11.0

5102-121

Thermal Power Systems
Advanced Solar Thermal Technology Project

Advanced Solar Thermal Technology: Potential and Progress

April 15, 1979

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

5102-121

Thermal Power Systems
Advanced Solar Thermal Technology Project

Advanced Solar Thermal Technology: Potential and Progress

L. Leibowitz
E. Hanseth

April 15, 1979

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Solar Thermal Power Systems Project is sponsored by the U.S. Department of Energy and forms a part of the Solar Thermal Program to develop low-cost solar thermal electric generating plants.

ABSTRACT

The Advanced Thermal Power Technology Program sponsored by the Department of Energy (DOE), develops and applies advanced technology for improved solar thermal energy subsystems and components. The advanced technology effort is aimed at systems which can achieve significant energy cost reductions. Increased efficiency has the potential for significantly lowering energy costs through reductions in the number of concentrators that must be purchased and their maintenance and operations. A net cost reduction will result provided higher efficiencies only impose modest cost increases on related subsystems and components. Generally, higher energy conversion efficiencies are achieved at higher temperatures and require the development of higher-temperature receivers, improved engines, and concentrators with high quality surfaces. This paper describes the potential for advanced technology to achieve commercially attractive solar thermal systems and describes some recent developments in advanced heat engines, high temperature receivers, chemical transport, and storage.

CONTENTS

I. INTRODUCTION

The declining supply of conventional fuels which currently supply a major share of the nation's energy and the increasing pressure by society for a cleaner environment are stimulating a search for alternative, inexhaustible and clean, energy sources. Thus a major thrust of the nation's solar energy program is the development of technologies that will supplement and eventually replace current means of power generation and thermal energy production. Solar thermal systems are technically feasible using existing technology and are currently being deployed. However, substantial cost reductions are needed for solar thermal power to compete with conventional energy sources on a national basis. These cost reductions impose significant technical as well as economic challenges.

The Department of Energy (DOE) Large Power and Small Power Applications programs are utilizing existing, proven technology wherever possible in order to meet the needs of their applications. The Advanced Thermal Power Technology Program, by contrast, develops and applies advanced technology to achieve significant energy cost reductions. Specifically, the goal of the program is to conduct research and development for materials, components and systems that by the mid-to-late 1980's will lead to solar thermal energy costs of 25 to 50 percent lower than systems based on current or near-term technology. Achievement of these goals may be expected to increase market penetration of solar thermal systems starting in the mid-1980's.

Energy costs of solar thermal power systems may be reduced by increasing system operating efficiencies, by reducing the requirements for maintenance and through the use of lower-cost, longer-life optical surfaces and components. At this time, emphasis is being placed on improving system operating efficiencies. This is achieved with higher efficiency engines, receivers, concentrators, and other subsystems. Development of these subsystems is being pursued by the Advanced Technology Program.

The progress of the Advanced Technology Program towards development of innovative subsystems and component concepts can be assessed using cost and performance targets. The purpose of this effort is to bring to bear the results of detailed solar thermal system studies on research and development program decisions. A simplified system simulation and energy cost computer model was developed and cost/performance analyses were performed to identify subsystems with the greatest potential for energy cost reduction. Allowable performance and cost for each subsystem necessary to achieve the assumed $1000/kWe system capital cost goal were determined. These targets can be used by DOE and supporting laboratories to help establish program priorities for the Advanced Technology program, assess relative progress of subsystem technologies, and assist in the screening of advanced component concepts. Attainment of the targets may not be possible without an Advanced Technology program. Based on present results, research and development emphasis has been directed towards several areas which will be briefly described.

