AMMONIA DISSOCIATION
DISTRIBUTED SOLAR ENERGY COLLECTION SYSTEM
AND SOLAR THERMAL CONVERSION POWER PLANT

PHASE I: CONCEPTUAL DESIGN AND ECONOMIC ANALYSIS

A STUDY PROPOSAL
SUBMITTED TO THE
U. S. DEPARTMENT OF ENERGY
WASHINGTON, D. C.

BY

OLYMPIC ENGINEERING CORPORATION
1214 JOHN STREET
SEATTLE, WASHINGTON 98109

ENGINEERING
OLYMPIC
CORPORATION

1214 John Street · Seattle, Wa. 98109
(206) 624-9444
Cable Address: ENGINEERS SEATTLE

TABLE OF CONTENTS

1.0 INTRODUCTION AND SUMMARY

Olympic Engineering Corporation, in a joint venture with Rocket Research Company and the Australian National University, proposes to conduct a feasibility study of a solar-ammonia electrical power generation system. The proposed system uses a reversible chemical reaction employing ammonia for energy storage and transport.

There are several aspects of this system which make it unique in contrast to existing solar power systems. The working substance, ammonia, is readily available and has an extensive background of supporting information from the agricultural industry. The focal point collector utilizes a countercurrent heat exchanger to permit ambient temperature pumping to and from a distributed collector field. Completing the reaction at a high pressure allows for a reduction in reactor and storage volumes. Separation of the reactants and products can be done utilizing the existing thermal gradients within the system. The overall concept can be incorporated into an extended system utilizing power generation and agricultural chemicals.

An additional benefit which will result from this study will be the development of a broader base of information for determining the most effective approach to utilization of solar energy.

This unsolicited proposal describes a system study for the collection and utilization of solar energy using a reversible chemical reaction. The deliverable end product of this study will be a preliminary design schematic, a final report, and a computer program which can be used for the cost estimation and optimization of the overall design. In particular, the study will provide economic data which will allow a cost comparison of the concept of distributed solar energy collection system to competitive schemes such as central receiver plants or solar thermal conversion plants using working fluids other than dissociating chemicals.

One of the central concepts of solar-ammonia systems has been the work of Dr. Peter Carden of Australian National University. His studies have outlined the concept of a self-contained solar system which would be applicable to isolated communities like those found within remote regions of Australia. His basic system uses distributed collectors which contain individual dissociators that in absorbing solar energy, produce Hydrogen and Nitrogen from Ammonia. Storage of these products gasses, potentially in geologic formations would provide for a baseload power system. Proposed U.S. solar systems have considered only short term storage to be feasible for thermal fluid systems. Recombination of the Hydrogen and Nitrogen in a central reactor would produce heat which would produce steam for a conventional turbine-generator facility.

In general, two different solar concentrator concepts have been proposed by numerous investigators in the past: central receiver power plants with a heliostat field of articulated mirrors and an array of comparatively small parabolic dish mirrors with a multitude of heat exchanges at each individual focal point ("distributed system"). Parabolic trough collectors will be neglected since they do not provide the desired temperature range for power generation, although a solar ammonia patent exists using the two dimensional collectors (Reference 28). The efficiency of the systems mentioned above depends on the chosen working fluid. Helium, air, molten sodium, molten salts, hot oil, steam or water have been considered as heat transfer and/or working medium (listed here in the order of decreasing temperature capability). These fluids would be heated at the focal point of the distributed collectors and pumped to a central power plant where energy conversion to electricity would take place.

While small heat exchangers in the focal points of parabolic collectors are easier to build and require less advances in new technology than the receiver cavity in a central receiver power plant, distributed systems which use the sensible heat of thermal fluids suffer from inevitable energy losses by convection and radiation from the conduits which carry the hot heat transfer or working medium from the collector to the central power plant (Reference 14). Energy losses would limit distributed collection systems using thermal fluids to comparatively small power plants with no potential for expansion at a later time.

Energy losses can be avoided or at least minimized if the transport of energy between the collector and the point of use does not occur as sensible or latent heat, but in the form of energy invested in dissociated chemical bonds. Thermal losses are avoided and minimized because the chemicals are transported at ambient temperature. Also, the incoming reactants and the outgoing reaction products exchange heat.

Ammonia appears to be a very promising chemical for this application. Ammonia is a bulk chemical and produced and handled in huge quantities. Most of the technology for transporting ammonia or selection of materials is available. However, the study proposed here is expected to identify some technology gaps where additional experimental work is warranted.

1.1 Scope

The purpose of the proposed project is to develop and demonstrate the use of solar thermal power systems. To accomplish this objective, a solar power system with distributed collectors is proposed using a reversible chemical reaction for energy storage and power generation. In the proposed system, the working fluid ammonia (NH_3) is broken down into its constituents, nitrogen (N_2) and hydrogen (H_2) using a point focusing solar collector. The recombination of nitrogen and hydrogen will yield, at a later time, the energy of combination.

The project defined herein is proposed in order that the use of solar energy as a true alternative to other sources of energy can be demonstrated. In the long term, solar energy, one of the few renewable resources for electric power, represents the only feasible alternative to nuclear power. Solar energy is a renewable source of energy that is environmentally acceptable and also reliable. To that end, large scale solar energy systems are required if solar power is to take a significant part in our energy program. We propose the project detailed herein as a first step in satisfying the needs for further research and feasibility demonstration of large scale usage of solar energy.

2.0 REVERSIBLE CHEMICAL REACTIONS FOR DISTRIBUTED SOLAR ENERGY COLLECTION SYSTEMS

Reversible chemical reactions, or, more accurately, reversible thermochemical reactions, can be compared to the charging and discharging of a lead/acid battery such as the ones used in automobiles. For the solar system in the charged state, there are two or more chemicals which, when allowed to combine, release heat. The reaction product of that reaction can be dissociated again when solar heat is available (e.g. during the hours of sunshine) and in so doing complete an energy cycle. Reversible chemical reactions have found increased interest during the past years as a means of storing or transporting thermal energy. The study program proposed here emphasizes the transporting/transmission aspect as opposed to the storage aspect. However, a certain amount of energy storage can be designed into the system to study the feasibility of intermediate duty that is not available with competitive solar thermal power plant designs.

Reversible Chemical Reactions (RCR) have significant advantages over other methods for collecting energy in distributed solar energy systems. As the name implies, individual collectors in distributed solar energy systems are scattered over a large area. If sensible heat or heat of condensation were used to transport energy from the collector to the point of use, all piping leading from the individual collectors to the trunk lines and eventually to a central power plant would have to be heavily insulated to minimize thermal losses. An optimal plant size based upon insulation capability could be developed.

In contradistinction, after initial heat exchange of the hot dissociation products with the incoming cold reactants, the energy-laden dissociation products can be transported over long distances at ambient temperature with the loss of energy only being that required for pumping power.

2.1 Historical Background on Distributed Solar Energy Collection Systems

The need for a working fluid that exchanges heat at the focal point of a solar collector, but would not lose a significant fraction of the collected energy has been recognized. As an answer to this, various reversible chemical reactions have been identified by different groups of investigators throughout the world. In many cases the reversible chemical reaction mechanism served not only for transport, but as a means of energy storage.

Several specific aspects of this project are a result of initial work done by Peter Carden of Australian National University. This concept of a self-contained system is being developed at ANU and several subcomponents have been tested to assess the feasibility. Then, if it is shown to be justified, a complete prototype will be tested. To accomplish a transfer of technology for this project from Australia to the United States an alliance has been developed between Australian National University, Olympic Engineering Corporation, and Rocket Research Company to cooperate in the study, design and building of a prototype system in the United States. The transfer of technology from ANU to the United States Energy program is to be achieved through the U.S. and Australian offices of Olympic Engineering Corporation utilizing its skills in project management for completion of the project. Rocket Research Company supports the U.S. effort by providing a technical resource and fabrication facility to build the prototype.

The concepts which have been developed in the proposed solar-ammonia project are directed towards the development of a self-contained solar power system. The losses that are associated with distributed systems using thermal fluids are absent in this system because a countercurrent heat exchanger within the solar collector allows the transport of the fluids at ambient temperatures. By using a reversible chemical reaction, the dissociated products, nitrogen, and hydrogen, can be stored to provide for power generation to meet a demand cycle that is different from the solar supply. The proposed process is isobaric (300 atmospheres) which gives a minimum storage and operating volume as well as reduce pumping costs. Much of the basic technology which exists to describe the process comes from the agricultural (fertilizer) industry as well as from academic studies. The concept can be developed to result in an extended facility that is integrated with the agricultural industry for remote locations.

The reversible dissociation of ammonia for a distributed solar energy collection system has first been described by Carden and coworkers at the Australian

National University (References 1,2,3,4). The system looks very promising and additional investigations are justified as described in more detail in the main part of this proposal.

Ammonia dissociation is one of the reactions considered in a NASA-JPL patent application for temperatures boasting from parabolic trough collectors to higher exothermic temperatures above 600°K (Reference 28).

A similar system called "SOLCHEM" based on the reversible dissociation of sulfur trioxide was proposed by CLUBB at the U.S. Naval Research Laboratory (References 4 through 6). So far, none of the systems described above has been carried beyond the concept stage and no results on experimental work has been reported. Key components for the SOLCHEM system, such as the high-temperature SO_x catalyst (Reference 7) or the NRL storage boiler tank (References 8 and 9) are currently under development. A recent announcement in the Commerce Business Daily (9 March 1978, p 20) seeking a contractor to design and analyze chemical converter - heat exchangers for use on small solar furnaces indicates that additional work on this system is anticipated. By comparison, only preliminary work at ANU was directed at the development of components such as counterflow heat exchanges, ammonia dissociation meter, and a high pressure flow rate meter. The Fiscal year 1977 Annual Operating Plan for the Thermochemical Energy Storage and Transport Program (Report SAND77-8226) has identified "Energy Transport for Distributed Solar Systems" as a likely research program to receive future funding. It is believed that the program described in this proposal meets exactly the criteria established in that program plan. In the assessment of other investigators, "the ammonia cycle is attractive because of low corrosion and low toxicity" (Reference 6). Ammonia which can be handled safely on a large scale, has been used as fertilizer and raw material in the chemical industry, as well as having been used as a fuel to propel manned rocket planes and automobiles. There are numerous cold storage facilities which use ammonia as a refrigerant.

The use of reversible chemical reactions for the collection of energy in distributed solar energy systems shares some technology with chemical heat pipes on one hand and thermochemical energy storage systems on the other hand.

Chemical heat pipes have been proposed to transport thermal energy from nuclear reactors to points of consumption. Reactions proposed include methane reforming (Reference 10), sulfur trioxide dissociation (References 11 and 12), and cyclohexane dehydrogenation (References 13). As will be discussed in a following paragraph, none of these reactions is particularly suited for a distributed solar energy collection system.

2.2. Selection Criteria for Reversible Chemical Reactions

The selection criteria for a reversible chemical reaction to be used in a distributed solar energy collection system are as follows:

- High enthalpy of reaction
- Ideal reversibility without formation of by-products
- Frozen equilibrium outside the catalytic reactor
- All-liquid or all-gaseous system
- High exothermic operating temperature
- Cyclic as opposed to steady-state operation capability

The relative importance of these criteria is discussed one by one in the ensuing paragraphs. The criteria are similar to but in many respects different from criteria used in the selection of reversible chemical reactions for thermochemical energy storage systems (Table 2-1).

2.2.1 Enthalpy of Reaction

A high enthalpy of reaction is desirable in order to minimize the amount of chemicals which have to be pumped through the dissociating reactor in the focal point of the collector and the adjoining piping system. A highly exothermic reaction translates into a more compact and, therefore, more economical system with a minimum of parasitic power requirements during operation. If large quantities of gases and liquids had to be moved to transport the same amount of energy, the heat exchangers, pipes, compressors and storage tanks would have to be sized much larger and more work would be required to overcome the pressure drop and frictional losses.

For practical reasons, the selection is restricted to reactions which do not include solid constituents. Transporting solids, as a slurry or a fluidized bed,

TABLE 2-1

SELECTION CRITERIA FOR CES SYSTEMS

- REVERSIBILITY OF REACTION $A \rightleftharpoons B$
- REACTION ON DEMAND, FROZEN EQUILIBRIUM OUTSIDE OF REACTOR
- SEPARATION TECHNIQUE FOR PRODUCTS
- ENERGY STORAGE CAPACITY Btu/lb J/g
- ENERGY STORAGE DENSITY Btu/cu. ft. J/cm^3
- HIGH EXOTHERMIC TEMPERATURE
- LOW ENDOTHERMIC TEMPERATURE

  WITHIN THE LIMITATIONS OF THE SECOND LAW OF THERMODYNAMICS
- OPERATING PRESSURE
- PRESSURE DEPENDENCE OF EQUILIBRIUM
- STORAGE PRESSURE OF REACTANTS
- HANDLING CHARACTERISTICS
  - STORABILITY
  - CORROSIVITY
  - TOXICITY
  - FLAMMABILITY
- REACTANT AVAILABILITY AND COST
- SYSTEM COMPLEXITY AND COST
- ABILITY TO ACT AS ENERGY TRANSPORT MEDIUM
- INTEGRATION WITH AIR CONDITIONING/COOLING SYSTEM

V02642

Table 2-1

Energy Content of Candidate Chemical Energy Storage Reactions, Excluding Those Containing Solids

Reaction exothermic $\rightleftharpoons$ endothermic	Reaction Enthalpy at 298°K (77°F)		Temperature (°K) at which	
	Ws/g	Btu/lb	90% Formed	90% Dissociated
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(L)$	7,345	3,160	–	–
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(G)$	6,053	2,604	754	1,466
$C_2H_4(G) + H_2(G) \rightleftharpoons C_2H_6(G)$	4,561	1,962	841	1,205
$2\,CO(G) + 2\,H_2(G) \rightleftharpoons CH_4(G) + CO_2(G)$	4,118	1,772	778	1,152
$CO(G) + 2\,H_2(G) \rightleftharpoons CH_3OH(L)$	3,996	1,718	345	434
$N_2(G) + 3\,H_2(G) \rightleftharpoons 2\,NH_3(L)$	3,861	1,661	–	–
$N_2(G) + 3\,H_2(G) \rightleftharpoons 2\,NH_3(G)$	2,695	1,159	346	528
$2\,NO(G) + O_2(G) \rightleftharpoons N_2O_4(L)$	1,750	753	549	930
$SO_2(G) + Air \rightleftharpoons SO_3(G)$*	1,544	644	806	1,270
$SO_2(L) + 1/2\,O_2(G) \rightleftharpoons SO_3(L)$	1,517	652	792	1,235
$SO_2(G) + 1/2\,O_2(G) \rightleftharpoons SO_3(G)$	1,235	531	792	1,235
$NO(G) + 1/2\,O_2(G) \rightleftharpoons NO_2(G)$	1,243	535	549	930
$CO(G) + Cl_2(L) \rightleftharpoons CO\,Cl_2(L)$	1,172	504	628	881
$NO_2(G) + NO_2(G) \rightleftharpoons N_2O_4(L)$	932	401	288	381
$SO_3(L) + H_2O(L) \rightleftharpoons H_2SO_4(L)$	885	381	535	723
$SO_2(G) + Air \rightleftharpoons SO_3(G)$	727	313	806	1,270
$NO(G) + 1/2\,Cl_2(L) \rightleftharpoons NO\,Cl(L)$	695	299	425	819
$H_2O(L) + H_2SO_4(L) \rightleftharpoons H_2SO_4 \cdot H_2O(L)$	279	120	–	–
For comparison: $H_2(G) + 1/2\,O_2(G) \rightleftharpoons H_2O(G)$	13,423	5,775	2,830	5,600

*Based on SO_2 weight only. Air open cycle.

V02529

ENERGY STORAGE CAPACITY OF CES REACTIONS

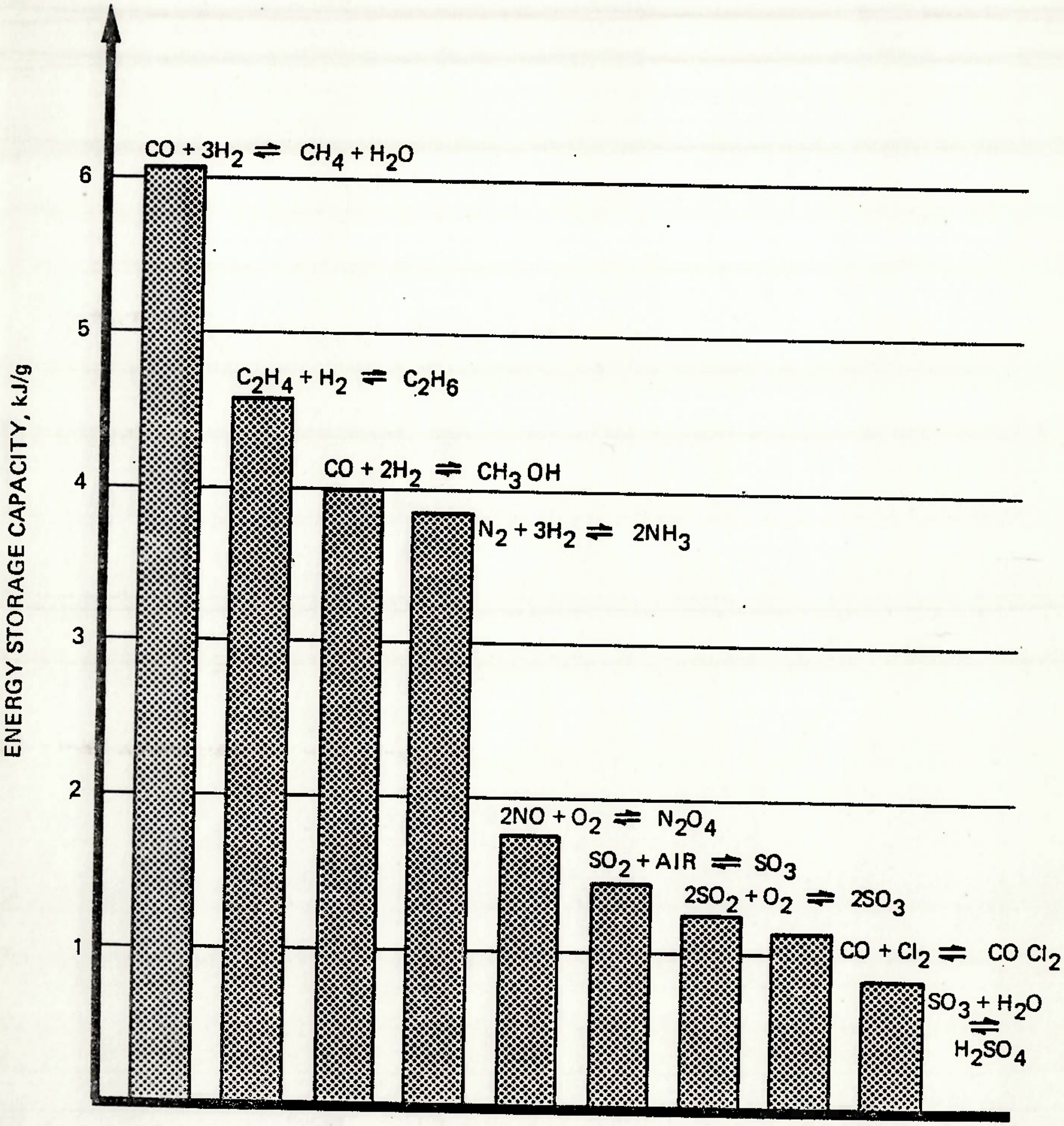


Figure 2-2

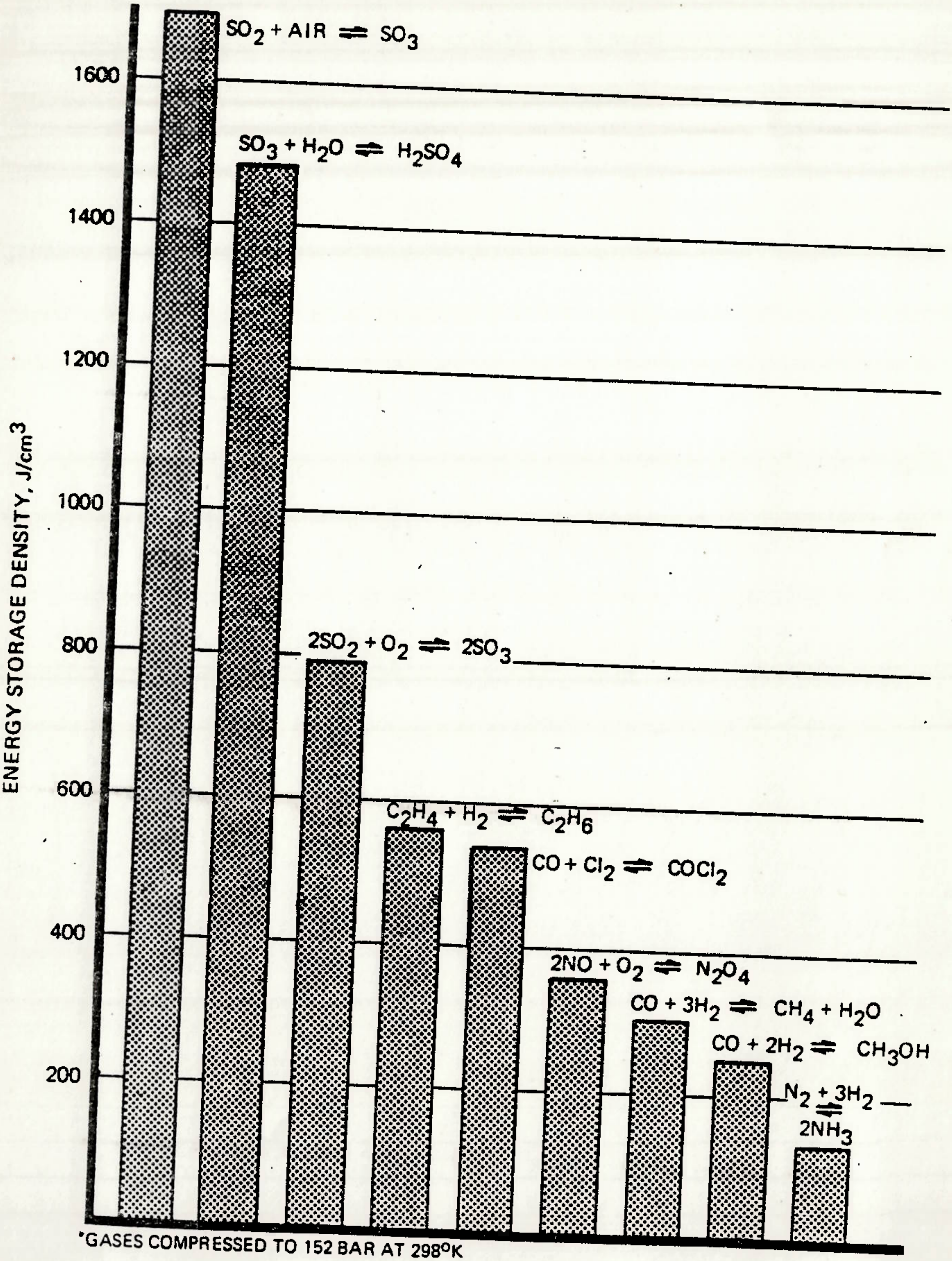
to and from the distributed reactors is viewed as a significant and possibly insurmountable technical problem.

