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Thermal Power Systems
Advanced Solar Thermal Technology Project

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Performance Prediction Evaluation of Ceramic Materials in Point-Focusing Solar Receivers

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U.S. Department of Energy
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Abstract

A Performance Prediction Model was adapted to evaluate the use of ceramic materials in solar receivers for point-focusing distributed applications. TPS system requirements were determined including the receiver operating environment (such as concentrator performance and environmental/natural occurrences) and system operating parameters for various engine types. Preliminary receiver designs evolve from these system requirements. Specific receiver designs evaluated in this report to determine material functional requirements include the NRL solchem converter/heat exchanger, MIT/LL ceramic dome, Black and Veatch/EPRI ceramic tube receiver, and the Sanders honeycomb matrix Brayton receiver.

This report covers the first phase of a continuing task of evaluation and reporting on high temperature ceramics for solar thermal receiver applications. Subsequent reports will develop the Performance Prediction Model in more detail and provide data on its use in the several high temperature receiver and reactor designs planned for or under development.

Acknowledgements

The author gratefully acknowledges the assistance and encouragement of many members of the TPS project especially that of Bill Carroll and Ed Chow. Special thanks is extended to Dr. Marc Adams of the Materials Research and Technology Group at JPL for his continuing involvement in this study. The author would also like to thank the Naval Research Laboratory, MIT/Lincoln Labs, Black and Veatch/EPRI, and Sanders Associates for contributions to this report.

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SECTION I

INTRODUCTION

An investigation into the use of high temperature ceramics for solar power, point-focusing distributed systems is a part of the Advanced Materials Task for the ASTT project at JPL. For solar thermal energy to become a viable alternative to conventional energy sources it must become cost effective. One method of increasing the cost effectiveness for electrical applications is increasing the efficiency of the power conversion subsystem of a thermal power system. Thermal to electric energy conversion is usually accomplished by a heat engine which converts thermal energy to mechanical energy. Mechanical to electric conversion takes place with a generator. Since few improvements remain to be made with generator technology the best chance for increasing the efficiency of the power conversion subsystem lies in increasing the efficiency of the heat engine. Heat engines theoretically become more efficient with increased inlet temperatures for a given outlet temperature. The predicted efficiency of a fully regenerated open cycle Brayton engine increases from 26.8% at an inlet temperature of 1850°F to 48.3% at an inlet temperature of 2500°F with the same outlet temperatures.[1] Increases in efficiency from increased operating temperatures for other heat engines are similar to that obtained for a Brayton engine. In addition, recent studies have shown that many cost-effective applications for thermal energy are available in the fuels and chemicals industry if the thermal energy can be provided at temperatures in excess of 2000°F. However, properties of metallic alloys that are candidates for high temperature receiver applications deteriorate with increasing temperature. Depending on the environment, these materials no longer retain adequate long term oxidation resistance and mechanical properties at temperatures of 1700°-1900°F.[2] Thus strong driving forces exist for developing high temperature ceramic materials for use in solar thermal receivers.

In addition to increased temperature capabilities, ceramic materials may provide other potential advantages. One advantage is an improvement in phase stability such as oxidation resistance and chemical inertness of ceramics over superalloys. Other advantages of using ceramic materials in receivers are probable cost and weight savings.

The objective of this study is to evaluate the use of ceramics in high temperature solar thermal applications. Evaluation of ceramics in solar thermal receiver applications can be greatly assisted by Performance Prediction Modeling.

Performance Prediction Modeling, as described in Section II, will aid in the evaluation of state-of-the-art performance of ceramic materials in solar thermal receiver applications. Several existing and proposed receiver designs will be examined. Some of the existing receiver designs are the NRL solchem receiver, MIT-LL ceramic dome, Black and Veatch tube receiver, and the Sanders windowed honeycomb receiver. Proposed receivers which hopefully will be examined if sufficient design information becomes available include a fuels and chemicals type receiver and the JPL contracted development for high temperature receivers. Emphasis will be on analyzing these receivers to obtain the material functional requirements. This study will not attempt to devise a model receiver having representative requirements of many different applications.

Current resources do not permit execution of the entire Performance Loop. This report will only determine the system requirements and examine preliminary receiver designs to determine the material functional requirements. Work will proceed during the remaining portion of this fiscal year on further examination of ceramic materials using Performance Prediction Modeling. Specific areas to be covered include candidate materials and processes, and failure/degradation mode identification. It is hoped some performance predictions can also be made this fiscal year. Materials development and the design and evaluation of test procedures are areas suggested for future work when resources become available.

Some of the limits of this study have already been discussed. In general, only receivers for point-focusing distributed applications will be considered. A size limit (maximum power capability) of 100-200 kWth will be imposed. One receiver that is an exception to these two conditions is the Black and Veatch receiver. This is a cavity type receiver designed for a central power tower with a power rating of 100-200 MWth. This receiver was selected for evaluation, despite the large size, because the design was considered a representative example of ceramic usage that is scaleable to point-focusing distributed applications. This study will not examine receivers for stationary collectors such as the one proposed for Crosbyton, Texas. One reason for this, which will be discussed in more detail later, is the variation of solar flux distribution with time and different requirements the receiver places on the concentrator. Also these applications are not immediately applicable to the goals of the ASTT project.

A limited examination of solar window functional requirements as they pertain to the Sanders receiver will be conducted in this study. Several promising candidate window materials known at this time will be examined. However, the scope of this study is necessarily limited because there exists sufficient information for an in depth study of window materials alone. A similar situation exists for high temperature thermal storage. Only a limited examination of sensible heat thermal storage systems as they pertain to the Sanders receiver will be conducted, because the topic is large enough to warrant a separate study in itself.

SECTION II

PERFORMANCE PREDICTION MODELING

Performance Prediction Modeling represents a systematic method for evaluating materials performance which has been developed at JPL.[3] Depending on the desired results, Performance Prediction Modeling can: a) determine the satisfactory performance of a material that is subjected to a given set of operating stresses (such as mechanical loads, environment, temperature, pressure, etc.) used in a specific design; b) define limiting values of stresses for materials in existing hardware or designs; or c) assist in the development of an appropriate set of design equations for a material that is exposed to generic stresses. The value of Performance Prediction Modeling is apparent when experimental investigations are necessary. Performance Prediction Modeling can identify missing data and assist in the development of tests to find this missing information. These tests do not necessarily need to simulate the operating stresses present in the design to reach a conclusion regarding the material performance under actual operating conditions.

A flow diagram of Performance Prediction Modeling used to evaluate ceramic materials in solar thermal receivers is shown in Figure 1. The determined requirements of point-focusing distributed solar thermal power systems form the cornerstone that Performance Prediction Modeling uses to evaluate the application of ceramics in solar thermal receivers. Performance Prediction Modeling is a tool that enables a designer or engineer to meet these stated system requirements. The next paragraphs describe the basic steps in applying Performance Prediction Modeling to this solar thermal engineering problem.

The first box in Figure 1 provides the TPS system requirements. The system requirements lead to the development of a conceptual receiver design. The primary requirement of a solar thermal receiver is to convert the sun's thermal energy into a useable form. For example a Brayton engine might be the type of heat engine selected to drive an electric generator. A solar receiver must then supply heated gas to the Brayton engine to satisfy this system requirement. Other system requirements in turn determine more of the conceptual design. A given Brayton efficiency dictates the temperature and pressure ranges of the gas at the turbine inlet. Similarly an open cycle Brayton engine must use an air working fluid. Satisfying the majority of the system requirements in the conceptual design permits a designer to proceed to a preliminary receiver design, (box 2 in Figure 1).

A designer refines his conceptual design to determine a preliminary engineering design. The designer uses his general knowledge (in structural and thermal behavior as well as basic material properties) to design a receiver that meets the stated system requirements including the interfaces with other systems. The preliminary design determines approximate values for the shapes and sizes of the receiver components. At this stage the design usually does not depend upon specific materials, but instead upon

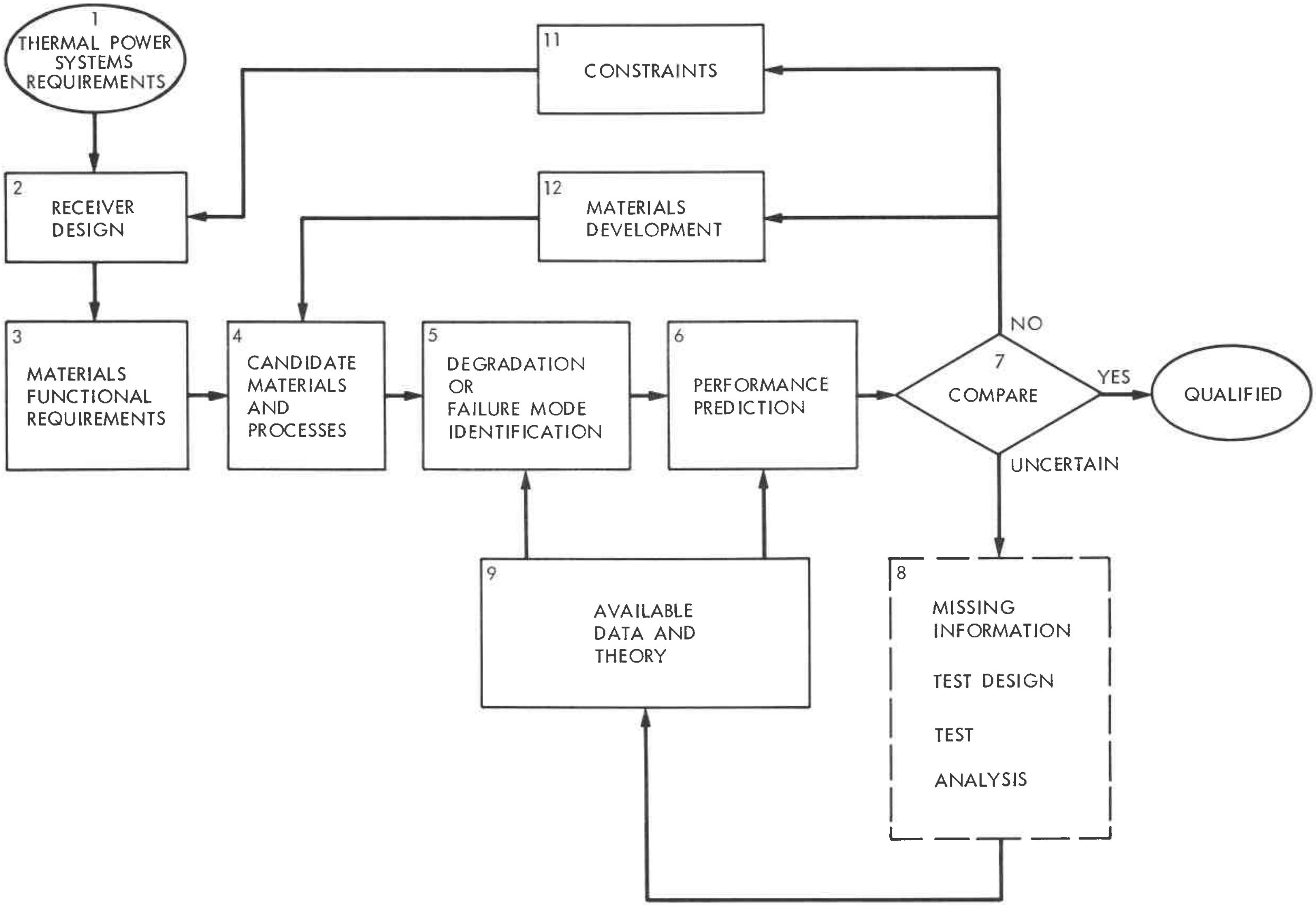

Figure 1. Performance Prediction Modeling of Ceramics in Solar Receivers

materials possessing properties within appropriate ranges. This study will use a number of preliminary receiver designs, in various stages of refinement, as a means for evaluating the use of ceramics in solar receivers. It is hoped that this study, with the aid of Performance Prediction Modeling, will provide a sufficient base to permit one to extrapolate the performance of ceramics in other receiver designs and to comment on the overall suitability of using ceramics in solar thermal receivers.

Determination of the material functional requirements (box 3 in Figure 1) is the next step in Performance Prediction Modeling. Functional material requirements are the minimum values of critical properties (i.e., strength, elastic modulus, thermal shock resistance, thermal conductivity, etc.) a material must have to perform satisfactorily in the specific engineering design. These values are obtained by analyzing the preliminary receiver design. The depth of the analysis varies according to the level of detail required. For example, finite element analyses might be used for stress and thermal analyses of complex designs whereas approximations of stress and thermal conditions using basic formulas might be sufficient for simpler structures. A rigorous determination of these material functional rquirements (i.e., the more quantitative the relations) improves the chances of successful performance prediction. However, a rigorous evaluation of the obvious operating parameters (i.e., pressure, temperature and working fluid) should not obscure the effects of less obvious factors (environmental effects, cloud coverage, and uneven flux distributions) on the functional requirements. The full benefit of Performance Prediction Modeling can only be obtained when all factors that affect the material functional requirements are considered.

Candidate ceramic materials and processes that have potential applications to solar thermal receivers are examined in box 4, Figure 1. First existing materials are surveyed to determine potential candidates. Material properties of promising candidates are then examined in detail. The properties relevant to performance in solar receiver applications are cataloged. The material properties are dependent on the type of fabrication process used. Fabrication processes applicable to producing solar receiver components have large affects on resultant material properties and therefore need to be considered simultaneously with the candidate materials.

Before any predictions can be made about the performance of the receiver, the failure or degradation modes should be identified (box 5, Figure 1). Some typical failure modes for a solar receiver might be catastrophic failure caused by stresses exceeding the fast fracture tensile strength, fracture related to thermal shock conditions or fractures induced from thermal gradients. Degradation modes might be slow crack growth at stresses below those required for fast fracture, oxidation which might result in changing thermal or structural properties, or creep deformation leading to reduced performance. It is necessary to identify all possible failure/degradation modes to ensure that the next step of Performance Prediction Modeling will be successful.

"Performance Prediction" (box 6, Figure 1) is the critical step in a rigorous application of Performance Prediction Modeling. "Performance Prediction" involves combining material property values of a candidate material with the appropriate failure/degradation mode previously identified. In the best case of "Performance Prediction" quantitative relationships result from available data and theory on the failure mode. By using these relationships and the data on properties of a candidate material (determined in box 4) values for the various failure modes can be calculated for that material. A less desirable but often useful form of "Performance Prediction" involves the determination of qualitative relationships that often lead to uncertain conclusions from Performance Prediction Modeling. Uncertain conclusions are not necessarily bad as will be shown later.

At the decision point (box 7, Figure 1) property values for each failure mode obtained by "Performance Prediction" are compared to the corresponding values determined in box 3, material functional requirements. For example the material functional strength requirement for a heat exchanger tube could be determined by considering all the various factors affecting the stresses in the tubes. The strength of a specific material for this failure mode and operating conditions can be determined by "Performance Prediction." Comparison of the two values dictate the direction to be taken from the decision point.

A "yes" decision means that the performance predictions exceed by a specified margin the values found in material functional requirements. If no errors have been made in either of these analyses the material will successfully survive the appropriate failure mode. A rigorous application of Performance Prediction Modeling qualifies materials by comparison of performance predictions to defined functional requirements not by qualification tests or proof tests.

A "no" decision leads to either system constraints, alternate material selection, design constraints or materials development. It may be found from "Performance Prediction" that certain design deficiencies exist. Performance Prediction Modeling assists the design review process by providing inputs and constraints. A second path available after a "no" decision is materials development. Material properties may be improved enough by new material formulations or processing developments to satisfy the functional requirements. A new performance prediction will determine if the improved material is now qualified for the given design.

The third decision option, an uncertain comparison, is particularly probable during the initial stages of Performance Prediction Modeling. An uncertain result may arise from the "Performance Prediction" and the functional requirement being close (within a predetermined range) or by some uncertainty in the "Performance Prediction" itself. An uncertain decision usually results from information that is required for successful "Performance Prediction." Once clear definitions of missing information are identified, appropriate tests can be performed to supply this missing information. The required accuracy of the tests can sometimes bedetermined by a sensitivity analysis of the appropriate equations.

