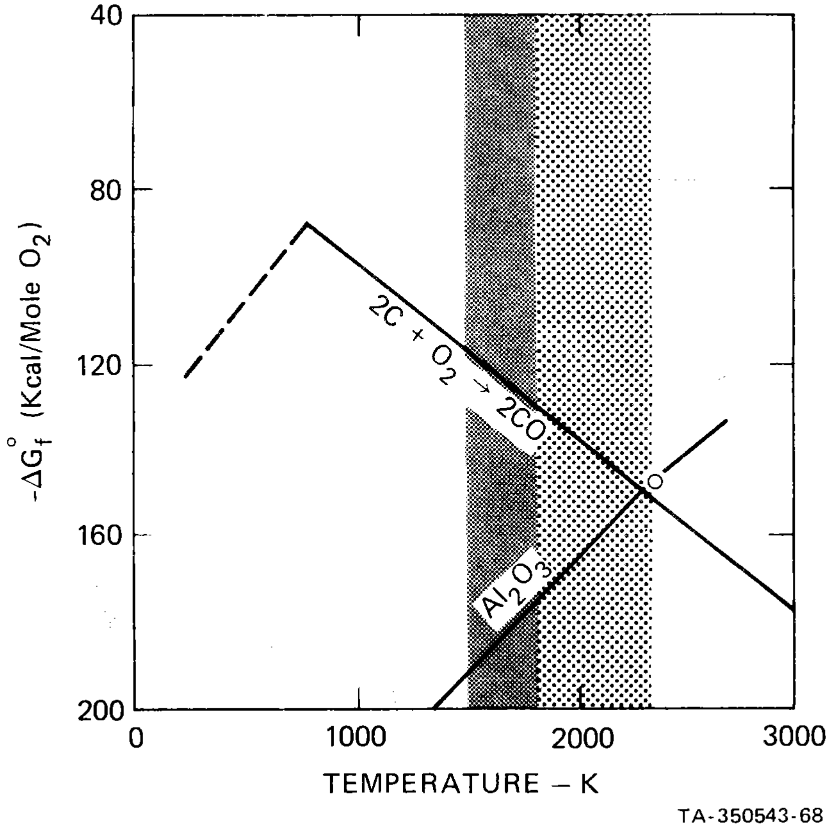


Figure 11

REACTION ENTHALPY IN REDUCTION OF IRON ORE CO, CO_2

Reaction	ΔH_r° (kJ/Mole·Fe)
$3/4\ C + 3/4\ CO_2 = 3/2\ CO$	130
$1/6\ CO + 1/2\ Fe_2O_3 = 1/6\ CO_2 + 1/3\ Fe_3O_4$	-8.5
$1/3\ Fe_3O_4 + 1/3\ CO = 1/3\ CO_2 + FeO$	11
$FeO + CO = CO_2 + Fe$	-17
$1/2\ Fe_2O_3 + 3/4\ C = 3/4\ CO_2 + Fe$	115.5

Table 6

GASIFIER AND IRON ORE REDUCTION

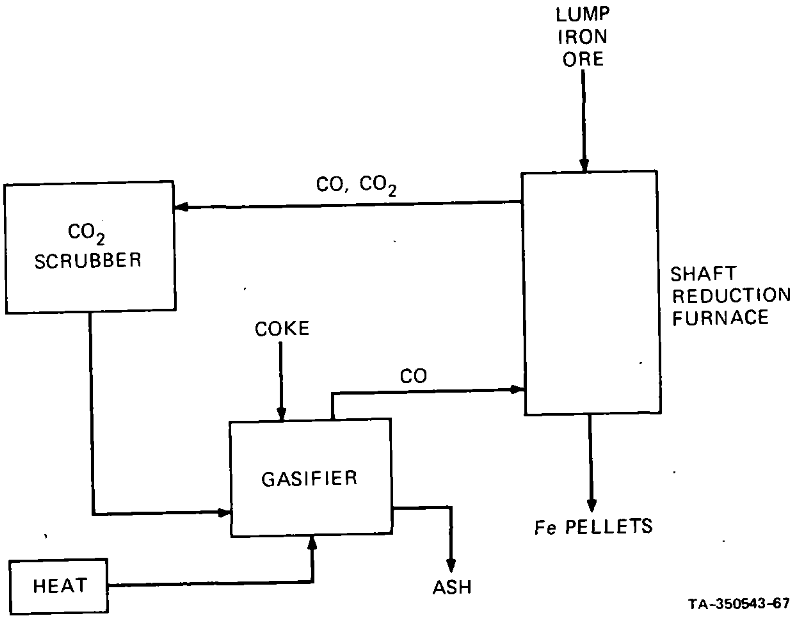


Figure 12

BETHLEHEM STEEL DIRECT REDUCTION PROCESS

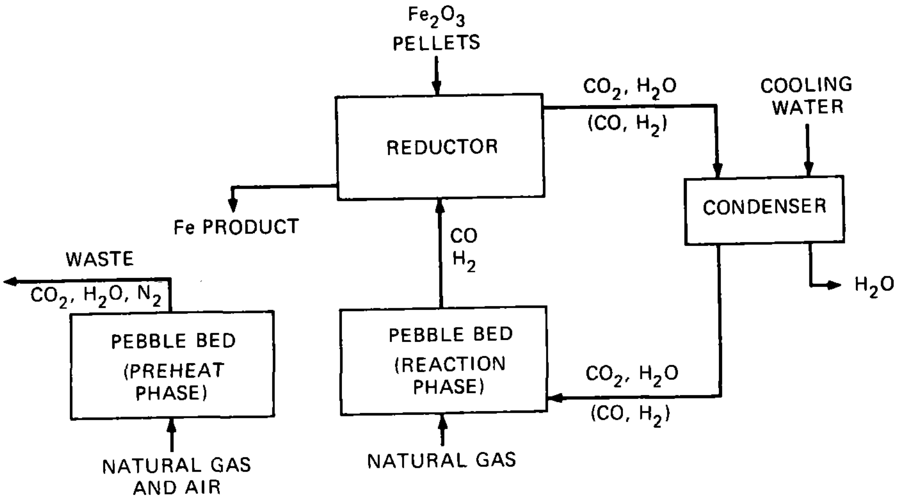


Figure 13

TREATMENT OF MOLYBDENITE ORE USING A 2-KW SOLAR FURNACE

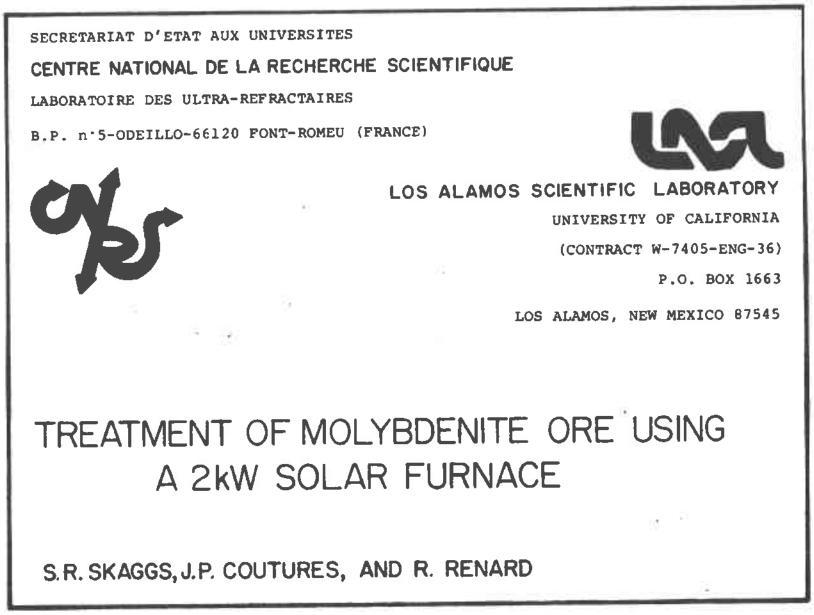
S. R. Skaggs
Los Alamos Scientific Laboratory

My talk will be in two parts. The first part is a description of the Odeillo facility where I have spent the last two months. We have with us today a member of the CNRS, Mr. Vialaron, who is associated with the Odeillo Solar Furnace, and I would like to say to this audience that the French treated me with the utmost hospitality while I was at Odeillo. I think that any of you who are able to make arrangements to go there to work will find the same conditions. The second part of my talk will describe the experiment that we did in the past two months and the results from it. The two gentlemen listed on the first slide (Fig. 1) as coauthors are at the Odeillo Solar Furnace and helped a great deal with the experiment. Several other people from France, and a goodly number of the staff of LASL were instrumental in the success of this experiment.

There are two laboratories at Odeillo--the CNRS Laboratoire des Ultra-Refractaires (High Refractories) and the CNRS Laboratoire d' Energetique Solaire. The total complement of people there in both laboratories is of the order of 100, and there are about 30 administrative and support people common to both labs. They have close ties with most of the technical universities in France and with the quasi-public organizations like the Iron and Steel Institute so there are always many young people from these places visiting the laboratories for various lengths of time.

The physical layout of the laboratory is probably of interest to most of you in the audience. Figure 2 is a view from the hillside looking southeast over the laboratory. The sun shines in from the south onto this hillside where there are 63 heliostats (Fig. 3). Each is controlled separately by a photocell-servo system which will be visible in a later slide. The sunlight is reflected into the large parabolic mirror on the side of the 9-story building (Fig. 4), and is then focused into the receiver station (Fig. 5). There is a pair of doors (Fig. 6) on the front of the tower which act as shutters to control the on/off characteristics of the sun onto the work (Fig. 7). This is the 1-MW facility.

On the back of the building (south side), located on the sixth floor overhang (Fig. 8), are several small vertical-axis searchlight mirrors. Several of the mirrors are operated off of one heliostat. The heliostat for the vertical-axis furnaces is located on the balcony above the second story (Fig. 9). It is not visible in any of the overall views; however, Figure 10 is a view of the details of these heliostats as seen from on the balcony. The next view (Fig. 11), looks up into the bays where the mirrors are located. Trap doors control the incoming light. Sometimes while working at this level equipment falls out of the bay and breaks a mirror, as you can see by the missing ones in Figure 9. The control panel (Fig. 12) is a rather simple system consisting of photocells which are in a square pattern so that the reflection of the sun's image into one of them causes the servo system to drive the mirror away from it and into the sun again.