Candidate reactions are listed in Table 2-1 and illustrated in Figure 2-2 in the order of decreasing energy content on a mass unit basis. As can be seen from these data, the ammonia dissociation reaction ranks among the top four reactions in terms of energy content per unit mass. For other reasons which will become obvious as the discussion progresses, the organic compounds with their multitude of possible by-products are less suitable for a distributed solar collection system, leaving the ammonia reaction as the prime contender for this application.

Rather than ranking candidate reactions in terms of energy stored per unit mass, similar tables and graphs can be arranged by energy stored per unit volume. As shown in Figure 2-3, the ammonia system ranks very poorly as a chemical energy storage device. This may be one reason why very little effort has been devoted to this reaction up to this time because until now the emphasis was on storage density and not on energy transportation ability for distributed systems. Its value as the working fluid for an intermediate duty system (3 - 6 hours storage) will be investigated during the study.

Discussing the various reactions listed in Table 2-1, beginning at the top, the steam reforming methanation reaction is plagued by various possible irreversible side reactions, shown in Table 2-2. In particular, carbon deposition tends to foul the catalyst beds and heat transfer surfaces, necessitating frequent

ENERGY STORAGE DENSITY* OF RCR REACTIONS



*GASES COMPRESSED TO 152 BAR AT 298°K

Figure 2-3

Table 2-2

METHANATION REACTION AND POSSIBLE SIDE REACTIONS

- HIGH ENERGY CONTENT
- REACTANTS VERY LOW COST
- FLEXIBLE CHARGE/DISCHARGE RATES AND ENERGY IS TRANSPORTABLE
- SIDE REACTIONS CAUSE SEVERE INEFFICIENCIES

DESIRED REACTION:	$CO + 3H_2 \longrightarrow CH_4 + H_2O$
SIDE REACTIONS:	$CO + 2H_2 \longrightarrow CH_3OH$
	$CO + nH_2 \longrightarrow$ PARAFFINIC HYDROCARBONS
	$CO + H_2 \longrightarrow C_s + H_2O$
	$2CO + 2H_2 \longrightarrow CH_4 + CO_2$
	$CO + H_2 \longrightarrow HCHO$
	$2CO \longrightarrow CO_2 + C_s$

V02537

catalyst replacement and heat exchanger cleanout. The same problem is shared by the ethylene/ethane and the synthesis gas/methanol reactions.

Catalyst problems - In the case of the methane steam reforming/methanation loop, an additional complication is caused by nickel carbonyl formation if any one of the endothermic or exothermic reactors is allowed to cool below the operating temperature in the presence of carbon monoxide. Nickel carbonyl, a highly toxic,very volatile liquid, does not form as long as all reactors are kept at high temperature. However, a distributed solar system undergoes numerous daily cycles and cannot be operated at constant temperature as can a nuclear reactor. Besides constituting a toxicity hazard, nickel carbonyl also acts as a vehicle carrying catalytically active nickel throughout the system and depositing it in places where catalytic action is not desired. Catalyst contamination in the heat exchangers would drastically reduce the efficiency of the system and the requirement of frozen equilibrium outside the catalytic reactors would no longer be satisfied.

The nickel carbonyl problem can be avoided by heating and cooling the reactors in an atmosphere of pure hydrogen and steam. Incorporation of a purge gas system to do this would unnecessarily complicate a distributed solar energy collection system.

None of the above problems is encountered when the reversible ammonia dissociation is chosen. Catalysts for the dissociation and snythesis of ammonia are commercially available, although some improvement is possible in the area of heat transfer in packed bed reactors employing such catalysts.

Selectivity - The main advantage of the reversible ammonia dissociation is the fact that it proceeds completely free from by-products. In addition, ammonia is the only thermally stable hydronitrogen compound. All other hydronitrogens, such as hydrazine, hydrogen azide or diimine are thermally unstable and decompose readily at temperatures at which ammonia synthesis takes place.

Exhaustive studies were conducted in search of reversible chemical reactions for energy storage and transportation applications (References 15 through 19). The typical methodology for selecting reversible chemical reactions for energy storage applications is outlined in Figure 2-4. A similar methodology is being applied to identify reactions for energy transportation systems. The conclusion of all data obtained to date is that the ammonia dissociation system is indeed a very promising candidate for the collection of energy in a distributed solar energy system.

2.2.2 Equilibrium Thermodynamics

The thermodynamics of the dissociation of ammonia and the reverse reaction, the synthesis of ammonia, have been thoroughly investigated and are frequently used as textbook examples for the las of mass action, the explanation of equilibrium constants, and the illustration of the dependence of the equilibrium constant on temperature and pressure. The decomposition of ammonia proceeds in accordance with the following equation:

$$2\ NG_3(G) \quad = \quad N_2(G) + H_2(G) - 2695\ j/g$$

According to the LeChatelier principle, the equili-

METHODOLOGY FOR EVALUATING CHEMICAL ENERGY STORAGE REACTIONS

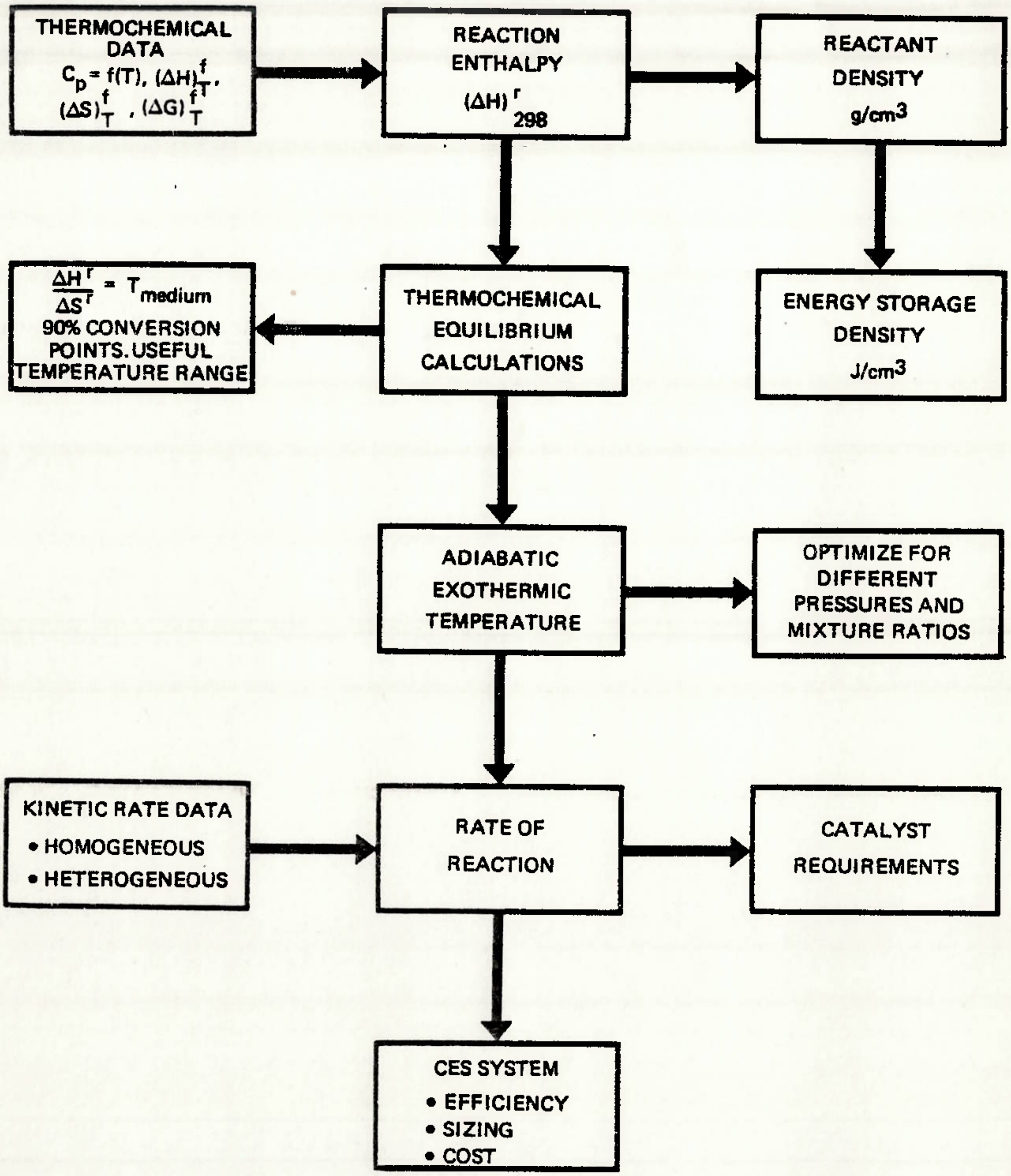


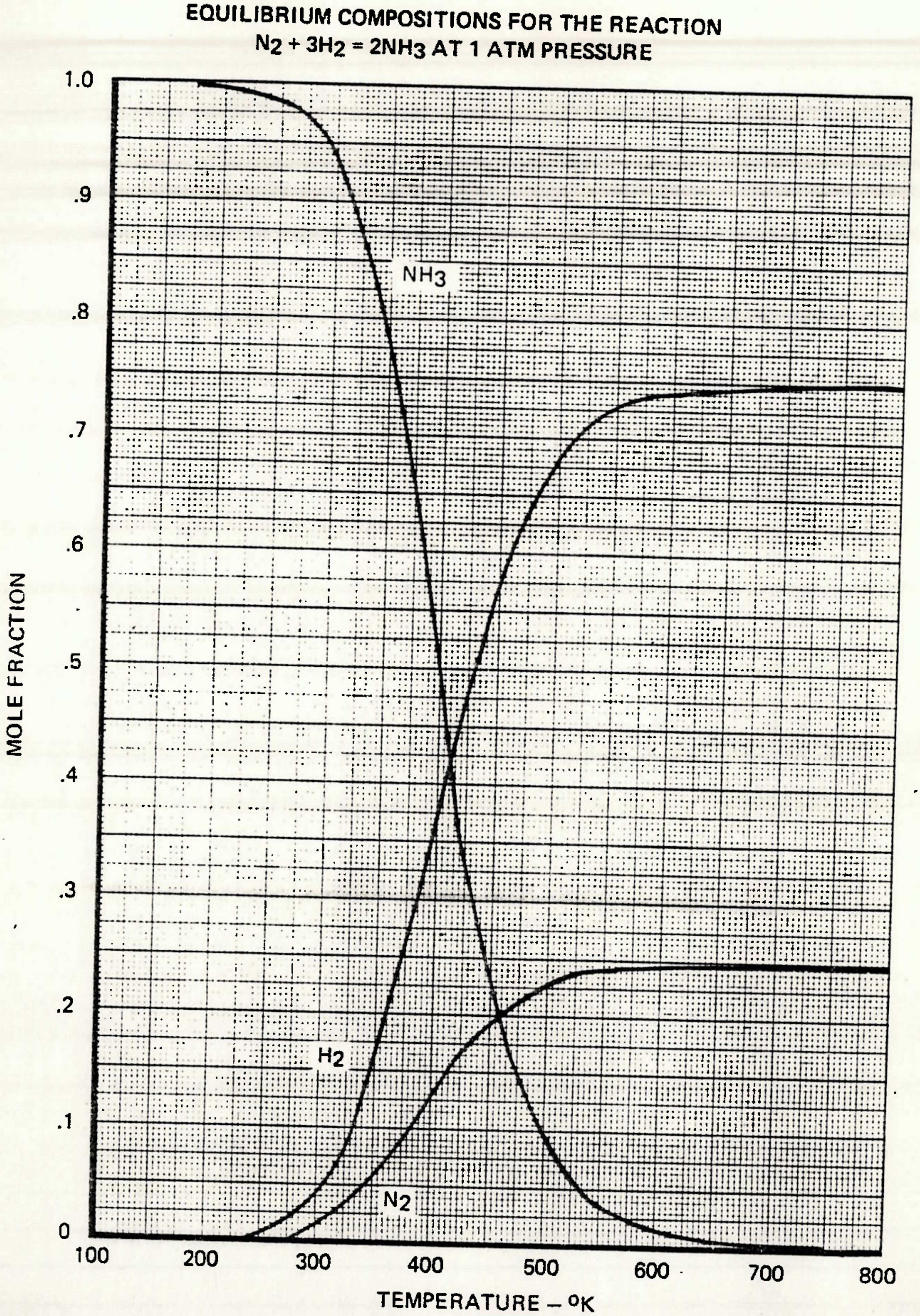
Figure 2-4

brium of a dissociated gas is highly dependent on pressure when there is a change in the number of molecules during the reaction. In the case of ammonia formation/dissociation this is extremely high; for this case two moles of ammonia dissociate into four moles of gas with a net change of 1 mole per mole of reactant. Hence, the ammonia formation/dissociation is very sensitive to pressure. This sensitivity can be used to advantage in order to shift an equilibrium condition in the desired direction. For instance, in the solar furnace dissociation reactor, it would be desirable to operate at low pressure in order to achieve maximum conversion. On the other hand, in the exothermic synthesis reactor, high pressure favors maximum ammonia yields. This is the basis of the HABER-BOSCH ammonia synthesis.

Equilibrium compositions in the ammonia/nitrogen/hydrogen system can be calculated using textbook thermodynamics. However, the calculation of the adiabatic reaction temperature requires a more elaborate computer program with numerous iterative processes. Rocket Research Company routinely uses the CECS 72 program developed by the Lewis Research Center of the National Aeronautics and Space Administration. Other computer programs on line at Rocket Research Company include the Naval Weapon Center Rocket Performance Program and the TIGER Detonation Code which accounts for nonideal gas behavior using the Becker-Kistiakowski-Wilson equation of state. All these programs will be available to predict performance of dissociation and recombination reactors in the distributed ammonia system.

When calculating equilibrium compositions in the ammonia/nitrogen/hydrogen system at high pressures such as 300 bar anticipated to be used in the distributes solar energy collection system, fugacity coefficients will have to be used to correct partial pressures from ideal gas conditions to non-ideal real gas conditions. The ratio of fugacity coefficients for ammonia synthesis is the correction factor to be applied to the equilibrium constant. Van der Waals forces cause the actual ammonia equilibrium concentration at high pressures and temperatures below 1000°K to be less than that predicted by ideal gas law.

The equilibrium compositions for ammonia dissociation at 1.01 bar and 300 bar pressure as a function of temperature are illustrated in Figures 2-5 and 2-6. As can be seen from Figure 2-5, under equilibrium conditions 90% of the ammonia is dissociated at 500°K.



EQUILIBRIUM COMPOSITIONS FOR THE REACTION $N_2 + 3H_2 = 2NH_3$ AT 1 ATM PRESSURE

Figure 2-5

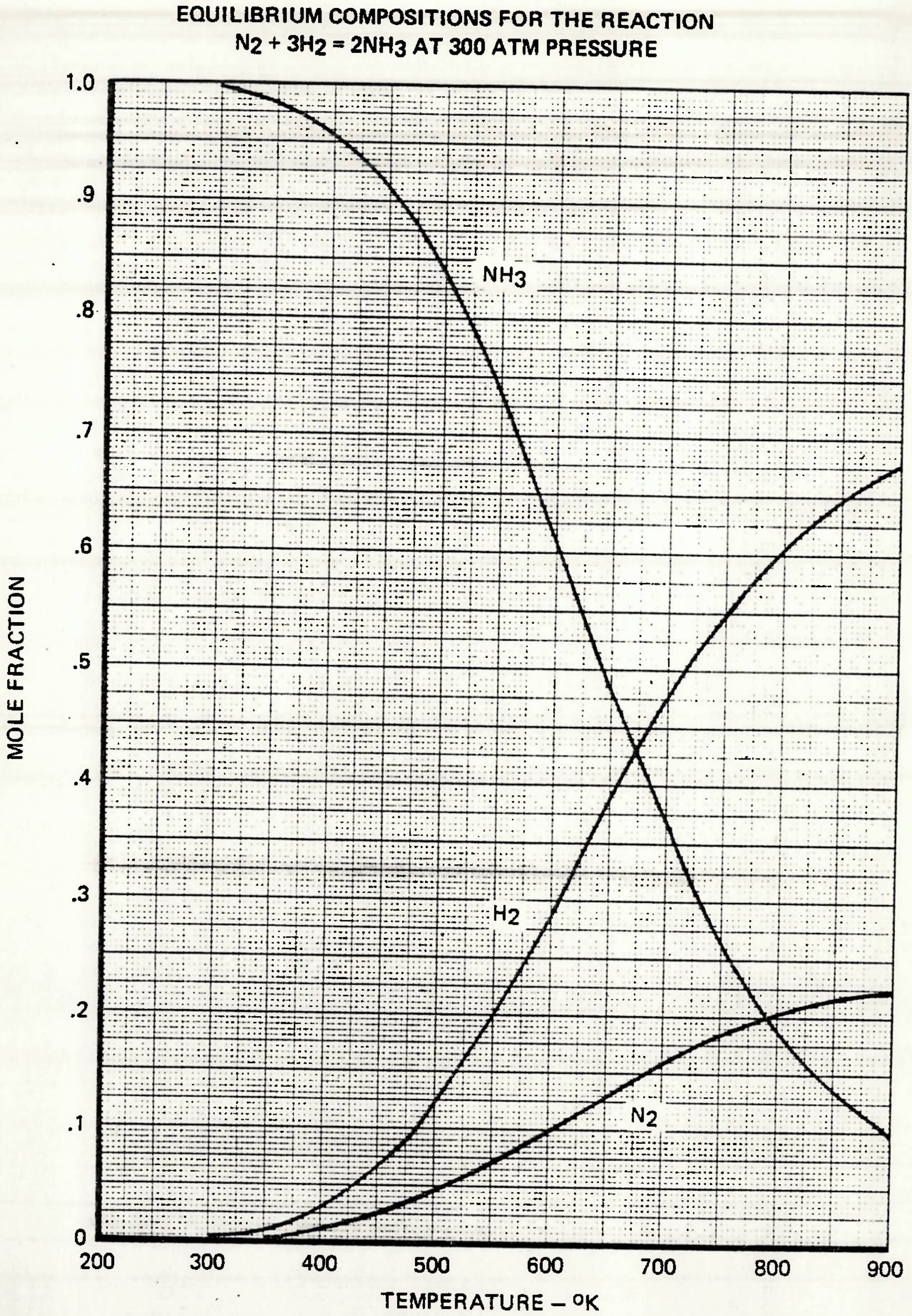

EQUILIBRIUM COMPOSITIONS FOR THE REACTION
$N_2 + 3H_2 = 2NH_3$ AT 300 ATM PRESSURE
MOLE FRACTION
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
200
300
400
500
600
700
800
900
TEMPERATURE — °K
NH_3
H_2
N_2

Figure 2-6

FRACTIONAL CONVERSION OF NITROGEN AND HYDROGEN TO AMMONIA AS A FUNCTION OF TEMPERATURE

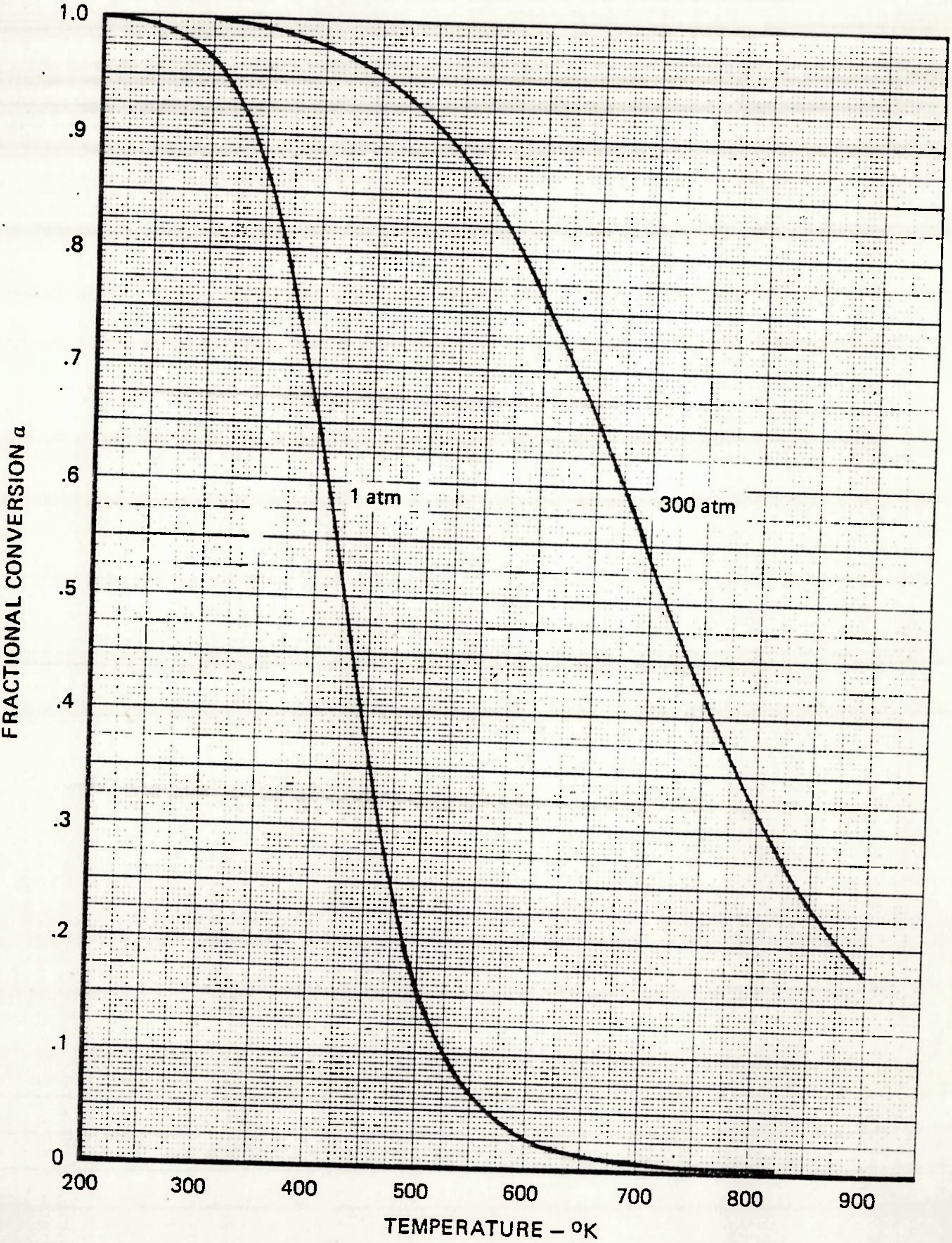


Figure 2-7

However, at 300 bar pressure, a temperature of at least $900^{o}K$ is required to achieve a comparable degree of dissociation. This is better illustrated by plotting fractional conversion as shown in Figure 2-7.

While it appears tempting to operate the dissociating reactor at low pressure and the synthesis reactor at high pressure in order to maximize conversion, one has to realize that the compression work required to compress dissociation products to synthesis reactor working pressure may result in excessive parasitic power requirements. These requirements would not fully be compensated by expanding the synthesis products through a turbine to the low dissociation reactor pressure. The initial system proposed by Carden (Reference 3) is an isobaric system with only minimal compressor requirements to overcome pressure drop.