Inadequacies in existing tests lead to either test modification or development of entirely new tests. Analysis of test results provides both empirical and theoretical data. The data in turn provides inputs to the identification of failure/degradation modes and to "Performance Prediction". This new information permits further iterations of "Performance Prediction". A benefit of Performance Prediction Modeling is that the tests do not have to simulate all the operating conditions present or even necessarily have to measure the missing engineering property. A "yes" or "no" qualification can be obtained by repeated iterations through the missing information-test-analysis loop with a minimum of wasted effort because the pieces of missing information have been clearly identified.

SECTION III

SOLAR THERMAL POWER SYSTEM REQUIREMENTS

The first step in Performance Prediction Modeling is determining the system requirements. There are two major groups of system requirements that influence the design requirements of solar receivers. In order to analyze the performance of ceramics in solar receivers information must be known about a) the operating environment of solar receivers and b) the system operating parameters imposed by the different types of energy conversion systems. This section will be divided into two parts. The first part will describe the general operating environment a solar receiver encounters. The second will describe the range of system operating parameters for open and closed cycle Brayton engines, steam Rankine engines, Stirling engines, and a chemical conversion receiver that is integrated into a solar thermal power system.

A. RECEIVER OPERATING ENVIRONMENT

Apart from the requirements the specific energy conversion process places on the solar receiver, all receivers will encounter an environment that is unique to point-focusing distributed systems. This general operating environment is dependent on two factors. One factor involves conditions related to the concentrator and performance of the concentrator. The other factor involves environmental conditions and natural events that are often uncontrollable.

1. Concentrator Requirements and Performance

The purpose of a concentrator is to concentrate the solar insolation to the focus. The purpose of the receiver is to convert this concentrated solar flux to thermal energy and thereby heat a working fluid or cause a chemical reaction to occur. Therefore, it becomes necessary to match the performance characteristics of the concentrator with the receiver. The receivers to be examined in this study are mostly high performance-high temperature applications. The concentrator should be able to provide high concentrations of flux with small errors (such as slope, tracking and structural deflections). The remaining discussion on concentrator requirements and problems assumes the concentrator is a paraboloidal reflector similar to the one shown in Figure 2.

One problem with paraboloidal concentrators is that even expensive and accurate concentrators will not focus to a point. There will be some three dimensional distribution of solar flux at the focus due to the finite diameter of the sun and the omnipresent imperfect optics of the system. It is an overall system question in determining what quality of concentrator is required, but this decision on the concentrator quality affects the receiver in several ways.

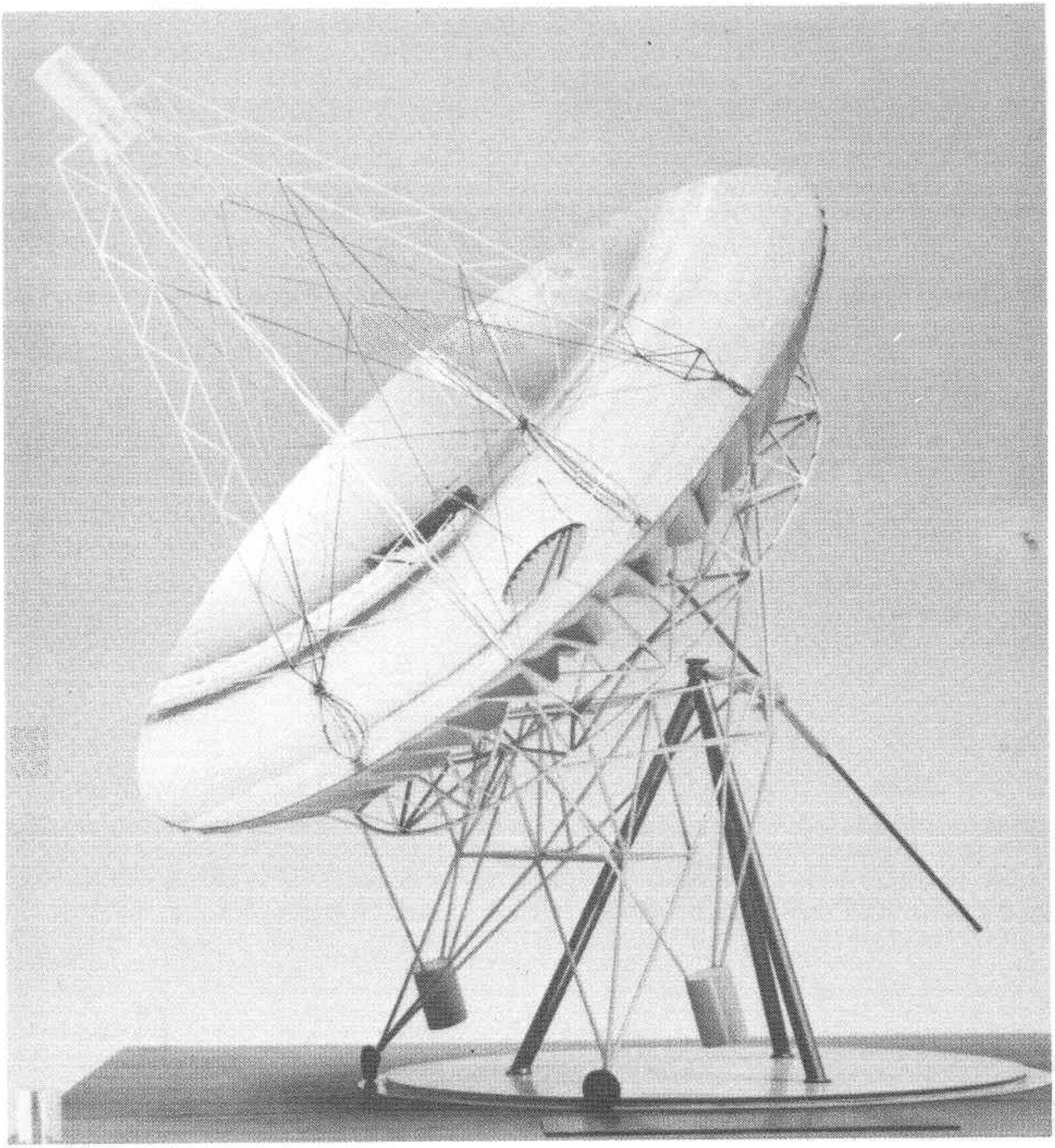

Figure 2. Proposed Point-Focusing Concentrator

The most important concentrator factor to consider is the flux distribution problem noted above. The unequal distribution of solar flux both in the focal plane and behind it are critical in determining the performance of the ceramic receiver. Unequal flux distributions can cause thermal gradients in the receiver with resulting thermal stresses. Some typical flux distributions for a reference concentrator are shown in Figures 3 and 4.[4] The assumptions made to determine these distributions are: F/D = 0.6, diameter = 11 meters, specular spreading angle = 0.5 mrad, slope error = 3 mrad, and limb darkening parameter = 1.15. Figure 3 shows the normalized concentration ratio at the focal plane, and at planes parallel to the focal plane. Figure 4 shows the normalized concentration ratio on cylindrical surfaces with varying radii. One comment should be made at this point about the Black and Veatch central receiver which also has uneven flux distributions present. One significant difference between central receivers and point-focusing receivers is that the flux distribution for a two-axis tracking paraboloidal dish parabolic concentrator is essentially constant during the day since relative sun/concentrator/receiver geometry is fixed, whereas a central receiver has flux distributions that vary during the day due to the independent motion of the heliostats.

The beam spreading also influences the receiver aperture diameter. A highly accurate concentrator permits the receiver to be designed with a smaller aperture while still capturing the same amount of solar energy. A small aperture reduces the amount of energy reradiated from the cavity. For a receiver near black body conditions the cavity temperature influences the characteristic radiation. The wavelength of radiation with maximum intensity is in the far infrared, near 3000 nm, for 700°C and near 2000 nm for 1200°C.[5] A more important benefit of a small aperture causing a receiver cavity to approach black body conditions is that reradiation within the cavity tends to equalize any temperature distributions present reducing associated thermal stresses.

The receiver itself places demands on the concentrator. In a point-focusing distributed system the receiver is supported at the focus of the concentrator. The receiver should not be so heavy that an excessive support structure is required in order to prevent structural deformation of the concentrator. Another physical constraint of the receiver is its actual dimensions. A large receiver/power conversion package at the focus can cause significant shading of the concentrator surface to occur.

2. Environmental and Natural Occurrences

Solar energy is an energy technology heavily dependent on nature. This fact must be taken into account when designing and analyzing receivers. One natural solar occurrence is the variation of solar insolation during the day. Figure 5 illustrates the variation of solar insolation on a clear day in Lancaster, California. Gradual variation of insolation levels is not itself critical to the performance of ceramics since the associated temperature changes are

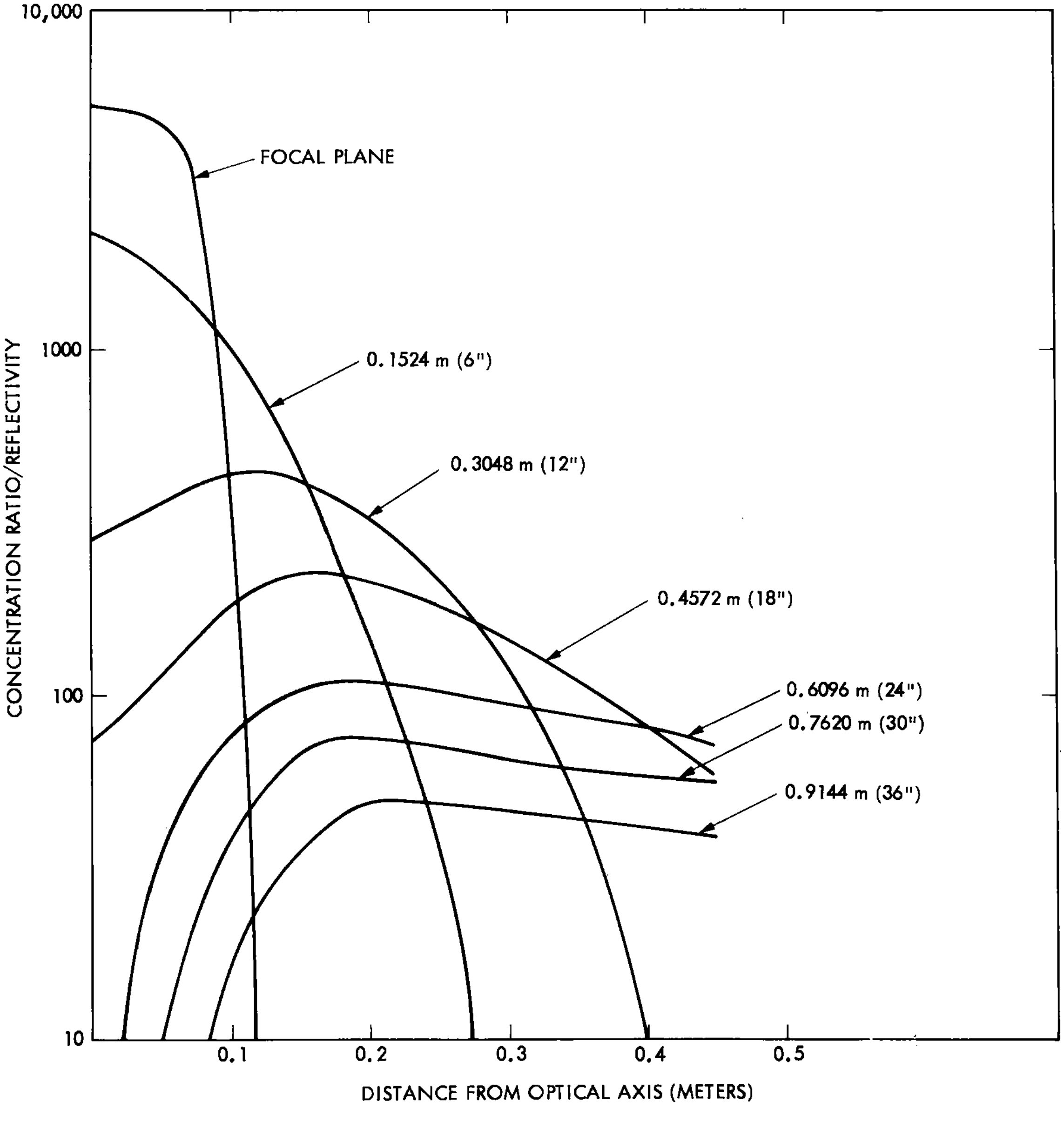

Figure 3. Distribution of Normalized Concentration Ratio on Planes Parallel to the Focal Plane as a Function of Distance from the Optic Axis

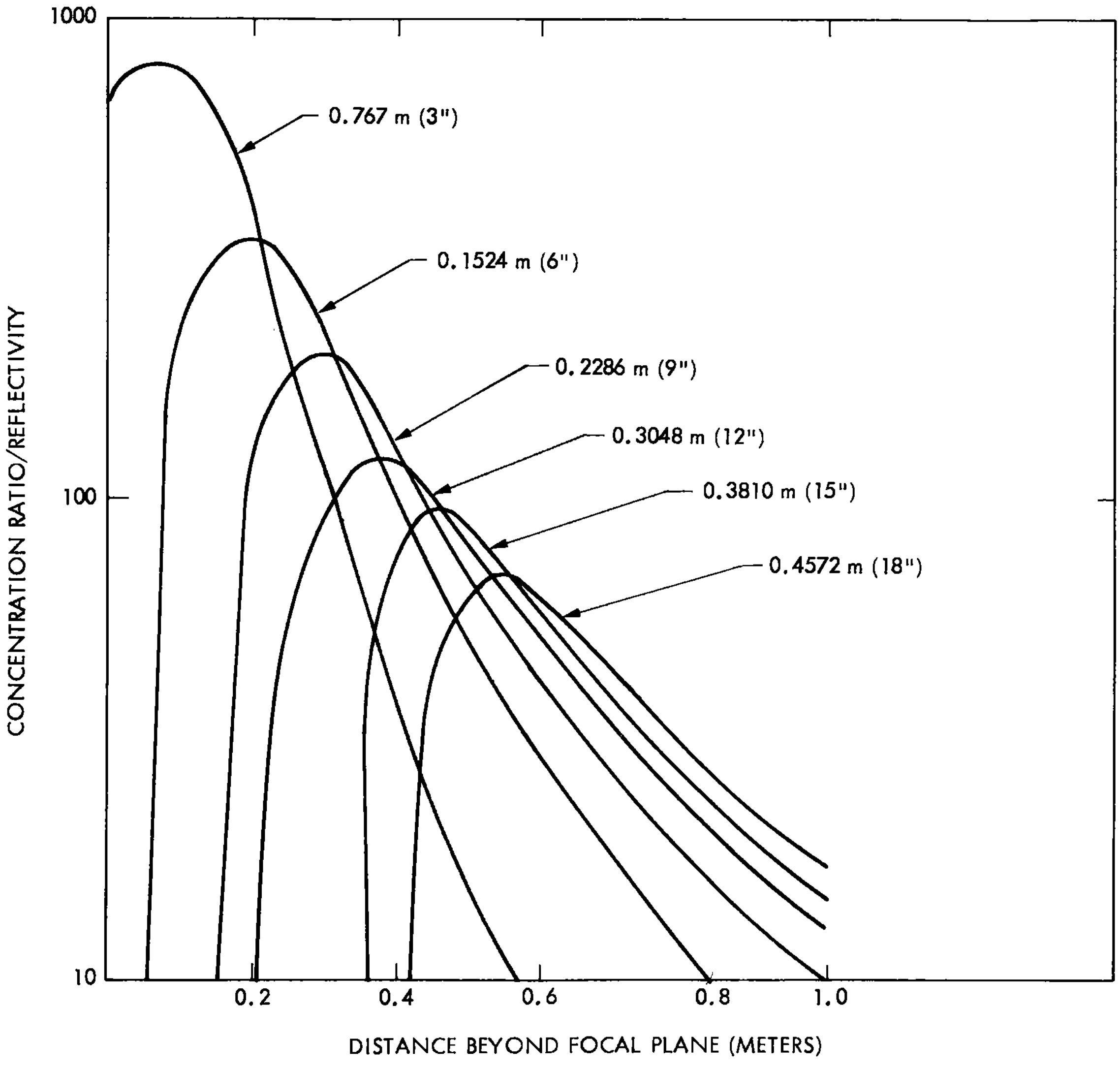

Figure 4. Distribution of Normalized Concentration Ratio on Cylindrical Surfaces with Varying Radii as a Function of Distance Beyond the Focal Plane

also gradual. Problems do arise when changes in insolation levels are sudden such as those caused by sunrise, sunset and cloud coverage. Figure 6 shows variation of insolation on a cloudy day in Tucson, Arizona.[6] Sharp changes in insolation can be seen in the morning and evening of Figure 5 and during the day in Figure 6. Ceramic materials are sensitive to thermal shock from sudden temperature changes. Typical temperature profiles of occultations of various durations are illustrated in Figure 7. Variations in temperature due to cloud coverage of the diurnal operation of the receiver can cause thermal shock damage to ceramic receiver components. This damage may be a cumulative effect. A distribution representing the number of thermal shock cycles versus the duration is shown in Figure 8. The effect of thermal shock is especially critical to ceramic materials and needs to be evaluated in a solar environment.