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TREATMENT OF MOLYBDENITE ORE USING
A 2kW SOLAR FURNACE

S.R. SKAGGS, J.P. COUTURES, AND R. RENARD

Figure 1

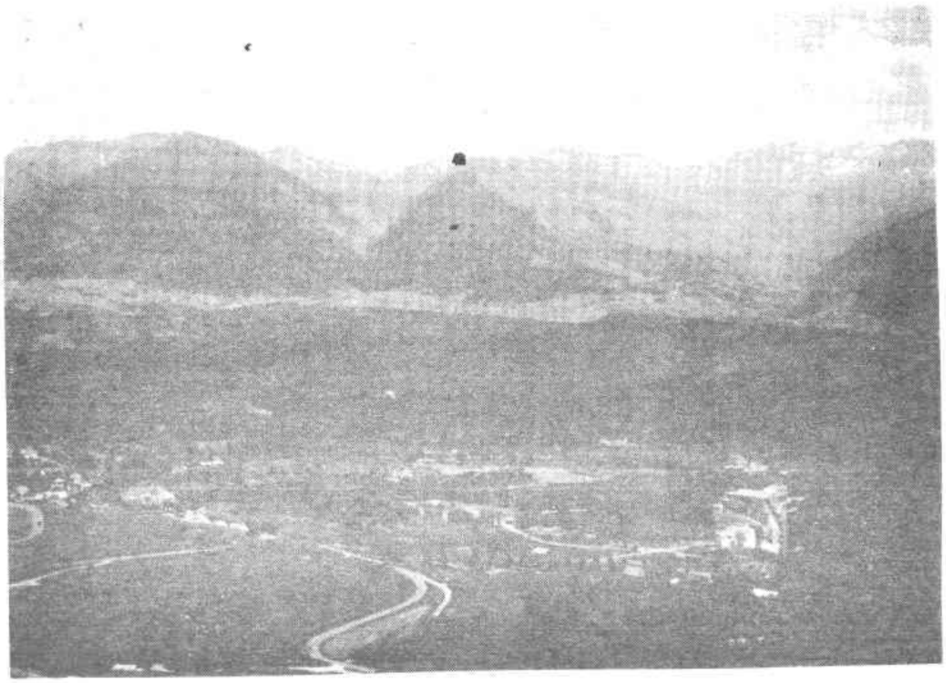


Figure 2

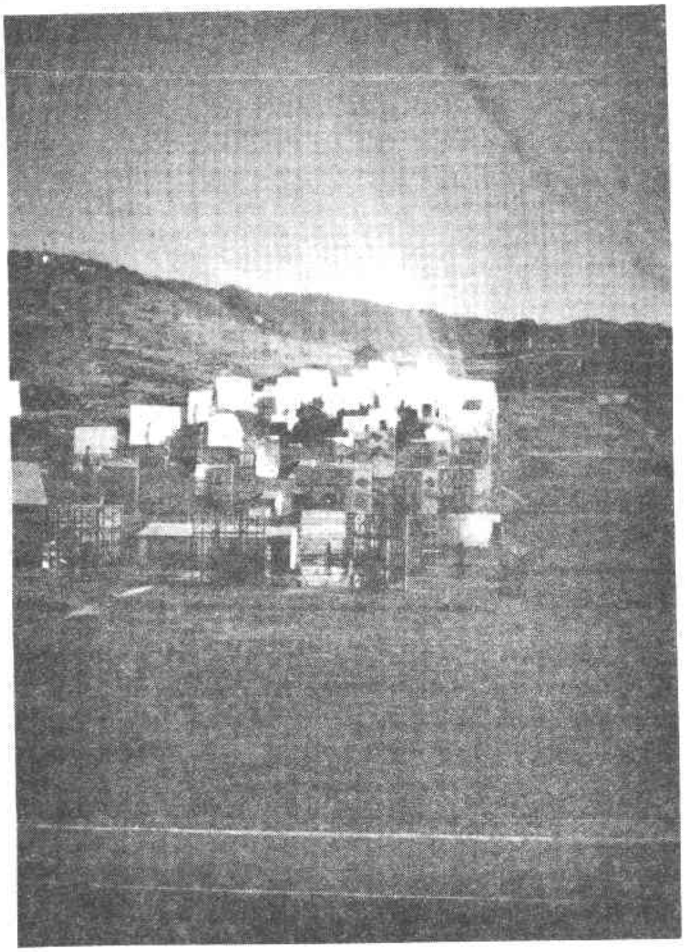


Figure 3

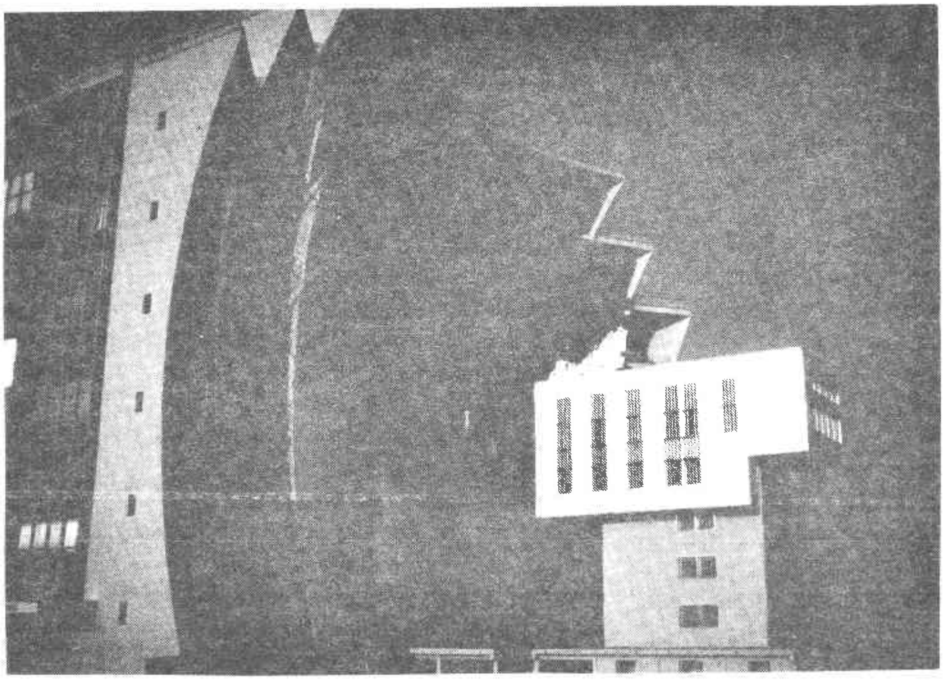


Figure 4

Figure 5

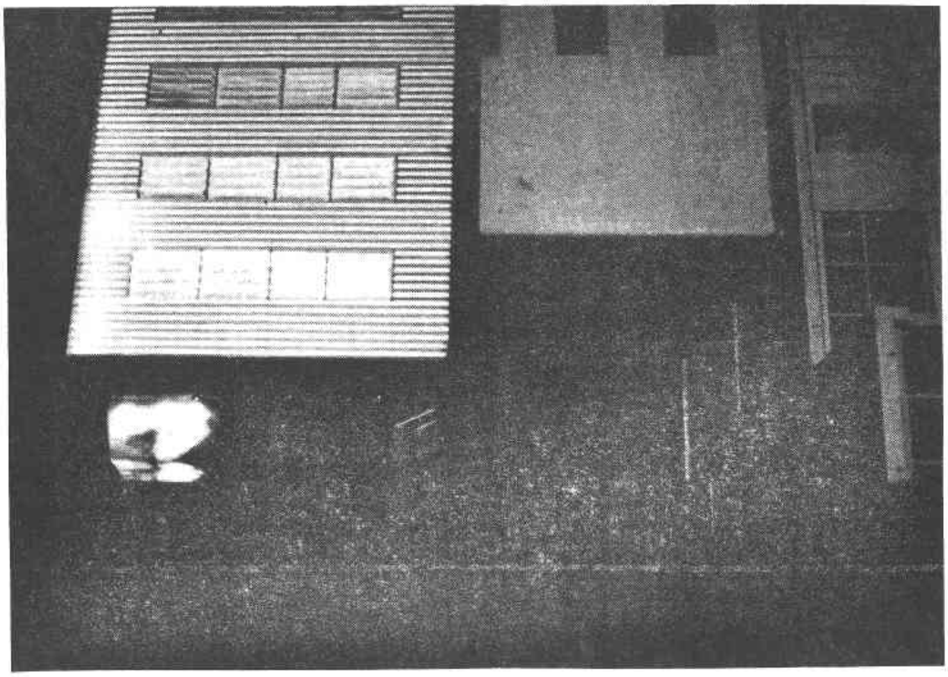


Figure 6

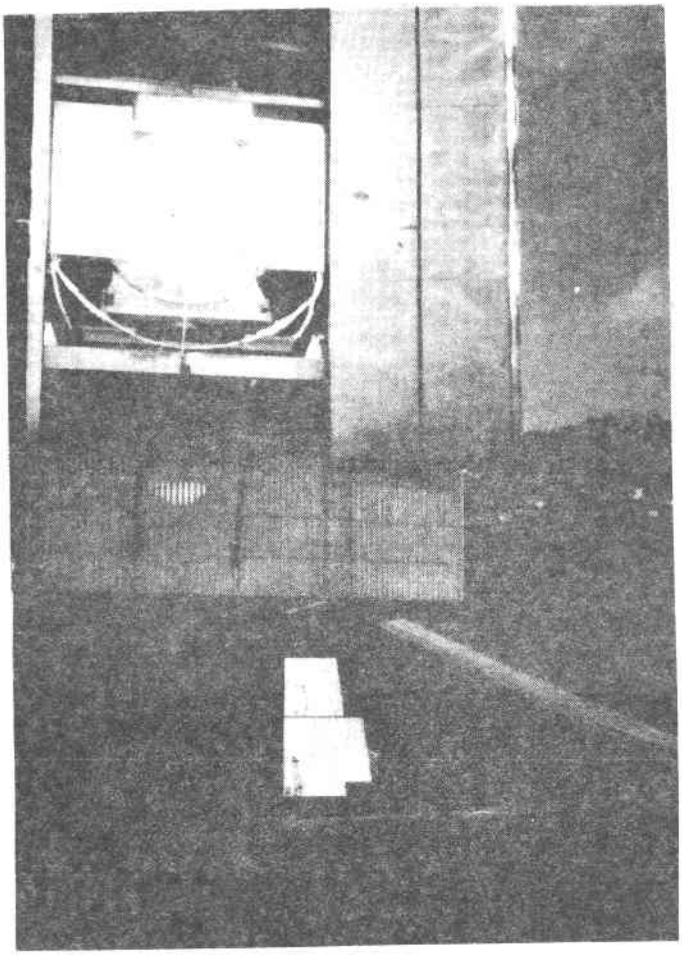
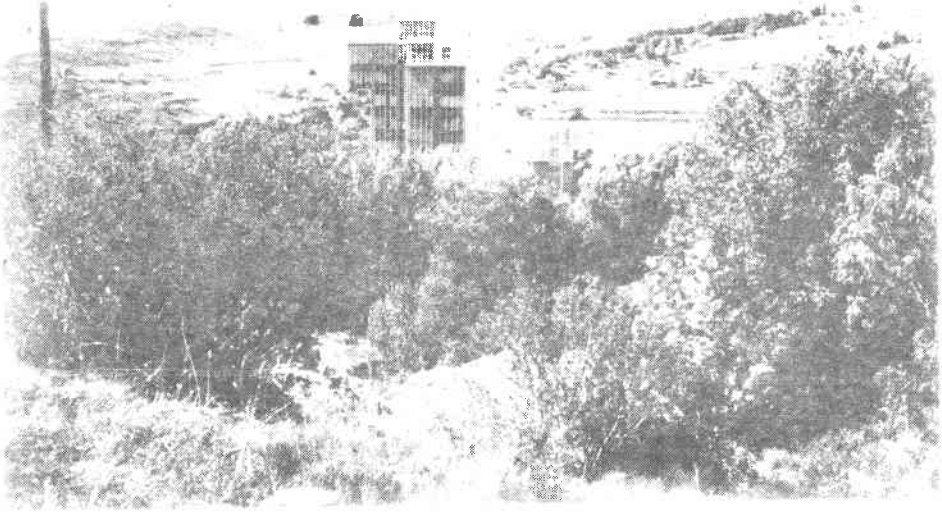


Figure 7



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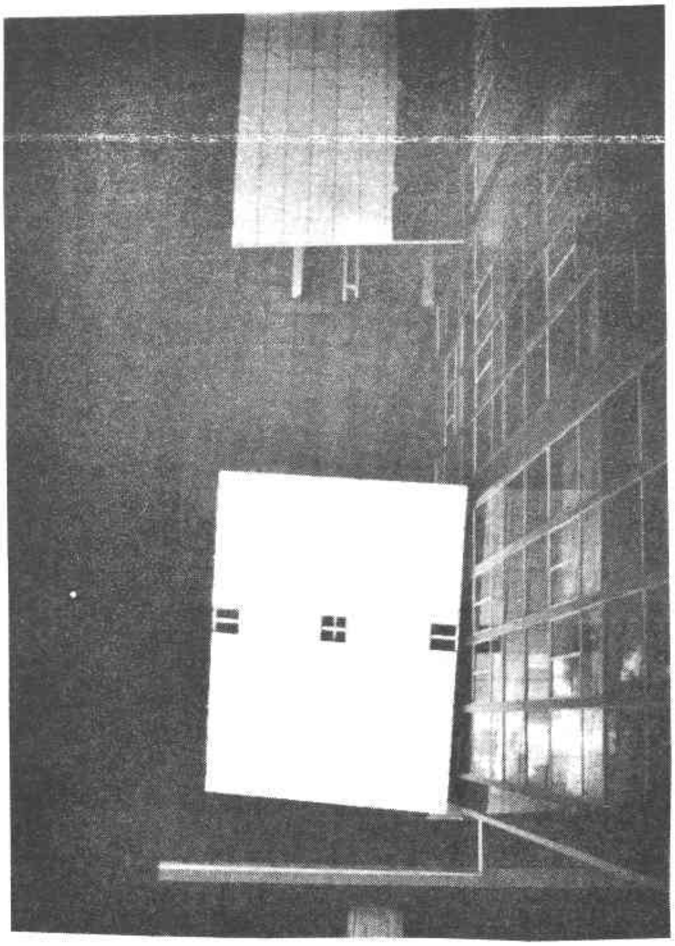

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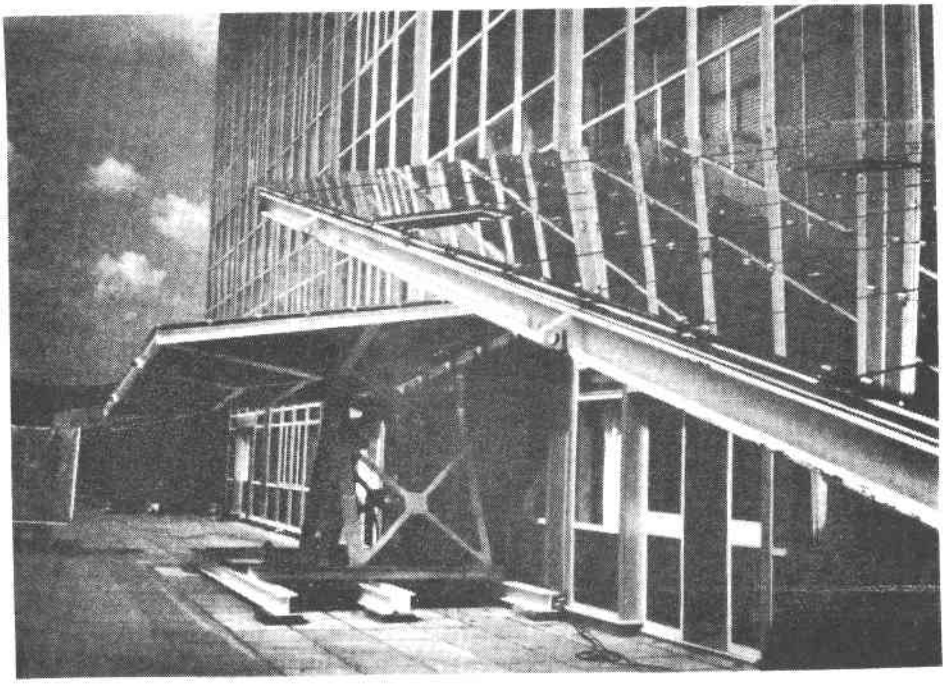


Figure 10

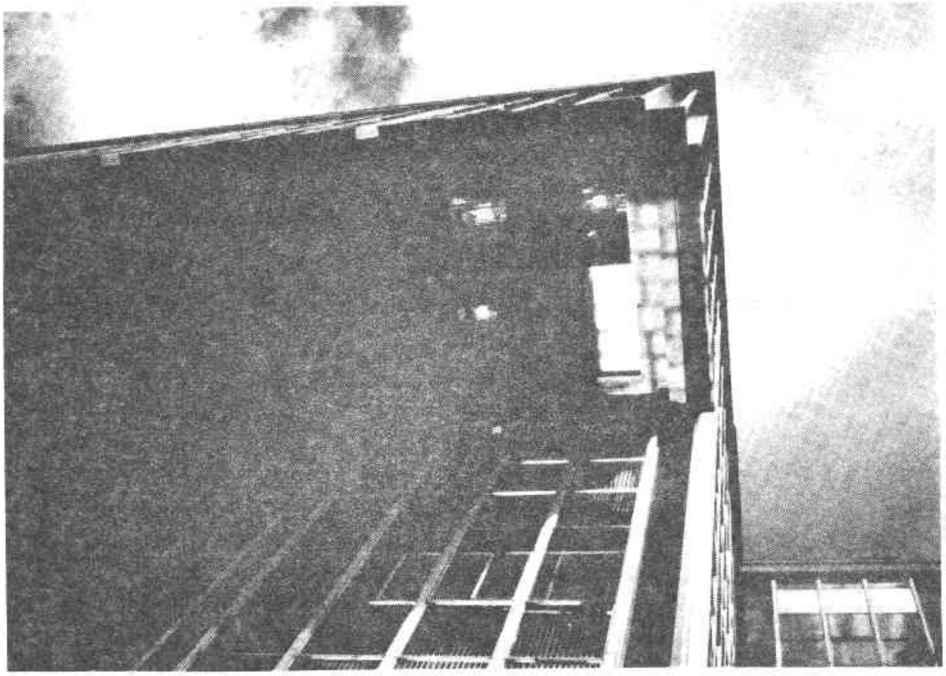


Figure 11

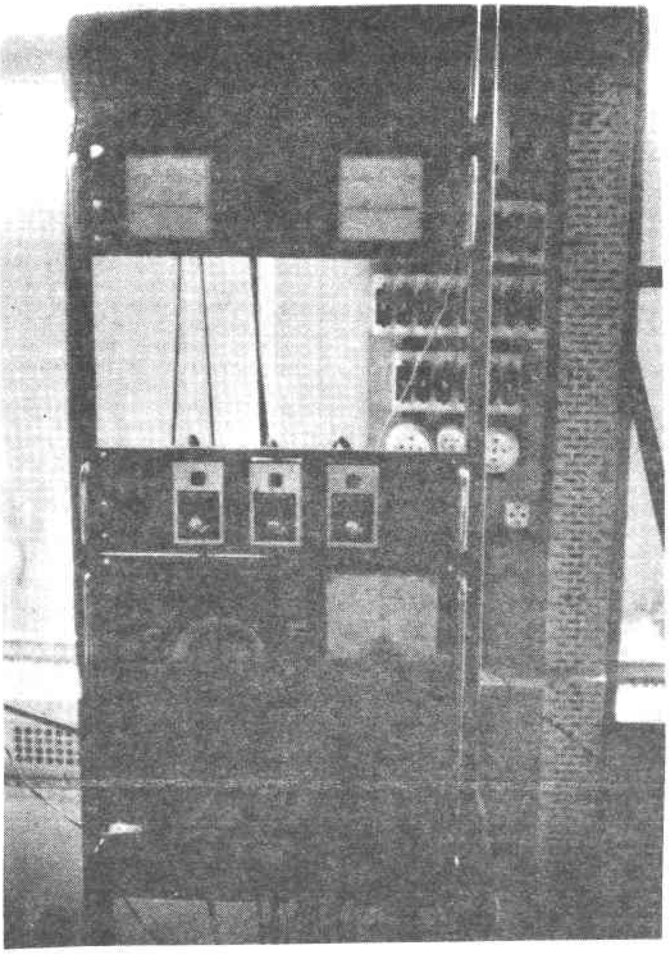


Figure 12

In addition to the vertical-axis furnaces which we will look at more closely in the second part of this talk, there are two mirrors with horizontal axes. These are located in a small building behind the main laboratory (Fig. 13), and are supplied with solar energy from one heliostat. The work zone (Fig. 14) is rotated by a variable-speed DC motor so the molten material will not run out of the hot zone. These furnaces are used mainly to study the melting points, cooling curves, and mass evolution from molten materials.

There are other furnaces in the laboratory that are used for splat cooling experiments (Fig. 15) to try to make glass-like compounds of metals. There are also furnaces that are used for just plain foundry work (Fig. 16).

Most of the small furnaces belong to the Laboratory for High Refractories. There is one large searchlight mirror of about 8 kW which belongs to the Laboratory for Solar Energy as does the large 1-MW facility. Because the groups are small and everyone knows everyone else, the facilities, for all practical purposes, are used freely among the individuals at the laboratories. The large system does require some planning ahead since it is the only one of its kind.

Just a brief note about the maintenance of the mirrors. All of the small plates that you see in the heliostats and the parabolic mirror (Fig. 17)are 0.5 x 0.5 meter square rear surface silvered mirrors with a protective coating on the rear to prevent deterioration of the silver. Over the 10-12 years of operation the reflecting surface had deteriorated quite badly on some of the mirrors because they are exposed directly to the elements year round. This summer all of the mirrors in the heliostats were changed. This is a rather monumental task when you realize that there are 180 mirrors in each heliostat and each one has to be separately aligned. The mirrors in the parabola are partially protected by the overhang of the building.

The only other problem is that occasionally the small flat-plate mirrors get broken by birds running into them or someone dropping a wrench or a piece of laboratory apparatus on them.

The second part of my talk will describe the treatment of molybdenite Mo_2 ore which we have done over the past three summers using the small furnaces. This project started in the summer of 1976 during a visit to Odeillo (Fig. 18). At that time we only discussed the treatment of molybdenite ore based on the attempts by two Brazilians, Goldfarb and Beserra, to treat it with a solar furnace (Fig. 19). In the summer of 1977, after the conference at Odeillo, Coutures and I began to treat 10-g quantities in a 2-kW furnace. This was a short experiment which only gave us qualitative data. The analysis, however, was very encouraging. We achieved very good separation of the molybdenum from its native silicate rock. In addition, we produced very pure silica powder, and separated several other elements as oxides in a chromatographic-like process. Based upon these preliminary results, we submitted a proposal to DOE to continue this work in the summer of 1978 by studying the parameters necessary to do continuous separation of molybdenum as the oxide from its native form as a sulfide in the ore.