The tradeoff between improved conversion and increased compressor work cannot always be decided based on point calculations alone. It requires an integrated computer model of the entire system to arrive at an optimum operating pressure for both reactors. For example, from the results of the study for the CESTOR model, an SO_x chemical energy storage system, the optimized operating pressures for the two reactors were closer to each other than a preliminary calculation had indicated. A computer model of the type described in paragraph 4.0 is, therefore, extremely useful not only in deriving dimensions and cost data, but also in optimizing the system operating parameters.

2.2.3 Kinetics

Under gaseous conditions and in the absence of a catalyst, ammonia decomposes very slowly. In many cases performance calculations involving ammonia dissociation were conducted where the finite rate of ammonia dissociation was neglected and it resulted in completely misleading conclusions. Extensive experience in the kinetics of ammonia dissociation and specifically in relation to the effects of supported catalysts is known by Rocket Research Company which is a leading manufacturer of monopropellant rocket propulsion systems that are based on the exothermic irreversible decomposition of hydrazine.

$$3\ N_2H_4 = 4(1-x)NH_3 + (1 + 2x)N_2 + 3xH_2$$

The variable x is dependent on the operating conditions of the catalytic reactor and has a pronounced effect on performance of the reactor as rocket (specific impulse) or gas generator (underwater buoyancy). Consequently, Rocket Research Company has studied geometries and catalyst arrangements which will maximize or minimize ammonia dissociation x, depending on the application of the hydrazine decomposition reactor.

The literature file for the project at this point already contains close to thirty references on heterogenous ammonia decomposition. Additional references will be retrieved using on-line computerized literature search services and the entire literature will be screened for the most suitable catalytic materials for this application and the kinetics associated with these materials.

The homogenous gas phase kinetics of ammonia dissociation and/or formation can usually be neglected in comparison to the heterogeneously catalyzed rates. Homogenous gas phase rates are several orders of magnitude slower than the heterogenously catalyzed rates. If this were not the case, the efficiency of the distributed collection system would suffer because some of the dissociation would reverse itself during cooling of the gases. Non-catalytic materials of construction must be chosen for heat exchangers downstream of the reactors in order to assure that the equilibrium composition remains frozen at the reactor outlet condition.

It can be seen from the above discussion that the question of kinetics is inseparably tied to the question of catalysis and catalyst selection for ammonia dissociation in a distributed solar energy collection system.

2.2.4 Catalyst Selection Criteria

Ever since the discovery of the HABER-BOSCH synthesis in 1910, a wide variety of catalysts have been tested for this application. A thorough survey of existing catalyst technology will be useful in the selection of a catalyst for the ammonia distributed solar energy system. The selection will most likely yield different criteria for the endothermic dissociator and the exothermic reactor.

Ammonia dissociation catalysts made of supported nickel are commonly used in dissociation reactors which provide a protective reducing atmosphere in electric furnaces for metallurgical operations, e.g., sintering or annealing. There is only a limited market for such reactors and the operating temperature is very low because ammonia is decomposed at ambient pressure. The catalyst for the solar ammonia dissociation will have to withstand much higher temperatures because the system will operate at a pressure of 300 bar. It is not known if existing catalysts will retain their activity under these conditions of pressure and temperature for any length of time, although experiments at the ANU have indicated the early performance criteria. Current ammonia synthesis reactors operate at temperatures as low as possible in order to optimize conversion to ammonia, hence, lifetime data from industrial materials under these conditions is limited. In commercial designs numerous heat exchangers are embedded in the reactor to keep the temperature low, and near optimum for maximum conversion. The energy released in the ammonia synthesis process is normally either used to preheat the feed gas or to generate steam for the associated steam reforming of hydrocarbon feedstock. A good part of the energy released in the commercial manufacture of ammonia is wasted. The prime objective in existing plants is to obtain a high yield of ammonia and not to generate high grade energy. The carnot efficiency of the power plant coupled to the exothermic reactor would improve significantly if the ammonia synthesis were allowed to proceed at higher than customary temperatures (at least in the upstream portion of the reactor). Again, it is not known if durability of currently available commercial ammonia catalysts will have reduced lifetimes if the reactor is operated at above nominal temperatures. A catalyst survey is proposed as part of the study program in order to identify possible technology gaps.

The selection criteria for a catalyst in the ammonia dissociator are more stringent than those for the ammonia synthesis/recombination reactor. The selection criteria for the ammonia dissociation catalyst are:

- Good conversion at high space velocity (a measure of dwell time of reactants in the reactor)
- Selectivity
- Thermal conductivity
- Thermal stability (retention of activity, lack of thermal shock effects, no shrinkage or sintering together)
- Ease of replacement
- Low cost
- No volatility of active metal

The selection criteria for the catalyst in the exothermic reactors are similar except that resistance to thermal shock is not as important.

Because the temperatures encountered in hydrazine decomposition reactors are much higher than those in ammonia synthesis reactors ($1300^{\circ}K$ as opposed to $730^{\circ}K$), Rocket Research Company has a significant amount of experience in selecting catalysts for high temperature operation in an ammonia/nitrogen/hydrogen environment. The same applies to the selection of nitridation resistant materials of construction (See paragraph 3.2.1). For space-limited applications in spacecraft, aircraft or submarines, it is imperative to select catalysts which can maintain high space velocities (high bed loadings) with good conversions. Other catalysts would result in bulky reactors which would occupy too much space. Similar space restrictions exist in the focal point of parabolic concentractors where every square centimeter occupied by the reactor is lost as concentrating area of the parabolic mirror because a shadow is cast on the mirror. For best performance, the dissociating reactor should be small and compact and should be located exactly in the focal point of the mirror. As long as supported heterogeneous catalysts are used, the limiting parameter, the weak link in the dissociator system is the poor heat transfer from the heated reactor wall to the catalyst surface where the endothermic reaction is taking place. Supported catalysts generally use porous ceramic carriers (aluminum oxide) which are excellent insulators, hence, very poor thermal conductors. Unless new technology catalysts are used, the dissociator reactors could be very bulky or sustain only very low flow rates.

New technology catalysts with improved thermal conductivity have been developed at Rocket Research Company. Two different approaches are possible to improve thermal conductivity in a heterogeneous catalyst bed: a so-called composite bed and a true monolithic catalyst. Both depend on the availability of open-cell metal foams.

In the composite bed, conventional granular ceramic-supported catalyst is embedded in a matrix of metal foam (Reference 20). The metal foam retains the catalyst and improves thermal conductivity throughout the bed. The result of this is that by incorporating metal foam in packed bed reactors, the useful lifetime of hydrazine rockets has more than tripled.

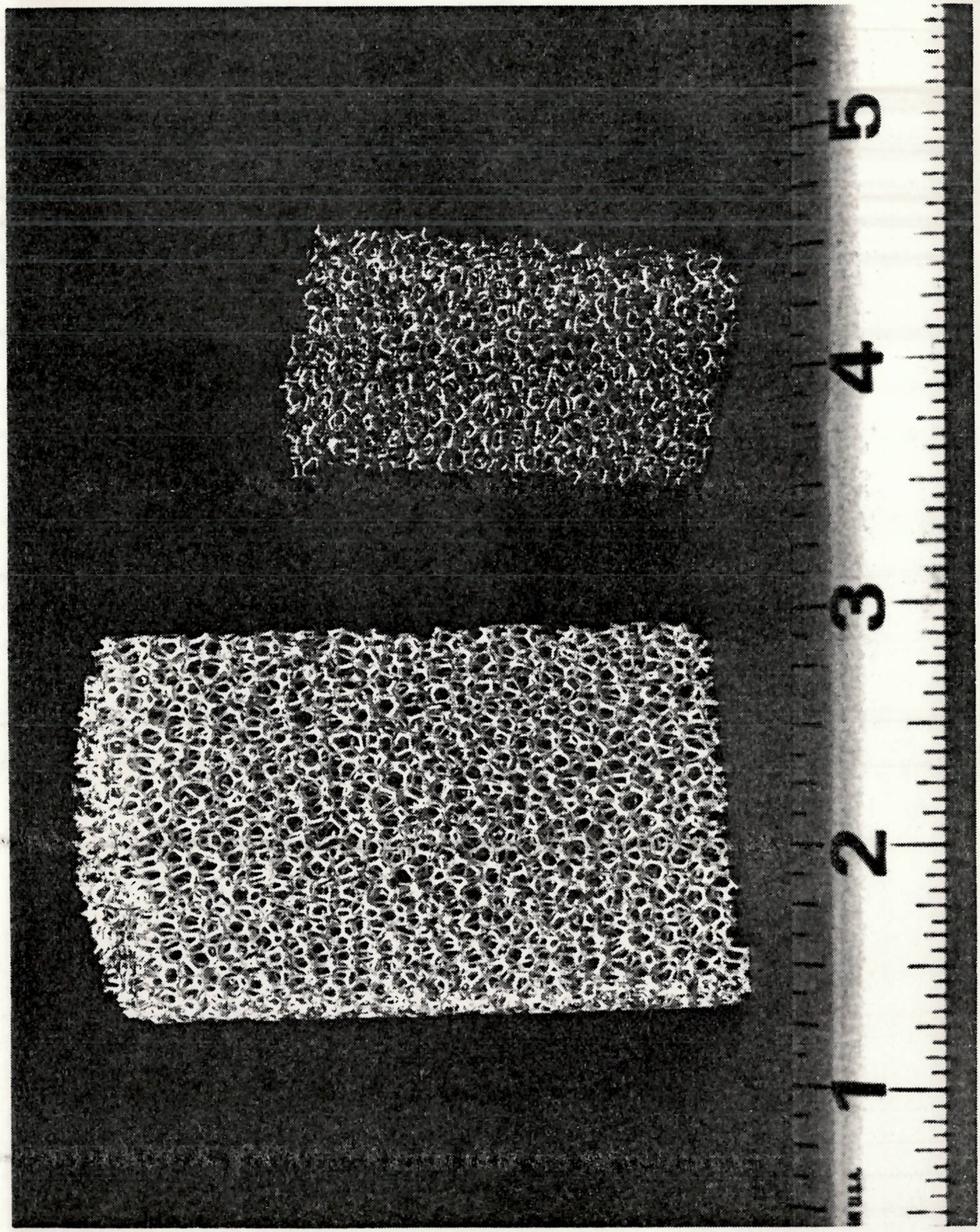


Figure 2-8

The monolithic catalysts carry a thin layer of catalytic material on a matrix of metal foam. See Figure 2-8 (Reference 21). During the development of monolithic catalysts for hydrazine reactors, nitridation resistance of the catalyst substrate became a very important evaluation criterion. The same nitriding condition prevails in ammonia dissociation reactors. Several materials have been identified which provide maximum catalyst integrity under such adverse conditions. Although typical operating times of hydrazine reactors are short in comparison to the required operating time of ammonia dissociation reactors, the same technology can be applied and metallic catalyst supports can be selected which will resist the nitriding conditions in the reactor.

Another advantage of monolithic catalysts is the low pressure drop compared to packed granular beds. A significant advantage in terms of turnaround time for catalyst replacement is the cartridge-type monolithic catalyst, which easily slides in and out of reactors regardless of their upside/downside/sideways orientation. Cartride catalyst replacement can be achieved in a fraction of the time required for replacing granular catalysts. Monolithic metallic catalysts proposed here must not be confused with monolithic ceramic catalysts such as those based on TORVEX^R or CELCOR^R currently used in automobile exhaust converters. The poor thermal conductivity of these materials would offer no advantage over packed bed reactors.

Ideally, a catalytic coating is sought which can be deposited on the inside of the dissociator tube in the focal point of the collector and which will provide an equilibrium conversion during a single pass through the reactor.

2.3 Integration of RCR Collection into System

2.3.1 Conversion to Electrical Energy

One of the principal considerations in the use of solar power is the possibility of conversion to electric power. In the thrust for energy independence,studies have been made which indicate that 1% of the surface area of the United States could provide all the Nation's energy needs by the year 2000. An NSF/NASA report indicates the possibility of reaching 10% of this goal by the year 2000. The primary problems associated with utilization currently are of an economic nature with technological advances being used to advance the most promising techniques into feasible methods.

The potentially feasible solar electric power systems utilize solar power to create thermal energy and then deal with the system as a conventional thermo-power cycle. Photo-voltaic systems which directly produce electricity without intermediate thermal-mechanical steps will not be discussed here. In the conventional system thermal energy is transferred by a working fluid to a turbine which drives an electric generator. In this way most of the power generation system is similar to a conventional nuclear or fossil-fuel plant.

The solar-ammonia process is a portion of the conversion from solar to thermal energy. The concentrating collector produces a high temperature region within the focal point. The size and temperature of the focal region depend upon the design of the receiver and reflecting surface. Employing ammonia as the working fluid uses a reversible chemical reaction to transfer energy within the thermal loop. The chemical reaction of dissociating ammonia to hydrogen and nitrogen is controlled by the physical conditions of temperature, pressure, flow rate, and catalyst within the dissociator. The dissociation temperature need not be the same as the synthesis reaction temperature allowing for the choice of various collector-dissociator configurations with fixed reactor designs.

One of the current funded projects using thermal fluids to convert solar to electric power uses steam at 900^{o}F and 1000 psig directly driving a turbine generator. Other options being considered are the closed cycle helium with a turbine inlet of 1500^{o}F at 500 psig and the open cycle air system at 1800^{o}F and 150 psig. These systems raise the fluid temperature before driving the turbine generator, and the energy storage is done as a thermal sink at these temperatures. Analyses of solar-thermal systems for electrical power generation indicate their current use is economically most cost competitive for intermediate-load applications (3 to 6 hours of storage for following daily load cycling). Optimization studies for thermal fluid systems indicate that the plant size should be near 100 MWt in regions of high solar insolation (southwestern United States). Specific solutions for RCR systems may dictate otherwise. Rocket Research Company's program on extended storage optimization will provide an evaluation of the storage capacity more suitable for RCR systems that can be utilized with this program.

The use of ammonia provides a working fluid and storage capability for baseload, intermediate load or hybrid plants.

In the current concepts of solar-thermal electrical power the dominant uncertainty is in estimating the cost of the heliostats. Current costs for prototype systems are well in excess of material costs because of the requirements for development testing and the refinement of manufacturing methods. For the case of an intermediate load system the cost of the energy storage and its attendant input/output efficiency is also of concern. Relating this to a reversible chemical reaction indicates that the storage of the working fluid can serve as the energy storage mechanism for the power system.

Current implementation studies have indicated that the major issue associated with solar thermal systems is the high initial cost and attendant problems of obtaining financing. The considerations for development will require analysis of the amortization schedules, tax incentives, and the relationship between private vs. public ownership.

2.3.2 Storage of Heat

The ability to store excess heat in a "buffer" volume of dissociated chemicals without actually losing heat offers a significant flexibility in operating the power plant in a load-following rather than baseload mode of operation.

Storage of heat is required for several reasons: primarily it is to keep the power plant operating during short occulations of the sun by clouds, but also to provide energy during transient periods in the morning and evening, when insolation is low but energy demand is high. The amount of mismatch between available insolation and demand load determines the amount of heat storage required. Rocket Research Company is currently conducting a systems analysis study to determine the storage requirements of stand-alone or hybrid (solar/fossil) power plants for a variety of geographical locations, using actual annual day-by-day insolation measurements and grid loads provided by electrical utilities (Reference 22). Preliminary results indicate that with some make-up heat provided by fossil fuels, storage requirements for seasonal operation are of the order of less than one hundred hours operating capacity at full load.

As this study progresses, it will provide valuable information which will help to define the H_2N_2 storage requirements (Figure 2-9, Mode 1) or possible fossil fuel (Mode 4) or hydrogen fuel (Mode 3) make-up requirements to keep the power plant operating around the clock throughout the year. Instead of rare fossil fuel, hydrogen gas could be burned to generate steam for the power plant (Mode 3). Another possibility is the use of ammonia itself as a fuel (Mode 2). The flammable range of ammonia in air is very narrow and it is difficult to stabilize ammonia flames on a burner, but if these problems were surmounted, ammonia could be burned to provide energy during the night hours. Of course, the source of make-up ammonia would depend on a water electrolysis and an air separation plant operated from surplus electricity during the daytime (Figure 2-8). The various modes

29014-59

AMMONIA DISSOCIATION DISTRIBUTED SOLAR ENERGY COLLECTION SYSTEM – MODE OF OPERATION SCHEMATIC

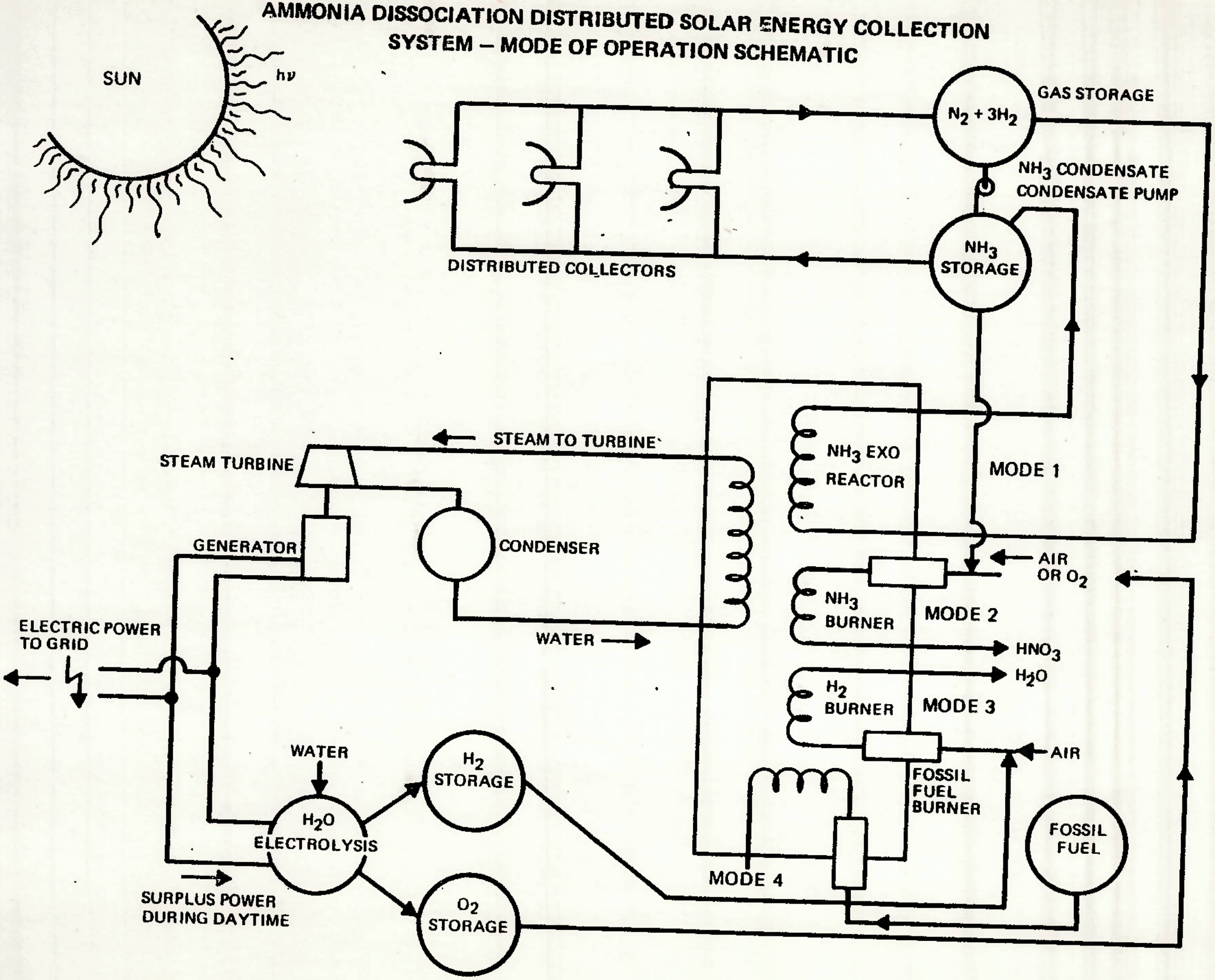


Figure 2-9

of supplemental heat for the boiler shown in Figure 2-8 would not all be used simultaneously. However, at least one of the modes 2 through 4 should be provided as a compliment to the baseline, but intermittent Mode 1.

2.3.3 Waste Heat Utilization

Waste heat utilization has become an established method for enhancing the overall efficiency of power generation equipment by refining thermodynamic cycles or utilizing previously wasted heat for other purposes. In addition the burning of waste material or other discarded residues has constituted a significant energy-saving method in solid waste and sewage treatment processes. Modification of processes requiring high temperatures for melting has become a requirement for improved energy use. Chemical processing plants which have exothermic reactions have now incorporated waste heat utilization techniques. Some specific examples of the above are: steel making using both electric arc and open hearth furnaces, H_2S combustion, refining furnaces, pyrite roasters, petrochemical cracking furnaces, ammonia combusion, sulphur combustion, zinc recovery, and glass melting furnaces.

Heat recovery methods for waste heat utilize heat exchangers can utilize energy for steam generation and superheating, water heating, organic fluid heating, gas to air heating and air to air heating. To accomplish heat transfer of this type there is a large field of literature on heat exchange from liquid to liquid, steam to liquid and fluid to vapor. This information is well detailed, being supported by empirical and analytical data. Much of this is in heat transfer literature as well as being available industrially as specifically designed heat exchangers.

The use to which the energy is put can take many forms. Steam cycles have been enhanced by using economizers, recuperators, and superheaters, along with extended thermodynamic cycles such as mercury upper loops and organic bottoming plants. Other uses of high temperature waste heat have included hospital sterilization systems and sewage heat treatment plants. Lower temperature heat sources have been adapted to absorption air conditioning and refrigeration, space heating, and desalting applications. The use of previously identified waste heat has been shown to be useful for improving the efficiency of existing thermodynamic cycles, adding additional thermal systems for new processes, or the direct use of the energy for heating purposes.

3.0 PRELIMINARY CONCEPTUAL DESIGN OF SPECIFIC COMPONENTS

Under this phase of the program, conceptual designs will be worked out for key components of the system, such as the solar concentrator, the tracking system, the endothermic reactor, the coaxial heat exchangers, the piping network, the separator, the exothermic reactor and the eventual storage requirements.

3.1 Solar Concentrator

The solar concentrator is conceived to be a point focusing device utilizing a reflecting surface to concentrate the energy to a receiver area significantly smaller than the capture area of the collector. The use of the two-dimensional trough collector is not to be a major part of the study. The parameters outlined by

Carden will serve as the starting point. In this concept, the dissociator will be mounted at focal point and be supported by the countercurrent heat exchanger projecting through the axis of the reflector surface. The concentration ratio (aperture to receiver area) and the physical size will be determined primarily by the trade-offs between heat transfer-dissociation rate, and structural support for wind loading.

The tracking system, weather protecting and other descriptive materials will be described in the following paragraphs

3.1.1. Reflecting Surface

Concentrating collectors can use either reflecting or refracting methods to achieve a higher energy flux into an absorber surface than is possible with flat solar collectors. The concentration ratio, that of the concentrator aperture area to the absorber area is commonly used as the primary characteristic to describe the projected performance. There are several areas of importance in the design of a reflecting concentrator which must be considered. The reflecting surface itself must have the required reflectivity to redirect the solar energy to the absorber, and its contour must be such that for the chosen design it can maintain the projected thermal performance. Longevity of the surface is of concern because it must be easily maintained at or near its initial reflectivity. Maintaining the surface will also require that the subsurface supporting design be stable with time and wind loading.

