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(NASA-CR-163882) STORAGE REQUIREMENT DEFINITION STUDY Final Report (General Electric Co.) 120 p HC A06/MF A01 CSCL 10C

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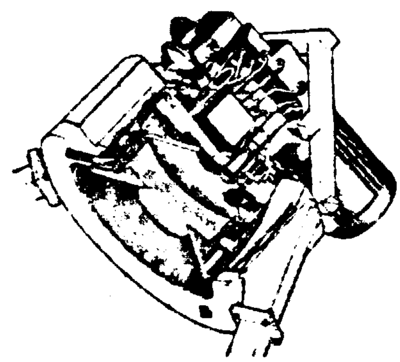
STORAGE REQUIREMENT DEFINITION STUDY

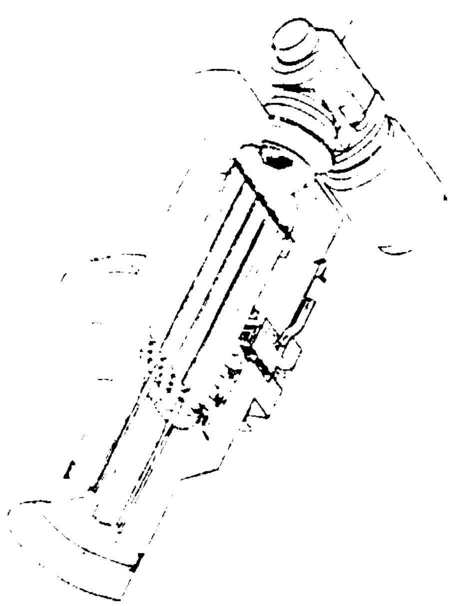
Final Report

TASK 10

Contract 955388

DECEMBER 15, 1980





Prepared for

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GENERAL ELECTRIC
ADVANCED ENERGY PROGRAMS DEPARTMENT
EVENDALE OPERATIONS
CINCINNATI, OHIO 45215

AED-EO-57

FINAL REPORT

STORAGE REQUIREMENT DEFINITION STUDY

by

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for

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CONTRACT 955388
TASK 10

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DECEMBER 15, 1980

GENERAL ELECTRIC
ADVANCED ENERGY PROGRAMS DEPARTMENT
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P O BOX 15132
CINCINNATI, OHIO 45215

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration."

ABSTRACT

A dish Stirling solar receiver (DSSR) and a heat pipe solar receiver with TES (HPSR) for a 25 kW_e dish Stirling solar power system are described. The thermal performance and cost effectiveness of each are analyzed minute-by-minute over the equivalent of one year of solar insolation. Existing designs of these two systems were used as a basis for the study; TES concepts for the DSSR and alternative TES concepts for the HPSR are presented. Parametric performance and cost studies were performed to determine the operating and cost characteristics of these systems. Data are reported for systems (1) without TES and with varying amounts of TES, (2) with and without a fossil fuel combustor, (3) with varying solar to fossil power input and (4) with different system control assumptions. The principal effects of TES duration, collector area, engine efficiency, and fuel cost sensitivity are indicated. Development needs for each of the systems are discussed and the need and nature of possible future TES modular experiments are presented and discussed.

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SECTION I

SUMMARY

The application of thermal energy storage (TES) to a 25 kW_e dish Stirling solar power conversion system was studied using two unique receiver components. The dish Stirling solar receiver (DSSR) is a direct receiver without TES in which the solar insolation impinged on a copper cone heat exchanger containing the Stirling engine heat exchanger tubes and protected from oxidation at operating temperatures above 1600°F by superalloy cladding. This receiver engine-generator system was supported by a fossil fuel combustor which operated continuously at a minimum of 10% power and which was modulated to supplement variations in solar power. The heat pipe solar receiver with TES (HPSR) featured a basic design containing 0.8 hours of TES and utilized heat pipe thermal transport from the receiver to a large secondary heat pipe containing the TES, the engine heat exchanger tubes and a shell-side "on-off" combustor heat exchanger. Both systems were sized at 25 kW_e output and their system design characteristics were utilized for performance analysis.

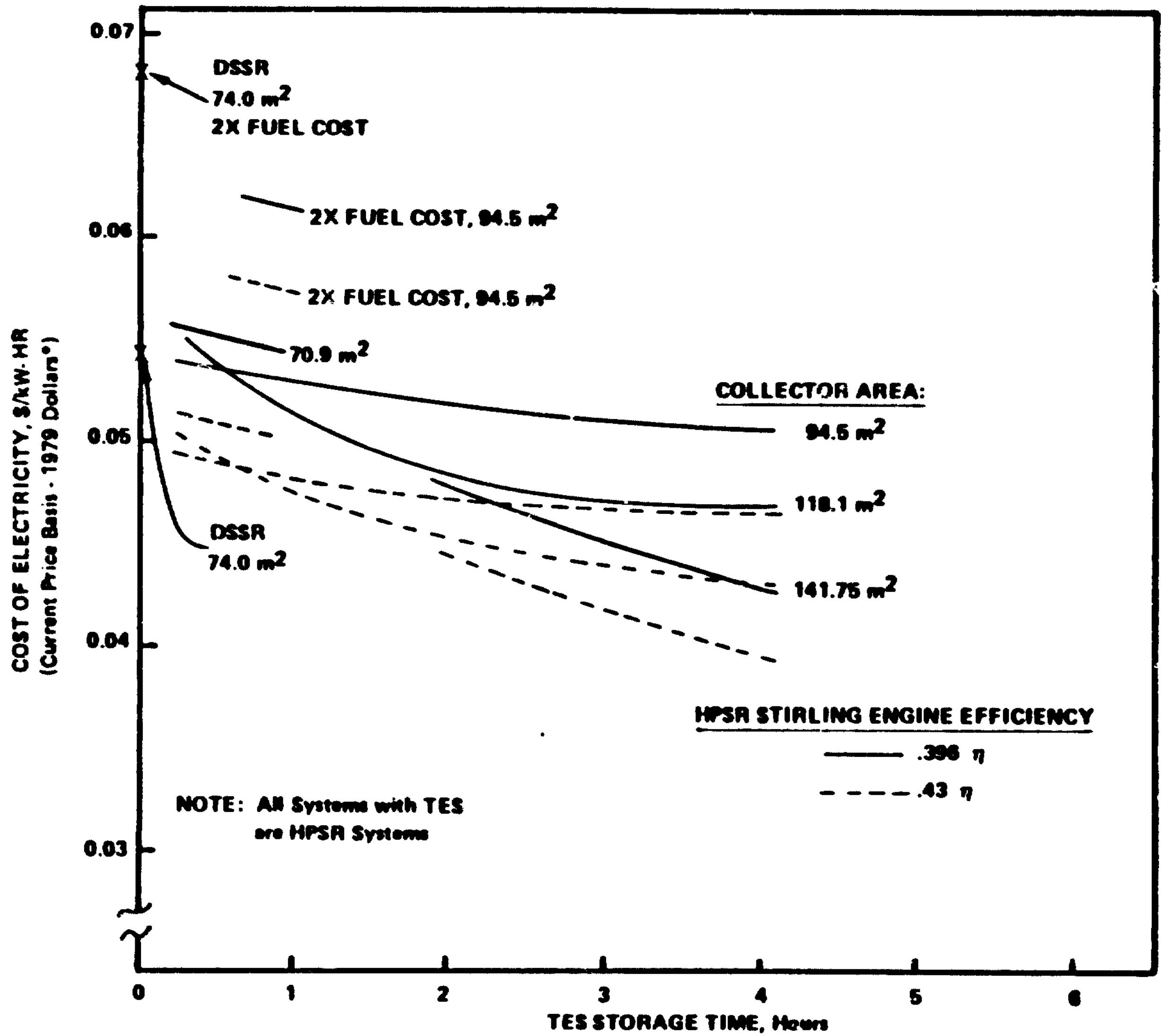
The thermal performance and energy conversion characteristics including thermal losses, were modeled in a finite element analysis using nodal networks appropriate to each design. Temperature, heat flow and energy conversion analyses were made by a computerized analysis of the daily solar insolation over a simulated one year period at one minute intervals and under control assumptions which (1) provided supplemental fossil fuel when needed, (2) defocused the concentrator as required and (3) started or stopped the engine.

The economic analyses of these systems were conducted over a 30 year period of simulated operation in accordance with accepted costing methods for solar utility systems including consideration for capital equipment, operating and maintenance expenses, inflation rates, etc. The levelized costs of electricity (COE) were determined for each system under various assumptions; they are reported here at deflated current values for comparison with present COE values.

As shown in Figure 1-1 the performance and economic analysis for the HPSR covered TES durations of 15 minutes and 0.8, 2 and 4 hours using concentrator collector areas from 71 to 142 m^2. The DSSR system with its continuous combustor had no advantage in adding brief buffered storage in this study and the addition of larger amounts of storage presented technical difficulties thus no effect of TES is indicated. These technical difficulties included the design integration of large amounts of TES in the DSSR. On the other hand, the HPSR model could be used to show the effects of incremental amounts of TES. The data indicates the decreased COE of the HPSR system as storage and concentrator size are increased. While both systems were compared at equivalent engine efficiency, a reduced COE effect is indicated by the potential improved engine efficiency using sodium heat transfer to the Stirling engine in the HPSR. Since the HPSR operates at a higher solar-to-fossil fuel ratio (not operating its combustor continuously at 10 percent or greater power), the HPSR is also less sensitive to increased cost of fuel.

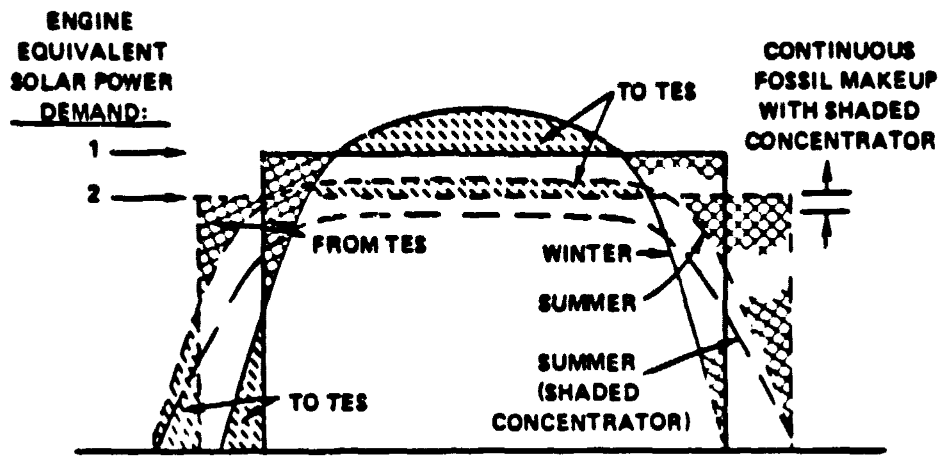
Additional aspects were studied of the operation of systems with or without TES and with or without combustors.

The continuous combustor on the DSSR provided full control without the need for defocusing. In systems without combustors a balance was required between peak solar insolation and the continuous equivalent solar power demand of the engine to make maximum use of TES and to accommodate variations in peak solar insolation between winter and summer. While the effect was not simulated in the analysis it was recognized that a scheduled reset in the equivalent solar power demand level of the engine (by a planned change in the working fluid pressure) would minimize the tendency for the required defocusing of the concentrator or for the cycling of the engine in the absence of a combustor. With a combustor the equivalent solar power demand of the engine could be set sufficiently high to prevent defocusing and, since the engine would run on fossil fuel alone, it never need encounter engine shutdown during normal operation. For a given engine operating power range it is economically advantageous to maximize the solar to fossil ratio and not shade the concentrator power back. These concepts are indicated in Figure 1-2.



*30 Year Levelized Costs are Higher by a Factor of 2.66

Figure 1.1. Cost of Electricity vs. TES Storage Time for Systems with Combustors



Engine Equiv. Solar Power Demand	Insolation Type	
	Summer	Winter
1	High Engine Power Discharges TES and Provides Engine Cycling in Absence of Combustor or in Absence of TES Recharging With a Combustor. A Combustor is Required	(As Diagramed-Solid) High Engine Power Prevents Defocus But is Low Enough to Provide Energy for Storage
2	(As Diagramed - Dotted) Lower Engine Power Prevents Engine Cycling (Without Combustor); But is High Enough to Utilize TES	Low Engine Power With High Insolation Requires Defocusing
2	Shaded Concentrator Reduced Solar Permits Use of Continuous Combustor to Prevent Engine Cycling or Defocusing but Utilizes High Fossil to Solar Power Ratio	

Figure 1-2. Illustration of Operating Advantages of Seasonally Scheduled Changes in Engine Power for Cost and Operating Effectiveness.

Various development requirements exist for both systems. The need for the DSSR is essentially the improved operating reliability in the copper heat exchanger (which also has some limited sensible heat TES capability). Since this design does not use latent heat, it can be tested and operated over a wide range in temperature and can readily be used without significant design change at a lower operating temperature, should high temperature materials problems of a life-limiting nature occur. While concepts were identified for incorporating TES into this receiver there were certain disadvantages which can be best be overcome by highly efficient thermal transport, an option already under investigation in the HPSR.

For the further exploitation of the HPSR, improved sodium wicking and wick joints are needed for cost reduction purposes. The conduct of modular TES experiments are one way in which these developments could be tested under the full capillary pumping heights and at the required sodium flow rates. These flow rates would be associated with the proper heat flux levels in a modular power train heat transfer mode within a full size, but readily changeable, heat transfer experiment.

The results of the study have provided a further understanding of the operating characteristics and costs associated with the use of TES and combustors in solar Stirling systems. A useful analytical tool is now available to investigate additional aspects of the performance and cost of such systems.

SECTION II

TECHNICAL RESULTS

A. INTRODUCTION

The operation of the solar Stirling power conversion system at the focal point of a tracking dish concentrator requires reasonably stable periods of operation in order to avoid life limiting cyclic operation during intermittent periods of cloud cover. Two types of solar receivers are being developed for the solar Stirling system. The first, the Dish Stirling Solar Receiver (DSSR) utilizes a combustor to back up variations in solar insolation. The second, the Heat Pipe Solar Receiver (HPSR) utilizes a significant amount of latent heat thermal energy storage (TES) to provide not only buffer storage but extended storage with intended capabilities for extended operation without solar insolation; the addition of a fossil fuel combustor is an intended part of this system, as well.

It is the purpose of work reported herein to analyze the operating characteristics of these systems with varying amounts of TES in thermal and economic assessments over a one year operating period on solar insolation data provided over one minute periods of operation. To do this required a definition of each system to be studied, the creation of operating model simulators and of computer analysis programs for treating the solar and fossil heat inputs to the system and for integrating heat storage and heat losses into the daily production of electrical power. An economic analysis of these systems was then performed over a 30 year period to determine the expected cost of electricity produced by such systems and the relative merits of changes in system variables such as TES duration, use of a fossil fuel combustor, sensitivity to costs of fuel and other variables.

Several alternative concepts for the addition of TES to the direct DSSR receiver and heat pipe or alkali metal thermal transport types of solar receivers were developed and their merits are briefly discussed.

An assessment is made of the nature of possible future developments which might be required to confirm the success and improve the operating performance and reliability of each type of system. These requirements can, in some cases be fulfilled either directly in modular TES experiments or in system, or modular tests, after a necessary development has been demonstrated. These development requirements and other possible needs for specific modular experiments are described.

The value and limitations of TES to each of the two systems and the critical operating factors and system definitions affecting performance and economics are presented. The value of TES in assuring smooth system operation and in offering possibilities for more extensive use of solar power are discussed.

B. SYSTEM DEFINITION

Two types of solar receivers were studied; namely, the direct dish Stirling solar receiver with a fossil fuel combustor (DSSR) being developed by Fairchild Stratos Division and Advanco Corporation and the heat pipe solar receiver with thermal energy storage (HPSR) being developed by General Electric Co., Advanced Energy Programs Department.

1. DSSR System

This heat receiver, shown in Figure 2-1 features a conical copper plate solar heat exchanger protected from oxidation on the surface by means of a brazed oxidation resistant alloy cladding; the Stirling engine heat exchanger tubes are contained both within and external to the cone. Solar heat is applied directly to the Stirling engine through the copper cone. Fossil fuel heat is applied to the back surface of the cone and to those heat exchanger tubes external to the cone. The system is operated continuously with a minimum of 10 percent power input through the combustor. As solar insolation changes, the required heat supply to the engine is provided by continuously modulating the combustor power. While no TES is provided in the original design, the present study considers the addition of limited amounts of TES along the surface of the cone or by other means.

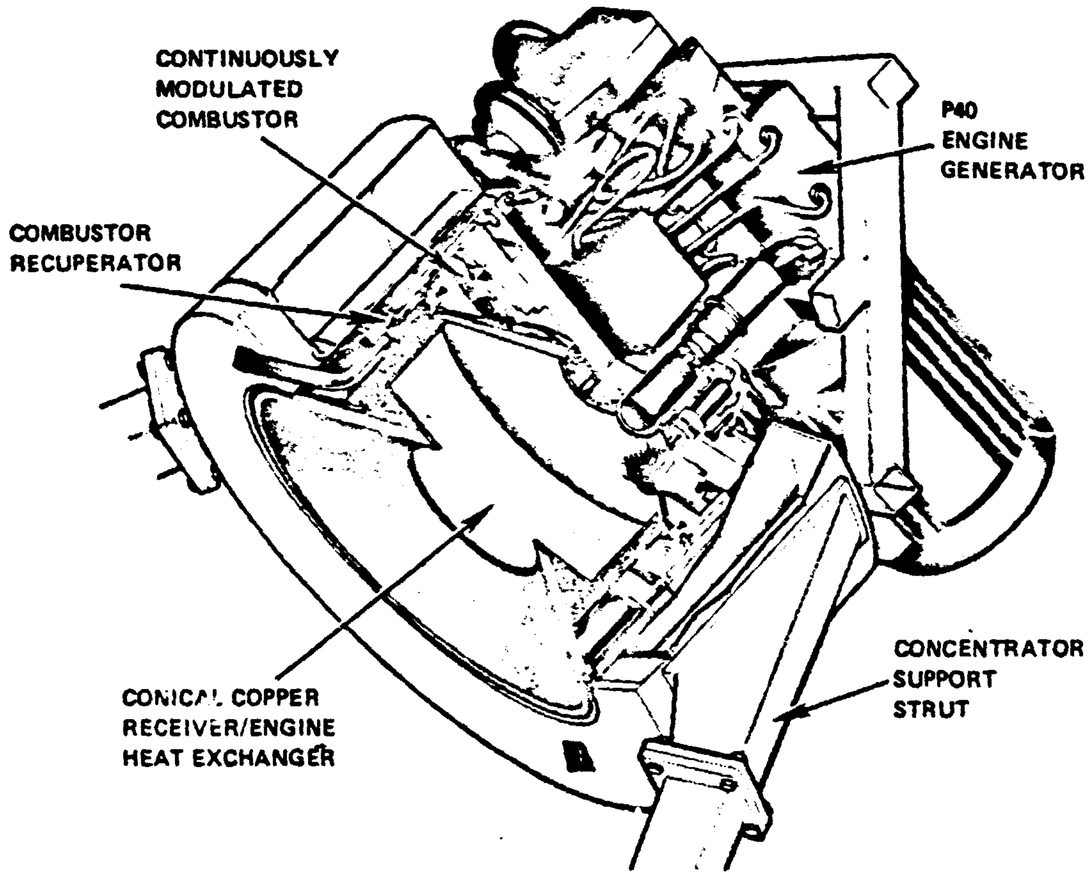


Figure 2.1. Dish Stirling Solar Receiver (DSSR)

Significant design factors necessary to the performance and economic analysis of the DSSR receiver over a one year solar insolation period are shown in Table 2-1.

A key factor in the DSSR system design is its continuously operating combustor which provides assurance of continuous power. However, the continuous use of a minimum of 10 percent fossil power reduces the portion of the delivered power which otherwise could be generated from solar insolation.

The objective of a relatively low system ΔT is attempted through the use of a high thermal conductivity material, namely copper. Initial system descriptions have indicated relatively large ΔT's between (1) the 1520°F heater head heat exchanger temperature at the design point and (2) the 1600/1735/1845°F local calculated temperatures on the surface of the receiver. To minimize such hot spots on the surface of the copper cone, which has a melting point of 1981°F, more extended use of Stirling engine heat exchanger tubing has been indicated and receiver temperatures are reportedly reduced to 1600°F. The effects of such tubing length decreases Stirling engine efficiency through increased engine working fluid void volume and pressure drop were not available, but significantly reduced efficiencies are anticipated below the 39.6% efficiency which has been credited to the system in this study. That efficiency was based upon a similar fossil fuel fired Stirling engine with an optimized heat exchanger.

2. Heat Pipe Solar Receiver System

The second type of solar receiver is the heat pipe solar receiver with TES (HPSR) shown in Figure 2-2. The key design factors are shown in Table 2-2. The solar insolation is absorbed on fourteen sodium heat pipes which supply heat to a near-isothermal secondary heat pipe. These heat pipes provided heat flow in only one direction. This secondary heat pipe contains (1) the condenser sections of the receiver primary heat pipes as a solar heat sources, (2) liquid metal wicked shell-side heat transfer surface area around the lower 180° of the secondary heat pipe as a fossil fuel combustor heat source, (3) sodium fluoride-magnesium

TABLE 2-1

RECEIVER PERFORMANCE AND OPERATIONAL DATA FOR DSSR BASELINE DESIGN

Concentrator Diam.		9.77 m
Active Concentrator Area		74.0 m^2
Concentrator Efficiency		0.9259
Focal Plane Power		68.5 kW_t
Aperture Diam.		20 cm
Intercept Factor		0.99
Solar Power Input, Rated (at 1 kW/m^2 insolation)		67.8 kW_t
Receiver Losses		
Reflection	0.49 kW_t	
Reradiation	3.4 kW_t	
Convection	3.06 kW_t	
Conduction	1.00 kW_t	
Total Receiver Losses		8.16 kW_t
Receiver Efficiency		0.897
Max. Power Output		59.6 kW_t
Min./Nominal/Max. HX Surface Temp. (at Design Point)		1630/1730/1845°F

COMBUSTOR	
Minimum Required Combustor Power (10% Turndown)	6.6 kW_t
Maximum Required Combustor Power to Engine	66.2 kW_t
Combustor Efficiency	0.575 (expt'l)
Operating Mode	Variable Turndown
STIRLING ENGINE/GENERATOR	
Engine Thermal Power	66.2 kW_t
Engine Efficiency - 150 ATM He - 1800 RPM - 1500°F	0.396
Engine Power at Above conditions	26.2 kW_s
Generator Efficiency	0.93
Generator Output	24.4 kW_e

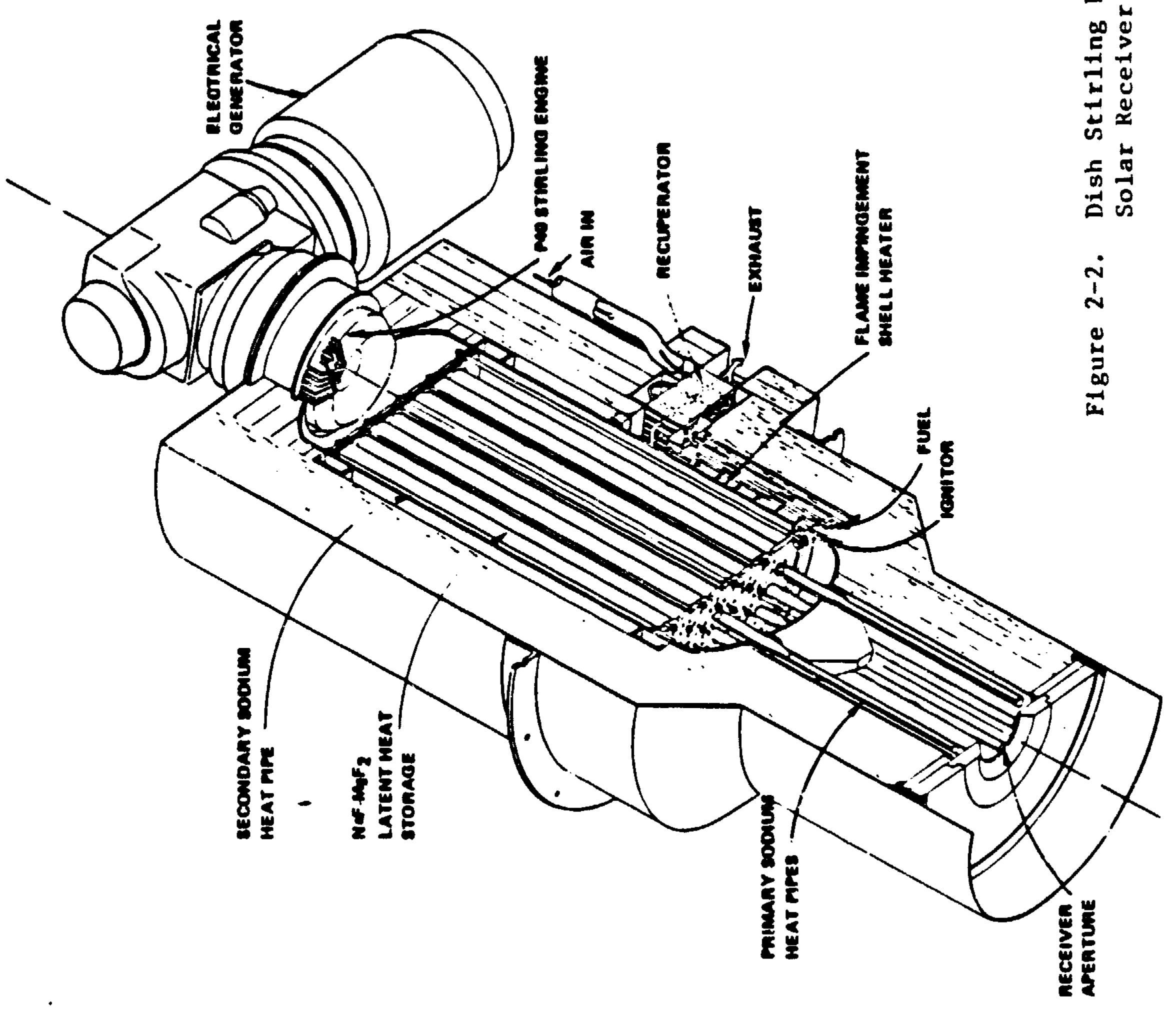


Figure 2-2. Dish Stirling Heat Pipe Solar Receiver with TES

TABLE 2-2

RECEIVER PERFORMANCE AND OPERATIONAL DATA FOR HPSR BASELINE DESIGN

RECEIVER

Concentrator Dia.		10.3 m
Active Concentrator Area		82.8 m^2
Concentrator Efficiency		0.9259
Focal Plane Power		76.6 kW_t
Aperture Dia.		16.9 cm
Intercept Factor		0.98
Solar Power Input, Rated		
Receiver Losses		
Reflection	0.85 kW_t	
Reradiation	3.99 kW_t	
Convection	1.30 kW_t	
Conduction	0.47 kW_t	
Total Receiver Losses		6.61 kW_t
Receiver Efficiency		
Maximum Heat Pipe Temperature		
Heat Pipe Total ΔT		
Power Output		68.5 kW_t

TES (SECONDARY HEAT PIPE)

Power Input, Rated	68.5 kW_t
Storage Time (Latent & Sensible @ 66.2 kW_t)	0.8 hour
Thermal Losses	2.3 kW_t
TES Operating Temperature	
Maximum	1535°F
Minimum	1480°F
Range	55°F
Power Output	66.2 kW_t

COMBUSTOR

Required Combustor Power to TES	68.5 kW_t
Combustor Efficiency	0.65 est'd
Operating Mode	On-Off

STIRLING ENGINE/GENERATOR

Engine Thermal Power Input	66.2 kW_t
Engine Efficiency*	0.396
- 150 ATM He	
- 1800 RPM	
- 1520°F	
- Sodium Condenser	
Engine Power at Above Conditions	26.2 kW_s
Generator Efficiency	0.93
Generator Output	24.4 kW_e

*Conservative estimate; with sodium heater head efficiency will be about 0.43 for approximately 8.6% greater electric output for the above design.

fluoride TES eutectic salt in cylindrical metal containers and (4) the directly exposed Stirling engine heat exchanger tubes. The system operates nearly isothermally with very little system ΔT because of the effectiveness of heat pipe thermal transport. Temperature differences influence the pressure of the sodium vapor in contact with liquid sodium on the heat source surfaces and provide rapid heat transfer at a low ΔT to the engine, to the TES and from the TES. Large TES surface areas are available for efficient heat transfer to, and from, the TES, at low thermal fluxes and at relatively low ΔT across the solidifying salt (which acts as a heat source during TES discharging). The thermal stability, the self regulating nature of heat flow and the low system ΔT's associated with the HPSR make it effective for a focal mounted solar Stirling system where a large mass flow of cycle working fluid is not required between the receiver, TES and engine as would be the case for a Brayton or Rankine system, particularly with engine or TES components remotely located or at local ground level.

One of the most favorable aspects of the HPSR, however, is its effective heat transfer to the Stirling engine heat exchanger and the complete design freedom it offers to the optimization of that heat exchanger. Removing heat-input-side heat transfer limitations and tubing geometry restrictions permits greatly reduced void volume and pressure drop in the Stirling engine working fluid. This results in increases in engine efficiency. While the present design and the initial results of this study utilized an engine efficiency of 39.6 percent (similar to a fossil fuel fired Stirling engine), efficiencies up to 43 percent are expected for the sodium engine configuration and, as indicated under Section II D5, the economic analysis shows the favorable impact of such improved engine efficiency.

3. System Operating Characteristics

For both of the above systems the power output is about 25 kW_e. Operating with the same engine-generator set at the identically specified engine-generator efficiencies and engine operating conditions, the data shown in Tables 2-1 and 2-2 provide a close comparison of the characteristics of the two solar receiver systems. This design data was based on the use of the JPL test bed concentrator (TBC); those concentrator characteristics were used to guide the design of these receivers (under separate contracts) and to define the required area and diameter of the concentrator for the purposes of the one year solar insolation performance and economic analyses of this study.

A comparison of the relative thermal stability, or thermal inertia, of each of the above systems can be made by comparing the product of the mass and specific heat for each system for those parts of the systems which supply heat to the Stirling engine. This quantity, divided into the Stirling engine power at the design point (66.2 kW_t), indicates the rate of temperature change of the system at full power but without solar or combustor power input. In the case of the DSSR, the temperature change rate is 134°C/min (241°F/min). For the HPSR this calculated temperature change rate is about 9°C/min (16°F/min) in the latent heat range. Earlier test effort on the TES modular experiment indicated a rate change of less than 2°F/min at a lower TES heat flux. In the TES latent heat range for the HPSR during which most operation should occur, the temperature rate change at full engine power without solar or fossil power input would be much lower, less than 0.5°F/min.

While the DSSR maintains constant temperature with modulated combustor operation, the HPSR can undergo extended periods without solar insolation and operate stably with either reapplication of solar insolation or the use of an "on-off" fossil fuel combustor.

Since the above baseline designs have been based on a significant amount of design study and experimentation supported under separate contracts, they provide a basis around which to perform parametric analysis of variations in TES storage time and use of fossil fuel combustors.

A qualitative visualization of the extent to which the TES and combustor can interact in providing operating flexibility to each of the above systems is shown in Figure 2-3.