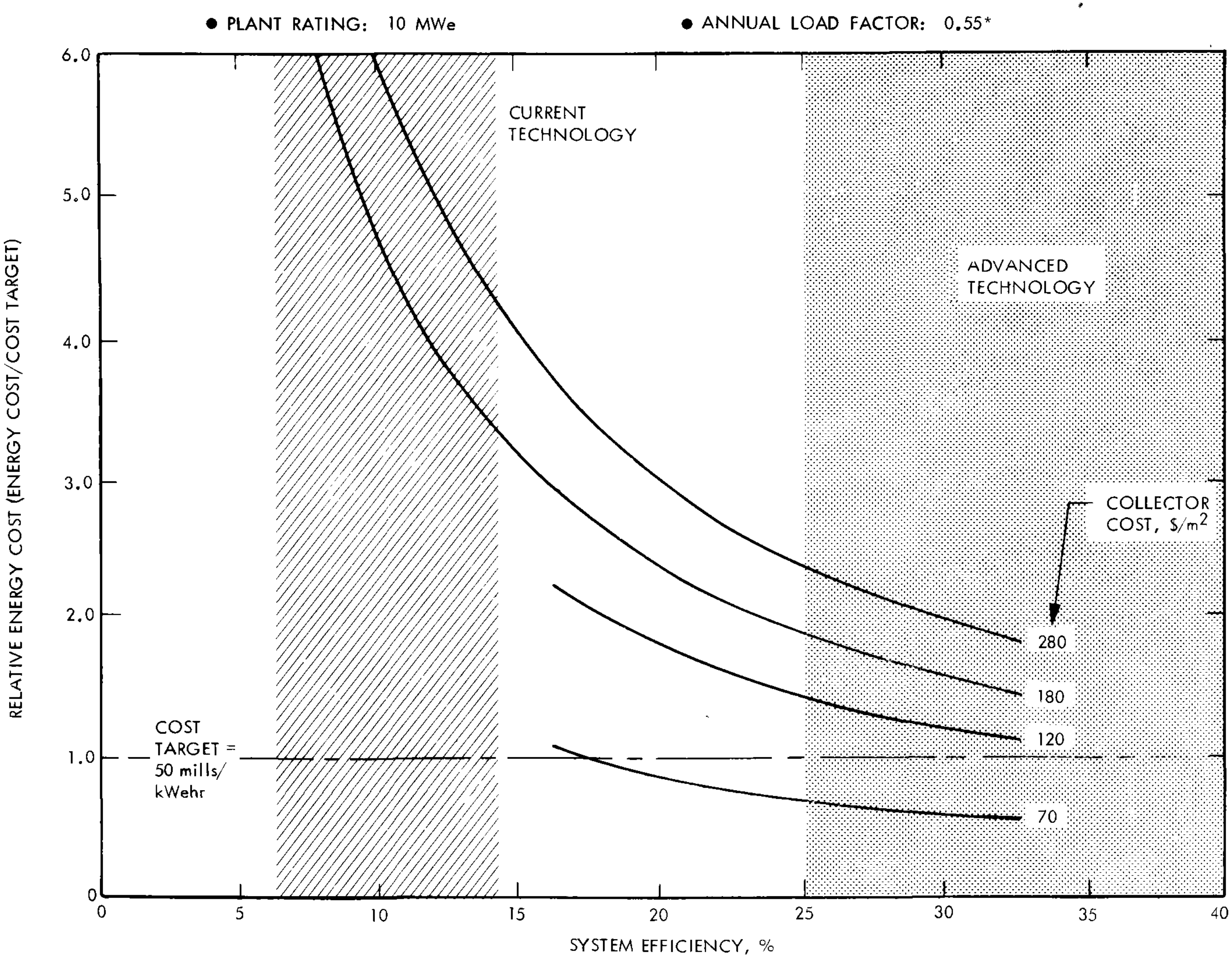

Figure 1. Effect of Improvements in System Efficiency on Achievement of Energy Cost Reductions

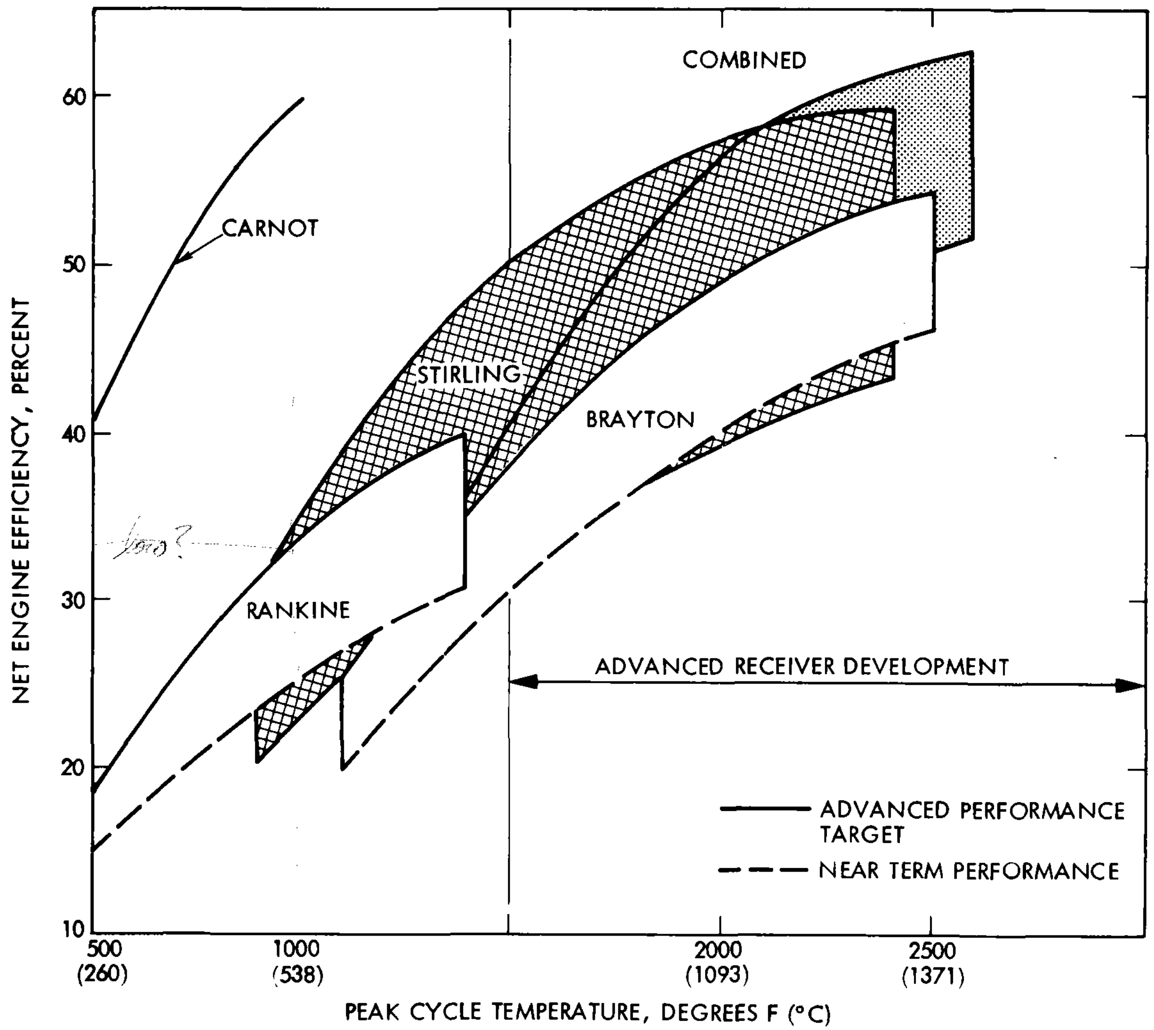

Figure 2. Advanced Engine Performance Potential for Rankine, Stirling, Brayton and Combined Brayton/Rankine Cycles

II. APPROACH TO IMPROVE PERFORMANCE

Preliminary evaluations of future solar thermal power plants indicate that advanced technology systems have a significantly greater potential for achieving economic plant operation than present systems (Ref. 1 & 2). Analysis indicates that increased system operating efficiency significantly lowers energy costs through reduction in the number of concentrators that must be installed for a given output and in reduced maintenance and land requirements. Effects of the improvements in system efficiency and reduction in collector cost on relative energy cost for a small power system are shown in Figure 1. Solar thermal systems currently being deployed are anticipated to have system efficiencies between 7 to 14 percent resulting in energy costs several times the energy cost goal of 50 mills/kWeh. The approach of the Advanced Technology Program is to develop those components and subsystems that will allow the attainment of system efficiency approaching 30 percent. With moderate to low concentrator subsystem costs this will result in the achievement of the energy cost target (see Fig. 1). The advantages of higher efficiency systems and subsystems must be traded off against their potentially higher capital costs. That is, advanced systems will provide reduced energy cost if increased energy production offsets any cost penalty.