Figure 13

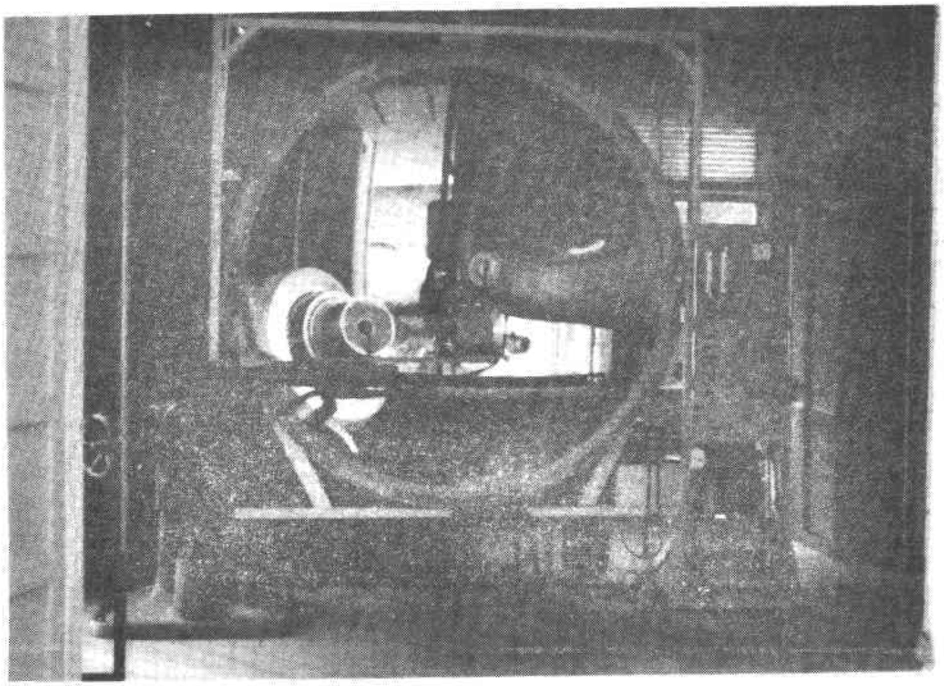


Figure 14

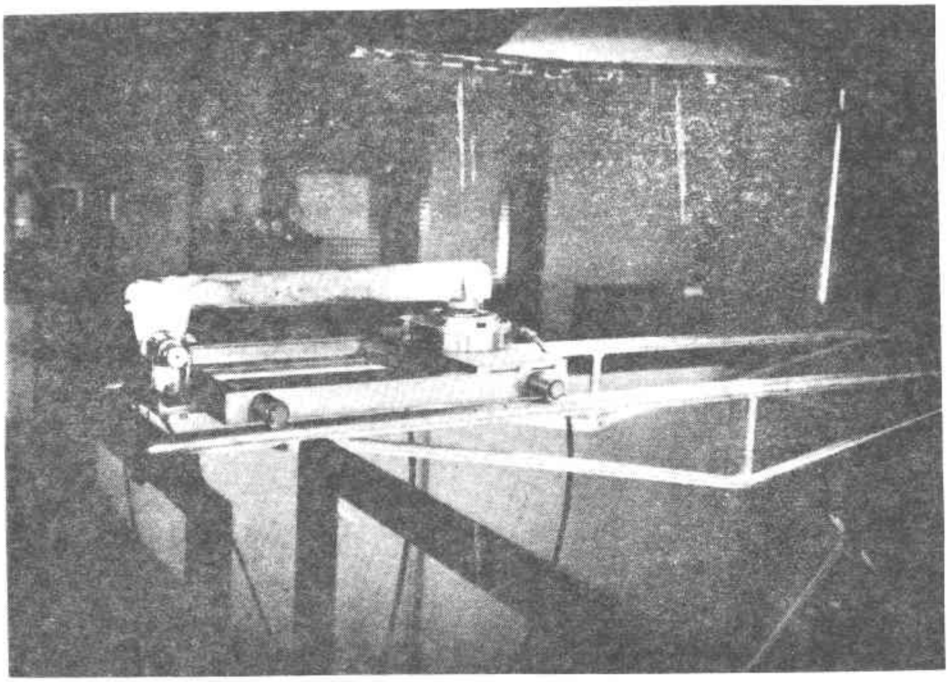


Figure 15

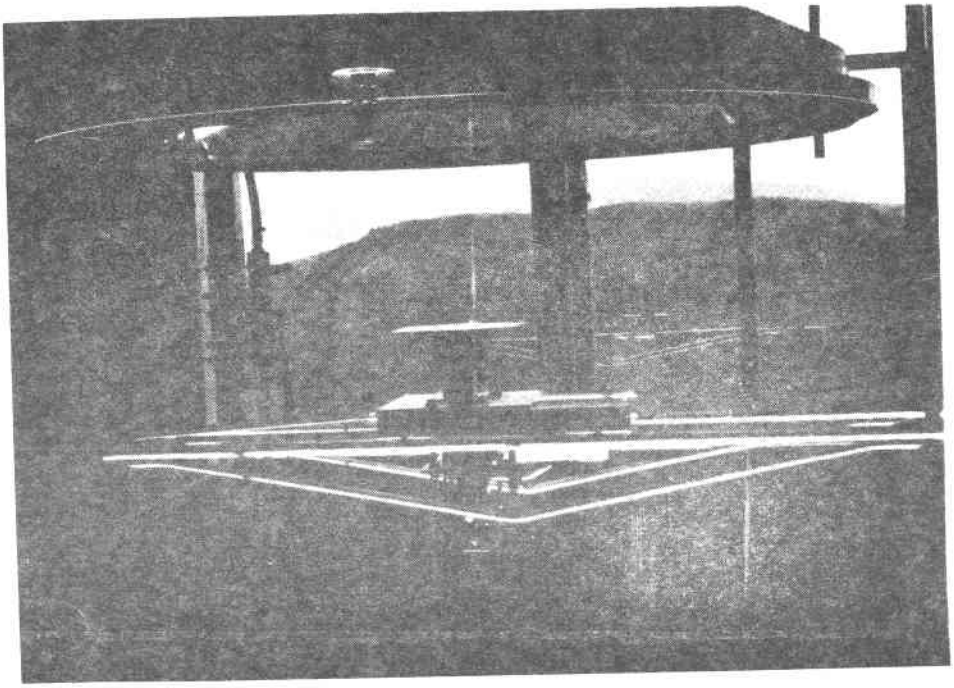


Figure 16

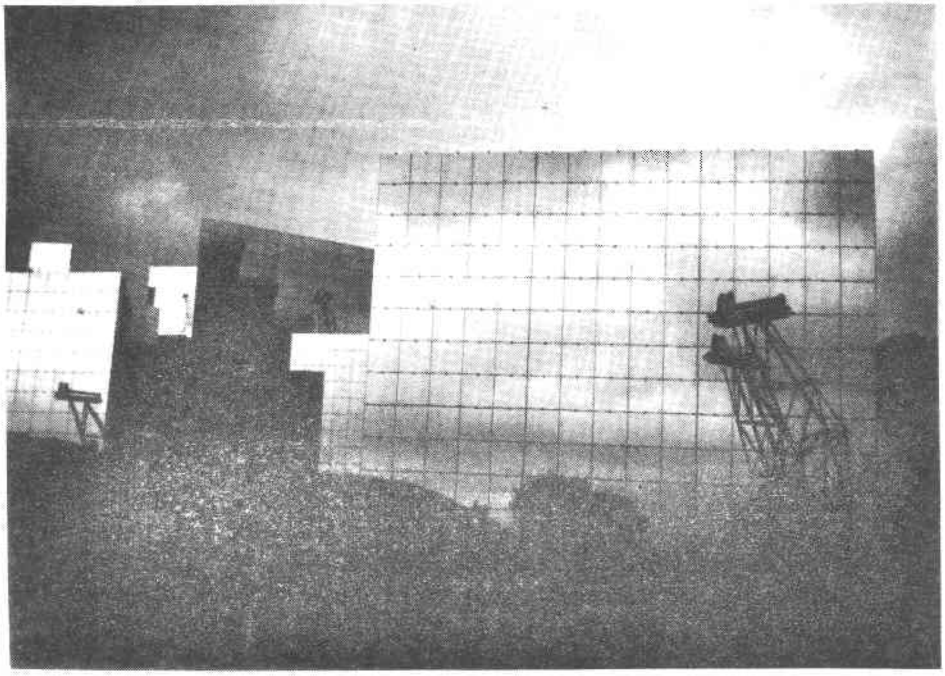


Figure 17

CHRONOLOGY OF ORE TREATMENT EXPERIMENT

Summer 1976 - Inception and Discussion

Late 1976 - Obtain Ores and Characterize

Summer 1977 - Experiments with 10 g's

Late 1977 - Report Results to STTFUA

Early 1978 - Proposal for Further Experiments

March 14, 1978 - Preliminary Approval from Both DOE and STTFUA

September 1978 - Pilot Plant Size Experiments with kg Quantities of Raw Ore and MoS_2 Concentrate

. . . . . ? 78-79?

Continuous Treatment in Solar Thermal Test Facility at Sandia Laboratories

Figure 18

OBJECTIVE

ORE → Mo + Si COMPONENTS

MOLYBDENITE	MoO_3 YELLOW CRYSTALS WHITE
+	SILICA POWDER OTHER GRAY
FELDSPATHIC ROCK	POWDERED OXIDES

Figure 19

Our experimental apparatus is shown schematically in Figure 20 and Figure 21 shows the system in operation. Take note of the numbers in the schematic as they are locations where we collected samples and performed several analyses. These analytical results will be presented later.

In the meantime, I want to show you just a few slides of the operation so that you can see how simple the system is and how easy it is to use. Figure 22 shows a slightly modified system with the cyclone separator removed and the gas stream passed through a filter and thence to an infrared analyzer. The initial puff of smoke is shown in Figure 23, and during the experiment one can observe the decrease of intensity onto the work and the resultant slowed reaction rate. As the smoke is removed by the oxygen sweeping through the globe, the intensity of sunlight on the ore increases and reaction increases, causing more smoke and slowing down the reaction. These oscillations in the reaction are visible on the trace of SO_2 production as a function of time. After the power is shut down and the globe is allowed to cool, there is a condensate on the inside (Fig. 24) which has been analyzed as mostly silica with a trace amount of molybdenum oxide present. This material is easily scraped off the inside surface but it has the property of reducing the intensity of sunlight on the ore. Interestingly enough, this silica does not contribute appreciably to the heat absorbed by the Pyrex globe. If the entire system remains in the focus of the 2-kW mirror for more than 10 minutes, it is necessary to allow it to cool for several minutes before it can be handled. However, if the heating is shorter than this, the globe can usually be handled as soon as it is removed from the focused beam.

The next four pictures (Figures 25-28) show close up what the material in the hearth looks like after it is heated. The yellow acicular crystals are MoO_3 which was transported to the edge of the reaction zone by sublimation of the vapor. The residue left behind is silicate glass and is shown in the last of these four views after the yellow crystals have been removed. Figure 29 shows the filter, which is heavily coated with MoO_3 condensed out of the gas stream.

Figures 30 and 31 show the results of the analysis made last year on the products. The molybdenum has been enriched from a level of 5-6 percent in the molybdenum sulfide and to 66 percent in the oxide. Silica is reduced to 4000 ppm in MoO_3 where it condenses out at the wall of the globe. The MoO_3 is greater than 99 percent pure as it condenses on the edge of the pile.

A schematic of the flow process for the ore treatment currently being employed to refine molybdenite ore is shown in Figure 32. The amount of energy required as a percent of the total is shown in the figure by the numbers on the right-hand side of the flow sheet. As footnotes around the edge of the flow chart you can see it takes 22¢/lb or 2FF/kg (French francs) to refine this ore for use in steelmaking. The total fossil fuel equivalent use of energy is 145×10^6 Btu/ton of MoO_3 produced. We are trying to bypass all of the hydrometallurgical processing which would result in a saving of about 56 percent in fossil fuel equivalent energy.

The experiments that were performed this summer at Odeillo are primarily ones to define the kinetics of the reaction (Fig. 33) of converting the