For equivalent power levels the TES, alone, (in the HPSR) provides design level power without the use of fuel provided the solar insolation

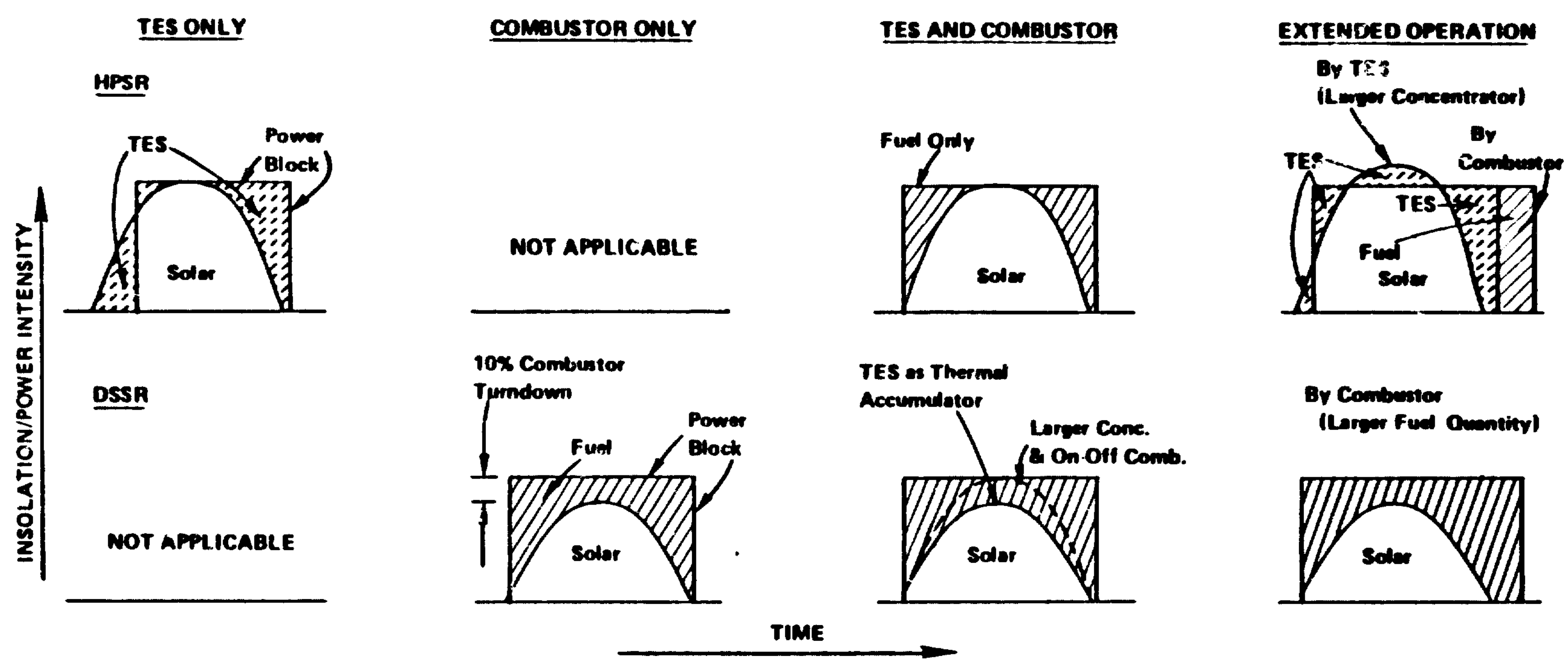


Figure 2-3. Qualitative Visualization of Various Uses of TES and Fuel Combustors with Daily Solar Insolation.

is uninterrupted. The duration of the power block can be extended, but the power level must be reduced to provide the solar energy for use over the extended period. Likewise, the power level can be lowered to accommodate periods of interrupted solar insolation, otherwise the power output must be terminated briefly during various periods of the day to allow for recharging. In any event the thermal cycling under varying solar conditions will be very much less than a direct receiver without TES or combustor.

The DSSR, with combustor only, provides reliable power over a potentially larger block time at the expense of less solar utilization and greater utilization of fuel. The combustor must be run continually at 10% or more of total power.

The HPSR with TES and combustor provides a high ratio of solar to fossil power and utilizes fossil power in a limited way only to make up for deficiencies in solar insolation. The TES provides the system thermal storage to permit efficient on-off combustor power and minimum use of fuel. As presently conceived, the DSSR with a continuous minimum 10% of power by combustor can utilize TES only as a thermal accumulator. With an on-off combustor however, a larger concentrator could be used and fuel consumption could be reduced.

Finally, extended operation of both systems of current design concept can be accomplished by the use of supplemented combustor power. The system with the capability for added TES, however, can introduce a large concentrator and provide some extended period of performance on solar power alone, whereas this added power must be provided by combustor power for the DSSR.

The above generalizations are intended to indicate the general characteristics of these systems. The merits and practicality of adding varying amounts of TES to both types of systems are discussed below.

C. ALTERNATE TES CONCEPTUAL DESIGNS

Three conceptual designs each of the DSSR and of the HPSR are described here.

1. DSSR TES Concepts

The different methods which have been conceptualized for the application of thermal energy storage (TES) materials to the DSSR copper cone receiver were done without intent for any major change in the basic receiver design. An assessment has been performed on each of the concepts in order to qualitatively rate each concept as to its practicality, performance and developmental risk.

The concepts employ three different methods of transferring thermal energy from the TES material to the Stirling engine heater head tubes. In the DSSR receiver these tubes are buried in a copper cone heat exchanger upon which solar insolation is directed by the concentrator. In the first concept, the TES material is applied directly to the receiver heat exchanger and the heat is transferred by conduction through the TES material. In the second concept, heat pipes transfer the heat from the receiver heat exchanger to the TES material and back to the receiver heat exchanger, and in the third concept, the heat is transferred by radiation from the TES to the heat exchanger. Since, in the latter concept the TES operates at a high radiating temeprature, it must be charged from the combustor only and cannot be recharged by solar insolation since the receiver (and engine) would be required to operate at the higher TES temperature.

The first concept, Figure 2-4, employs TES material applied directly to the copper cone. This method of TES application is appealing in its simplicity and because it requires the smallest overall change in the DSSR receiver structure. This is its main advantage. The major drawback with this system is that the outer surface which contains the TES material, the surface upon which the sunlight would fall, is forced to go to a very high temperature especially if more than a few minutes of TES material is used. Figure 2-5 shows the temperature rise above the current cone outer surface temperature (when the Stirling engine is

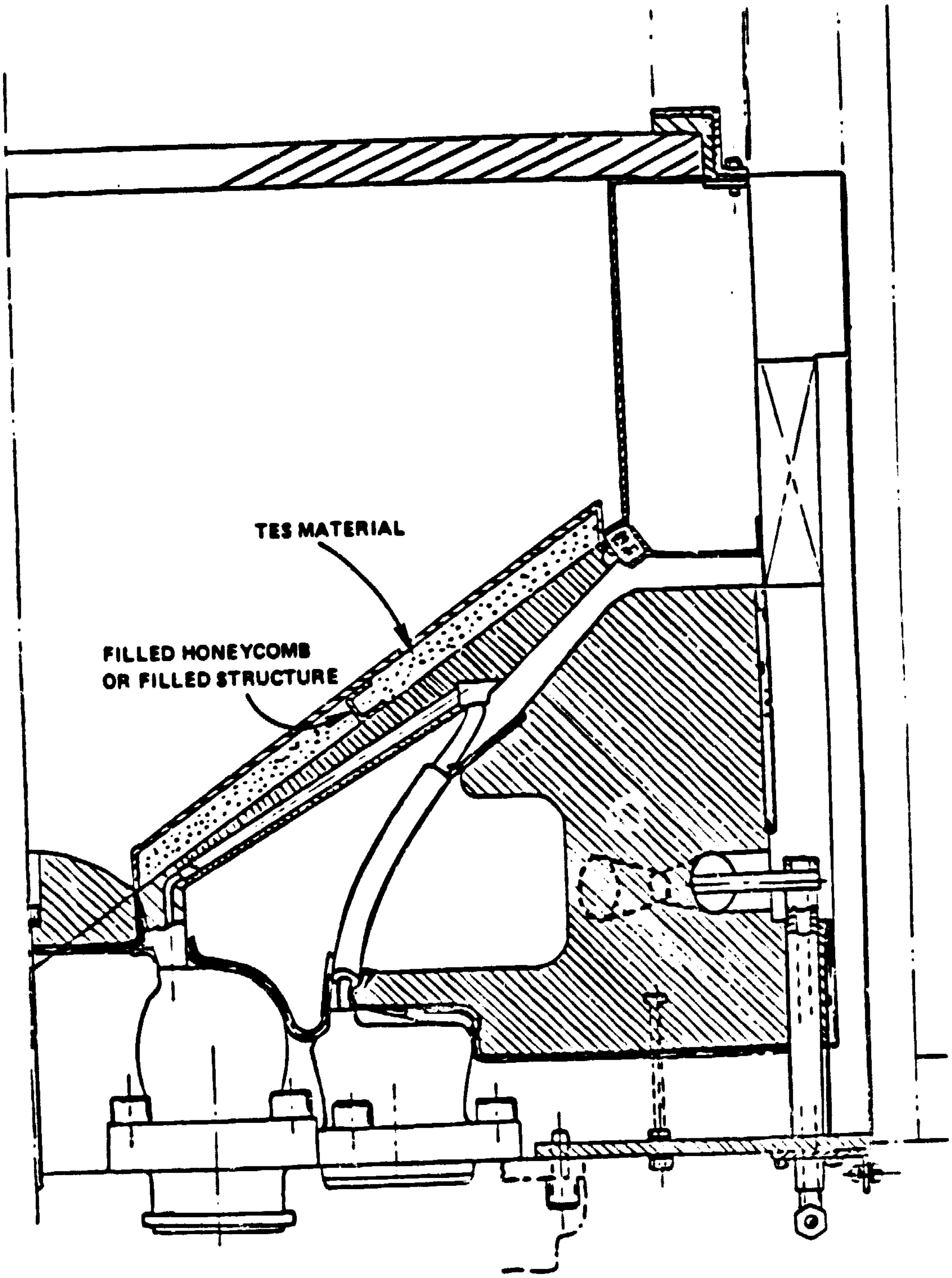


Figure 2-4. DSSR with TES on Front Face of Copper Cone.

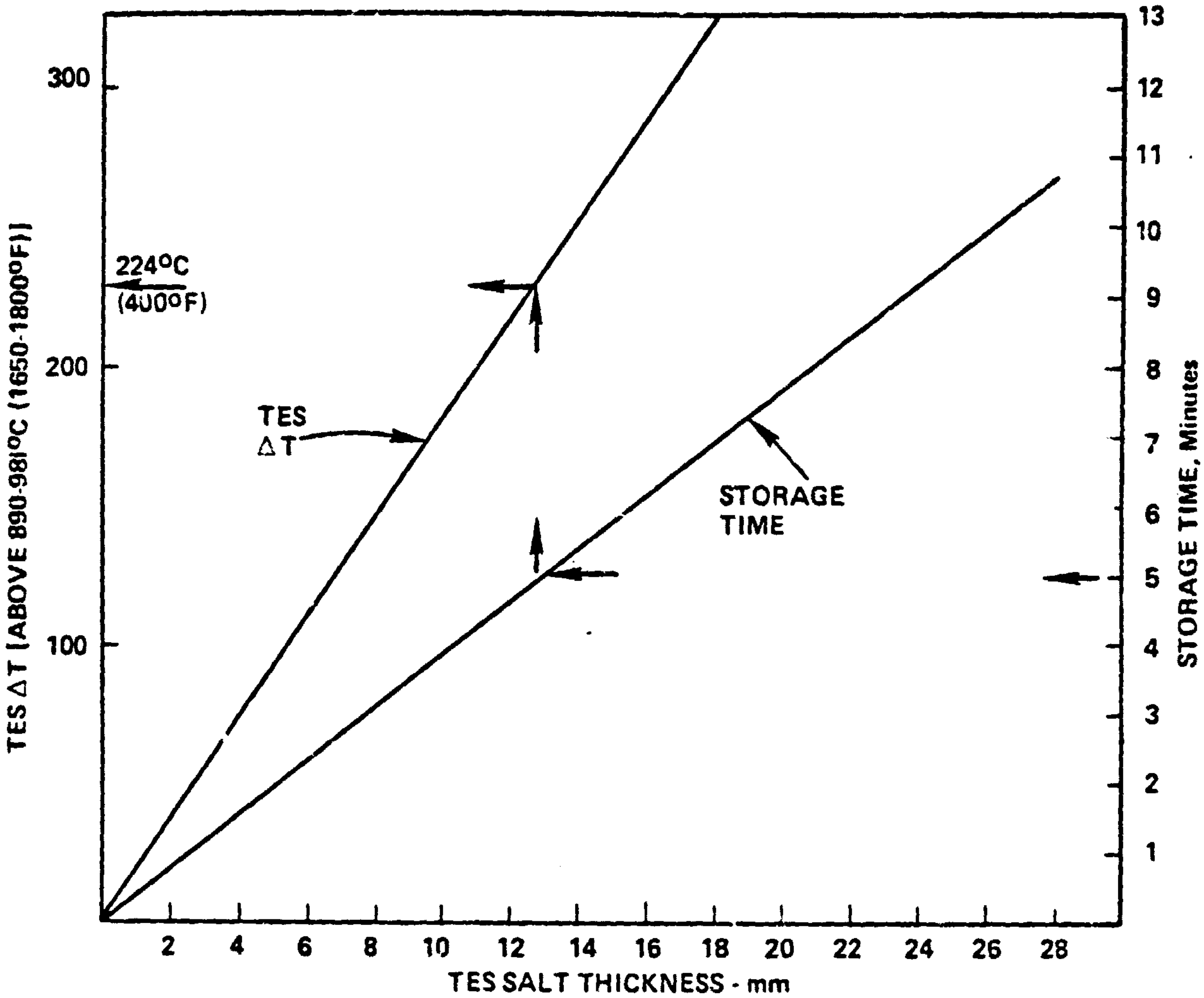


Figure 2-5. Surface Temperature and Storage Time for TES Added at DSSR Conical Hx Surface.

operating at 1500°F) for various storage durations at a power extraction rate of 66.2 kW_t. To provide 5 minutes of storage time would require approximately one half an inch thickness of TES material over the receiver heat exchanger. The temperature drop through the TES material would be 225°C or just over 400°F. This brings a present 1845°F peak surface temperature to over 2200°F and raises serious questions about possible materials selections for the hot surface. Or, if the ΔT is taken with the TES salt melting point (1520°F) maintaining the heat exchanger outer surface temperature, the ΔT across the salt during TES discharging would result in a 400°F drop in engine temperature. Both a high solar side surface temperature and a severe reduction in engine temperature are not acceptable. While it might be possible to improve the thermal conductivity of the TES material, a tradeoff involving a low of storage time must be made due to the loss of phase change material displaced by whatever conductivity enhancement material is used to improve the thermal conductivity of the mixture. Table 2-3 lists the pros and cons of this thermal energy storage concept.

The second concept uses heat pipes to transport the receiver thermal energy to, and from, the thermal energy storage. The heat pipes are simple, completely wicked tubes and thus represent very little technical risk. The thermal energy storage material is stored around the circumference of the receiver cavity with the heat pipes inserted in it. In this conceptual design, no attempt has been made to have any sort of a thermal switch as have the heat pipes in the HPSR. Thus the TES could discharge to the receiver cone and reradiate its heat out the aperture when solar insolation stops. Because of various heat pipe orientation a partly wicked heat pipe concept with one direction heat flow is not readily useable.

Figure 2-6 shows this concept. Table 2-4 presents the system performance characteristics of this TES concept.

This system has the asset of having the lowest system peak temperature of the three DSSR TES conceptual designs presented. Furthermore, the heat pipes would serve to homogenize the temperatures on the copper cone by transferring heat from the region of the cone beyond the Stirling

TABLE 2-3

ADVANTAGES AND DISADVANTAGES OF DIRECTLY APPLYING TES MATERIAL TO THE DSSR RECEIVER CONE

Advantages	Disadvantages
• Probably minimum cost addition to existing receiver.	• High ΔT through salt produces possible high surface temperature on the inside of the receiver or severe reduction in engine operating temperature.
	• Relatively limited amount of TES possible with available material.
	• High surface temperature would decrease receiver efficiency.
	• Low engine temperature seriously decreases engine efficiency.

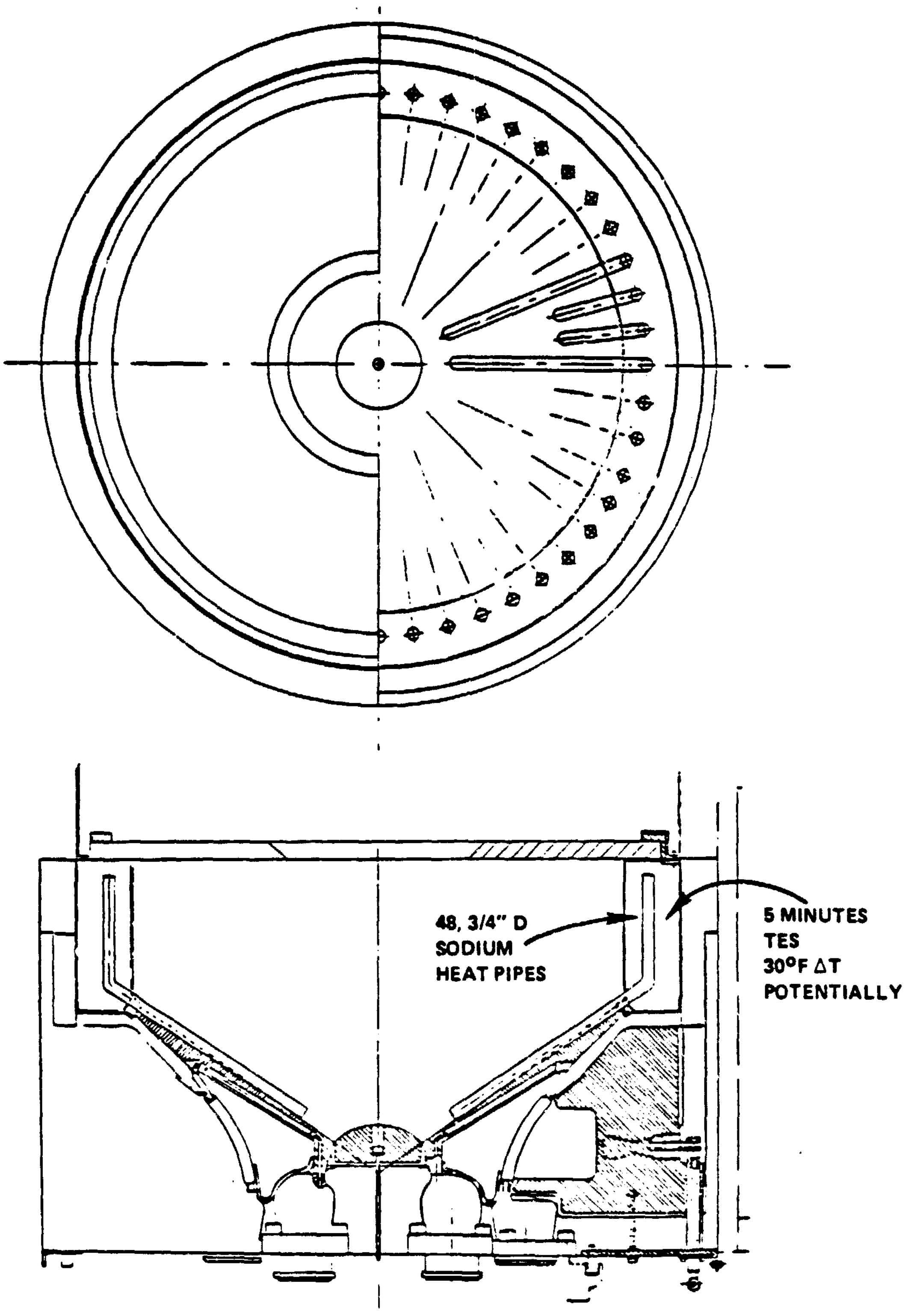


Figure 2-6. Concept for DSSR with Heat Pipe Thermal Transport To/From TES.

TABLE 2-4

HEAT PIPE TES FOR THE DSSR

Assumed Salt	67 NaF/33MgF_2
Salt Melting Point	826°C (1520°F)
Thermal Transport	Heat Pipes
ΔT	~ 30°C (Estimate)
Storage Time	~ 5 min. as shown
Power Level	66.2 kW_t

engine tubes inward to the Stirling engine. This would have another desirable effect in that the efficiency of the present receiver would be increased. Finally the amount of TES material could be increased relatively easily. The sketch shows a system with approximately five minutes of thermal energy storage time at 66.2 kW_t. This could be increased by increasing the complexity of the heat pipe network within the TES material. The only recognized real detriments to this system might be low cycle fatigue problems (which should not be increased over those of the current design), and the fact that, as designed, the TES could discharge itself through the receiver aperture.

Table 2-5 summarizes the advantages and disadvantages of this system.

The third concept, shown in Figure 2-7 and Table 2-6, combines the functions of the combustor and TES by having the combustor fire through the TES material which is contained within ceramic. The TES material, in turn, radiates to the back of the copper cone and that radiation is controlled by a radiation curtain which is moved in order to adjust the view between the back of the cone and the thermal energy storage. Because of the fourth power of absolute temperature nature of radiation heat transfer and the temperatures at which the system is running, the difference in temperature between the TES and the copper cone is not as high as might be expected for the amount of heat being transferred. The TES temperature would be on the order of 2100°F. Through the TES calculations have been performed using the thermal characteristics of 1520°F MP Sodium Fluoride-Magnesium Fluoride salt, it is obvious that the choice of TES material would be made of a TES material with the correct high temperature melting point. It is representative, however of some materials, listed in Table 2-7, that might be considered as candidates in this temperature range.

This system has several advantages and several disadantages with respect to the previous two thermal energy storage systems for the DSSR. First, it has the largest thermal energy storage time, as sketched, of

TABLE 2-5

ADVANTAGES AND DISADVANTAGES OF DSSR WITH HEAT PIPE TES

Advantages	Disadvantages
• Lowest system peak temperature	• Potential for low cycle fatigue
• Easily increased TES time	• Possible TES discharge by reradiation
• Simple heat pipe design	
• Heat pipes can homogenize cone temperatures	
• Reduction in receiver cone temperature (more efficient receiver)	

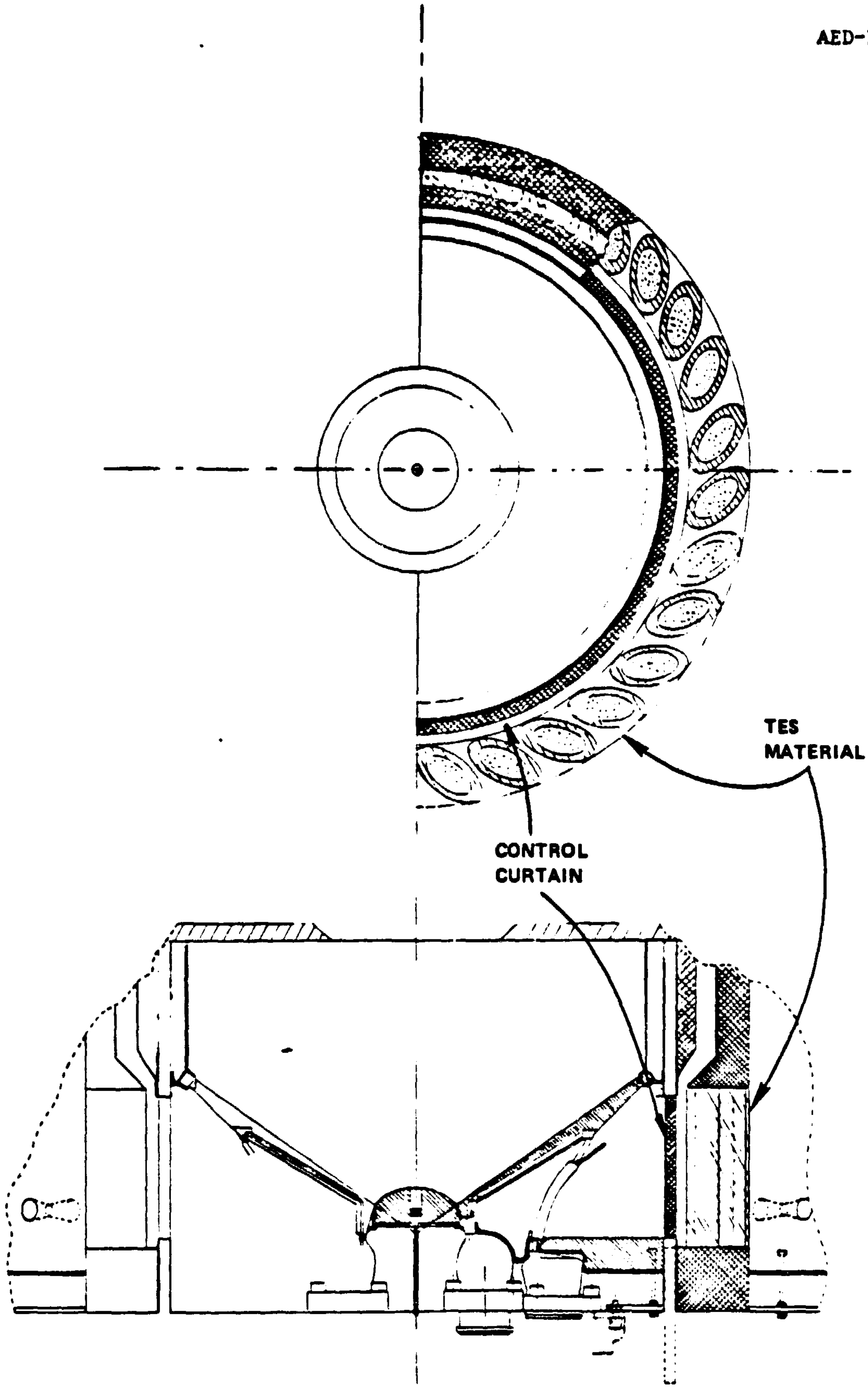


Figure 2-7. Radiant Heat Transport TES Concept for the DSSR.

TABLE 2-6

RADIANT HEAT TRANSPORT SYSTEM FOR THE DSSR

Assumed Salt Characteristics	67 $NaF/33MgF_2$*
ΔT	Ceramic would run 1200°C up to ~ 1500°C
Storage Time (66.2 kW_t extraction)	~ 11 min. as shown

*Melting temperature of 67 $NaF/33MgF_2$ itself, is too low. See Table 2-7 for list of candidate TES materials.

TABLE 2-7

TES MATERIALS CANDIDATES FOR HIGH TEMPERATURE RERADIATING TES

Melting Temp. °C	Nominal Composition (Wt. %)	Hf kJ/kg
830	67 NaF/33 MgF_2	200
855	24 NaF/75 SrF_2	
882	75 NaF/25 AlF_3	
921	82 Na_3AlF_6/18 MgF_2	
945	74 Na_3AlF_6/26 CaF_2	
975	34 NaF/46 KF/20 MgF_2	
995	NaF	245
1008	30 KF/70 MgF_2	
1110	FeF_2	337
1030	$NaMgF_3$	220
1070	$KMgF_3$	
1252	MgF_2	288
1418	CaF_2	117
1420	Si	1640

any of the three systems and it does not impact the copper cone design. Secondly, this TES system can be charged, by an "on-off" combustor, independently of Stirling engine and once charged, can be stored without significant thermal reradiation loss (by putting the curtain between the TES and the copper cone). The curtain makes the thermal control of this TES system a relatively simple procedure; the curtain is pulled aside when more TES power is needed, and is put back when less is needed. The higher temperature of the TES also prevents charging by solar insolation. The TES and combustor are a single integral unit, which could be fabricated at the same time and therefore could be simpler to produce. Another significant problem with this concept would lie in the area of high temperature TES salt and containment materials compatibility; the TES material and its containing ceramic must be able to be used together without significant corrosion or without brittle failure.

Table 2-8 summarizes the advantages and disadvantages for this TES system.

2. Heat Pipe Solar Receiver TES Concepts

The heat pipe solar receiver concept for the basic prototype design, as described above, was evolved over a considerable period of time with the objectives of achieving significant amounts of thermal storage as contrasted to brief buffer storage. Heat pipes were used for thermal transport since it was recognized that (1) they would help to maintain small system ΔT as energy was transported within the heat pipe and that (2) high heat fluxes were possible in accepting and rejecting heat at heat transfer interfaces. To maintain low ΔT within a significant amount of TES material required large TES surface areas, low heat flux to the TES and significant thermal transport distances. While these same objectives can be met in larger Rankine or Brayton systems using pumped heat transfer fluids, the compactness of the integrated, focus mounted solar Stirling system with TES favored the use of heat pipes, particularly so since the engine working fluid was closely contained and utilized within the engine alone.

TABLE 2-8

ADVANTAGES AND DISADVANTAGES OF DSSR WITH RERADIATING TES

Advantages	Disadvantages
• TES application does not impact cone design.	• Containment of salt in ceramic poses possible materials compatibility problems.
• Longest storage time of the concepts developed.	• Increases receiver diameter.
• Thermal reradiation losses controlled by thermal curtain.	• Very high temperature materials required.
• TES thermal transport simple to control.	• Combustor must operate in "on-off" mode.
• TES containment & combustor are single integral unit.	• Possible added thermal control problems.
	• Heat flow is not self regulating.
	• High temperature TES compounds combustor design problems.
	• Recharging TES by Solar Insolation Not Practical

The secondary TES heat pipe was of single heat pipe construction to permit near isothermal operation of the TES. Thus, heat could flow from any primary heat pipe condensor to any part of the engine or to any TES salt container; likewise, heat from the shell-side combustor could do the same. Furthermore heat could be supplied to any part of the engine heat exchanger from any unit surface area of the TES. The performance and cost effectiveness of this system is better if the TES duration is not limited to very brief periods of TES.

In addition to the basic TES system, which was described above, several alternative TES designs have been considered under the present basic contract of which this report is a part. These included (1) a direct sodium pool boiler receiver with TES, (2) a primary/secondary heat pipe system with a common TES contained in a single volume between two headers with sodium vapor tubes penetrating the salt mass and (3) a direct receiver concept with TES material surrounding the engine heat exchanger tubes. Several other concepts were studied, but will not be discussed here.

The first of the above HPSR TES alternative design concepts, the pool boiler, with about 1.25 kW TES at 52.5 kW_t, is shown in Figure 2-8. The TES salt containers were contained in a thermally conducting pool of sodium surrounding the receiver. Since the sodium pool was in direct contact with the receiver wall (not separated by thermal diode primary heat pipes) reradiation losses from the TES through the receiver and out the aperture required the consideration for addition of an actuated receiver aperture plug. The static head of sodium in the receiver offered the adverse prospect for superheating and "bumping" of the liquid sodium at the receiver wall. The mass of sodium required to maintain the pool also added unwanted weight to a focus mounted system.