The contour design will be dependent upon the chosen operating temperatures and the cost trade-offs which must be made to require more or less sophisticated designs and tracking techniques.

A proposed method from the initial ANU studies uses individual concentrating collectors which focus to nearly a single point maintaining a 700°C dissociation temperature. The specific surface material has not been chosen, but the initial design studies indicate that the supporting contour can be stamped from a single metallic plate using existing metal-forming equipment.

3.1.2 Support Structure

The foundation, mounting, and positioning mechanism must be designed to resist wind loading, provide tracking mobility, and stow for reflector surface protection as well as include pipe and fluid control mounting. The foundation structure for the system should have the capability of being adapted to various soil grades from hard rock structures to loose soils. The mounting structures shall become a portion of the overall support system for the reflectors, dissociation tracking mechanism and piping. Olympic Engineering Corporation possesses the capability of designing integrated mechanical systems, orienting them towards minimum cost, optimum strength, or extreme environmental applications. One aspect of development of the support structure will include a careful analysis of the clamshell arrangement for collectors proposed by ANU. In this design two opposed collector systems would be supported upon a single foundation mount and would have the capability of being able to be closed upon each other for the evening cycle or adverse weather storage.

3.1.3 Tracking Mechanism

The choice of tracking method used is dependent on many of the factors chosen for the design of the system. In flat plate collectors it may be nonexistent or only involve a twice-a-year adjustment. For sophisticated control of concentrating collectors that must be stowed in the evening and for weather protection, a two-axis active closed-loop system controlled by a dedicated computer could be chosen although developments in microelectronics may become a future alternative. The need for a sophisticated tracking system is dependent upon the chosen design parameters, such as the requirement of accurate placement of a point focus upon a received area, the minimization of thermal shocks for non-optimal positioning, or the necessity for weather stowing during rapidly changing atmospheric conditions. The ability to link multiple distributed collectors to a central controlling system can provide the ability to distribute the cost of a sophisticated control system over a large number of individual collector systems.

The design of the central controlling system is initially expected to be high, but with increased size and numbers of installations the system cost can be reduced to be closer to that of the material costs.

The evaluation of active systems will include open and closed loop control systems. At ANU a tracking system with an active sunfollowing detector and solar drive mechanism is currently under development. This system is to be used with a central dedicated computer which will also handle the decision functions required for the overall plant operation.

3.1.4 Weather Protection

Weather protection for the collector system is related to protection from both adverse and normal weather conditions. In addition to this is the need to account for normal aging and maintenance. The need is present to insure that not only structural but also functional components such as piping, process control, and tracking systems are protected from adverse environmental effects.

The initial concept of weather protection relates to the need to protect the collector systems during storms which could both produce excessive wind loadings that may damage and upset the collector as well as blow sand or hail against the reflector surface degrading its performance. The size of the reflector may be limited more by the expected wind loading than the need to optimize the energy input per receiver element. Modeling will determine these trade-offs for the ammonia distributed collector system.

Normal weather conditons of rain, wind, and condensation can also act as a means of detracting from the performance. The high operating pressure of the design should preclude water or other material from leaking into the process piping. Normal wind loads for the chosen location will be included in the design for all support, pivot, and drive mechanisms. Consideration for evening condensation will be included as a normal requirement for the adverse weather stowing procedure.

3.2 Endothermic Reactor

The endothermic reactor requires a major new design effort because to our knowledge there are no existing dissociators in operation anywhere in the world. Key questions to be solved are those of heat transfer, chemical reaction rates within the reactor, and materials compatibility. Current experimental studies at ANU using electrically heated dissociators can serve as a basis for these studies. Currently used commercial ammonia dissociation furnaces operate at ambient pressure and comparatively low temperatures. These furnaces can accumulate several years of continued operation. Design information will be obtained from manufacturers of commercial dissociation units in metal treatment furances which may be useful in the design of corresponding high-pressure units.

A concurrent effort is currently underway by the U.S. Naval Research Laboratory to find a contractor qualified to design the sulfur trioxide dissociaton reactor for the Solchem system. Rocket Research Company believes to be in a prominent position to win this competitive procurement. Although the chemicals used are much different, heat transfer relationships are expected to be very similar for the two types of dissociators. Having work on both dissociators eventually being carried out within the same organization will provide mutual benefit to both programs.

Another application of ammonia dissociation reactors has been in an experimental automobile operating on liquid ammonia instead of gasoline as fuel. Improved engine operation was obtained with the pre-dissociated fuel/air mixture as opposed to ammonia/air mixtures alone.

3.2.1 Materials Selection

The success of the HABER-BOSCH ammonia synthesis hinged on the availability of structural materials strong enough to withstand the pressure and resistant enough to withstand nitridation and hydrogen permeation under reactor conditions. These problems have been solved so that materials selection for the exothermic reactor can be based on several decades of experience in the design of ammonia plants. In contrast to the exothermic reactor, the endothermic dissociator is exposed to a different set of conditions, strongly reducing/nitriding conditions on the inside and strongly oxidizing conditions on the outside. It appears that special alloys developed for aerospace applications will have to be selected to withstand this unusual environment. There are currently several super alloys which combine nitridation resistance with excellent mechanical strength at high temperatures. However, because rocket engines built from these materials usually operate in the vacuum of outer space, oxidation resistance is not a prime requirement. It is anticipated that this problem can be met by technology obtained by Rocket Research Company in the development of the gas generator for the auxiliary power unit in Space Shuttle Orbiters and Space Shuttle Solid Rocket Boosters. These catalytic reactors see intruding conditions on the inside and oxidizing conditions on the outside. The reactor shell is made from Haste-alloy-B which combines good nitridation with fair oxidation resistance. Better nitridation resistance can be achieved by going to alloys with higher nickel

MATERIAL NITRIDING EXPERIMENT – INCO 617

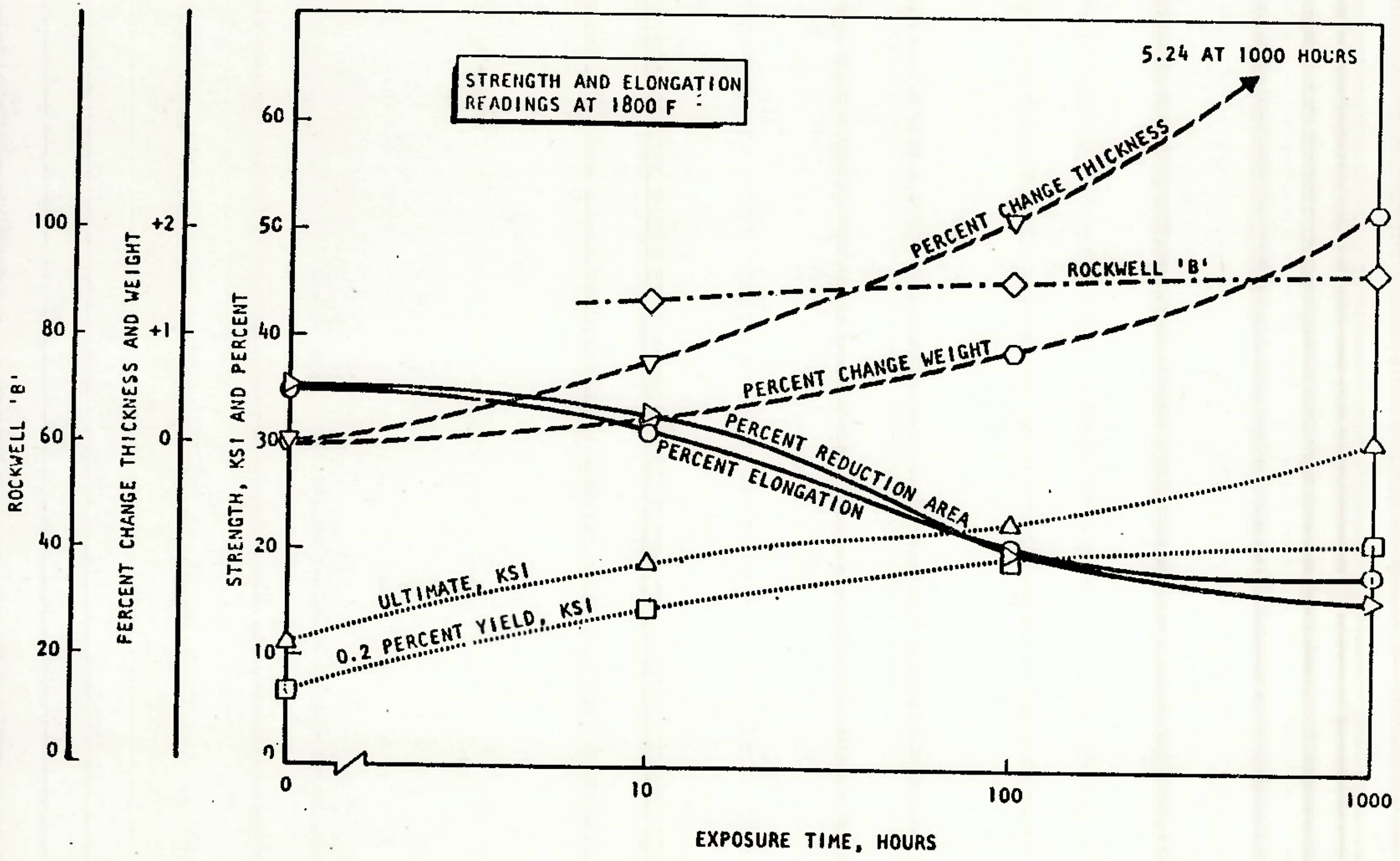


Figure 3-1

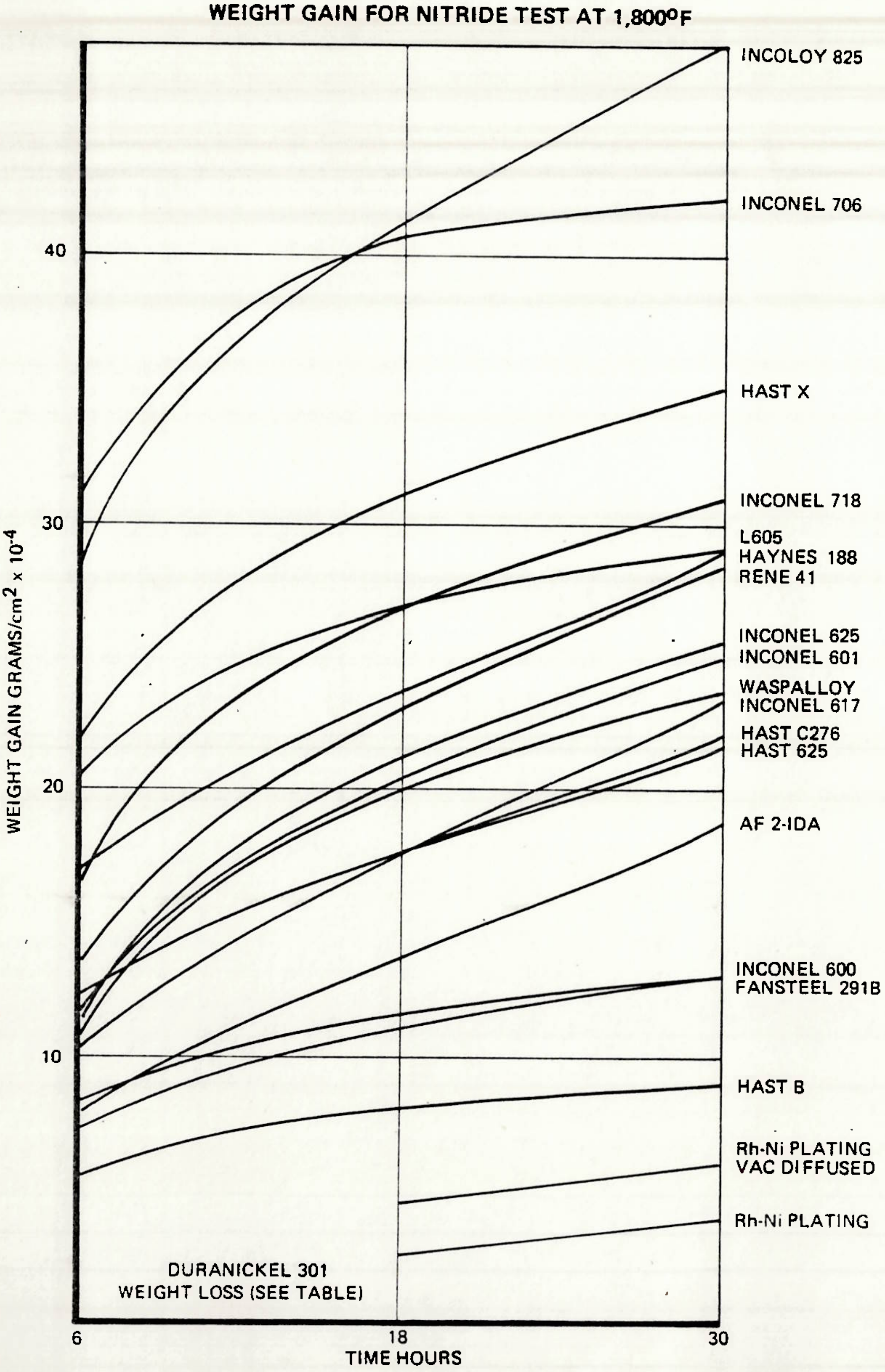

WEIGHT GAIN FOR NITRIDE TEST AT 1,800°F
WEIGHT GAIN GRAMS/cm² x 10⁻⁴
40
30
20
10
6
18
30
TIME HOURS
INCOLOY 825
INCONEL 706
HAST X
INCONEL 718
L605
HAYNES 188
RENE 41
INCONEL 625
INCONEL 601
WASPALLOY
INCONEL 617
HAST C276
HAST 625
AF 2-IDA
INCONEL 600
FANSTEEL 291B
HAST B
Rh-Ni PLATING
VAC DIFFUSED
Rh-Ni PLATING
DURANICKEL 301
WEIGHT LOSS (SEE TABLE)

Figure 3-2

11061-53

NITRIDE DEPTH AND STRUCTURE FOR 30-HOUR TEST AT 1,800°F

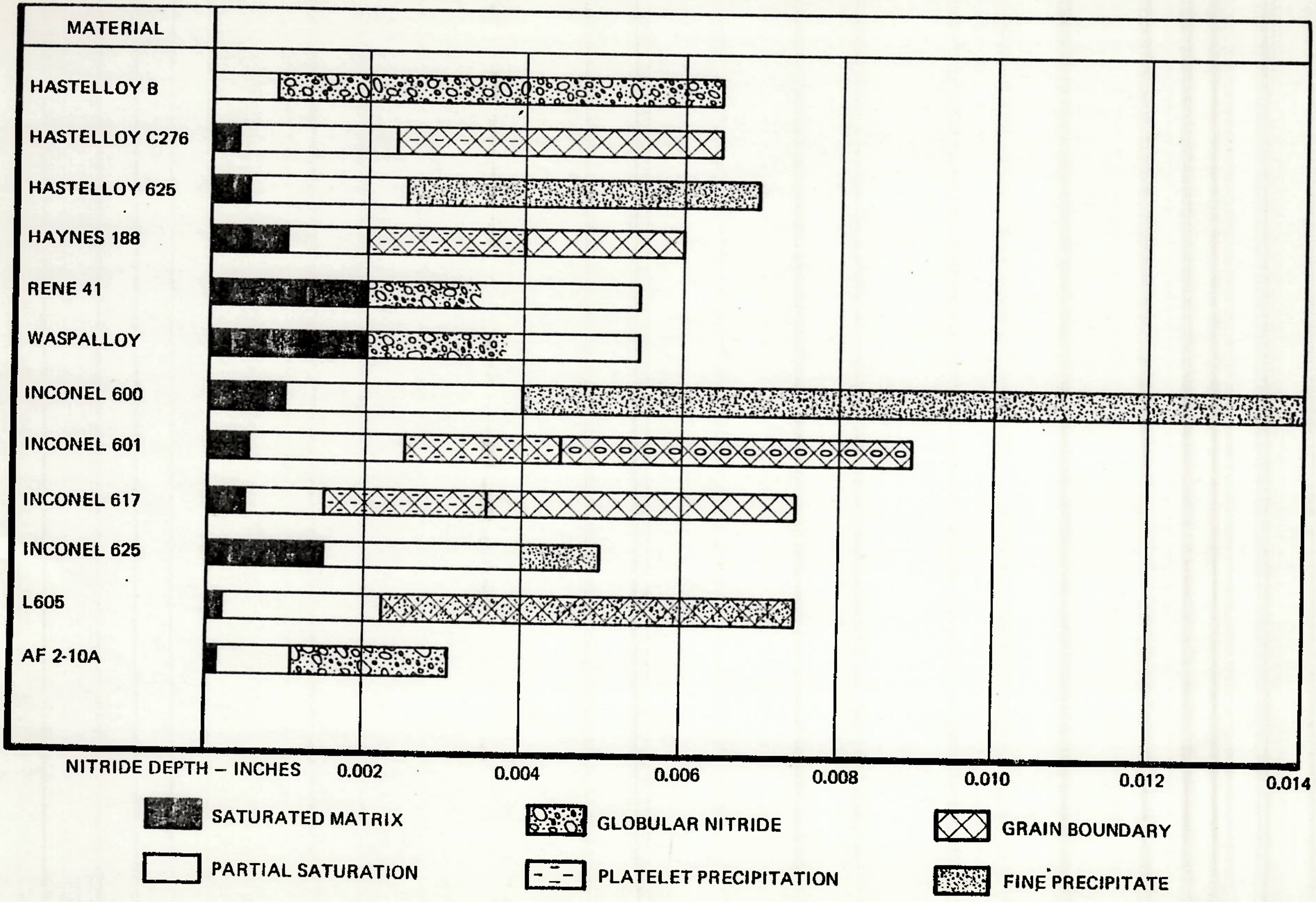


Figure 3-3

content, e.g. Incouel 600 and better oxidation resistance can be obtained by going to alloys with higher chromium content. The extensive metal nitridation studies which were conducted to select materials for the various nitriding/reducing environments can serve as a basis for these which are expected to be encountered in ammonia dissociation reactors in the focal point of solar furnaces (Figures 3-1 through 3-3). Nitridation tests under carefully controlled conditions have been conducted for up to 1,000 hours. This experience will help in the selection of materials for the solar ammonia dissociator. In many cases, protective coatings can be applied to base alloys to prevent nitridation/oxidation attack and to alter emissivity in the desired direction. For the solar ammonia dissociator, a metal with a high absorptivity and low emissivity in the infrared region is sought in order to maximize energy transferred to the reacting medium and to minimize energy lost through re-radiation. The radiation balance of spacecraft components, e.g., hot rocket engines in immediate vicinity to infrared sensors in satellites, requires a thorough understanding of the radiative behavior of materials of construction. It appears that the technology base exists for the selection of materials for a solar ammonia dissociator.

Test methods for materials selection for the dissociator will be defined during the initial program. It is anticipated that such laboratory tests will use a nitriding environment on the other side of the sample. Rather than heating the samples externally, the metal tubes themselves can be necked down and heated by passing a low-voltage current through them.

In addition to metals, ceramic materials will be considered as construction materials for the solar ammonia dissociator. Ceramic materials can withstand higher temperatures than metals, but are very susceptible to thermal shock (thermal transients). Also, themal conductivity of ceramics (except beryllia) is extremely poor and Beryllia cannot be used because it is very toxic. A compromise might be sought by using a metal shell for mechanical strength and ceramic coatings for oxidation and nitridation protection. This can be done with flame-sprayed and plasma-sprayed alumina (Rockide-A) and zriconia (Rockide-Z) as is done inside some catalytic hydrazine reactors. These reactors are also exposed to rapid thermal transients during pulse mode operation of the rocket engine in a satellite of other spacecraft.

Ceramic heat exchangers are currently under development for a variety of solar and waste heat recovery applications. Developments in this area will be carefully reviewed for eventual applicability to the ammonia dissociator. Ceramics currently tested and to be evaluated for the ammonia application include alumnia, zirconia, mullite, silica (quartz), cordierite and silicon carbide. It is expected that some of the exotic metal nitrides may be useful for the ammonia environment.

3.2.2 Transient Effects

The importance of transient effects on materials selection for this particular application has already been emphasized in the preceding paragraph. It has been noted in reviewing the literature that numerous studies on utilization of solar energy are based on the assumption that sunlight will be available without interruption throughout the day. Depending on the geographical location, this is not always true and the system has to be designed with the capability to adjust to rapid changes in insolation. The proposed study will, therefore, attempt to address the transient operation problems in as much detail as possible so as not to follow the obvious mistakes that resulted from the total neglect of transients.

Temperature transients such as those occurring during brief sun occulations by clouds cannot only cause excessive material thermal stresses and subsequent failure, but may also adversely effect the catalyst. An example of this in another system is the potential of carbonyl formation in the case of the reformation/methanation or the synthesis gas/methanol cycle. No such problem is expected for the ammonia dissociaton catalyst. Nevertheless, some testing will be required to assess the potential of catalyst inactiviation by ammonia absorption or iron nitride formation.

Transient effects of a more controllable sort occur in the morning while the reactor/collector is brought into focus and in the evening after the reactor is turned off. These transients are more benign but should be calculated anyway. Calculation of transient effects will require a computer model similar to the ones currently used for hydrazine reactor. It is expected that with some adaption part of those computer programs can be used for the ammonia reactor transient model.

3.2.3 Catalyst Selection

The catalyst is the heart of the ammonia dissociaiton distributed solar energy collection system. Consequently, the feasibility and economic viability of the overall system hinges on this part of the system. The criteria for selection of catalysts were already discussed in Paragraph 2.2.4. It is not expected that existing technology catalysts will be directly applicable to the harsh temperature and pressure conditions in the solar ammonia dissociator. Preliminary testing in the laboratory can be carried out with supported granular or pelletized catalysts. However, in the long range, a catalyst will have to be developed specifically for this application.

It is the objective of the study proposed here to evaluate existing catalysts, point out the shortcomings, and prepare a laboratory test plan for subsequent experimental testing under an eventual follow-on contract. This sequence of events is similar to those which have already taken place on the SO_x chemical energy storage system. As a result of a paper study and a market survey, Rocket Research Company has identified a technology gap and has received a DOE contract to develop a high temperature catalyst specifically for the SO_x chemical energy storage system.

3.3 Coaxial Heat Exchange

The design of heat exchangers is part of conventional engineering with sufficient technical literature to describe the necessary calculations. However, in the case of the solar ammonia dissociator and the adjacent heat exchanger, unique design constraints have to be considered. If the heat exchanger is mounted on the collector, its weight should be minimal because it has to be moved around in tracking the sun. It would be desirable to have the heat exchanger on the moving part because then the flexible joints have to handle only cold gases. Flexible joints for hot and high-pressure gases are invariably problem-prone. The heat exchanger should be compact so it occupies a minimum space within the collector. The outer heat exchanger wall does not necessarily have to be insulated if it is inside the parabolic dish where there may be sufficient stray radiation to keep its outside (which carries the cold feed gas in the annulus) warm. A countercurrent design will allow feed gas and product gas to exchange a sensible heat for ambient temperature pumping and storage.

