SANDIA REPORT SAND84-8229 • Unlimited Release • UC-62e
Printed July 1984

Technical Review of the Solid Particle Receiver Program January 25–26, 1984

P. K. Falcone

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF 2900-Q(6-82)

Printed in the United States of America
Available from
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A04
Microfiche copy: A01

SAND84-8229 UC-62e
Unlimited Release
Printed July 1984

TECHNICAL REVIEW OF THE SOLID PARTICLE RECEIVER PROGRAM
January 25-26, 1984

Compiled by
Patricia K. Falcone
Solar Components Division
Sandia National Laboratories, Livermore

ABSTRACT

A technical review of the solid particle receiver program was conducted on January 25-26, 1984, at Sandia National Laboratories in Livermore, California. The meeting was held to discuss the status of the technical feasibility investigations one year into the study and to set direction for the future. This document includes summaries of the presentations made at the meeting as well as an overview of the program.

CONTENTS

Paper 1.0
P. K. Falcone
Sandia National Laboratories

Introduction and Overview

The use of solid particles as the working fluid and storage medium in solar central receivers is one approach to delivering solar energy at temperatures above the nominal 550°C (1100°F) peak of current water-steam and molten salt central receiver technologies. The technical feasibility of the solid particle concept is the subject of an ongoing examination at Sandia National Laboratories Livermore (SNLL). A review of the individual investigations in this program was conducted in Livermore on January 25-26, 1984. The meeting was held to discuss the status of the technical feasibility investigations one year into this phase of study and to set direction for the future. The technical review meeting served three purposes. It provided a follow-up to the reviews held in January and July 1983. It afforded a means of reviewing what had been accomplished over the last year, and it presented an opportunity for adding to and revising planned work. Summaries of each of the individual presentations at the review meeting, as well as the meeting agenda and a list of meeting participants, follow this overview.

Motivation

Applications of current interest to the U. S. Department of Energy Solar Thermal Technology Program include the production of fuels and chemicals, the production of high-temperature industrial process heat, and the generation of Brayton cycle electricity. The development of central receiver technology to meet these applications builds upon the successful development of technologies for the production of Rankine cycle electricity and industrial process heat at temperatures up to about 550°C (1100°F). To achieve energy delivery at temperatures above these, the development of new working fluids and receiver hardware is required. Working fluids under consideration for these higher-temperature central receivers include gases--(e.g., air), liquids (e.g., carbonate salts), and solids (e.g., doped alumina pellets). The focus of the work described in this report is the assessment of the use of solid particles as a high-temperature working fluid. Also investigating solid heat exchange media in solar systems is C. Royere at C.N.R.S., Odeillo, France. Programs to investigate gaseous and liquid working fluids are ongoing elsewhere in the U. S. and foreign solar thermal programs (c.f. Ref. 1, 2).

Relative to these other high-temperature working fluids, especially air, solid particles appear to enjoy several positive features. Solids have high volumetric heat capacity and may receive concentrated solar radiation by direct absorption and transfer the energy to an application by direct heat transfer. Relative to the liquid systems, solid systems can be used over a wider range of temperatures and have minimal corrosion problems. Drawbacks of a solid working fluid include potential abrasion and solids handling difficulties.

Technical uncertainties which may limit the use of solid particles in a high-temperature central receiver were identified in early studies. Current work is focused on examining the uncertainties in greater detail with the emphasis on providing an assessment of the technical feasibility and recommended development path to the Department of Energy.

Background

A chronology of Sandia studies in this area is illustrated in Figure 1. The use of solids as the heat transfer and storage media in a high-temperature central receiver was initially investigated at Sandia in the summer of 1981 by J. Martin and J. Vitko (Ref. 3). In that work, they proposed a receiver and system concept for central receiver applications, performed scoping estimates, and investigated previous industrial use of solids as heat transfer media especially for chemical processing applications.

Following that study, an assessment study was initiated to evaluate the solid particle concept relative to other high-temperature receiver concepts (Ref. 4). In the assessment study, potential receiver configurations for solid working fluids were evaluated and the free-fall cavity concept illustrated in Figure 2 was selected as the candidate conceptual design. Performance estimates for the receiver required predictions of the residence time of the particles and of the heating rate. Simple models of particle aerodynamics and particle heating were developed in this study. Initial performance estimates of particle heating indicated that particle residence times should be on the order of two seconds. Single particle aerodynamic velocity estimates predicted that particle sizes of 0.1 to 1.0 mm were required to achieve such residence times.

The availability of components in a basic system configuration as illustrated in Figure 3 was investigated as part of the assessment study. Capabilities of solid lift systems, in particular, were examined. In addition, material availability and characteristics were investigated.

For comparison of this system with alternative high-temperature air systems, a systems analysis of a solid particle receiver was performed in which a solid-to-air heat exchanger is the end-use process. The estimate of the cost of energy delivered as hot air at nominally 1000°C was performed using the DELSOL II design and optimization computer code for central receivers. The specific application of heated air was selected so that the solid particle receiver concept could be compared directly with seven air-heating receiver concepts. Capital cost estimates for the solid particle receiver are compared with costs estimated in the hot air study (Ref. 5) in Figure 4. Costs are allocated among various plant components. For the solid particle receiver, costs for the solids themselves and the solid-to-air heat exchanger are indicated in lieu of the compressor required for air systems. As indicated in Figure 4, the solid particle receiver can be used to heat air for costs comparable with the least expensive air receiver concepts. Also included in this study was a parametric study to identify critical assumptions in the systems analysis. This analysis, coupled with the results of the other aspects of the assessment study, formed the basis for the ongoing investigations in the technical feasibility study.

Current Work

Ongoing investigations in the solid particle program are all oriented toward addressing the technical feasibility of the concept. These studies range from research-oriented examinations of specific aspects to engineering-oriented hardware experiments.

Understanding the receiver performance continues to be an important element of this investigation. Of principal concern is the prediction and verification of particle heating. Modeling activities have been carried out at SNLL focusing on the aerodynamics and the radiative heating processes in a receiver. Aerodynamic models and experiments have been directed at predicting and measuring particle velocities and particle volume fraction. The determination of particle velocity is necessary to predict the residence time of the particles in solar flux. Particle volume fraction is also required since radiative transfer depends on optical thickness. Aerodynamics results are described in summary 2.1

Thermal modeling of the solid particle solar receiver consists of two key items: modeling of radiation absorption and emission by the particle curtain, and modeling of momentum and energy exchange between the particles and intervening air. Work to date has focused on modeling the radiation emission and absorption. Once this model is complete, the radiative transfer in the curtain will be combined with the aerodynamics in an energy equation to determine the temperature of the particles as a function of height. A sensitivity analysis is being conducted to determine the importance of key parameters on radiative transfer. Results of the radiation modeling work are described in summary 2.2.

Radiative properties of the solid particles - the absorption coefficient, scattering coefficient, and scattering phase function, each as a function of wavelength and temperature - are important input parameters to the radiation transfer model. These properties are not well known for pure crystalline samples of the materials and are less well-characterized for irregularly shaped particles in dilute suspensions. Work initiated to measure these quantities directly as well as results of preliminary solar absorptance measurements for initial screening of the particle materials are described in summary 2.3.