A second alternative TES concept, a primary heat pipe/secondary heat pipe HPSR of equivalent power and thermal storage duration, is shown in Figure 2-9. It has a tube and header design within the single secondary heat pipe. The salt is contained in a single continuous mass through which sodium vapor passages carrying thermal energy to the salt

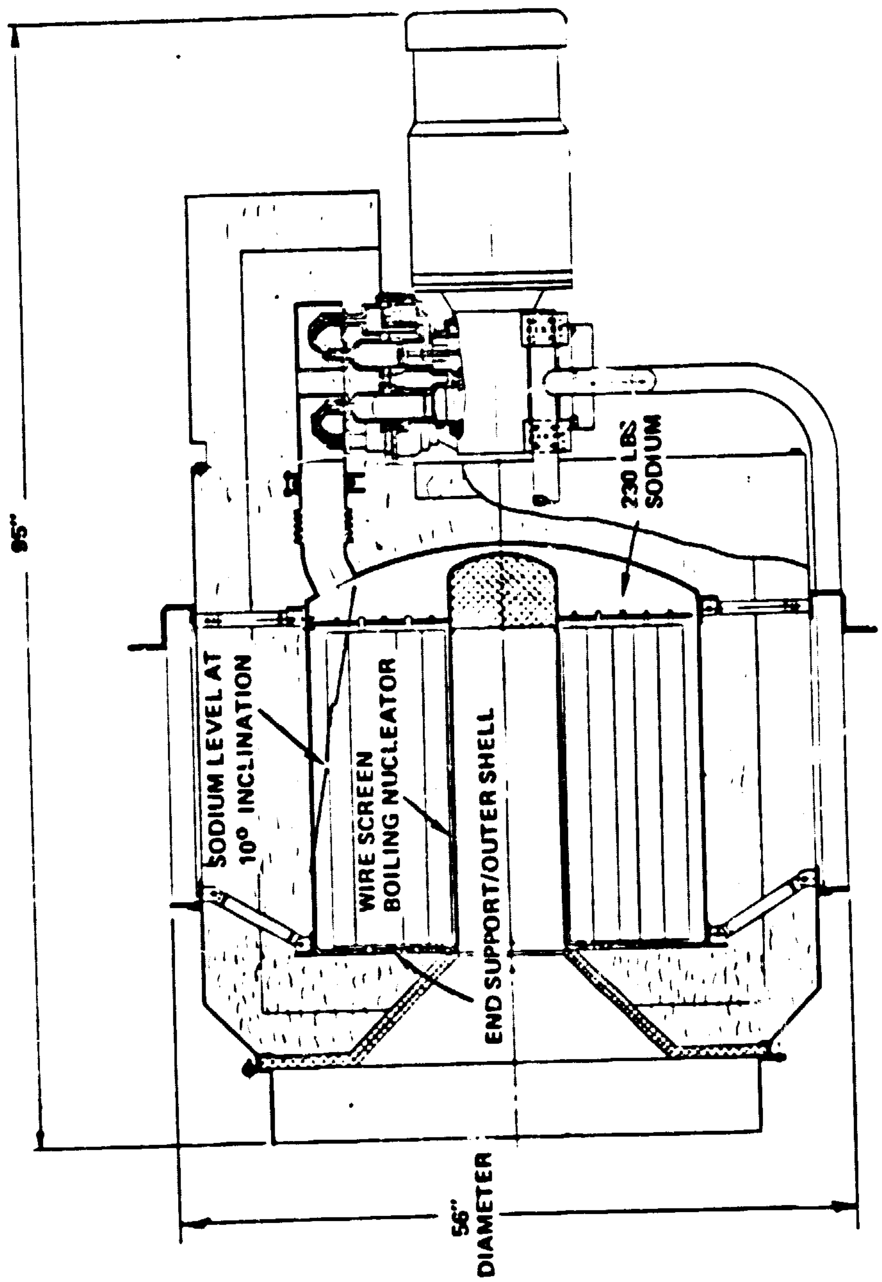


Figure 2-8. Pool Boiler Solar Receiver with TES.

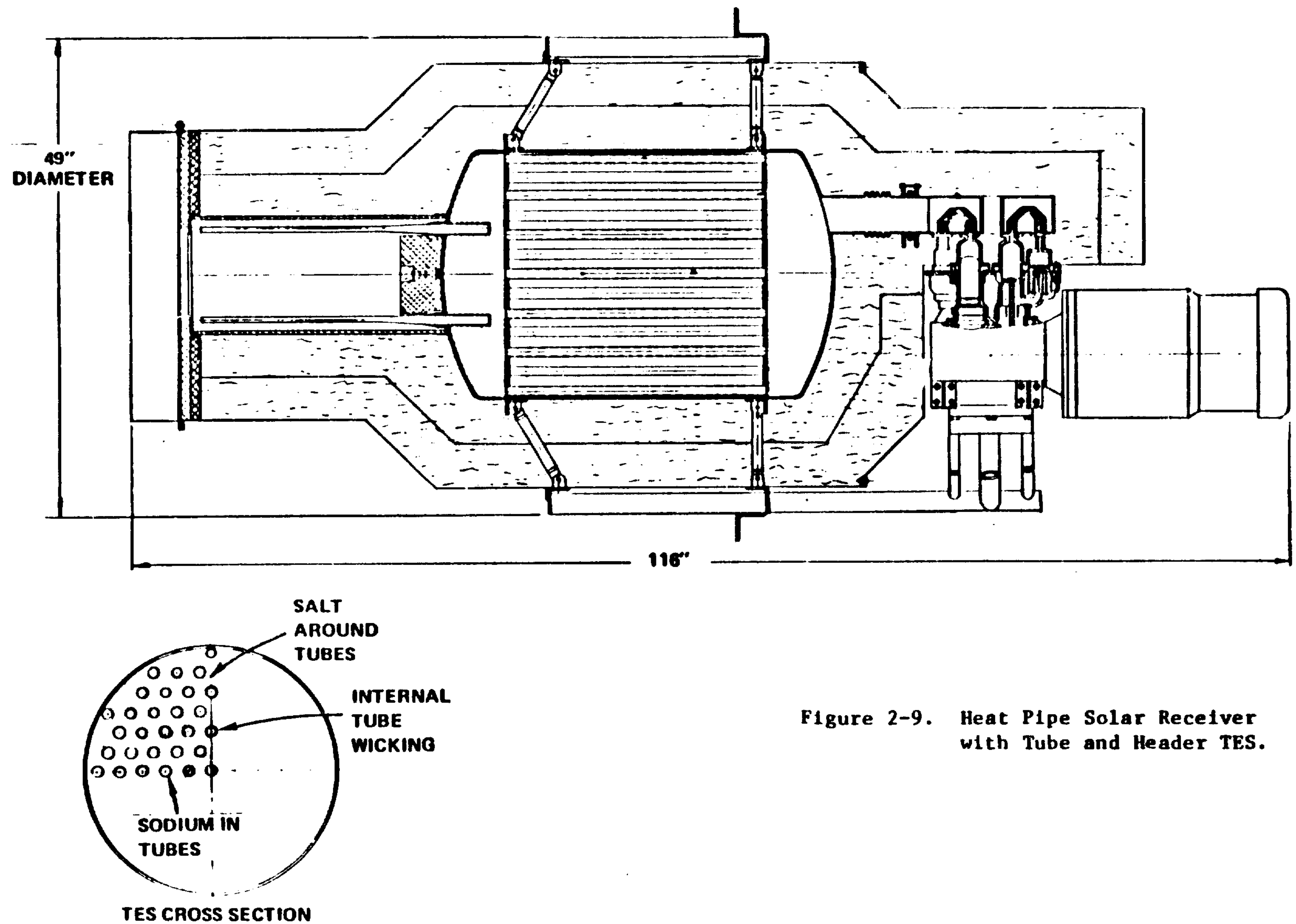


Figure 2-9. Heat Pipe Solar Receiver with Tube and Header TES.

storage or directly to the engine from the primary heat pipe condensers. This system required the wicking of the interior of a large number of sodium vapor tubes. Its rigid tube and header construction made it more susceptible to thermal restraint and to low cycle fatigue. It was felt that the common salt volume would make the system more susceptible to possible adverse thermal ratcheting efforts caused by melting expansion and solidification contraction of the salt.

A major objective in studying these alternative designs in this earlier work was to evolve lowest cost concepts. Table 2-9 indicates the relative weights and costs of these. From these studies the current HPSR design was selected for both cost and technical reasons. It has been designed and is currently under initial phases of construction.

3. Directly Coupled Receiver/TES Concepts

Buffered TES had been considered without the use of heat pipe thermal transport but was earlier discarded from consideration because of its limitations on storage time. Large temperature gradients within the TES are necessary to extract thermal energy at required rates in the range of 52.5 - 66.2 kW_t. To circumvent this problem it is necessary to create a heat receiver, Stirling engine heat exchanger and TES material geometry which reduces the length of the heat conductance path in TES.

Based on a very limited analysis of a single cylinder Stirling engine heat exchanger, it was determined that the engine exchanger could be designed for direct TES purposes to consist of only 12 tubes, each 762 mm (30 in.) in length. This would permit a much deeper penetration of the TES material by the Stirling heat exchanger tubes and it would allow more material to be wrapped around the tubes than is possible for the type of shorter tube heat exchanger that has been used with the HPSR design; thus, a longer direct thermal energy storage duration could be achieved using long Stirling engine heat exchanger tubes.

Two overall system geometries were investigated for direct conductance TES. The first, shown in Figure 2-10, has the finned Stirling engine heat exchanger tubes (fins not shown for clarity) running cir-

TABLE 2-9

WEIGHT AND MASS PRODUCTION COST COMPARISONS FOR THREE ALTERNATIVE TES/RECEIVER DESIGN CONCEPTS*

(52.5 kW_t; ~ 1.25 HOURS STORAGE)

Concept Description	Weight Lbs.	Material Cost-$	Selling Price-$
Basic HPSR Concept	2150	776.00	1552.00
Sodium Pool Boiler with TES Capsules	2279	1199.00	1298.00
Tube and Header TES	2287	1017.30	2035.60

*Excluding engine and generator.

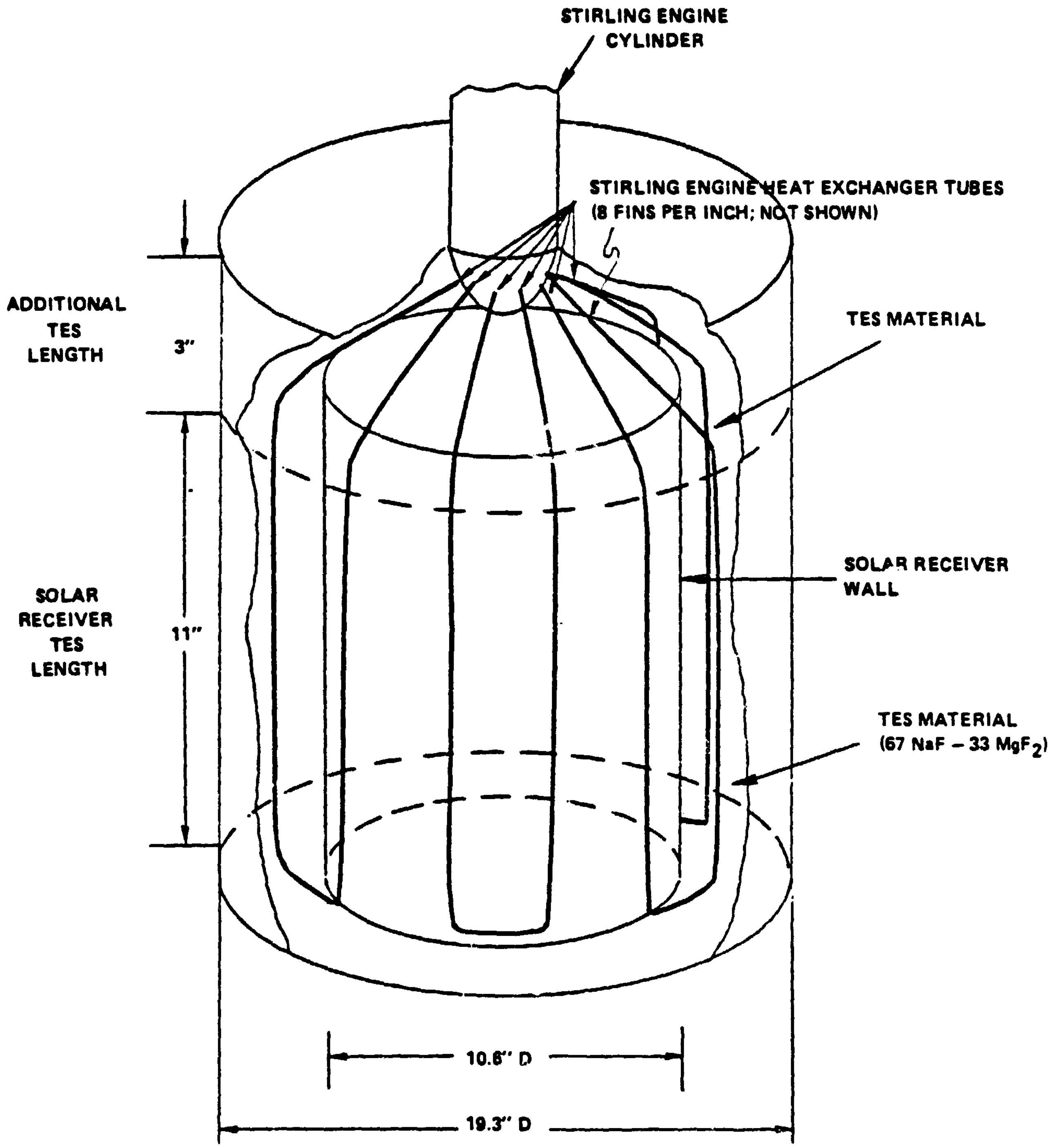


Figure 2-10. Single Cylinder Stirling Engine Concept with 15 Minutes TES Directly Coupled in the Solar Receiver. (Circumferential Tube Arrangement)

cumferentially around the wall of the receiver in the middle of an annular region filled with salt. This arrangement would probably have the most uniform temperature in the TES material around the exchanger tubes and therefore the minimum thermal expansion induced stresses. In the second system, depicted in Figure 2-11, the heat exchanger tubes run radially outward, which allows the wall of the receiver to be scalloped; this in turn, increases the surface area of the receiver and improves the absorption of the solar energy.

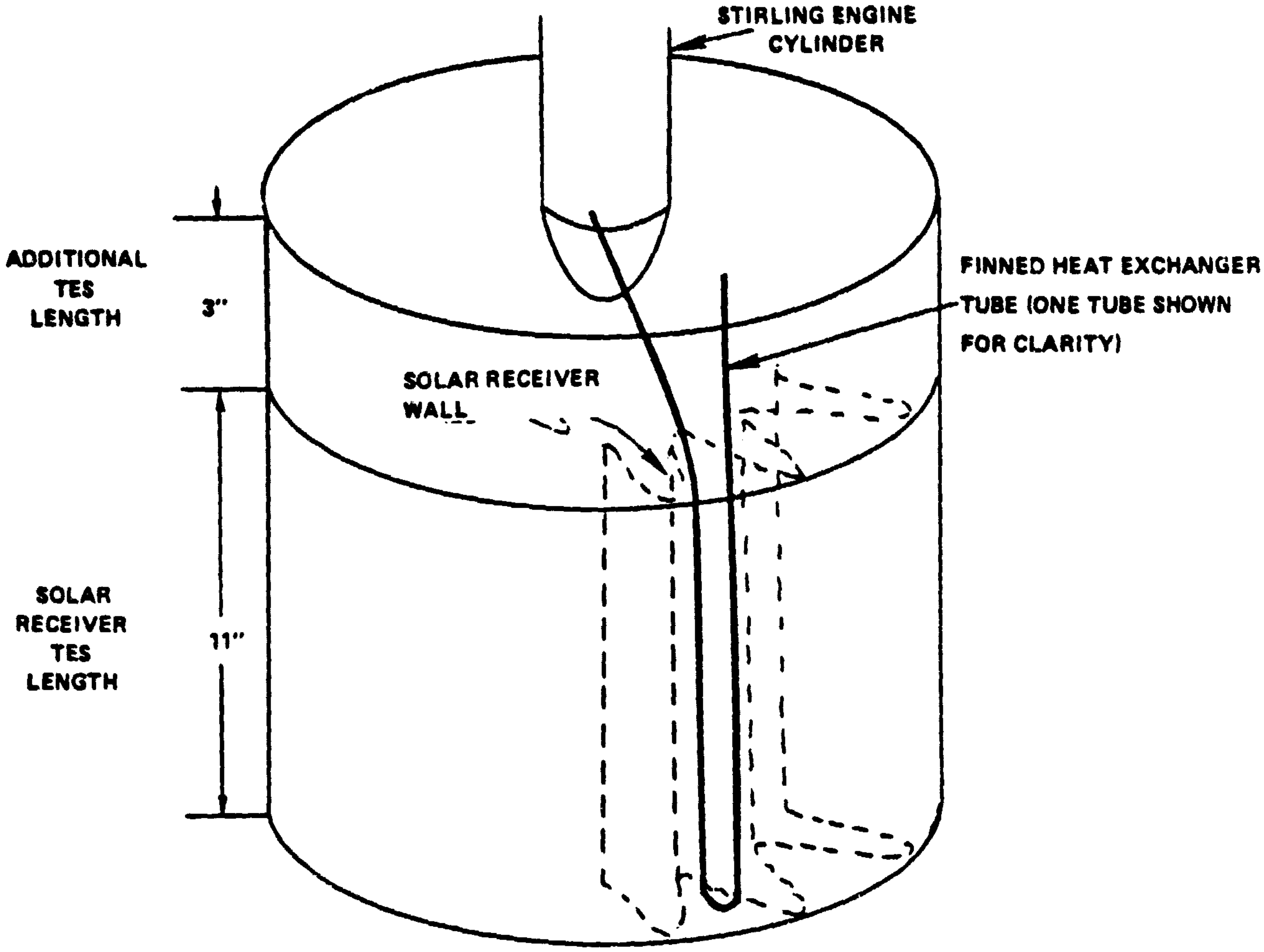
While the direct coupling of up to 15 minutes TES to the Stirling engine heat exchanger is possible, such integration of TES becomes a closely linked design problem involving the design of the Stirling engine heater head itself. Such detailed effort lies outside the scope of the present study. It is a fundamental advantage of the heat pipe solar receiver with TES that heat pipe thermal transport provides completely independent freedom for optimum design of the engine heater head without restrictions, being imposed by either receiver or TES design or by heat transfer considerations.

D. SIMULATED SOLAR PERFORMANCE AND ECONOMIC ANALYSIS

1. Overall Approach to Solar Performance and Economic Analysis

An integrated transient thermal analysis of both the DSSR and HPSR systems was performed using real solar insolation input and including combustors, transient thermal losses, and control assumptions which dictated responses from the system in a manner similar to that which would be used in a real system; that is, control decisions were made on the basis of temperatures at a given instant, with no knowledge of the future. This thermal analysis resulted in estimated fuel use and electricity production for a year for the given system; these were then input into a financial analysis which yielded the cost of electricity (COE).

The solar insolation data was taken at Goldstone, California, throughout the year 1979 between 0500 and 2200 hours at one minute intervals. In order to run more system configurations, 20 characteristic



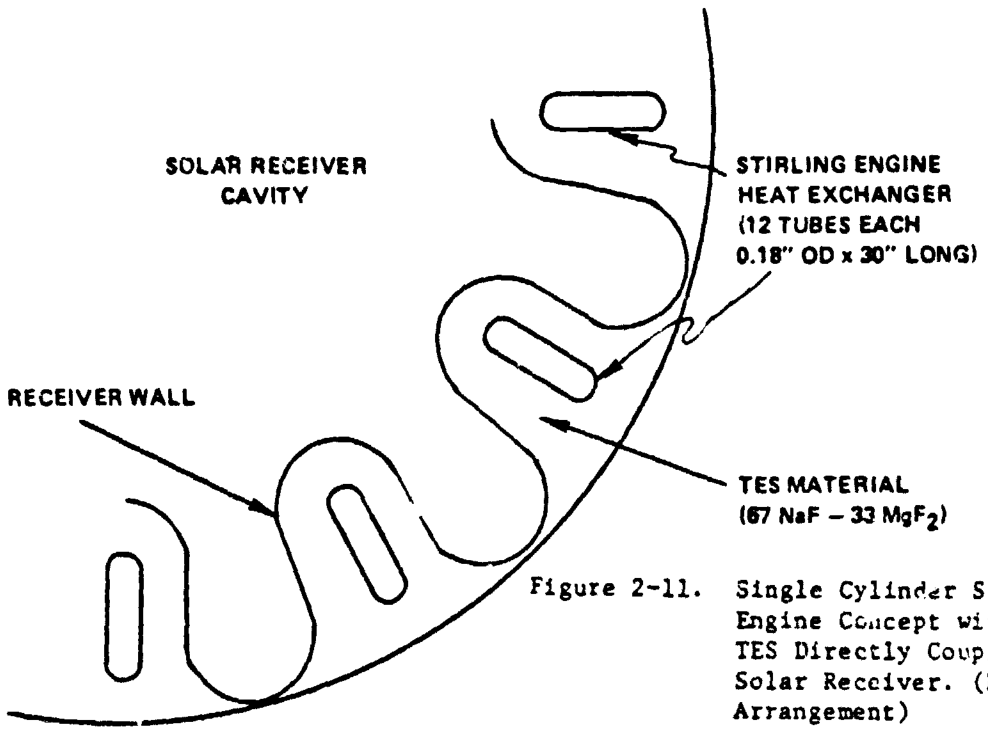


Figure 2-11. Single Cylinder Stirling Engine Concept with 15 Minutes TES Directly Coupled in the Solar Receiver. (Radial Tube Arrangement)

days were selected for use and the results extrapolated to a year, as will be shown later. This data was supplied by JPL in the form of a transcription of actual raw data which included instrumentation errors. A significant amount of effort was expended to reduce this data to useable form.

Finite element thermal performance models were made of the DSSR and HPSR systems employing six or twelve isothermal nodes respectively. The simultaneous differential equations of heat transfer were written for each node and then integrated by computer. The solar insolation data were applied to the nodes which made up the receivers in each model, the model temperatures responded, and control decisions were then made based upon the nodal temperatures. A running total was kept of each day's use of fuel and of the energy produced.

An economic analysis was performed to determine the cost of electricity based on accepted electric utility standards. This analysis calculated the electric energy busbar cost for a utility-owned solar electric system. This cost was the minimum required to produce energy consistent with producing revenues equal to the total system cost. Costs included capital, O&M and fuel costs and took into consideration all economic factors such as the general rate of inflation and the rates of inflation of fuel and operating costs. The base year for the dollar costs used was 1979.

After performing the economic analysis on each system, parametric plots were drawn to see the effects of variation of TES quantity, operating power levels, operating assumptions and whether or not a combustor was present in the system.

2. Weather Tape Data

The weather tape data consisted of a transcription from analog form to digital form of actual raw data which included original instrumentation errors. Thus the first task in reconciling the weather data was to process into useable form approximately 11 million pieces of data (two insolation values and ambient temperature, minute by minute, for each day of an entire year). Actually more data than this was processed since the first tape which was supplied and processed contained data only through May; the process had to start over when the second tape, containing the full year's data was supplied by JPL.

It was decided that the large majority of the data processing would be done as the information on the tape was converted into a binary file on the computer. This up front weather data conversion procedure was used because it would eliminate, for each future case to be run, the necessity of writing a data processing program to reprocess the same raw data every time. Errors encountered in reconciling the data as it was initially processed included missing data, data that was obviously out of bounds, (i.e., negative data), duplication of successive days, extraneous numerals and format errors. During the development of the binary file of the weather data, the program reading the tape had to have each error in the tape programmed into it as an exception and the process of reading the tape had to be restarted each time an error was encountered and its resolution specifically programmed. To give some indication of the magnitude of this effort the listing of the weather tape contained an estimated 1500 pages of data, each page totally filled with numbers, and on lightweight (laser printer) paper, stacked over 5-1/4 inches high.

Generally, the problem of using the computer to process raw data (the job of judging raw data as good or bad and eliminating the bad) is one of the most significant types of computer programming problems ever encountered. Indeed, some of the largest and most sophisticated computer programs that have ever been written have been written for this general purpose.

The process of data processing followed three basic steps. First, the data tape was converted into a system standard ACSII tape, a process which removed the extraneous data and format errors. Then the data that was missing, e.g., temperatures for the first four months, was added and duplicated days were removed. The final step converted the tape into a mass data file (MDF) which contained three pieces of data for each minute of each day between about 0500 and about 2200 hours. It also had each day's data preceeded with a flag indicating whether or not the data for that day was complete. The start and stop times for the data of that day were also identified.

An MDF file provides rapid access to a large quantity of data at low cost. Generally the options open to programmers for storage of as much data as was required in this analysis consist of the use of either a magnetic tape of a quick-access disc file. The use of magnetic tape was undesirable since each time the data was to be used it required manual operations to mount this tape; this would add to the cost of the run. Furthermore, the magnetic tape limited the program to batch operation which, in turn, increased the time required to run individual cases over timeshare. This proved to be significant since, at one point in the study, there was a need to generate case data quickly. The use of a quick-access disc file was also not available because of arbitrary space allocations on the system. The MDF file system solved the data problem by providing storage data capability in excess of disc space allocation. It automatically mounted a casette tape which created a temporary disc file containing the data. Nontheless, some delay was encountered since this was the first use, on the Evendale computer system, of the MDF system to its full extent and some system problems were discovered.

3. System Computer Modeling

The very short time intervals of the solar insolation data dictated that the system models used be of a commensurately detailed nature yet still be cheap enough to run through the required number of cases within budget. Minutewise solar insolation data implied that transient system thermal response and loss should certainly be considered and thus the formulation of suitable transient system models proved to be a significant challenge during the course of the program.

A transient finite element thermal analysis was finally used because of its high accuracy and adaptability to different systems and configurations within systems. In a finite element analysis, the structure is broken down into a number of isothermal, or constant temperature, elements. In theory, this would require an infinite number of elements but it has been found that for most system wide applications, the number of elements or nodes really needed is surprisingly small.

Another assumption that was made for this analysis was that the thermal conductivity and the specific heats of the nodes remained constant with temperature. In design studies these effects are usually accounted for but, again, experience has shown that the use of constant properties is acceptable for system models. This is particularly true when determining relative thermal characteristics between two systems where the error in thermal property variations would tend to cancel.

In assembling these models there were a number of factors that had to be taken into consideration. The overall accuracy of the model could be increased by increasing the number of nodes but this would increase the cost of running the model and any increase in accuracy would not be proportional with the increase in the number of nodes. Furthermore there were integrator stability considerations. The larger the node (the more temperature inhomogenity that was present) the greater the mc_p product for that node and, as can be seen in equation (4) below, the smaller the time derivative of temperature for a given heat imbalance and hence the more stable the model. This allowed the time step of the integrator to be larger and reduced the amount of computer time required to run the model through a days data. Another problem which could occur when the temperature of interacting nodes is close together is that accumulated integrator error can sometimes cause an artifically reversed temperature gradient to form between nodes; that is, heat could flow in a direction contrary to physical law. Using fewer nodes with larger temperature differences between them reduces the possibility of this sort of error. The models that resulted considered all these factors in their formulation and to a large degree were based upon analytical experience.

The construction of the models started with energy flows (q_i) and temperature distributions from the design studies performed on the respective systems. Using an arbitrary level of temperature inhomogeneity, nodes are specified that make up each model and then surface averaged temperatures for those nodes are determined. Between any two nodes, i and j, the energy transfer would be given by

$$q_{ij} = C_{ij} (T_i - T_j), \tag{1}$$

assuming heat flow from node i to j is positive.

If the mode of heat transfer were radiation, equation (1) would be,

$$q_{ij} = R_{ij} (T_i^4 - T_j^4), \tag{2}$$

again assuming that heat flow from i to j is positive.

The temperatures and the q_i were known for each node from earlier thermal design work. Thus, using equations (1) and (2), a set of conduction or convection conductances (the C_{ij}) or radiation conductances (the R_{ij}) could be derived.

For the i^{th} node, the sum of the q's is equal to the mass of the node times the specific heat of the node times the derivitive of temperature of the node with respect to time. Stated mathematically,

$$m_i C_{p_i} \frac{dT_i}{d\tau} = \sum_{j-i}^{n} q_{ij} \tag{3}$$

where j is summed over all the nodes to which or from which the i^{th} node exchanges heat. Other sources of energy gain or loss might be present in any given node; e.g., solar insolation, combustor energy, or the energy required by the Stirling engine. These are also summed with the q_{ij} so that the general differential equation for the temperature of a given node would be,

$$\frac{dT_i}{d\tau} = \frac{1}{m_i C_{p_i}} \left[\sum_{j-i}^{n} q_{ij} + Q_{sol} + Q_{se} \right] \tag{4}$$

The set of differential equations (4) constituted, in essence, the model of the system. For the HPSR, a diagram of conductances is shown in Figure 2-12, parallel conductances not being shown for brevity. Between nodes 6 and 7 a very high conductance was used into the TES area to characterize the heat pipe performance while a smaller conductance was used in the reverse direction to characterize conduction. Node 1

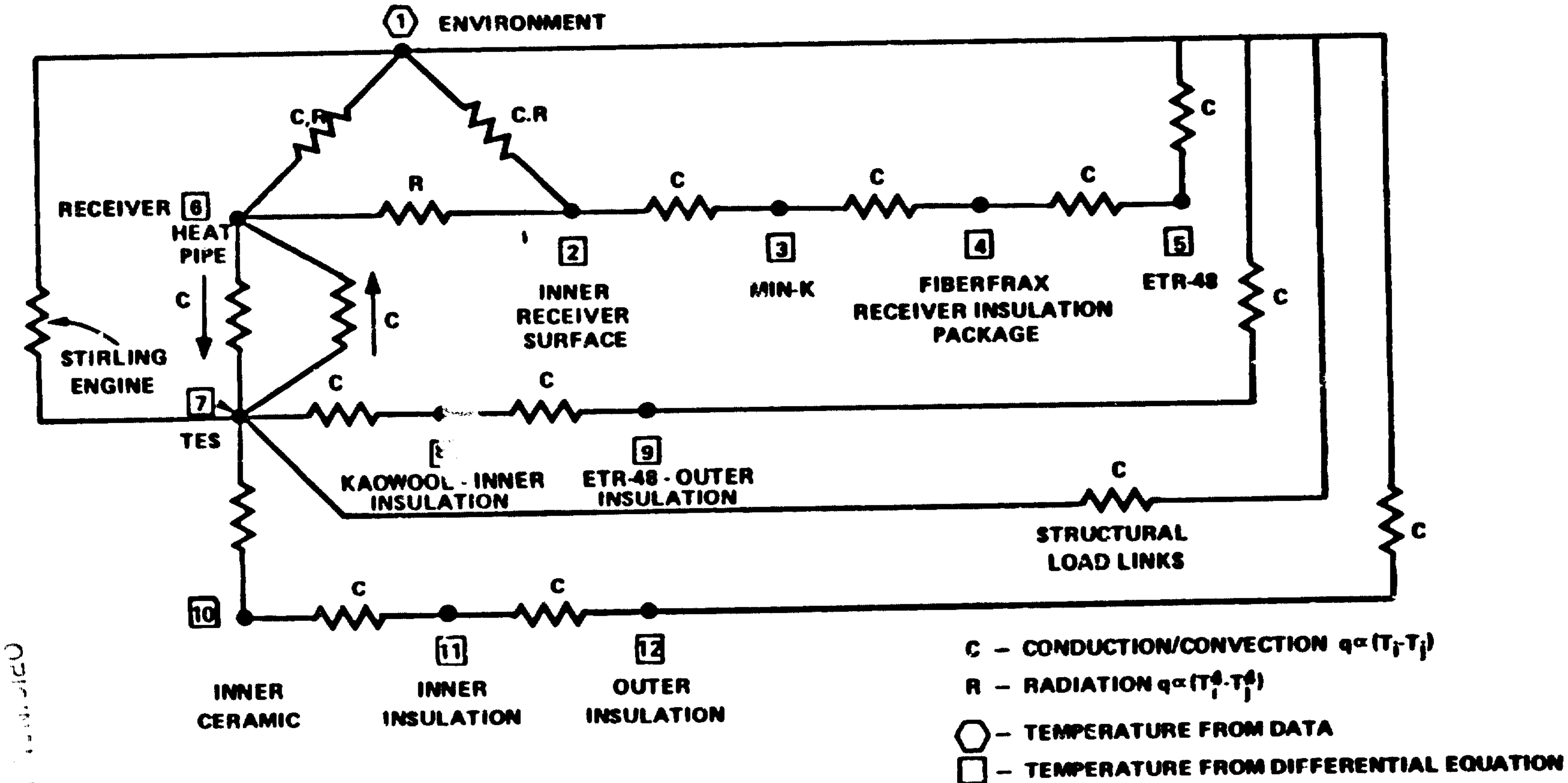


Figure 2-12. HPSR Nodal Network.

represented the environment; its temperature was set by the ambient temperature data. Solar insolation energy was applied, in proportion to exposed surface, to nodes 2 and 6 while the Stirling engine took its power from the TES (node 7). Energy from the combustor was also applied directly to the TES. Figure 2-13 shows a nodal network diagram for the DSSR system.

Having generated a set of differential equations, the next step in the analysis consisted of determining what integrator would be the most economical to calculate the temperature as a function of time for each node. Since minimizing calculation cost was so important, the desirable characteristic in the integrator was its ability to perform the integration with the smallest number of evaluations of the derivative equations, (4). Accuracy was of secondary importance so long as inaccuracy remained reasonably small, since the integrator error would be applied randomly to all the systems and would therefore not alter the relative trend of results.