The largest energy loss in a solar thermal system is from heat rejected by the engine. Thus the greatest potential for improving system efficiency is through the utilization of high performance, high efficiency engines. Substantial improvement in the efficiency of small engines for solar thermal applications are possible (Ref. 3). The potential increase in engine efficiency compared with near-term performance is presented in Figure 2. It can be seen that the Stirling cycle offers the greatest promise for improved efficiency for temperatures between 1200°F and 1900°F. The Brayton cycle also shows promise for high efficiency, but primarily at operating temperatures greater than 2000°F. Achievement of engine efficiencies greater than 40 percent will be a key step towards achieving energy cost targets.

The utilization of high efficiency heat engines will require an advanced technology program in high temperature receivers. High temperature receivers are also a key to the development of the industrial process heat and fuel and chemicals application for thermal power systems. The requirement for increased receiver operating temperature must be balanced against an increase in thermal energy losses at these higher temperatures. Thermal energy losses from a receiver consist of reradiative heat loss through the aperture, convective heat transfer through the aperture, and conductive/convective heat losses through the receiver insulation. As operating temperatures increase, the radiative heat losses increase most rapidly. Reduction of reradiative losses is a key factor in the utilization of high temperatures to achieve increased system efficiency, Figure 3. (Ref. 4)

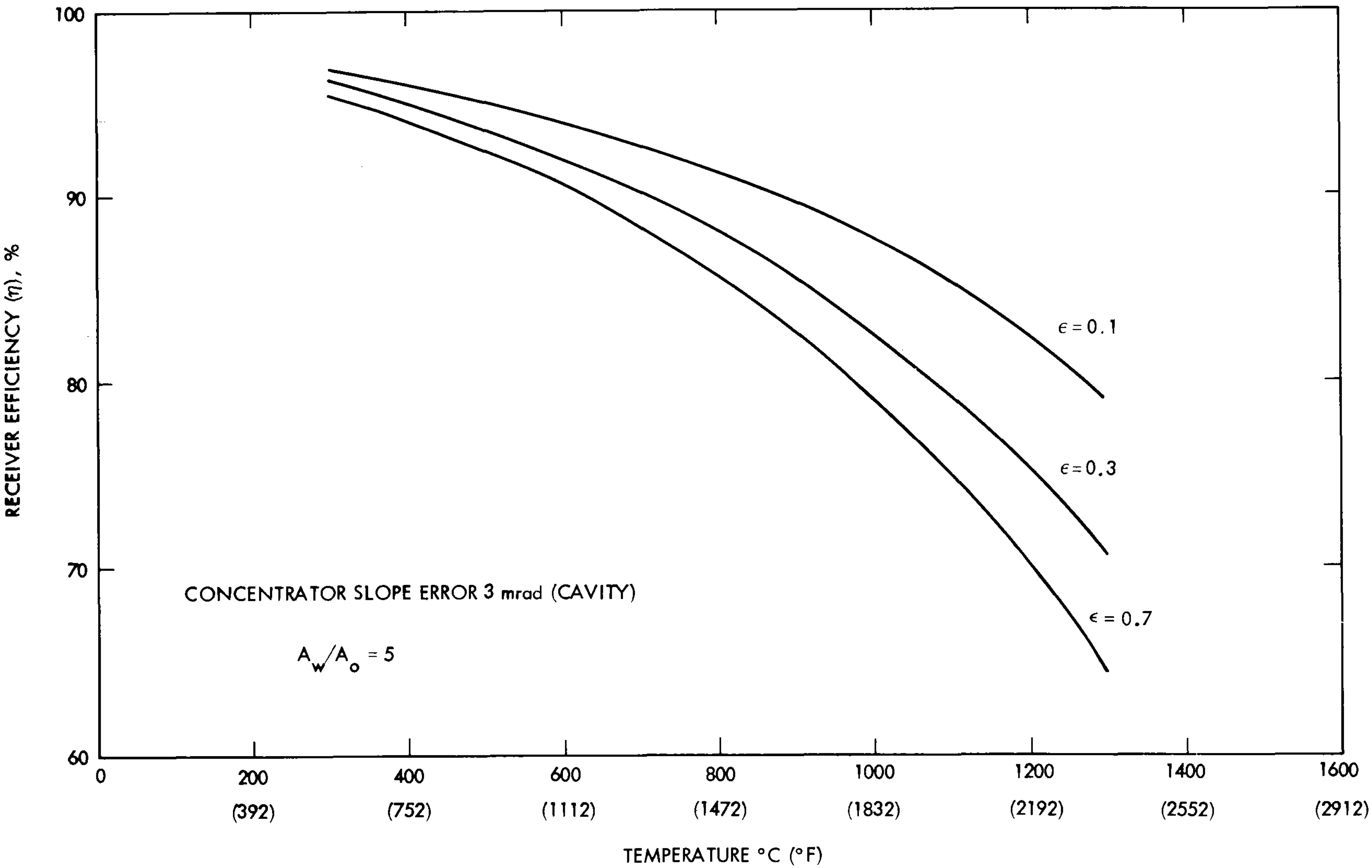

Figure 3. Receiver Efficiency vs Temperature for a Point Focusing Cavity Receiver where ε is Emmitance of the Receiver Surface and A_W/A_O is the Ratio of the Heat Transfer Area to the Aperture Area