Other environmental factors that affect a receiver include wind, rain and freezing. Wind can increase convection losses from the receiver and vary the temperature distribution. The effects from rain and freezing are unknown, but they should be considered when evaluating a receiver.

B. SYSTEM OPERATING PARAMETERS FOR VARIOUS ENGINES

The most common engine type associated with ceramic solar thermal receivers is the open cycle Brayton. The operating parameters that make ceramic receivers attractive for this type of energy conversion process will be discussed. Typical operating conditions for other engine types, potentially ideal for ceramic receivers because of the higher temperatures obtainable with ceramics, will also be discussed. However, no large effort will be made to discuss the detailed operating principles of the various engine types. A comprehensive discussion of the various engine types can be found in References 1, 7, 8. Specific engine interfaces with the solar receiver and the requirements each engine type places on the receiver will be examined here.

1. Open Cycle Brayton

The Brayton engine is a heat engine that consists of three basic thermodynamic steps. The working fluid is first compressed from atmospheric pressure to an evaluated pressure. Heat is then added at a constant pressure. Finally, work is obtained when the working fluid expands back to atmospheric pressure. The Brayton cycle can be either a simple cycle or a regenerative cycle. In a solar thermal power system the pressurized working fluid is routed to the receiver. The receiver provides the source of heat to increase the temperature of the working fluid. This differs from a conventional gas turbine engine in which the source of heat is an internal combustion chamber and the combustion products are part of the working fluid. The receiver acts as a heat exchanger similar to what would be found in a closed cycle Brayton. Thus there must be a temperature gradient through the walls of the receiver where the heat transfer takes

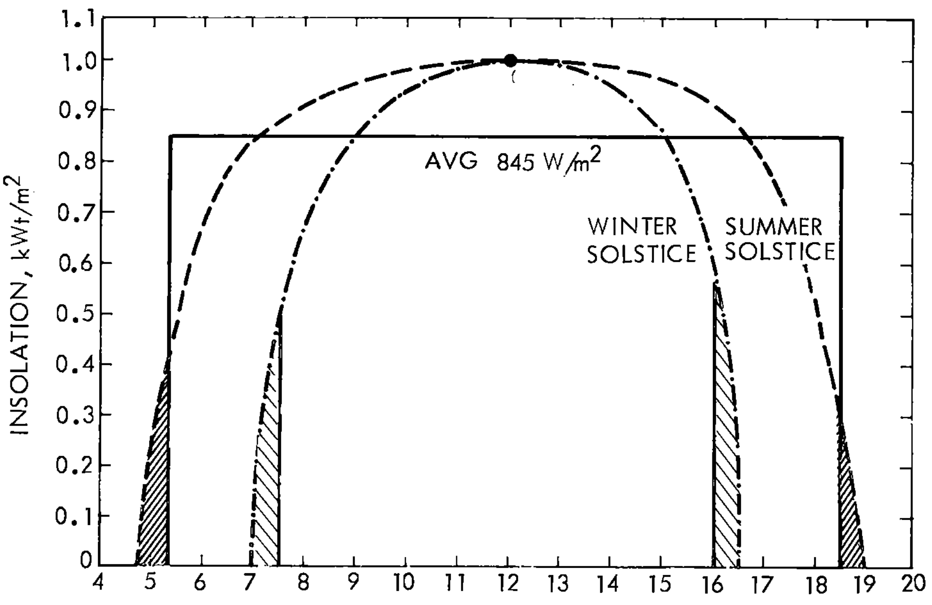

Figure 5. Variation of Insolation as a Function of Time on a Clear Day

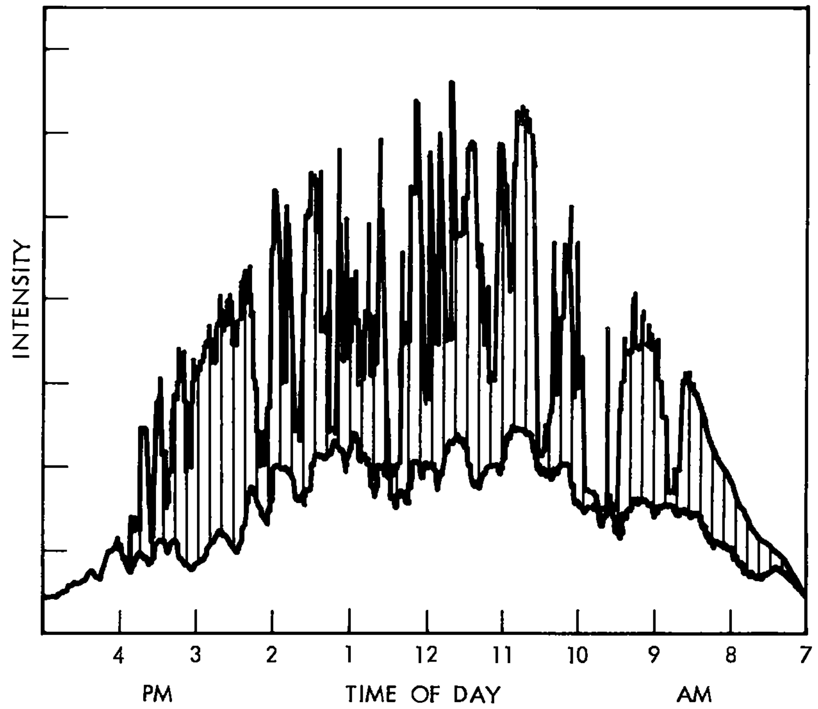

Figure 6. Variation of Insolation as a Function of Time on a Cloudy Day

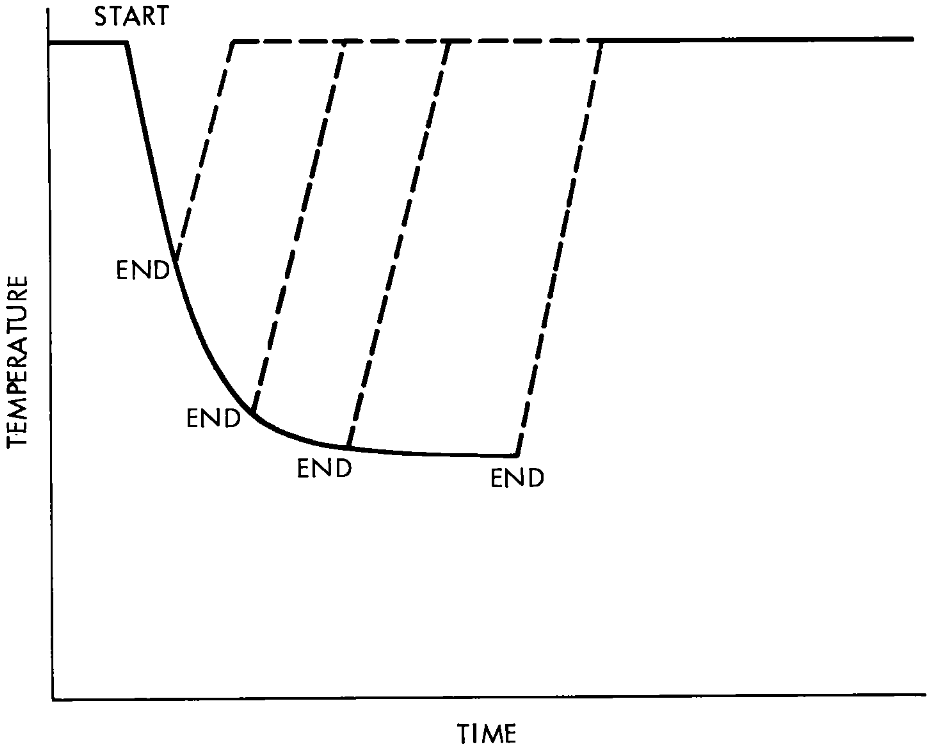

Figure 7. Temperature Profile vs Time for Occultations of Various Lengths

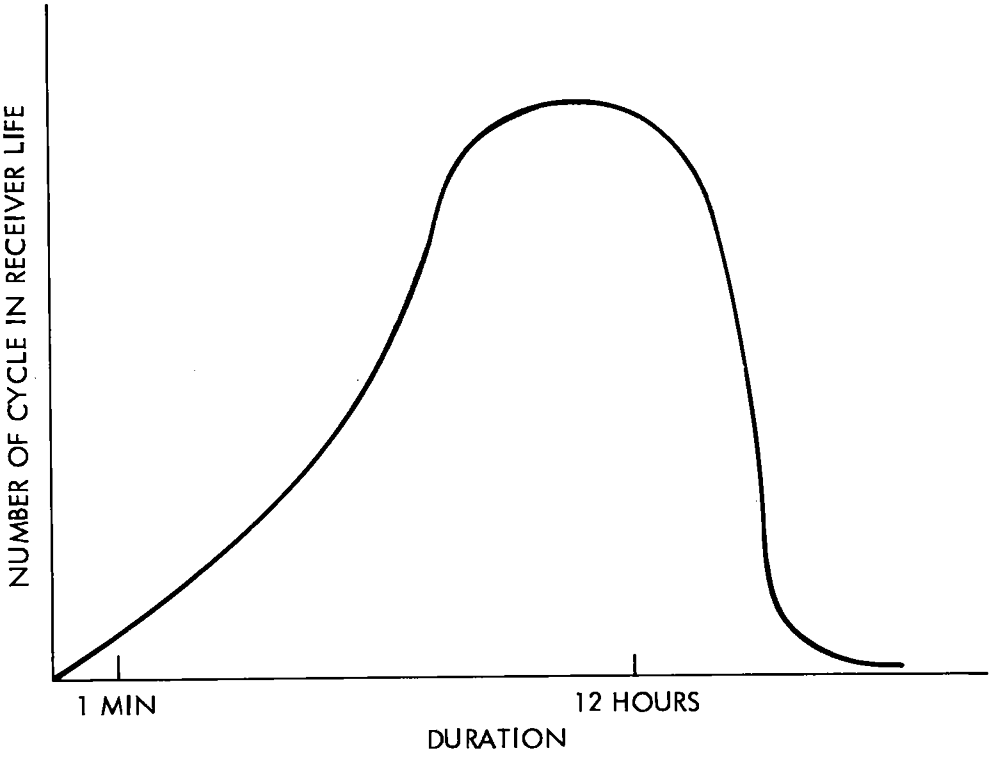

Figure 8. Distribution of Thermal Shock Cycles for Occultations of Different Times

place. There will also be a temperature drop from the receiver to the engine because of the physical separation of these two components. Both these factors combine to make the turbine inlet temperature less than the hot face temperature in the receiver. A turbine can be designed to operate either in a constant RPM or constant inlet temperature mode. This choice depends a great deal on the type of generator that is selected. A constant RPM turbine maintains a nearly constant air flow rate and pressure drop during reductions in solar flux. A constant temperature turbine must reduce the flow rate, which causes the system pressure drop to decrease, to maintain a constant inlet temperature.

Several operating parameters of a Brayton cycle are important in determining the functional requirements of the solar receiver. These include:

- turbine inlet temperature
- mass flow rate
- pressure ratio
- pressure drop in system
- working fluid

Problems arise from combining present turbine technology with the small power output of a distributed concentrator. The maximum inlet temperature at which a conventional turbine can operate is around 2000°F. To operate at temperatures of this magnitude some type of blade cooling is required. However, on small turbines, it is usually not as economically feasible to provide blade cooling (due to increases in machining and fabrication costs and reduced efficiencies) as it would be for larger turbines (10 MW). Considering present and near term future turbine technology, it is reasonable to assume a maximum turbine inlet temperature of approximately 2000°F is obtainable if some type blade cooling and improved alloys (nickel based) are incorporated into the turbine design.[9]

It would appear that the maximum turbine inlet temperature will be determined both by the turbine design and by the temperature capability of a solar receiver using high temperature ceramic components. Full advantage of the higher temperatures (greater than 2000°F) associated with ceramic receivers in terms of Brayton engine performance can only be obtained by concurrent use of ceramic turbine components. Even though current ceramic turbine technology is experimental, it is still necessary to use ceramics to obtain inlet temperatures of 2000°F. To obtain inlet temperatures in this range, hot face temperatures up to 2400°F are necessary.

Another operating parameter that is very important to the functional requirements of a solar receiver is the pressure ratio. A fully regenerative turbine cycle has the benefit of lower pressure ratios. Small turbines are most efficient at pressure ratios of slightly less than 3:1. The maximum pressure ratio for a fully regenerative cycle would be 4:1. This corresponds to a maximum pressure at the receiver of 60 psia. A simple cycle requires higher pressure ratios to obtain efficiencies similar to regenerated cycles. A turbine must have more stages in both the compressor and the expander to achieve these higher pressures which increases the turbine cost. Pressure ratios will be in the range of 15:1 (225 psi) for simple Brayton cycles. The pressure drop in an open cycle regenerative system has a large effect on the overall Brayton efficiency. Since the pressure ratio is low, increases in the total system pressure drop (whether from leaks or obstructions) causes sharp decreases in the cycle efficiency. In a simple cycle, increases in the pressure drop have smaller effects on the efficiency due to the higher operating pressures found in a simple cycle.

The working fluid is the final parameter that is important to the solar receiver. Open cycle turbines use air as the working fluid. If hybrid operation (burning fossil fuels during periods of reduced solar insolation) is desired the working fluid will also contain by-products of combustion. These products include CO, CO_2, H_2O, and sulfur oxides such as those found in a conventional fossil fueled turbine engine. In receivers not using a hybrid design, the working fluid would be air. Oxygen and water vapor are two constituents of air which could adversely affect the receiver materials. Hybrid operation would increase the water content of the working fluid in addition to adding other potentially detrimental gases. Thus, it is important to consider the effect of the working fluid on the receiver. Results of typical operating parameters for an open cycle Brayton engine are summarized in Table 1.

Table 1. Summary of Solar Receiver Requirements for Point-Focusing Application with Present or Near-Term Engine Technology

Engine Type	Working Fluid	Maximum Temperature	Max. Pressure
Open Cycle Brayton (fully regenerative)	Air	2400°F	60 psi
Open Cycle Brayton (simple cycle)	Air	2400°F	225 psi
Closed cycle Brayton (fully regenerative)	Air	2400°F	75 psi
Rankine	H_2O	1400°F	1000-2000 psi
Stirling	He, H_2	1400°-1500°F	3000 psi

2. Closed Cycle Brayton

A closed cycle Brayton engine operates on similar thermodynamic steps as the open cycle Brayton. The working fluid is totally contained in the engine and is recycled through the basic thermodynamic steps of compression, heat addition, and expansion. A conventional closed cycle engine requires a separate heat exchanger to heat the working fluid after compression. A solar receiver would serve this function similar to the way it would in an open cycle process. Many of the operating parameters discussed for the open cycle engine also apply to the closed cycle engine. The maximum inlet temperature is near 2000°F and has the same limitations as discussed previously. The pressure ratio will be approximately 4:1, but the absolute pressure will be higher. Air will be the most likely working fluid. Several other gases (Ar, He, H_2) are not viable candidates for small power turbines because the compressor and expander components for these gases are too small to be fabricated accurately. The typical operating parameters for a closed cycle Brayton are shown in Table 1.