Four integrators were tried out on the HPSR system model to determine which was capable of having the largest time-step for the least number of derivative evaluations. The primary source of instability, and hence short time-steps, in equation (4) was the nonlinear radiation problem. There is only a very little information in the literature on selecting the optimum integrator for a given set of nonlinear differential equations. Usually a number of integrators are tried out and that was what was done in this case. Variable time-step integrators were discarded since the possibility existed that the integrator would reduce the time-step to a very small value and remain there over the course of a run involving several days which would lead to unpredictable and high computer costs. It was decided, therefore, to set the time-step by the day that had the very highest insolation for the longest time so if there was any instability due to the radiation terms, it would be triggered. Typically, variable time-step is used where the forcing functions are reasonably well known, but in this case a manual review of the insolations over the year was out of the question.

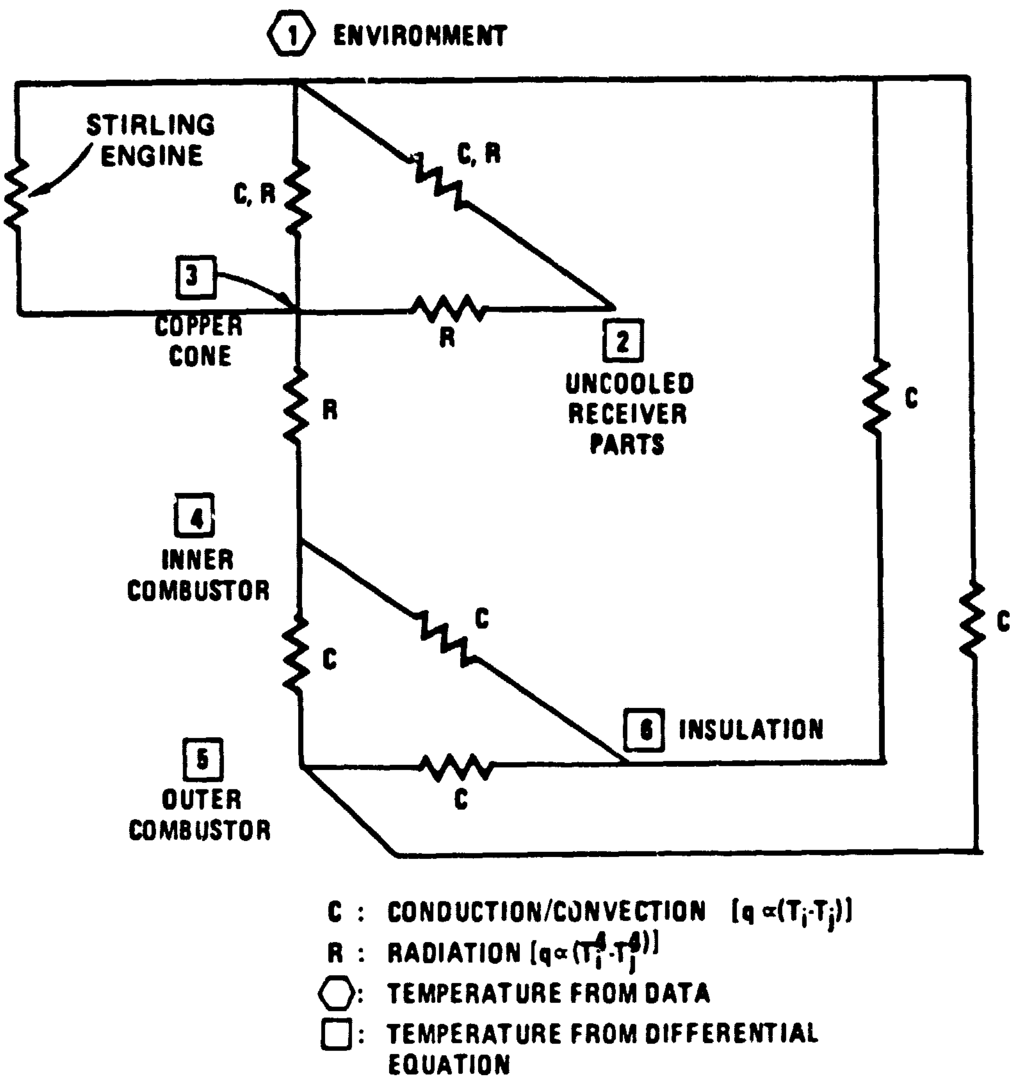


Figure 2-13. DSSR Nodal Network

The four integrators tried out on the HPSR system model were the Simple Euler method, the Modified Euler method, a 4th order Runge-Kuta method with Gill coefficients and a Hamming method predictor-corrector type. It was noticed that the multistep integrators tended to be more stable than the Runge-Kutta integrator at large time-steps, probably because the past history in the multistep methods tended to dampen out oscillatory behavior. In the end, a Hamming method integrator, started by a Modified Euler integrator, was used.

The control assumptions were probably the least developed part of the analysis since, in both systems, little or no work had been done in this area. For the DSSR, the model was allowed to arrive at the design point temperature by the combination of combustor and solar insolation and, once at the design point, combustor firing was controlled by a scheme employing the negative derivative of the cone temperature with respect to time.

Throughout the bulk of the performance and economic analysis, the control assumption was made that the combustor would be turned on if the TES temperature was below 826.7°C and off if it was greater. Likewise the Stirling engine was operated about 817°C. An investigation was made into the effects of using a dead band control assumption scheme and the results will be presented later on.

In the HPSR model, the latent heat of the salt was modeled by a large mC_p product over an arbitrary 20°F range which started at the melting temperature of the salt.

A flow chart for the computer simulation program is presented in Figure 2-14. Required data for each run was obtained from a number of files which modularized the parametric analysis process. The MDF file containing the weather data was never altered once it was made, the global data file was specific for each system configuration and the days of the year that were run was maintained constant. The program worked on a day basis, getting data for use one day at a time.

The sequence for each minute began when the collector performance and the ambient temperature were determined from the weather tape data.

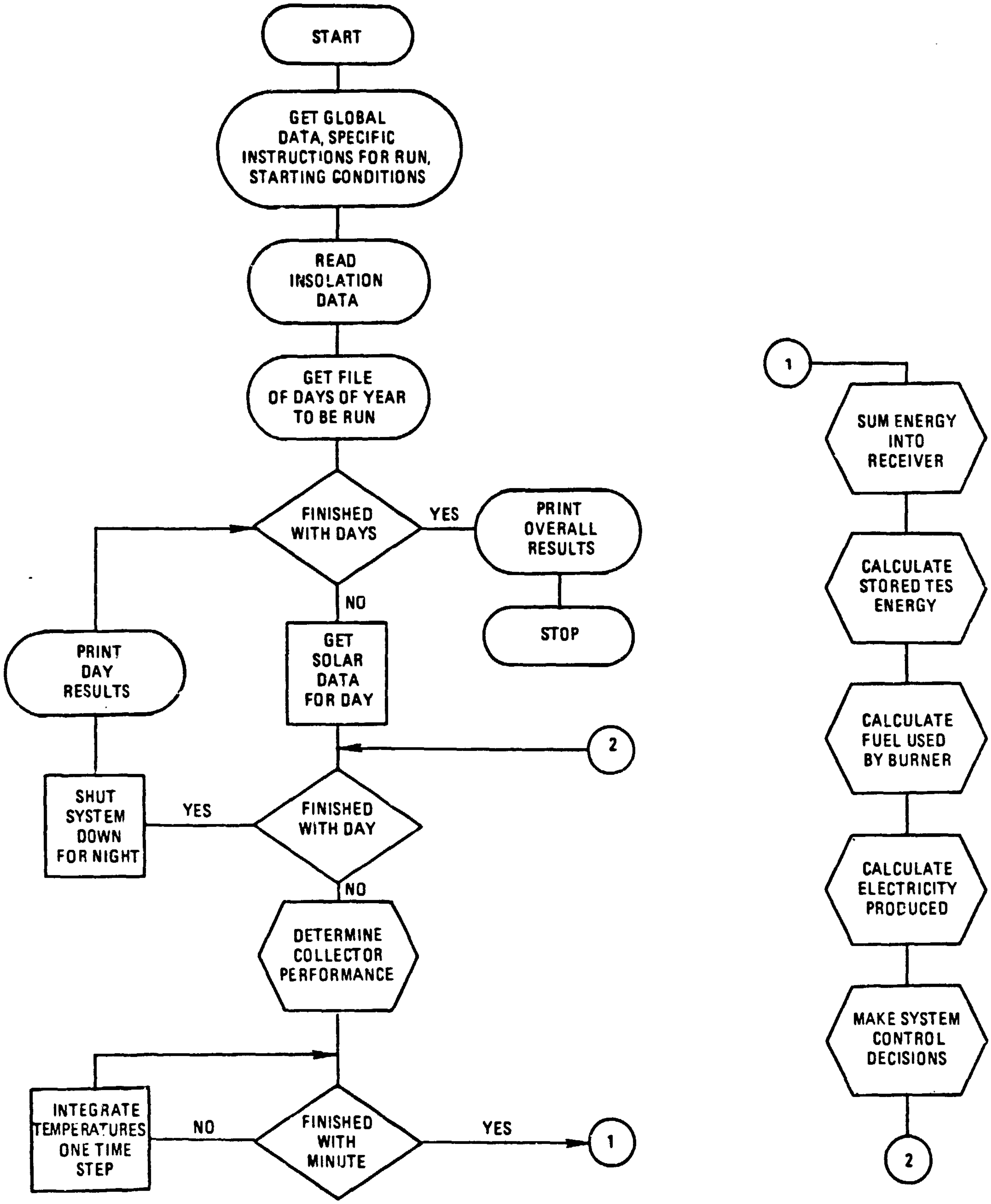


Figure 2-14. Flow Chart for Solar Insolation Computer Code

The integrator then integrated the temperatures forward one minute in four second intervals. Finally, at the end of the minute, the quantites for which a running total was being kept such as the amount of electricity produced were summed.

In order to avoid the necessity of running cases over 365 days and to permit inclusion of more cases in the parametric analyses that were performed, a limited number of types of days, specifically nine, were selected; these represented insolation types throughout the year. The process of selecting the days started by categorizing the daily insolation profiles into nine characteristic types as shown in Figure 2-15. Next, each daily solar profile types were checked for the season in which they appeared, as shown in Table 2-10. Extrapolation to one year was accomplished by multiplying the results for the specific or averaged daily results by the number of times that daily insolation profile type occured in each season. Thus a representative solar year was developed and only 20 days of solar operation involving specific daily solar insolation patterns of the nine day types were utilized with the necessary multiplication factors to develop annual performance data.

4. Basis of Economic Analysis

The cost of electricity (COE) was calculated over a 30 year period using the methodology of J.W. Doane, et al.* developed for utility owned solar electric systems. It calculates the electric energy busbar costs, which represents the minimum price of energy consistent with producing revenues equal to the sum of system resultant costs. The annualized system resultant cost, in dollars per year, represents an amount which, if collected in revenues per year would constitute a revenue distribution with exactly the same present value as the summed present values of all the system cost distribution. Levelized busbar energy cost is the quotient of annualized system-resultant cost divided by the expected annual energy output, as calculated by the performance simulation model.

*J.W. Doane, et al., "The Cost of Energy From Utility-Owned Solar Electric Systems", JPL 5040-29, ERDA/JPL-1012-76/3; June 1976.

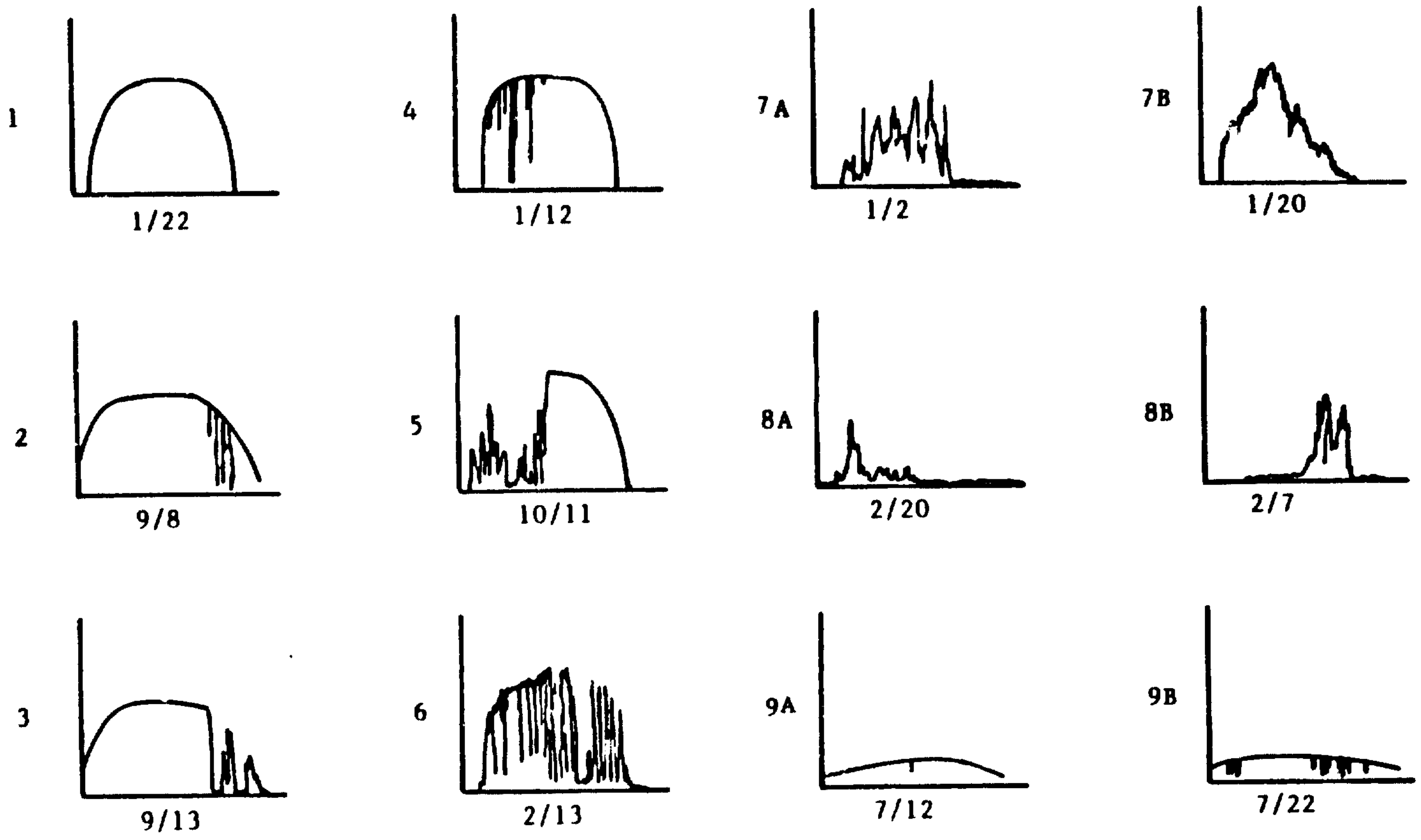


Figure 2-15. Daily Insolation Profile Types.

TABLE 2-10

DISTRIBUTION OF DAILY INSOLATION PROFILE TYPES

Daily Profile Type	Frequency of Occurrence: January Thru March	April Thru June	July Thru September	October Thru December	Total
1	16	46	52	14	128
2	4	13	15	9	40
3	2	1	2	4	9
4	4	7	4	14	29
5	2	-	-	6	8
6	27	19	15	24	85
7	13	3	1	14	31
8	18	-	2	7	27
9	-	-	2	-	2
No Sun	5	-	1	-	6
Total					365

Input data for the economic analyses included the utility description data and the general economic conditions shown in Table 2-11. Additional inputs are the capital costs and the years in which they are incurred and the fuel, operational and maintenance expenses. The annual system output and fuel requirements were determined from the performance analyses of the various conceptual designs.

The capital costs were estimated using the assumptions shown in Table 2-12. Most of these cost values were obtained from JPL personnel. The values for thermal energy storage were goals used throughout this study. Costs for the Stirling engine were those reported by Fortgang and Mayers*.

Under balance of plant, the costs for temporary facilities, substation and control building were based on costs for a larger electrical power system and prorated for the 25 kW_e system of this study. The last three items were estimated as percentages of the cost of the major components.

The costs for land, site preparation and temporary facilities were assumed to be incurred in 1983, all other capital costs were assumed to be incurred in 1984, with the first year of commercial operation in 1985.

The assumptions for operational and maintenance expenses are shown in Table 2-13. The Stirling engine was assumed to operate about 3750 hrs./yr. to determine maintenance expenses. The expenses for the operations and maintenance personnel were scaled down from values for a larger power plant, assuming that there will be multiple 25 kW_e systems in one power complex. The costs of fuel shown in Figure 2-16**. Average gas costs, at 10% per year inflation, were selected as the basis for determining COE, but new gas prices were also used to show the sensitivity of the systems to fuel cost.

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*Fortgang, H.R. and Mayers, H.F., "Cost and Price Estimate of Brayton and Stirling ENgines in Selected Production Volumes, DOE/JPL-1060-35, May 30, 1980.

**Robertson, C.S., Jr., "Pipeline Bottoming Cycle Study-Economic Assessment", GESP-815, Contract No. EM77-C-03-1381, April 16, 1979.

TABLE 2-11

INPUT FOR ECONOMIC ANALYSIS

N	System Operating Lifetime, Years	30
β_1	Other Taxes	0.02
β_2	Insurance	0.0025
τ	Effective Income Tax Rate	0.4
D/V	Debt to Capitalization Ratio	0.5
C/V	Common Stock/Capitalization	0.4
P/V	Preferred Stock/Capitalization	0.1
k_d	Annual Rate of Return on Debt	0.08
k_c	Annual Rate of Return on Common Stock	0.12
k_p	Annual Rate of Return on Preferred Stock	0.08
g	Rate of Inflation	0.08
g_c	Escalation Rate for Capital Costs	0.08
g_o	Escalation Rate for Operating Costs	0.09
g_m	Escalation Rate for Maintenance Costs	0.09
g_f	Escalation Rate for Fuel Costs	0.10
y_b	Base Year for Constant Dollars	1979
y_{co}	First Year of Commercial Operation	1985

Multiplier to get COE in constant-value dollars 0.37525

TABLE 2-12

ASSUMPTIONS FOR CAPITAL COSTS

Concentrator $\$85/m^2$

Receiver $\$10/m^2$

Structure $\$6.50/m^2$

Thermal Energy Storage $\$15/kW_t + \$10/kW_t$ hr

Electrical Transport $\$13.24/m^2$

Combustor \$118 + Piping \$827 = \$945

Stirling Engine \$4145

Generator $\$33/kW_e$

Balance of Plant

Land \$5000/acre [area = (collector dia.)^2/0.3]	
Site Preparation $\$3.50/m^2$ land area	
Controls and Cables $\$15/m^2$ concentrator area	
Temporary Facilities	$\$3000/25\ kW_e$
Substation	$\$1725/25\ kW_e$
Control Building	$\$1600/25\ kW_e$
Fees (A.E.& Const.)	20% Major Components
Shipping Cost	1.5% Major Components
Spare Parts	5% Major Components

TABLE 2-13

ASSUMPTIONS FOR O&M EXPENSES

Concentrator	2.1% of Capital Cost
Receiver	2.0%
TES	2.0%
Electrical Transport	2.0%
Combustor $15/yr + $195/7500 hrs.	(Assumed $49 or 1/4 of 7500 hrs.) (Assumed $98 for Advanco System)
Stirling Engine $50/yr + $235/7500 hrs. + $1658/15000 hrs.	(Assumed 3750 hrs/yr)
Generator	2%
Fuel	(See Figure 2-16; $1.03/1000 ft^3 in 1979)
Balance of Plant	
Controls and Cables	1.9%
Substation	2.0%
Control Building	2.0%
Operatins Crew	$1000 ($40,000 for 1 MW_e Plant)
Maintenance	$ 500 ($20,000 for 1 MW_e Plant)

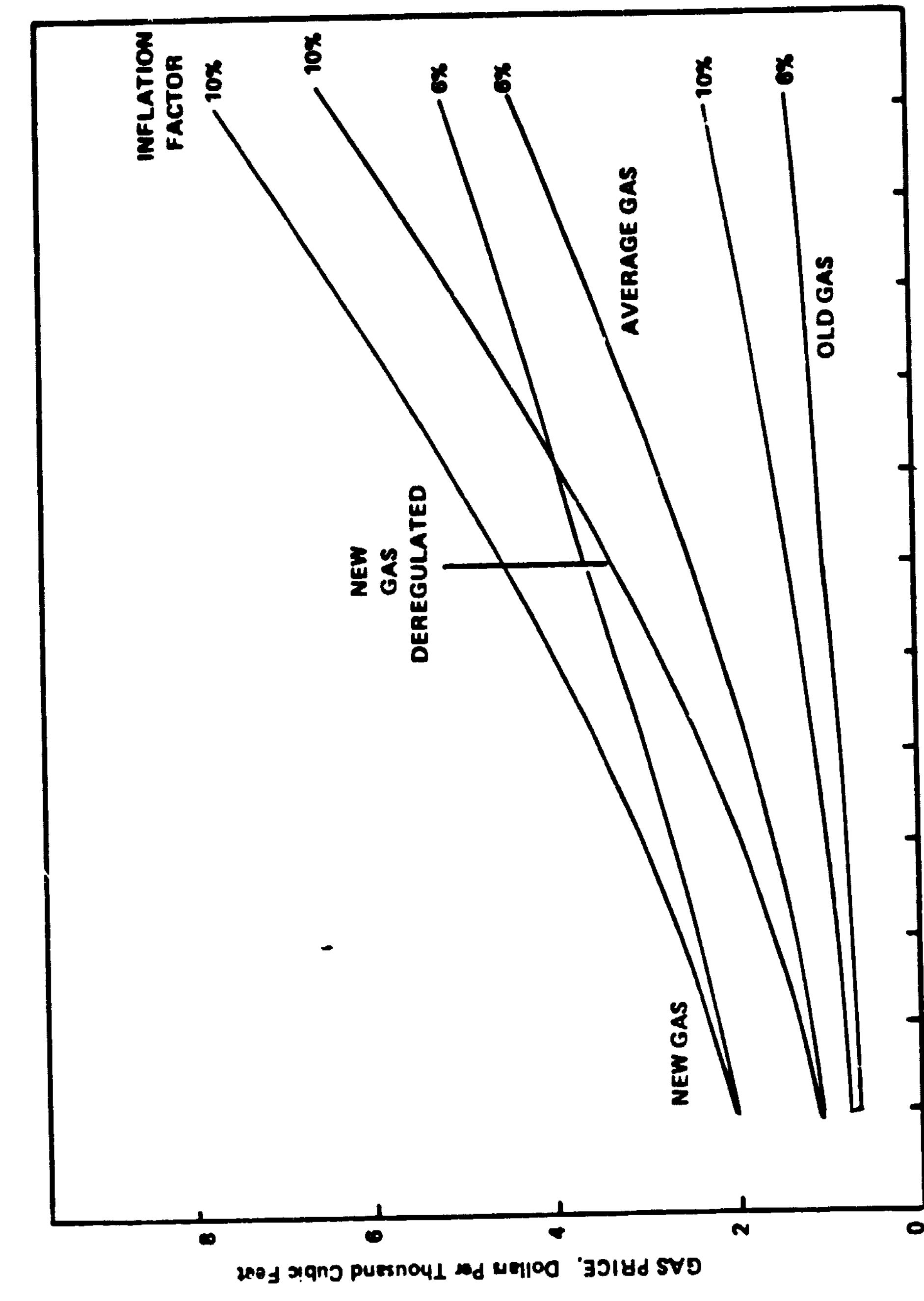


Figure 2-16. Projection of Natural Gas Prices.

5. Performance and Economic Analysis Results

A total of 71 cases were run using the nodal networks and computation methods described above. Of these a total of 29 were extrapolated to one year and used for data record pruposes. The principal variables studied were the TES duration, concentrator size, the presence of absence of a combustor, continuous vs. "on-off" combustion and various alternative system control assumptions; in the economic analysis the sensitivity of COE to fuel cost and to engine efficiency were assessed since the DSSR and HPSR were characteristically different in their fuel utilization features and, while similar engine efficiencies were attributed to both, a significant difference in engine efficiencies is expected since the receiver designs directly affect the engine heater head.

The DSSR, operating with a minimum of 10% combustor power input generated a smaller portion of its power with solar insolation than did the HPSR. Its concentrator was never required to defocus since it was always deficient in self-sustaining solar insolation even under peak annual solar insolation conditions. With a continuous combustor, and under the presumption that the combustor could respond satisfactorily to solar insolation variation, there was no need for added TES for system stability or continuing operation. Furthermore, the addition of limited or extended TES was not attractive for technical reasons. See Section II-C-1. Therefore the effect of TES duration on the Stirling engine power conversion system was studied only for the HPSR system with, or without, its "on-off" combustor. The additon of significant TES duration to the DSSR would permit the use of an "on-off" combustor and reduced use of fuel but would require thermal transport effectiveness like that of the HPSR and its re-design in that case would tend toward that of the HPSR.

The HPSR took effective advantage of a larger portion of solar insolation because of its TES. It was discovered that the concentrator for the system could be sized near the peak annual solar insolation to minimize the prospects for defocusing and to utilize as much solar insolation and as little fuel as possible. Independent increases in the collector area and TES duration reflected the ability of the system to absorb and utilize, daily, a larger amount of solar insolation. Since summer and winter peak solar insolations differ by as much as 10 percent, the sizing of the concentrator collector area will either lead to defocusing of the collector area, if larger than needed (over 90 m^2 for peak winter insolation), or to the under utilization of the TES and the need for more fuel use, if the collector area is smaller than needed. The ability of the Stirling engine to operate at alternative fixed power levels over a design range other that at the one fixed design power level used in the current study would greatly improve the utilization of the TES; it would increase solar utilization and reduce the use of fuel, although at a change in power output related to changed peak solar insolation.

Analysis of the insolation data indicated that, while systems had to be able to withstand the very hottest day, the usual day had some cloud interruption. Indeed, cloud interruption was more the normal mode of operation than the exception and future systems design will need to pay additional attention to the problem of transient system response and control. For combustor equipped systems, the combustor can handle such cloud cover periods and it, in turn, is aided by the presence of TES.

System control assumptions were also found to singificantly reduce the number of start/stop cycles of either the Stirling engine or the combustor. For the study, an initial control assumption was made that the Stirling engine would be turned "on" whenever the TES temperature was above 817°C and turned "off" whenever the TES temperature fell below that temperature. During periods when the solar insolation was not enough to sustain the Stilring engine, the engine would cycle "on" and "off" as frequently as every minute. The number of cycles can be greatly reduced if dead band operating control is used; i.e., the Stirling engine is turned "on" when the TES temperature reaches a given high temperature and is allowed to run while heat is extracted from the TES and is turned "off" only when a given lower temperature is reached.

Typical daily performance curves were plotted for the HPSR with 0.8 hours of storage, a 90 m^2 collector area and both with and without a combustor.

Figures 2-17 through 2-19 indicate the operation of this system without a combustor on the peak solar insolation day of the year for which the concentrator was sized to charge the TES fully without the requirement for defocusing. Figure 2-17 indicates the solar insolation input to the receiver the thermal power going to the engine and the engine shaft power output. A portion of the receiver output is lost through conductance and reradiation; the remaining power not required to operate the engine is stored in the TES. After over 8 hours of operation the TES is fully changed and the solar insolation to the receiver has dropped below that required to operate the engine and satisfy thermal losses. Thereafter the engine thermal power and the thermal losses are provided by mixed mode operation on both decreasing solar insolation and heat drawn from the TES.

During initial operation of the system in which the engine is started after less than one hour of low level solar insolation, the engine can be run intermittently on solar insolation and TES at less than the minimum solar insolation required to operate the engine. The engine is commanded to stop, briefly, as the TES temperature drops below its control point, but the frequency of these engine stops decreases as the increasing solar insolation partially recharges the TES. Such engine cycling could be minimized or eliminated completely by delaying the start of the engine and drawing down the initial TES charge with engine operation such that the TES is again nearly completely discharged as the excess solar insolation becomes available for recharging the TES during mid day operation. Figure 2-18 illustrates the temperature of various components during relatively steady state operation. The shell side temperatures are initially at TES temperature as the combustor is used to attain the TES subcool (discharge) temperature prior to startup. The degree of charge during the day builds, as indicated in Figure 2-19, as the result of excess solar insolation and is discharged in mixed mode powering of the engine or direct operation on TES after solar insolation is lost for the day.

Figures 2-20 through 2-22 show the daily operating characteristics for a similar system with a combustor on a day featuring irregular solar

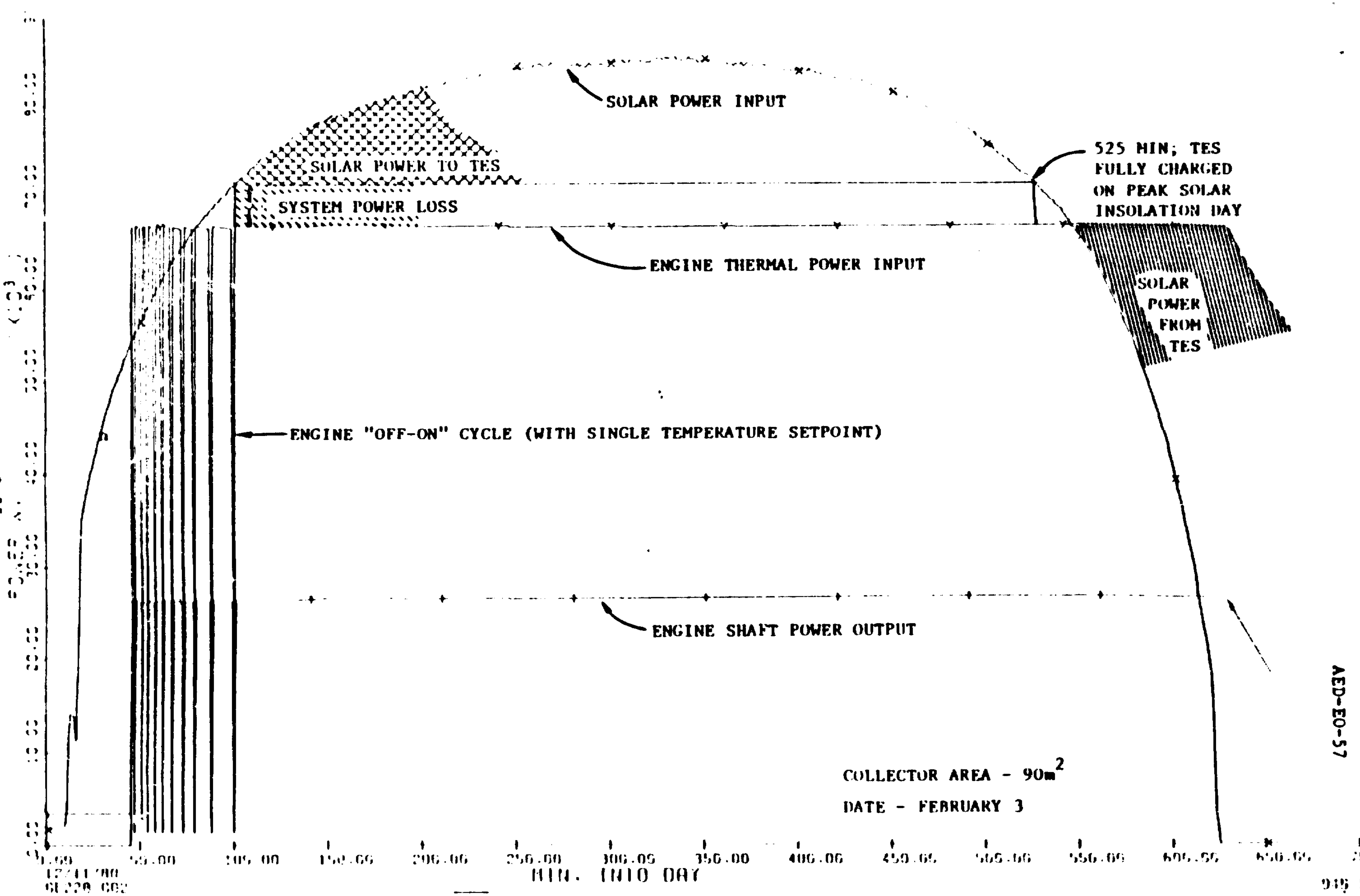


Figure 2-17. Solar and Thermal Power - Time Profiles for HPSR System with 0.8 Hours TES and No Combustor On Optimum Solar Insolation Day.