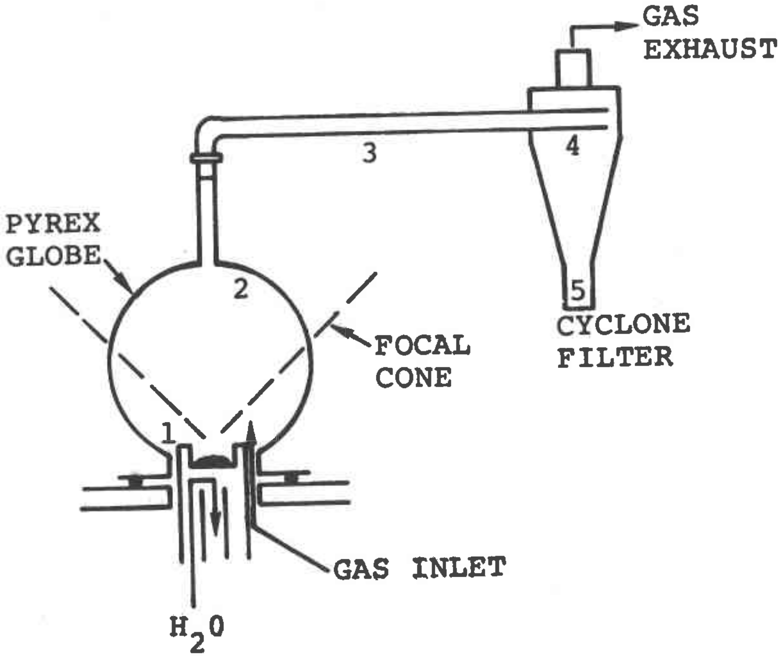


Figure 20

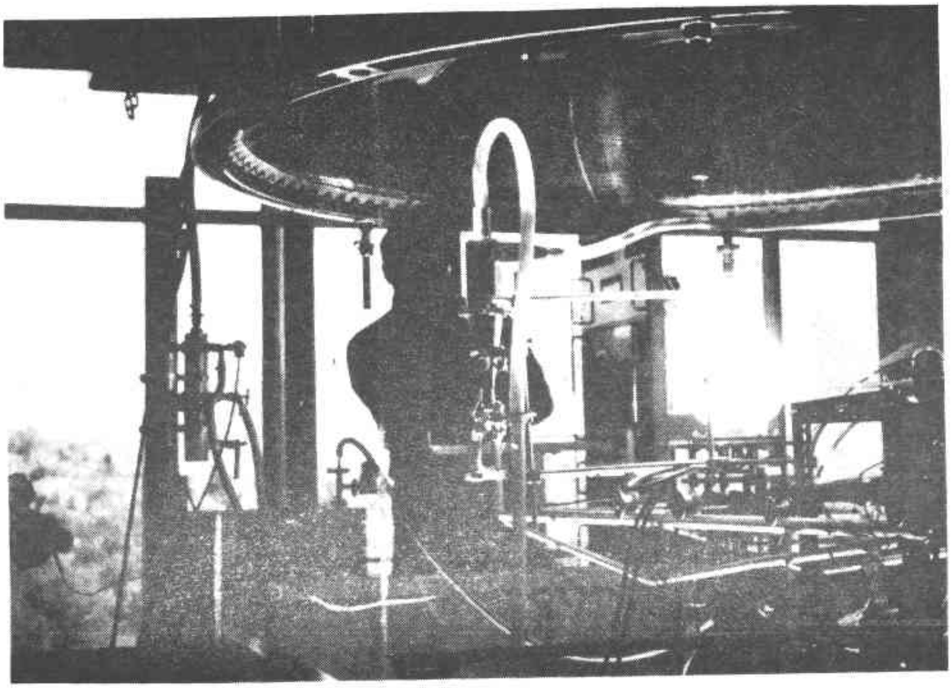


Figure 21

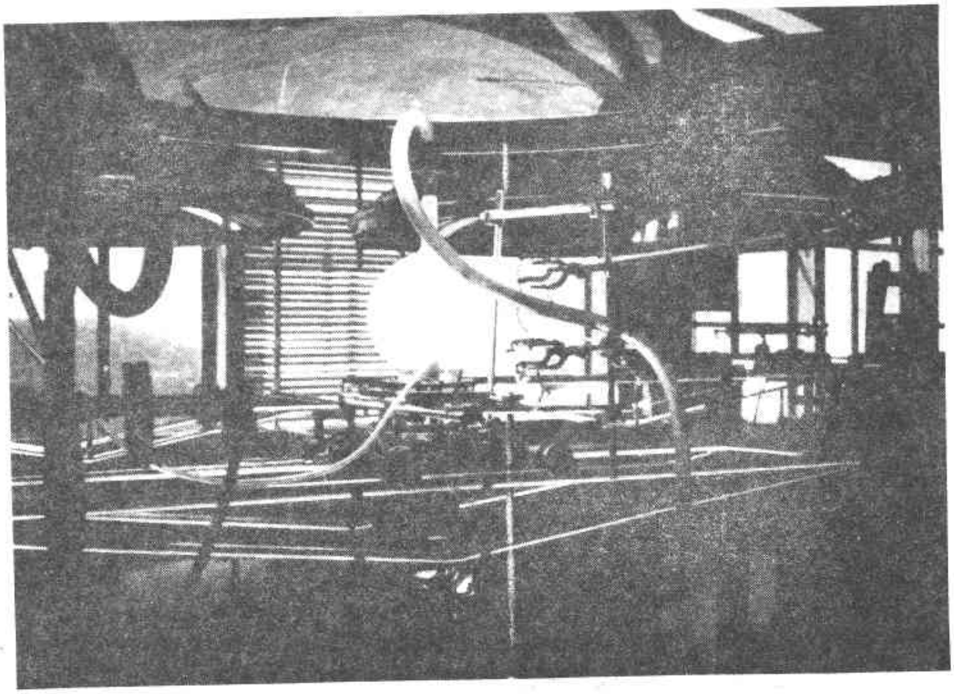


Figure 22

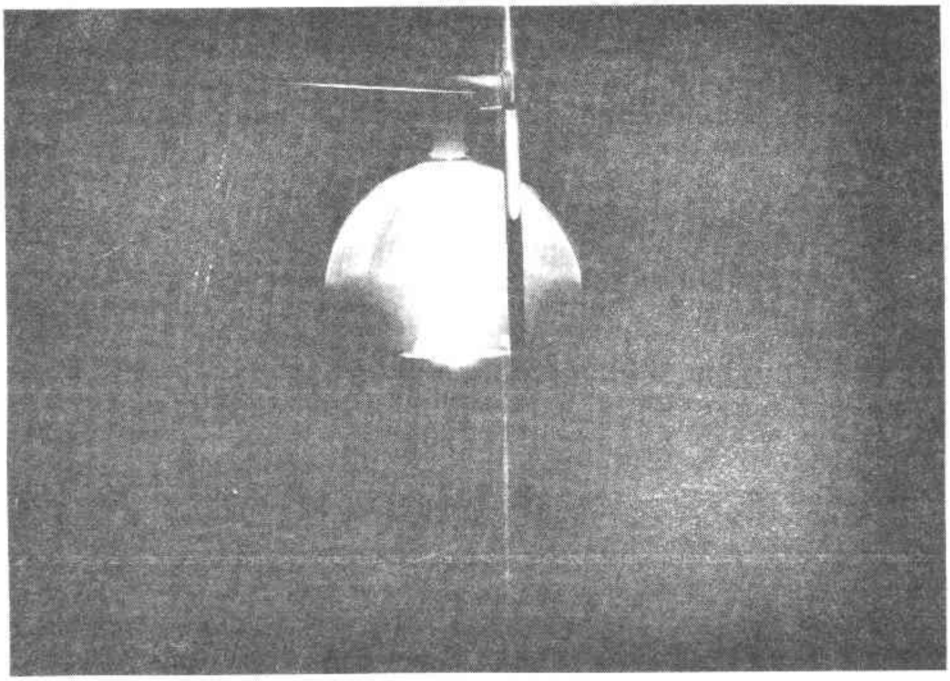


Figure 23

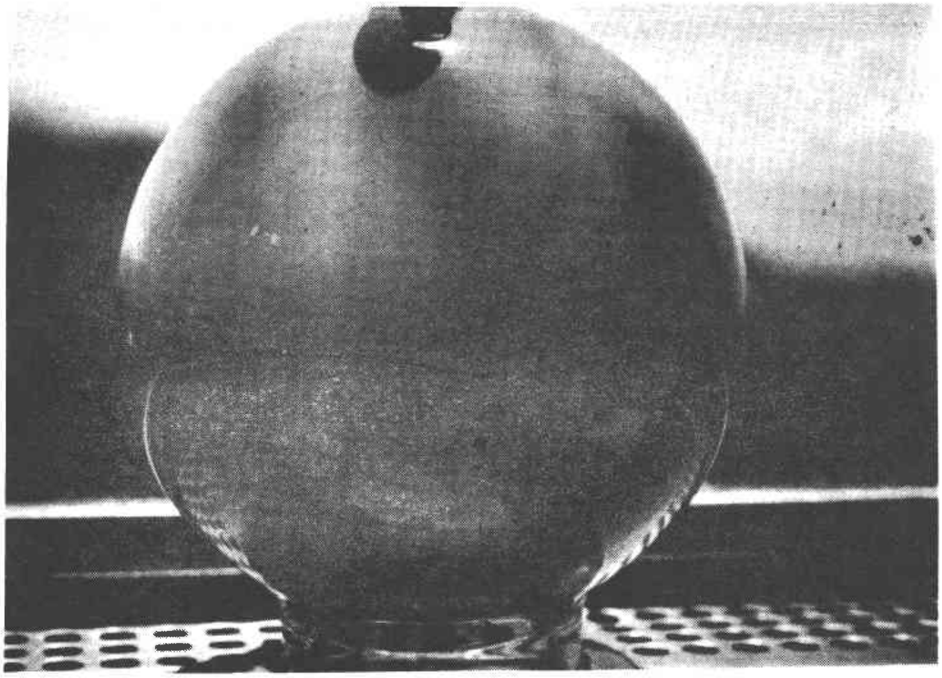


Figure 24

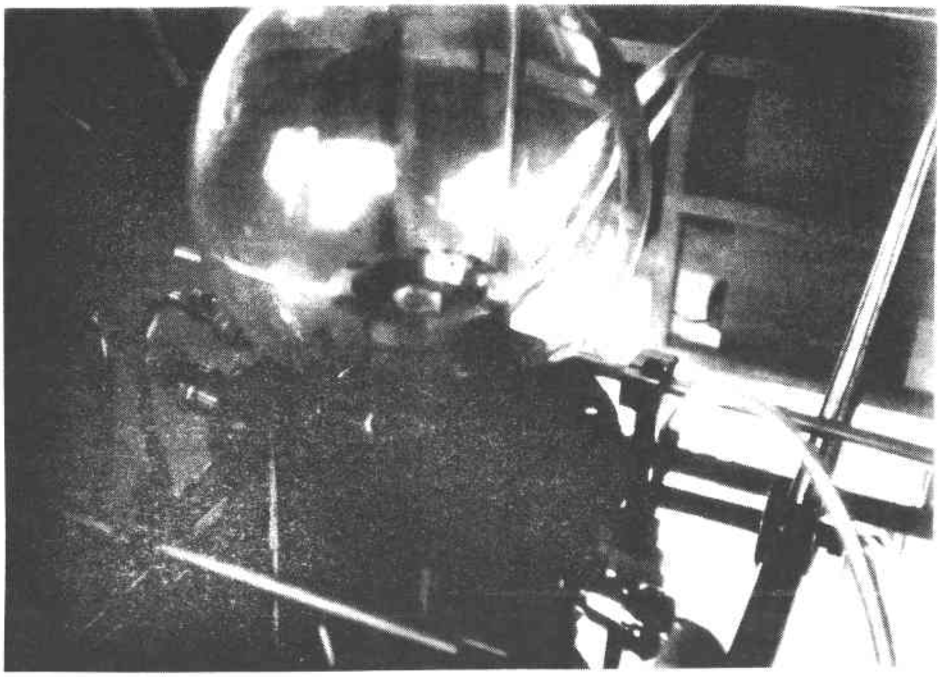


Figure 25

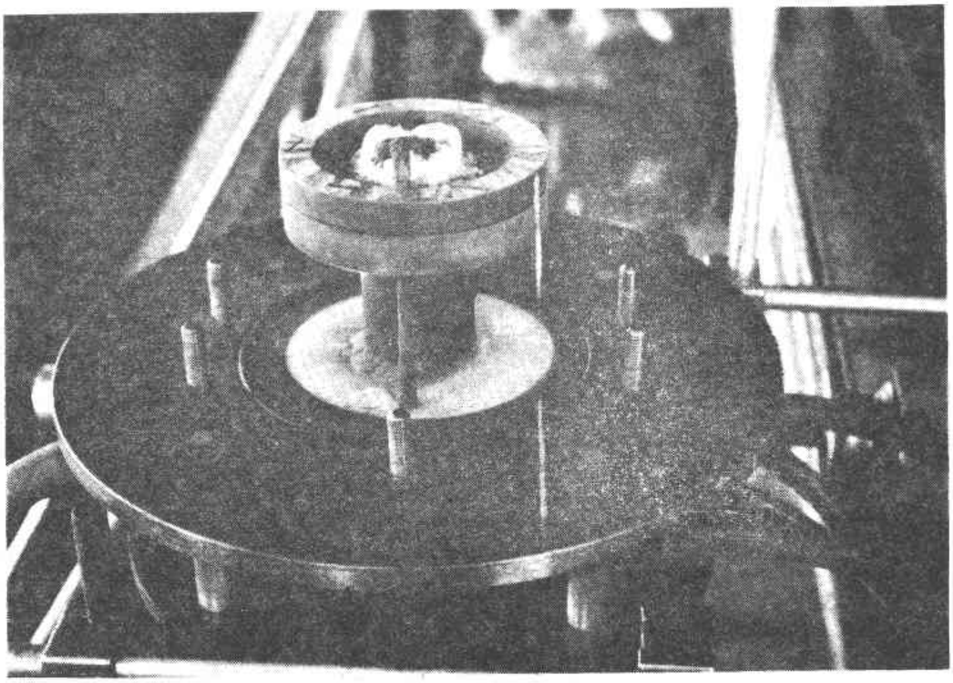


Figure 26

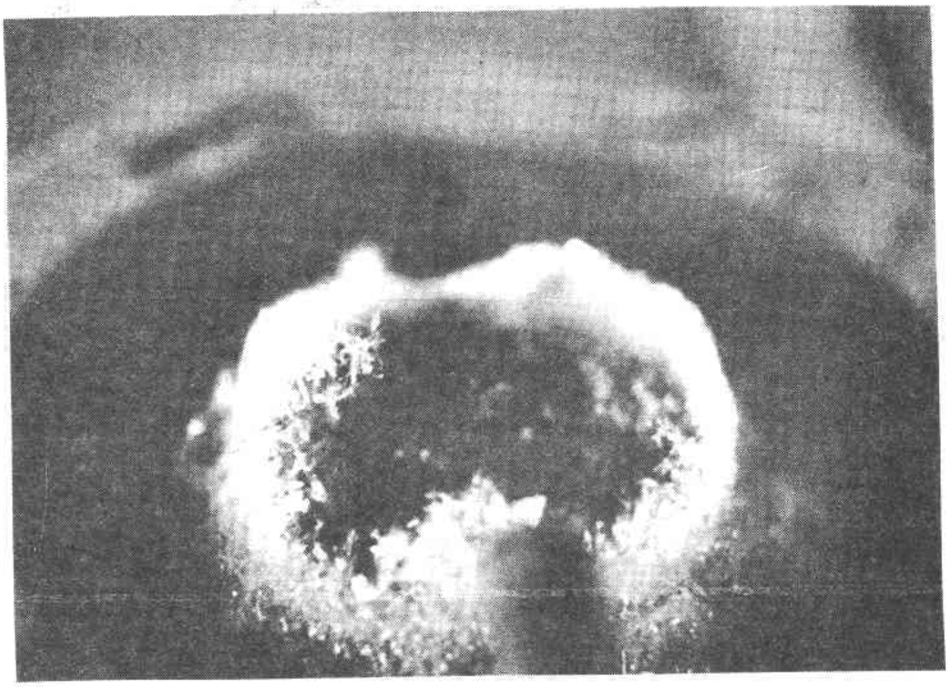


Figure 27

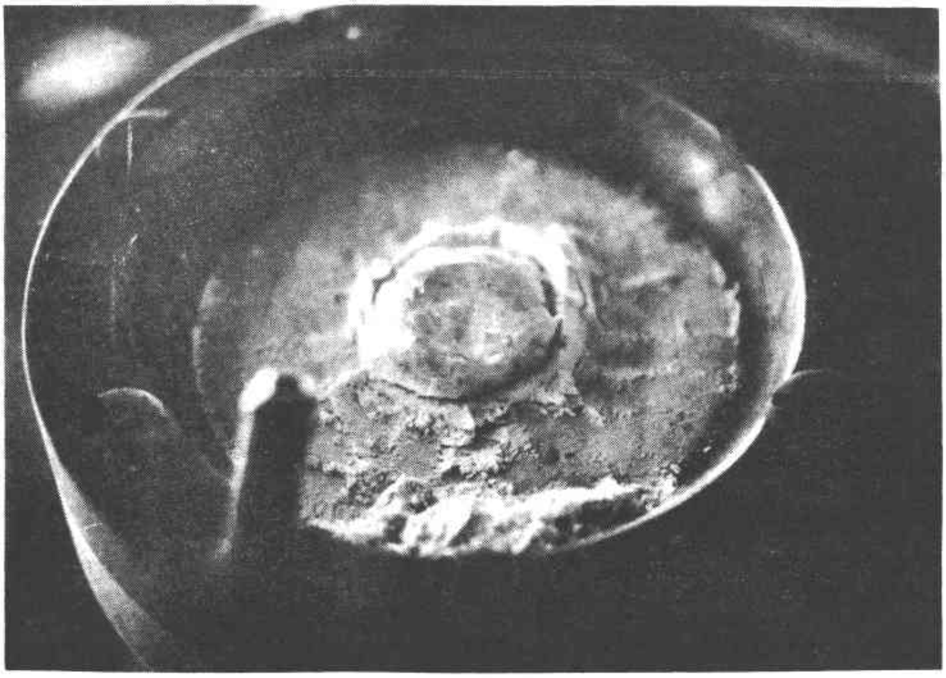


Figure 28

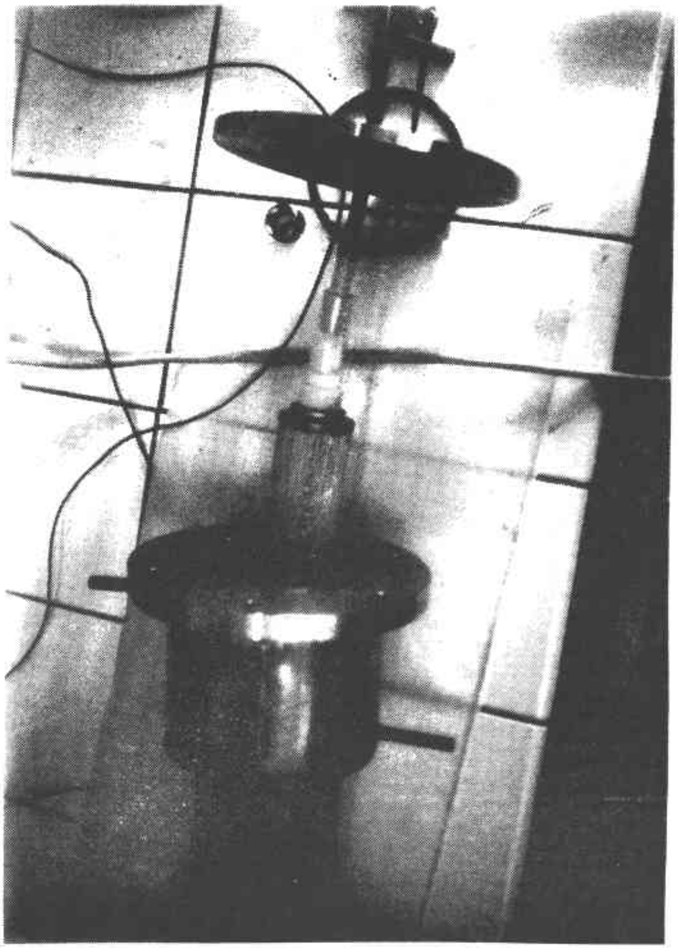


Figure 29

LOCATION	MATERIAL	COMPOSITION
Edge of Pile	Yellow Crystals	99% MoO_3
Inside Globe	White Powder	Pure Amorphous Silica Very Fine Crystal
Transfer Tube	Gray Powder	Si, Al, K, Na, Mg
Filter Screen	Gray Powder	Ni, Cu, Sn, Pb
Cyclone Receiver	Residue	Fe, Cr, Mn, Ni

Figure 30

ELEMENT	ORE CONC$^{\underline{N}}$	CONC$^{\underline{N}}$ AFTER HEAT
Mo	5-6% as MoS_2	66% as MoO_3 MoO_3 > 99%
Si	30%	4000 ppm in MoO_3 > 99% in White Smoke
Al	1.5%	50 ppm in MoO_3
K	1%	<200 ppm
Cu	25 ppm	1500 ppm in Residue
Fe	6000 ppm	6000 ppm
Sn	<30 ppm	400 ppm
Ag	6 ppm	30 ppm
Cr	5 ppm	1000 ppm
Ni	30 ppm	400 ppm

Figure 31

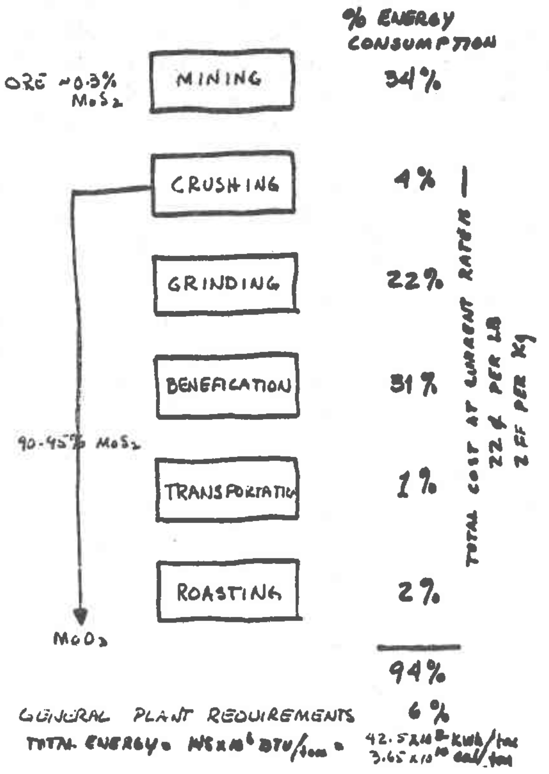


Figure 32

KINETICS EXPERIMENTS

$MoS_2 + 7/2\, O_2 \longrightarrow MoO_3 + 2\, SO_2\uparrow$	GAS MEASUREMENT WITH IR SPECTROMETER
MASS LOSS MEASUREMENTS	MICRO TGA
SPECIFIC HEAT AND HEAT OF $MoS_2 \rightarrow MoO_3$ REACTION	CALORIMETRY
REACTION TEMPERATURE	MICRO TGA + PYROMETRY
SUBLIMATION OF MoO_3	MASS SPECTROMETRY + TRANSPIRATION
MASS BALANCE	WEIGHING OF PRODUCTS + VOLUME OF GAS PRODUCED

Figure 33

sulfide to the oxide. These included calorimetry, microthermogravimetic analysis, gas volume and concentration with the infrared spectrometer, mass spectrometry, transpiration, and mass balance. We used three different concentrations of MoS_2 in these experiments. We had obtained from Climax Molybdenum Company several pounds of concentrate, and 100 kg of raw ore. After sieving the ore to get it into 12 graded sizes, we mixed some of the concentrate with it. We finally settled on three separate compositions to work with. For sample number one we used the concentrate which was about 95 percent MoS_2 with the balance of the material being water and organic compounds; a mixture of 10 percent concentrate with the raw ore was the second sample; and we used the raw ore as the third sample.

The results of the integrated amount of SO_2 produced from each of these three sets of materials is shown in Figures 34-36. It is interesting to note that the reaction takes place quite rapidly and for all practical purposes is complete in a period of about two minutes. This is true for all three concentrations.

We also tried to do a rather crude mass balance. After each trial there was a crust of material on the surface of the powder similar to what you have seen in some of the previous photographs. This crust of material was fused by the heat from the solar image and the exothermicity of the reaction. We carefully collected that fused material, and then collected the residue left behind on the hearth. We calculated the fraction of material that was fused product and compared it with the SO_2 gas production. This second set of curves is shown in Figures 37-39. If one compares these with the figures for the SO_2 gas production, it is immediately noted that the curves are very similar in shape and their relative positions with respect to each other is the same.

On the microthermogravimetric balance we looked for reaction temperature in the same three mixtures. Figures 40 and 41 show there are three distinct reaction temperature ranges. The first of these is the water and volatile organics that are driven off between 80° and 100°C and is just what we would expect from a material that is processed hydrometallurgically with several organic additives to change surface tension in order to promote flotation. The second reaction temperature range is from 400-500°C and is associated with the oxidation of the pyrite (FeS_2) in the ore to iron oxide (Fe_2O_3). The third reaction temperature which occurs in the concentrate at about 700-800°C and in the raw ore at 900-1000°C is associated with the oxidation of the molybdenum sulfide to molybdenum trioxide. This reaction is exothermic and in the concentrate is autogenic, whereas in the raw ore energy must be continuously added to the material in order to sustain the reaction.

We also heated some raw ore in argon to remove the organic vapors and water. Later this same material was heated in oxygen to 1000°C and the reaction isotherms (not really isothermic but ranges instead) were observed to be substantially the same as the unheated raw ore (Fig. 42).