In addition to the examination of the optical properties of candidate materials, their mechanical and agglomeration characteristics are also being investigated. Particle lifetime and handling may be affected by sintering processes in the high-temperature storage. Coarsening or agglomeration of particles may limit the peak temperatures at which some materials can be used. The effect of particle fines on agglomeration and determination of a flowability test are being examined. This work is summarized in 2.4. Particle lifetimes in a central receiver system may be reduced by fracture processes including thermal shock, impact-induced cracking, and wear and erosion. These processes will affect the size distribution of particles in the system and will likely result in the production of fines. A study to understand which material parameters need to be optimized to minimize particle degradation is underway and summarized in 2.5.

The solid particle receiver may be used for a variety of applications depending on the design of the ground level heat exchanger. A new study to look at the production of pressurized air for industrial process heat and Brayton cycle electricity generation is described in 2.6.

Engineering experiments to examine particle control, heating, and measurement techniques in bulk flows have culminated in a large experiment currently underway at the Radiant Heat Facility in Albuquerque. The objective of this test is to examine the absorption of radiant energy in a falling ensemble of particles. Summaries 2.7.1 - 2.7.5 are devoted to various aspects of this test.

Future Plans

Activities to be carried out or initiated during the next two quarters reflect the results reported at this program review. Of most importance is the validation of the basic concept by results of the Radiant Heating Experiment. In these tests to date, 500 μm silicon carbide particles falling over 10 m have been heated to 850°C by radiation with an incident flux of 0.25 MW/m^2. These promising test results have encouraged an aggressive approach to tackling the technical feasibility issues. Follow-on work in each of the areas reported in this document as well as initiation of some new efforts is anticipated.

In the analytical modeling work, the aerodynamics model and the radiation transfer model will be combined through a comprehensive energy equation which may be used to predict particle temperatures in the curtain. A remaining uncertainty which will be examined initially through parameter studies and later in planned laboratory experiments are constants describing convective transfer between the particles and air. Temperature predictions from the model will rely upon results of the optical properties measurements. In this period, construction of the test apparatus for optical property measurements in particle curtains should be completed as well as characterization of the currently identified candidate materials.

Design of a solid particle receiver is a new effort to be initiated which will immediately use the results of the analytical and heating model. The objectives of the design are to predict the particle temperature distribution in a receiver, to estimate the cavity efficiency and to predict the cavity wall temperatures. Development of receiver design tools in this work will enable more advanced concepts for high temperature concentrating to be examined quantitatively.

Results from the various studies dealing with particle materials have also suggested a new initiative investigating doped particle materials as well as continued studies of particle sintering and fracture processes. Investigation of doped materials is motivated by the fact that no single material has yet been identified which meets the important criteria of high solar absorptivity, minimal aggregation at storage conditions, minimal attrition, and optimal size availability. Strong initial candidates with high solar absorptivity included silicon carbide (SiC) and rutile (TiO_2). In laboratory testing, silicon carbide, however, has demonstrated significant agglomeration due to the formation of an oxide layer between particles as well as significant particle attrition in fracture tests. Rutile, while promising in these areas, is unavailable in sizes above

100 μm. Initial results from the radiant heat facility tests indicate that convective currents are sufficiently strong that particle sizes at the large end of the size range under consideration are preferred (at least 500 μm or larger). Other particle materials under study have poor solar absorption despite acceptable agglomeration and attrition characteristics. One such material which has the potential of being doped to change its optical properties is alumina. Doping in alumina may be performed, in principle, in ways that shouldn't affect its sintering or fracture performance. Identification of industrially available "dark" aluminas will be performed as well as investigation of the potential of specially fabricated particles for this application.

A strategy for a system conceptual design will be developed which incorporates the technical information which has been developed together with industrial design expertise. In addition, initiation of basic experimental studies of material handling and control techniques will be explored.

References

1. "Evaluation of Solar Air Heating Central Receiver Concepts," Battelle Pacific Northwest Laboratories, PNL-4003, June 1982.

2. R. T. Coyle et al., "High Temperature Molten Salts for Use in Solar Thermal Energy Systems," in Proceedings of the Seventeenth Intersociety Energy Conversion Engineering Conference, Vol. 4, pp. 2032-2036 (1982).

3. J. Martin and J. Vitko, Jr., "ASCUAS: A Solar Central Receiver Utilizing a Solid Thermal Carrier," Sandia National Laboratories, SAND82-8203, January 1982.

4. P. K. Falcone, J. E. Noring, and C. E. Hackett, Proceedings of the Seventeenth Intersociety Energy Conversion Engineering Conference, Vol. 3, pp. 1498-1503 (1982).

5. P. De Laquil III, C. L. Yang, and J. E. Noring, "Solar Central Receiver High Temperature Process Air Systems," Sandia National Laboratories, SAND82-8254, February 1983.