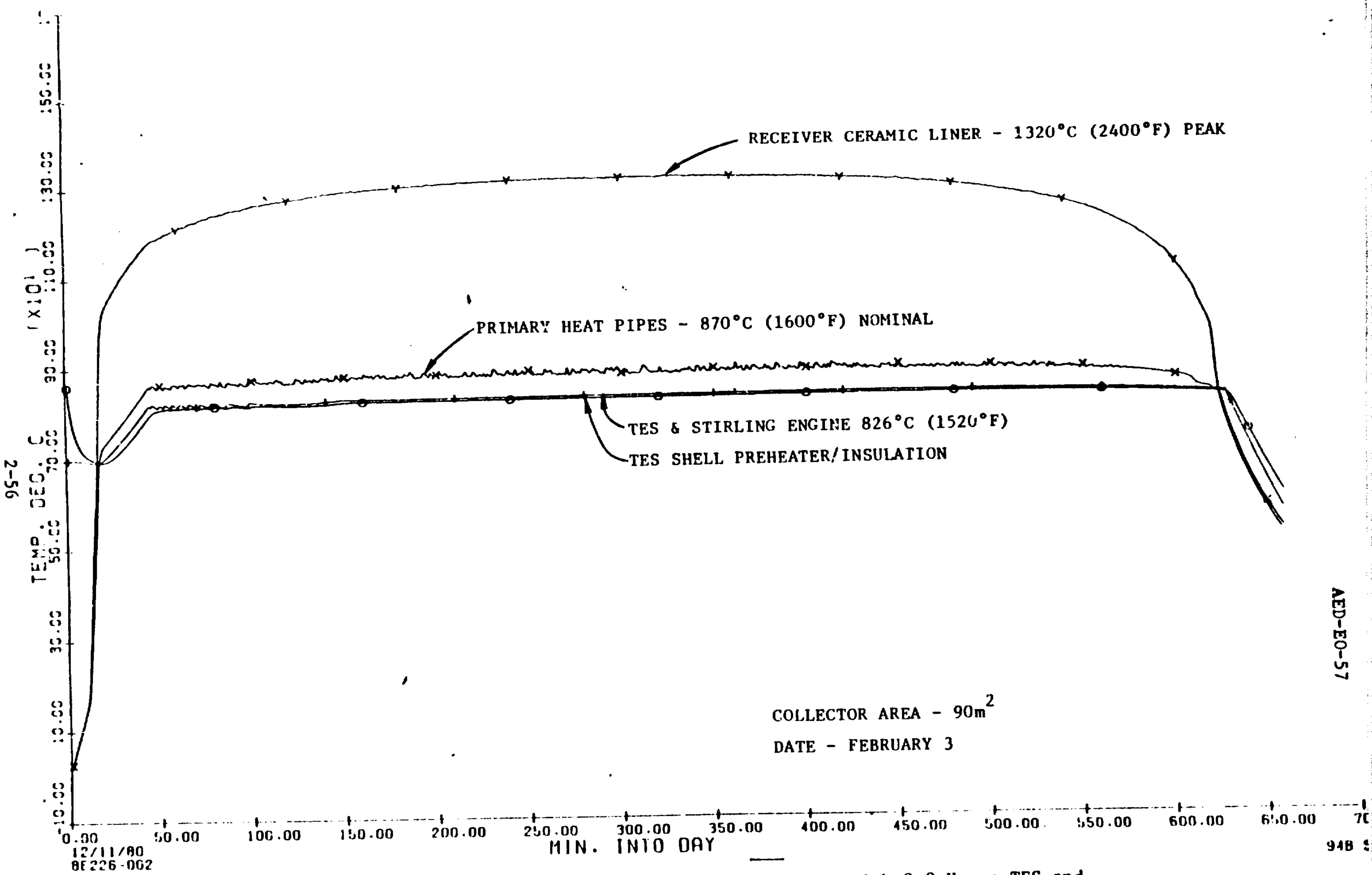


Figure 2-18. Temperature-Time Profiles for HPSR System with 0.8 Hours TES and No Combustor On Optimum Solar Insolation Day.

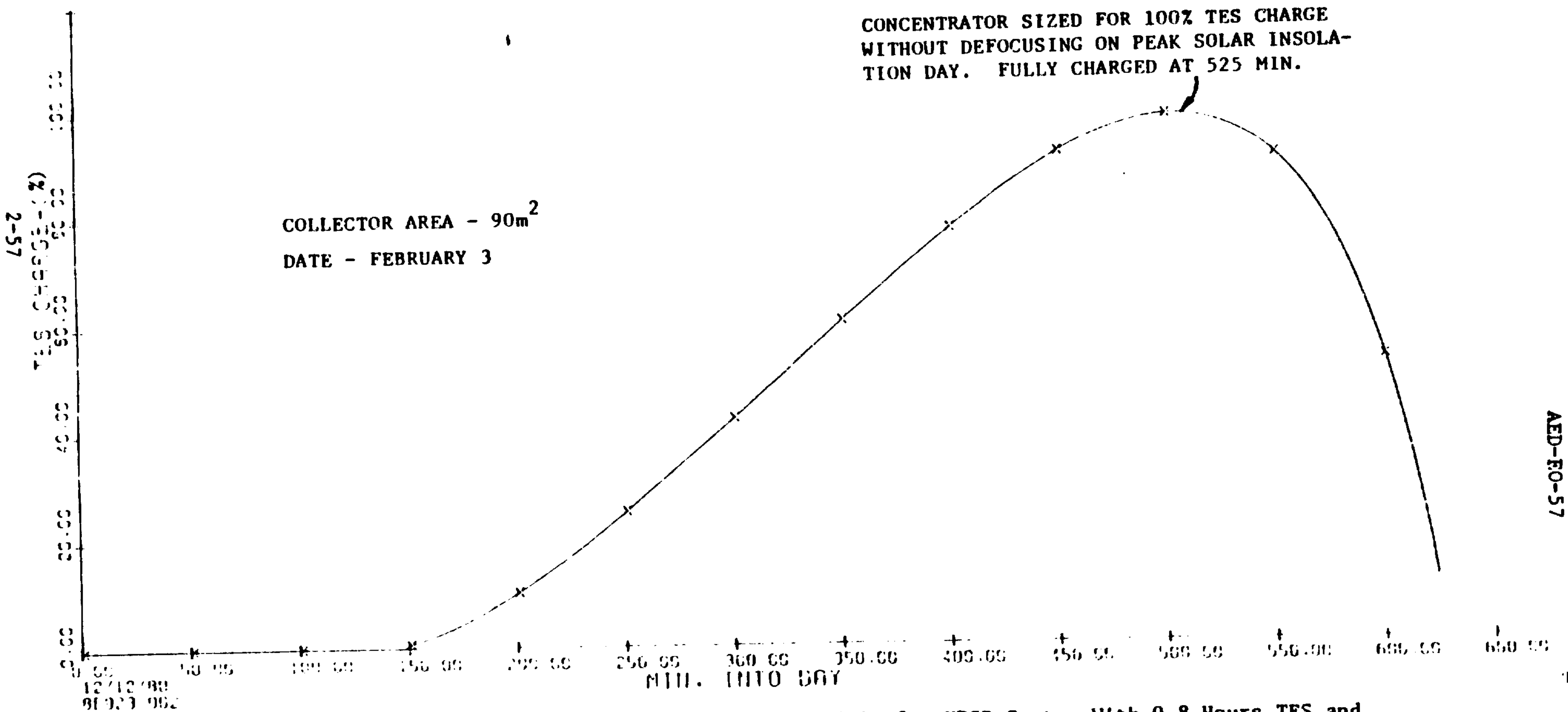


Figure 2-19. Percent TES Charge - Time Profile for HPSR System With 0.8 Hours TES and No Combustor On Optimum Solar Insolation Day.

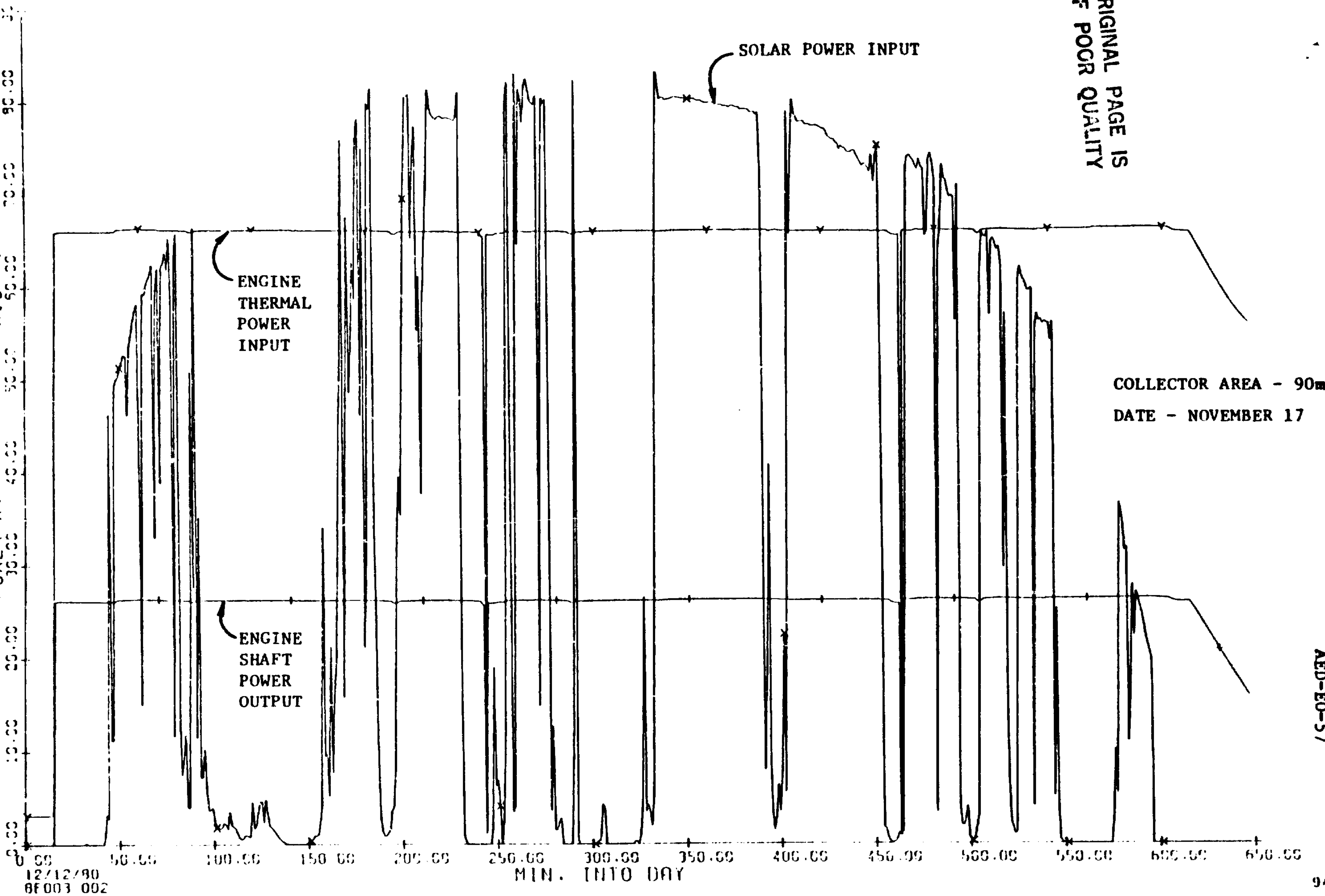


Figure 2-20. Solar and Thermal Power - Time Profiles for HPSR System with 0.8 Hours TES and "On-Off" Combustor on Poor Solar Insolation Day.

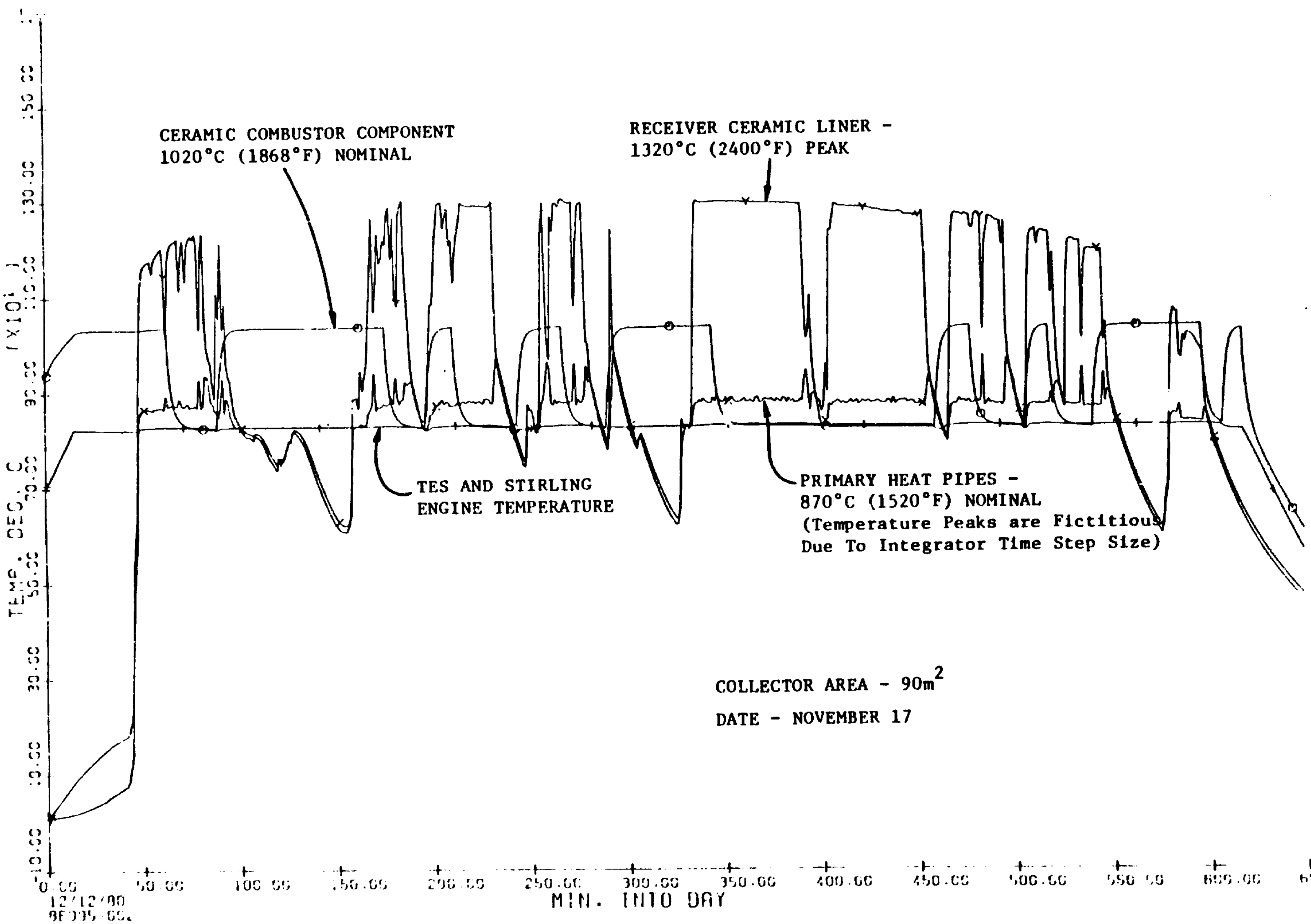


Figure 2-21. Temperature-Time Profiles for HPSR System with 0.8 Hours TES and "On-Off" Combustor On Poor Solar Insolation Day.

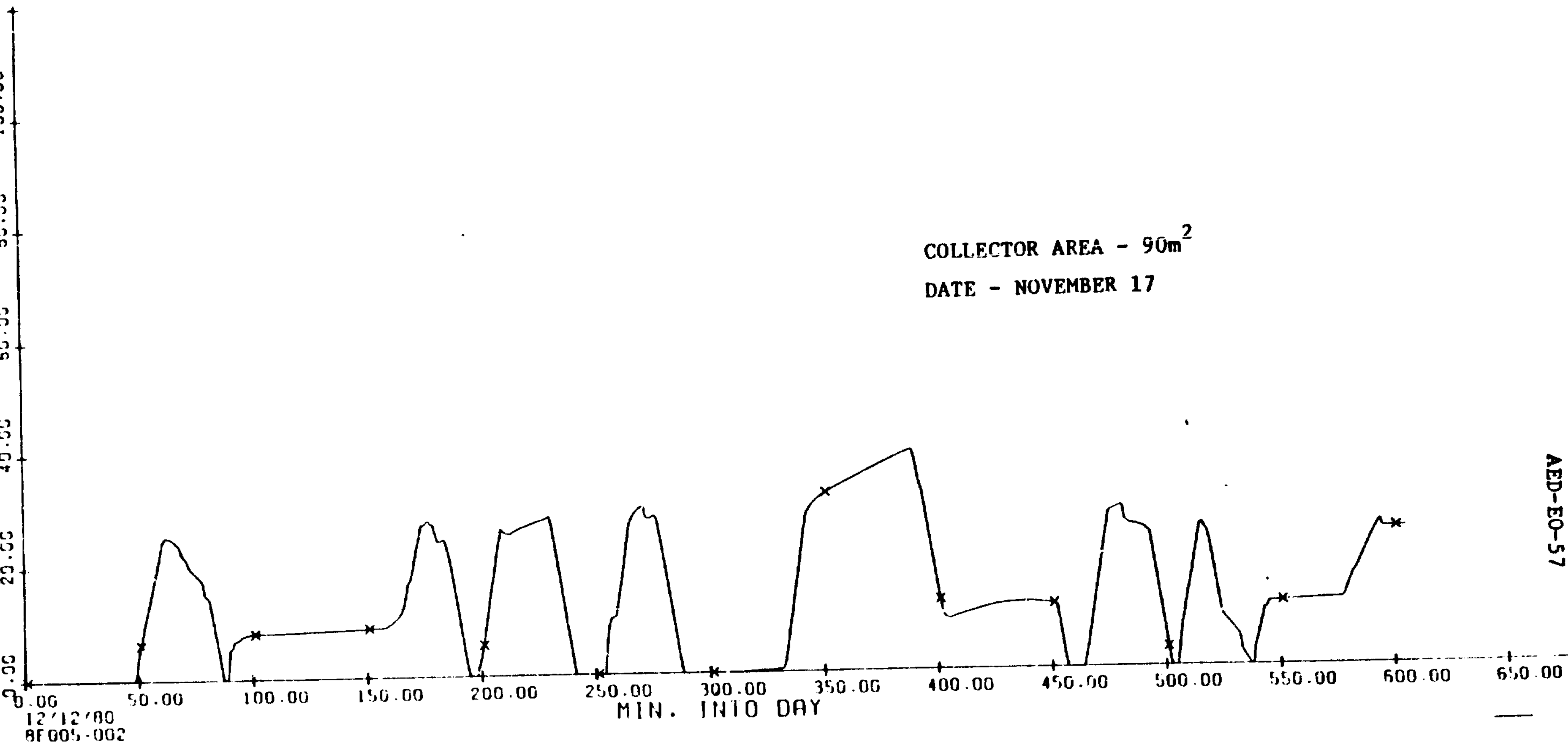


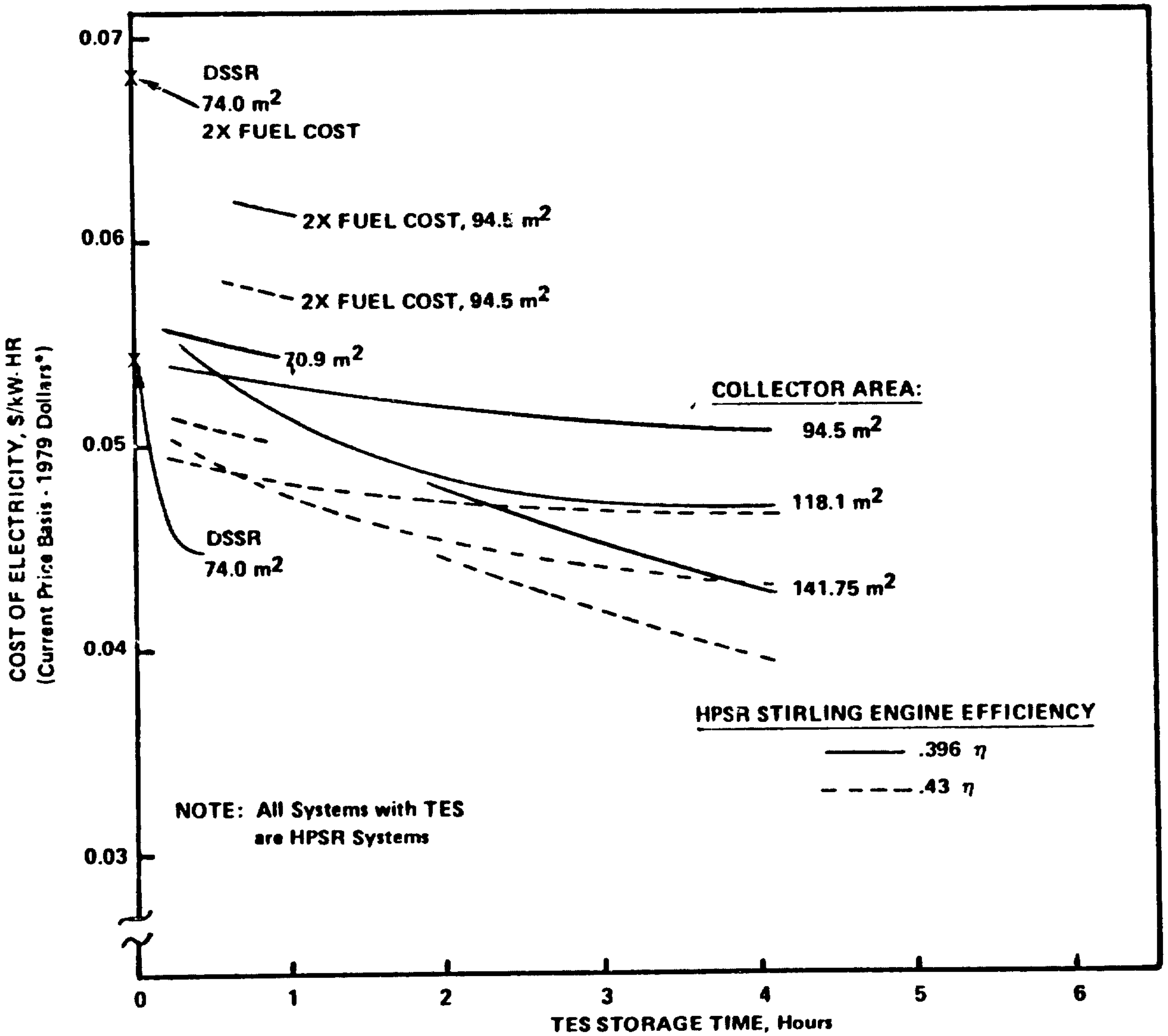
Figure 2-22. Percent TES Charge - Time Profile for HPSR System with 0.8 Hours TES and "On-Off" Combustor on Poor Solar Insolation Day.

insolation. The engine power is maintained by means of TES and the "on-off" combustor. Two artificial engine stops are indicated for the day caused by transient conditions and the single temperature set point for combustor "on-off" operation. Stable power is provided and, as indicated in Figure 2-21, the combustor is fired a total of only nine times during the day to maintain stable TES and Stirling engine temperatures. The temperature peaks indicated for the primary heat pipes are fictitious and are due to the integrator time step size. Since these heat pipe temperature peaks are associated with combustor shutdown and are not associated with transients in solar insolation it is evident that they are spurious in nature. The control assumption that called for turning the combustor "off" just as the TES material began to "melt" resulted in a relatively low average TES charge during the day as shown in Figure 2-22. Operating the system with the TES at a higher charge level would further minimize the number of combustor cycles required during the day but would create the possible necessity for defocusing the concentrator should cloud cover interruptions cease completely. It is evident that much flexibility in control assumptions is possible in optimizing the operation of a system with both TES and a combustor.

In general, the most cost effective amount of TES depends upon the dynamic interaction of the TES with the rest of the system components. The results which have and will be discussed here should be taken as general guidelines for all systems, acknowledging that exceptions may occur.

An overall comparison of cost of electricity results for both systems are shown in Figure 2-23. The thermal energy storage durations for the HPSR were 15 minutes and 0.8, 2 and 4 hours. The concentrator area was varied from 70.9 m^2 to over 140 m^2. The DSSR concentrator was fixed at its design point since TES was not added.

The cost of electricity for the DSSR and the HPSR are similar at negligible TES for the basic case in which engine efficiencies for both are assumed equal. An improvement in the HPSR is shown when its performance at an expected higher engine efficiency is compared with that



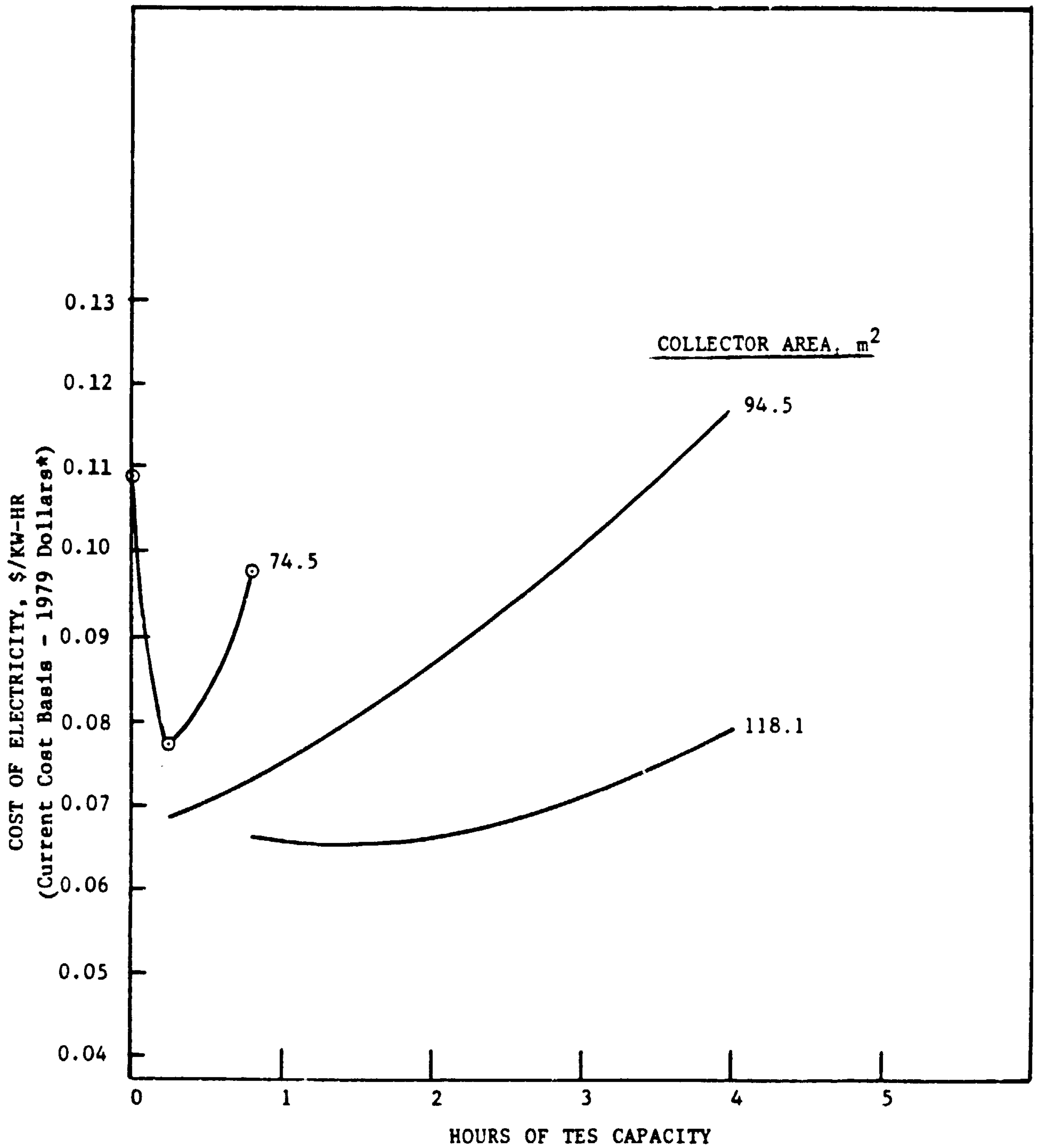
*30 Year Levelized Costs are Higher by a Factor of 2.66

Figure 2-23. Cost of Electricity vs. TES Storage Time for Systems with Combustors of the DSSR. Further differences could be expected to account for the further reduction in engine efficiency expected in the DSSR because of its limitations on the heater head design. Since the HPSR has a larger solar to fossil power input, it utilizes less fuel for the same electrical power output and its COE is less sensitive to increases in fuel costs such as use of deregulated gas or purchase of fuel at internationally competitive prices. Reductions in the COE for the HPSR with increasing TES are the result of greater utilization of solar insolation accompanied by increased concentrator size required to provide additional energy for storage.

Figure 2-24 shows the cost of electricity for the HPSR as a function of TES capacity for systems without a combustor. The cost behavior of systems without a combustor was markedly different from systems that did have a combustor and the effect of collector area was even more pronounced. Principal reasons are the increased utilization afforded by systems with combustors and the effect of certain fixed costs as will be discussed below.

The results of this analysis fall into two categories, depending upon (1) whether the collector is correctly sized, or smaller than it must be to provide, on the average, enough power to run the Stirling engine or (2) whether it is larger than is necessary, and therefore provides a surplus of solar energy.

In the case where the collector is either just large enough or smaller than it needs to be to supply the needs of the Stirling engine over most of the year, the results indicate that only a very small amount of thermal energy storage, 15 minutes or less, should be present for the most economical system since there will be little surplus solar energy to store even as tES is increased. Note that with this small amount of storage, one might consider running the Stirling engine over a temperature band as a trade off for either some or all of the TES. Work was stopped in trying to find greater definition for the effects of limited (buffer) storage when it became apparent that systems without a combustor were not as economical as systems which did have one.



* 30 Year Levelized Costs are Higher by a Factor of 2.66

Figure 2-24. Cost of Electricity vs. Hours of TES Capacity for HPSR without a Combustor.

For systems whose collector area was greater than necessary for just running the engine most of the time, there exists some amount of TES material which, on the average, will be sufficient to store the extra energy. For a collector of 118.1 m^2 this appears to be about 1.5 hours of storage. In any event the cost of the system is still greater than systems with combustors since the fixed costs are not amortized over as large a block of power production. This non-combustor system is penalized by operating costs which are believed to be higher than appropriate, as will be discussed later.

The number of times the combustor was started was counted and is presented in Figure 2-25 using the control assumption that the combustor would shut off after charging approximately 10 minutes of storage time into the TES system. In this case the number of combustor cycles is most strongly a function of the size of the collector since increased solar collection reduces fuel required. The amount of TES had only a relatively second order effect which would become more significant with larger firing times and significantly higher amounts of TES charging. Increasing the combustor firing time above 10 minutes would decrease the combustor cycles but would increase the tendency toward more solar defocusing since the TES capacity would be more nearly filled and, under peak solar insolation, would more readily overcharge requiring defocusing.

For the HPSR, as it is currently being designed with 48 minutes storage time, the average number of combustor cycles would be seven per day. If the day produced relatively good solar insolation, there would be, at the most, only three or four cycles; but if the day produced unreliable solar insolation, there would be very many cycles.