The design of the heat exchanger will become very complex if it is to be fed with liquid ammonia. At least four different regimes of heat transfer will be encountered and each is described by a different set of equations: laminar or turbulent heat transfer, film heat transfer, and finally, laminar or most likely turbulent heat transfer to flowing ammonia gas (Reference 24 and 24). No chemical changes are expected to occur during the evaporation/warmup process. However, the liquid ammonia may be saturated with dissolved hydrogen and nitrogen gas which will tend to come out of solution before the ammonia begins to boil. Phase boundaries may be less distinct because vaporization conditions are above the critical temperature of ammonia. Very little is known of heat transfer to ammonia in the supercritical state.

In selecting materials of construction for the heat exchanger, it is important to select materials which are noncatalytic. If the heat exchanger material is catalytic or if the heat exchanger becomes contaminated by catalyst materials which have been carried away from the upstream dissociators, the dissociation will reverse itself during cooling of the gases, resulting in an undesirable reduction in round-trip efficiency.

3.4 Gas Distribution/Collection Network

The gas distribution system will involve the piping, valves, pumps, seals, and control system to functionally operate the ammonia-solar system as a distributed collector system. The system will tie into the reactor, storage, and separator units to link the distributed collector system into an integrated unit. The flow control system must be one that responds not only to diurnal solar cycles, but also transients of cloud cover and localized malfunctions, and adverse weather stowing.

3.4.1 Process Control

The control of the dissociation and storage will be part of the process control for the solar absorption system. The transients of the solar system will be included in the metering and control functions to insure that incoming solar energy is absorbed, but possibly as important will be the requirement to utilize the process stream for adequate receiver cooling to prevent thermal damages in a no-flow conditon. Understanding the dynamics of the flow control as related to the heat transfer major off and on functions, and the effects of local transients due to cloud cover or an adverse weather scram function will be used to develop an integrated performance model.

3.4.2 Piping and Seals

The piping and seals chosen for the system as presently conceived should be capable of withstanding the proposed 300 bar operating pressure. Piping will be chosen for adequate structural capability, but will have to account for possible hydrogen embrittlement when dissociated hydrogen is being transported from the collectors or to the reactor. Seals may constitute a major consideration especially in the design of the solar collector. The requirements of tracking, weather protection, and stowage may make rotary seals a requirement in some design concepts. A background at Olympic Engineering Company in ultrahigh pressure seal design and some proposed solution techniques will be used to evaluate potential problems in the prototype and to develop solutions for the working model.

3.4.3 Existing Technology

The pumping of liquid ammonia and hydrogen-containing synthesis gas by pipeline over long distances is a common practice in the chemical process industry. Presurized liquid ammonia pipelines extend over 860 miles from Borger, Texas to Garner, Iowa. A distribution system network with over 2000 miles of pressurized liquid ammonia pipelines carries this fertilizer from Louisiana to the U.S. corn belt in the central states. An 8500 mile nonpressurized ammonia network extends from Tulsa, Oklahoma. A 1500 mile ammonia pipeline is planned between Odessa and Toglatti in the U.S.S.R.

As part of the hydrogen economy concept, high pressure hydrogen pipelines are receiving renewed interest. Not all steels are suitable for high-pressure hydrogen pipelines because hydrogen embrittlement may occur. Hydrogen pipelines are already connecting several chemical process plants in Western Europe.

3.5 Reaction Product Separator

For the operation of the overall system it is necessary at two functional locations to separate ammonia (NH_3) from the components nitrogen and hydrogen (N_2 and NH_3) from the components nitrogen and hydrogen (N_2 and H_2). The economic feasibility of this separation device is critical to the total justification of the project. Initial concepts indicate that a refrigeration system which condenses the ammonia leaving the nitrogen and hydrogen as gases will achieve separation. Thermal inefficiencies, available regenerative methods, and orders of scaling are to be studied. Other physical mechanisms such as gravity settling, possibly with cyclone centrifuge or other acceleration device should also be investigated.

The boiling points of ammonia, nitrogen and hydrogen are sufficienlty apart that separating undissociated ammonia or unreacted permanent gases from each other does not constitute a major technical problem. Existing equipment in ammonia synthesis plants can be adapted to this task. The objective is to first cool the reaction products sufficiently below the dew point of ammonia so that most of the ammonia is condensed. In the case of dissociation products flowing from the distributed collectors, the cooling may already have occurred by flowing the dissociation products from the more remote collectors through uninsulated pipes to the central power plant. However, dissociation products from the close mirrors would need additional cooling before phase separation occurs.

The design of the condenser/separator has to be such that a minimum of ammonia is entrained with the permanent gases and as little as possible hydrogen or nitrogen remain dissolved in the liquid ammonia leaving the separator. The design tank is not as difficult as for the commercial separator which carry along a certain percentage of inert gases (argon for air, helium from natural gas, excess hydrogen or nitrogen). Because the solar dissociator starts with pure ammonia feed, no inert gases will have to be carried along as ballast.

Data on the liquid/vapor phase diagram of the three-component mixture ammonia/hydrogen/nitrogen will be gathered from the literature in addition to that currently being developed at Auatralian National University, and will serve in evaluating the efficiency of the separator. In commercial plants, remaining ammonia which is still contained in the tail gas can be washed out with water and sold as aqua ammonia. This type of ammonia removal prior to recycling unreacted hydrogen and nitrogen is not applicable to the solar ammonia dissociator/reactor plant because it would be difficult to remove remaining moisture from the synthesis gas.

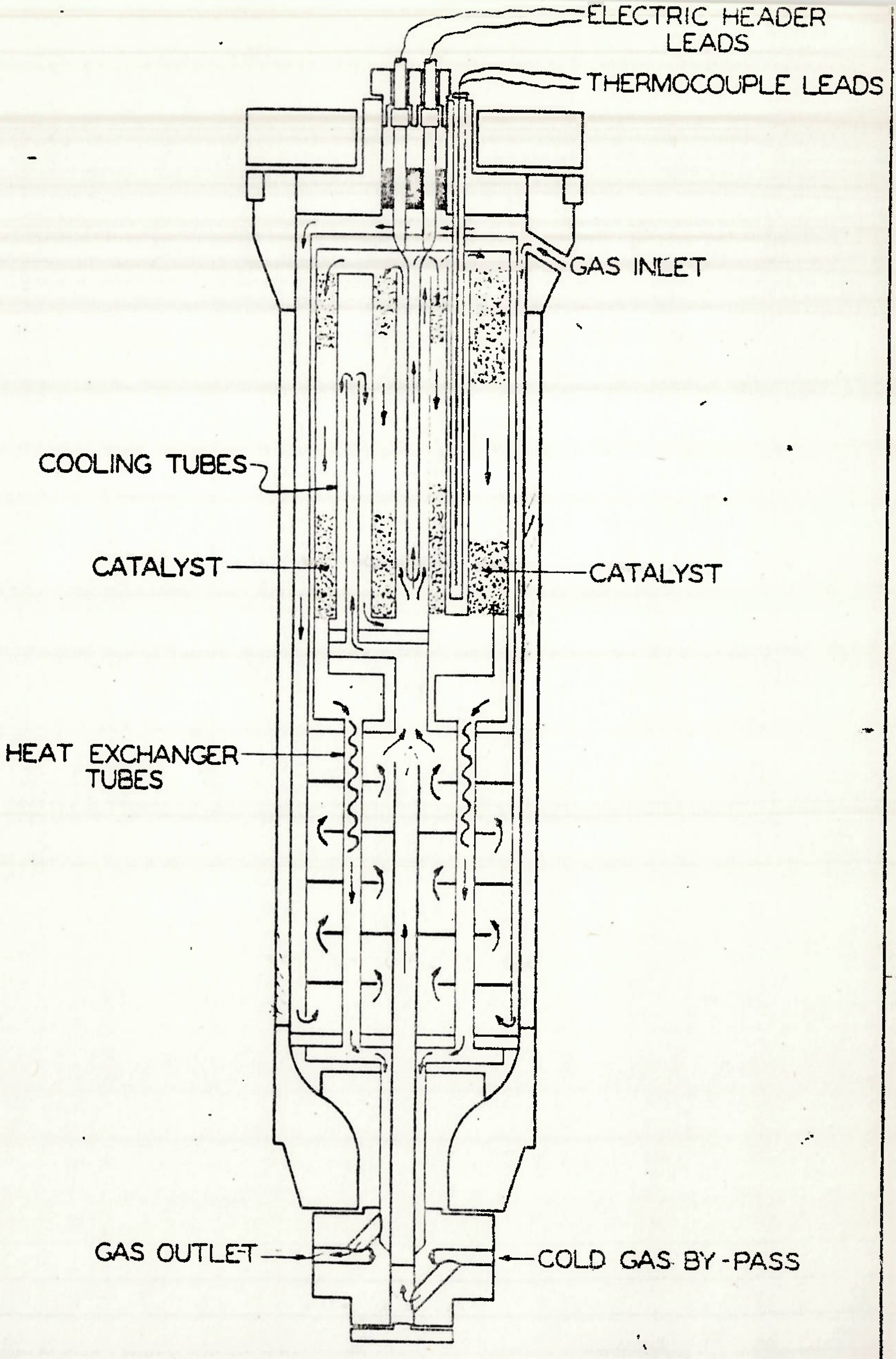
3.6 Exothermic Reactor

From the viewpoint of energy utilization, the central exothermic reactor is the link between the ammonia dissociation distributed solar energy collection system and the power plant. It is assumed that the heat released in the exothermic reactor will be converted to electricity at the site and fed into an existing grid of power lines. Alternatives to this baseline case will be discussed in paragraph 5.3.

3.6.1 Existing Exothermic Reactor Technology

It would fill several shelves in a library trying to gather all the available information on ammonia synthesis reactors. It is expected that most of the information required for the preliminary design of the exothermic reactor can be obtained from the published literature and brochures available from chemical equipment construction firms such as W.M. Kellogg. Scaling criteria will be obtained from the literature and used to optimize the reactor size. In particular, it may be desirable to operate with several incremental parallel reactors rather than one huge central exothermic reactor. This was one of the conclusions drawn from a design study for the SO_2/SO_3 solar thermal power plant (Reference 25). Several small reactors have advantages over one single central exothermic reactor. First, the thermal output may not be uniform throughout the day if the plant operates in a load-following rather than baseload mode of operation. Therefore, it is easier to shut unnecessary reactors down and operate only a few reactors at nominal reactant flow conditions, instead of operating a big reactor at off-nominal conditions. Second, if the reactor is segmented into several reactor modules, it is possible to keep a spare module as a backup in case of unexpected shutdown of one of the more active reactors. And third, scheduled maintenance can be carried out on the inactive module without having to shut down the entire plant. One disadvantage of the modular approach is the increased insulation material requirements and inevitable heat losses because more hot surface area is exposed to the envirnoment.

A typical ammonia synthesis reactor is shown in Figure 3-4.



DIAGRAMMATIC GAS FLOW THRU AMMONIA CONVERTER

Figure 3-4

AMMONIA VAPOR IN A 3:1 MIXTURE OF HYDROGEN AND NITROGEN IN EQUILIBRIUM WITH LIQUID AMMONIA

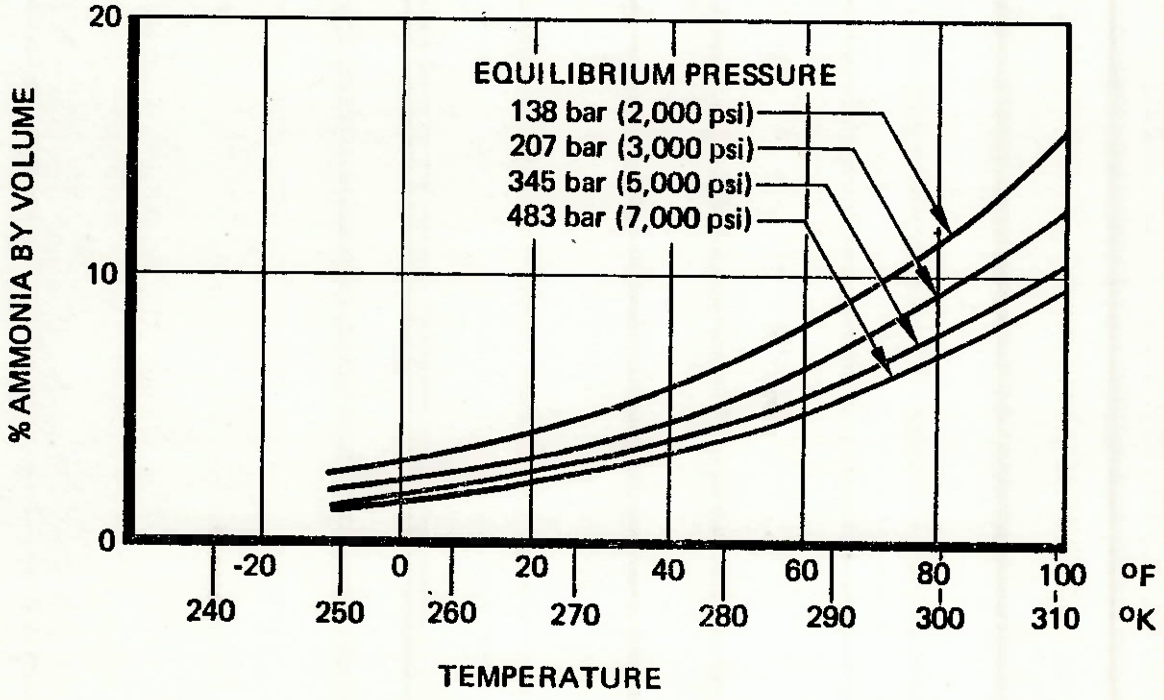


Figure 3-5

POWER REQUIREMENTS FOR SYNTHESIS GAS CIRCULATION

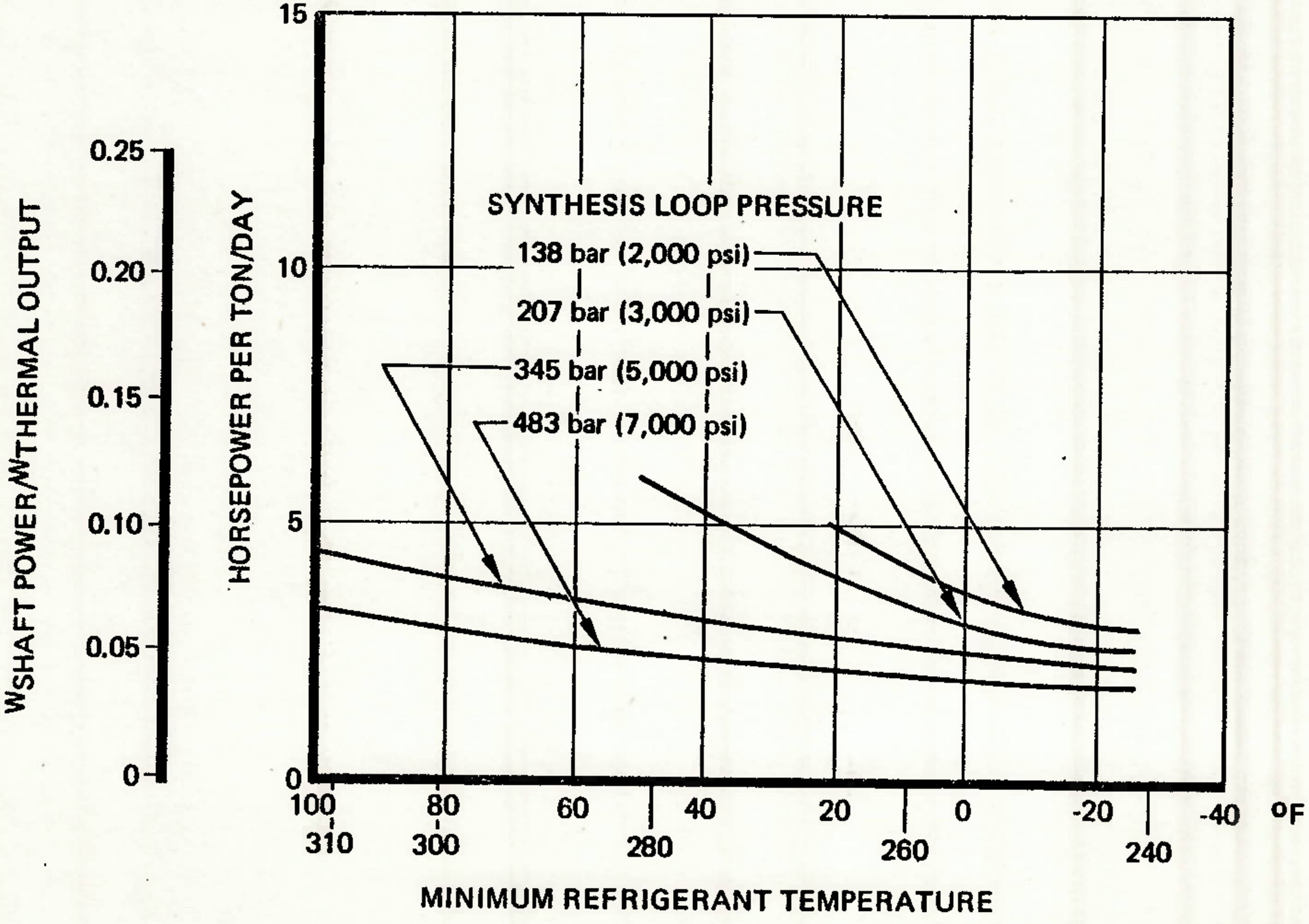


Figure 3-6

3.6.2 Catalyst Selection

Catalyst selection for the exothermic reactor is a straightforward process based on existing technology. Available catalysts will be reviewed in an effort to optimize exothermic reactor temperature and space velocity. Because the baseline system described here would be a closed-loop system, catalyst insensitivity to catalyst poisons that are commonly introduced with fossil fuel feedstock is no longer a determining selection criterion. This increases the possible candidate materials to include highly active, but very poison-sensitive catalysts which would not be economical for open-cycle fossil fuel feedstock ammonia plants.

Most commercial units use space velocities between 20,000 and 40,000. At the assumed maximum of 4,000 and an operating pressure of 3000 bar, the ammonia concentration in the exit gas is only 17% by volume. This assumes a typical reactor outlet temperature of $770^{\circ}K$ ($930^{\circ}F$). If a catalyst of higher activity were used in the downstream position of the reactor, single-pass conversion could be improved somewhat. Higher activity catalyst most likely would require expensive noble metals.

The loss conversion percentage requires that the reaction products be separated into ammonia and permanent gases and that the permanent gases be recycled until complete conversion is achieved. The product gases have to be cooled until ammonia condenses. The energy efficiency of the entire exothermic process hinges on the efficiency of heat transfer until most of the ammonia is condensed and/or the parasitic power required to recycle the unreacted gases. The product gas at 300 bar (4350 spig) has to be colled to 260^{o} (0^{o}r) to lower the ammonia content from 17% to 3% (Figure 3-5).

3.6.3 Working Fluid Heat Exchanger

The working fluid heat exchanger serves as the energy removal method within the reactor. It is the means by which the energy of combimation of ammonia is converted to steam for driving the turbine-generator. Heat exchange on the water-steam side of the heat exchanger will be governed by liquid, boiling, two-phase and gaseous heat transfer effects. There is a large amount of data on heat exchanger-boilers and this will serve as the basis for the design. But, within the reactor the heat exchanger also serves as a portion of the control system which regulates the reactor temperature and specifically temperature gradients. It is the temperature distribution within the reactor on the ammonia side of the heat exchanger which is related to the conversion percentage of ammonia, and also the amount of energy extracted.

Design of a reactor heat exchanger will be somewhat simplified in that the unit may at times be run in a steady state configuration. However, if the overall system is to be designed as load-following, then off-design economics of conversion within the transients of the reactor will have to be studied. This may require the design of the reactor and its control to be much more carefully done than with the existing commercial reactors which are operated in a steady-state mode.

3.6.5 Feed Gas/Product Gas Heat Exchange

The heat exchanger within the solar collector is an integral part of the receiver structure and serves as the recuperator technique which allows pumping to and from the distributed collectors to be accomplished at ambient temperatures.

In the initial concepts of the receiver, the gas supply of ammonia travels to the receiver-dissociator structure along a countercurrent heat-exchanger. The dissociated products return from the receiver along the return path of the heat exchanger giving up sensible heat to the gas stream.

The initial concept of the counter current heat exchanger uses it as the structural element supporting the receiver-dissociator mounting through the center of the reflector disc. This provides a support mechanism which is compatible with a double receiver which closes in a clamshell fashion for weather protection.

Within the reactor where nitrogen and hydrogen are combined to form ammonia, a heat exchanger will be used to remove the heat of formation to be used in generating electrical power. Also included will be recuperators for supply and return gas supplies to minimize the waste heat loss. A carefully balanced low temperature system may be possible to incorporate into the central synthesis plant by using waste heat from the reactor and steam cycle (condenser) to augment a heat pump cycle to refrigerate and separate the mixed gas product from the reactor. The study phase of this portion of the project will examine the trade-offs between the requirements for parasitic power to change the reactor pressure from that of the dissociator and the energy input to separate the gas mixtures for optimum system function.

3.7 Chemical Storage

The ability to store chemicals in the charged and/or discharged state is a major advantage of the ammonia dissociation distributed solar energy collection system compared to solar thermal power plants which produce steam directly in a boiler heated by focused sunlight. Current technology would store ammonia or compressed gases in steel tanks above ground. However, depending on geological site conditions, unconventional storage methods should be considered as well.

3.7. 1 Above-Ground Storage

Above-ground Storage of liquid ammonia and compressed gases in existing technology and no major design problems are anticipated in this area.

3.7.1.1 Ammonia Storage Tanks

Design and cost data for ammonia storage tanks will be obtained from ammonia tank farm operators.

3.7.1.2 Compressed Gas Storage Tanks

Compressed gas storage is not as common as liquefied ammonia storage. Design and cost data for manifolded compressed gas storage batteries will be obtained from U.S. Steel and other high-pressure vessel manufacturers. The cost of compressed gas vessels may have significant impact on the cost of the overall buffer capacity of the solar plant. In the case of the SO_2/SO_3 chemical energy storage system, compressed gas storage vessels were needed to store oxygen in the charged state. It is anticipated from preliminary estimates that the number of tanks and the storage pressure will have a significant impact on capital cost and cost effectiveness of the system.

3.7.1.3 Cryogenic Storage

Cryogenic storage of hydrogen and nitrogen is a theoretical possibility but it is not expected to be cost effective except for extremely large facilities. Boiloff from tanks would have to be recondensed and would represent a constant power drain.

3.7.2 Alternate Storage Methods

3.7.2.1 Aquifer Storage

Storage of gases (natural gas or even helium) in depleted natural gas fields is common technology. This technique applies to hydrogen/nitrogen gas storage only because ammonia is readily/soluble in water. The feasibility of storing hydrogen/nitrogen in aquifer will be considered. Because hydrogen diffuses more rapidly than nitrogen, make-up hydrogen will be required to restore the stoichiometric ratio after gases are withdrawn from storage. Also, the gases will have to be carefully dried and oxygen and carbon containing gases have to be removed.