3. Rankine Engine

A Rankine engine cycle consists of four processes. These are isentropic compression of a liquid, constant pressure heating, isentropic expansion, and constant pressure heat removal. The Rankine cycle uses phase changes of vapor to liquid in order to convert heat into mechanical work. Water is the most traditional working fluid, thus, the engines are referred to as steam Rankine engines.

Typical expander turbine temperatures for present technology Rankine engines are around 1000°F. Temperatures up to 1400°F can be expected in the near future. The pressure of the steam in the coiler section is approximately 1000-2000 psia. Table 1 summarizes the operating parameters of steam Rankine engines.

Receivers for steam Rankine engines are not attractive candidates for ceramic useage for three major reasons. First, the pressures required for operation of a steam Rankine cycle are difficult to contain with current ceramic technology. Successful use of ceramic tubes in the superheater (or reheat section depending on the design of the receiver) would be difficult from a structural design view. A tube of a high performance ceramic (SiC or Si_3N_4) with sufficient wall thickness to contain pressures of 1000-2000 psia would have very poor heat transfer characteristics. Failure of a superheater tube could be a serious safety hazard. It is also doubtful that current ceramic to metal seal technology could produce a leak tight joint at 1000-2000 psia. Secondly, the temperature range for a steam Rankine engine is not high enough to justify ceramics. Finally, there could be environmental or structural degradation of ceramic components from the steam or water present. Water and water vapor have been shown to enhance the slow crack growth of various ceramics. Slow crack growth could lead to catastrophic failure of a ceramic component. For these reasons there seems to be little benefit in further exploring the use of present technology ceramics in solar receivers used in a steam Rankine cycle.

4. Stirling Engine

A Stirling engine also produces mechanical work from the conversion of heat. A confined working fluid is compressed at a low temperature. The cold working fluid is passed through a regenerator and a heat source where it is heated. The heated working fluid then expands into a hot space to produce work. A constant volume transfer of the working fluid through the regenerator and the cooler to the cold space completes the cycle.

As with all heat engines the theoretical Carnot efficiency increases with higher temperatures. Thus there is a desire to obtain high operating temperatures. Ceramics in a heat exchanger for Stirling engines have similar problems to those encountered in a Rankine heat exchanger. The major limiting factor a Stirling engine imposes on the heat exchanger is the high pressure. Pressures range up to 3000 psia. These pressures are very difficult to contain since any leak will severely reduce efficiency. There is no known, current ceramic technology that can either withstand the structural requirements of these high pressures or the demanding leak conditions. Stirling engines range from 1400°-1500°F. These limits arise from the stress-rupture and creep characteristics of the heater tubes. Working fluids are usually either He or H_2. Typical operating parameters for a Stirling engine are listed in Table 1.

One final consideration in using a ceramic receiver/heat exchanger for a Stirling engine is the dead volume ratio. It is doubtful a ceramic receiver can be designed with a small enough dead volume ratio to maintain engine efficiency. With these considerations in mind there appear to be serious shortcomings associated with the use of present ceramic technology in Stirling engine heat exchangers (receivers).

SECTION IV

RECEIVER DESIGNS

Preliminary receiver designs evolve from the solar TPS system requirements. Performance Prediction Modeling will examine these receiver designs to determine the material functional requirements. Specific receiver designs chosen for examination are: a) NRL solchem converter/heat exchanger, b) MIT/LL ceramic dome, c) Black and Veatch/EPRI ceramic tube receiver, d) Sanders ceramic honeycomb receiver. In addition, several proposed receivers for which design data are not yet available will be examined when sufficient data can be obtained. These receivers are a general fuels and chemicals receiver and the proposed high temperature receivers.

The operating principle, temperature, pressure, working fluid, size, etc. will be stated for each receiver. The specific technical details of the receivers will be discussed in more detail in the next section when the structural, thermal and chemical characteristics are analyzed to determine the material functional requirements. These receivers are at different stages of development. System considerations account for the majority of variation in status. Receivers such as the Black and Veatch/EPRI and Sanders Air Brayton have developed as part of a well defined system. Many of the operating parameters of these receivers have been necessarily determined by the system requirements, therefore the receiver design is more mature. A more mature receiver design should not greatly affect the material functional requirements except by increasing confidence in the material functional requirements determined from the design. The basic characteristics and operating parameters of the various receivers are presented in the following section.

A. NRL SOLCHEM CONVERTER/HEAT EXCHANGER

The NRL solchem receiver (Figure 9) operates on a chemical conversion principle. SO_3 gas is catalytically converted to SO_2 and O_2 with the absorption of heat. This endothermic decomposition occurs in the range of 700°-1000°C. The NRL receiver is designed to operate with a cavity temperature of 950°-1000°C (1742°-1832°F) at a pressure of 3 atmospheres (45 psi). This receiver consists of several layers of ceramic spirals. SO_3 enters the outer portion of a spiral at 90°C. SO_3 flows toward the center of the receiver in the spiral heat exchanger. The center of the spiral (the portion that forms the cavity) that is exposed to the concentrated insolation contains a catalyst where the decomposition of SO_3 occurs. The decomposition products flow outward in channels adjacent to the SO_3 inflow channels. Heat is transferred from the hot SO_2/O_2 gas mixture through the common wall to the inflowing SO_3. The SO_2/O_2 mixture exits the receiver at 110°C. A 3-6 kWth bench test is planned with eventual scale up to 25 kWth. Design information pertaining to the NRL receiver is summarized in Table 2.

Table 2. Operating Conditions for Various Receiver Designs

	Working Fluid	Max. Temperature	Max. Pressure	Size
NRL Chemical Conversion	SO_3, SO_2, O_2	1000°C (1832°F)	45 psi	25 kWth
MIT/LL Brayton	Air	1200°C (2192°F)	60 psi	Not Avail
Black and Veatch/EPRI Brayton	Air	1200°C (2192°F)	140 psi	25-50 MWth
Sanders Assoc. Brayton	Air	982°C (1800°F)	35 psi	60-85 kWth

B. MIT/LL CERAMIC DOME

The MIT/LL ceramic dome is a cavity type receiver designed to heat air for an open cycle Brayton engine. Figure 10 shows an artist's conception of how a ceramic dome could be used in a 1 MWth central receiver design. The concave side of the dome forms part of the cavity which is heated by the concentrated solar flux. Heat is transferred through the dome wall to the convex side. Impinging air jets from a pressurized plenum cool the convex side of the dome. The heated air is collected in manifolds and transported to the Brayton engine.

Air is the proposed working fluid. The exit temperature of the air is 1000°C (1800°F) at a pressure of four atmospheres (60 psi). This corresponds to a hot face temperature of 1100°-1200°C (2000°-2200°F). At present no firm decision has been made on the specific size of the receiver. Information pertaining to the MIT/LL receiver is summarized in Table 2.

C. BLACK AND VEATCH/EPRI CERAMIC TUBE

Even though each Black and Veatch cavity receiver (Figure 11) is designed for 25-50 MWth (there are four cavity receivers on the tower) this design was determined to be a representative example of how ceramics might be used in a small distributed system.[10] A measure of downward scalability has been shown by the design of a 1 MWth bench model receiver. This receiver is an octagonal cavity that is lined with ceramic U-tubes containing the working fluid. The air working