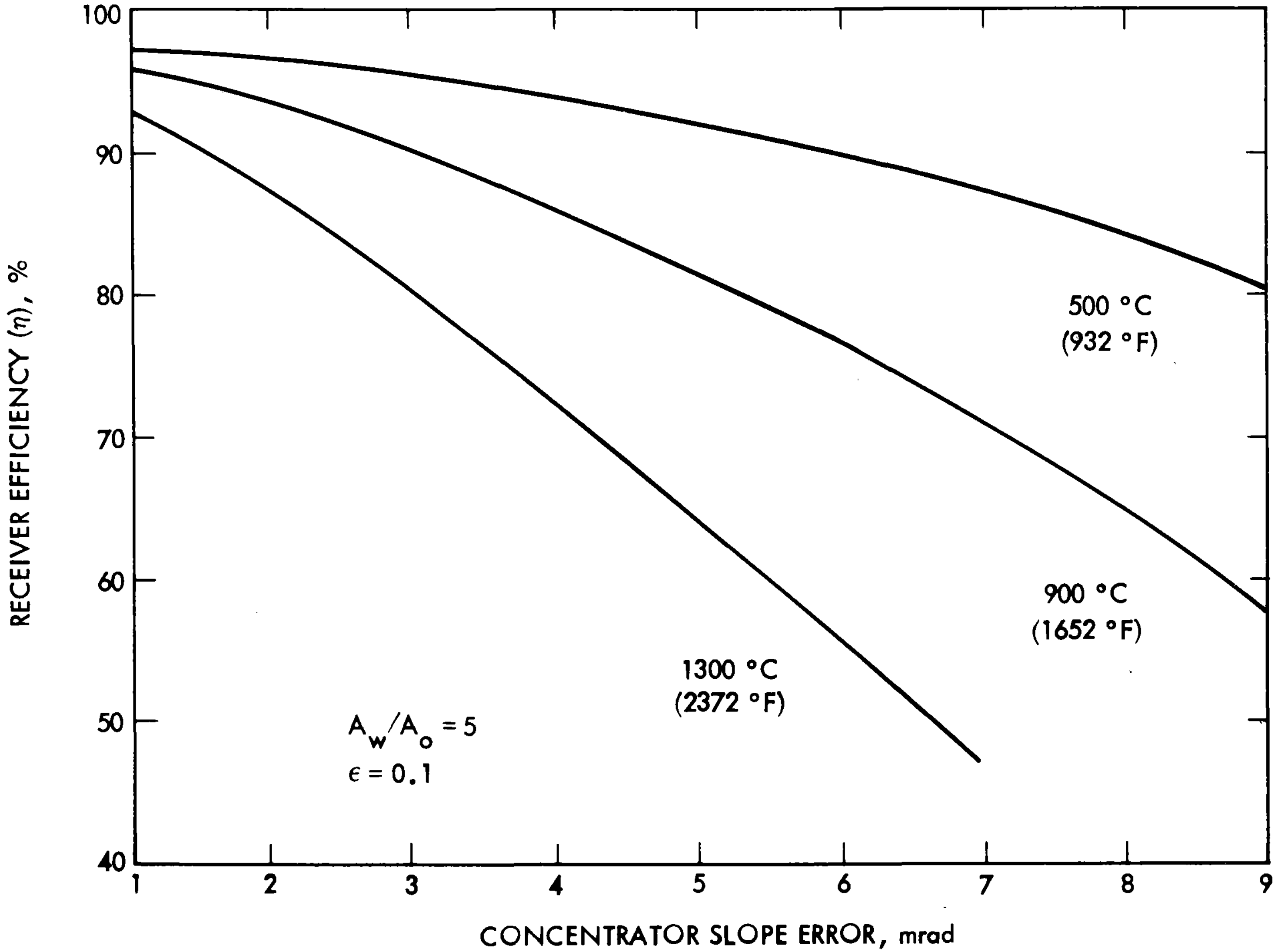

Figure 4. Receiver Efficiency vs. Concentrator Slope Error at Several Temperatures

The concentrator represents the greatest area for improvement in a solar thermal power system. The achievement of energy targets by advanced solar thermal power systems imposes requirements on concentrator cost and quality. The optical quality and reflectivity of the concentrator impacts the attainment of high system efficiency. The size of the solar image created by the concentrator is directly proportional to the concentrator surface error. Since the heat loss through the receiver aperture is proportional to the aperture size, then the thermal performance of a receiver is directly related to the concentrator quality (see Fig. 4).

Because of the diffuse nature of solar energy, concentrator capital cost is the largest contributor to the energy cost of solar thermal systems. Determination of concentrator cost is difficult because few concepts have been built or even developed to the detailed design stage. Accurate concentrator mass production cost analysis requires a detailed and optimized design. Up to now, only first order concept cost analysis is available. However, this analysis indicates that cost reductions of a factor of five or more from current costs of concentrators are possible. Because of the lack of detailed designs, assessing the effect of concentrator quality on cost is not yet possible. As concentrator production cost data become available, cost/ quality tradeoffs can be made for specific systems and applications.

Priorities for the Advanced Technology Program have been established based on the above considerations. Emphasis is being placed on improving system efficiency through the use of high performance heat engines, highly efficient receivers, and also by pursuing concentrators with high potential for cost reduction and accuracy.

III. COST/PERFORMANCE TARGETS

An initial set of subsystem cost/ performance targets has been established to assist in the assessment of progress of advanced system developments, and in the screening of advanced component concepts. There is a moderate uncertainty in current data on subsystem performance while cost data has a high degree of uncertainty. The approach taken has been to establish consistent cost/performance tradeoffs between subsystems. Thus the subsystem costs are determined by how much can be afforded to meet energy cost targets and not by production cost analyses. While a large number of variables can impact the energy cost of a solar power plant, only those related to advanced subsystem development will be addressed in some detail.

In order to facilitate cost/performance target allocation and advanced component concept screening, a simplified simulation model, Solar Energy Cost program (SEC), has been developed. The model as currently developed is specific to point focusing dish systems. The model uses established solar economics methodology and follows the same approach as more detailed solar simulation models (Ref. 5). Agreement within 5 percent of the more detailed code is obtained when the efficiency of each subsystem is assumed to be a constant. This assumption is reasonable for advanced system studies and new concept screening where uncertainties in performance data are significantly larger than any simulation penalties. The simplified program can perform calculations in a fraction of the time of the more detailed codes. The program determines minimum energy cost for a given capacity factor using actual annual insolation data (Barstow, 1976).