3.7.2.2 Cavern Storage

A variety of petroleum chemicals are currently stored in solution-mined caverns in salt mines. Similar storage can be prepared in dry-rock mined salt domes. Sweden is currently preparing a granite cavern for cryogenic storage of liquefied natural gas. In Germany, a salt dome receives compressed air from a load-leveling fossil-supplemented gas turbine power plant. The applicability of these various underground storage methods to ammonia and hydrogen/nitrogen will be studied.

3.7.2.3 Ammoniate Storage

Additional energy can be stored if the ammonia is stored as metal ammoniates rather than as a liquid (Reference 26). The advantage of this method is that storage pressure of ammonia is negligible and light-walled tanks can be built. Also, the risk of spillage is eliminated because the ammoniates are stored as solids.

3.7.2.4 Hydride Storage

Hydrogen can be stored at pressures much below 300 bar with storage densities approaching those of cryogenic liquid storage if it is stored as metal hydride, e.g. iron-titamum hydride. Unfortunately, the presence of nitrogen interferes with this storage method. The hydrogen/nitrogen gas mixture would have to be passed through as palladium membrane before hydrogen could be stored as a hydride. The energy required to release hydrogen from the hydride could be provided by the environment ("chemical heat pump").

4.0 COMPUTER MODEL OF INTEGRATED CLOSED-LOOP SYSTEM

Prior to construction of an integrated ammonia dissociation distributed solar energy collection system, it is advisable to analytically model the performance of such a system with a computer model. Such a model will enable the investigator to determine dimensions, cost and performance as a function of energy input (insolution) and output (baseload, load-following, peaking power) conditions.

RRC has successfully modeled the SO_x chemical energy storage system illustrated in the flow charts Figures 4-1 and 4-2 in a digital computer simulation program called CESTOR (Reference 25). Experience gained during development of this computer model is directly applicable to a computer model of the ammonia distributed collector system. The main difference between the SO_x system already modeled and the distributed system is the different number of reactors. For the sake of commonality, only one reactor was required for the SO_x system which served the endothermic and exothermic mode equally well. With a slight modification in programming strategy, an integrated system consisting of a multitude of endothermic reactors and a single exothermic reactor can be modeled as well. Connecting pipes between the various components shown in Figures 4-1 and 4-2 were comparatively short and had no significant effect on pressure drop, performance losses and cost of the overall system. In contrast to this for the present study, the length and diameter of pipes will have a pronounced effect on the cost of the distributed system. This aspect will receive proper attention when designing the new model. The model of CESTOR is illustrated in Figure 4-3. The program has two distinctly different operating modes. In the one mode it sizes all components for a given set of input conditions and calculates nominal performance. In another mode, it freezes all dimensions and calculates performance at off-nominal load conditions, e.g. partial flow. This same option would also be desirable for the distributed ammonia system.

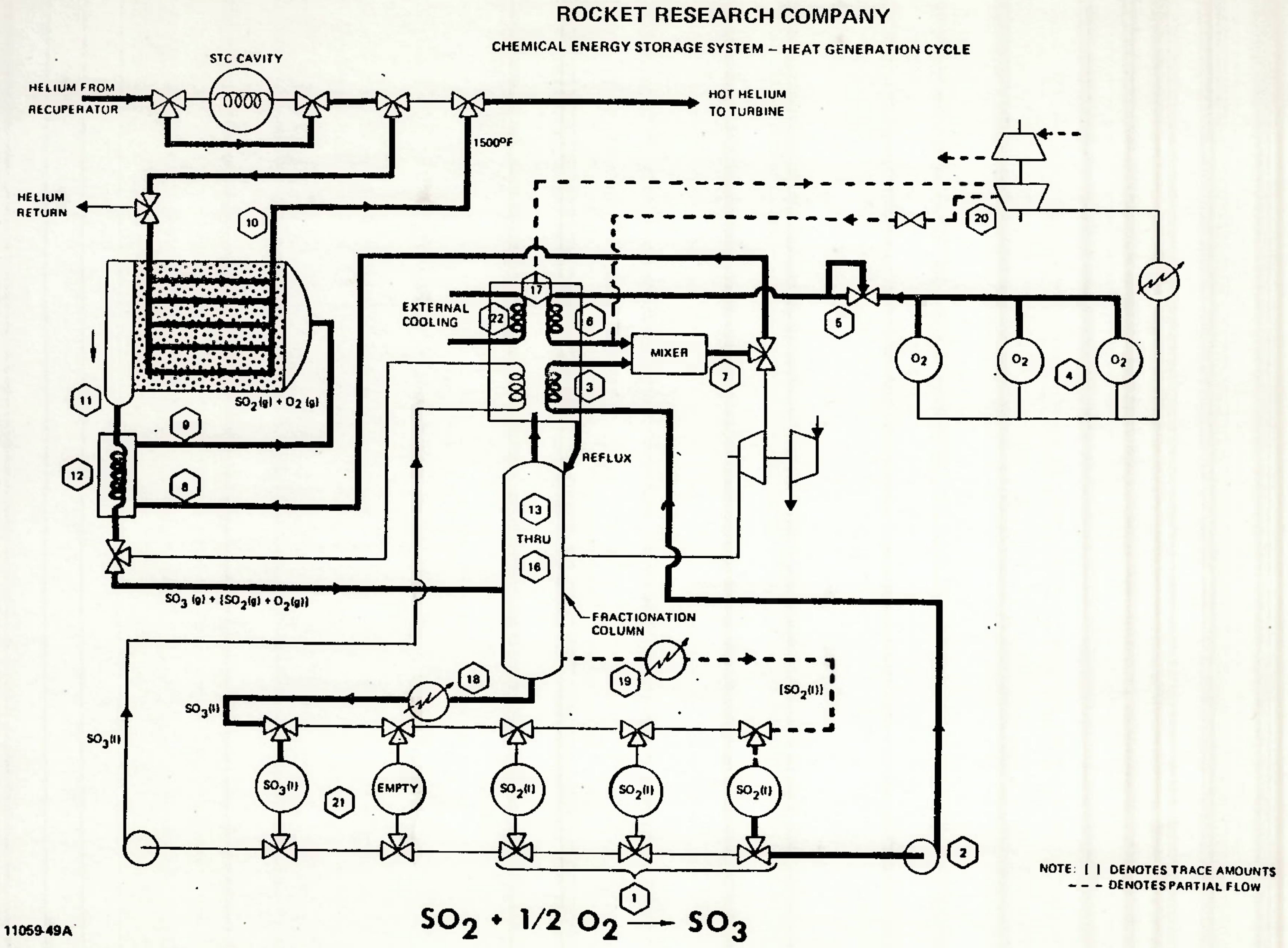
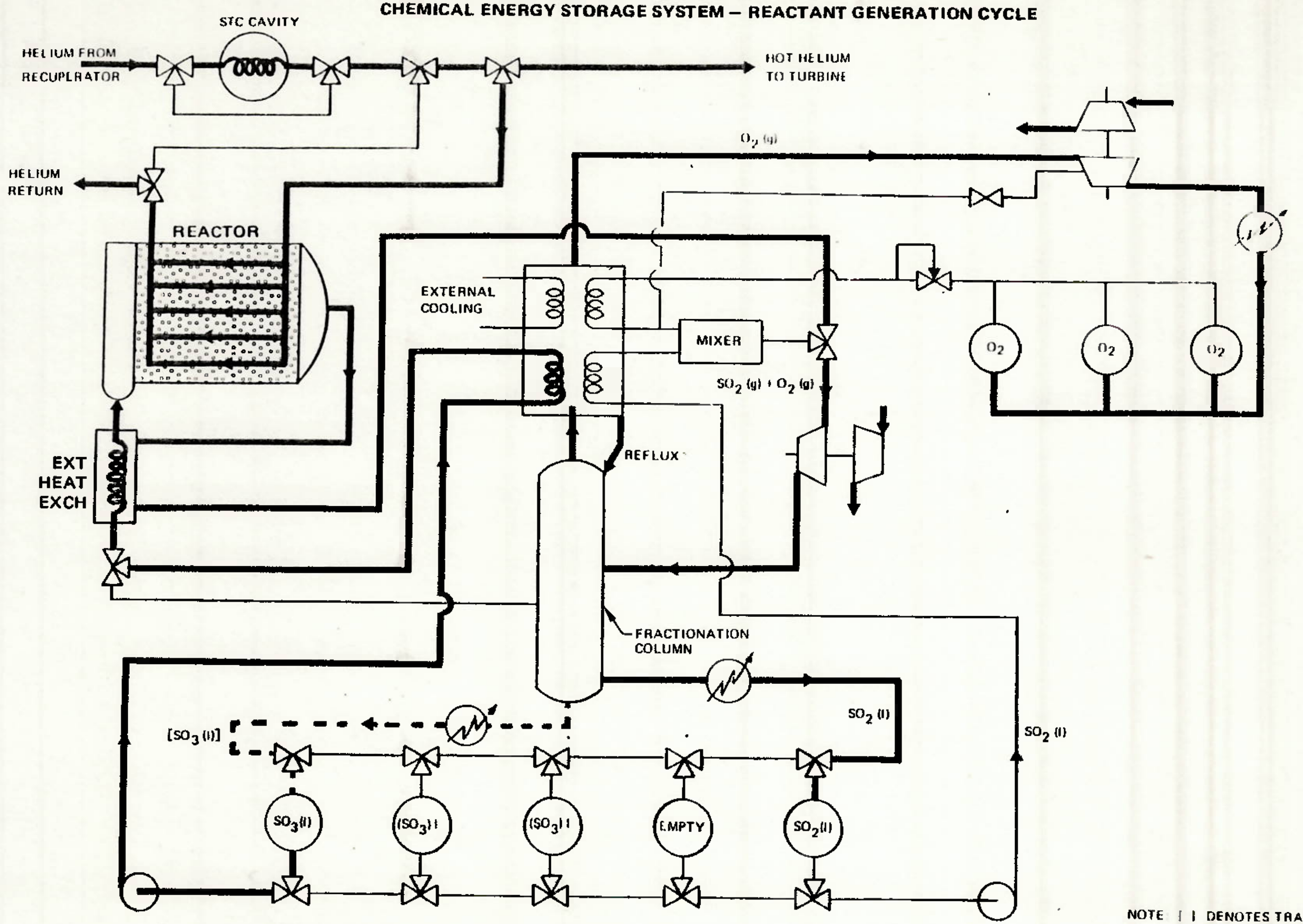

ROCKET RESEARCH COMPANY
CHEMICAL ENERGY STORAGE SYSTEM – HEAT GENERATION CYCLE
STC CAVITY
HELIUM FROM RECUPERATOR
HOT HELIUM TO TURBINE
1500°F
HELIUM RETURN
10
11
12
9
8
$SO_2(g) + O_2(g)$
EXTERNAL COOLING
22
17
6
3
MIXER
7
5
4
O_2
O_2
O_2
20
REFLUX
13
THRU
16
FRACTIONATION COLUMN
$SO_3(g) + (SO_2(g) + O_2(g))$
18
19
$SO_3(l)$
$SO_3(l)$
$(SO_2(l))$
$SO_3(l)$
EMPTY
$SO_2(l)$
$SO_2(l)$
$SO_2(l)$
21
1
2
NOTE: ( ) DENOTES TRACE AMOUNTS
– – – DENOTES PARTIAL FLOW
$SO_2 + 1/2\ O_2 \longrightarrow SO_3$
11059-49A

Figure 4-1

ROCKET RESEARCH COMPANY

CHEMICAL ENERGY STORAGE SYSTEM – REACTANT GENERATION CYCLE



NOTE [ ] DENOTES TRACE AMOUNTS
– – – DENOTES PARTIAL FLOW

$$SO_3 \longrightarrow SO_2 + 1/2\ O_2$$

11059-50A

Figure 4-2

CHEMICAL ENERGY STORAGE (CESTOR) MATH MODEL STRUCTURE

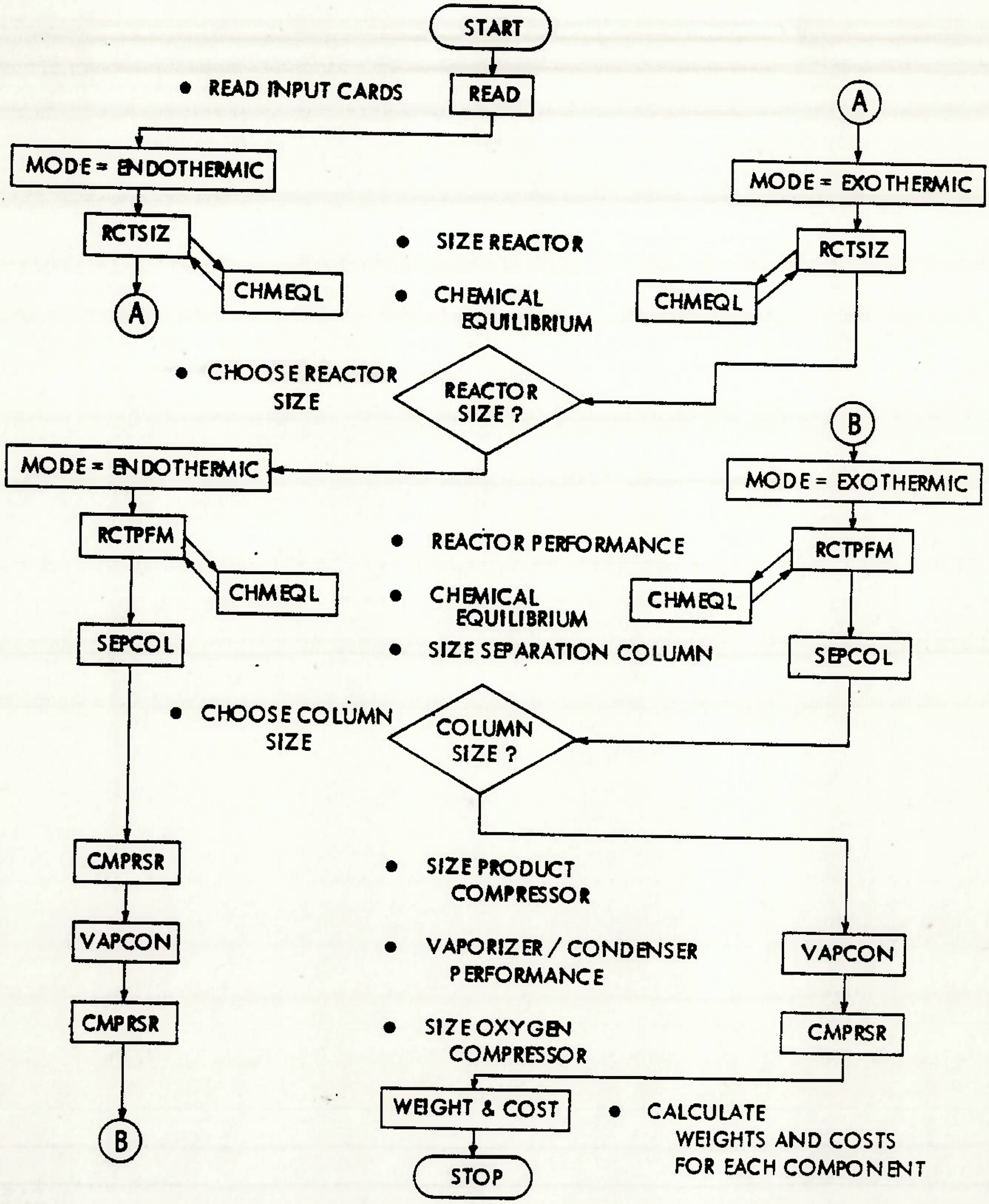


Figure 4-3

The CESTOR program accepts forty input variables as shown in Table 4-1. Unless a new parameter card is entered characterized by a Z number, the program will calculate the case with the default values stored in the program. The amount of output data can be varied by changing the DEBUG identifier (Z=24). The minimum output contains performance (Table 4-2) and size, weight and cost data (Table 4-3).

```
CASE 2   SAMPLE OUTPUT - POWER RATING = 100.0

 Z                                INPUT DATA

  1       100.0000  MW     = PLANT POWER RATING
  2         6.0000  HRS    = DISCHARGING TIME
  3         0.6000         = CHARGE TO DISCHARGE RATIO
  4         0.0            =
  5       855.0000 DEG K   = HELIUM INLET TEMP.,DISCHARGE CYCLE
  6      1089.0000 DEG K   = HELIUM OUTLET TEMP.,DISCHARGE CYCLE
  7      1089.0000 DEG K   = HELIUM INLET TEMP.,CHARGE CYCLE
  8       855.0000 DEG K   = HELIUM OUTLET TEMP.,CHARGE CYCLE
  9         0.8002         = WEIGHT FRACTION OF SO2,DISCHARGE CYCLE
 10         0.1998         = WEIGHT FRACTION OF O2 ,DISCHARGE CYCLE
 11         0.0            = WT. FRACT. OF SO2 CONTAMINATION IN SO3
 12         0.0            = WT. FRACT. OF SO3 CONTAMINATION IN SO2
 13       318.0000 DEG K   = STORAGE TEMP. OF SO3
 14       318.0000 DEG K   = STORAGE TEMP. OF SO2
 15       318.0000 DEG K   = STORAGE TEMP, OF O2
 16  15168466.0000 N/M**2 = STORAGE PRESSURE OF O2
 17   1266563.0000 N/M**2 = REACTOR INLET PRESSURE,DISCHARGE CYCLE
 18    172369.0000 N/M**2 = REACTOR INLET PRESSURE,CHARGE CYCLE
 19       373.0000 DEG K   = SEPARATION COL. TEMP., DISCHARGE CYCLE
 20       678.0000 DEG K   = SEPARATION COL. TEMP., CHARGE CYCLE
 21   1266590.0000 N/M**2 = SEPARATION COL. PRESSURE,CHARGE CYCLE
 22         1.4400         = CE COST INDEX (1970)
 23         0.0            =
 24         0.0            = DEBUG

                           REACTOR INPUT DATA

 25    172367.8750 N/M**2 = HELIUM PRESSURE DROP LIMIT
 26         0.8500         = HEAT EXCHANGER EFFECTIVENESS
 27         3.0000         = HEAT EXCHANGER NTU
 28         0.9000         = REACTOR EFFICIENCY
 29         1.0000         = REACTOR TEMP.EFFICIENCY
 30   3447368.0000 N/M**2 = HELIUM EXIT PRESSURE
 31         0.3500         = BED POROSITY
 32         0.0071  M      = BED PARTICLE DIAMETER
 33        10.0000         = NUMBER OF REACTOR SEGMENTS
 34         0.0            =

                       SEPARATION COLUMN INPUT DATA

 35         0.0200         = WT. FRACT. OF SO2 CONTAMINATION ALLOWED
 36         0.0200         = WT. FRACT. OF SO3 CONTAMINATION ALLOWED
 37         1.2500         = RATIO OF ACTUAL REFLUX TO MIN. REFLUX
 38        17.0000         = PACKING FACTOR
 39         0.2500 INW/FT  = SEPARATION COL.MAX. PRESSURE DROP
 40         0.9144  M      = SEPARATION COL. HEIGHT/TRANSFER UNIT
```

Table 4-1

```
      CASE 2   SAMPLE OUTPUT - POWER RATING = 100.0

                    ELECTRICAL POWER REQUIREMENTS (KW)

                                 CHARGE                DISCHARGE

HELIUM                          60000.0                 99999.9

REACTOR                         68937.7                 99999.9

OXYGEN  COMPRESSOR              11063.7                    56.7

PRODUCT COMPRESSOR              65433.4

HELIUM  COMPRESSOR              20310.9

PUMPS                              25.6                   137.7

COOLER                              1.5                     5.1

TOTAL   INPUT                  156834.9                 99999.9

TOTAL   OUTPUT                  68937.7                 99800.4

CONVERSION EFFICIENCY             0.440                   0.998

                   ROUND TRIP EFFICIENCY  =  0.44
```

Table 4-2

```
CASE 2   SAMPLE OUTPUT - POWER RATING = 100.0

                                     CHEMICAL ENERGY STORAGE SYSTEM

                              NUMBER        DIAMETER     LENGTH        WEIGHT          COST
                                            (METERS)    (METERS)        (KG)           ( $)


REACTANT   SO3                                                      0.437E 07      578315.

REACTANT TANKS

         SO3/SO2               11.             5.65       11.31     0.495E 06      418176.

           O2                 314.             1.62        4.86     0.356E 07     3617278.

PUMPS

           SO2                                                      0.739E 03        8998.

           SO3                                                      0.132E 04       62051.

MIXER                                                               0.136E 04       22427.

FILTERS                                                             0.289E 05       60192.

REACTOR                                       12.94       10.61     0.498E 07    14558764.

HEAT EX    TUBES             62025.            0.02        9.15

EXTERNAL HEAT EX                                                    0.679E 05     1761299.

SEPARATION COL.                                5.19       12.62     0.744E 06     1035703.

VAPORIZER                                                           0.257E 05       51408.

COOLER                                                              0.488E 05       26305.

COMPRESSOR

        PRODUCT                                                     0.105E 06     5861745.

        OXYGEN                                                      0.710E 04     1341874.

        HELIUM                                                      0.585E 05     1684438.

                TOTAL                                               0.145E 08    31088912.
```