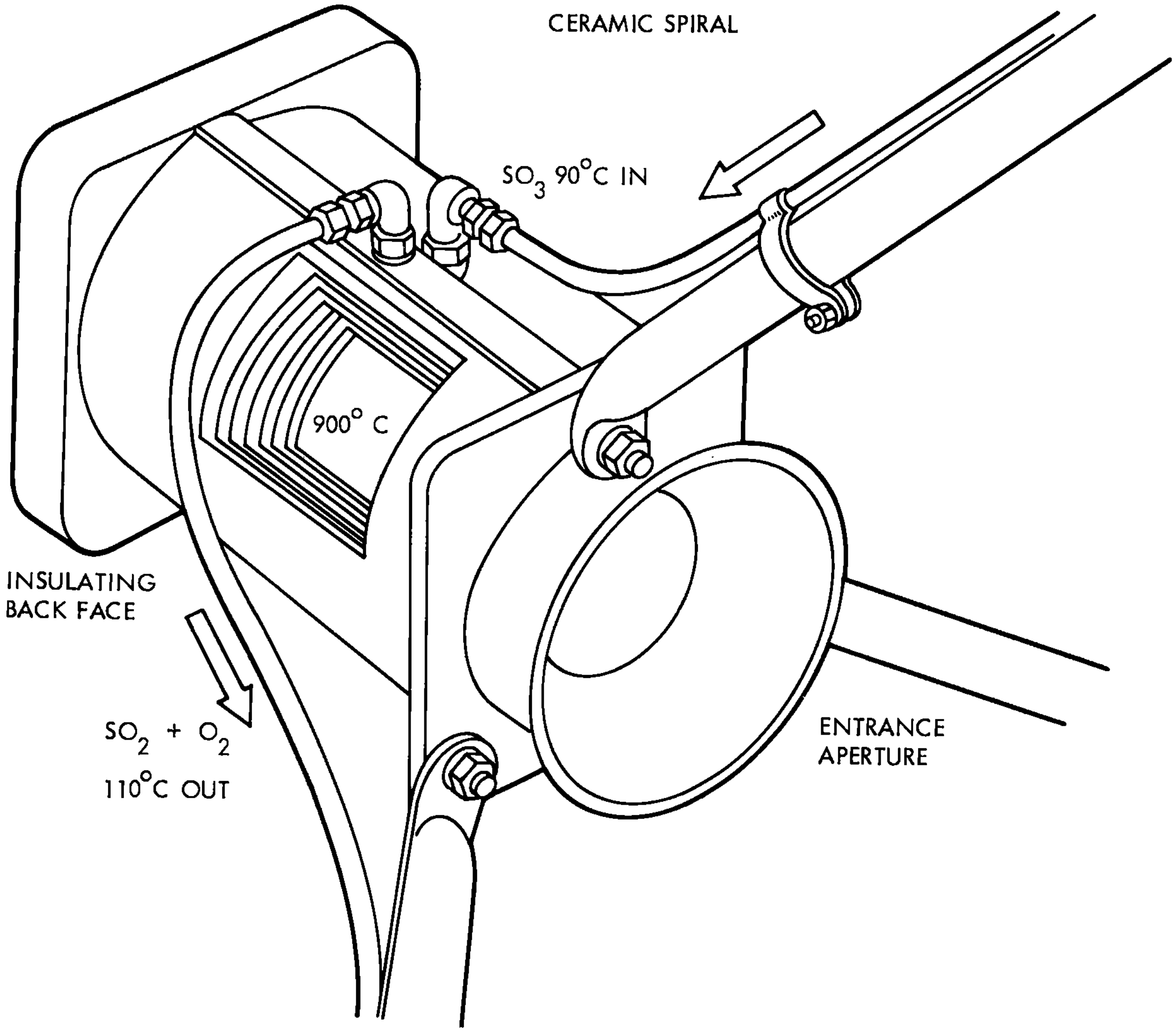

Figure 9. Artist's Conception of NRL Solchem Converter/Heat Exchanger

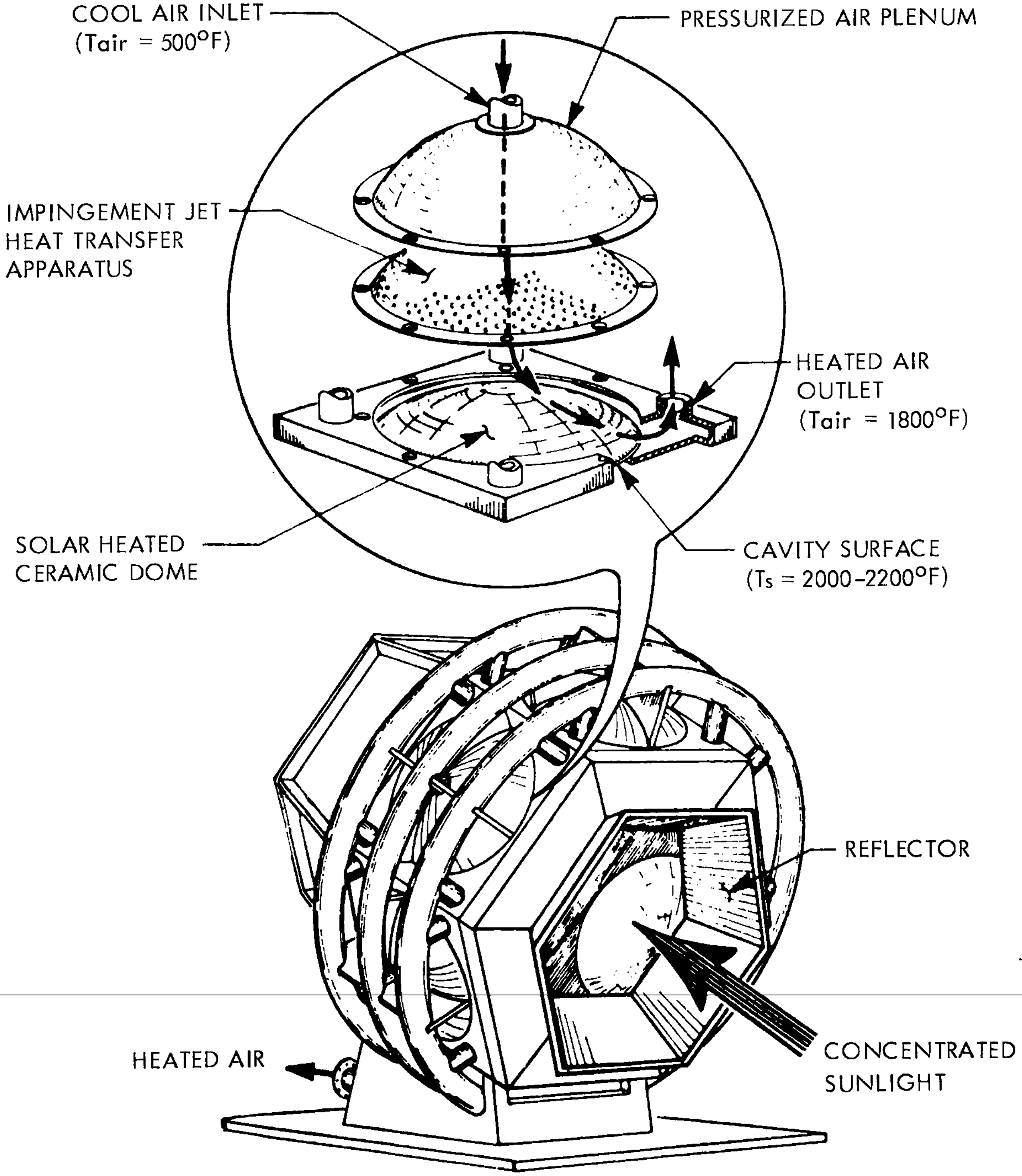

Figure 10. Artist's Conception of a MIT/LL 1 MWth Ceramic Dome Receiver

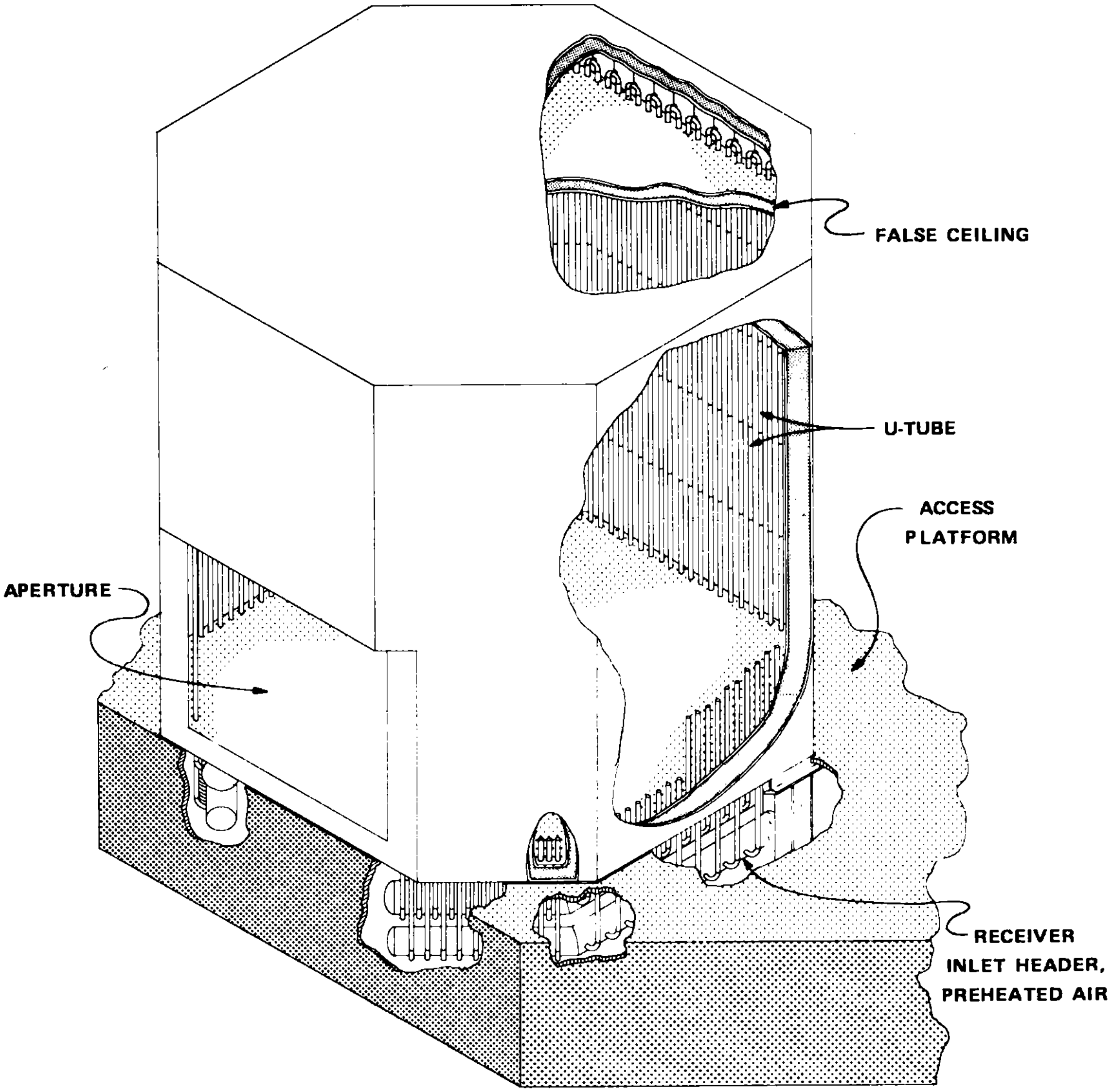

Figure 11. Cutaway View of Black and Veatch/EPRI Ceramic Tube Cavity Receiver

fluid is heated by flowing through the tubes to power an open cycle Brayton engine. The outlet temperature of the air is 1000°-1100°C (1832°-2012°F). Maximum hot face temperature is approximately 1200°C (2200°F). The internal operating pressure is about 140 psi. The operating conditions of the Black and Veatch receiver are summarized in Table 2.

D. SANDERS CERAMIC HONEYCOMB

The Sanders receiver designed to heat air to power an open cycle Brayton engine is shown in Figure 12.[11] Air is supplied to the constant RPM turbine at a temperature of 1500°F and a pressure of 35 psia. The receiver has several interesting ceramic features even though the body of the receiver remains metallic. First there is a fused silica window over the aperture sealing the cavity from the outside atmosphere. The second feature is a ceramic honeycomb structure that serves as the heat exchange medium for the working fluid. The air enters the receiver upstream of the honeycomb structure at a temperature of 1050°F and is heated as it flows through the honeycomb. The hot face temperature of the honeycomb structure is approximately 1800°F. A third ceramic feature in this receiver design is a 10 minute storage buffer which consists of a ceramic storage medium. This buffer is designed to provide heat to the turbine during short periods of reduced solar flux and is controlled by appropriate valving. This receiver is designed to operate with an input of 60-85 kWth for use with distributed systems. A variable flux controller on the aperture is used to block excess solar flux when the input power exceeds a given level. The aperture size is 18-20 cm, and the diameter of the window is 21.6 cm. Information pertinent to the Sanders honeycomb receiver can be found in Table 2.

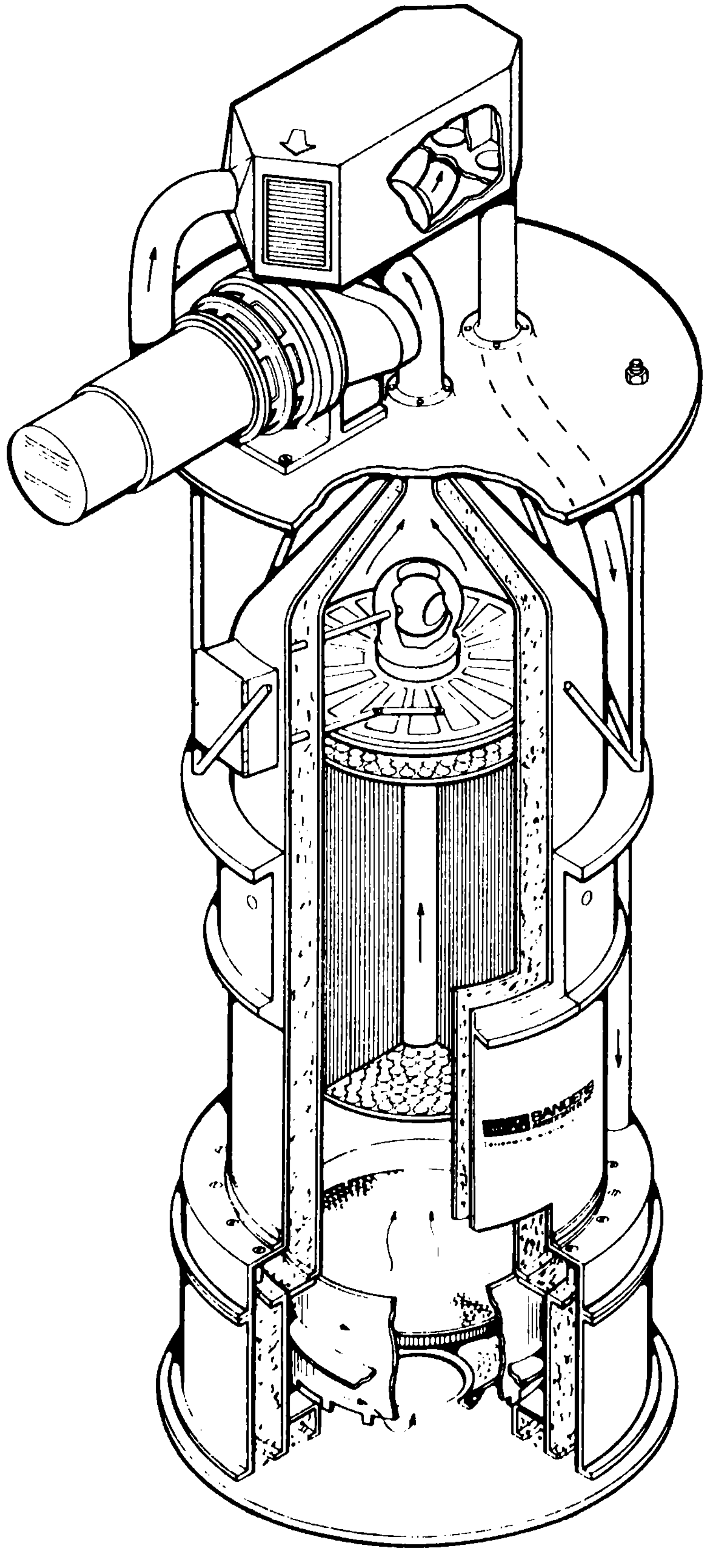

Figure 12. Sanders Receiver with Air Brayton Engine Attached

SECTION V

MATERIAL FUNCTIONAL REQUIREMENTS

An integral part of Performance Prediction Modeling is the determination of the material functional requirements. The previous sections examined system requirements (which either directly or indirectly affect the performance of ceramics in solar thermal receivers) and the preliminary receiver design. This section will use that information and specific technical design data to determine the functional requirement of ceramic components in the existing receiver designs discussed. Some material properties which are expected to be potential problem areas include: strength, elastic modulus, slow crack growth, creep behavior, thermal shock, thermal conductivity, thermal expansion, oxidation, working fluid compatability, and sealing/joining problems. Generic problems of using ceramic materials in solar thermal receivers will be identified from this analysis. The establishment of functional requirements permits Performance Predictions of various candidate ceramic materials.

It should be noted that in the majority of the receiver designs a particular material has been specified. The intent of this study is to use the receiver designs as a means to determine functional requirements independent of particular materials. The baseline material candidates will function as starting points for Performance Prediction Modeling. These baseline materials should not affect the material functional requirements determined for each receiver design.

A. NRL SOLCHEM CONVERTER/HEAT EXCHANGER

Two basic receiver designs exist for the NRL converter/heat exchanger. One is a calendered tape design developed by Coors Porcelain Co. A second design consisting of a coiled extruded tube network has been developed by Ontario Research Foundation.

The Coors approach to generating circumferential flow passages involves use of calendered tape similar to the tape process used in the manufacture of turbine regenerator discs. The difference in the two processes is that the ribs are parallel to the center line of the tape for the receiver and perpendicular to the center line in the regenerator disc. A thin wall calendered tape is shown in Figure 13. Two layers of this ribbed tape are coiled on a mandrel while still in a plastic state. The diameter of the receiver cavity is varied by changing the mandrel diameter. The current mandrel size is eight inches.

The tape material is Coors CD1 cordierite with a nominal composition of $2M_gO\cdot 2Al_2O_3\cdot 5S_iO_2$. Two percent barium oxide is added to increase the firing range. The tape is plastic ceramic (a glass frit which has been plasticized) that is extruded into tape form and then rolled with a calendered roller to produce the ribs. The glass frit crystallizes during carefully controlled firing to form a polycrystalline cordierite ceramic.

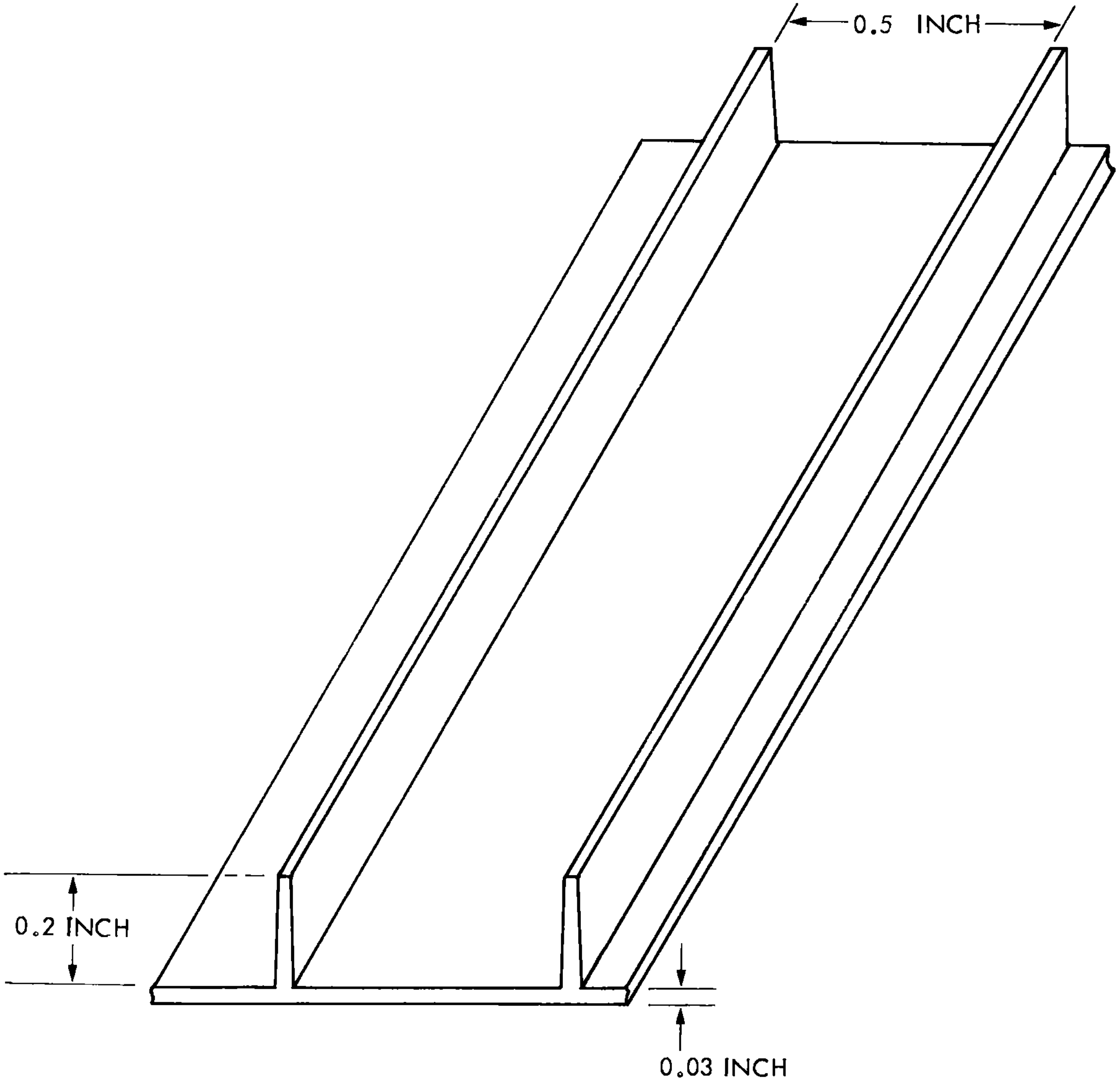

Figure 13. Portion of Coors Thin Wall Calendered Tape

The Ontario Research design is an extruded tube network that is coiled into a planar spiral. The receiver is formed by stacking these spirals onto one another. A typical coil with cross section detail is shown in Figure 14. The spirals are formed by coiling the plastic extrusion on mandrel similar to the Coors design. This design is different from the Coors design in that insulating airspaces exist between layers. Both designs have the inner ends sealed together to form one continuous flow passage for the gas mixture. The catalyst (probably platinum) will be applied either to the inner coil surfaces or on catalyst supports which are inserted into the coils.

The Ontario Research coils are also composed of cordierite. This material is a traditional ceramic formulated by mixing the appropriate raw materials. The final composition is 98% crystalline cordierite with a glassy phase between grains. This type of ceramic must be carefully processed to avoid the formation of a detrimental phase like free silica. Silica undergoes volumetric phase transformations with temperature changes that can cause cracking of the ceramic and increases in the thermal expansion coefficient.

The Coors and Ontario designs will be analyzed together since many similarities exist between them. This analysis will be divided into three areas each concerning a group of properties. The first area is mechanical properties which include strength, elastic modulus, thermal stresses, slow crack growth, and creep. The second area is thermal properties which include thermal shock, thermal conductivity, and thermal expansion. The final area is chemical properties. Included in this area are working fluid compatability, oxidation, vaporization, and sealing/joining problems.

The high temperature strength of the receiver material is important since failure of the receiver would release potentially dangerous gases. The working pressure of 45 psi for the NRL receiver does not generate severe stresses. The pressure must be contained within the structure of the receiver body. Typical forces exerted on each design from the internal pressure are shown in Figure 15. The Ontario coils have an additional stress created due to forces that attempt to unwind the coil similar to forces in a Bourdon tube. The Coors design does not have this problem because it is a monolithic honeycomb type structure.