Calorimetry was done on the raw ore to determine what the specific heat was in order to calculate the amount of heat necessary to drive the reaction to completion. The last curve (Fig. 43) shows the trend of the energy

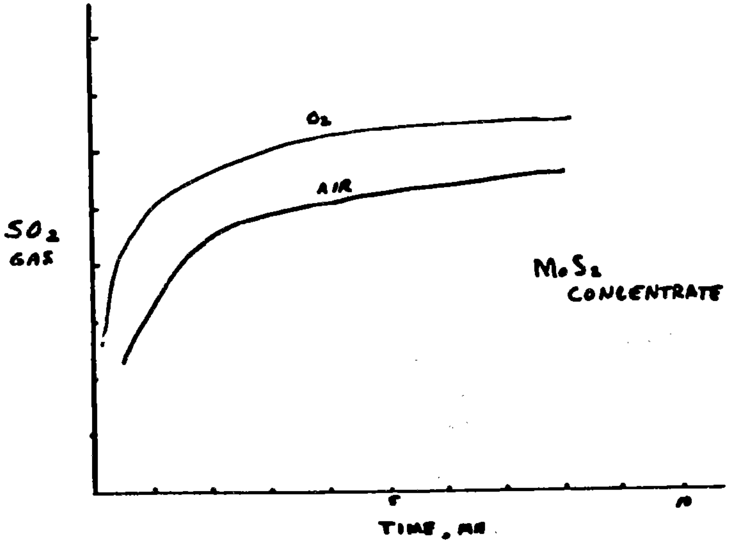


Figure 34

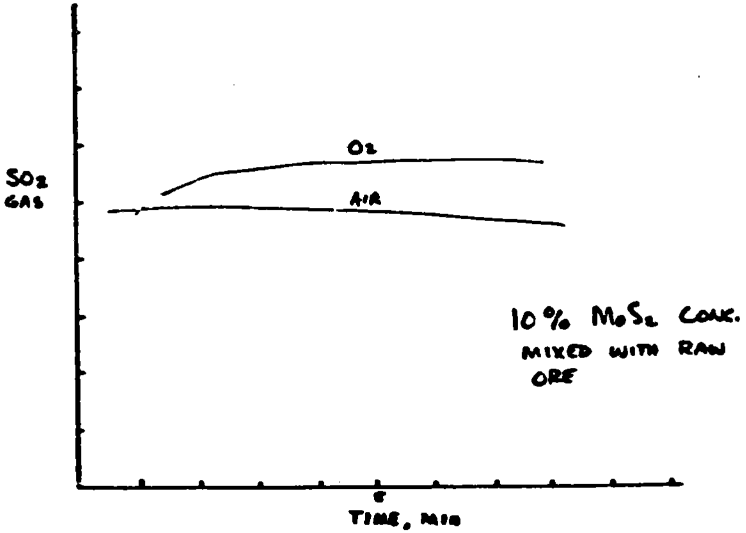


Figure 35

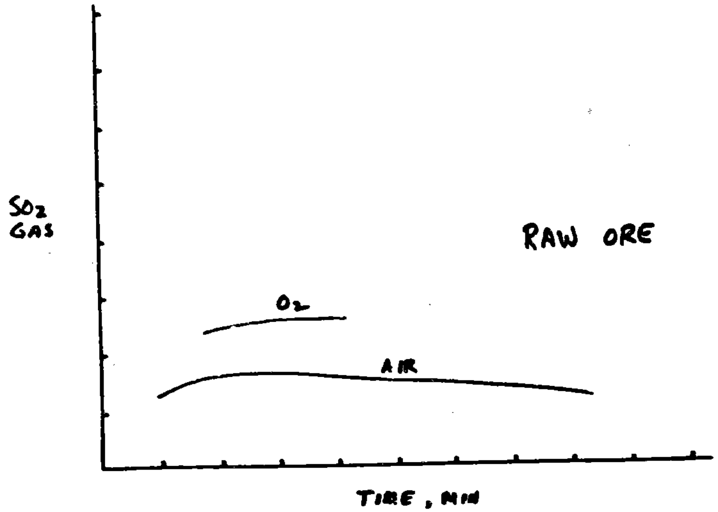


Figure 36

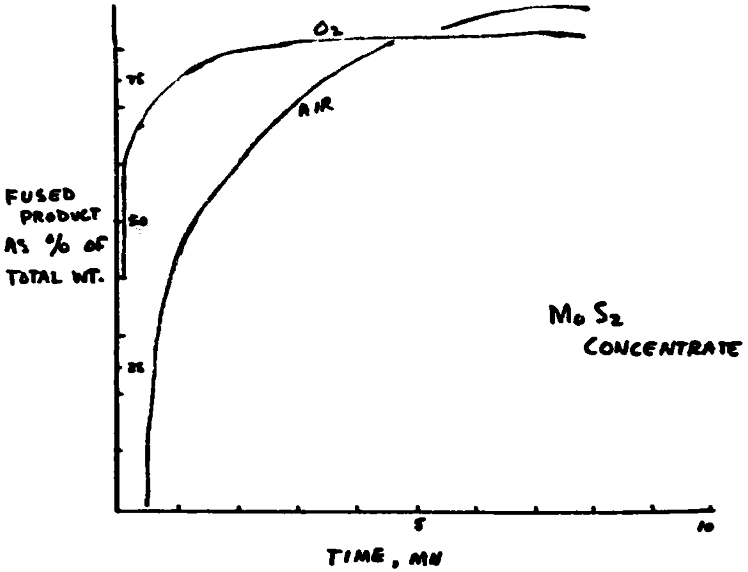


Figure 37

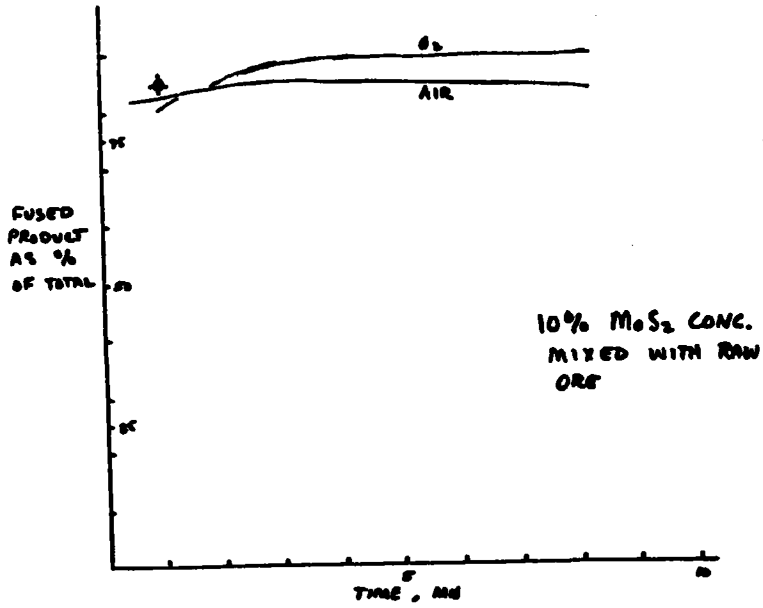


Figure 38

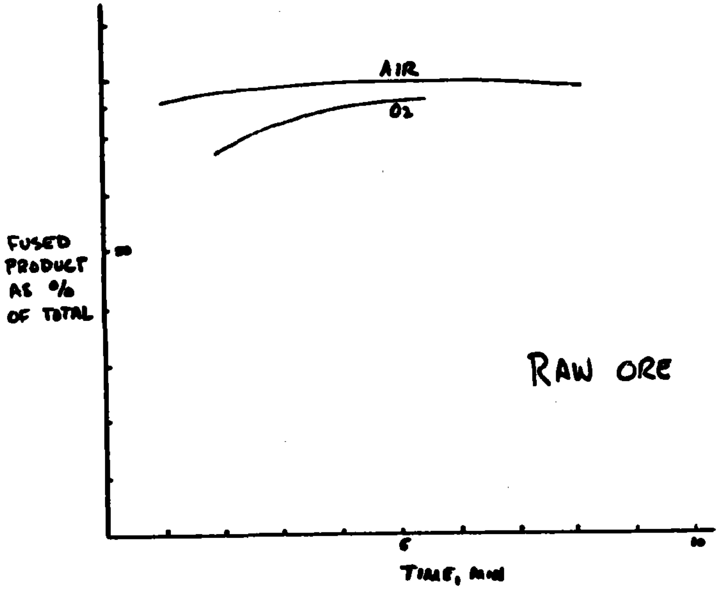
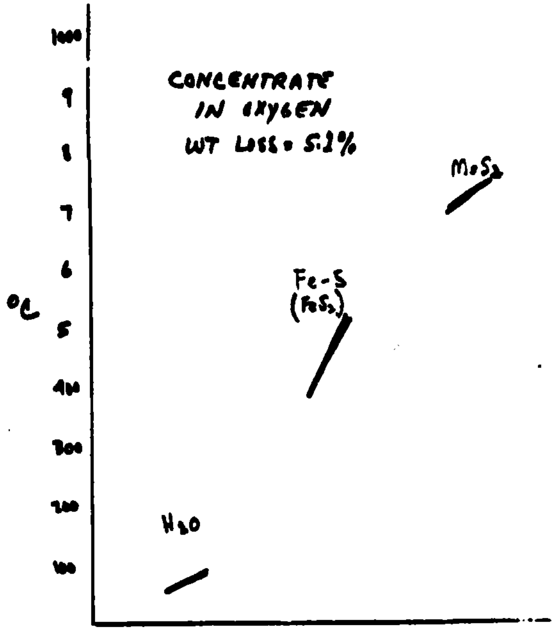
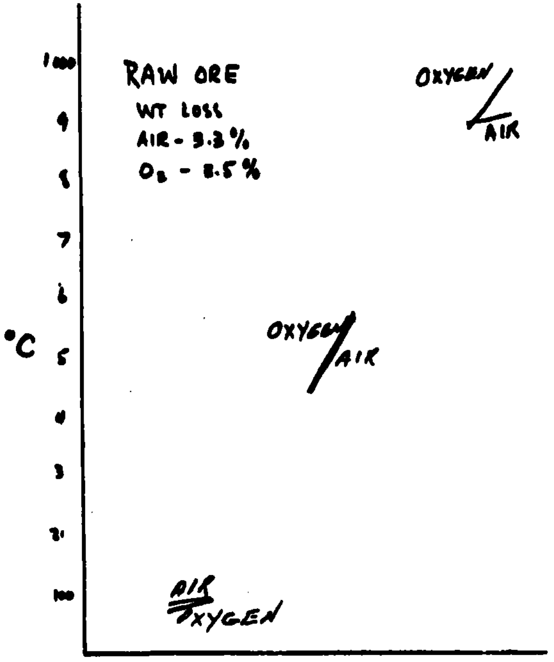


Figure 39





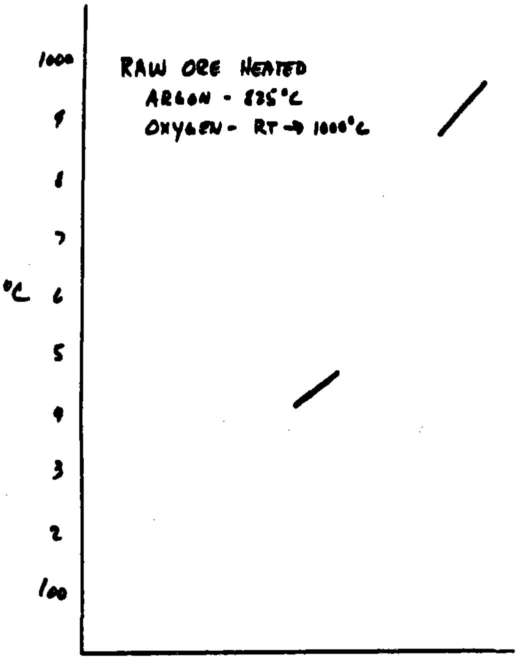


Figure 42

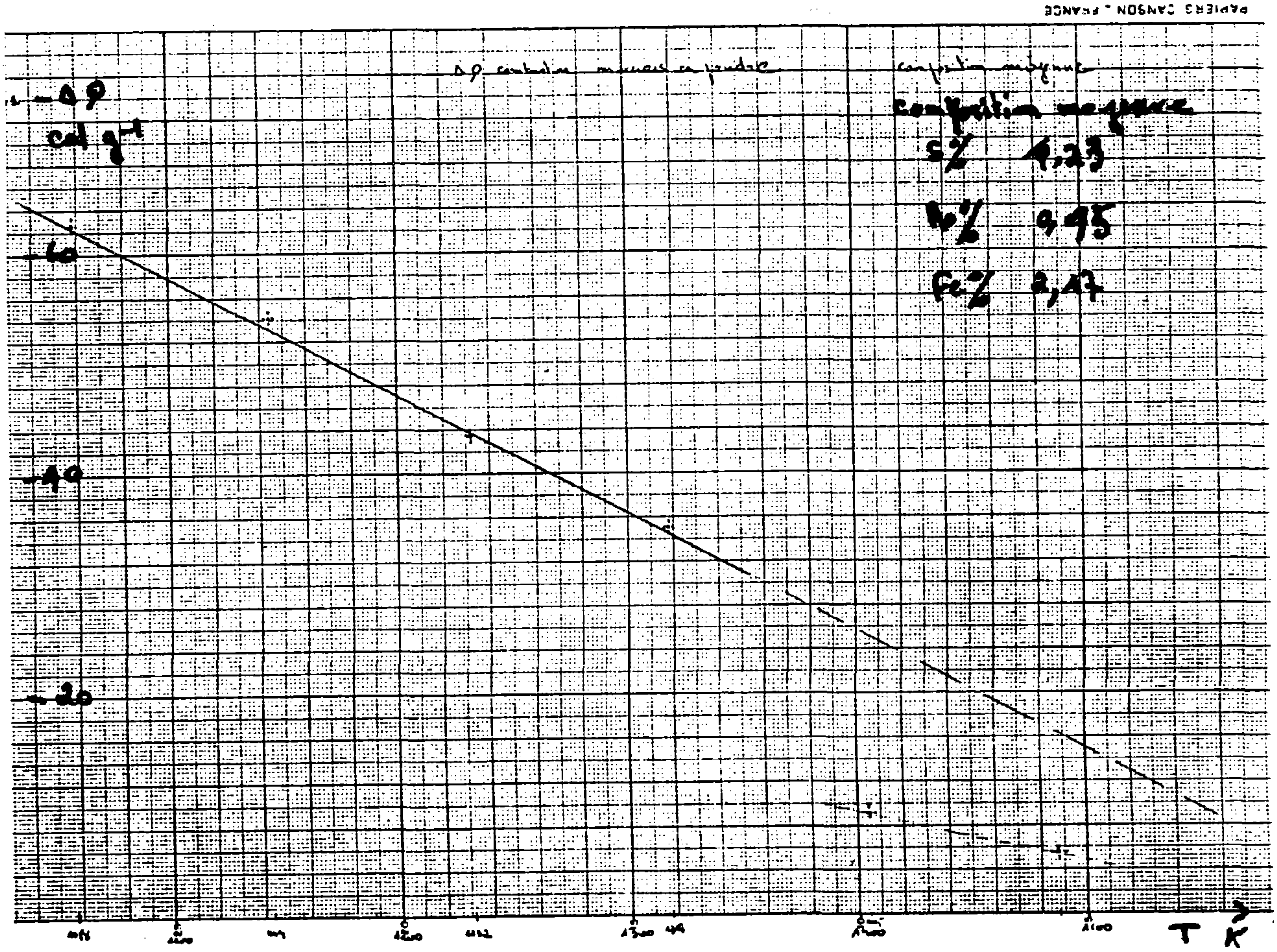


Figure 43

required to sustain the reaction as a function of temperature of the reaction. For the raw ore used in this experiment, the curve extrapolates to approximately 1600 K (1325°C) in order to sustain the reaction at a reasonable rate.

Finally, we looked at the schedule of the events necessary in order to complete this project up to the level of a pilot-size production facility (Fig. 44). The line on the chart indicates the beginning of each week in European style, i.e., day/week, and shows that we have completed a major portion of the experiments, but that there are still several measurements to be done. We have talked to several people about the various techniques used in handling large quantities of material and have come up with an idea that is attributed to a young engineering student at Odeillo, M. Flamand. The technique is essentially a solar-heated rotating kiln which allows the raw material to be passed in one end and the sublimed vapor to be collected in the effluent gas stream. We are preparing to make a system like this which will be small enough to be placed in one of the 2-kW furnaces and operated for some length of time.

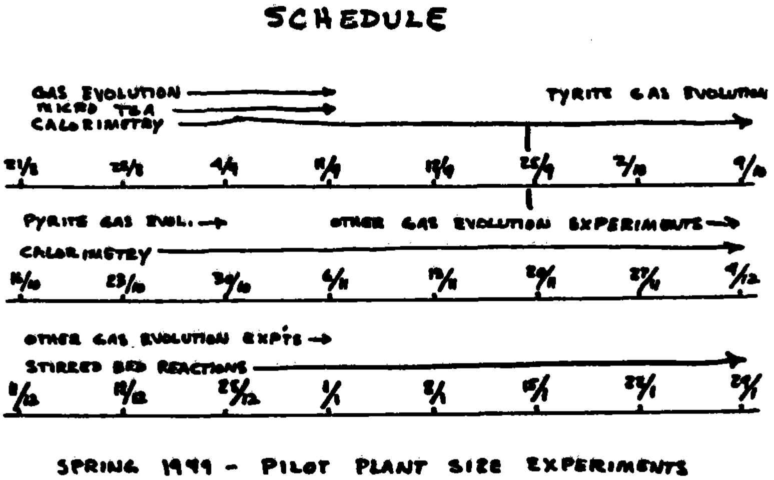


Figure 44

In closing, I would just like to say that the experience of working with the French, who have more than 15 years of operating experience with solar furnaces, is of such inestimable value to us in the United States that I would encourage all who are able to arrange it to go there and work for a few weeks.

Comments afterward:

Somebody has mentioned that they would like to absorb solar energy in an artificial rain storm. I would like to comment that this will not work well because the incoming insolation is absorbed by the water in the high atmosphere before it gets to the surface of the earth. This absorption band is centered at 2.91 m in the near infrared and is useful for doing pyrometric measurements of temperature. This means that very little energy from incoming solar radiation is left in the solar spectrum to heat water.

Question: Have you looked into the silicon part of the experiment at all?

Dr. Skaggs: Only to the extent that we asked, can this silica be used by the transistor industry because it is so pure. I would be interested in using that silica as a raw material for transistors. The answer right now is, no, they grow it by another process and they are not interested in it. But I think that if we can work on it a little, maybe we can convince them that it's very good and useable.