Table 4-3

SIMPLIFIED SCHEMATIC OF CHEMICAL ENERGY SYSTEM USING AMMONIA

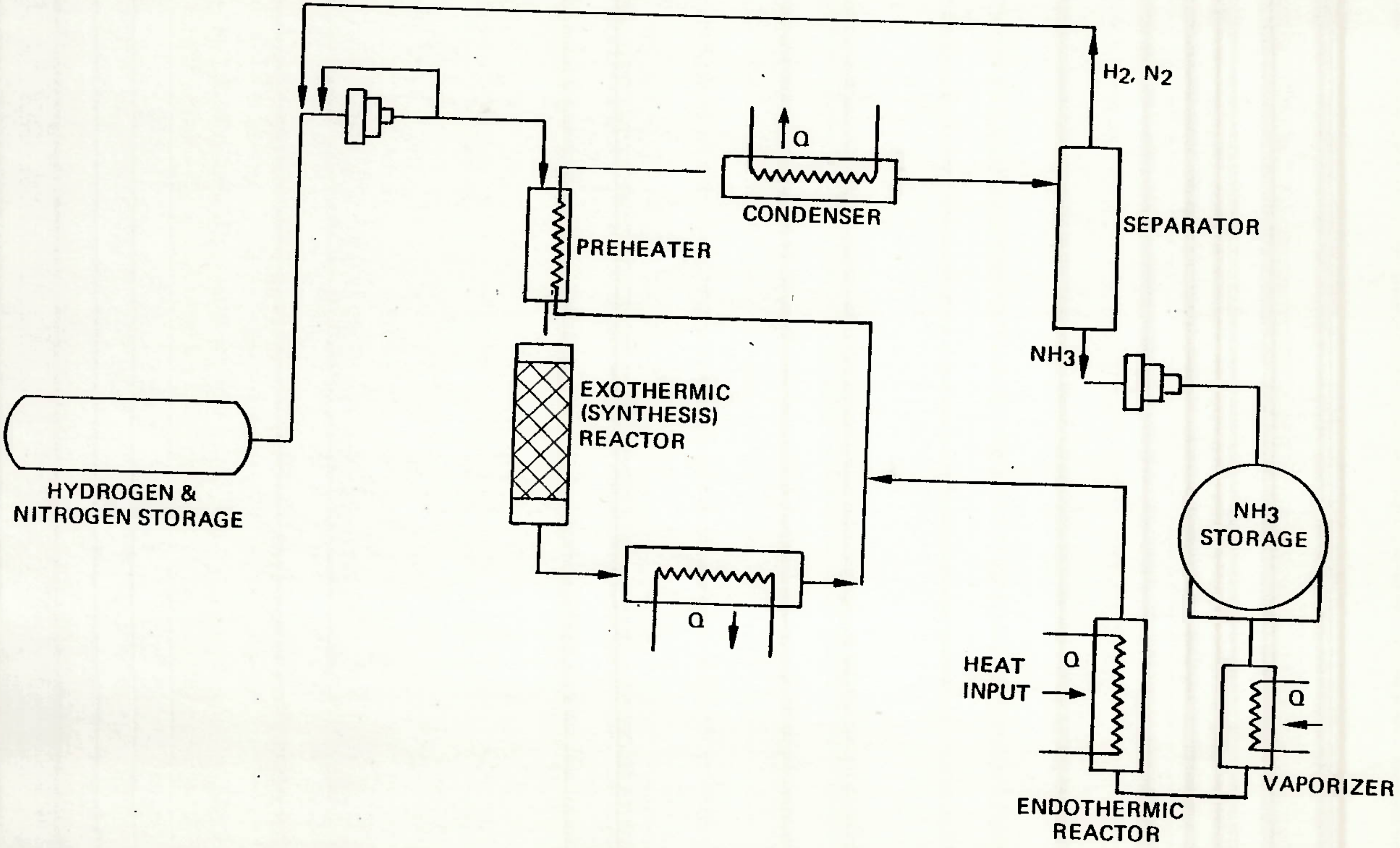
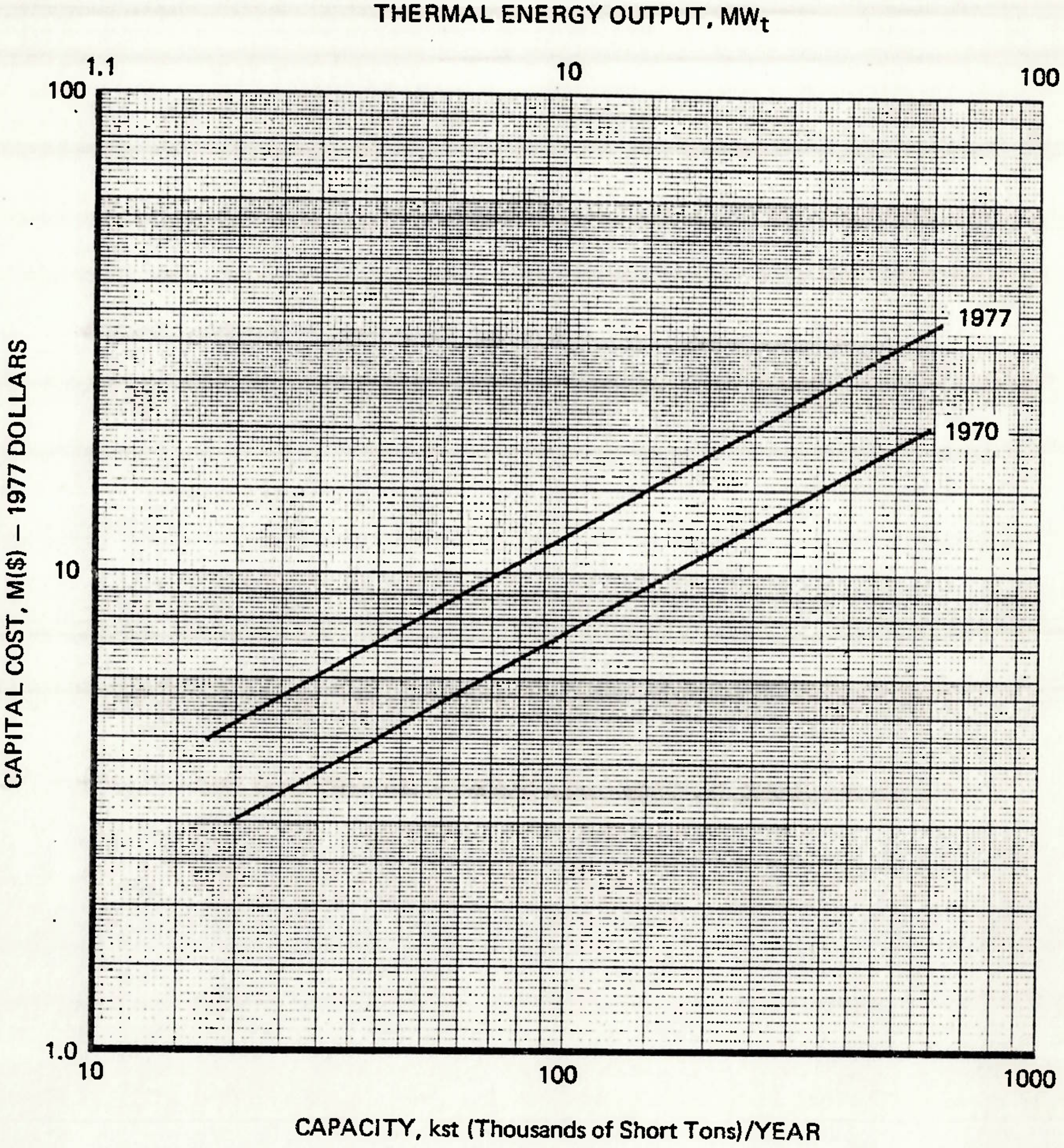


Figure 4-4

CAPITAL COST OF AMMONIA PLANTS AND EXOTHERMIC REACTOR



Source: Chem. Eng. 15 June 1970

Figure 4-5

4.1 Description of Reversible Chemical Reactor Model

During the evaluation of a large number of reversible chemical reactions, RRC has begun to size an energy storage system based on the reversible dissociation of ammonia, Figure 4-4 (Reference 18). In this preliminary design, separate endothermic and exothermic reactors were assumed very similar to the concept proposed by Carden.

4.2 Cost Estimation

Typical ammonia plant costs as a function of capacity are shown in Figure 4-5. However, the central exothermic reactor would cost only a fraction of these estimates for several reasons: First, a major fraction of commercial ammonia plant costs is attributable to cleanup equipment of the feed stock derived from natural gas or naptha. Second, very powerful compressors and compressor drives are required to compress the purified synthesis gas from ambient pressure to reactor operating pressure.

In the case of the Ammonia Dissociation Distributed Solar Energy Collection System (ADDSECS), the chemicals would be recycled in a closed loop. Once the system is loaded with pure ammonia, no further contaminants have to be removed from a closed loop system and the elaborate feed purification systems usually found with commercial plants are no longer needed. Second, the dissociation and recombination reactors are expected to operate at very similar pressures, thus eliminating the need for powerful compressors.

As a first approximation, it is assumed that the ammonia synthesis reactor will cost only 50% of the total plant cost shown in Figure 4-5.

In figuring ammonia plant cost, it is common practice to express capital cost as a function of yearly capacity. For the application anticipated here, it is more practical to express cost as a function of thermal energy capacity. A scale showing the megawatt thermal equivalence has been added to Figure 4-5, assuming that all energy between the adiabatic reaction temperature and cooling to ambient (29 8^{o}K) is useful energy. The proportionality factor is 0.11MW_t/ 1000 short tons/year capacity, based on an enthaply of reaction of 3861 J/g liquid ammonia formed.

4.3 Selection of Insolation Data

Computerized insolation data tapes are currently available for 26 cities in the United States. It is assumed that similar data exists for candidate locations in Australia.

Data has been chosen for Miami, Florida and Madison, Wisconsin for calculating energy storage requirements for autonomous and Hi hybrid solar thermal electric power plants (Reference 22). It would be advisable to include these two locations in future cost/economics comparisons of distributed ammonia versus central receiver SO_x solar thermal electric power plants because a good data base exists for comparison.

In a similar process, load profiles of electric utilities should be obtained for utilities in the vicinity of planned solar power plants. Some load profiles are already available.

4.4 Site-Specific Performance Analysis

After specific sites for candidate solar thermal electric power plants have been selected and the reliability of insolation data for these locations has been examined and found to be acceptable, plant capital and operating cost data will be calculated for a range of plant sizes and required time of operation on storage. These calculations will be performed for a maximum of three sites agreed upon between the DOE project manager and the contractors. Additional sites can be included for a yet-to-be determined slight increase in total contract cost.

4.5 Comparison to Competitive Systems

As already indicated in the introduction, the ammonia dissociation distributed solar energy collection system and the integral steam power plant are not the only way to harness the sun's energy and convert it to electricity. The results obtained during the proposed study will be compared to published estimates for central receiver or other distributed solar thermal power plants.

Previous publications (Reference 27) have concluded that chemical collection methods would be most economical for distributed solar energy systems. These calculations were based on the steam reforming/methanaton cycle, which, as was already discussed in this proposal, may be plagued by operational problems under cycling conditions. It is planned to substantiate conclusions by previous investigators with more firmly founded results based on the ammonia cycle. Capital and operating costs of distributed plants obtained here and published costs of central receiver power plants will be plotted on a common scale as a function of power level and time of operation of storage. If a cross-over point exists where distributed systems are more economical below, and central receiver systems are more economical above a certain power level or certain durations of operation on storage, it will be attempted to pinpoint the crossover point as accurately as possible. What is meant is that if initial cost data within the power or time range chosen results in two converging lines or curves, the range of data will be extended to see if the curves intersect or not.

5.0 RELATED CONCEPTS

The ammonia dissociation distributed solar energy collection system opens new possibilities for electrochemical processes, energy transmission, fertilizer production, synthetic fuel production and off-shore nuclear energy transmission. The concepts are only mentioned here, and it is not intended to conduct a full feasibility study on each.

5.1 On-site Utilization of Electricity

Electricity which is not fed into the utility grid could be used on the site to power production facilities, and in particular, electricity-consuming electrochemical processes which tolerate interruptible power could be operated at the site. Such processes are water electrolysis for hydrogen and oxygen production or chlorine/alkali electrolysis for production of hydrogen, chlorine and sodium hydroxide. Hydrogen could be used at the site for production of additional ammonia during nighttime or as a supplemental fuel for a steam boiler or a gas turbine to provide power during peaking load or during nighttime baseload.

The shaft power available from a steam turbine could be used directly to drive compressors for an air separation plant. The air would be separated into nitrogen and oxygen. The nitrogen would go into ammonia production together with the electrolysis hydrogen mentioned above.

5.2 Process Heat Utilization

The heat released by the central exothermic ammonia reactor can be used for a variety of processes other than generating steam and electricity. One possibility is the operation of thermochemical water splitting cycles to produce hydrogen. Process steam could be used for food processing, canning and a variety of other industrial applications which might be attracted to the vicinity of the solar power by low electricity and thermal power rates.

5.3 Long-distance Transmission of Heat by Chemical Heat Pipes

One has to realize that transmission of electric energy from the plant site to the point of consumption is not possible without transmission losses. It has been claimed that over long distances, transmission of hydrogen gas (open loop) will be able to transport energy more efficiently than the familiar overland high tension power lines. On the other hand, reversible chemical reactions have been discussed to transport heat from nuclear reactor to population centers. In a similar scheme, the dissociation system could be over-sized and physically separated from the exothermic reactor. On-site energy consumption by a small-scale exothermic reactor/electric power plant would be entirely devoted to synthesis of ammonia from air and water. Dissociated ammonia could then be transported over long distances to population and high intensity agricultural centers, where power and fertilizer are needed simultaneously. Power could be used in the form of electricity or as district heating for residences or greenhouses. One large distributed collector dissociator could thus supply synthesis gas to a multitude of satellite exothermic reactor stations. If the exothermic station is in a coastal city, it would be easy to ship ammonia fertilizer as an export commodity. This would be preferable to the alternate of transporting ammonia liquid and electricity to the city separately and converting high-grade energy (electricity) to low grade energy (heat) for space heating.

In some geographical locations, abundance of sunshine may exist on one side of a mountain barrier which may be separated from areas of high energy consumption but little sunshine by only several hundred miles. In this case, it may be possible to transport thermal energy via chemical heat pipe across the mountains and return the ammonia for re-dissociation by co-radiation.

5.4 Open Cycle Options

Various open cycle options were already mentioned in the preceding paragraphs. In these cases, ammonia would be synthesized at the site from air and water and sold as fertilizer. Ammonia also constitutes a useful starting material for other fertilizer such as ammonium nitrate or urea, which are solids and more easily stored in bulk than liquid ammonia. The manufacture of ammonium nitrate occurs by neutralization of ammonia with nitric acid. Nitric acid is prepared by catalytic combustion of ammonia with air of oxygen, which by itself is a strongly exothermic process quite suitable to provide heat for the steam power plant during nighttime. Nitric acid production would preferably be carried out during the nighttime when there is demand for supplemental heat to keep the power plant operating.

5.5 Off-shore Nuclear Energy Transmission

Ammonia has been generally recognized as a useful high-energy commodity and plays a vital role in a number of advanced energy schemes. For instance, it has been proposed to use the electricity from floating ocean thermal gradient power plants to synthesize ammonia from air and water at the equatorial locations. Ammonia could then be shipped by barges to shore and sold as fertilizer.

In another scheme, as the result of increasing difficulties in obtaining sites for nuclear power plants, it has been proposed to use the energy available from off-shore nuclear power plants to steam-reform liquefied natural gas which will be imported from Algeria for several decades. The nuclear energy would be piped ashore in the form of synthesis gas ($CO+3H_2$) instead of electricity. The synthesis gas can be pumped to a network of methanation stations, where heat is released upon methanation and the newly formed methane can be pumped into the existing pipeline network for natural gas distribution and ultimate power plants could dissociate the ammonia arriving from OTEC plants and bring it ashore in the form of N_2+3H_2 instead of NH_3. The N_2+3H_2 synthesis gas could then be piped to locations of energy and ammonia consumption.

6.0 PROGRAM PLAN FOR LABORATORY STUDIES

It is expected that the study program described herein will identify several technology gaps which should be investigated in an experimental program in the laboratory before a pilot-plant with a full-size collector is designed. It is the advantage of a distributed system that a single collector unit can be tested much easier than a full-scale boiler for a central receiver power plant.

The experimental program to be proposed will assemble unit operations, test them individually and will eventually join them to a closed loop system using an electric resistance heater as a substitute for a solar furnace. This "breadboard" pilot plant system is expected to deliver several kilowatt thermals.

References

1. Carden, P.O.: Corradiation Using the Reversible Ammonia Reaction, Paper, Presented at 1975 Conference of International Solar Energy Society, Los Angeles, California
2. Carden, P.O.: Corradiation Using the Reversible Ammonia Reaction, Solar Energy 19, 365-78 (1977).
3. Carden, P.O., and S. Kaneff: Mass Utilisation of Solar Energy, A Submission to the Standing Committee on National Resources of the Australian Senate. Submitted by Australian National University, Canberra (May 1976).
4. Clubb, T.A.: Analysis of Gas Dissociation Solar Thermal Power System, Solar Energy 17, 129-36 (1975).
5. Clubb, T.A.: Gas Dissociation Thermal, Power System, U.S. Patent 3 972 183 (17 April 1975/3 Aug. 1976).
6. Clubb, T.A.: A Chemical Approach to Solar Energy, Chemtech 6, 654-7 (October 1976).
7. Schmidt, E.W.: Development of a Long-Life High-Temperature Catalyst for the SO_2/SO_3 Energy Storage System US DOE Contract SAND 87-9119, Rocket Research Company, Redmond, Washington, Interium Status Report RRC 77-H-169 (October 1977). Proceedings of the Second Annual Thermal Energy Storage Contractor's Information Exchange meeting, Gatlinburg, Tennessee p. 340-5 (September 1977), CONF-770955.
8. Clubb, T.A., J.J. Nemecek and D.E. Simmons: Energy Storage - Boiler Tank: Boiler Design, Materials Compatibility Tests, Proceedings of the International Solar Energy Society Meeting, Orlando, Florida, Paper 18-10 (1977).
9. Clubb, T.A., J.J. Nemecek and D.E. Simmons: Energy Storage Boiler Tank: Progress Report, ERPA Thermal Energy Storage Contractor's Meeting, Gatlinburg, Tennes-

see (September 1977), CONF-770955.

14. Caputo, R.S.: An Initial Study of Solar Power Plants Using a Distributed Network of Point Focusing Collector. JPL Tech. Rept. 900-724 (1975).
15. Schmidt, E.W., and P.A. Lowe: Thermochemical Energy Storage Systems, 11th Intersoc Energy Conv. Eng. Conf., Vol. I, p. 665-72 (1976); also: Rocket Research Corporation 76-R-221 (June 1976).
16. Schmidt, E.W.: Reversible Chemical Reactions for Heat Storage, Rocket Research Company 77-R-570 (July 1977).
17. Schmidt, E.W.: "Reversible Chemical Reactors for Storage of Heat" (in German), Verein Deutscher Ingenienie Meeting, Stuttgart, West Germany (Oct. 1977), VDI Bericht 288, p. 115-25.
18. Poole, D.R.: Chemical Energy Storage for Solar-Thermal Conversion, Rocket Research Corporation, Interim Report Number 2, (Contract NSFAER 75-22176, RRC 77-R-558 (April 1977)
19. Poole, D.R.: Reversible Chemical Reactions for Electrical Utility Energy Applications, Rocket Research Corporation, Final Report, Contract EPRI TPS-76-658, RRC-77-R-559 (April 1977).
20. Schmidt, E.W.: C-mposite Catalyst Bed and Method for Making the Same, V.S. Pat. 4-027-476 (15 Oct. 1975/ 7 June 1977) Rocket Research Corporation.
21. Schmidt, E.W.: Monolitlic Catalyst Beds for Hydrazine Reactor, Rocket Research Corporation, Final Report, Contract NAS7-755, RRC-73-R-360 (2 May 1973).
22. Ianncci, J.J., R.D. Smith and C.J. Swet: Energy Storage Requirements for Autonomous and Hybrid Solar Thermal Electric Power Plants, Paper, presented at International Solar Congress, New Delhi, India (1977)
23. Noel, M.B.: Experimental Investigation of the Forced Convection and Nucleate-Boiling Heat Transfer Characteristics of Liquid Ammonia, JPL TR-32-125, NASA CR-79088, N66-39951.

24. Perroud, P. et al.: Forced Convection Heat Transfer to Ammonia (in French), Comm. Energie Atomigne, France, CEA-R-3088 (Dec. 1966) N67-33286.

25. Gintz, J.R.: Advanced Thermal Energy Storage Concept Definition Study for Solar Brayton Power Plants, Boeing Engineering and Construction, Final Report, Contract E (04-3)-1300 (1977).

26. Hall, C.A., M.T. Howerton and S. Pdlasek: Thermal Storage by Paired Ammoniated Salts, Int. Solar Energy Society, Winnipeg, Canada (Aug. 1976).

27. Turner, R.H.: Economic Optimization of the Energy Transport Component of a Large Distributed Collector Solar Power Plant, 11th Intersoc. Energy Conv. Eng. Conf., Vol. II, p. 1239-43 (1976).

28. Miller, C.G., NASA Tech. Brief, Item No. 31, from JPL Invention Report 30-3180/NPO-13510, March 1977, "Energy Conversion System: Temperature Transformer".

7.0 PROPOSED STATEMENT OF WORK

The contractor will furnish the necessary personnel, services, materials, and facilities and will subcontract to the extent necessary to carry out a feasibility study and a conceptual system design of an ammonia dissociation distributed solar energy collection system as outlined below. For convenience of scheduling and budget control, the overall effort has been subdivided into nine tasks.

Task 1 - Concept Development

The contractor will develop an integrated concept of the solar-ammonia project which uses a distributed collector system, definable energy storage, and a central electrical generating facility.

Task 2 - Evaluation of Existing Technology

In conjunction with the two anticipated subcontractors, Australian National University and Rocket Research Company, the contractor will evaluate existing technology such as component prototypes tested in Australia and high-temperature materials nitridation tests conducted in the United States.

Task 3 - Computer Model

The contractor will develop a computer model of the closed-loop ammonia dissociation distributed solar energy collection system. The program will be written in FORTRAN-IV and will be compatible with the CDC 6600 computer. The program will be used for optimization of operating parameters such as system pressure under steady-state operating conditions (no transients). The program will provide parasitic power requirements, round-trip efficiency, system dimensions, and plant equipment cost (less installation cost) as a function of up to forty input variables.

Task 4 - Collector, Dissociator and Reactor Conceptual Design Study

The contractor will investigate existing collector, dissociator, reactor and heat exchanger designs, assess their applicability to the proposed closed-loop concept, specify tracking accuracy and computer control requirements, and identify possible technology gaps requiring further study.

Task 5 - Economic Analysis for Three Selected Locations

Using the computer model developed in Task 3, the contractor will study plant economics in terms of \$/kW and \$/kWh ("bus bar energy cost") for two U.S. locations to be designated by Sandia Livermore Laboratories and one Australian location to be identified by Australian National University. Plant layout will be for three cases: autonomous baseload, autonomous load following and autonomous baseload output with excess power used for open-loop chemical products.

Task 6 - Open-Loop Concepts

The feasibility of operating the plant in an open-loop mode, i.e., produce ammonia or synthesis gas to be sold at a profit, will be investigated for selected paint designs. The cost of solar-produced ammonia will be composed to fossil-fuel derived ammonia using current technology.

Task 7 - Laboratory Test Plan

Including technology gaps identified during Task 4, the contractor will prepare a laboratory test plan to build key components and integrate them in a closed-loop laboratory test facility.

Task 8 - Deliverable Items

Subtask 8.1 Computer Card Deck

The contractor will provide to Sandia Livermore Laboratories one card deck of the computer program, a program listing, a user's manual, and original printouts of a typical sample case (usually the default case which is executed by the program unless different input is provided).

Subtask 8.2 Reports

A. Final Report

1. Requirements

A final report following completion of the work required by this contract will be submitted in 8 copies and one set of reproducible masters will be preceded by a draft for approval, unless otherwise specified below. The draft is due 20 days after completion of work. The final report is due 20 days after approval of the draft.

2. Report Content

The final report shall cover: work accomplished; results obtained; problem areas; and recommended solutions for actions. This rpeort shall be a summary of technical activities during the entire contract performance and a comprehensive evaluation of progress in the area of research, study or development supported by this contract.

3. Specifications

The report shall consist of: a typewritten original comprising a cover; the written matter; and illustrations as appropriate. The copies may be either carbon or a facsimile reproduction acceptable to the Sandia contracting representative.

Contractor shall affix a label (form SF6432-CTR) to the report cover.

The label contains: Sandia contract number; Sandia requester name and org. number; Sandia contracting representative name and org. number; and Sandia report number.

Reproducible masters and illustrations shall have: black letters on white bond paper; and black ink on white paper or black drawing pencil on mylar for charts, line drawings and sketches.