Allocation of cost/performance targets has been performed for each subsystem of a Small Power System meeting the 1990 capital cost target. A parabolic dish with a Stirling engine/generator mounted at the focus using electric power transport was assumed. The attainment by 1990, of a system capital cost of $1000/kWe has been established as a system target for thermal power systems by DOE. An electric energy cost of 50 to 60 mills/kWeh in 1978 dollars is associated with this target. Because little substantive information currently exists on subsystem cost, a range of targets are considered. These ranges, shown in Table 1, are considered in view of recent technology development program results. Nominal cost and performance targets are allocated to make attainment equally challenging for each subsystem.

The subsystem cost/performance targets that have been allocated are shown in Table 2. It can be seen that concentrators represent the largest single contribution to the energy cost of a solar thermal plant. The concentrator cost target, although considerably lower than current standards, appears to be well within the projections for advanced technology. The costs used here are the total for installation of the subsystem and include shipping, installation, and alignment charges. The unit costs and efficiencies selected all fall within the range of what is considered reasonable for advanced technology but represent a substantial challenge for the technologies within each area.

The sensitivity of system capital cost and busbar energy cost to variations in subsystem unit cost and efficiency has been explored. The most important variable for system cost is the concentrator unit cost; its effect is shown in Figure 5. Thus meeting or exceeding the concentrator cost target is a key towards successfully attaining the system cost target. Another key variable is the energy conversion efficiency. Its effect on system energy cost is shown in Figure 6. This illustrates the importance of obtaining high performance heat engines in order to produce successful solar thermal power systems. The tradeoff of the two key variables, concentrator unit cost and energy conversion efficiency, is shown in Figure 7. This figure illustrates the interrelationship of these two factors and the tradeoff that can be made and yet still achieve the system cost target. In Figure 8 a similar tradeoff between concentrator efficiency and cost exemplifies the relationship of concentrator surface quality to allowable manufactured cost. Based on the progress of the Advanced Technology Program, these target allocations can be adjusted to take account of successes and disappointments within the development of individual subsystems.

Additional factors that are beyond the scope of the Advanced Technology Program can have a substantial impact on the attainment of solar

Table 1. Advanced Subsystem Cost/Performance Ranges

DISH-STIRLING
YEAR 1990 PLANT STARTUP - 1978 DOLLARS

SUBSYSTEM	UNIT COST	EFFICIENCY
CONCENTRATOR	$70 - 130/m^2	0.85 - 0.93
RECEIVER	$ 5 - 20/m^2	0.80 - 0.90
ENERGY CONVERSION	$50 - 200/kWe	0.33 - 0.50
ENERGY TRANSPORT	$10 - 60/kWe	0.94 - 0.98
ENERGY STORAGE	$20 - 40/kWe-hr	0.70 - 0.80
BALANCE OF PLANT	$75 - 200/kWe	———

Table 2. Advanced Subsystem Cost/Performance Targets

DISH-STIRLING

10MWe - 0.40 CAPACITY FACTOR

YEAR 1990 PLANT STARTUP - 1978 DOLLARS

SUBSYSTEM	UNIT COST	EFFICIENCY	CAPITAL COST 10^5 DOLLARS	ENERGY COST mills/kWe-hr	% ENERGY COST
CONCENTRATOR	$\$100/m^2$	0.90	44.8	19	36
RECEIVER	$\$10/m^2$	0.85	4.5	2	4
ENERGY CONVERSION	$100/kWe	0.42	14.4	6	11
ENERGY TRANSPORT	$40/KWe	0.96	5.6	2	4
ENERGY STORAGE	$30/kWe-hr	0.75	4.1	2	3
BALANCE OF PLANT	$100/IWe	-	10.0	4	8
OTHER CAPITAL	20% OF DIRECT COST		16.6	9	17
O & M (FIRST YEAR)	1.5% OF DIRECT COST		(1.2)*	9	17
TOTAL		0.308	$1000/kWe	53	100

* O & M NOT INCLUDED IN SYSTEM CAPITAL COST TOTAL

thermal cost targets (Ref. 1, 2). System design factors such as the capacity factor for the plant affect the overall system cost. Plant operation for longer periods than available insolation requires the addition of storage capacity. Busbar energy cost is increased due to increased subsystem sizes, additional storage capital cost, and storage associated inefficiency. For example, the energy cost for the system depicted in Table 2 with a capacity factor of 0.55 would increase from 53 mills/kWehr to 61 mills/kWehr; a 0.70 capacity factor would increase the cost to 67 mills/kWehr.

Other factors which impact energy cost are operation and maintenance cost and "Other Capital" cost, which includes spares, contingencies, and indirect costs for plant design and engineering construction. Each of these two factors account for approximately one-sixth of the busbar energy cost for the assumptions shown. Also accounted for is a Balance of Plant cost. The energy conversion unit cost includes the Stirling engine, generator, and governing controls while Balance of Plant accounts for other plant costs such as buildings, substations, computer and display, computer input/output instrumentation, and temporary construction facilities. While many of these costs relate to the reliability and simplicity of the system, they are not explicitly tied to Advanced Technology development.

Economic assumptions can make a significant impact on the overall energy costs calculated for a given solar thermal system. Variations in estimates of cost of capital and escalation rates for solar plant analyses can result in over a 40 percent difference in projected busbar energy costs.

Finally, the amount of yearly insolation energy available to a solar power system and the time history of its intensity determine the amount of electricity producible by a given plant design. Both energy available and insolation time history vary with geographical location and on a year-to-year basis. Their combined effect on plant capital cost and energy cost can be very significant (Ref. 6).

Although operational and economic factors are beyond the scope of this study, the Advanced Technology Program must concern itself with these considerations. All of these factors are being pursued in detail by investigators within the solar thermal program.