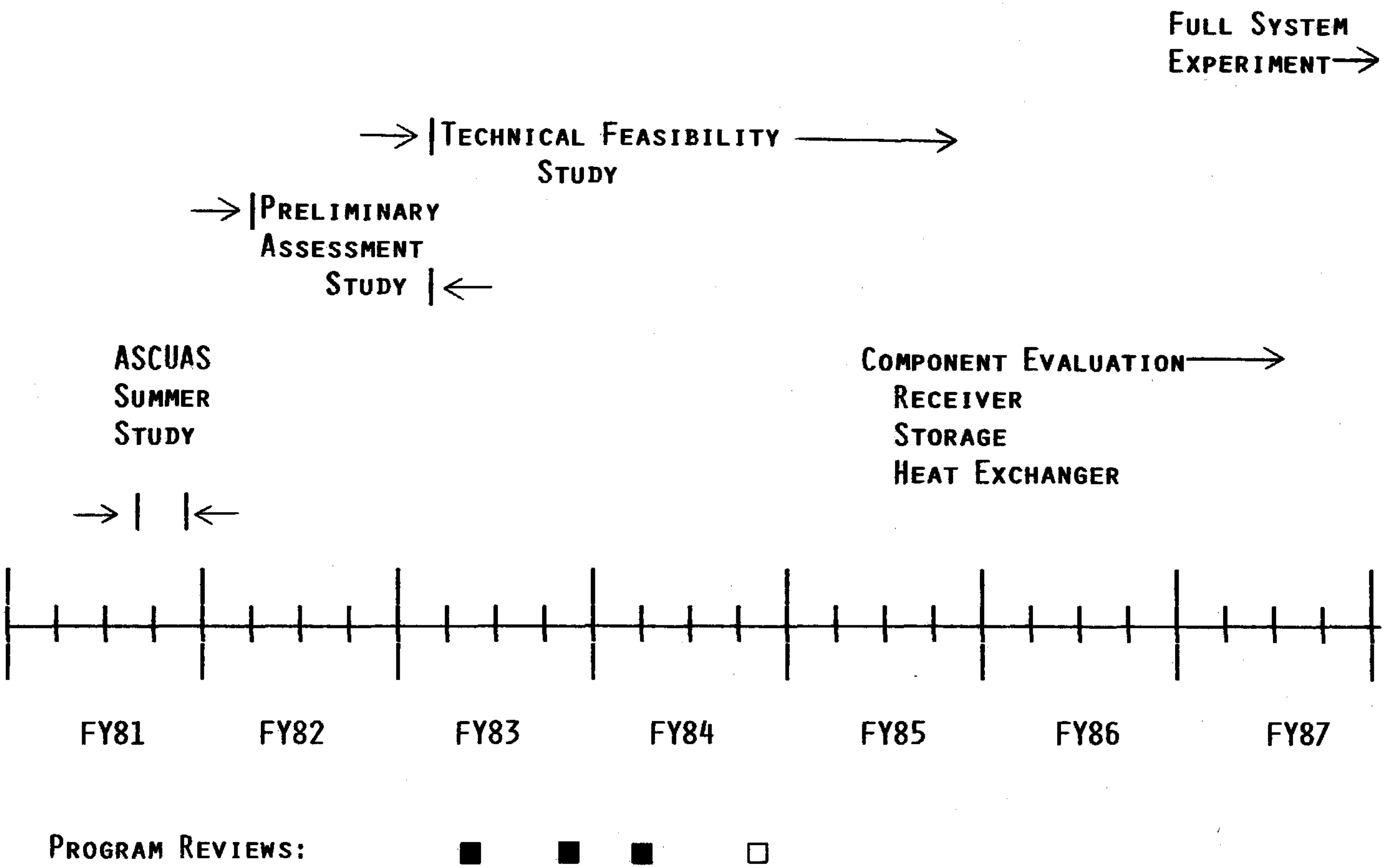


Figure 1. Sandia Studies Chronology

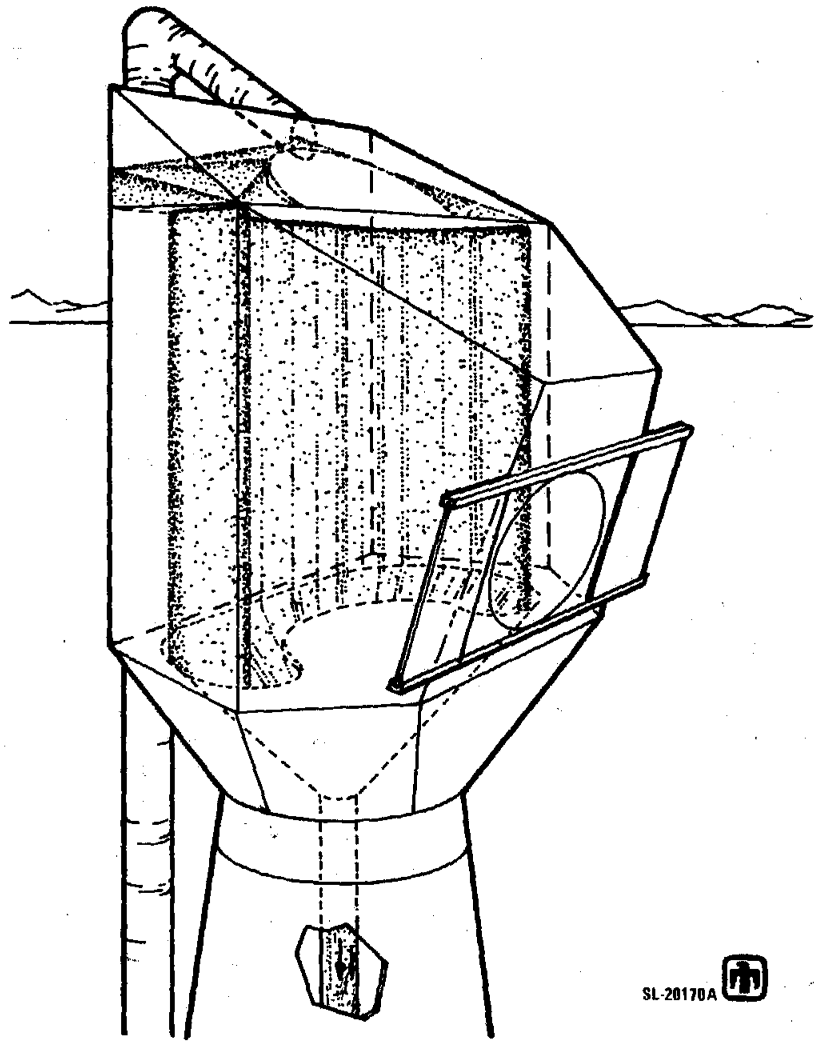


Figure 2. Conceptual Design of Solid Particle Receiver

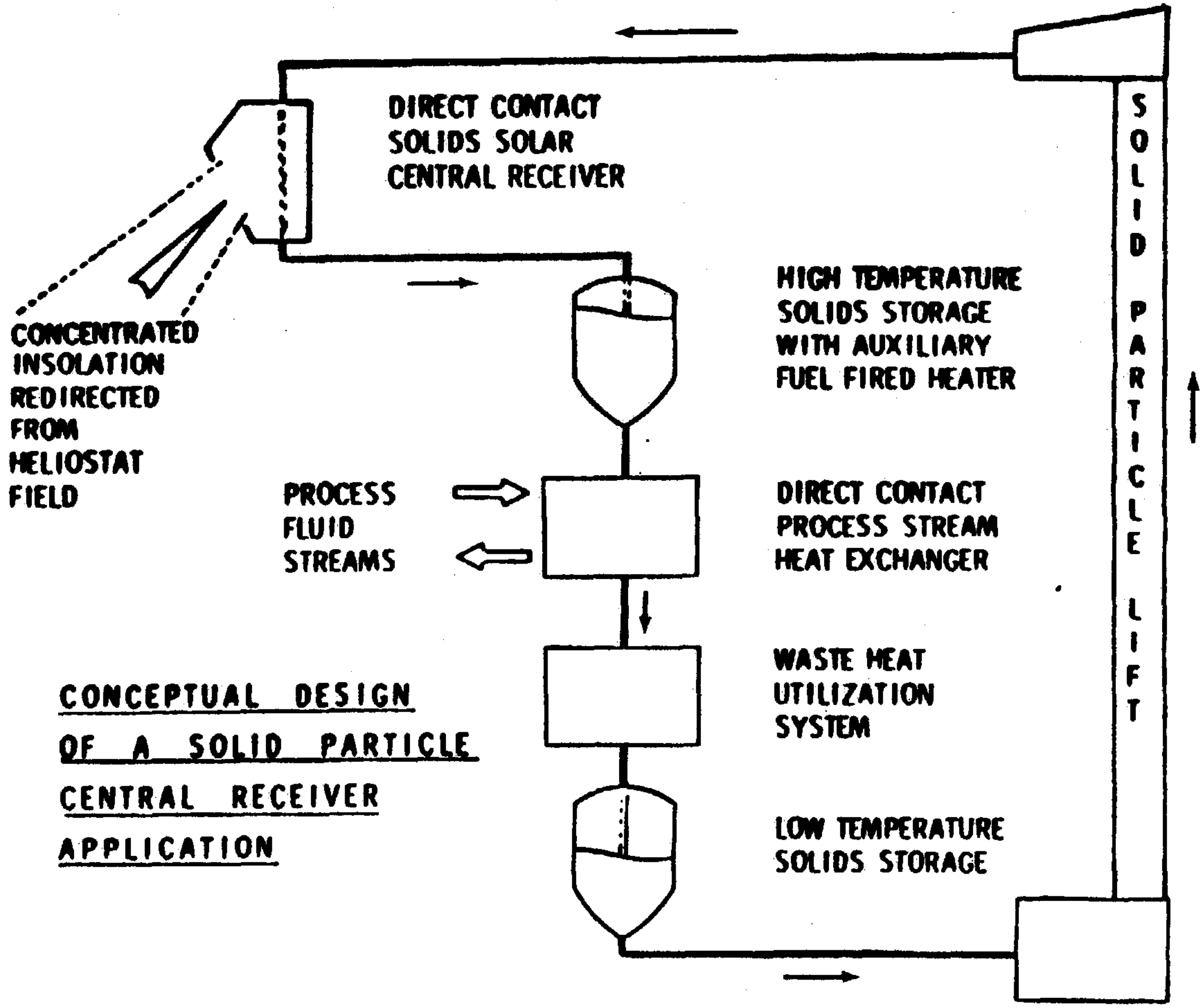


Figure 3. Conceptual Design of Solid Particle Receiver System

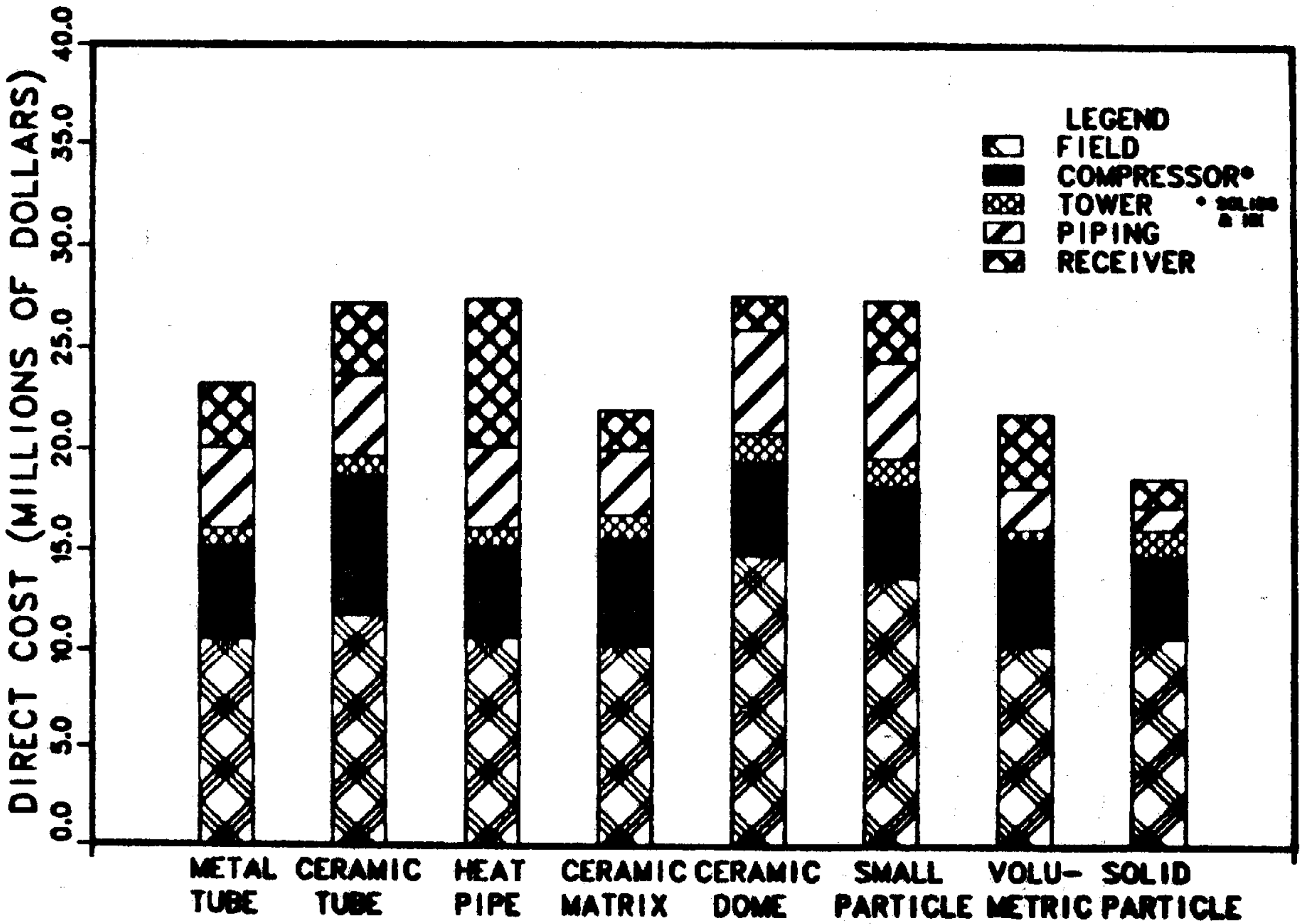


Figure 4. High Temperature Receiver Costs

J. M. Hruby
Sandia National Laboratories

Aerodynamics Modeling/Experiments

An aerodynamic study, consisting of both analytical and experimental work, was initiated for the primary purpose of predicting residence time of free-falling particles in a solar central receiver cavity. The residence time of particles in the solar flux is a critical parameter because it will influence the final temperature of the particles.

The analytical portion of the work focused on one-dimensional continuity and momentum equations for the gas and solid phase. The point equations were written and then volume averaged to obtain the averaged equations of motion. The resulting ordinary differential equations are shown below.

$$m_s = \rho_s \epsilon_s v_s \tag{1}$$

$$m_g = \rho_g \epsilon_g v_g \tag{2}$$

$$\epsilon_s \rho_s v_s \frac{dv_s}{dZ} = \epsilon_s(\rho_s - \rho_s)g - F_{gs} - (P_g - P_s)\frac{d\epsilon_g}{dZ} \tag{3}$$

$$\epsilon_g \rho_g v_g \frac{dv_g}{dZ} = \epsilon_g \rho_g g + F_{gs} - \epsilon_g \frac{dP_g}{dZ} \tag{4}$$

$$F_{gs} = \frac{-150\mu_g(1-\epsilon_g)^2}{d\epsilon_g^2}(v_g - v_s) - \frac{1.75\rho_g(1-\epsilon_g)}{d}(v_g - v_s)|v_g - v_s|$$

where
- $d =$ particle diameter
- $F =$ drag force
- $g =$ acceleration due to gravity
- $m =$ mass flow rate/unit area
- $P =$ pressure
- $v =$ velocity

$\rho =$ density
$\epsilon =$ volume fraction

Subscript

$s =$ solid
$g =$ gas

Equations (1) and (2) are the continuity equations for the solid and gas phase, respectively. These equations are a result of assuming constant mass flow rates and areas for both the particle and gas phase (m_s and m_g are constants).

Equation (3) represents a force balance on the particle phase. It simply states that the change in velocity is equivalent to the sum of the gravitational force, drag force, and the normal force.

Likewise, equation (4) is a force balance on the gas phase. The acceleration in the gas phase is a result of gravitational, drag, and pressure forces.

These equations were solved numerically to yield velocities and volume fractions as a function of distance for each phase. Although the particle velocity is of primary interest for predicting residence time, the particle volume fraction and gas velocity are necessary in order to understand the transfer of heat in the system. Radiative transfer of energy to and between the particles is the focus of a parallel effort. The radiation model which results from that effort will be merged with the energy equation. Final particle temperature will then be predicted by the simultaneous solution of the continuity, momentum, and energy equations for each phase.