The increase in the number of combustor cycles as the collector size decreased is, once again, due to the fact that at some point the collector becomes too small to run the Stirling engine under the average insolation conditions. Longer combustor firing periods would, of course, help. Here again, temporarily lowering the engine-generator power level would optimize the daily operation of the system and minimize this type of cycling.

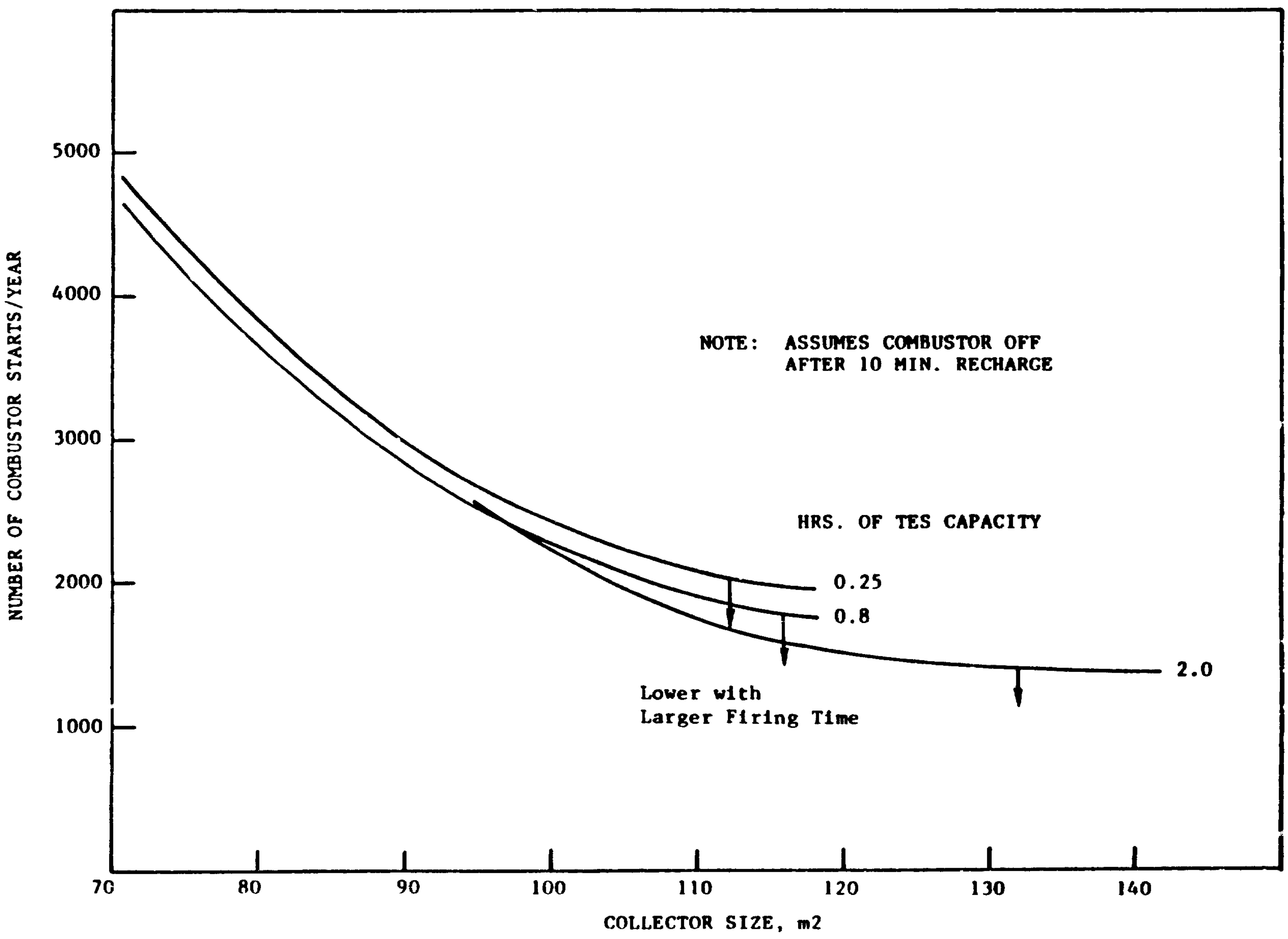


Figure 2-25. Number of Combustor Starts vs. Collector Size for HPSR

Without a combustor, a measure of the number of times the HPSR Stirling engine was commanded to cycle "on-off" is given in Figure 2-26, for various collector sizes and TES periods and for a single engine temperature set point. As in Figure 2-25, there is a knee to the curve, though not so pronounced, at around 90 m^2 and, once again, this is not a strong function of the amount of TES in the system. It is interesting to note that, without a combustor, the HPSR, as it is currently being designed, would cycle the Stirling engine approximately 18,000 times a year. Where the collector area is greater than that required to run the Stirling engine, on the average, systems with smaller amounts of TES would tend to defocus more frequently and to reduce the number of engine cycles. Thus, significant amounts of TES, proper concentrator size and an ability to vary the fixed power level at which the engine-generator runs would improve system operation.

The number of "on-off" cycle commands overstates the actual number of Stirling engine cycles. This is due to the complexity of making an accurate thermal and dynamic model of the Stirling engine. A Stirling engine may be said to have actually cycled when the movement of rotating machinery stops or the hot head of the cylinders goes through some temperature change large enough to adversely affect the life of those parts or the performance limits of the engine-generator. In the first instance, not enough was known about the dynamics of the engine itself to model it to the point where the time at which rotation stopped was known. At times during the analysis the control command was cycling every minute; this is the greatest frequency with which the control routine was called. Under such frequent engine "on-off" commands it is suspected that the Stirling engine would never really stop rotating. Also during these times the Stirling engine head tempeature never varied more than a few degrees around the set point temperature so there probably was no thermal cycling or power fluctuation either. Thus the number of control cycles represents an upper bound on the number of actual cycles of the Stirling engine and, for the control assumptions used, is roughly proportional to the actual number of cycles an actual Stirling engine would go through.

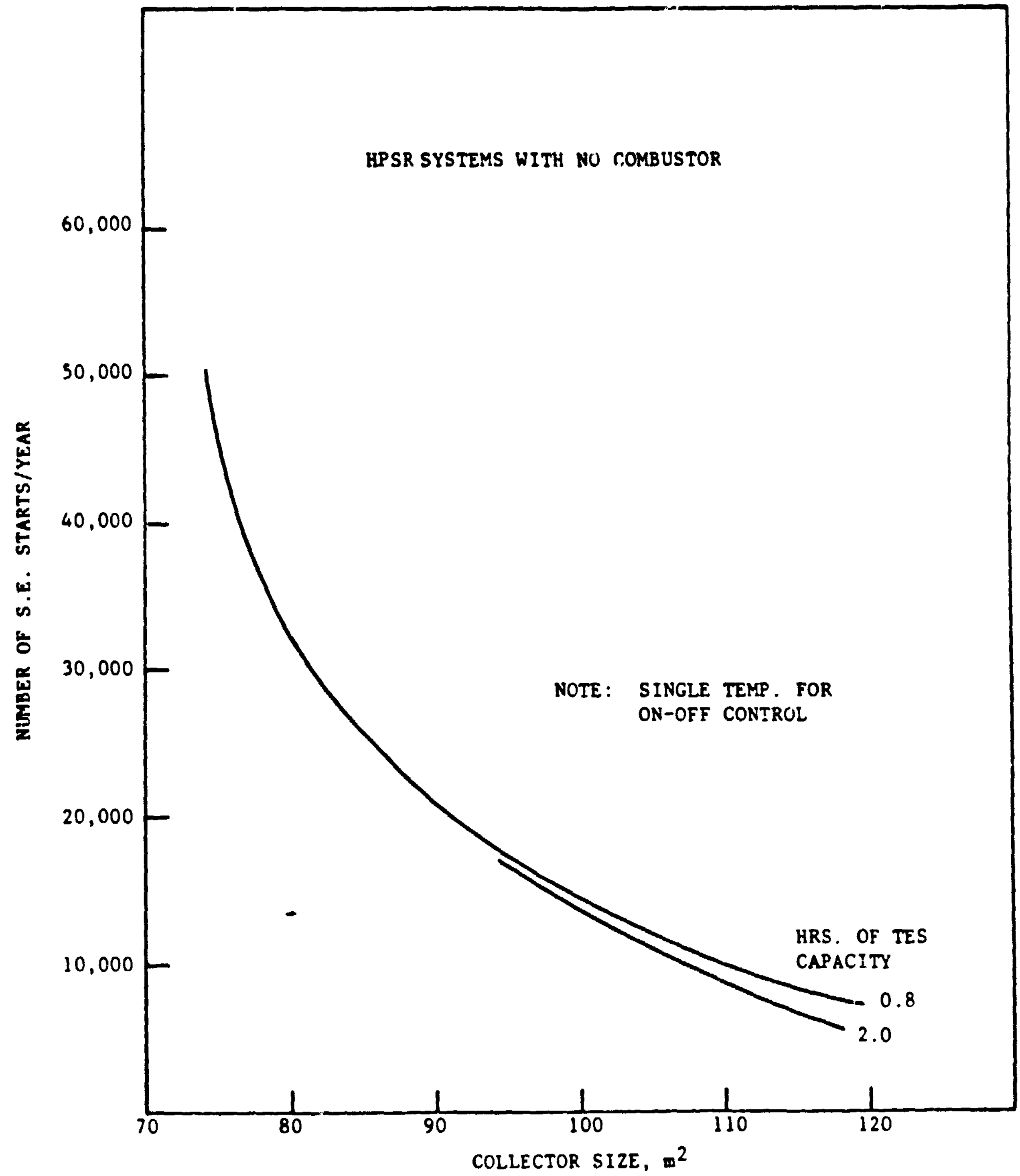


Figure 2-26. Number of HPSR Stirling Engine Starts vs Collector Size

Cycling "on-off" at one set temperature thus accentuates the number of reported cycles and overstates the number of actual cycles experienced by the engine.

Operating the Stirling engine through a wider set point temperature range has the same effect as adding TES to the system since it permits the engine to continue to run on sensible heat in the wider set point temperature range. The effect on the number of control cycles of the Stirling engine as is shown in Figure 2-27 for single temperature set point and for deadband operation. In this analysis two systems with different amounts of TES and without combustors were run through the one day indicated in Figure 2-27 and the number of Stirling engine control cycles were counted. Two control assumptions were tried out on the systems, the first being the single temperature "on-off" point control for the Stirling engine which was assumed at the beginning of the task as the control assumption for the system, and a second control assumption where the engine was started at the high side of a 37°C dead band and not turned off until the bottom side was reached. As can be seen, for this kind of day, parts of which can be found in the majority of the days of the year, a significant reduction in the cycles of the Stirling engine was achieved. Time and funding did not allow more analysis of this phenomena. However, larger TES, higher charge levels and a wider dead band of engine "on-off" control could significantly reduce engine cycling.

Figures 2-28 and 2-29 present the contributions of capital, O and M and fuel costs to the cost of electricity for some selected systems, both as actual costs and as a percent of the total cost. The systems that are presented are: (1) the HPSR as it is currently being designed, (2) the Advanco DSSR as it is currently being designed, (3) the HPSR with the collector sized so it is just sufficient to fill the 48 minute TES on the brightest winter day, (4) the HPSR with 15 minute TES for comparison to the Advanco system, (5) the lowest cost of electricity (4 hours TES, 141.8 m^2 collector) HPSR system and (6) one of the lowest COE HPSR systems without a combustor. The HPSR was not credited with the significant improvement in engine efficiency which is expected because of the

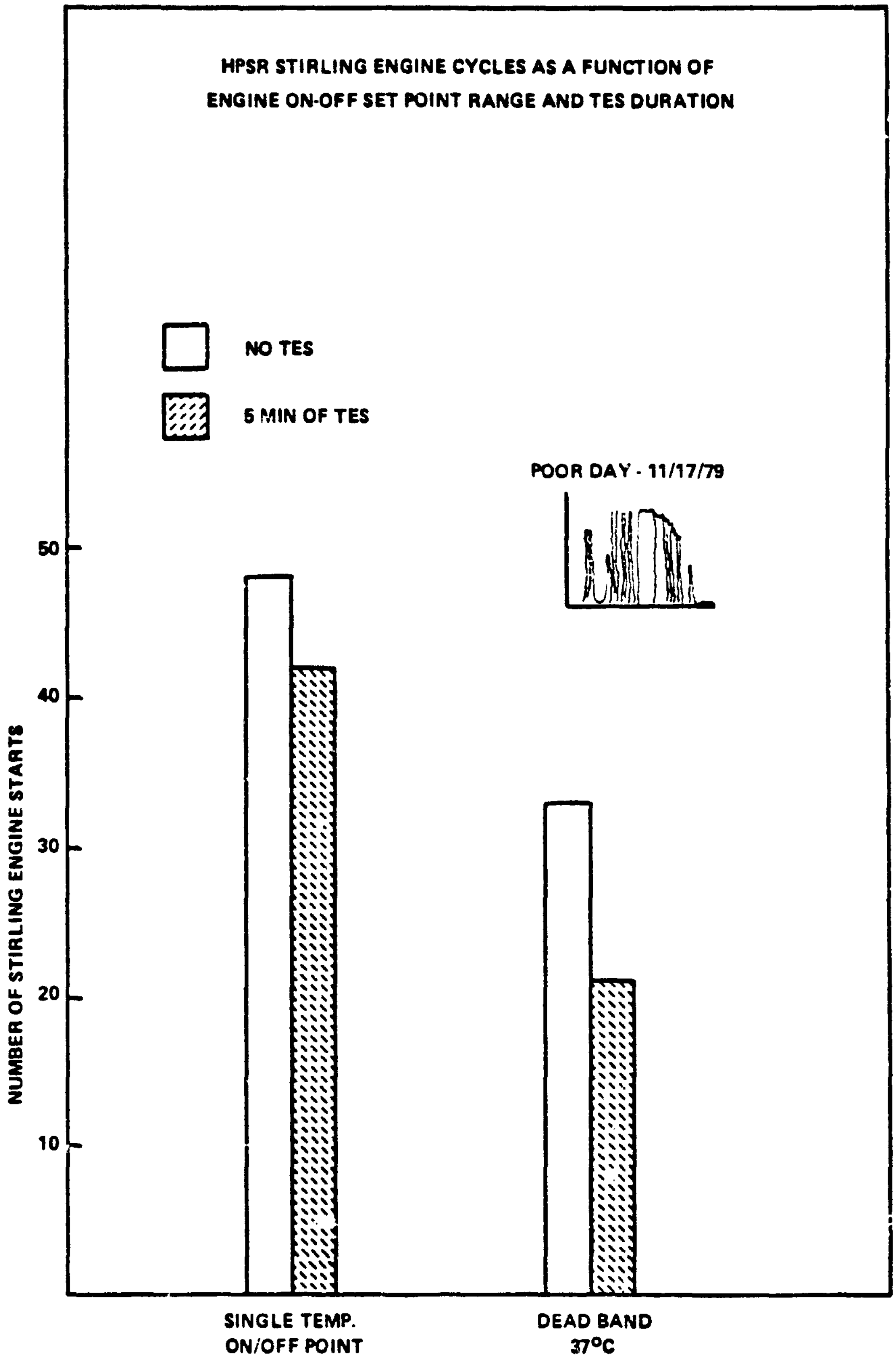
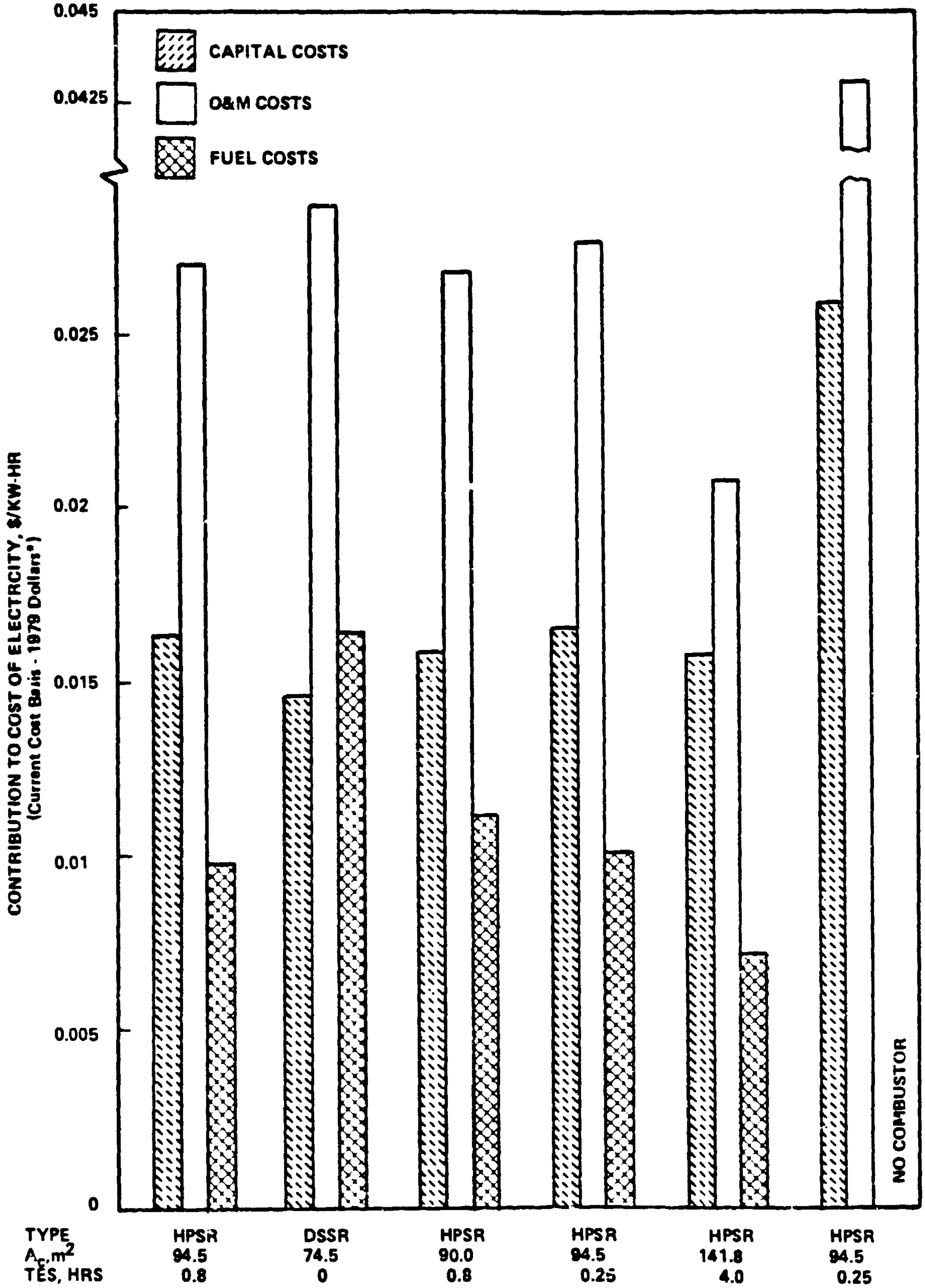


Figure 2-27. Effect of Combustor Dead band Operation on Daily Engine Cycles



*30 Year Levelized Costs are Higher by a Factor of 2.66

Figure 2-28. Capital, O&M and Fuel Cost Contributions to COE for Various Systems

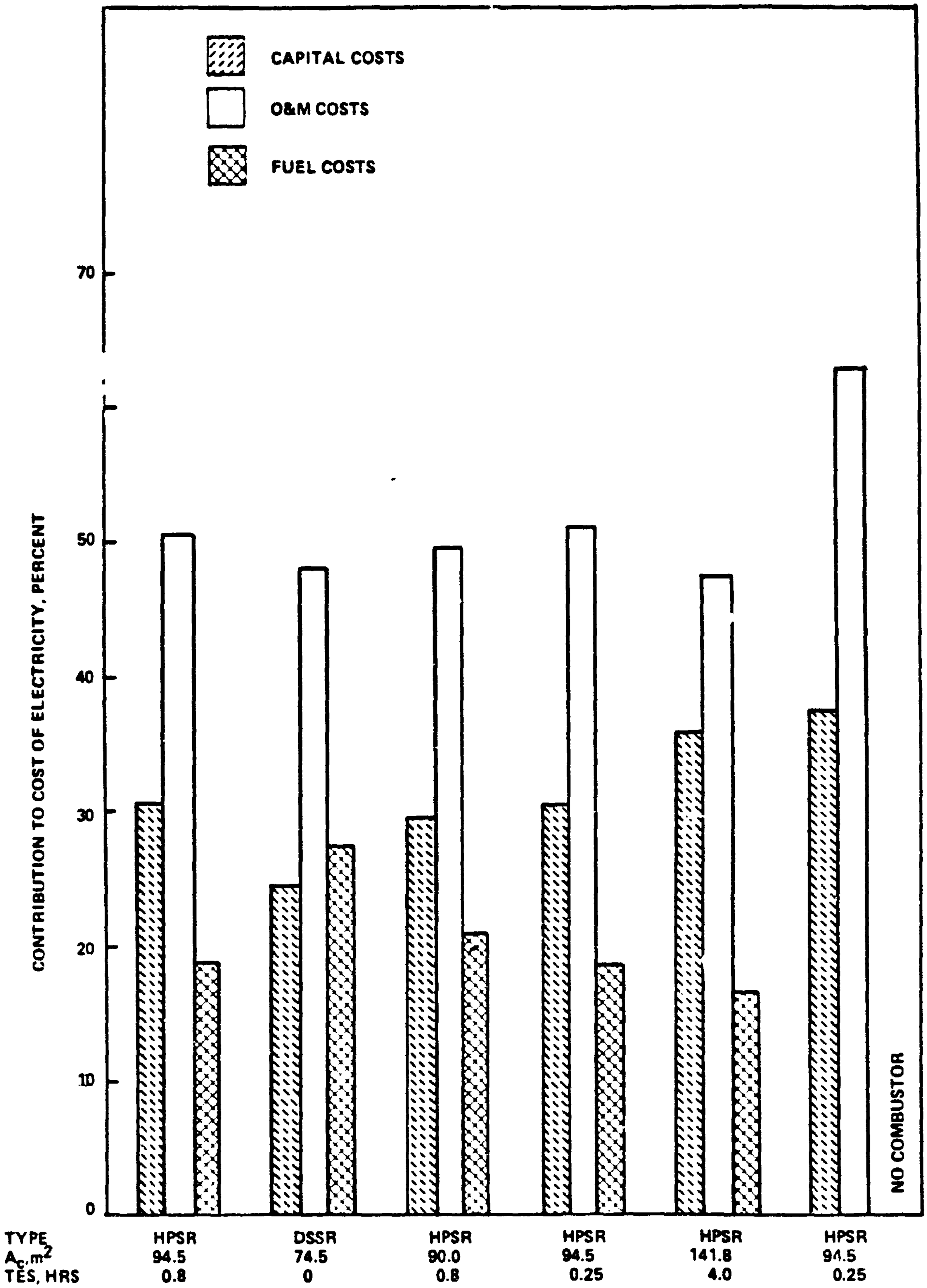


Figure 2-29. Capital, O&M and Fuel Percent Contributions to COE for Various Systems

use of sodium for heat transfer purposes nor was it favorable insensitivity to increased fuel costs considered.

The overall cost is dominated by the large O&M costs for the systems, which make up approximately 50% of the cost of electricity. This is made apparent when the remainder of the costs of electricity are summed, as is done in Figure 2-30. The O&M costs used in this analysis were scaled down from larger (1 MW_e) plant on the basis that each unit developed 25 kW_e. When compared with more conventional power plants, this O and M cost is between 4 and 20 times higher for this study than in a conventional coal or nuclear plant. Furthermore, the difference in personnel to run a 150 MW_e and a 1000 MW_e plant is only about 8, with the number being required to run the smaller plant being about 70*. This shows that for a nearly seven fold increase in plant power, the manpower requirements only increased 11%, indicating plant manpower requirements are a very weak function of plant power, if they are related at all.

Having spotlighted O&M costs as both extremely significant to the overall cost of the systems and having indicated that scaling on the basis of power is questionable, it is pertinent to consider the effect if the O&M costs were very significantly reduced. Figure 2-31 shows the percentage breakdown of the assigned O&M costs for the HPSR as it is currently being designed. Figure 2-30 has presented the cost of electricity without these O&M costs included. It is most significant that the system without the combustor now becomes one of the more attractive systems economically. The investigation of systems without combustors was stopped because the costing method indicated that they would not be as cheap as systems that did have them. Thus, if the O&M cost assumptions made for this analysis are in error, and the O&M costs are, in fact, significantly lower than those used in this study, systems without combustors would be much more competitive than has been indicated here. Since the labor constitutes over half of the COE costs and the opera-

*Guide for Economic Evaluation of Nuclear Reactor Plant Designs, NUS-531, NUS Corporation, Rockville, Maryland, January 1969.

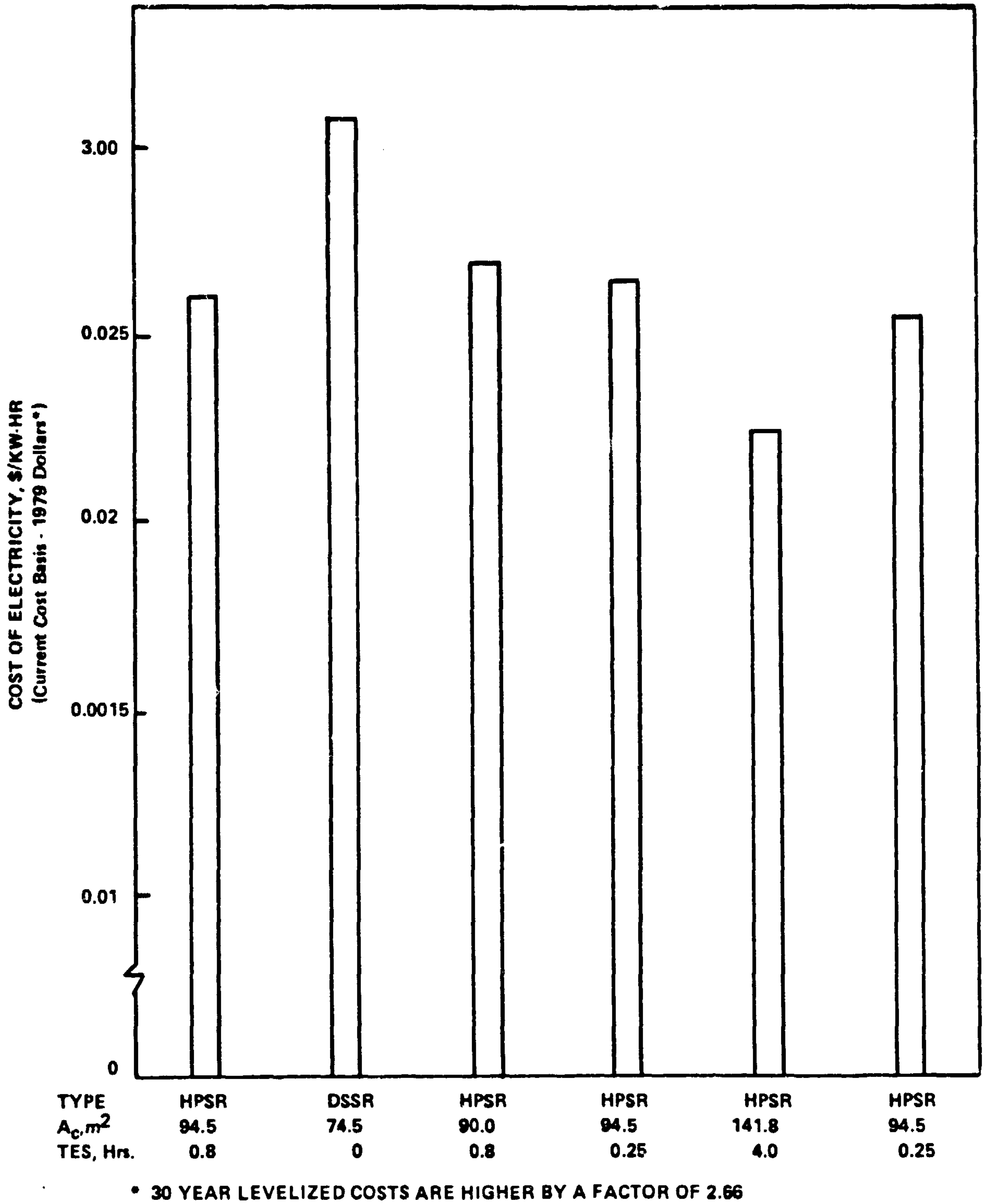
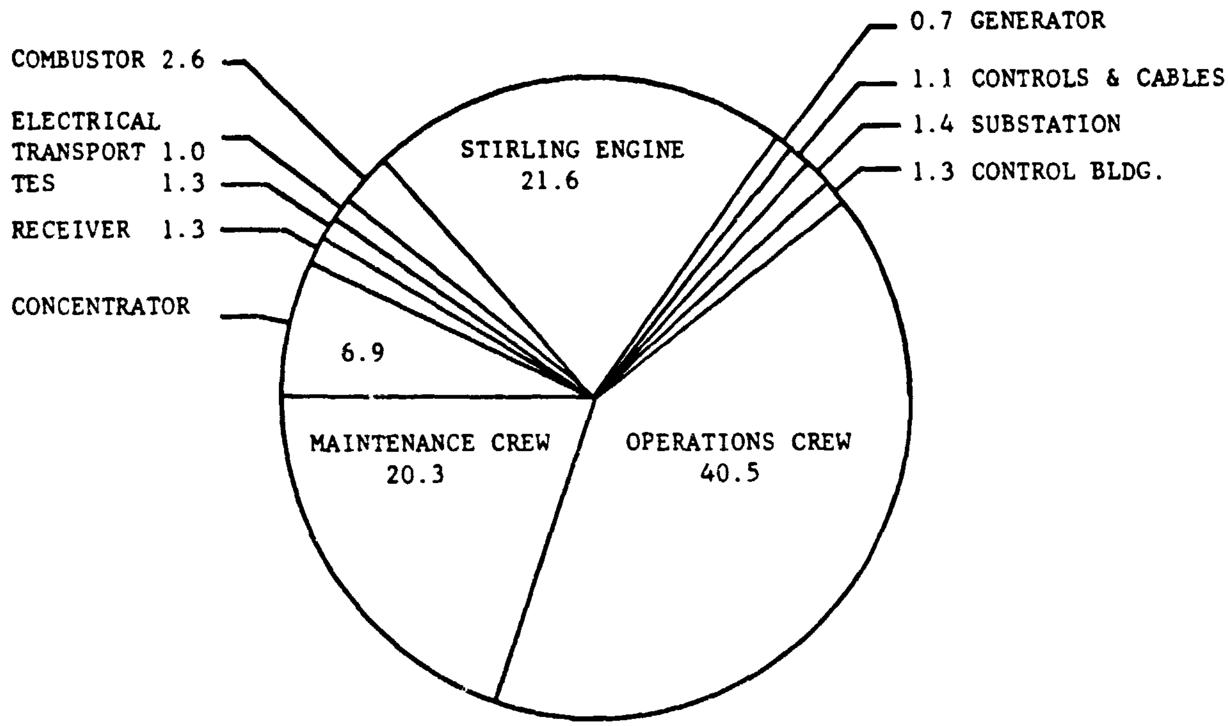


Figure 2-30. COE with Reduced (Negligible) O&M Costs



SYSTEM: HPSR 94.5 m^2 COLLECTOR
0.8 HR. TES
COMBUSTOR

Figure 2-31. O&M Expense Breakdown by Percent tions crew constitutes 2/3 of the labor total reduced operating manpower requirements for solar systems would work to the advantage of the non-combustor systems.

E. DEVELOPMENT REQUIREMENTS

A consideration of the further development of the DSSR direct receiver and of the Heat Pipe Solar Receiver provides a basis for reviewing possible avenues of further potential developments and improvements in the receiver and thermal storage areas.