IV. THE ADVANCED TECHNOLOGY PROGRAM

The Advanced Technology Program is currently pursuing efforts towards meeting the subsystem cost/performance targets described above. The Advanced Technology Program is divided into four subprograms which are: Advanced Systems, Advanced Component Demonstrations, Materials and Coating Supporting Technology, and Technology Assessment. The Advanced Systems subprogram provides a focus for identification, subsystem development, and demonstration of technical feasibility of the Large Power and Small Power systems. Advanced Component Demonstration subprogram provides the initial demonstration of the technical feasibility of new innovative ideas for

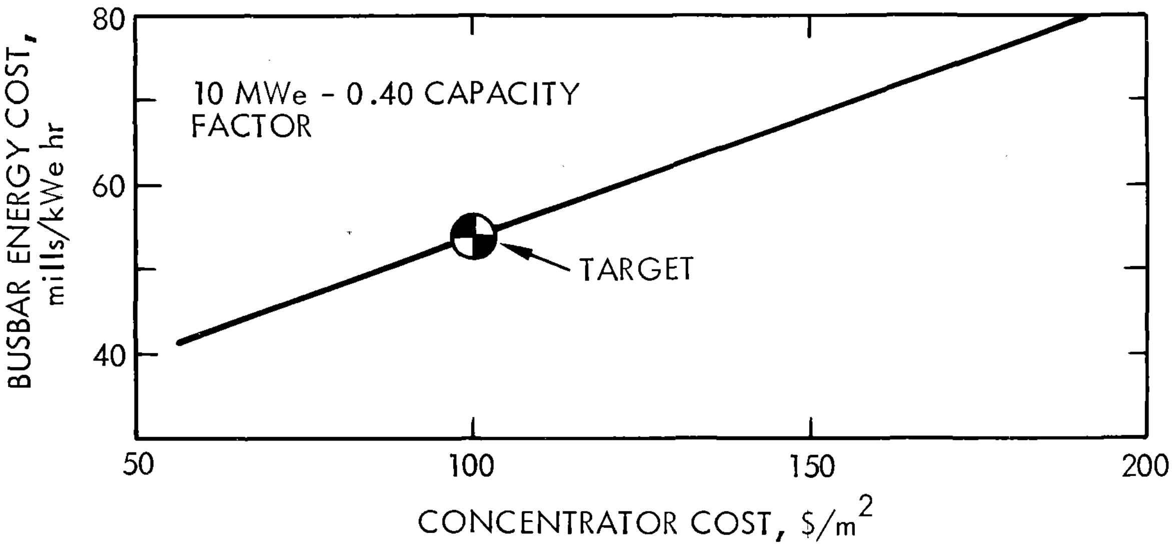

Figure 5. Dish-Stirling Busbar Energy Cost vs. Concentrator Cost

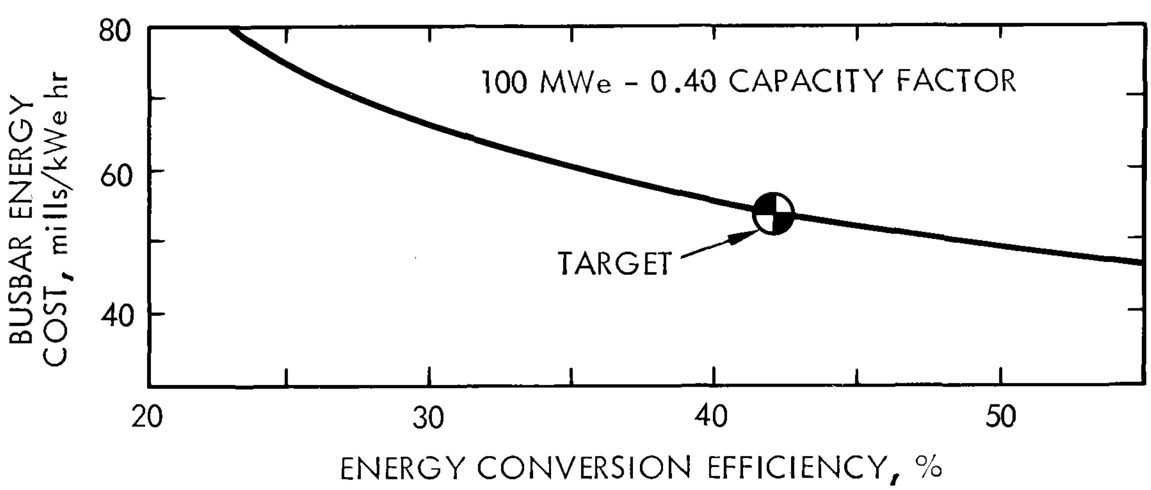

Figure 6. Dish-Stirling Busbar Energy Cost vs. Energy Conversion Efficiency

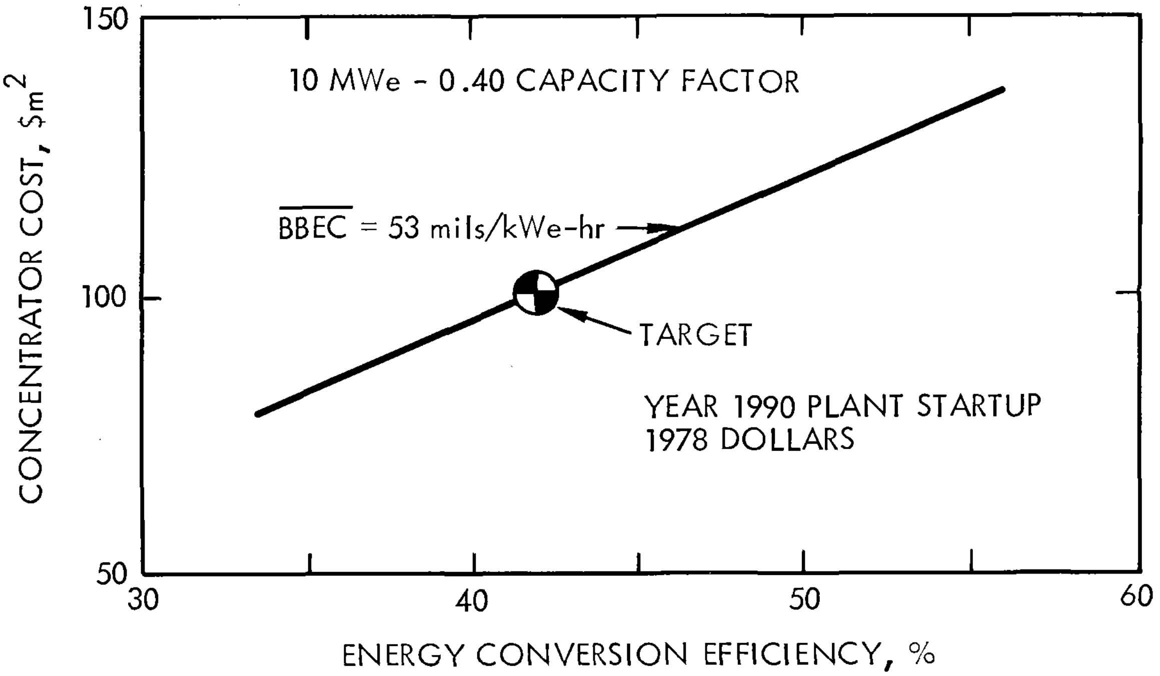

Figure 7. Dish-Stirling Concentrator Cost vs. Energy Conversion Efficiency

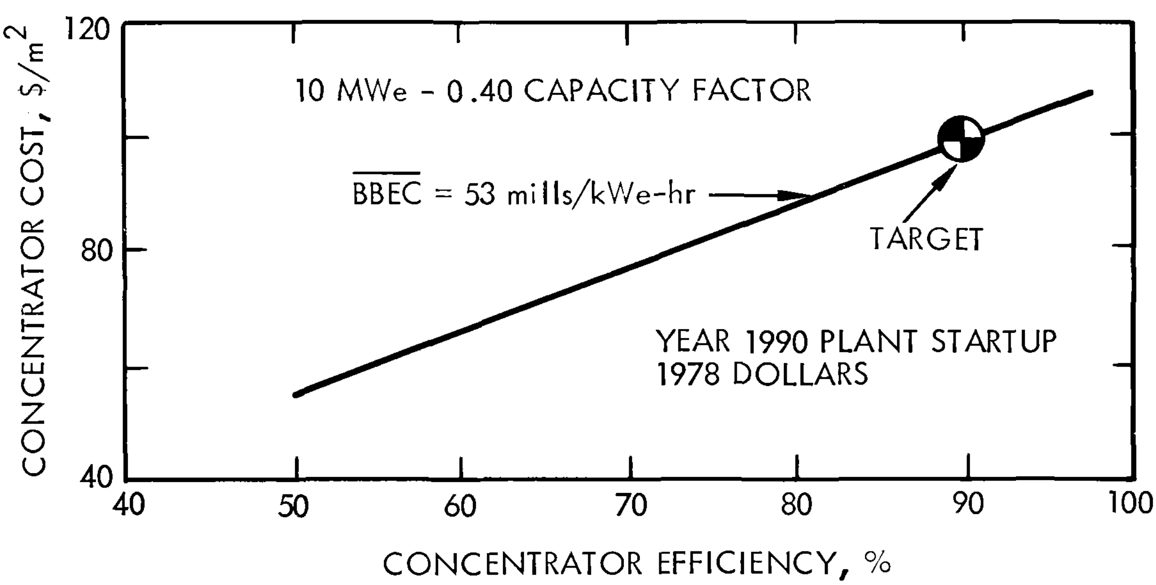

Figure 8. Dish-Stirling Concentrator Cost vs. Concentrator Efficiency

components and processes. Long-life, low-cost materials and coatings are being developed for use in solar thermal applications. Technology Assessment provides the direction and evaluation for the program including setting of targets and priorities.

The Advanced System subprogram will provide the design, construction, and integration of the components for selected Advanced System demonstrations. The purpose of this subsystem integration and demonstration is to verify the performance of the components when operated in the context of a system. Completion of the subsystem integration and test will establish the technical viability of the system and establish its readiness for subsequent introduction into applications programs. The dish-Stirling concept has been tentatively selected as the first Advanced Small Power System (see Fig. 9). In the initial effort, a near-term kinematic Stirling engine will be adapted for an early solar thermal power demonstration. The early Stirling engine-generator will produce 15 to 20 kWe at a conversion efficiency of 35 to 40 percent. Based on the successful completion of this demonstration, a program to upgrade engine efficiency will be undertaken with a target of producing conversion efficiencies of 45 to 50 percent. The second engine may be an advancement of the kinematic engine or may be obtained from the Advanced Component Demonstration subprogram described below.