The prediction of particle velocity from the solution of the continuity and momentum equations can be used to calculate residence time of cold particles. The one-dimensional particle velocity limits were established and are shown in Figure 1. The upper limit is the case for unrestricted air flow into the particle curtain. In this case, the gas velocity and particle velocity are equal and the particles fall as though they were in a vacuum. The lower limit for particle velocity is for no influx of air into the particle curtain (pipe flow).

Experimental efforts focused on measuring average particle velocity as a function of position. The first phase of the experimental program was the development of a velocity measuring technique. Several methods for remote velocity measurement were considered, and the technique developed was laser Doppler velocimetry. Once this technique was proven, a cold flow velocity measurement program was initiated. Velocity measurements were made on a relatively small scale particle curtain that was constructed in the laboratory at Sandia, Livermore. A comparison of experimental data and anaytical predictions is shown in Figure 2. The experimental data is bounded by the analytical limits, and agrees most closely with the particle flow which allows no influx of air.

From the experimental data, it is clear that some restrained influx of air must occur. Therefore, modification of the analytical model to include this effect was considered. Because a two-dimensional model requires understanding and quantifying effects in the boundary layer, it involves an intensive research program. As a first attempt to modify the model a pseudo two-dimensional approach was taken. This model assumed a linear velocity gradient of air into the sides of the curtain. The continuity and momentum equations for this direction of flow were written and solved assuming the linear velocity profile. The results were then embedded into the previous one-dimensional equations. Unfortunetly, solution of these equations required knowledge of initial conditions which did not exist. It is clear, therefore, that a two-dimensional approach is necessary in order to accurately predict the particle velocity and volume fraction.

The present plans call for the development of a solution scheme for the continuity, momentum and energy equations for each phase. This will include radiative transport. A parameter study will then be conducted to look at the effect of each variable on final particle temperature. At that time, a priority list will be developed for the most crucial components of the equations. A two-dimensional aerodynamic program may be undertaken then if it is deemed necessary.

The experimental velocity program is also continuing. The current focus is particle velocity measurement in hot flow. These tests include measurements at the Radiant Heat Facility at Sandia, Albuquerque and hot particle flows at Sandia, Livermore.

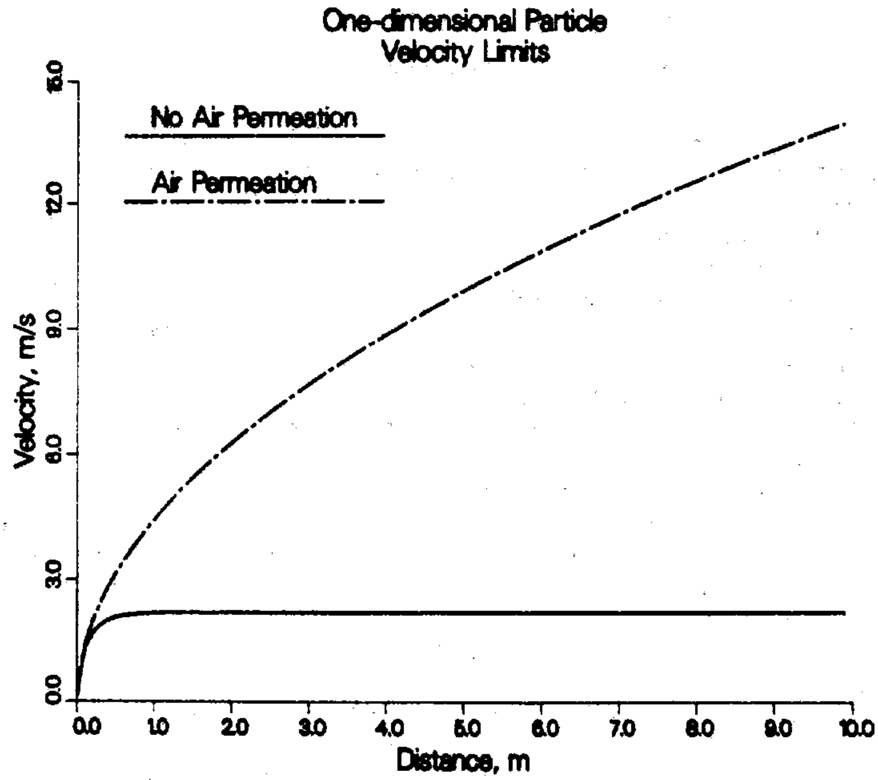


FIGURE 1

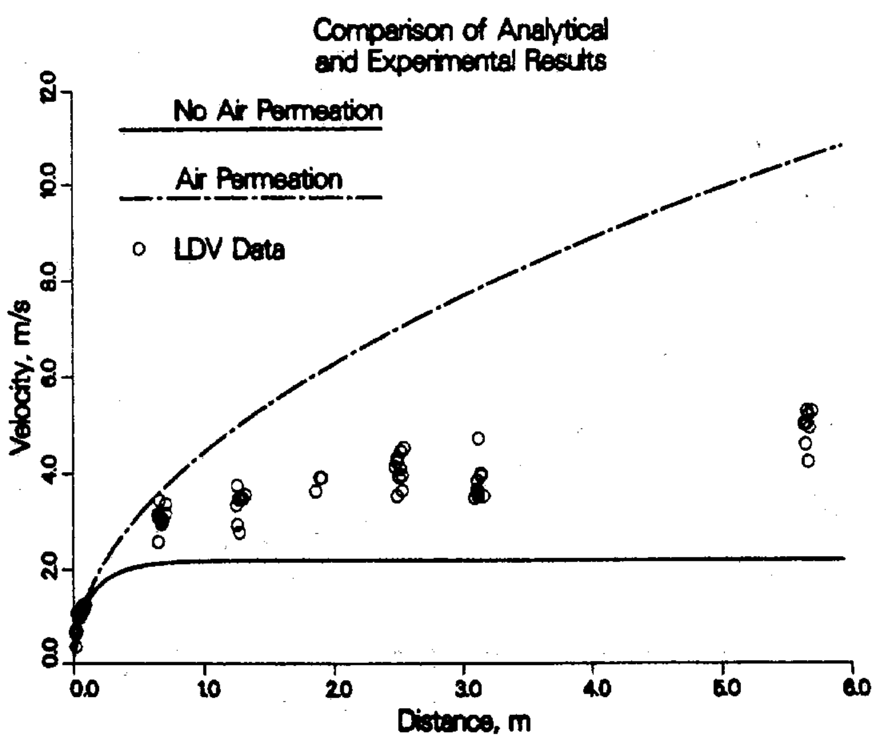


FIGURE 2

Paper 2.2
W. G. Houf
Sandia National Laboratories

RADIATION MODELING

The prime objective of the radiation analysis is to provide a reliable prediction of the local rate of radiative heating throughout the falling particle curtain. To this end, a discrete ordinate radiation transfer model has been developed which predicts the local rate of radiation absorption and emission for any point within the particle curtain. The model is based on the equation of radiative transfer as applied to a plane parallel particle curtain with a rear wall. The model accounts for the directional nature of the propagating radiation field, intra-particle scattering, and wavelength dependencies in the particle optical properties. The radiative heating rates predicted by the model will be used with companion thermal and aerodynamic models to predict the overall performance of a particle receiver.