Static thermal stresses are present and should be considered. The thermal stresses developed depend on the magnitude of the thermal expansion coefficient, but since it is the strength of the material which determines whether failure occurs thermal stresses will be discussed with mechanical properties. Both designs will have axial thermal stresses created on the walls of the receiver cavity due to uneven flux distributions. The Ontario design should tolerate these stresses easily since many different layers of coils form the cavity. The temperature gradient on each separate layer is small. This prevents large thermal stresses from developing. Radial thermal stresses will be developed. Radial stresses are due to a decreasing temperature profile outward from the center of the cavity. The Coors design is better suited to accomodate these stresses since the temperature difference between adjacent layers is small. Radial

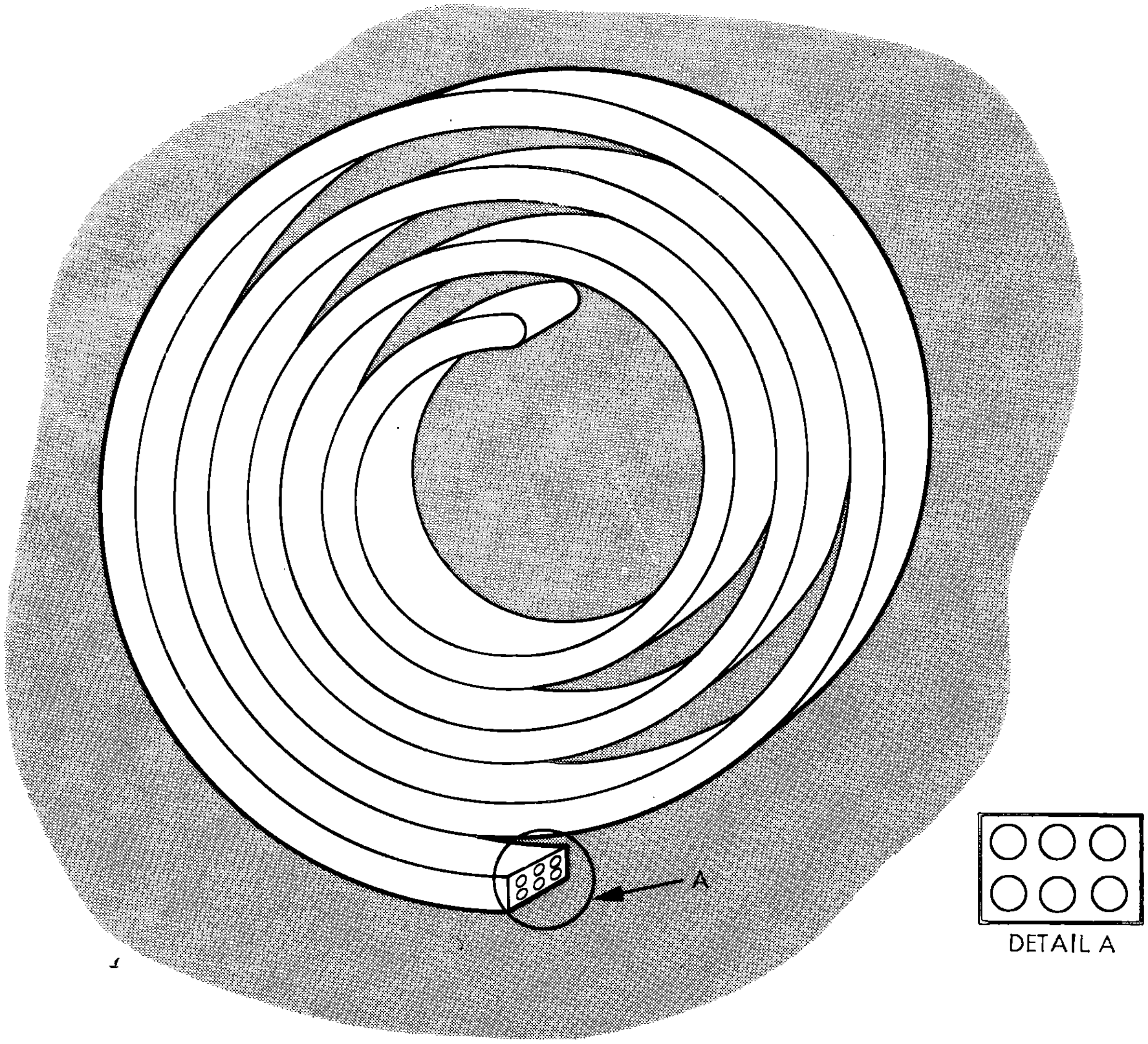

Figure 14. Ontario Research Foundation Extruded Coil

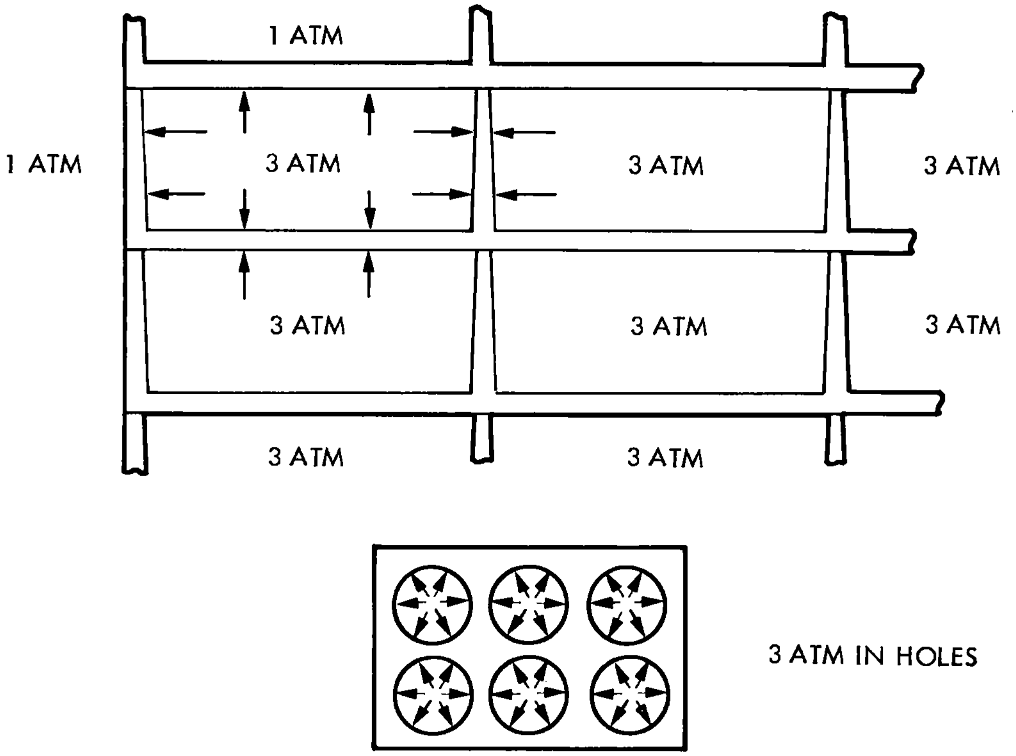

Figure 15. Forces Exerted on NRL Solchem Receivers Design Due to Internal Pressure

thermal stresses created in the Ontario design because the outside of the coil is cooler than the inside, will be of the same type as the stresses created by the forces trying to unwind the coil.

Slow crack growth resistivity is important. The receiver material is at a stress level that is less than the level required for fast fracture to occur, however the growth of microcracks or flaws present in the receiver can cause unpredictable failure to occur. Slow crack growth often progresses through various stress corrosion mechanisms, so the effect of the SO_2/SO_3 environment on the slow crack growth resistivity should be determined. The temperature dependence of the slow crack growth resistivity should be determined since the receiver operates at elevated temperatures for long periods of time.

Creep is another property that becomes more important as use temperatures increase. The creep rate is primarily dependent on the stress, temperature and environment. Our current understanding of the NRL receiver designs indicate relatively low stresses, so creep should not be a problem at the proposed operating temperatures. It is difficult to distinguish creep behavior from slow crack growth at high temperatures since both cause the same type of deformation in a specimen. Separation of slow crack growth and creep phenomenom is important since they affect the structural performance of the receiver in different ways.

Thermal shock is a very critical condition that the receiver must survive. The worst case of thermal shock would occur when a heavy cloud obscures the concentrator on a sunny day for several minutes. In this case the solar insolation will drop from a high level to zero instantly. The magnitude of the thermal shock will be determined by the rate of temperature drop in the receiver. The rate of temperature drop will primarily be determined by the rate of heat removal. In the NRL Solchem receiver, it is difficult to determine the exact heat transfer rate because it depends on the rate of chemical reaction. Thermal shock is also possible when the cloud uncovers the concentrator causing the temperature to increase rapidly. Thermal shock from a temperature increase is not as extreme as for a temperature decrease because the surface is put in compression. Ceramic materials are stronger in compression than in tension. Thermal shock conditions will be encountered both on startup and shutdown.

The thermal conductivity at the operating temperature is an important property of the receiver material. Good thermal conductivity tends to lessen the danger from thermal shock. It will also help lessen the thermal stresses created from unequal flux distributions. Materials with good thermal conductivities can have greater wall thicknesses to improve the structural integrity while still maintaining adequate heat transfer rates. The Coors design does not appear to be limited by heat transfer rates because of the thin wall dimensions. The Ontario design has potential heat transfer problems due to the thick walls of the extrusion. Heat transfer problems will be compounded if catalyst supports are placed in the coils, rather than having the catalyst on the channel walls.

Thermal expansion is the final thermal property important to material performance in solar receivers. Thermal expansion in itself is not a critical property, but it does greatly influence both the thermal shock resistance and thermal stresses. Materials with low thermal expansion coefficients have better thermal shock resistance and smaller thermal stress levels. No problems are foreseen with regards to thermal expansion in the NRL designs other than the affect on the thermal stresses created and the thermal shock resistance which have been discussed previously.

Working fluid compatability is one of the chemical properties that is especially important in the NRL receiver. SO_3 and SO_2 are both very corrosive gases which can affect the receiver material in several ways. These gases can have detrimental affects on the strength and slow crack growth resistivity. SO_3 will react with any water present in the system to form sulfuric acid. Sulfuric acid has caused degradation of glass ceramic regenerator cores in gas turbine engines so this is a potential problem. SO_3 itself is very reactive and might react with the receiver material to form some type of sulfate. Oxidation of the surfaces exposed to air is not expected to be significant since the material is itself an oxide.

Sealing problems are not expected since neither the inner seal nor the outer seal are subjected to high stresses. Both the inner connection of inflow and return channels at the end of the spiral and the outer connection of the channels to the manifold are made while the coil is in a plastic state. This lessens the problems expected since the seals are fired as integral parts of the coil.

B. MIT/LL CERAMIC DOME RECEIVER

A specific receiver design for point-focusing distributed applications has not been developed. A likely receiver design would use one or more ceramic domes to form the cavity. To date a 12-inch diameter dome mounted in a support structure has been discussed and this design will form the basis for analysis in this study (Figure 16) The current dome material is SiC. Both Norton NC-430 (a siliconized SiC) and Materials Technology Corporation chemical vapor deposited SiC are being fabricated into dome structures. The current dome is a 12-inch diameter hemisphere. Several seal techniques have been explored. The most likely seal candidate is a mechanical contact seal formed by lapping the dome to an insulating support ring. The opposite side of the support ring is sealed by a pressurized metal O-ring as illustrated in Figure 17. Alternate seals include metallization of the dome to which a diaphragm seal is brazed.

A structural benefit of using ceramic materials in compression is obtained by the MIT/LL design. In the absence of a thermal gradient a pressure on the convex side of the dome creates compressive stresses throughout the dome.[12] The compressive stresses calculated for a simply supported hemispherical dome (6 inches radius, 0.125 inch thickness) from an external pressure of 45 psi is 1080 psi.[13] A thermal gradient through the dome wall of 400°C/inch was assumed. This type of gradient puts the top of the dome in tension and the bottom in compression because the bottom expands a greater amount than the top. The compressive stresses from the external pressure can be superimposed over the thermal stresses. Even though this reduces the tensile stresses created, some residual tensile stresses remain which must be taken into account in the dome design.

Thermal stresses are created by the temperature gradient through the dome wall, assumed to be 50°C for an 1/8 inch thick wall, and by an uneven flux distribution on the dome surface exposed to the solar flux. The temperature gradient through the dome wall was taken into account in the earlier stress analysis. The thermal stress created from the solar flux distribution will alter the stresses expected in the dome. This is one source for tensile stresses in the dome. Thermal stresses may contribute to seal leakage or failure. A tensile stress created will tend to rock the dome on the insulating ring which will reduce the seal contact area (Figure 18) possibly causing the leak rate to increase. A design goal for the ratio of leakage flow to impinging flow is 10^{-2}.