The purpose of the Advanced Component Demonstration subprogram is to identify new, innovative concepts for solar thermal components, subsystems, and processes and to provide the first experimental demonstration of their technical feasibility in a solar thermal environment. The Advanced Component Demonstration subprogram provides the focus for taking risks where the payoff in terms of cost and performance improvements is commensurate. Activities are currently underway in these areas of high temperature receivers, low cost concentrators, advanced heat engines, and thermo-chemical transport and storage.

Advanced receivers are being developed for applications with Brayton cycle and Stirling cycle heat engines and for chemical and high temperature applications. Advanced receivers and components are under development to supply high temperature heat for use in high performance Brayton engines with a minimum of losses. A 250 kW ceramic honeycomb receiver using air at ambient pressure as a working fluid has been designed, fabricated, and tested by the Sanders Corporation. This receiver has been tested successfully at the Advanced Component Test Facility, at Georgia Institute of Technology, and reached operating temperatures of 1065°C (1950°F). A ceramic dome receiver concept has been under evaluation and test by the MIT/Lincoln Laboratories which would allow the heating of pressurized working fluid to temperatures of 1000°C. The development has focused on the identification of high temperature sealing techniques between the pressurized air and high temperature ceramic dome material.

The successful development of chemical and high temperature ceramic receivers opens the door to the utilization of solar thermal chemical transport and storage systems, fuel and chemical processes, and industrial high temperature process heat. The initial steps have been to prove the technology feasibility for receivers operating at high temperatures. A ceramic counterflow heat exchanger/converter is being developed by the Naval Research Laboratory to chemically dissociate SO_3 in a high temperature solar receiver. This effort will provide an early demonstration of the feasibility of chemical energy transport using reversible, catalyst controlled, gas-based chemical reactions. High temperature ceramic receiver concepts for operation between 1000° to 1500°C are currently being investigated. Parametric analysis identifying key design features and thermal losses and identification of interface and operations will be performed. The most attractive concept identified will be fabricated and tested in a follow-on effort.