The radiation model requires optical property information concerning the scattering and absorption characteristics of the individual particles. Work is underway at Pacific Northwest Laboratories to measure these optical properties for the candidate solid carriers. Preliminary test calculations have been done using nominal values of the nondimensional version of these optical constants. The most significant parameters are the single scattering albedo and the optical depth. The optical depth is a nondimensional measure of the opacity of the particle curtain, while the single scattering albedo gives a measure of the relative significance of scattering to absorption. Figure 1 shows an example radiative flux calculation for highly absorbing particles in a moderately opaque curtain. Note the rapid attenuation of the radiative flux near the front of the particle curtain.

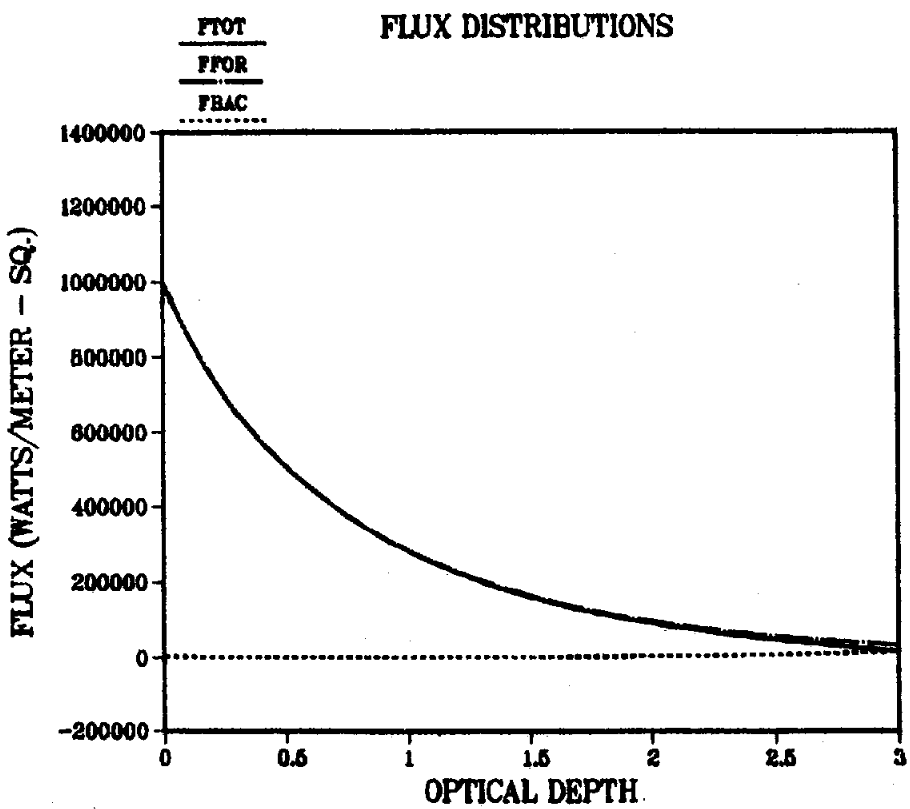


FIGURE 1

Parameters:
Albedo = 0.2 Incident Flux = 1.0 MW/M-SQ. Wavelength = 0.5 microns
Temp. constant at 1000 deg. K Wall reflectivity = 0.50 Diffuse Irradiation

Paper 2.3
J. W. Griffin
Battelle Pacific Northwest Laboratories

OPTICAL ABSORPTION AND SCATTERING CHARACTERIZATIONS OF CANDIDATE MATERIALS FOR A SOLID PARTICLE RECEIVER

Optical spectrophotometry procedures have been developed for characterizing the absorption of candidate solid particle receiver sands over the solar insolation spectrum (300-2500 nm). Measurements of reflection and transmission are performed over a range of sand areal densities (g/cm^2) to derive spectral absorptances. These absorptance values are then weighted according to the NASA Air Mass = 1.5 solar spectral distribution to derive a solar weighted absorptance value. Measurements were performed on six materials in particulate form: mullite, garnet, SiC, Al_2O_3, TiO_2, and common beach sand. A summary of solar absorptance values for the six materials appears in Table I. These values are in good agreement with values for the same materials measured by R. B. Pettit, Sandia, Albuquerque. (Ref. 1)

Initial mid-infrared (2-10 μm) optical absorption measurements were performed on the candidate sands using Fourier Transform Infrared (FTIR) photoacoustic spectroscopy. This spectral region is important because of the large amount of particle radiation (blackbody emission) exchange expected within the curtain and receiver volumes. Assuming that an absolute calibration can be performed for this measurement system, the acquired infrared absorptance values should aid analytical model predictions for receiver performance.

A new instrumentation system has been designed for the in situ measurement of optical extinction (scattering and absorption components) for particulate curtains. A schematic of the preliminary design for this instrument appears in Figure 1. This instrument enables calculation of curtain absorptance from the measurement of curtain total extinction (scattering and absorption loss) and curtain optical scattering. The curtain generators, which are being designed and built by Sandia, Livermore (B. R. Steele), will be capable of providing stable curtains with thicknesses ranging from a single particle to many particles (opaque). Another new instrumentation system is being developed for determination of angular scattering distributions (phase functions) for a range of curtain geometries and materials. A schematic of the preliminary design for this instrument is depicted in Figure 2. This instrument is capable of measuring particle-scattered light in both the forward and backward directions as a function of azimuth angle or as a function of solid angle about any azimuthal direction within the horizontal plane. Data derived from both of the above instrumentation systems will enable more accurate analytical modeling of optical radiation transfer in the solid particle receiver.