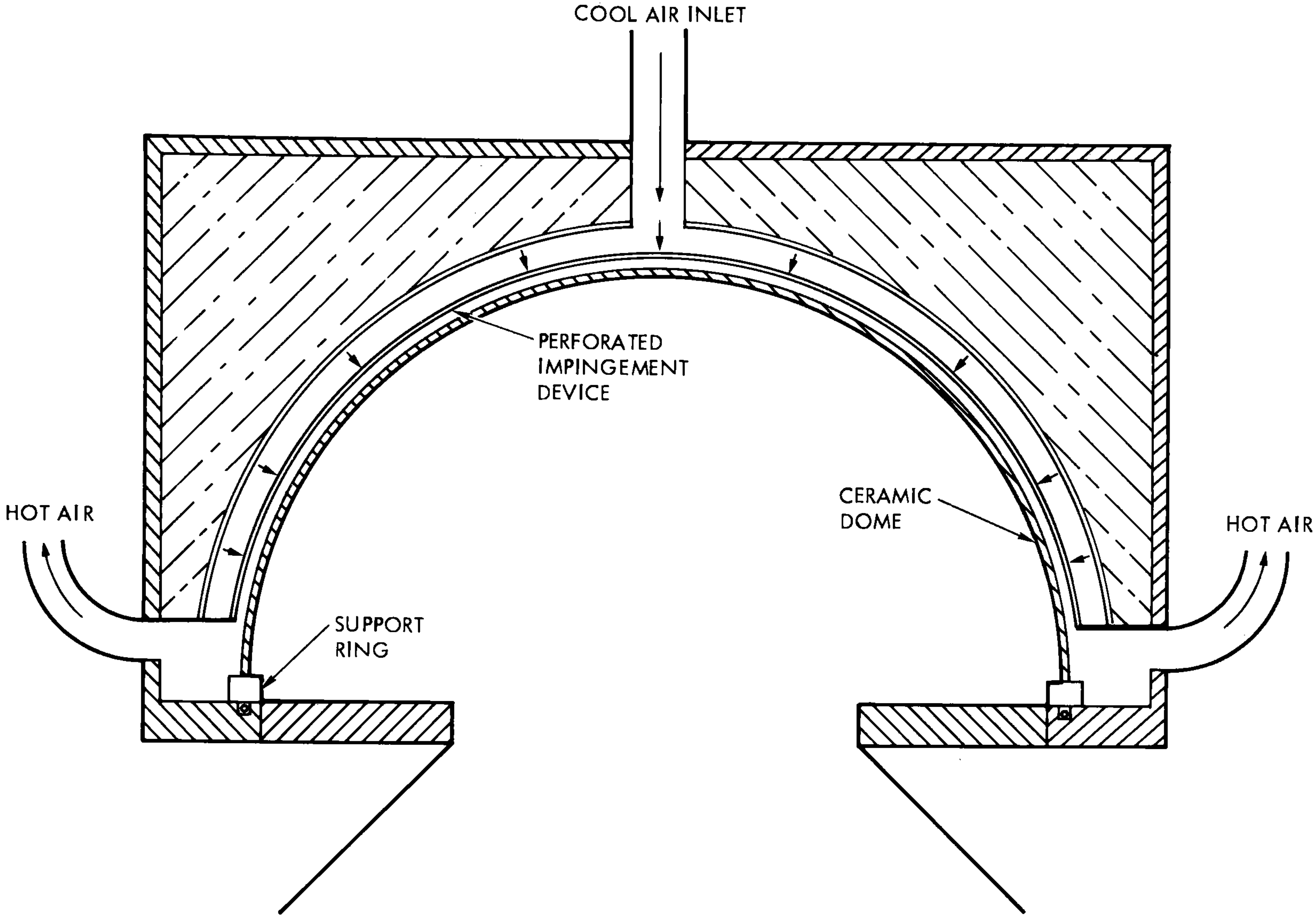

Figure 16. Possible Brayton Receiver Design Employing MIT/LL Ceramic Dome

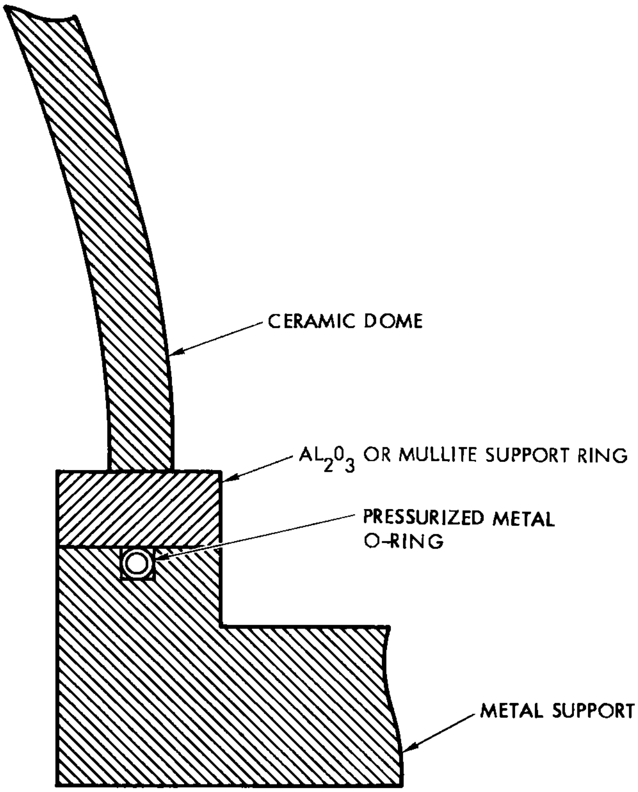

Figure 17. Leading Candidate Seal in MIT/LL Ceramic Dome Receiver

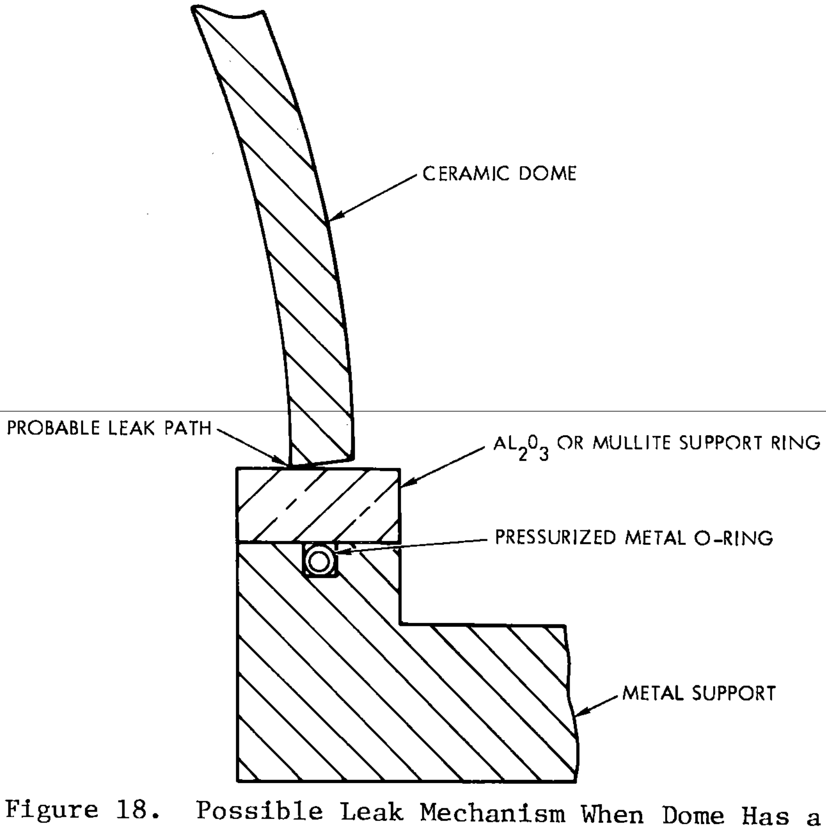

Figure 18. Possible Leak Mechanism When Dome Has a Radial Temperature Gradient Present

The variation of elastic modulus with temperature is important because buckling of the dome can cause failure. The dome acts as a thin wall membrane so buckling criteria must be examined for this receiver. A decrease in elastic modulus with increasing temperature can cause the dome to buckle even though the dome was stable at lower temperatures. Once buckling occurs tensile stresses created in localized regions can initiate failure.

Slow crack growth should be considered for this application. Potential for slow crack growth exists when tensile stresses are present in the dome. Slow crack growth should not be enhanced by anything in the proposed receiver environment. Slow crack growth is not anticipated to be a problem in compressive states.

Creep has a high potential for trouble because of the combination of relatively high temperatures and stresses. Creep can occur at temperature when the receiver is in either compression or tension so there are no circumstances when creep will be eliminated totally. Creep of the dome may slowly change the tolerances of the sealing surface increasing the leak rate.

Thermal shock resistance of the receiver is a major problem. A large area of dome surface is exposed to the solar flux. The dome surface is at a high temperature and the heat transfer process is very efficient. A large temperature drop in the dome surface is unavoidable when a cloud covers the concentrator. Thermal shock may cause seal failure since the seal forms discontinuity in the structure.

Thermal conductivity affects the rate of heat transfer through the dome. Good thermal conductivity of the dome material allows a thicker wall for better strength. The temperature gradient and associated thermal stresses will be reduced as thermal conductivity increases.

Working fluid compatability and oxidation resistance are the same since air is the working fluid. An oxidation resistant material is necessary to reduce loss of structural material through oxidation. If the oxidation rate is reduced by the formation of a protective oxide layer the effect of thermal cycling on this layer must be known. Air flow over the receiver dome is increased by the impingment device. Dust present in the air might eventually cause erosion of the back side of the dome. The air should be clean to prevent turbine damage as well.

Finally, seal techniques involving metallization and brazing are classified as a chemical problem. The braze material should adhere to the metallized ceramic without peeling or fracture. Vaporization or oxidation of the refractory metals used here could be a problem.

C. BLACK AND VEATCH/EPRI CERAMIC TUBE RECEIVER

The Black and Veatch receiver is an octagonal cavity (Figure 11). The inside of the cavity is lined with 9 inches of firebrick. Subsequent layers of insulating materials reduce conduction through the receiver wall. Ceramic U-tubes are located on the cavity side of the firebrick lining. The supply leg of the U-tube is attached to an inlet header that supplies preheated air. The return leg of the U-tube is attached to a manifold that carries heated air to the turbine. The option exists to place the top portion of the U-tube above the cavity ceiling which would allow the U-tubes to be loaded in compression. The diameter of the U-tubes is four inches. The cavity height is 40 feet. The north facing cavity rated at 69 MWth contains 88 U-tubes and is the largest of the four cavities. Tube spacing and size is affected by two parameters. Two ratios, the tube spacing to tube diameter (S/D) and tube offset from the cavity wall to tube diameter (O/D), that were developed to maximize the tube placement are shown in Figure 19.

Strength is of primary importance in this application. The tube must contain the working fluid at a pressure of 135 psi. The internal pressure creates tensile circumferential stresses in the tube wall. When no thermal stresses are present, a 4-inch diameter tube with a 1/8-inch wall thickness will have circumferential stresses of 2160 psi.[14] The S/D ratio is important in determining the thermal stresses created. Thermal stresses are critical in this design because it is very difficult to evenly heat a tube that is exposed to direct solar flux from only one side. Heating the back and sides depends a great deal on reradiation from the cavity lining. Black and Veatch (Figure 20)[15] has shown the minimum stress levels are found with a S/D ratio of around 3:1. The stresses developed in the tubes are quite complicated due to the different factors affecting the tubes. Compression loading of the tubes will reduce the axial tensile stresses in the U-tubes. If compression loading is not employed axial stresses of about 1050 psi will be developed.

The temperature gradient through the tube wall is much smaller in magnitude than the circumferential temperature gradient and will not contribute significantly to the thermal stresses created. Similarly a temperature gradient in an axial direction will not cause significant stresses if the tube is free to expand axially. Use of a compressive tube loading mechanism would reduce the tensile stresses created from axial temperature gradients. It appears that localized stresses (i.e. circumferential stresses) created are the most critical design requirement in determining performance of the tube. The design of the tube and receiver is such that other thermal stresses are largely eliminated.

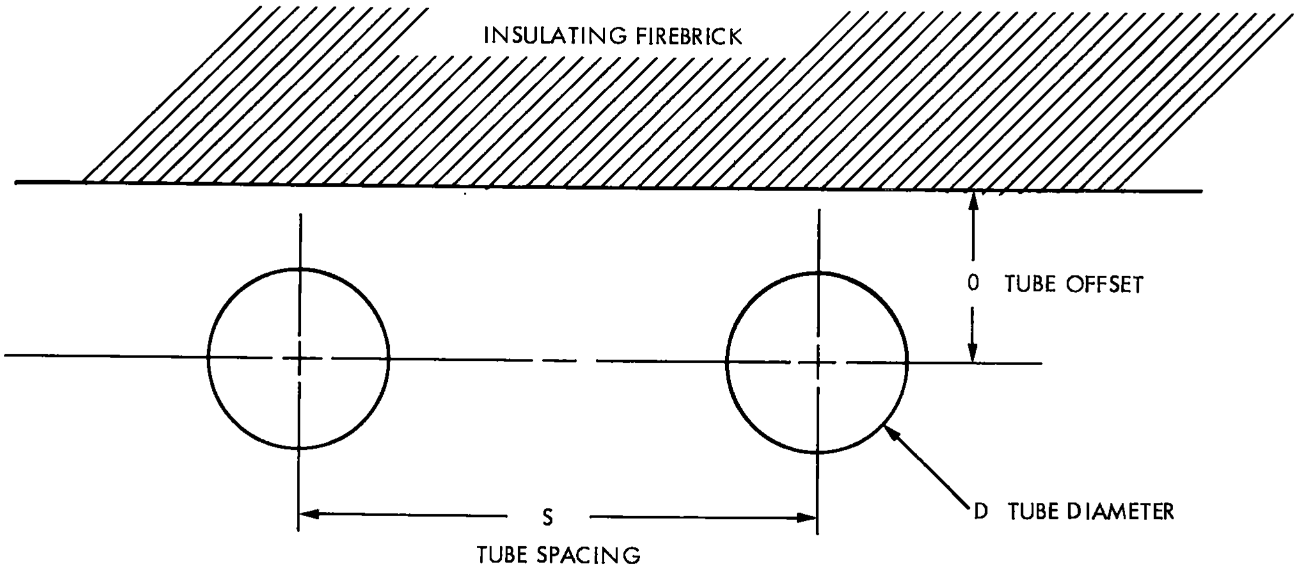

Figure 19. Diagram Illustrating S/D and O/D Parameters in Black and Veatch/EPRI Receiver

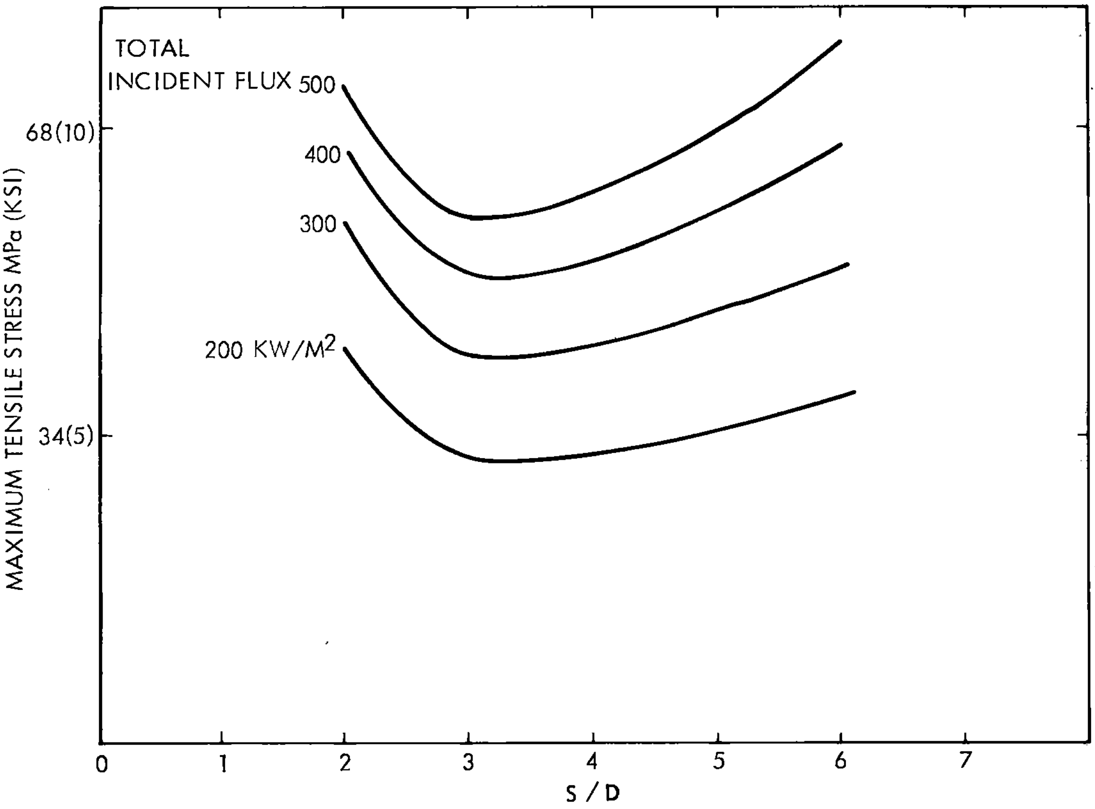

Figure 20. Tube Stresses as a Function of S/D Ratio in Black and Veatch/EPRI Receiver

Slow crack growth resistivity of the tubes is important. There are sufficient stresses present for microcracks in the tubes to grow large enough to cause failure. Creep of the tubes is another critical design requirement. The tubes are at stress/temperature combinations where creep of the tube material could be important during the predicted lifetime of the tube.

Thermal shock can affect either the ceramic tubes or cavity lining. Thermal shock from cloud coverage would be more severe on the tubes than it would on the receiver lining. Air would continue to be supplied to the tubes until the power output of the turbine drops enough to equal the power required by the compressor. After this point the airflow through the tubes will drop. This is the most severe case of thermal shock that can be developed. The maximum temperature drop of the tube material was calculated to be 100°C/minute.[16] Thermal shock conditions of the firebrick lining will not be as severe as for the tube since the rate of temperature drop will be less. Any thermal shock damage that does occur will probably be some type of surface spalling. Spalling would eventually cause the loss of enough material to necessitate relining of the receiver cavity. Thermal shock from a sudden temperature rise would be better tolerated by the tubes than by the lining, especially if the lining had cooled down significantly.

Thermal conductivity of the tube material is important in reducing thermal gradients in the tube. High thermal conductivity through the tube reduces the radial temperature gradient, but does not significantly affect the circumferential or axial gradients. These temperatures are primarily determined by the flux distribution (both direct and reradiated).

The working fluid is air. Oxidation of both the inside and outside of the tubes will occur since both hot surfaces are exposed to air. Oxidation of the firebrick lining will not be a problem since the firebrick are composed of oxide materials.