Advanced concepts in free-piston Stirling engines are currently under investigation. The free-piston Stirling engine does not have the mechanical drive losses of the kinematic machines and therefore has potential for higher efficiency. It also eliminates the need for a working seal between the mechanical drive and the engine working fluid. There are, however, several practical problems and technology developments that must be solved. The inherent simplicity and reliability of this class of machine has led to its consideration for a new component feasibility demonstration.

New approaches to thermal chemical transport subsystems are under investigation. These subsystems have potential application for both electric power generation as well as the application to industrial and high temperature process heat utilization. Areas to be considered include new thermal chemical processes, converter configurations, and catalyst systems.

Advanced concentrator concepts are under development which offer high potential for low cost production. Novel concepts for point focusing concentrators which utilize advanced materials or innovative design features which will allow them to be mass-produced at substantially lower cost than current design concepts are being pursued.

In conclusion, the Advanced Technology Program is expected to be at the forefront of technology, providing the Solar Thermal Program with significantly improved components, subsystems, and with new capabilities for using solar thermal power. The progress of the Advanced Technology effort towards successful developments can be assessed and guided using costs and performance targets. Successful commercial utilization of solar thermal power can be expected if these cost targets can be achieved.

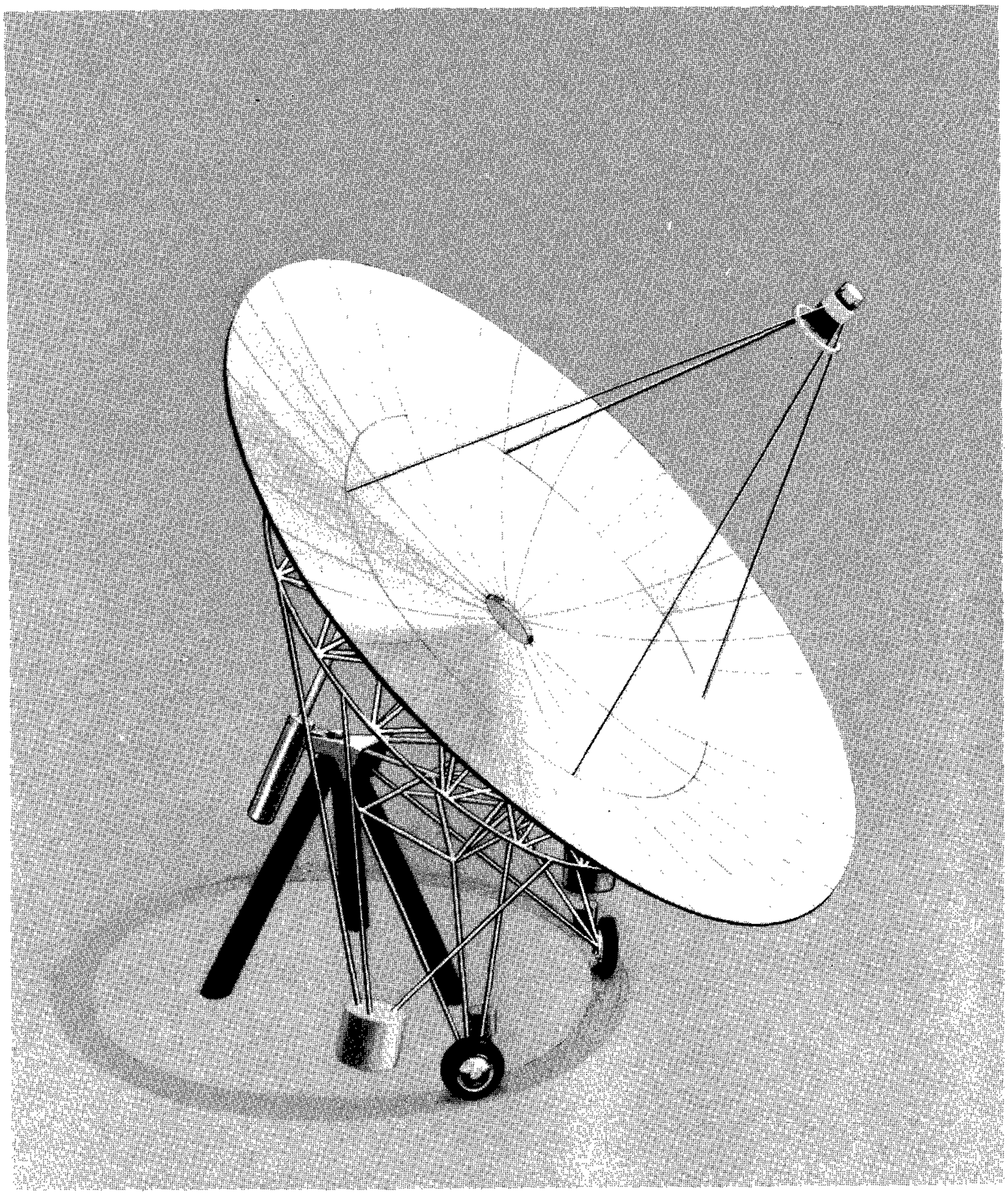

Figure 9. Dish-Stirling System Concept

REFERENCES

1. T. Fujita, et al, "Projections of Distributed Collector Solar-Thermal Electric Power Plant Economics to Years 1990-2000," Department of Energy/JPL-1060-77/1, (1977).

2. T. Fujita, et al, "Techno-Economic Projections for Advanced Dispersed Solar-Thermal Electric Power Plants to Years 1990-2000," Department of Energy/JPL-1060-78/4, (1978).

3. "Advanced Technology Development," Thermal Power Systems Semi-Annual Progress Report, Department of Energy/JPL-1060-78/3, (1978).

4. Y. C. Wu and L. C. Wen, "Solar Receiver Performance in the Temperature Range of 300 to 1300 C," Jet Propulsion Laboratory Document No. 5102-82, (1978).

5. N. El Gabalawi, et al, "A Modularized Computer Simulation Program for Solar Thermal Power Plants," Jet Propulsion Laboratory Document No. 5102-80, (1978).

6. A. F. Latta, et al, "The Effects of Regional Insolation Differences Upon Advanced Solar Thermal Electric Power Plant Performance and Energy Costs.," Jet Propulsion Laboratory Document No. 5102-115, (1979).