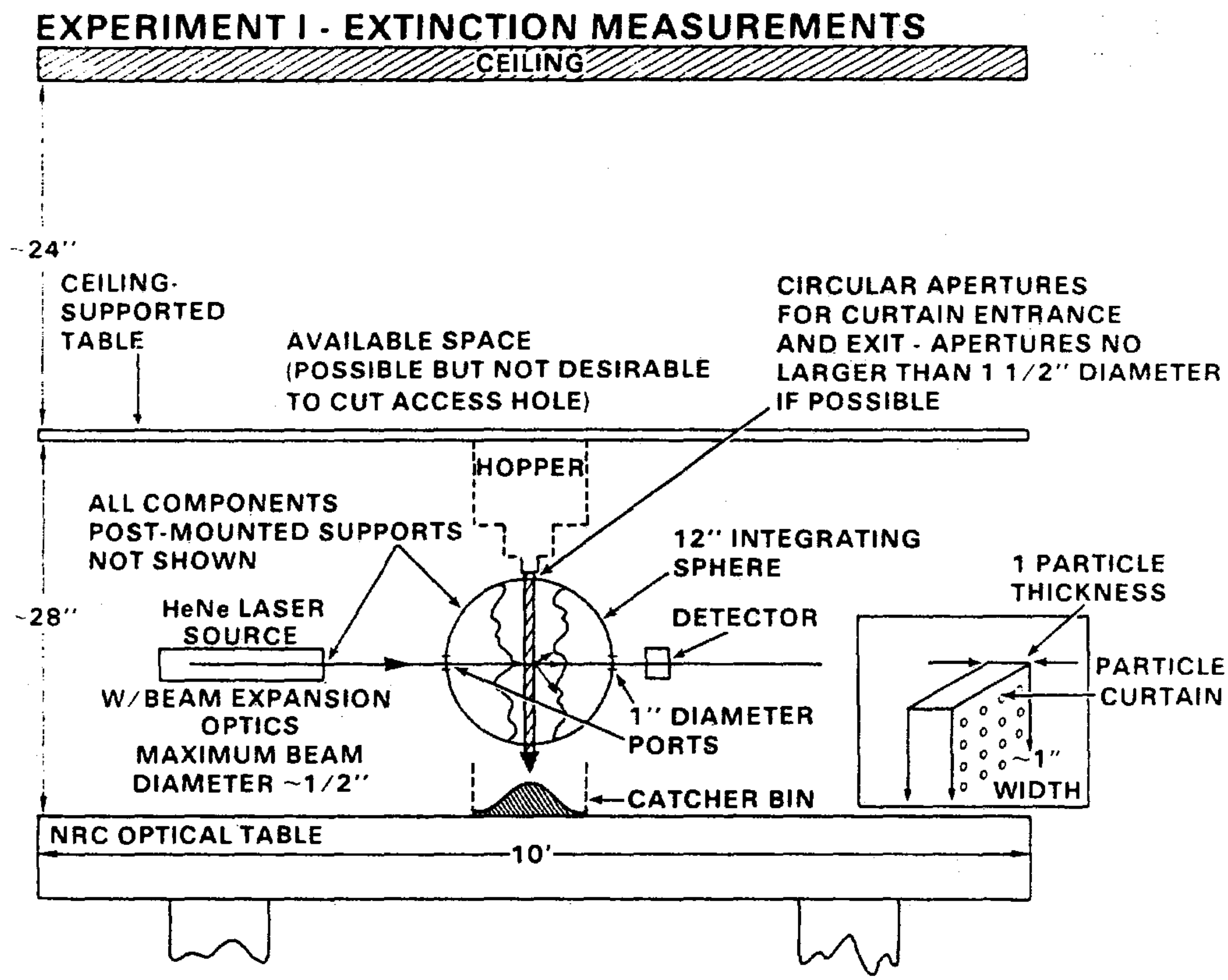
Reference

1. Internal memo, R. B. Pettit and A. R. Mahoney to B. R. Steele, "Optical Properties of Ceramic Particles," September 1, 1983.

TABLE I.

SUMMARY OF SOLAR ABSORPTANCE DEPENDENCY ON AREAL DENSITY FOR THE SEVEN PARTICULATE SAMPLES

SAMPLE	AREAL DENSITY (mg/cm^2)	SOLAR ABSORPTANCE
MULLITE #14	50	0.163
C.E. MINERALS	111	0.251
	229	0.267
	417	0.295
GARNET #8	98	0.807
CONT. MIN. PROC. CO.	217	0.830
	448	0.816
	819	0.814
SiC #4	64	0.815
CARBORUNDUM	142	0.819
	293	0.823
	379	0.827
Al_2O_3 #2	83	0.146
NORTON	183	0.201
	379	0.224
	690	0.252
TiO_2	113	0.793
	251	0.808
	517	0.798
	886	0.800
SAND, HEATED 60 MESH	65	0.466
	145	0.608
	300	0.640
	546	0.681
SAND, UNHEATED 60 MESH	65	0.445
	144	0.577
	298	0.639
	542	0.652



EXPERIMENT I - EXTINCTION MEASUREMENTS
CEILING
~24″
CEILING-SUPPORTED TABLE
AVAILABLE SPACE (POSSIBLE BUT NOT DESIRABLE TO CUT ACCESS HOLE)
CIRCULAR APERTURES FOR CURTAIN ENTRANCE AND EXIT - APERTURES NO LARGER THAN 1 1/2″ DIAMETER IF POSSIBLE
HOPPER
ALL COMPONENTS POST-MOUNTED SUPPORTS NOT SHOWN
12″ INTEGRATING SPHERE
1 PARTICLE THICKNESS
~28″
HeNe LASER SOURCE
DETECTOR
PARTICLE CURTAIN
W/BEAM EXPANSION OPTICS
MAXIMUM BEAM DIAMETER ~1/2″
1″ DIAMETER PORTS
~1″ WIDTH
CATCHER BIN
NRC OPTICAL TABLE
10′

FIGURE 1

EXPERIMENT II - ANGULAR SCATTERING DISTRIBUTION MEASUREMENTS

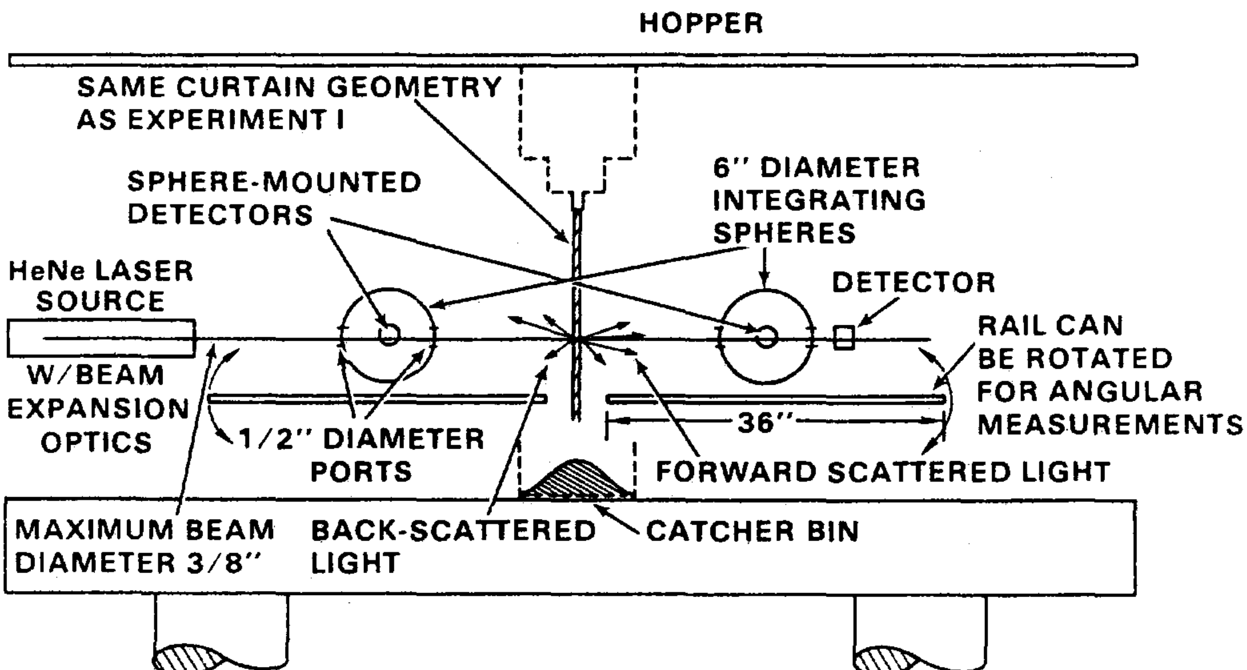


FIGURE 2

Paper 2.4
G. L. Messing and D. M. Kupp
Pennsylvania State University

Sintering of Coarse Ceramic Particles

Five ceramic materials have formed the focus for research into ceramic materials that are acceptable for use in the solid particle receiver. These materials are alumina, zircon, silicon dioxide, rutile, and silicon carbide. Each of the commercially materials obtained has been size classified to give 100 micrometer particles that have been characterized for flowability and sinterability. At this point of the research experiments were designed to enable a further reduction of the candidate systems. Two sets of sintering experiments were carried out at 1000 and 1250 c for 24 hrs. Samples were qualitatively analysed for aggregation between particles by observation and the effect of aggregation was judged by particle flowability. SEM studies were used to assess the nature of bond formation between particles that exhibited aggregation.