Photographs are to be glossy prints, size 8 x 10 preferred, but any size between 4 x 5 and 8 x 10 is acceptable providing sufficient detail is shown.

4. Transmittal

Unclassified matter is to be sent by first class mail. All reports (drafts, masters, illustrations) shall be addressed to:

Sandia Laboratories
Livermore, California 94550
Attn: Library Division 8266

5. Distribution

Except as otherwise provided in the anticipated contract (which exception includes DOE patent representative requests) no distribution or dissemination of a report in whole or in part will be made by the contractor without specific prior written approval by the Sandia contracting representative.

B. Interim Reports

Monthly interim reports in a form acceptable to the Sandia contracting representative, are due 15 days after the reporting period. These reports shall cover the work accomplished during the reporting period and that planned for the subsequent period. Such report shall indicate: compliance with contract requirements and any failures to comply; the current status and technical effort expected to be devoted to the next period; and the best estimate of probable events during the remainder of the contract.

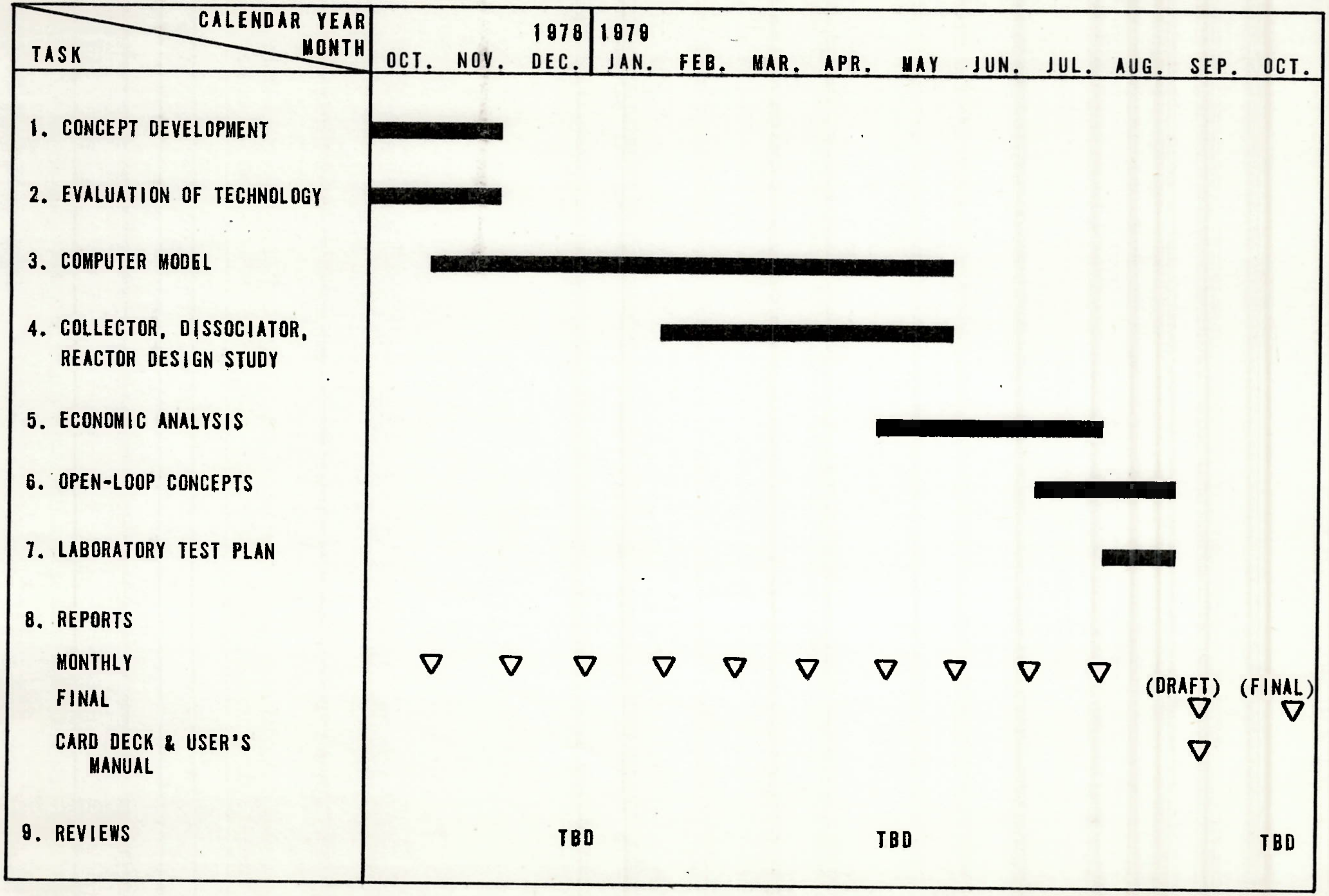
C. Monthly Cost Status Reports

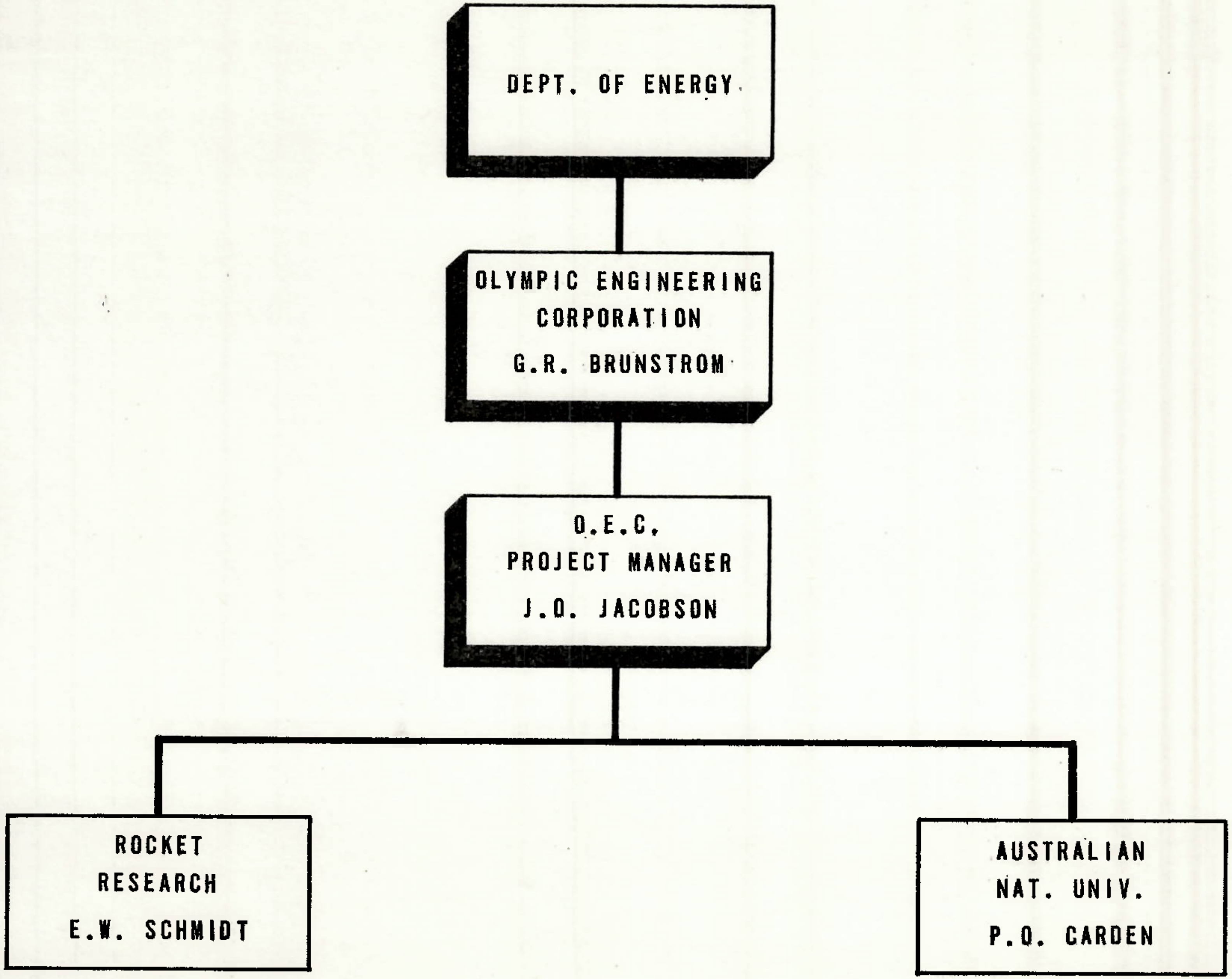
Monthly cost status reports are to be submitted to the Sandia contracting representative not later than the 20th of each month; the report shall be submitted on Sandia form SF-6432-CS (3-76).

Task 9 - Contract Status Reviews

During the ten-month technical effort, the contractor will provide up to four contract status reviews for DOE/SANDIA representatives but no more than two shall require travel of the principal investigator and/or subcontractor outside Seattle, Washington. The principal investigator will attend the DOE Storage Division Annual Contractor's Meeting if so desired by the Sandia technical program monitor.

8.0 AMMONIA DISSOCIATION SOLAR ENERGY COLLECTION SYSTEM PROGRAM SCHEDULE





9.0 PROGRAM MANAGEMENT STRUCTURE

10.0 RESUME'S

The following resumes support the preceeding Program Management Structure as graphically presented in Section 9.0.

Gerald R. Brunstrom, President of Olympic Engineering Corporation, will serve as Principal-in-Charge for the project, while Dr. Jon O. Jacobson, also of Olympic Engineering Corporation will be the Project Manager.

Working with Dr. Jacobson will be Dr. Eckert W. Schmidt of Rocket Research Company, and Dr. Peter O. Carden of Australian National University.

GERALD R. BRUNSTROM
President
Olympic Engineering Corporation

EDUCATION - Washington State University, B.S. Civil Engineering,
University of Wisconsin, M.S. Civil Engineering
Johns Hopkins University, University of Washington
Business Administration Courses

MEMBERSHIPS - American Society of Civil Engineers
American Concrete Institute
Consulting Engineers Council
Society of American Military Engineers
American Arbitration Association

PROFESSIONAL LICENSES - Registered Professional Engineer
Washington, California and Oregon
Fellow, The Institution of Engineers,
Australia

SPECIAL QUALIFICATIONS - Instructor in:
Critical Path Method of Scheduling
Originator of firm's program in CPM

PAPERS PRESENTED - Construction Management, 26th Annual Road Builder's Clinic, Washington State University, (March 1975)

Critical Path Method - An Application to Highway Construction. Montana State University (1972)

CPM in Construction - Proceedings, Australian Institution of Engineers (1966)

Applying the Critical Path Method - Pulp & Paper International, (1964)

Use of CPM in Highway Construction, Proceedings, Association of Western State Highway Officials, Denver, Colorado (1963)

The Application of CPM in Industry, Proceedings, American Institute of Industrial Engineers (1962)

OTHER - Editorial Review of Project Management by Network Analysis, First and Second Editions, published by Olympic Engineering Corporation 1962, 1975.

SUMMARY OF EXPERIENCE -

Mr. Brunstrom has 24 years of experience in professional engineering and construction, including 22 years as principal and senior partner. He has participated in the management, planning, design, and construction supervision of projects ranging in cost up to $520 million.

During the past 11 years he has been instrumental in guiding the firm in the fields of project management, coordination, cost control, claims analysis, value engineering, quality assurance and human factor engineering.

Mr. Brunstrom has served as principal-in-charge of the firm's assignments to accomplish many construction management projects including Hanford Square (a solar demonstration project) in Richland, Washington; the Navy Polaris Missile Facility, Bangor, Washington; a Communication Facility for the U.S. Navy at Northwest Cape, Western Australia; for a pulp and paper mill at Larisa, Greece; a Copper Mining and Processing project at Bougainville in New Guinea; Nuclear Power Test Facilities at Hanford, Washington; and several other projects in the United States. He has also served as an Expert Witness and Construction Advisor on construction claims cases up to the level of United States Court of Claims, Washington, D.C.

He has also participated in numerous civil and structural engineering projects accomplished by the firm as principal-in-charge and/or designer. Projects have been commercial, industrial, institutional and/or miscellaneous types involving new facilities, expansion, restoration and remodeling.

In the above projects, responsibilities have included economic and feasibility studies, preliminary concepts and calculations, working drawings, specifications, cost estimates, construction management, construction approval, bid negotiations, and client-contractor coordination. His experience includes the use of all types of timber, concrete and structural steel and their adaptation to the problems of seismic, climate, vibratory, marine and hostile environments including tropical and arctic conditions.

JON O. JACOBSON

EDUCATION - Washington State University, B.S. Mechanical Engineering
University of Washington, M.S. Mechanical Engineering
Ph.D. Mechanical Engineering

EXPERIENCE SYNOPSIS -

Engineering Science - 15 years
Knowledge of the range of engineering practice from numerical analysis to product fabrication
Demonstrated accomplishments in heat transfer and fluid dynamics
Program Management
Large-scale Computer Applications
Biomedical Engineering capability with applied physiology and instrumentation development
Practical knowledge of piping systems (journeyman plumber)

PROFESSIONAL EXPERIENCE -

Olympic Engineering Corporation (3 years)

- Senior Scientist - Dr. Jacobson has served as expert witness for personnel risk and damage involving the design of mechanical systems.

- He performed an analysis of a chain reaction vessel and modification to acceptable safety levels for selected reaction systems, and in the analysis, design and supervision of testing of energy conservation equipment for an electric arc steelmaking facility.

- Dr. Jacobson conducted a design analysis of passive solar structures with developed computer codes for simulation of dynamic changes related to atmospheric, solar, and building use conditions.

- He performed an analysis of heat-transfer equipment utilizing fluid dynamics at freezing conditions to determine off-design safety and risk assessment conditions.

- On a sodium-cooled nuclear systems project, he performed numerical analysis and design of sodium purification equipment, free and forced convection heat transfer; developed a liquid sodium centrifuge concept and design studies, and thermal stress analysis.

Flow Research (1 year)

- Research Scientist - Dr. Jacobson was responsible for the design, development and testing of hydraulic seals for a 60,000 psi pumping system, and for the supervision of the hydraulic testing laboratory. He developed finite element stress analysis for production parts, was involved in new product development, grant application and logistics.

Virginia Mason Research Center (3 years)

- **Biomedical Investigator** - Dr. Jacobson was responsible for the development of ultrasonic bubble detection equipment and related signal processing for the investigation of decompression sickness, and for the design and application of surgical instrumentation equipment. He was manager of an optical research project for clinical detection of occipital lobe tumors, and a co-investigator in multidisciplines atherosclerosis detection and risk evaluation studies.

Self-Employed Consultant (5 years)

- Developed a computer-simulated water system for municipal communities.
- Developed a people-moving feasibility study.
- Aligned a celestial tracking tower in England.
- Developed a computer-simulated traffic facility in Alaska.
- Conducted a market study for multiphasic screening center.

Boeing Company (2 years)

- **Research Engineer** - Dr. Jacobson was the supervisor of design of a testing facility for full-scale tests of aeroacoustic noise generation in the fan section of a turbojet engine. He worked with the application of fault tree analysis to the Minuteman Safety Program, and developed safety procedures for the DynaSoar Maintenance Crew using chlorine-trifluoride and fluorine.

Engineered Industrial Systems (1 year)

- **Consulting Engineer** - Work consisted of engineering analysis and design of mechanical systems, and the development of computer implementation of engineering solution methods. Dynamic stress analysis and design of the missile container was conducted on the SRAM millile. He also performed the design of quick-change cargo systems for airline companies, erection procedures for Libby, Montana bridge, and stress-weight optimization for airframe subunits.

Lockheed Shipbuilding and Construction (1 year)

- **Supervisor** - in charge of engineering and supervision of facility improvement which included $1 million responsibility. Equipment included computer-controlled flame cutting, modular structural fabrication facility, and automated personnel services.

JON O. JACOBSON resume continued. . .

Safety Engineer (1 year)

- As a supervisor of safety engineering, he conducted personnel hazard analysis, elevated structures, chemical exposure, and acoustic and thermal environments. He also worked on system safety development and fault tree analysis.

OTHER QUALIFICATIONS -

Coauthor of four publications in fluid dynamics

PROFESSIONAL AFFILIATION AND ACTIVITIES -

Registered Professional Engineer, Washington
Institute of Electrical and Electronic Engineers

ECKART W. SCHMIDT

EDUCATION - Marburg University, West Germany, B.S. Chemistry
Tuebingen University, West Germany, M.S. Chemistry
Tuebingen University, West Germany, Ph.D. Chemistry

EXPERIENCE SYNOPSIS -

Technology Management - 7 years
Research - 16 years
Rocket Propulsion - 14 years

PROFESSIONAL EXPERIENCE -

Rocket Research Company (1966 to present)

- Senior Staff Scientist - In his function as senior staff scientist, Dr. Schmidt is pursuing new business acquisitions in the area of energy storage through reversible chemical reactions, novel energy conversion schemes, and other energy-related projects. He is currently the program manager and principal investigator on a two and one-half year DOE/Sandia Laboratories contract for the development of a high-temperature catalyst for the reversible dissociation of sulfur trioxide in energy storage systems.

- Manager, Chemical Research - Dr. Schmidt has worked as the program manager and principal investigator on three study contracts on a high temperature chemical energy storage system using the reversible dissociation of sulfur trioxide. This chemical energy storage system is to be integrated with a solar thermal conversion power plant under study at Boeing Engineering and Construction for the Electric Power Research Institute and DOE. In addition to work on more efficient utilization of solar energy through energy storage, Dr. Schmidt has been assigned as program manager and principal investigator on a DOE contract for the development of a high temperature explosive for stimulation of geothermal resources.

- A major part of Dr. Schmidt's effort with Rocket Research Company has been directed toward a better understanding of the spontaneous catalytic decomposition of hydrazine as a monopropellant. These studies have led to improved catalysts and identification of possible catalyst poisons. A new method to measure monopropellant ignition delay was successfully applied to the solution of a number of hydrazine monopropellant problems. In addition to efforts to improve the existing Shell 405 catalyst, new hydrazine decomposition catalysts were developed and successfully tested, including the LCH-101 catalyst for the Viking Mars lander and the LCH-202 catalyst for Space Shuttle RCS. This experience is currently being applied to the development of catalysts for non-aerospace applications such as methanation, reformation, and sulfur oxide conversion catalysts.

- Significant improvements in hydrazine monopropellant reactor life have been possible through the incorporation of metal foams in the catalyst bed. Under Contract NAS 8-28950, Dr. Schmidt developed metal foams of improved nitriding resistance for high temperature applications in rocket engines and gas generators. The use of metal foams for catalyst retention has more than tripled the useful life of conventional reactor designs. Dr. Schmidt was the principal investigator in the "Evaluation of Monolithic Catalyst Beds for Hydrazine Reactors" under Contract NAS 7-755. The new catalyst developed under this program performs similar to Shell 405 with significant advantages over conventional granular catalyst beds (NASA CR-132983, May 1973). He also is the co-inventor of a unique tribrid fuel grain which may lead to the realization of ultimate specific impulses achievable with high energy chemical rocket propellants (Contract NAS 1-8792).

- During the development of aircraft emergency rescue slides, the cool gas inflation system currently used on the Boeing 747 aircraft, Dr. Schmidt made important contributions with regard to propellant and working fluid selection and safety of the gas generator. Toxicity and safety studies under the direction of Dr. Schmidt have led to the discovery of a potential problem area in early design of occupant restraint systems (air bags) in automobiles. Consequently, the air bag designs were modified to generate a breatheable, safe exhaust. Safety considerations ranked first in the selection of gas generators for man-rated applications as documented in numerous publications authored by Dr. Schmidt.

- Other studies at Rocket Research in which Dr. Schmidt participated were concerned with subliming solid propellants, high energy monopropellants, high burning rate solid propellants, fire extinguishing systems, two-component explosives, gas generators for undersea applications, fluidic control systems, auxiliary hydraulic power systems, jet engine starters, production of hydrazine, coal liquifaction and gasification catalysts, and alternate fuels for automobiles.

<u>German Research Institute for Aero/Astronautics, Institute for Rocket Propellants,(1964-66)</u>

- During his years with the West German Research Institute for Aero- and Astronautics in Stuttgart, Dr. Schmidt continued his systematic search of the chemical literature on rocket propellants. This search was already initiated during previous years as a part-time job while the Institute was still under the direction of Dr. Eugen Saenger, a well-known rocket pioneer. The work is documented in an 800-page book, <u>Raketentreibstoffe</u> (Rocket Propellants). Dr. Schmidt, as one of the three authors, has contributed the major part of this book which turns out to be the most comprehensive reference book ever written in this field. In addition to the book Raketentreibstoffe, Dr. Schmidt has published numerous articles on rocket propellants.

- Experimental effort during the years with DVLR was directed at the synthesis and characterization of storable high energy propellants such as tetrafluoro hydrazine, nitrogen trifluoride, oxygen difluoride, and chlorine trifluoride. Dr. Schmidt also took part in high altitude testing of the European ELDO satellite launcher third stage ASTRIS in the rocket test facility in Lampoldshausen, West Germany, where he designed a plant for decontamination of waste water and assisted in propellant quality control.

Tuebingen University (1962-64)

- Teaching Assistant - While working on his doctoral thesis, Dr. Schmidt held a position as teaching assistant with the University of Tuebingen where he taught chemical laboratory classes with up to 40 students. His thesis in organic preparative photochemistry entitled Photo-Sulfenechlorination received a rating of "magna cum laude".

PROFESSIONAL AFFILIATION AND ACTIVITIES

American Institute of Aeronautics and Astronautics, Associate Fellow
Society of Automotive Engineers
German Society for Aero/Astronautics
American Men and Women of Science
Who's Who in the West

PETER O. CARDEN

EDUCATION - University of Queensland, Bachelor of Engineering
(with honors)
Masters of Engineering
Australian National University - Doctor of Philosophy

EXPERIENCE SYNOPSIS -

Academic Posts - Research Fellow/Engineer, 1955-72
Senior Fellow of Research since 1972 to present

PROFESSIONAL EXPERIENCE -

Australian National University (1955 to present)

- Senior Fellow - In charge of the Energy Conservation Group. This group of eight academic, professional and technical personnel is interested in solar energy conversion as a primary power source (conversion to electrical energy). This group is one of a few solely interested in developing thermochemical processes directly related to solar energy systems. They have pioneered in the investigation of high pressure systems for this application, and were one of the first in the world to investigate the ammonia cycle.

  Other projects in solar energy are:

  1) Steering and control of large arrays of distributed collectors;
  2) Underground storage of gasses with high percentages of hydrogen;
  3) Thermochemical energy transport systems;
  4) Monitoring of direct solar radiation in Australia;
  5) Developing inexpensive metal paraboidal reflectors.

- Research Fellow/Engineer - For 10 years, Dr. Carden worked with Sir Mac Oliphant as a nuclear physicist in the development of a homopolar generator. It is the largest currently operating in the world, and has been doing so for the past 15 years.

- Dr. Carden worked with Dr. Bruce Montgomery of the Massachusetts Institute of Technology for one year in high magnetic field magnetism.

PROFESSIONAL AFFILIATION AND ACTIVITIES -

Australian Institute of Engineers
Institute of Mechanical Engineers