METAL HEAT TREATMENT BY SOLAR ENERGY

James M. Schreyer
Oak Ridge National Laboratory*

The purpose of this suggested project is to develop materials with properties tailored to meet specific physical and mechanical requirements using solar energy as a unique technique and fossil energy replacement.

Many companies are engaged in high-temperature metal treatment. Most metal products are heat treated at some point in their manufacture. This creates a demand for research in the application of solar energy to metal heat treatment.

The objective of this proposal is to develop heat-treatment techniques unique to concentrated solar sources and to replace fossil fuels through superior solar treatment and replace old heat-treatment techniques.

The present furnace capabilities in the Oak Ridge Y-12 Plant are:

1. Metal components up to 30 inches in diameter can be prepared in non-carbon atmospheres at 2600°C.
2. Facilities are available for heating in carbon atmospheres at temperatures greater than 3000°C.
3. Facilities are available for quick-cycle brazing in furnaces which operate at 1000°C and a vacuum of 0.05 μm.

As an example of where high-temperature solar energy might apply, the phase changes associated with uranium are discussed.

Unalloyed cast uranium when cooled crystallizes into grains of alpha phase which is soft and not easily worked. A scanning electron micograph is shown in Figure 1.

When alpha phase uranium is worked by rolling, crystals are distorted and elongated, but no phase change occurs. These distorted crystals are shown in Figure 2.

When alpha phase uranium, worked by rolling, is heated to 600°C and cooled, the distorted grains recrystallize into small, equiaxed grains of alpha uranium. This uranium is ductile and easily shaped. A micrograph of this change is shown in Figure 3.

During the welding of fine-grained alpha uranium, a heat-affected zone is produced which returns the grains into the soft, as-cast crystals. This change is shown in Figure 4.

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*Operated by Union Carbide Corporation under contract W-7405-eng-26 with the U. S. Department of Energy.

When uranium 6 W/O niobium is rapidly cooled from 800°C, gamma phase uranium is produced. This form of uranium is more resistant to corrosion and is easily formed into shape.

In addition to changes in the bulk metal, surface changes occur during manufacturing which can produce adverse surface reactions.

It is suggested that studies using high-temperature solar energy could be carried out in reactive atmospheres which could apply to case hardening, nitriding, protective oxidation, surface coatings, and solid-state transformations.

Some questions to be answered concerning solar heat treatment of metals are:

1. Can metals be heated quickly and uniformly?
2. Can metals be quenched uniformly to give desired properties?
3. Can temperature gradients be attained for zone refining in superclean systems?
4. Can vaporization and purification be attained to remove impurities?
5. Can high solar intensity be substituted for electrically powered furnaces?
6. Can improved metal properties be attained with a high solar flux?

Comment - Having a fair amount of experience with laser heat treatment, the problems are uncoupling the light energy in a piece. A piece will absorb light. I expect this experience again would be applicable to things Dr. Schreyer is talking about.

Dr. Schreyer - Yes, the same type of thing.

Dr. Blieden - Did you say something about the flux that we are talking about and the amount of energy? Just give a typical figure.

Dr. Schreyer - I have not looked into that. I am only comparing flash temperatures where I have treated the materials in furnaces. I'm very much interested in temperatures that you could obtain above 600°C, even up to 2000°C, what you might do in volitization of impurities and that type of thing. I have not looked at the application of this.

Figure 1. Alpha phase uranium developed from unalloyed cast uranium.

Figure 2. Alpha phase uranium worked by rolling.

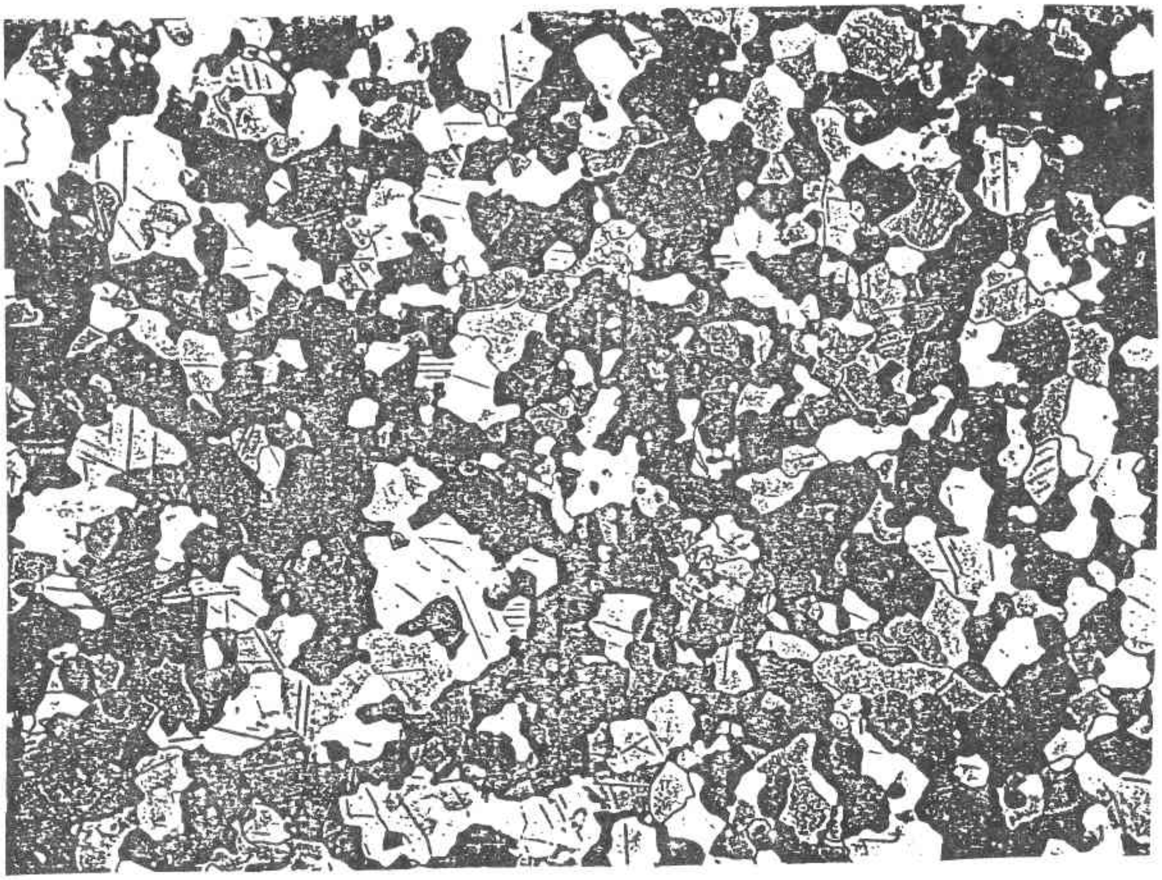

Figure 3. Alpha uranium crystallized into small, equiaxed grains,

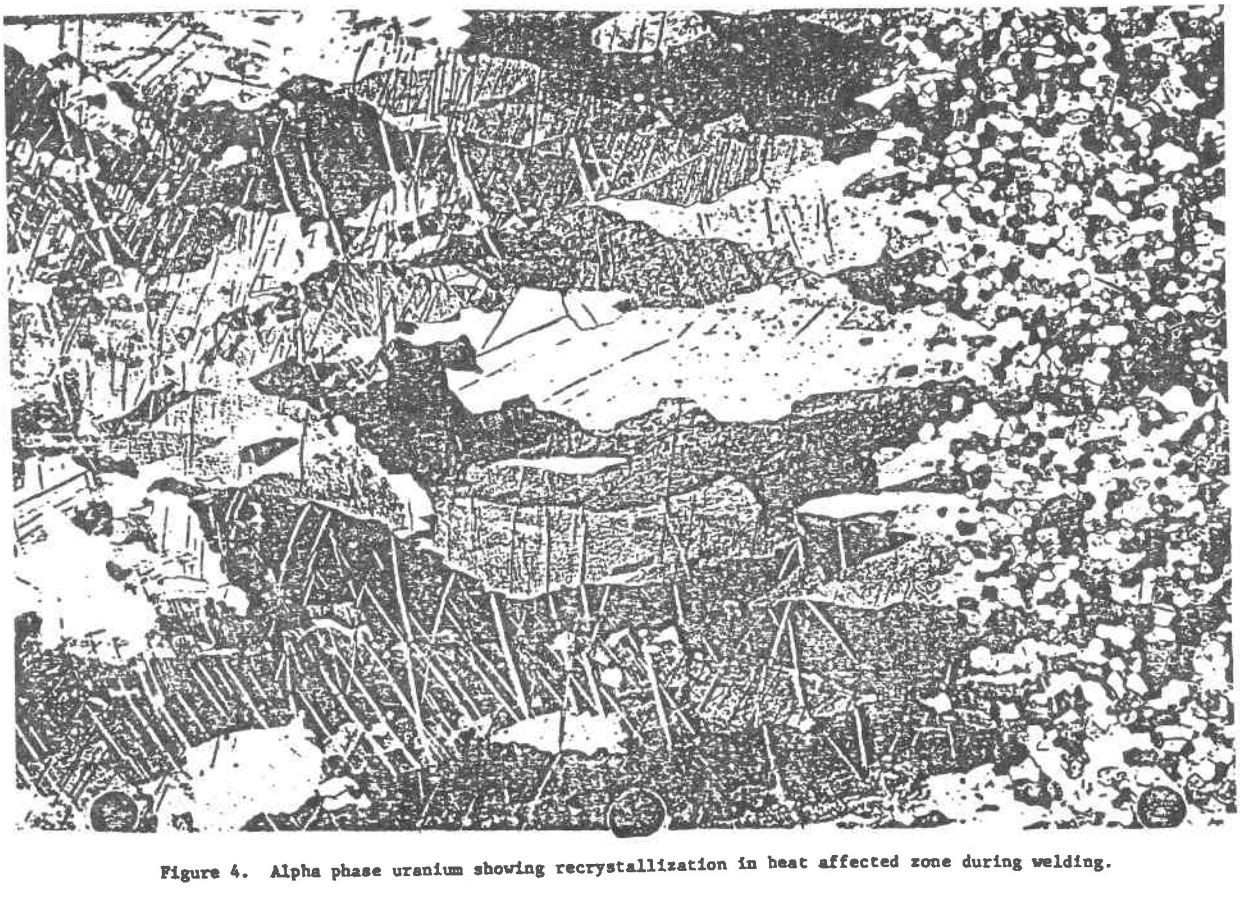

Figure 4. Alpha phase uranium showing recrystallization in heat affected zone during welding.

SECONDARY OIL RECOVERY

J. E. Rogan
McDonnell Douglas Astronautics Company

This paper was unavailable for publication. Anyone wishing information may contact Mr. Rogan.

COST/ECONOMICS PANEL DISCUSSION

Cost of Solar Versus Other Energy Systems

Chairman: T. Whaley

Mr. Whaley - We are now going to introduce the panel: Bob McBride, Union Carbide; Paul Curto, Mitre Corp.; Jim Rogan, McDonnell-Douglas; Karl Geoca, Shell Development; Jack Mulloy, Dow Chemical; and Mike Antal, Princeton University. We have asked them to be prepared to make a short opening statement. We'll begin there and then have a discussion with interaction with the panel. Mike, we'll ask you to be first.

Dr. Antal - The President's Council on Environmental Quality has played a major role in the Domestic Policy Review and they asked me to do a study on biomass energy enhancement, which is basically the subject of the talk I gave yesterday. One chapter of that study had to do with economics and I wanted to very briefly go through it here.

Figure 1 is a biomass gasification system which I suspect could be built rather easily today. You combine two systems. This, for my IGT friends, looks like the U Gas Process. One introduces biomass into storage, takes metal recovery out of that (for municipal refuse only), puts it into a lock hopper and into a fluidized bed gasifier operating at substantially atmospheric pressure. When pyrolyzed, the biomass char comes out the bottom. The char produced by the process is burned to provide heat for the reformer furnace.

I have three scenarios. The first, no solar tower, is a baseline case. The volatiles are taken into the reformer furnace and recycled into the fluidized bed. A fraction is then taken out of the fluidized bed and goes to gas cleanup. Tars and oils are condensed and recycled. So, scenario one is something which could be done today. In fact, I think I may have convinced my friends in EPA to set up such an operation in Cincinnati.

Scenario two is a slight modification of one. We put a solar power tower beside the reformer furnace. When the sun is shining we use the tower and when the sun is not shining we burn char produced by the gasifier in the reformer furnace.

Figure 2 is a schematic of the third scenario. We are undertaking a design effort now. I have a much better approach to this than that given in the schematic, but for the sake of argument let's suppose we are able to use concentrated solar radiation directly in dilute phase transport phase reactor similar to a so-called third-generation coal gasifier. One achieves flash pyrolysis of the biomass, and, if what limited evidence that exists is correct, the biomass will entirely gasify and not leave any char. There is evidence for that from nuclear weapons tests. So, the third scenario is one where no char is produced, and there is no reformer furnace. One simply uses concentrated radiation to achieve flash pyrolysis.

Elizabethtown Gas Company has been interested in this for some time. They service five counties in New Jersey. Their output is 25 trillion Btu's

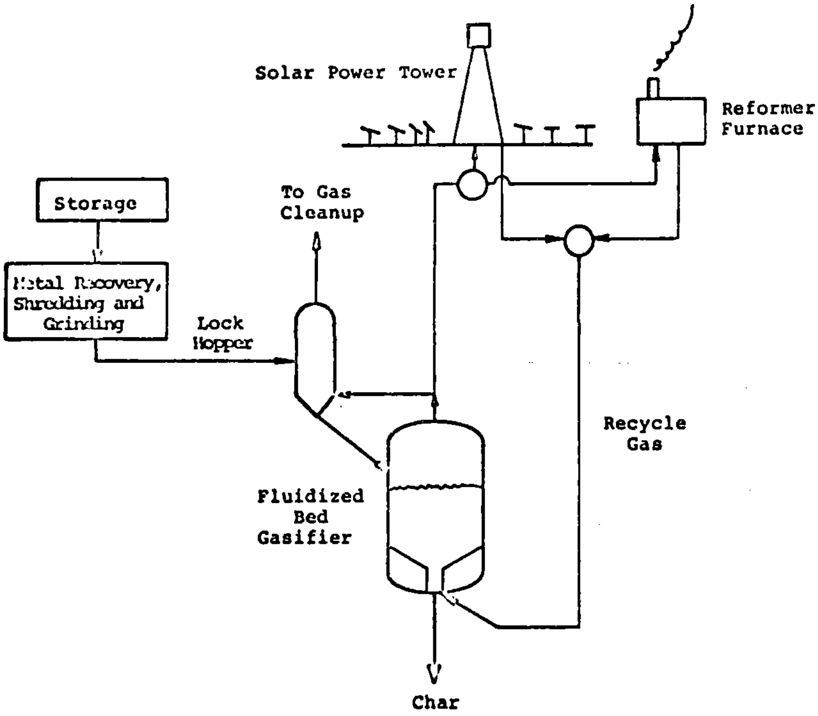

Figure 1 Solar assisted pyrolysis/steam reforming of biomass.

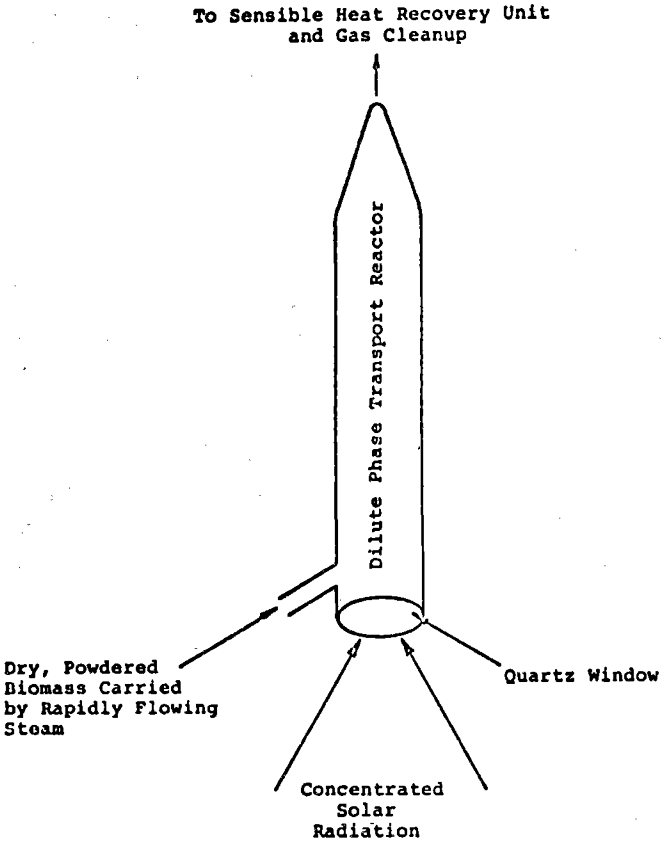

Figure 2 Schematic of a reactor designed for direct solar flash pyrolysis/steam gasification of biomass.

yearly. Roughly half of their output is for industrial-commerical users. I have said, let's supply the industrial-commerical users with this median Btu gas produced by biomass, and it is reasonably well known that commercial use of a median Btu gas is considered very desirable. So, we are producing about 11 trillion Btu's per year.

Figure 3 shows the capital costs of the three alternatives. The solar furnace for the second alternative, requires about 70 acres of land. The land is in the center of Newark and costs $25,000 an acre. The third alternative requires about 90 acres of land. Again, at $25,000 an acre. New York City insolation, not southwest insolation, was used in the calculations.

EPA was kind enough to give me a report, which is about to be published, prepared by the Monsanto Corporation. It is a study of the ERCO Pyrolysis Gasification Process. It uses fluidized beds. All the data pertaining to front-end plant, pyrolysis plant, and auxilliary equipment was obtained from that study, and it was 1978 data. Monsanto and EPA believe it to be relatively good data on the process; I updated it. The solar concentrator data is that available from Livermore: $465 a square meter, and it is assumed that the cost of the receiver equals the cost of the mirror field. Total plant investment for the three alternatives is 43 million, 61 million and 60 million dollars.