1. Direct Receiver Development Requirements

The DSSR direct receiver, operating with limited inherent sensible heat TES and supported by a gas fired combustor, is flexible in design capability and in operation. Since the combustor is potentially capable of providing thermal energy under varying solar insolation conditions, it can operate continuously, utilizing all available incoming solar energy and it is not required to rely upon thermal energy storage nor can it be forced to defocus. The addition of buffered thermal energy storage, however, would be warranted as a development requirement under two conditions; namely inability of the combustor to meet its control objective and the possible advantage of using "on-off" combustion.

The first condition for development of additional TES capacity would involve unexpected initial solar operating test results which might indicate the combustor could not maintain a sufficiently stable operating temperature within the copper cone receiver and in the Stirling engine heater head. In this case some additional buffered storage would be neccessary to ease the combustor control and system thermal response demands necessary to assure reasonable constant operating temperature.

In the present design concept or with the addition of limited sensible heat buffer storage the power conversion system could be operated flexibly, with the DSSR receiver, over a wide range of solar inputs and over a range of heater head engine temperatures from 1300-

1550°F. Thus the system would not be limited to a fixed operating temperature as would be the case if a latent heat TES were used. Operating the DSSR receiver at higher engine heater head temperatures near 1520°F results in high temperatures in the solar receiver. Local surface temperatures may reach a peak temperature of 1835°F as indicated in design studies, but lower surface temperatures have been calculated when design compromises are made by increasing the heater tube lengths. Unfortunately, this increases the engine working fluid void volume and pressure drop which results in decreased engine efficiency. In the present DSSR receiver and Stirling engine system, the Stirling engine has been credited with an efficiency of 39.6 percent which is equivalent to the efficiency of the fuel fired automotive version of the Stirling engine; a recalculated efficiency has not been reported for the DSSR receiver and the actual efficiency may be significantly less, perhaps in the 35-37 percent range. The key to improving this efficiency lies in freeing the heat exchanger configuration from the limititations of combustor and solar heat input surfaces. This has been accomplished in the HPSR using the effective thermal transport of alkali metal heat pipes. Modification of the DSSR receiver to achieve more effective heat transfer, such as by the addition of heat pipe concepts within the receiver cone, would be a helpful development.

Other heat transfer aspects to the DSSR receiver and the possible developmental addition of TES are the potential for high receiver surface temperatures and the materials and processes limitations which such high temperatures present.

Present solar receiver surface temperatures in the 1600-1835°F range would be increased by the addition of latent or sensible heat TES material to the face of the receiver as indicated earlier. Such increases in surface temperature would crowd the operating temperatures more closely toward the melting point of the braze used to assemble the receiver to the Stirling engine heater head (~ 1900°F for braze alloy AMS4777) and towards the melting point of the copper cone, itself, (1981°F). At high heat fluxes and under thermal cycling of the heat receiver surfaces (INCO 617 alloy brazed to the copper surface) thermal fatigue, thermal ratcheting within the copper and debonding of the braze joints become possibilities with life being more severely limited as the engine operating temperature increases toward 1520°F and receiver temperatures approach 1800°F. The use of copper casting methods to provide the high conductivity medium between the solar receiver surface and the heater head tubes and the use of hot isostatic pressing to achieve a diffusion bond (in lieu of a braze bond) between the copper and superalloy components are both favorable future developments which may be warranted or required. From a life viewpoint the current system can be demonstrated with expected long life in the 1300°F engine operating temperature range and much less life (but performance demonstration, nonetheless), as the engine temperature is increased to 1520°F. With the addition of TES on the solar side of the receiver cone, ΔT across the salt increases the surface temperature and, aggravates these materials problems further. The ΔT on discharging the TES will also result in reduced engine operating temperature and reduced efficiency. It is doubtful whether any significant latent heat TES could be added to the cone surface in future developments unless the engine operating temperatures were significantly reduced.

A second condition for the addition of TES to the DSSR receiver in future developments would involve sufficient TES to permit the use of an "on-off" combustor. This would provide this receiver with certain advantages similar to the HPSR receiver; namely, increased ratio of solar-to-fossil-fuel power. Since the combustor need not operate continually at 10 percent or more of its total power, the system's solar concentrator could be enlarged and only the use of supplemental fuel would be required to replace the solar insolation shortage through "on-off" combustor recharging of the TES. The amount of TES required to minimize combustor cycling could be analyzed in a fashion similar to that which has been done for the HPSR.

The method of achieving added TES would probably require the development and addition of heat pipes (or other efficient thermal transport) to provide an extended surface area and volume of TES material for energy storage and transport with a minimum ΔT; while this would improve the solar energy utilization of the DSSR receiver it would not achieve, in itself, the increased engine efficiency associated with condensing

ing sodium heat transfer at the engine heat exchanger. Nor would it achieve the reduced thermal power input requirements and more efficient TES utilization inherent in a higher efficiency engine. The DSSR system, thus revised, would also face the possible necessity for defocusing should the thermal storage capacity be exceeded under high solar insolation periods.

2. Heat Pipe Solar Reiver Development Requirements

The HPSR, as presently conceived, provides both thermal storage and combustor capabilities. These permit the use of "on-off" combustor power to maintain the TES charge and to avoid the necessity for continuous fossil fuel combustion. Its thermal transport option (1) provides heat transport with small ΔT's which prevent high receiver metallic component temperatures, (2) makes its receiver more efficient through controlled reradiation losses and (3) minimizes higher temperature materials problems; it also provides efficient thermal transport to and from large surface areas and volumes of TES material permitting more extensive energy storage with little system temperature drop and relatively low ΔT across the latent heat TES material. This enables longer storage periods and a higher degree of solar utilization. In addition, heat flow is self regulating without complex fluid pumps, valves, sensors and controls. Finally, the highly efficient, hot-side heat transfer coefficient at the Stirling engine permits engine heater head redesign for increased engine efficiently; this, in turn, results in lower power input requirements and increased stored energy duration for a given storage system.

While the above advantages of the HPSR are apparent, future developments can result in further improvement in system performance, operating life and cost. Several opportunities are evident.

The present study indicates lower costs of electricity can be achieved for a given power unit if the concentrator size is enlarged and the TES storage time is increased to a size appropriate to the concentrator, engine and solar insolation condition. Cost parameters for concentrators do not currently incorporate the cost effects of variable focal point mass at various concentrator sizes. More accurate cost projections in this area would permit the continued performance and economic evaluation or re-evaluation of focus mounted HPSR/TES/Stirling engine-generator systems with greater solar to fossil fuel capability including swing load analysis, and load matching, both on an individual concentrator basis and upon the basis of multiple concentrator power conversion systems with programmed release of stored energy from individual concentrator systems. The need for this work is not immediate, but the results could aid in the evaluation of long term merits of focus mounted thermal storage.

A most significant development opportunity lies in the area of cost reductions and reliability demonstrations in the thermal transport and storage areas.

Heat pipe long term operating life and reliability and cyclic performance characteristics can be demonstrated in heat pipe life tests under temperature and other test conditions appropriate to system designs. Testing of this type is not limiting the initial demonstration of prototype systems but would be effective in demonstrating satisfactory life, selection of most economical materials and extension of heat pipe technology to higher temperatures.

Thermal transport in the secondary, TES heat pipe is dependent upon capillary pumping of liquid sodium to various portions of the primary heat pipe condensers, TES salt containers and combustor heat transfer surfaces. The system is arranged such that all liquid metal flow is basically gravity assisted, but liquid metal must be sustained in capillary wicks at various required heads. The current design is based on sound capillary pumping and liquid flow considerations and redundant wicking methods are used including arterial, composite and conventional wicking with wire screen. The elimination of redundant wicking, the verification of fluid flow across relatively simple wick joints and the development of lower cost wicking materials and methods of applying wicks will be necessary as prototype development continues. The experimental proof of new wicking concepts and materials can be conducted under single modular experiments as will be discussed next. Powder metal sintered wicks, diffusion bonded composite wicks and flame sprayed composite wicks are potential areas for development with improved reliability and low manufacturing cost as goals.

Also in the area of heat pipe thermal transport in TES systems, further creative design thought should be given to more effective use of gravity return of liquid metal condensate to minimize reliance on wicking. The locallized use of weirs to maintain pools of liquid metal above wicked heat sources is a possibility which has been considered and discarded, for the moment, for a seemingly valid reason; either the pools only provide liquid while they are overflowing or, if they contain a wick leading downward to a heat source, the wick could drain the pool to a lower level unless the wick has the capillary pumping power to maintain the head at the upper pool height. The use of local pools and of discrete and individual wicking systems operating from those pools could break the system into smaller wicking units with lower capillary pumping requirements and, thus, permit simpler and coarser wicking characteristics and lower wicking costs. This general concept is being partially implemented in the first HPSR prototype design in the TES area; the TES is divided into two zones in which the upper is fed by gravity from condensate from the engine and the lower is fed from the lower liquid pool. Each wicking systems can maintain liquid sodium in the wicks at the highest capillary pumping height required within that system; however the upper, gravity-fed system is simpler in concept and cost for equivalent sodium flow rates. The extension in the development of such compartmentalized wicking concept can be studied and evaluated in TES modular experiments.

Further development requirements of a much less immediate nature include improvement in the capabilities of the TES heat storage system itself. Specific needs here encompass the following. First, more accurate thermal and physical property data on selected latent heat salts are essential to improved design accuracy. This would include (1) latent heat, (2) the specific heats and thermal conductivities of liquid and solid phases, (3) volume change on solidification and (4) liquid and solid densities near the salt melting point. Secondly, while some corrosion and materials compatibility tests have been conducted by others in the area of high temperature fluoride salts, much additional long life and cyclic testing of specific TES salts and their containment configurations should be conducted on appropriate designs under required test environments. Thirdly, design and materials improvements in the salt containment and load support structure are needed to improve the weight, volume and cost efficiency of the TES system. This effort might include such items as use of low cost ceramics for containment and structural support, use of section stiffened support plates to accommodate the axial TES loads at the ends of the TES cylindrical cannisters and use of larger diameter containers (with commensurately higher ΔT across the solidified salt). The objectives of these are to increase the ratio of TES salt weight to that of the non-salt items in the TES system. Fourthly, modifications in the configuration of the TES salt containment itself may be possible for the purposes of (a) improving conductivity of heat from the salt, (b) reducing the temperature gradient through the salt, (c) improving the packing density of the salt containers (d) improving the method of transferring salt weight loads to the TES shell, (e) facilitating use of larger volume salt containers without increasing ΔT across the solidifying salt and (f) effecting [illegible] of salt containment. The above may be accommodated by uniqu[illegible]igurations, by the incorporation of thermal conductivity enhancement materials in various forms within the salt and by the selection and use of alternate materials. Some current effort, sponsored by JPL, is being conducted currently at a separate source on salt container configuration and thermal conductivity enhancement.

3. Common HPSR Development Requirements

Certain future development requirements are common to both the above systems. Of particular value would be the continued evaluation of these systems using the data base, thermal analysis program and economic analyses methods, so painstakingly developed under the current study. The evaluation of performance and cost characteristics of these systems with TES and "on-off" combustors utilizing maximum solar-to-fossil power ratios under alternative control and engine power assumptions would provide a more complete understanding of system operating potentials. Since the concentrator should be sized to accommodate TES charging requirements at some typical daily solar insolation input, alternative levels of solar insolation would either require occasional extensive operation of the combustor or varying requirements to defocus the concentrator. A more intensive study of assumptions regarding combustor operation, concentrator defocusing and engine power would aid in defining those system characteristics which require modification in order to permit most reliable power production with a minimum cyclic effect on the engine, receiver and combustor. For example, by varying the engine power on a seasonal or daily basis (depending upon the solar insolation characteristics) defocusing might be eliminated and combustor cycling and fuel utilization might be minimized.

While all the above development requirements relate to the application of TES to a distributed concentrator solar Stirling power conversion system, development efforts of the above type would prove beneficial in the use of high temperature thermal energy storage for other applications as well.

F. MODULAR EXPERIMENTS

Modular TES experiments serve the useful purpose of providing, at relatively low cost, proof of new design concepts and engineering performance data on thermal transport and thermal storage systems. One such modular experiment, as shown in Figure 2-32, was fabricated and conducted under a separate task of this contract. Its brief description here is intended to illustrate the type of subscale engineering experiment which can be conducted and the nature of the results which can be obtained. A full report on this subject will be prepared at the conclusion of the present contract.

The above modular experiment simulated the TES thermal performance and heat transfer characteristics of an earlier HPSR system which was designed to operate with a total of 728 pounds of NaF-MgF_2 TES storage

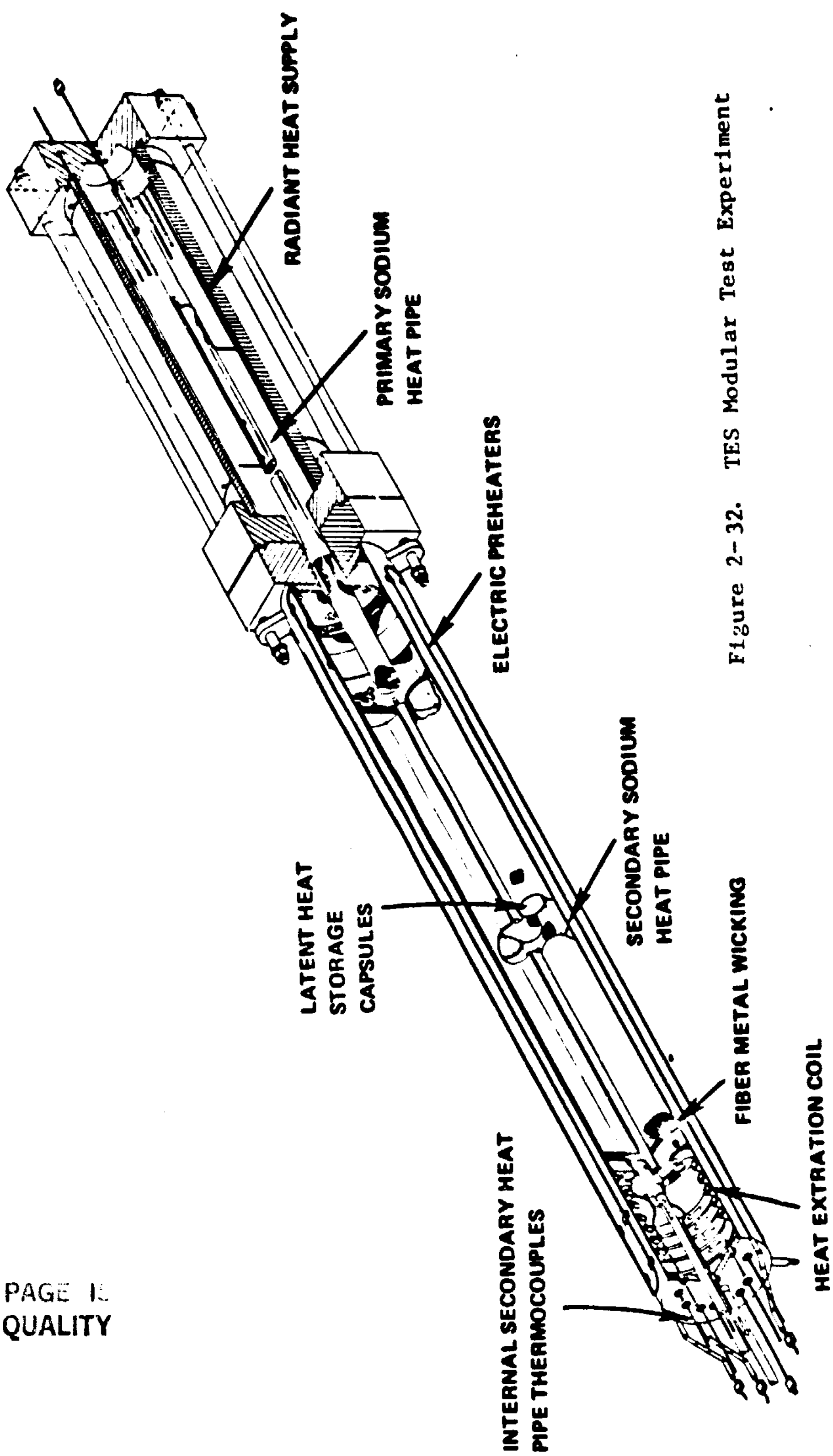


Figure 2-32. TES Modular Test Experiment

material in containers approximately 2 inches in diameter and 26 inches in length. This system provided approximately 1.25 hours of latent and sensible heat storage at 52.5 kW_t.

The modular experiment was designed to operate at the same heat flux on the surface of the TES containers as the design of the full system. Thus, charging and discharging of the system and its thermal response would approximate that of the original design. The salt containers were 2 in. OD x 26 in. long AISI Type 321 stainless steel. Three of these salt containers, each containing 5.65 pounds $NaF-MgF_2$, were enclosed in a 5 in. OD x 40 in. long AISI Type 316 stainless steel secondary heat pipe. A conventional HPSR primary heat pipe introduced heat into the secondary TES heat pipe at one end and an air-cooled condenser extracted heat at the other end. The surfaces of the secondary heat pipe, of the condenser of the primary heat pipe, and of the salt containers were wicked with wire mesh screens. The forward end of the heat pipe and the ends of the salt containers were wicked with sintered wire wicks. An exploded view of these components prior to initial assembly is shown in Figure 2-33. The capabilities of the system and the extent of instrumentation are indicated in Table 2-14.

The primary heat pipe/secondary TES heat pipe test module was installed within a thermal insulation system with provision for measured electric heat input to the primary heat pipe, energy calibrated heat extraction by means of preheated cooling air and extensive thermocouple instrumentation for both thermal performance measurement and thermal conductance heat loss calculation. The system was capable of being tested at various operating angles and under heat throughput, TES charging alone, TES discharging alone and various mixed modes of operation.

During testing, the system operated satisfactorily at all operating angles and in all conventional and mixed modes of thermal transport and storage. Typical charging and discharging characteristics are indicated in Figures 2-34 and 2-35.

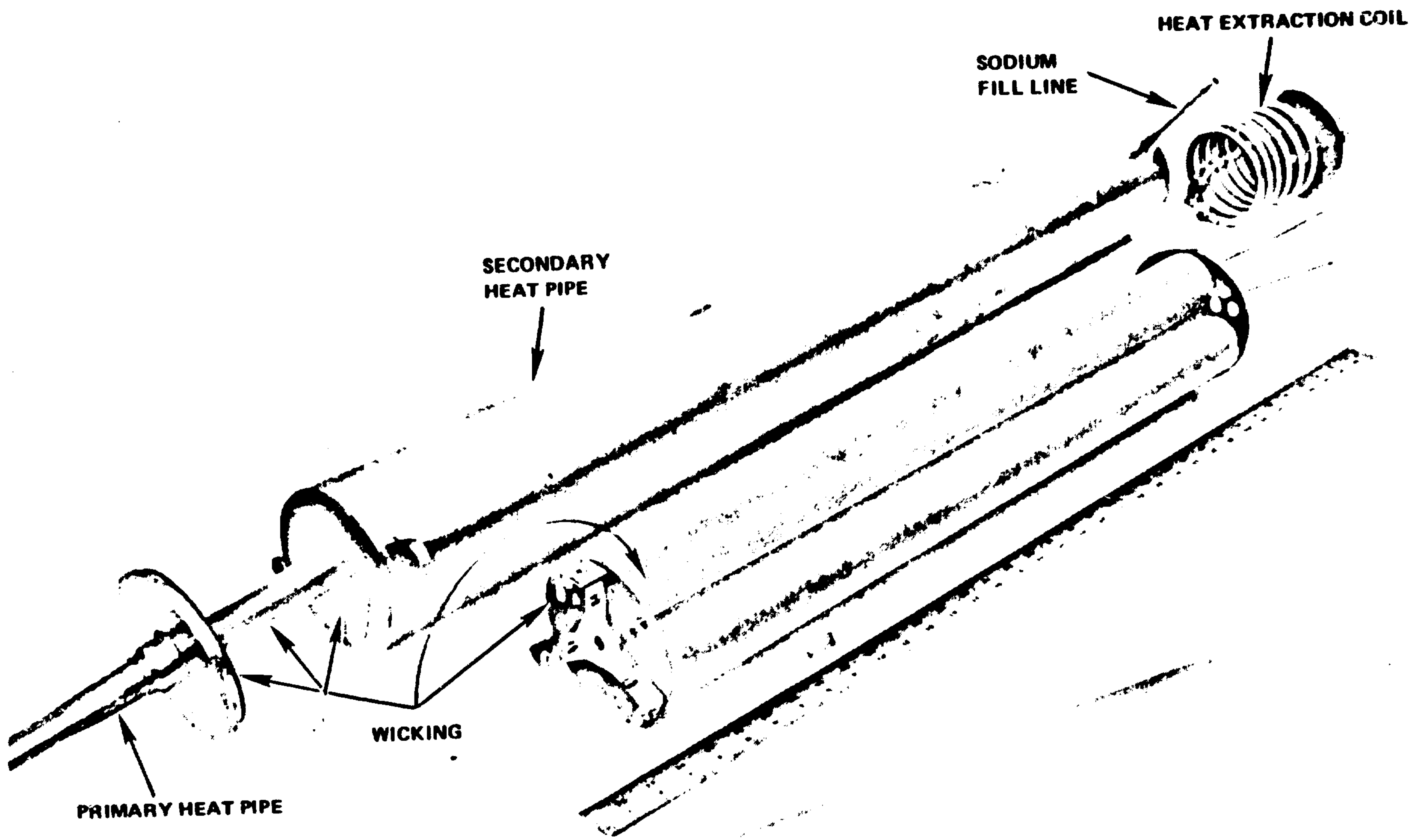


Figure 2-33. Exploded View of TES Modular Experiment Components Prior to Assembly

TABLE 2-14

TES MODULAR TEST CAPABILITIES

Primary Heat Pipe

6 kW_e Electric Power Input Capability

4.43 kW_t Rated Power at 1550°F (14 Heat Pipes for 62 kW_t)

2.3 kW_e Rated Power at 1550°F (27 Heat Pipes for 62 kW_t)

Evaporator Area Wicking Only, 60 Mesh Screen

Secondary Heat Pipe/TES

Rated Power of TES; 1.04 kW_t

Rated TES Storage; 1.304 kWh_t

Storage Duration at Rated Power; 1.25 Hrs.

Cylinder Wicking; 3 Layers, 200 Mesh + 3 Layers; 150 Mesh

Header Wicking; 1/8 in. Feltmetal 1108

Capsule Support Wicking; 1/16 in. Feltmetal 1103

TES Capsules; 2 Layers, 200 Mesh

Instrumentation

Primary Heat Pipe Evaporator; 5 TC's

Primary Heat Pipe Condenser; 1 TC

Electric Heater; 4 TC's

Secondary Heat Pipe Vapor Areas; 2 TC's

Secondary Heat Pipe OD; 12 TC's

Capsule Interior; 3 TC's

Capsule Exterior; 3 TC's

Cooling Coil Inlet, Outlet; 2 TC's Each on Vapor Side

Outer Cold Shell; Approx. 23 TC's

Power Input; Voltage/Amperage

Power Output; Air Mass Flow and ΔT

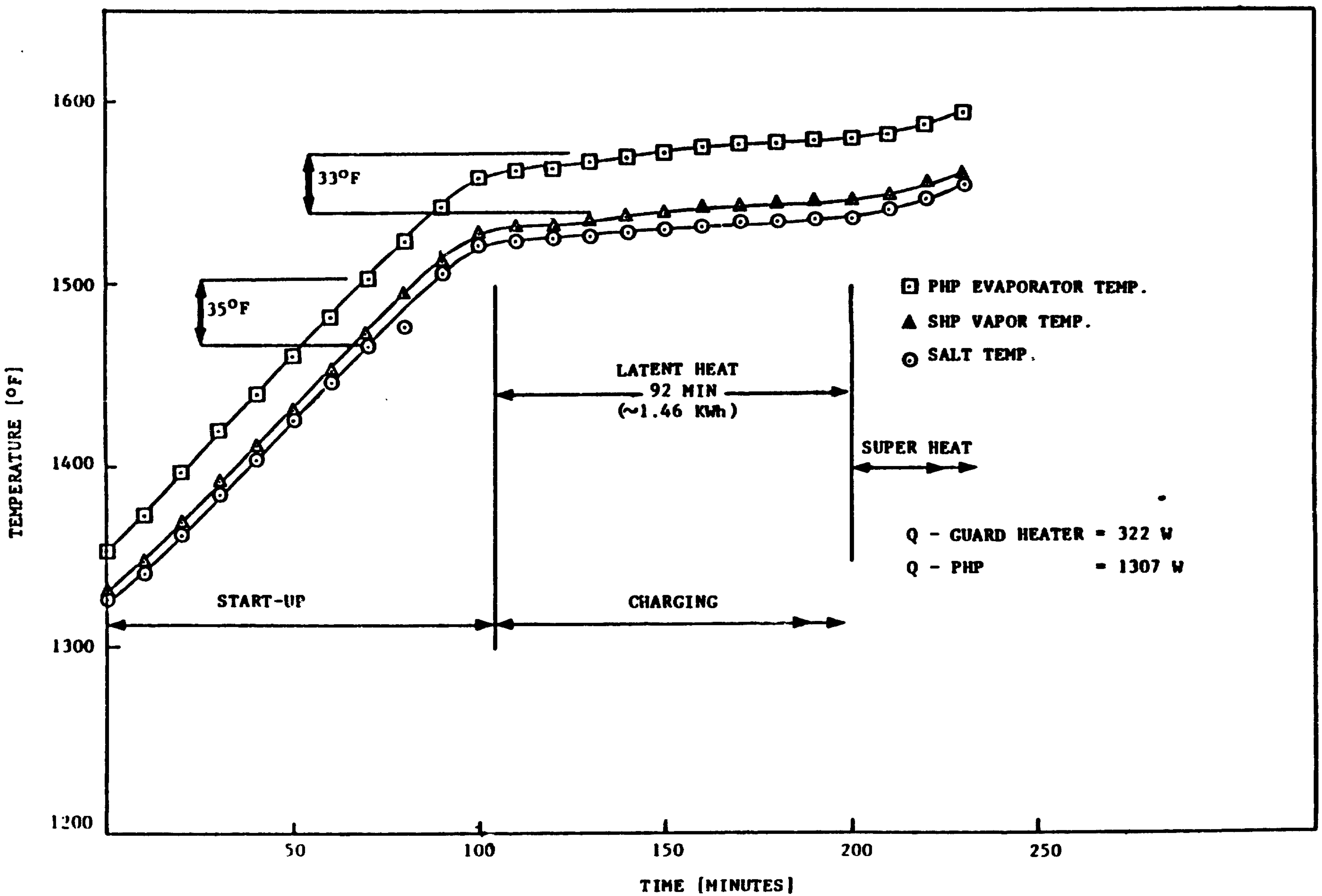


Figure 2-34. TES Start-up and Charging Cycle

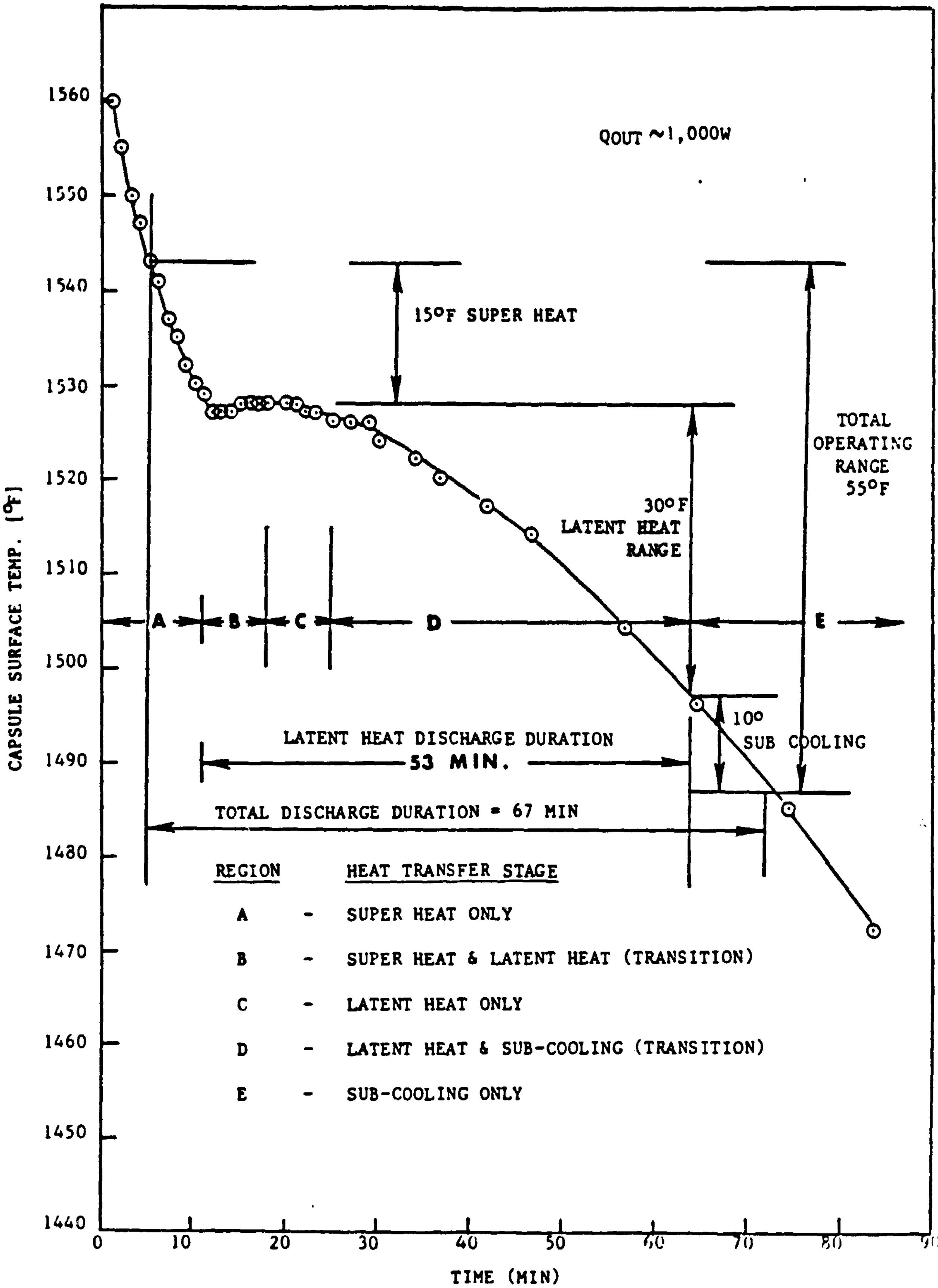


Figure 2-35. Secondary Heat Pipe Vapor Temperatures during TES Discharging.

The system demonstrated effective thermal transport, isothermal secondary heat pipe operation within the accuracy of thermocouple readings, a relatively low temperature drop across the heat pipes and lower-than-anticipated maximum ΔT across the solidified salt. The thermal inertia of the TES system was excellent in the latent heat range and, even in the sensible heat range, the temperature change did not exceed 2°F per minute. The results of the modular experiment helped to provide a sound basis for the thermal performance analysis of the presently proposed HPSR prototype design for which predicted performance characteristic have been described in Section II-B-2 of this report.

While the thermal response of the TES system, and its charging and discharging conditions were clearly characterized and the thermal transport capabilities were demonstrated in the above experimental effort, additional modular experiments are warranted for several reasons, both immediate and developmental in nature. Near-term modular experiments could be used to confirm and improve exiting design concepts and later developmental experiments could be used to develop design inovations.

Possible modular experiments of value in the development of TES systems for the DSSR and HPSR systems are discussed below.

1. Direct Receiver Modular Experiments

As discussed under Section II-C-1, TES can be added either directly to the copper receiver with the requirement for high flux heat transfer over a limited area, or it can be added at a removed location which requires thermal transport by conduction, radiation or thermal transport in heat pipes.