D. SANDERS CERAMIC HONEYCOMB RECEIVER

A section of the Sanders receiver is shown in Figure 21.[17] This receiver has three separate ceramic components. Two of these components, the window and the honeycomb heat exchanger, are exposed to concentrated solar flux. The third ceramic component is a honeycomb matrix that serves as a thermal storage medium. The honeycomb heat exchanger is the critical component in this design and its requirements will be examined in detail. A limited examination of the functional requirements pertaining to the receiver window and thermal storage medium will be performed.

The inlet scroll is an important part of this design. Both the scroll and a series of screens combine to distribute the air flow uniformly through the honeycomb matrix by means of a slight pressure drop. A uniform flow through the honeycomb matrix heat exchanger reduces the probability of a localized hot spot and increases the efficiency of the receiver.

The honeycomb heat exchanger matrix is a 22-inch diameter disk mounted in a compliant structure. The matrix is located 11 inches behind the aperture. This distance minimizes the radial flux distribution across the honeycomb (Figure 3) while still capturing a large portion of the incident flux. Since the matrix is mounted in a compliant fixture, the strength requirements are minimal from a structural aspect. Very slight mechanical stresses are applied since the pressure drop through the matrix is only 0.012 psi.[18]

Strength requirements due to thermal stresses are more severe in this application due to the thermal gradient through the honeycomb matrix. A temperature drop of 300°F occurs through this honeycomb since the hot face is at 1800°F and the back face is at 1500°F. Figure 22 shows a typical temperature profile through the heat exchanger matrix. A matrix material with a high absorptivity can reduce the thickness of the disk while still maintaining adequate heat transfer properties. Thermal stresses created can be reduced by placing two thinner honeycomb sections together thus reducing the temperature drop through each section. The effective stresses for a 1.3 inch thick cordierite honeycomb section have been calculated using

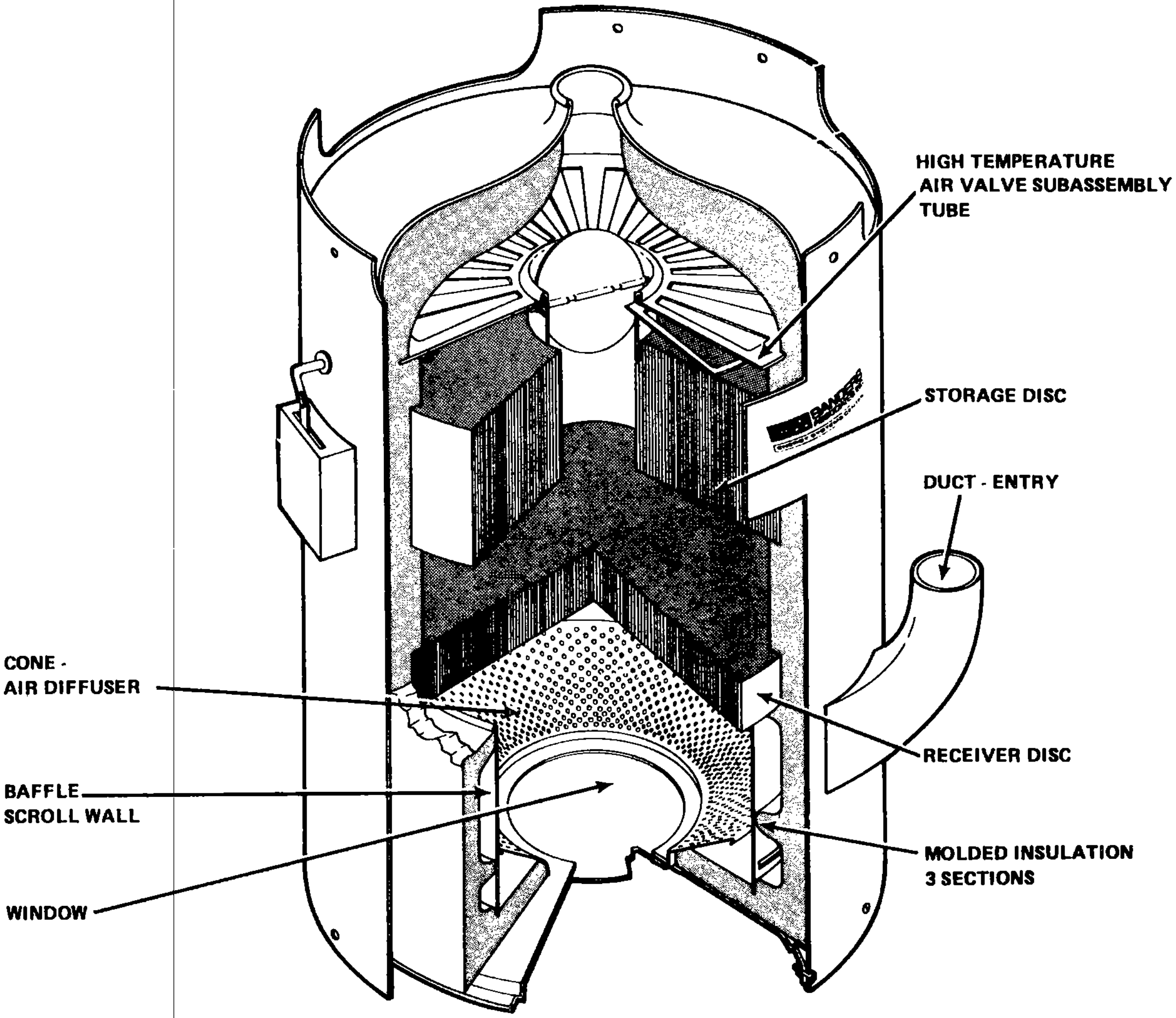

Figure 21. Section View of Sanders Receiver

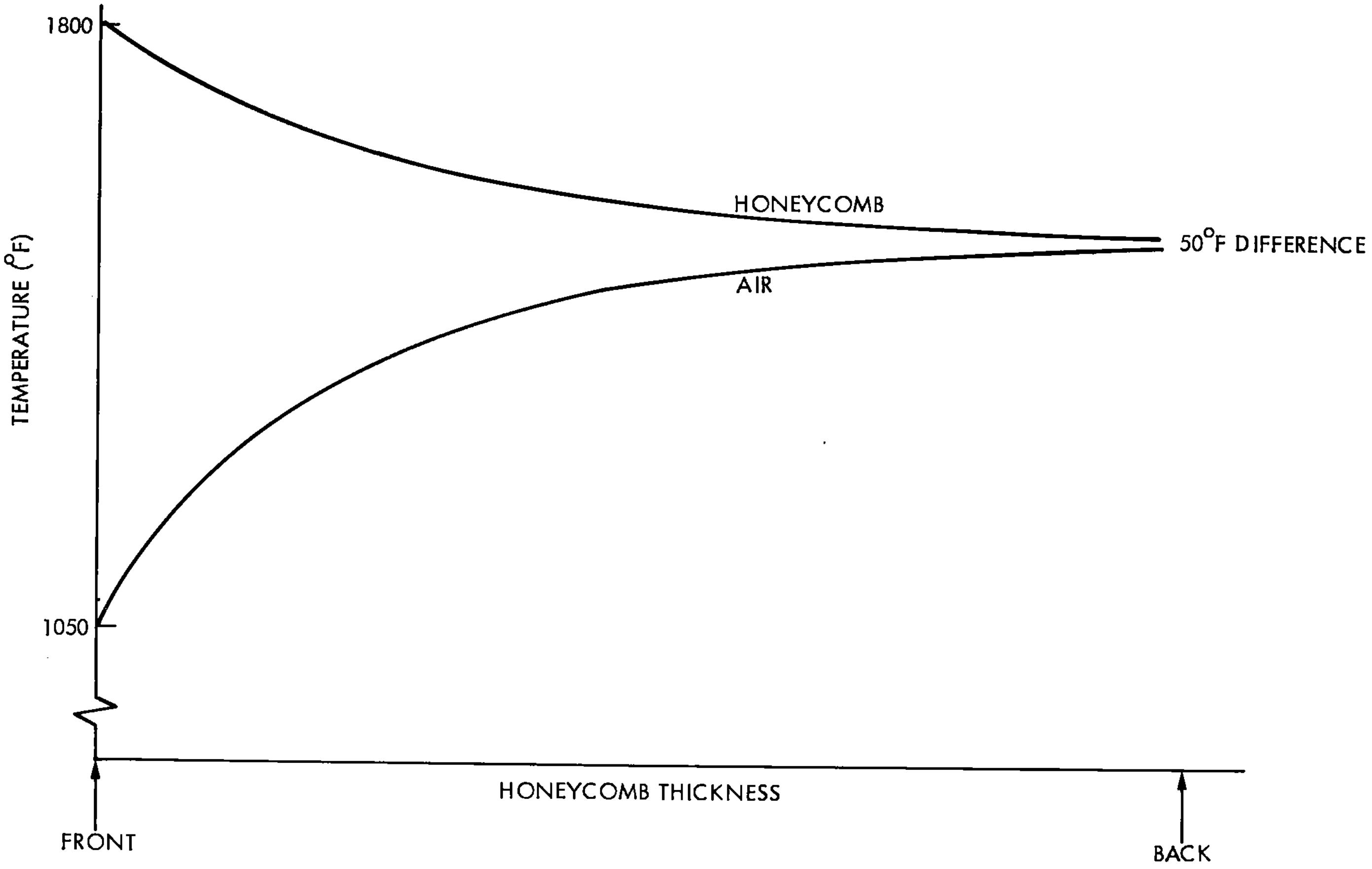

Figure 22. Temperature Gradient through Honeycomb Heat Exchanger Matrix

finite element analysis to be 220 psi.[19] For a 1.3 inch thick SiC honeycomb section the stresses are 20,000 psi. A low thermal expansion coefficient and a high modulus of elasticity can reduce the thermal stresses that are created.

Slow crack growth resistivity of the honeycomb material is not as important as in other receiver designs since local failure of the honeycomb heat exchanger does not represent a serious safety or performance problem. Local failure consists of cell wall cracking resulting in obstructions in the air flow. Gross failures of the honeycomb matrix from slow crack growth should be addressed, since this type of failure would reduce the receiver performance. Therefore, the probability of failure from slow crack growth at the normal operating stresses should be considered. Replacement of a defective honeycomb heat exchanger in this design should be relatively inexpensive and easy.

Thermal shock to the honeycomb matrix is a potential problem. The effect of thermal shock on honeycomb geometries has not been well documented. Therefore, a question of the performance of the heat exchanger matrix when thermally shocked should be considered. Cloud coverage will be the most severe case of thermal shock encountered. The temperature of the heat exchanger will decrease rapidly if the large air flow rate is maintained. Heating after the cloud passes should similarly produce a rapid increase in temperature. The temperature drop will be more rapid for a constant RPM turbine since a nearly constant air flow is maintained during cloud passage.

Compatability of the matrix material with the air working fluid should be considered. Oxidation will be the principal concern in this design. The effect of oxidation on properties such as slow crack growth resistivity, strength, and absorptivity will be important for matrix materials other than oxides. The heat exchanger material must not erode significantly in the air flow. Erosion of the heat exchanger matrix should not be significant since the air velocity through the matrix is low. The effect of erosion of small particles on the turbine will be discussed in the thermal storage section.

Heat losses which reduce the efficiency of any non-windowed receiver fall into three categories. These are: reradiation, conduction, and convection. Reradiation depends primarily on aperture size and cavity temperature. At the design point reradiation losses are 4% for this receiver. Four inches of insulation reduce conduction losses through the wall to maintain a 150°F shell temperature. Convection losses are largely eliminated through the use of a window over the aperture.

This receiver design utilizes a transparent window 8.5 inches in diameter to contain the working fluid and reduce convective losses. A fused silica window 0.625 inches thick is sealed by a high temperature gasket. For a pressure of 30 psi the maximum calculated tensile stresses are 1700 psi.[20] Exhaust air from the recuperator cools the window. A window reduces the amount of flux reaching the receiver cavity. Losses from reflection average 8% for solar windows (4% from each surface). Flux reductions also occur from absorption of the solar radiation in the window itself. These losses approximately equal the convective losses so windows do not greatly alter overall receiver efficiency.

Windows for solar receivers should have several properties. Good windows should have a high transmission in the solar spectrum. The window material should resist degradation from high temperatures. A window near the focus of the concentrator will be exposed to the high temperature of the receiver. Heating of the window will occur by convection and by direct absorptance of both incident and reradiated energy. A window material with a low absorptance will also increase the efficiency of the receiver since more energy reaches the heat transfer surface, and will reduce the window temperature increase caused by absorption. The change in absorptance (both in the solar and infrared spectra) with temperature is important since the window will operate at elevated temperatures, and much of the reradiated energy is in the infrared region. The absorptance also increases with increasing window thickness.

Low window temperatures are often necessary to maintain the phase stability of the window material. For example, high temperatures would increase the natural tendency of fused silica to devitrify. Devitrification due to continued exposure to elevated temperatures would reduce the amount of transmitted light. Reasonable window temperatures should be maintained by auxiliary cooling. The window must also be able to withstand all the operating conditions of the receiver. In addition to temperature and pressure requirements, windows used in other applications (such as a fuels and chemicals process) would have to be compatible with the chemical compounds of the reaction and still maintain their structural and optical properties. Any reaction of the window material with the fuel or chemical present could increase the absorptance of the window and decrease the structural properties. The Sanders window should not experience any compatability problems with air. Slow crack growth may eventually cause failure at the predicted operating stress.

The thermal shock resistance of the window material is important, but not as important as in receiver heat exchange material. Thermal shock conditions are lessened because the temperature rise is gradual, thus allowing a majority of the radiation is transmitted through the window. The thermal shock conditions encountered will be aggravated by a window that has a high absorptance. Thermal shock of fused silica from the concentrated flux levels anticipated for this design should not cause failure.

This report will not describe all the different types of heat storage designs. Since the Sanders design uses heat storage, its particular requirements will be discussed here. The Sanders receiver uses a sensible heat storage design to provide a 10-minute buffer during periods of solar outage. A perforated retaining grid supports a mullite honeycomb storage medium.

The mullite honeycomb has a diameter of 1.76 feet and a solid fraction of 0.4. The mullite matrix is 18 inches long. A system of valves and ducts permits the air flow to be directed as required. Air bypasses the storage section once it is completely charged. A pressure drop of 0.175 psi through the honeycomb occurs during storage operation.

The thermal storage system is designed such that a thermal front propagates through the storage matrix. Air enters at a high temperature and rapidly looses its thermal energy as it proceeds through the storage matrix during the charging operation. A thermocline thus exists between the inlet and exit of the storage. The thermal and mechanical stress levels are low in this design. No mechanical loads are placed on the storage honeycomb except for a very low pressure differential. A gradual increase and decrease in the temperature during operation of the honeycomb storage matrix prevents large thermal stresses. Thermal shock should not be a severe problem since the heat exchanger honeycomb is located in front of the storage section. This arrangement should eliminate the thermal shock conditions encountered at the storage section. The honeycomb matrix must be stable and not produce dusting. Dusting of ceramics is the erosion of small particles which can have adverse affects on the turbine blade materials.

SECTION VI
SUMMARY

This report covers the first part of an effort that has been undertaken by the JPL/ASTT project to evaluate the use of ceramic material for applications in point-focusing distributed solar receivers. A Performance Prediction Modeling methodology has been utilized to facilitate this effort. Performance Prediction Modeling, under development at JPL, is a systematic assessment methodology for evaluating materials performance. The methodology has been defined and described.

The information presented in this report comprises the first part of the Performance Prediction Modeling process as applied to ceramics in point-focusing distributed solar receivers. This commenced with the determination of the thermal power systems requirements including the effects due to the operating environment upon the receiver and also the operating parameters required by the various receiver heat engines. Following in sequence, the existing receiver conceptual designs were described. These included the NRL solchem converter/heat exchanger, the MIT/LL ceramic dome receiver, the Black and Veatch/EPRI ceramic tube receiver and the Sanders ceramic honeycomb receiver. To conclude this interim report, the material functional requirements were determined for each of these designs.

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