The mothodology I have used in Figure 3 is the methodology used by Detman in his recent studies of coal gasification. I believe it is a widely accepted standard. I am using utility cost financing, 11 percent return on investment, I believe. It is essentially the method Elizabethtown uses to cost their own plants.

The solar concentrator in this case is supplying 236 million Btu's per hour on a peak basis. This is in July. These are operating costs. I am assuming one is paying $1.20 per million Btu's for the garbage that one has collected. This is quite a contrast to the practice where one is paid to take garbage. But there is evidence that that is changing. So, one in this case is paying for garbage.

You can see gross operating costs in Figure 4. One gets by-product credit for recovered metals and aluminum char. And, the key thing is alternative two. With the solar furnace you make a lot more char, which you can sell. So, you are conserving char.

These are costs by the utility financing method, Figure 5. You can see gas costs in dollars per million Btu's. You can also see biomass priced at $1.20 per million Btu's. The price of char, $1.50, $2.00 and $2.50. Point of reference: In New Jersey we pay something like $1.60 to $1.80 per million Btu's for coal. So, $1.50 per million Btu's for char is probably not bad.

You will note that alternative two does not compete with alternative one. Putting the solar furnace beside the reformer furnace, having more char to sell, will not compete; and, in fact, when you get the char price up to about $3.50 per million Btu's it still does not compete. Char would have to be priced at 4 or 5 dollars per million Btu's to compete.

BASIS FOR CALCULATING TOTAL CAPITAL REQUIREMENT

Plant Investment	Alternative* 1 (thousand dollars, 1978)	2	3
Land[a]	900	2820	2940
Front End Plant[b]	26000	26000	18830
Pyrolysis Plant[c]	6300	6300	---
Auxiliary Equipment[d]	900	900	670
Process Furnace[e]	2400	2400	---
Solar Concentrator[f]	---	16000	18800
Compressor Station[g]	7200	7200	19220
Total Plant Investment	43700	61620	60460
Allowance for Funds Used During Construction	7870	11100	10880
Start Up Costs	6700	7120	5400
Working Capital	2550	2740	2350
Total Capital Requirement	60820	82580	79090

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*Alternative 1: Char fired pyrolysis/steam gasification plant.
Alternative 2: Solar assisted pyrolysis/steam gasification plant.
Alternative 3: Direct solar flash pyrolysis/steam gasification plant.

Each alternative is sized to generate Elizabethtown's average daily commercial and industrial demand for gaseous fuel energy (33.2 billion Btu per day). Yearly production is 10.9 trillion Btu with a 90% operating factor.

Figure 3

BASIS FOR CALCULATING GROSS AND NET OPERATING COSTS

	Alternative* 1 (thousand dollars, 1978)	2	3
Raw Materials[a]	19800	19800	13200
Chemicals[b]	10	10	---
Labor and Supervision[c]	2580	2580	2020
Maintenance[d]	2290	3490	3050
Administration and General Overhead[e]	1550	1550	1170
Mobile Equipment Charges[f]	410	410	290
Supplies[g]	1460	1820	1500
Electric Power[h]	3800	3800	3800
Miscellaneous[i]	400	400	270
Residue Disposal[j]	180	180	120
Local Taxes and Insurance	1180	1660	1630
Total Gross Operating Cost Per Year	33660	35700	27050
By Product Credit			
Char[k] ($1.50 per MM Btu)	760	2540	---
Ferrous Metal[l]	5900	5900	3920
Aluminum[m]	2380	2380	1580
Total Net Operating Cost	24620	24880	21550

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Figure 4

PROJECTED AVERAGE GAS COST BY UTILITY FINANCING METHOD

Char Value ($ per MM Btu)	Alternative* 1 ($ per MM Btu)	Alternative* 2 ($ per MM Btu)	Alternative* 3 ($ per MM Btu)
Biomass Priced at $1.20 per MM Btu (1978)			
1.50	2.93	3.20	2.85
2.00	2.91	3.12	2.85
2.50	2.89	3.04	2.85
Biomass Priced at $2.00 per MM Btu (1978)			
2.50	4.10	4.25	3.66
3.00	4.07	4.17	3.66
3.50	4.05	4.10	3.66

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Figure 5

CAPITAL AND OPERATING COST COMPARISON

Technology	Capital Cost ($ per bbl per day equiv.)	Net Operating Cost ($ per bbl equiv.)
Alternative 1	10600	13.10
Alternative 3	13800	11.46
Lurgi Coal Gasification	30300	8.02

Figure 6

The solar furnace using direct gasification is, admittedly, a hypothetical process. The research I have proposed to accomplish in France should help to clarify the utility of direct solar gasification. The economic data in Figure 5 indicate that direct solar gasification will be cheaper than the baseline case.

Now, the other interesting thing that I want to draw to your attention is that if biomass goes up to $2.00 per million Btu's, which is not at all inconceivable, the third case, with the solar furnace, because it is a much more efficient case, is somewhat decoupled from the cost of the input biomass feedstock. So, where the price went from $1.20 to $2.00, an increase of 80 cents, here the gas price increased from $2.93 to $4.10, which was about $1.20. Here, it went from $2.85 to $3.60, which was again about 80 cents. So, the point is that by having a solar furnace in a system conserving energy, you are less strongly coupled to the price of the input feedstock.

This is something the Germans have pointed to in their use of nuclear coal gasification. They point out that if coal goes up in price, and you use a nuclear facility to gasify the coal, the price of the gas is decoupled, to some extent, from the price of the coal.

I also want to compare alternative one and alternative three in terms of capital cost, dollars per barrel per day, equivalent to about half Lurgi, Figure 6. I hope you also notice that power towers do not dominate the cost of chemical processing, only a very small fraction of it. That was one thing I wanted to go back to and point out in Figure 3.

The operating costs are somewhat higher. The price of gas from Lurgi is supposed to be $4.50 per million Btu's. I myself find it difficult to believe that the price of gas from this process would be as cheap as the numbers turned out. But that is the best data I am able to get from industry.

In Figure 3, compressor station costs, operating at atmospheric pressure, compressing gas up to 150 pounds, which is what Elizabethtown would like to have, is 19 million dollars compared with the solar concentrator at 18 million. Note the front-end plant is 18 million. What I am getting at is that if you want to make a gas that you can sell, and if you are going to operate a facility at atmospheric pressure eight hours a day, you are going to pay a factor of three on the normal cost of compressors, which are large anyway, for an atmospheric process because you are only making gas eight hours a day. That price of 19 million dollars is very large. It's almost one-third of the total cost. So, there will be a large benefit from operating gasifiers at increased pressures. How one does that with a window is somewhat of a mystery to me. Thank you.

Question - Wood is a lot more dense than biomass and would make more fuel, would it not? I wonder if this is a significant problem and if you had address it, Mike?

Dr. Antal - What is the difference between wood and biomass? I thought they were the same thing.

Comment - Yesterday you mentioned manures and things like that.

Dr. Antal - Biomass is a term which generally refers to any organic residue or purposefully grown waste. The best thing I can say is that there have been numerous studies made of wood residues, and $1.20 per million Btu's will get you all the wood chips you want, and that includes transportation of 20 to 50 miles. The transportation is not the bulk of that number. The bulk is the harvesting of the wood. So, it's clear that you cannot affort to transport wet biomass great distances, but the scale the towers are presently being built on, 10, 20 and 50 megawatts, are about the right scale for a suitable gathering area. I think the scales will match nicely in the transportation and it won't be difficult.

Mr. McBride - I will try to focus on the history and the way it is today rather than projecting the future. When Tom called on us to sit on this panel, he was interested in possible applications of solar energy in the petrochemical industry. I am Energy Coordinator for the Union Carbide Plastics and Central Engineering Department.

The chemical companies I speak for represent two of the three largest, each selling on the order of eight billion dollars a year of products.

We hear a lot about the transportation sector, the residential sector, etc., as consumers of energy in America. In 1971 the Federal Power Commission addressed the question of what the energy is actually used for--not how do you make it or what is the source--but, what is it being used for. Those numbers have probably changed but I suspect the ranking hasn't.

The biggest use is for space heating, two-thirds domestic and one-third commercial. Close behind that is the passenger automobile, and then the primary metal industry. But it has been said that much of that is coal. Then you come to chemicals and allied products. The four of them put together add up to almost 60 percent of the total. Significant energy decreases in those segments can make an impact on our so-called energy crisis. An equal amount of effort in hundreds of other uses, even reducing many of them to zero, still wouldn't change the picture a great deal.

The petrochemical industry is a big user because we use hydrocarbon fuel as feedstock as well as fuel. It is also stated that the chemical industry consumes the greatest amount of three chemicals: ammonia, which has been discussed; chlorine, which I haven't heard discussed and don't know much about as it is inorganic; and ethylene, which I do know about. I am told that 70 percent of the consumption of these three chemicals is by the chemical industry.

Ethylene dominates the petrochemical industry. On the order of a quarter or a third of the total energy consumed by that industry is consumed in converting ethane-propane from natural gas processing, or naphtha from crude oil processing or refining, into ethylene, which is the building block from which we make the hundreds of products that the petrochemicals produce.

Looking at our company, the energy consumption is concentrated in five, six or maybe seven products and over 80 percent of the manufacturing energy is consumed in products like polyethylene, ethylene oxide, ethanol, isopropanol, and they all come from either ethylene or propylene. So, let's look at the temperature range of interest in this conference. In our plants, we have 15-lb process steam headers which run at 121°C, 60-lb headers at 153°C, 80-lb headers at 163°C, and 200-lb headers at 196°C. The bulk of our process heat comes from those temperature ranges. Above that we have 400-lb headers in a plant or two, and they are sort of between the steam used to drive turbines, or high-temperature reboilers, etc., and process heat. Then we have the 1000 to 1700-lb headers that are exclusively used for electric power generation.

The noncondensing turbines produce 200-lb steam, which we use for processing the so-called cogeneration. We have a few diatherm heaters which run in the range of 233° or 399°. But the biggest heat loads in the temperature range of interest to you are the ethylene furnaces, or reactors. About two-thirds of the feedstock is ethane-propane. About one-third is naphtha, a light distillate from crude oil. The temperature ranges from about 800-900°C for those feedstocks.

One typical heat load is the ethane furnace, which burns 9000 Btu's per pound of ethylene produced. In this country we produced 27 billion pounds of ethane this past year; Union Carbide produced 4 billion. So, the total US demand for heat in those furnaces comes to 250 trillion Btu's, or a quarter of a quad. The total Btu content of the ethylene ready to go on to the derivative units contains on the order of 39,000 Btu's per pound. I don't want to leave the impression that we burn all this gas to feed the furnaces, because a fraction of the feedstock is hit with a thermal sledgehammer. Not only do we get a battery of products such as ethylene, propylene, acetylene, etc., but we also get hydrogen-methane, and that pretty much satisfies the need for heat.

Another example of a heat load is the olefin furnace. Except for what we lose in the flue gases beyond waste heat recovery boilers, I am unaware of any heat regenerators which bring the temperature of the gas down. We probably lose on the order of 1000 Btu's per pound of ethylene with the relatively hot flue gas in most of the furnaces that were built some time ago. I guess there are probably 120 of them. Also, it's an endothermic reaction, 2200 Btu's per pound; and there are about 400 Btu's per pound of undesirable by-product reactions that we don't know how to get rid of. But all of the derivative units, ethylene oxide, for example, are exothermic reactions. So in a certain sense, the energy that you put into the manufacture of the olefin or the unsaturated bond, you get back when you saturate it in the units downstream before it's sold to the customer. So these furnaces, by our standards, are big and they have a multiplicity of burners. We transmit the heat through metallic walls.

I believe we and Dow are working on the concept of cracking crude oil directly. None of those are in commercial operation at this time. The prototype is under construction. That would involve temperatures considerably higher, about 3300°C. So, it's high-temperature, low-residence, very low-residence time, cracking. But as we go to heavier feedstocks, we get into problems with carbon deposition in the tube walls. So there have been two other kinds of furnaces used. One, for example, is a Wolf furnace, which has refractory masses where one runs a combustion reaction to heat up the refractory and then switch valves and that serves as the heat of cracking.

The Germans had a moving bed, a so-called sand cracker, which had two separate vessels. They carried the heat around with moving streams of sand where they had a combustion chamber and then a cracking chamber to try to keep the product's combustion separated from the product's cracking. It's hard for me to see, though, how there is enough money in the fuel to justify what would be required to convert those to solar heat. We do have excess furnaces. First, you understand it's a chain of millions of dollars for processing a unit from beginning to end. Consequently, when you make that investment you have to keep them running as close to 7860 hours a year as you can. And we do put in extra furnaces so that some of them can be off the line for maintenance, getting the carbon out or replairing the hole in the tube, or something of that sort.

If you had a different design furnace that used solar heat and you had to double the whole furnace unit, that would be a substantial capital investment and you would only have a pay-back part-time unless you put in an awful lot of storage. If you had to store all of this heat I think it would take an enormous investment. That is not to say that if you get to $9 per million Btu's, as someone has mentioned, that it might not be different. With enough incentive, I'm sure you probably could design an olefin furnace, too, and feel relatively secure in saying that it could operate with solar and fossil fuel energy.

A gentleman raised a question which was interesting to me about the photochemical effect. If the sunlight gave you a bonus in that the reactions went preferentially to the products that you wanted, might it not be worth your while to design an entirely new set of furnaces. Of course, you would have the problem of storing everything up and shutting everything down all day. But we don't normally shut down unless we have to, but then it might be six months. That is a possibility if by chance there were a significant improvement.

There are a few other applications but nothing of great consequence. The only one that I see in the petrochemical plant in the temperature range that you are dealing with here is an olefin furnace. Thank you.

Comment - I wanted to make you aware, as I'm sure many people are, that there are other collectors available at the lower temperature ranges, for instance 400° to 600°F. Of course, those systems even today are projected to say $25 to $32 per square foot. In the applications for some of the lower cost systems you were talking about, they would be quite possible.

Mr. McBride - Yes, we do have a near-term problem. By that I mean ten years. We do have a problem with plants that are built with a balance between our needs for electrical power generation and process heat. But we have been pretty successful in coming down to this low-pressure steam requirement. Consequently, in a couple of our big complexes, like Puerto Rico and Texas, the big problem is to stop the venting of the low-pressure steam because we don't have any need beyond what has been built in. We'll say we'll shut that down and rebuild the complex. But you are talking billions of dollars to rebuild those complexes, and it's a long-term thing. So, right at the moment, I would say we already have in place the distribution systems in our complex. That would be an inhibiting factor.

Comment - I just want to make people aware that there are collectors in the lower temperature range and much nearer so-called commercialization in the central receiver system.

Mr. Whaley - We have a couple of comments with respect to the percentage of contribution to the total cost in the process industries of energies of feedstocks and, I believe, I heard a figure mentioned by somebody. Maybe, Bob, it was you--it was something like 25 percent of the total cost was represented by feedstocks plus external energy. Is that right?

Mr. McBride - That's the number that we use in our advertising. I don't exactly check them. I'm not sure just what that is, but it is on the order of 22 or 28.

Mr. Whaley - Do you know approximately what part of that may be energy versus feedstock costs?

Mr. McBride - It's about an even split. As I pointed out, some of the raw material is really fuel, but masquerades as well as feedstocks. For example, hydrogen-methane is broken away in the ethylene furnace and in our Texas City complex, one-third of the input in our mixed fuel header cuts hydrogen-methane from the separation unit.

Mr. McBride - I'd just like to say that I don't think I made it clear that the petrochemical industry is natural gas oriented. We use a combination. Present-day split in our company is on the order of 65 percent gas to maybe 12 percent oil. So, this action in Congress, deregulating the price of gas, is the sort of thing the petrochemical industry will be watching and I think we will probably continue to stick with gas for process usage and feedstocks. Although there is a lot of talk about it, in our case, we don't use much oil. We use about 75 percent gas and about half is purchased. And, even throwing in power and coal and all the rest, two-thirds of it is natural gas.

Mr. Curto - I have a couple of comments I'd like to make. The low-temperature concentrator, the troughs, are going to be available shortly in the cost range of probably $15 a square foot. The latest DOE contract was let fora system at $19 a square foot. They are coming on in cost and production. But the central receiver components would probably be a lot less than that and collect a lot more energy.

In my paper, there are some comments I'd like to direct to the industry people here. We don't know how much land you have at your sites. You need to have land to do anything solar at your existing sites, and if you plan to expand, plan it in areas where you have some land or some flexibility in getting land that's close by. You should consider 20 to 30 years from now. I wasn't talking about $6 to $10 dollars IBP for the raw energy. That's your energy. It's your work piece. You have to go through some efficiency. At higher temperatures you get lower efficiencies; at lower temperatures you get higher efficiencies, as you well know.

Now, let's talk about the cost of solar. If you're in the southwest you have insolation of about a million Btu's per square foot per year. You can collect about half that at the work piece. That's a good healthy amount of insolation. That means two square feet are going to collect about a million Btu's. Now your economics--you could work out straight from there and you can use any kind of an economic scheme. You are going to get something between about a 3-year pay-back for some extremely good cases and a 10 to 15-year pay-back for other cases. But always consider using the idea of a hybrid. You are not going to be able to get radiant heat at the temperature you want all the time; in fact, very rarely will you be able to get it at one kilowatt per square meter insolation. Bear that in mind. Therefore, I don't think the hybrid systems are going to be near term. I believe that your fuel saver mode, that is, considering the thing as a fuel saver, is very, very important and probably the most near-term of all the solar applications.

The low-temperature applications are important, too, if you have steam in mind. Low-temperature with the central receiver will look good once they start building them. But let's get them built. Let's get these mass production facilities up. We've got to get some kind of consortium together to get cost-effective and you've got to put out at least 50,000 units a year of heliostats. Those things cost $4000 apiece, or something on that order, and keep that in mind too. You've got a healthy investment involved. A lot of capital has to be put together. That's a large number of systems. You don't know the solar industry and the solar industry doesn't know you. Let's try to get this worked out and try to build an industry that can grow to multibillion dollar levels very shortly. Thank you.