In the first case the high heat fluxes lead to large ΔT's across the solidified salt and, to minimize this, the salt film thickness and TES duration must be minimal. Possible improvements in this situation might be made through the introduction of conductivity enhancement within the salt. Such conductivity enhancement methods might also be incorporated as a part of the salt containment structure on the face of the receiver; the use of salt filled metallic honeycomb or finned structure to fulfill the containment and conductivity enhancement functions is an example. The honeycomb or fin material should have high hot strength, excellent thermal conductivity and an ability to be fabricated with joint strengths appropriate to the higher hot face temperatures expected as the result of ΔT across the salt. Use of alternative materials such as molybdenum for honeycomb or fins with a compromise in strength and conductivity (as compared to copper) is a possibility. The requirement for oxidation resistance and the need for joining dissimilar materials is a further consideration. In addition, the necessity, for, and difficulty of, filling the honeycomb or finned passages with salt must be considered. The ability to achieve all these requirements in a practical design represents a serious engineering challenge.

A concept for such a modular experiment is indicated in Figure 2-36. The required high heat fluxes into and out of the module are significant factors to consider in setting up the module and in assessing the validity of the concept itself. A gas fired burner or radiant heat flux from a high temperature heater such as molybdenum or graphite would be required as would the use of a protective atmosphere for the electric heater. Heat extraction from the simulated heat receiver cone would require cooling by high pressure, high velocity gases (as in the Stirling engine, air impingement cooling on the rear face or heat removed by means of a flat heat pipe in the back surface of module with controlled heat removal from the heat pipe. Under such high heat fluxes the possibilities are high for local overtemperature and/or cyclic fatigue of the face of the receiver heat exchanger in the event the liquid or solid salt did not maintain intimate contact with this heat transfer surface.

A modular TES experiment for the direct receiver in which buffered or larger quantities of TES could be remotely located from the receiver heat exchanger and serviced by heat pipes is indicated in Figures 2-37 and 2-38. A flat rectangular or flat sector type module is shown which for simplicity could represent the cone/cylinder design discussed in Section III. The same methods discussed above of applying heat to, or rejecting heat from, the module are applicable. However, the receiver,

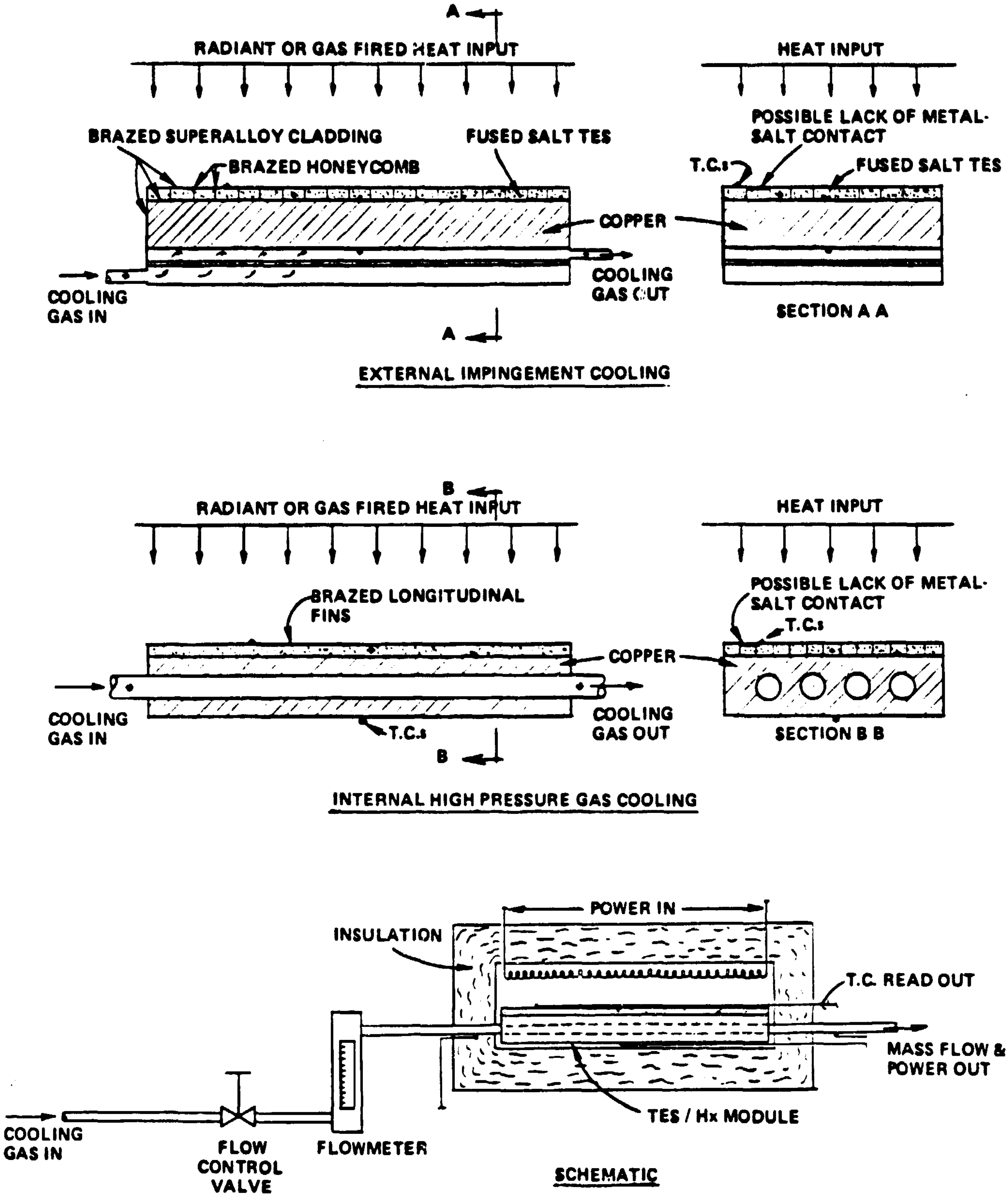


Figure 2-36. Rectangular Flat Plate Modular TES Experiment Concepts for DSSR Receiver

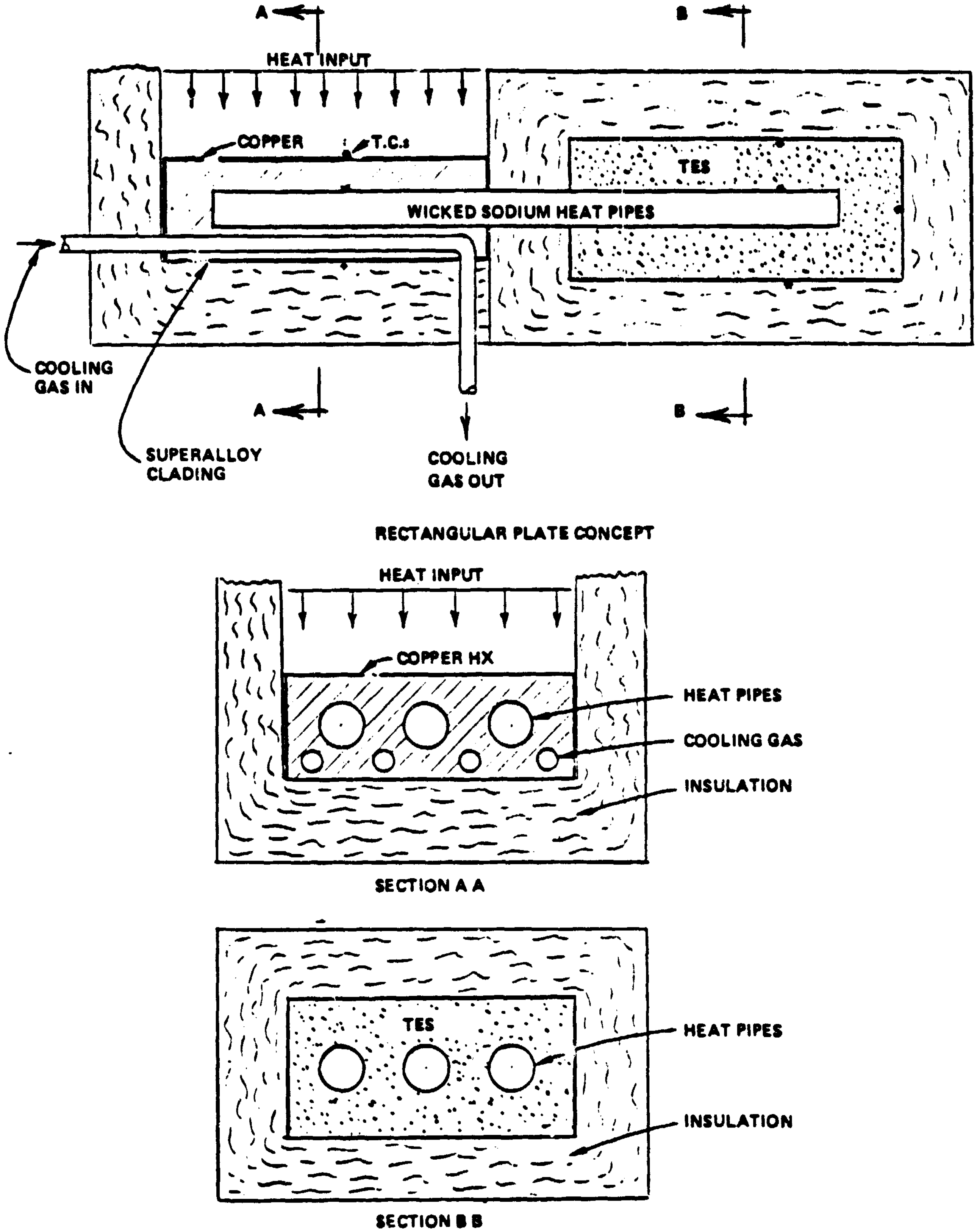
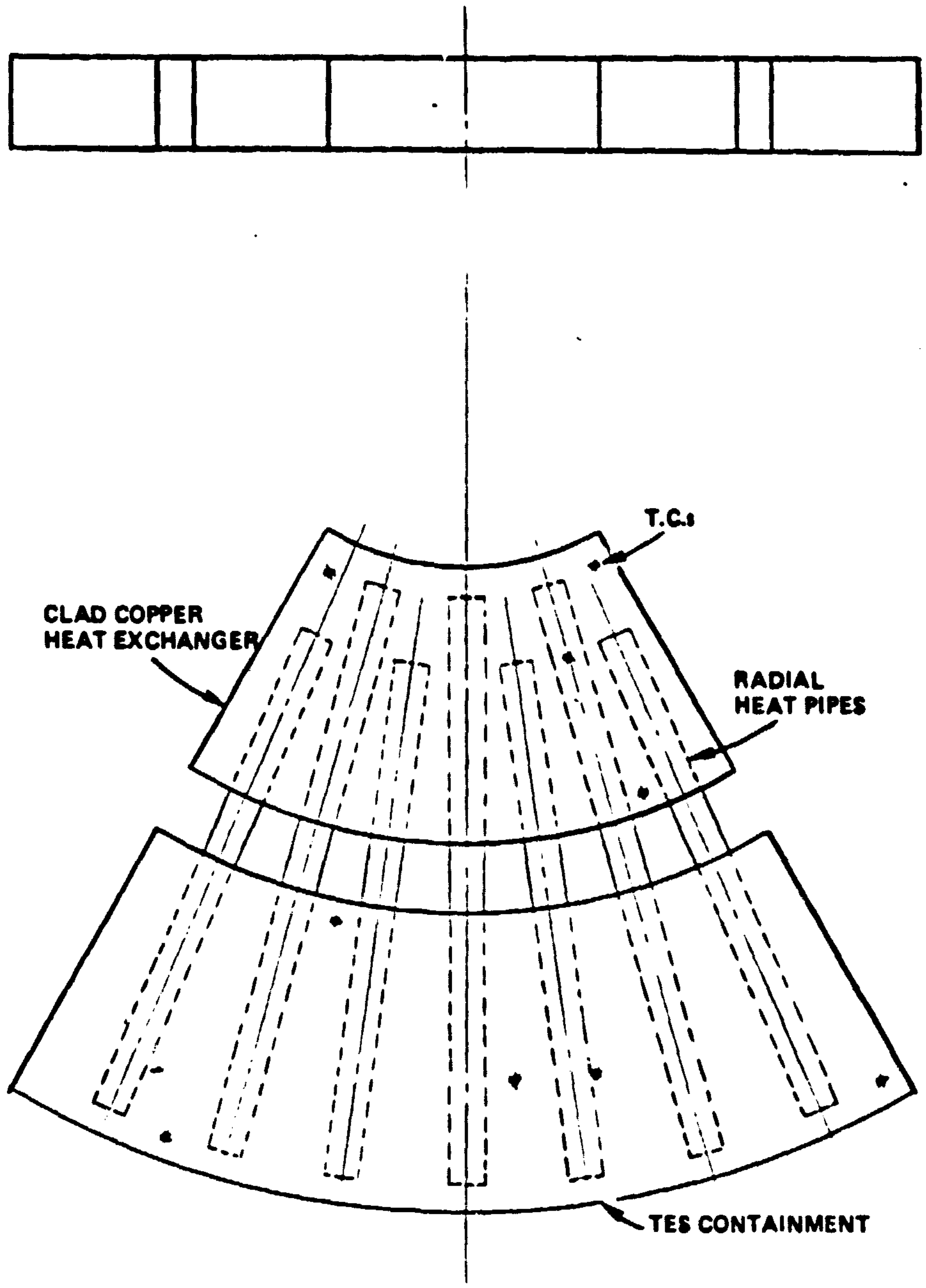


Figure 2-37. Rectangular Heat Pipe Modular TES Concepts for DSSR Receiver



SECTOR PLATE CONCEPT

Figure 2-38. Sector Heat Pipe Modular TES Concepts for DSSR Receiver being of continuous thermally conducting metallic construction, would be less sensitive to local surface overheating and to cyclic fatigue of the protective superalloy cladding and brazed joints on the copper heat exchanger cone.

While the rectangular module would be simpler to construct and interpret, the sector module would provide a greater appreciation for the temperature distribution on the surface and within the copper heat exchanger under both transient and steady state conditions. The presence of heat pipes in the copper heat exchanger should improve the radial temperature gradient. The thermal inertia and near constant temperature of the latent heat TES material and the effective two way flow of heat within the heat pipes should also operate to reduce circumferential gradients. However, the module is still limited by the thermal conductance within the copper and the inability to array the heat pipes in a completely uniform manner. Finally, the heat pipe thermal transport to the TES salt does not operate in an isothermal way in the midst of all the TES but must rely upon conductivity within the TES and, more significantly, within the copper receiver heat exchanger to achieve a near isothermal temperature in the circumferential direction.

In all the above potential DSSR modular TES experiments complete thermocouple instrumentation and heat flow analysis would be required to access the thermal storage and thermal performance characteristics including temperature distribution, system ΔT, TES duration, etc., It would appear from these early considerations that the heat pipe type of modular experiment would be more promising. However, a more extensive engineering analysis of each of the design concepts and the preparation of a complete modular experiment design would be required, ultimately, should a decision be made to add buffer storage to the DSSR receiver and should a modular experiment be an appropriate development tool.

2. Heat Pipe Solar Receiver Modular Experiments

The use of a modular experiment in defining the TES characteristics of the HPSR has proven beneficial, as described earlier. Additional modular experiments are worthwhile (1) to confirm existing and modified design concepts and lower cost methods for wicking cf liquid metal and (2) to demonstrate inovative concepts for further performance and cost improvement in both wicking and TES.

The previous modular experiment demonstrated the thermal response of the TES salt containers in terms of storage time, ΔT across the solidifying salt, isothermal performance of the secondary heat pipe and heat transfer at various angles and operating modes. The experiment was limited, however, in that the required liquid sodium flow rates to various design elevations in the actual prototype could not be simulated. The capillary pumping and flow capabilities of the design, however, have been based on sound capillary pumping and flow considerations and, in addition, redundancies have been designed into the demonstration prototype because of the immediate necessity for assuring that liquid metal will be delivered to all heat sources with reliability.

A full scale modular experiment operating with only one or two TES salt capsules and one primary heat pipe is suggested. It would operate under actual sodium flow conditions and hydrodynamic heads for the capsules and for the primary heat pipe. It would feature controlled and measured heat input through the primary heat pipe, determination of calculated heat losses from the system, operation at various angles and operating under liquid sodium capillary pumped head and flow requirements for (1) the highest primary heat pipe condenser, (2) the highest TES capsule, in each of two tiers and (3) the highest point on the combustor shell wicking (where fossil fuel combustor heat is applied through the TES secondary heat pipe shell). Operation of the system at various angles could be conducted to verify the stable, steady state transfer of heat over an extended period of time in various pure operating modes such as direct heat throughput, TES charging, TES discharging and simulated combustor heat input as well as in various mixed modes of operation (e.g., partial primary heat pipe heat input mixed with partial TES discharge). Success in transferring heat from the several heat sources within the modular experiment apparatus would indicate the adequacy of the wicking and of the wick joints necessary to transfer sodium between components. The simplicity of this full size, but modular simulation of the HPSR would permit its rapid modification to permit alternate wicking and wick joint concepts to be tested with liquid metal under simulated design conditions. New wick concepts and/or materials such as diffusion bonded wicks, flame sprayed composite wicks, sintered wire wicks, arterial rope wicks, flexible wick joints, mechanical compression joints, modified gravity flow distribution concepts and reduced redundancy in wicking could be evaluated in this fashion once the concept had been fabricated and tested under easy fluids such as water, ethanol, etc.

Alternate concepts for the TES salt containment configuration including the TES-to-sodium heat transfer surface can be tested under more conventional electrical heating and air cooling as has been proposed separately. The behavior of the salt storage up to the point of heat transfer by liquid metal would be similar. Such a modular test concept is shown in Figure 2-39. Several types of salt containment configuration, shown in Table 2-15 have been considered as has the possible effectiveness of adding thermal conductivity enhancement material to the interior of the latent heat salt; the latter, if effective, could permit the use of larger diameter, more cost effective salt containers without increasing the ΔT across the salt. For initial evaluations, a cylindrical $NaF-MgF_2$ salt container was recommended which was 4 inches in diameter and 19 inches long and had a power rating of 1 kW_t and a storage time of about 1 hour, similar to the earlier heat pipe TES modular experiment. The heat transfer area was slightly more than 1/2 of that of the TES modular experiment such that the power density was less than twice that used in the modular experiment. This heat extraction rate could be very easily handled by the high film coefficients of liquid metal heat transport methods in practical, lower cost TES systems with such larger containment sizes. Similarly, heat extraction by gas cooling could be accomplished with even less surface area as demonstrated in the air cooling coil of the TES modular experiment. (The use of a large cooling air ΔT in that test facility was particularly helpful to offset the lower air cooling film coefficients). For active gas cooled thermal power system TES designs, at some later date, the gas side heat transfer

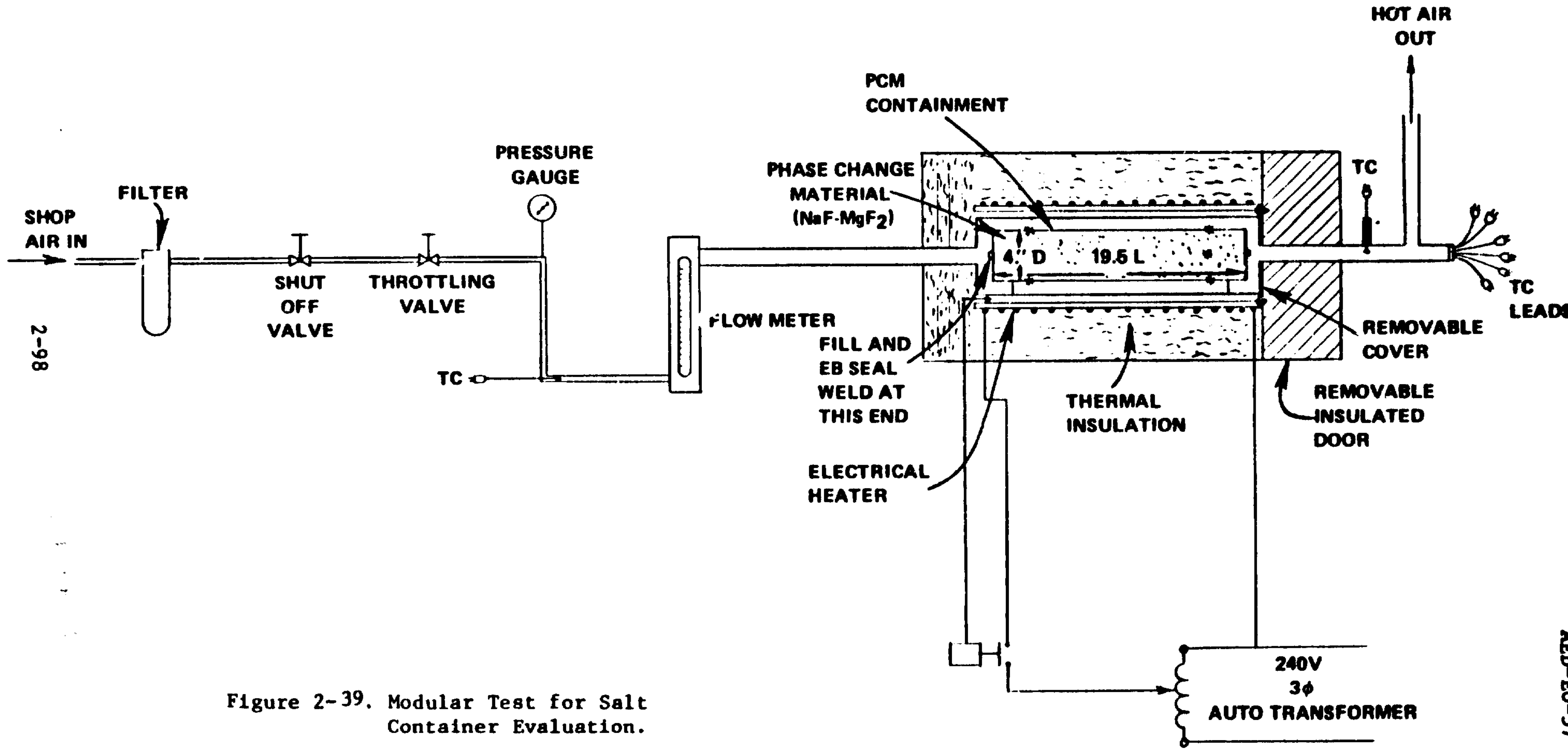


Figure 2-39. Modular Test for Salt Container Evaluation.

TABLE 2-15

SPECIMEN DESIGN

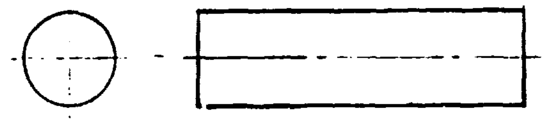
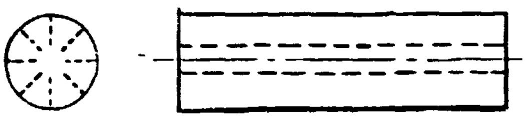
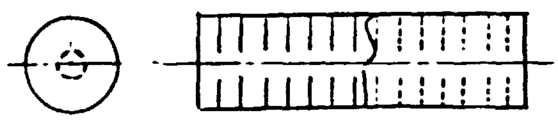
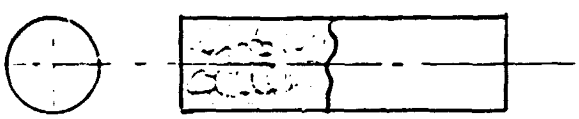
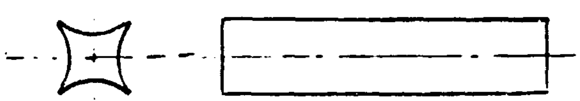
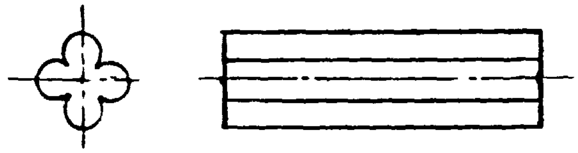
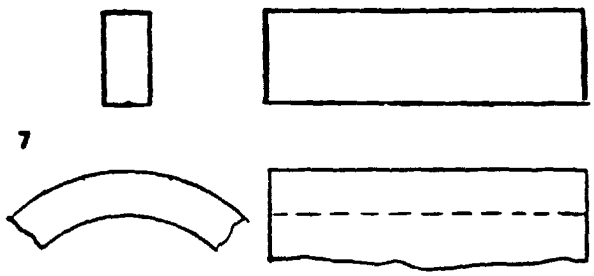
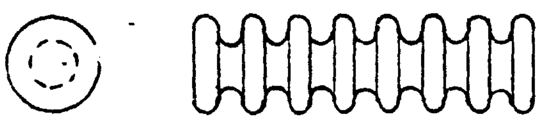
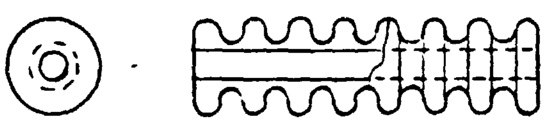
NO.	CONCEPT	DESCRIPTORS
1		BASIC CYLINDER (REFERENCE)
2		INTERNAL LONGITUDINAL FINNED CYLINDER • VARIATION IN FIN VOLUME FRACTION (Spacing and Thickness) • SIMPLE FABRICATION
3		INTERNAL RADIAL FINNED CYLINDERS • VARIATIONS IN FIN VOLUME FRACTION (Spacing and Thickness) • MORE COMPLEX FABRICATION REQUIRED
4		WIRE FILLED CYLINDERS • VARIATIONS IN WIRE DIAMETER • VARIATIONS IN WIRE VOLUME FRACTION • VARIATIONS IN WIRE CONDUCTIVITY
5		CONCAVE • HIGH SURFACE/VOLUME RATIO • REVERTS TO CYLINDRICAL SOLIDIFICATION MODE

TABLE 2-15 (Cont'd)

SPECIMEN DESIGNS

NO.	CONCEPT	DESCRIPTORS
6		CONVEX • HIGH SURFACE TO VOLUME RATIO • COMPLEX FABRICATION • SOMEWHAT RESTRICTED OD GAS SIDE HEAT TRANSFER
7		SLAB (OR ANNULUS) • HIGH SURFACE TO VOLUME RATIO • FLEXIBLE FOR SOLIDIFICATION ΔV
8		BELLOWS - EXTERNAL HEAT EXTRACTION • HIGH SURFACE/VOLUME RATIO • POOR SOLIDIFICATION PATTERN • FLEXIBLE FOR SOLIDIFICATION EXPANSION
9		BELLOWS/TUBE - INTERNAL HEAT EXTRACTION • LOW SURFACE/VOLUME RATIO • EXCELLENT SEGMENTATION OF LIQUID SALT DURING SOLIDIFICATION
10		SPHERE • MINIMUM SURFACE TO VOLUME RATIO • FABRICATION/FILLING DISADVANTAGES • POSSIBLE HEAT TRANSFER DISADVANTAGES

could be handled without significant degradation in the working fluid temperature by either (1) the use of fins or other extended surfaces, (2) the use of larger TES containment surface areas associated with longer storage times and TES volumes and (3) other conventional gas side heat transfer considerations which are appropriate to specific designs. Those gas side heat exchange considerations do not, in themselves, affect thermal transport from the salt to the containment wall surface. Thus, in this modular TES experiment emphasis could be placed upon thermal transport within the salt and in solidification patterns affected by container configurations, without the urgent necessity to consider heat extraction from the containment surface; that design consideration could be handled separately. It was, of course, necessary to assure that heat could be extracted at the necessary rate from the TES containment in this test facility. This could be accomplished using cooling with room temperature or preheated air where a large heat transfer ΔT was practical.

The advantages in incorporating this type of modular experiment in future work is that the thermal conductance and storage characteristics of the salt, its container size and its configuration could be assessed separately without the need for heat pipe experiments provided the exterior of the TES containment was conducive to wicking for liquid metal flow purposes.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

1. The dish Stirling solar receiver (DSSR) with a continuous fossil fuel combustor capable of maintaining a constant engine heater head temperature under varying solar insolation does not require the addition of TES for reliable continuous operation.

2. Concepts for the addition of even brief duration TES to the DSSR involve either unacceptally high ΔT across the TES material under high heat flux and limited TES surface area or the utilization of efficient thermal transport in the form of heat pipes or reradiation mechanisms. These concepts have materials and design limitations and cost implications which do not appear to warrant their incorporation.

3. Since the DSSR is always operated on 90% or less solar power the need to defocus the concentrator for this system is relatively nonexistent.

4. Notwithstanding the higher system efficiency of heat pipe solar receiver (HPSR) and its Stirling engine over the DSSR system the present HPSR design does not lend itself well to minimal buffer storage where the TES' contribution to system advantages are minimal when compared to a direct receiver with a continuous modulated combustor.

5. TES is effective in the HSPR when significant amounts of storage are involved and the heat pipe principle can effectively transfer heat to, and extract heat from, large surface areas of TES (a) at low heat flux, (b) at minimum ΔT in both the heat transfer medium and across the latent heat salt and (c) in a self regulating manner without complex sensors, pumps, valves or flow controls.

6. Low ΔT in the HPSR heat pipe thermal transient minimizes the probability of hot spots or high temperatures in the receiver and reduces reradiation losses.

7. The effectiveness of the HPSR is favored by high receiver efficiency and high engine efficiency the latter of which results from freedom to design the engine heat exchanger without the limitations of outside surface heat transfer coefficients.

8. The use of TES, of a duration larger than buffer storage, can increase the solar-to-fossil fuel power ratio and reduce COE by permitting the use of a more efficient "on-off" combustor without the alternative necessity for continuous combustion at a minimum of 10 percent combustor power.

9. Further increases in solar-to-fossil power and reductions in COE can be achieved by a balanced increase in both the concentrator size and TES duration to extend the duration of solar power production in the HPSR system.

10. The frequency of engine cycling in the absence of a combustor is reduced by increased TES and concentrator size.

11. When the constant engine thermal power demand is set at a point below that delivered at peak solar insolation, the possibility exists for occasonal defocusing of the concentrator. An ability to change the daily fixed thermal power demand level of the engine by a change in engine working fluid pressure can minimize, if not preclude, the occasional necessity to defocus the concentrator of the HPSR system. Such change in set power input levels to the engine can also decrease the required fuel consumption of the HPSR system at an equivalent reduction in total power output.

12. The COE is higher for TES supported systems without a combustor compared to similar systems with a combustor because of the lower system utilization. A re-evalaution of certain fixed O&M costs, particularly operating labor could change this conclusion.

13. For further development of the sensible heat TES inherent in the DSSR copper receiver, process improvements and cyclic thermal testing are worthwhile. Potential process improvements might include (a) diffusion bonding of the oxidation protective cladding to the copper by heat treatment and/or hot isostatic pressing and (b) casting the copper within the cladding and around the Stirling engine heat exchanger tubes. Such process development and testing could identify improvements in fabrication techniques to assure the integrity of the receiver heat exchanger under cyclic conditions which might cause thermal ratcheting, debonding of the superalloy cladding with the copper and the development of hot spots on the debonded cladding.

14. It is recommended that future concentrator parametric cost studies include the effect of variations of focal point mass to provide systems cost data for inclusion of larger amounts of TES at the focal point.

15. For the purposes of effective TES thermal transport, it is recommended that heat pipe operating life and cyclic operation be verified in long term testing at temperatures appropriate to the operating temperatures of the HPSR system selected for long range development and transition to mass production.

16. It is recommended that modular TES experiments be conducted to determine the satisfactory operation of potentially lower cost wicking and wick joint concepts. Such experiments should be modular in nature. But they should use full scale measurements for achieving liquid sodium pumping height. They should involve only partial power for simulating liquid flow and pumping capacity at actual design conditions over a limited portion of the TES secondary heat pipe power system.

17. It is recommended that more accurate design data be obtained regarding the thermal and physical properties of selected latent heat materials and their compatibility with containment materials over long periods of time.

18. An excellent analytical tool has been developed for the evaluation of distributed concentrator hybrid solar Stirling power conversion systems with TES in the areas of operating characteristics and economic performance. It is recommended that additional studies be undertaken to assess the effects of various operating and control assumptions intended to avoid the need to defocus and to minimize engine cycling.