Mr. Whaley - Jack, what are your experiences involving energy costs and that sort of thing?

Mr. Mulloy - First I'd like to characterize the typical petrochemical complex. These are huge in size with very high capital investments and are located close to market, cheap transportation and water, and a cheap source of raw materials. The major portion of this industry is located along the Gulf Coast, Mississippi River Valley, north central states, and the central mid-Atlantic states. These are not areas notoriously noted for their insolation values, except maybe the Gulf Coast, but even on the Gulf Coast, I've seen many, many days of haze. In Michigan my experience has been that we have on the average of 60 full days of sunlight a year. If you count the half days, we may have 90 half days of sunlight.

The characteristics of chemical processes are that they are energy-intensive, use very large quantities of heat and power, require a large capital investment, are large-capacity, continuous-operations, and average 5 to 10 years in technology and age in existing plants. Most present-day facilities were built during times of relatively low energy cost. Today's emphasis in new facilities is being placed on the construction and operation of energy-efficient plants. We are considering alternative energy sources. We concentrate on heat recovery and process improvement. As energy costs continue to escalate, the chemical industry will phase out old processes and new processes will be brought on-stream. Our experience in the past 10 or 15 years has been that by paying proper attention to housekeeping and process improvement, we have been able to reduce our energy consumption per pound of product by about 20 or 25 percent.

Dow Chemical is the third largest chemical company in the United States. Our Texas Division facility is located in Freeport, Texas. Our Michigan facility is located in Midland. They are perhaps the two largest petrochemical complexes in the United States. The Michigan Division is about 1200 acres. We do have a little land out in the countryside. The Texas Division is about 2000 acres and we don't have any place to go there. There is no place to expand in California. You folks in California know of the experiences we had out there. The company has the capacity for generating 2000 megawatts of power. We generate over 20 million pounds of steam per hour. We are the largest cogenerator of industrial power in steam in the nation. But a breakdown of our steam requirements indicates that 50 to 60 percent of our process heat requirements can be met with 150-pound steam, 22 percent with 250-pound steam, and the balance with 500-pound steam.

As Bob pointed out, high-temperature, high-pressure steam is very seldom used for chemical processing. It's used for shaft horsepower, vacuum jets, turbines, pumps and that sort of thing. All high-pressure chemical processing is usually accomplished by direct-fire furnaces or with some form of heat transfer fluid reboilers. If Dow would consider high-temperature heat, the central receiver tower, we would also have to consider cogeneration in this process. Now, with the exception of power generation, and again this is my personal opinion, I can't say that we have much application in our operation for the 3000° or 4000° heat. To use this heat, we would have to parallel what the solar people are doing: redesign our plants, and come up with radically new designs for chemical reactors, kilns, and chemical processing equipment. All is not dark, though. Foster Wheeler Energy Development Corp. and Dow Chemical Company have recently been selected by the DOE, for Phase One design competition to design, install and operate a solar process steam facility in our Dalton, Georgia, plant. Hopefully by the next time we meet we will have something to show you. It's just up the road about 60 miles. We are going to use the steam for latex stripping. The demonstration will be designed to produce about 1500 pounds of 150-lb steam per hour. This will be about 10 percent of our steam requirements for that plant.

There is a lot of room for high-temperature solar heat, but this has to be looked at on a process by process basis. Thank you.

Comment - I'd like to emphasize his comment. I don't think anybody really knows what you are going after as far as the temperature and the geographics are concerned. I don't know if people know the process heat market in detail. We have recommended strongly that the DOE get into this and make a good analysis. We have used the Dow data. I think it's important that DOE get together a group of people from fossil-solar conservation and start looking at some of this.

Mr. Mulloy - The point I want to make is that decisions have been made, are in the process of being made, and will continue to be made that are going to impact our industry for the next 50 to 75 years.

Comment - I understand the petrochemical industry, in terms of new production is going to the Middle East. I understand that they are putting large investments in Saudi Arabia, in that area.

Mr. Mulloy - I don't think I'm saying anything proprietary, but about six months ago, it was announced that we were working on building a plant in the Middle East. Referring to our sad experience in California with the complex we were going to build across the river from our existing plant, when we found we couldn't build it there, we signed an agreement with the Saudi Arabians. I think this plant, or a similar plant, is going to be moved to the Middle East. Again, I don't have the figures but it's around a 500 million dollar petrochemical complex going in overseas.

Question - Do you see this as a trend for the future?

Mr. Mulloy - With the EPA regulations and actions of environmental groups, I don't see any way but for us to move. We had one experience in California where we had 65 permits to get and we got 4 and it cost us 4.5 million dollars. So, we just gave up. Karl can tell you the problems in building chemical complexes in New Jersey. I mean it's impossible. You can't build anything because of the environmental problems that you face. So, where else can we go.

Question - Would solar help?

Mr. Mulloy - You are going to run into the same thing with solar. You run into the primary environmental impact, which is enough, but then you run into the secondary environmental impact, people coming in and building roads, homes, sanitary systems, and that sort of thing. We ran into that on the Gulf Coast. The secondary environmental impacts were horrendous.

Mr. McBride - An individual product may grow, but on balance it's a relatively modest growth rate, taking into consideration the falling birth rate and the high cost of energy. Wholesale building of new complexes just for the trade-off between the capital cost factors plus the operating cost factors of solar versus the capital cost versus the operating cost of, say, natural gas, makes it hard to see who is going to be building all of these big complexes or where the money is coming from. Capital is likely to be a bigger problem than energy nonavailability. So, I don't really see a whole lot of petrochemical complexes going up in this country.

Mr. Rogan - I have a real quick statement. We have touched on several occasions about the cost of heliostats. I think that's way down stream on your cost-reduction curve and the number of units produced. In going through this we have fun with the electric utilities. They are biting the bullet first and they are starting us down that production curve. So, any more participation in the area of both industrial process heat and temperature range, I think, is a versatile concept.

Solar total energy has been alluded to by Jack Mulloy; he called it cogeneration. We can provide both electricity and process steam given the right balance of loads, plus the small system; not necessarily the 10 to 100 megawatts but in the area of one megawatt. All these things are going to have to come together and when they do you are going to be faced with the problem of not whether solar is going to compete with fossil but rather when that's going to occur. Thank you.

<u>Mr. Whaley</u> - That concludes our panel discussion.

SECTION XIII

CONCLUDING REMARKS

P. P. Turillon
International Nickel Company

The objectives of this workshop were twofold:

1. To identify industrial process experiments to be run on high-temperature solar test facilities, and

2. To determine who might design and run these experiments.

I would like to address these two objectives and to add a third comment regarding the important problem of cost of experiments.

Various presentations during the workshop have indicated that the use of high-temperature solar energy for industrial processes poses unique problems which must be resolved by experiments. For instance:

1. Materials resistant to high-temperature cycling.

2. Coupling of incident solar energy with the receiver operating at high temperature.

3. Long-term reflectivity of heliostats at high incident solar flux.

4. Overall efficiency of selected processes under actual operating conditions.

5. Ability of selected processes to withstand intermittent operation inherent to solar energy.

These are serious problems which cannot be resolved on paper, or by computer studies alone.

In order to carry out experiments of any value, it is essential to design them for specific reactions or products. Industry must cooperate with researchers from universities or government laboratories to provide specific boundary conditions for any given process. It is unlikely that industrial firms would devise and execute high-temperature solar experiments individually. I would rather suggest that they form teams with universities or government laboratories.

Finally, I would like to point out that design, construction and testing of experimental processes is a very costly operation. Since the supporting government agencies, as well as industrial firms, have limited resources, this means that it will be necessary to concentrate on a few large projects instead of many smaller ones. The decision to select one process from many prooposals will be a difficult one. Yet, to continue to disperse available funds over many small projects would slow down our efforts to develop an industrial process utilizing high-temperature solar energy.

CLOSING REMARKS

C. J. Bishop
Solar Energy Research Institute

I tend to agree with the comments that have been made during this conference and we do need your input. But, we have done enough paper and computer studies. Now we need to get to the practical experiments that will advance us down the road.

The solar thermal test facilities were not in existence before and many people don't know what they are. Our first objective is to make various groups knowledgeable of their availability and capabilities through the Users Association.

The second objective is, hopefully, to stimulate you to go back and talk to your basic research and laboratory people and let them know what we have, give them Frank's name, and tell them that if they have ideas they should contact him for more information. We are trying to stimulate the growth of a new industry. We are also trying to get university students involved, as you saw with Richard Zito this morning. He is now going to get involved. He may be the fellow who, 10 or 15 years from now, comes up with the answers.

I worked at Boeing before I came to SERI and we made a chart which showed the first Boeing airplane, which was in about 1915, and the 747 next to it; then it showed the present-day solar system with a question mark next to it. The point is that I think we are all working on the Model T's and the Model A airplanes right now. We don't know what's going to happen in the next 20, 30 or 40 years. We are looking ahead and, hopefully, developing systems to advance the technology and, as Marty says, establishing a technology base that will help us make solar really work.

The important point I want to make is that there are three ways we can try to use solar energy in the industrial world. One, we can try to use it with existing industrial processes to make existing products. I told you there will be a conference in Denver in October which will specifically address the subject of how to use the low- to intermediate-temperature solar technology to provide industrial processes right now. I encourage any of you who are interested, or any others from your companies, to attend and participate. If what they say is wrong, tell them, so they will not go down the wrong paths. If there are things that may be applicable, let them know.

The second thing we can try is to make the same products we use now but with different processes. Get your basic research people to consider how we can start with solar energy and make PVC, and have them provide a whole set of new processes.

An example of the third thing we can try was discussed by Dr. Skaggs this morning. He is trying to mate the sulfides and molybdenum but eliminate all of the current process steps. That is not something that will be introduced tomorrow in the industry. He realizes we have tremendous problems. How do you scale it up? How do you make continuous processes? But he is trying to prove the scientific feasibility of it. If we can prove that, then we can move into the engineering feasibility. It may be something that might find its way into the industry 20 years from now.

The last item is: Can we make new products using new processes? Solar energy has unique attributes that you cannot get from other energy sources. What can we make new?

Jim Schreyer mentioned using it to heat-treat surfaces, things we possibly cannot do right now. Bob Skaggs mentioned that he was getting silica and I was disappointed that he said nobody wants to buy it. But one of these days the solar research scientists are going to come up with these new products and that is what we are trying to encourage with the Users Association.

As Frank mentioned, we have some money to do these proof-of-concept experiments. I fully appreciate that big experiments are expensive; therefore, we need to do more proof-of-concept experiments. If it proves useful, and if it can be successful, and if it's important, DOE will find the money to make the big experiment happen.

What I want you to do is go back and mention this activity to the appropriate people in your companies and, if they have any questions, get back to us and we will try to answer them and give them further guidance. We'd like you to work with us, guide us in our direction, and with your problems.

We are trying to perceive the problems in your industry but it's difficult. We are outsiders looking in. Get some of your research people to participate in these meetings with us in the future so they can start bringing to the surface some of the problems that are bothering you. Hopefully, by working together, we can really make this thing happen some time in the future.

Go back and think about it and if you come up with any ideas call Frank, please.

Again, thank you very much for participating and we appreciate your being here.

AGENDA

SOLAR HIGH-TEMPERATURE INDUSTRIAL PROCESSES WORKSHOP

SEPTEMBER 27-29, 1978, ATLANTA, GEORGIA

WEDNESDAY, SEPTEMBER 27, 1978

INTRODUCTORY COMMENTS

CHAIRMAN: F. SMITH

GEORGIA TECH - WELCOME	J. WALTON, GIT
SERI PLANS AND PROGRAMS	K. TOURYAN, SERI
DOE PLANS AND PROGRAMS	G. BRAUN, DOE
STTFUA	A. HILDEBRANDT, U OF H
WORKSHOP PLANS AND OBJECTIVES	F. SMITH, STTFUA
SOLAR POSSIBILITIES FOR 500-2500°F	H. WEBB, AEROSPACE CORP.

SOLAR CENTRAL TECHNOLOGY STATUS/PLANS

CHAIRMAN: L. HILES

BARSTOW, CALIFORNIA, 10-MW SOLAR ELECTRIC PILOT PLANT	L. HILES, SLL
CENTRAL RECEIVERS	L. HILES, SLL
HIGH-TEMPERATURE CERAMIC RECEIVER	D. GRAY, BLACK & VEATCH
HELIOSTAT DEVELOPMENT AND COSTS	W. WILSON, SLL
SANDIA SOLAR CENTRAL POWER TEST FACILITY	F. SMITH, STTFUA
GEORGIA TECH SOLAR TEST FACILITY	J. WALTON, GIT
LUNCH: C. S. SELVAGE, US REPRESENTATIVE TO THE INTERNATIONAL ENERGY AGENCY SOLAR THERMAL PROJECT, "SOLAR CENTRAL TECHNOLOGY IN EUROPE"	
VISIT TO GEORGIA TECH SOLAR FACILITY	T. BROWN, GIT
WHITE SANDS HIGH-TEMPERATURE SOLAR TEST FACILITIES	R. HAYS, WSSF
MARKET ANALYSIS OF HIGH-TEMPERATURE SOLAR PROCESS HEAT	P. CURTO, MITRE

CHEMICAL CONVERSION AND TRANSMISSION OF SOLAR THERMAL ENERGY

CHAIRMEN: A. HILDEBRANDT, T. CHUBB

DOE CHEMICAL STORAGE AND TRANSMISSION PROGRAMS	W. WILSON, SLL
THERMOCHEMICAL CYCLES AND DISTRIBUTION OF PROCESS HEAT	K. KUGELER, HTGR INSTITUTE, W. GERMANY
INTERFACING METHANE-CARBON MONOXIDE CHEMICAL HEAT PIPE WITH SOLAR TOWER: PRELIMINARY DESIGN & ECONOMIC STUDY	J. RICHARDSON/S. DAS GUPTA, UNIV. OF HOUSTON

THURSDAY, SEPTEMBER 28, 1978

CHEMICAL CONVERSION AND TRANSMISSION OF SOLAR THERMAL ENERGY (CONT.)

PROCESS STEAM END USE FOR SOLAR ENERGY USING CHEMICAL HEAT PIPES	J. FLOCK, GE
ENERGY COLLECTION & TRANSPORT USING THE SO_3/SO_2 - OXYGEN THERMOCHEMICAL CYCLE, PF_3H_2 AS A POSSIBLE THERMOCHEMICAL FLUID	T. CHUBB, NRL
$NH_3/N_2\text{-}H_2$ THERMOCHEMICAL CYCLE	T. LENZ, CSU
AMMONIA-HYDROGEN SULPHATE STORAGE CYCLE	W. WENTWORTH, U OF H
CHEMICAL CONVERSION & TRANSMISSION SUMMARY & DISCUSSION	A. HILDEBRANDT, U OF H

CHEMICALS, FUELS AND PROCESS HEAT - I

CHAIRMAN: S. BEALL

DOE PROGRAMS IN HYDROGEN PRODUCTION	C. ENGLAND, JPL
SOLAR CENTRAL RECEIVER FOR PRODUCTION OF CARBON AND NITROGEN OXIDES	S. BEALL/H. GOELLER, ORNL
AMMONIA AND NITRATE FERTILIZER	D. WAGGONER, TVA, NATIONAL FERTILIZER RESEARCH CENTER
HYDROGEN BY THERMOCHEMICAL REACTIONS	C. BAMBERGER, ORNL
LUNCH: "DOE SOLAR THERMAL FUELS AND CHEMICALS PROGRAM"	M. GUTSTEIN, DOE

CHEMICALS, FUELS AND PROCESS HEAT - II

CHAIRMEN: J. DAFLER, T. WHALEY

PROFILE OF SOLAR CHEMISTRY	T. WHALEY, IGT
SOLAR FLASH PYROLYSIS SYNGAS FROM BIOMASS	M. ANTAL, PRINCETON U
FUELS AND CHEMICALS FROM SOLAR-PRODUCED HYDROGEN	W. SUMMERS, WESTINGHOUSE
SOLAR APPLICATION & COST FACTORS IN PROCESS INDUSTRIES	K. GEOCA, SHELL DEVELOP.
FUELS AND CHEMICALS FROM SOLAR ENERGY	J. DAFLER, IGT
COAL GASIFICATION	D. GREGG, LLL
VERTICAL HIGH-TEMPERATURE SOLAR KILN	R. KRETSCHEK/W. MOORE, VEDA

CHEMICALS, FUELS AND PROCESS HEAT PANEL DISCUSSION

CHAIRMAN: M. GUTSTEIN

PARTICIPANTS: S. BEALL, ORNL
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F. LAXAR, BETHLEHEM STEEL
R. SPRAGUE, US BORAX RES.

FRIDAY, SEPTEMBER 29, 1978

CHEMICALS, FUELS AND PROCESS HEAT - II (CONT.)

TWO-DIMENSIONAL MELTING PHENOMENON IN SOLAR HIGH-TEMPERATURE PROCESSES	R. ZITO, U OF ARIZONA

METALS AND OIL RECOVERY

CHAIRMAN: R. BLIEDEN, ARCO

NITROGEN FERTILIZER PRODUCTION BY SOLAR THERMAL ENERGY	R. TREHARNE, KETTERING
ENERGY REQUIREMENTS AND POSSIBLE SOLAR USE IN METALS REDUCTION	R. BARTLETT, SRI
SOLAR ENERGY FOR HEAT TREATING	J. SCHREYER, UNION CARBIDE
ENHANCED OIL RECOVERY	J. ROGAN, MCDAC
MOLYBDENUM ORE REDUCTION EXPERIMENT AT ODEILLO, FRANCE	R. SKAGGS, LASL

COST/ECONOMICS PANEL DISCUSSION

CHAIRMAN: T. WHALEY

COST OF SOLAR VERSUS OTHER ENERGY SYSTEMS	PARTICIPANTS:	M. ANTAL, PRINCETON U P. CURTO, MITRE K. GEOCA, SHELL DEVELOP. R. MCBRIDE, UNION CARBIDE J. MULLOY, DOW CHEMICAL J. ROGAN, MCDAC
SUMMARY		C. BISHOP, SERI
		P. TURILLON, INCO
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September 27-29, 1978

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