The results of the above analyses are presented in summary form in Table 1. A detailed description of the observations and reasons for aggregation was presented. It was clearly shown that after 24hrs at 1250 C, the silicon carbide and rutile formed strong, coherent masses whereas the silicon dioxide and zircon formed aggregated masses that significantly reduced particle flowability. Alumina was unaffected at this temperature. At 1000 C the silicon dioxide,zircon and rutile were unaggregated and showed no adverse effect due to the thermal treatment. Silicon carbide formed a strong, coherent mass at 1000 C as a result of extensive oxidation. The aggregation in all cases was a result of a viscous, silicate phase forming during heating which in turn formed a strong bond between particles. It was suggested that in most cases that liquid phase formation is enhanced by the presence of impurities in the commercially available materials. It was concluded that only alumina and rutile be used in further testing. The alumina is clearly the better material for temperatures up to 1250 C. Rutile is suggested for use as a low temperature (1000 C) material because of its perceived better optical properties and stability at this temperature. Furthermore,it does not oxidize during air sintering experiments.

Future research needs include a more comprehensive testing of these two materials over the anticipated time, pressure and temperature conditions of the solid particle receiver. Additionally, an extensive investigation of chemical and physical effects on the sintering of the candidate materials is required. This need is based on the realistic expectation of particle modification during the process (especially attrition) and the desire to modify the optical properties of the ceramics by chemical additions. Details of the future research are unspecified pending discussions at the review meeting and the results of other studies in the solid particle program.

Initial Candidate Materials

Materials	Flowability	Sinterability (1000° C., 24 hrs.)	Sinterability (1250° C., 24 hrs.)	Attrition (24 hrs.) (% -100 mesh)
Alumina (Al_2O_3)	good	---	no	1 %
Silica * (SiO_2)	good	---	aggregation	1 %
Silicon carbide (SiC)	good	yes	yes	93 %
Rutile * (TiO_2)	best	no	yes	1.5 %
Zircon * ($ZrO_2 \cdot SiO_2$)	best	yes	---	3 %

* natural material

Paper 2.5
S. M. Wiederhorn
National Bureau of Standards

REFRACTORY PARTICLES AS SOLID THERMAL ENERGY CARRIERS IN HIGH TEMPERATURE SOLAR SYSTEMS

<u>Objective</u>: Research on this project will be directed towards the development of experimental data, theory and techniques of measurement that can be used to assess the performance of solid thermal carrier particles where mechanical wear and thermal shock are important. Critical materials properties such as fracture toughness, hardness and strength will be measured to develop acceptance criteria that can be used to establish the best composition and microstructure for thermal carrier particles.

Review of Progress

During the past year we concentrated our research efforts on three areas: (1) evaluation of the effect of thermal radiation on the structural integrity of ceramic spheres; (2) evaluation of the effect of mechanical contact on the structural integrity of glass spheres, and (3) the development of test procedures to evaluate the wear resistance of solid thermal carrier particles.

Paper 2.6
E. Fisher and D. H. Johnson
Solar Energy Research Institute

CRITICAL REVIEW
OF THE STATE OF THE ART
OF PARTICLE-GAS HEAT EXCHANGERS

OBJECTIVES OF THIS ACTIVITY

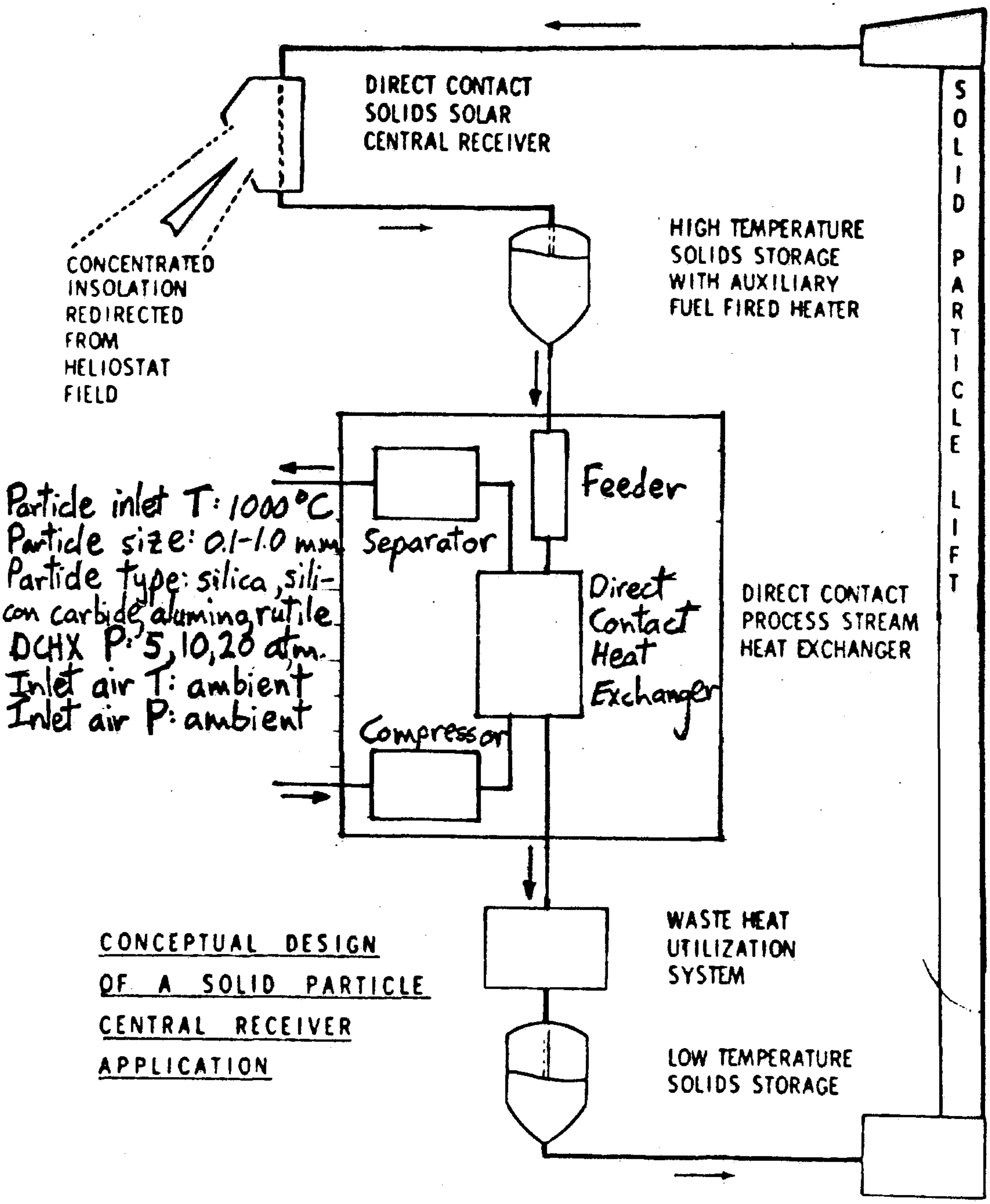
COLLECT AND REVIEW EXISTING INFORMATION ON SAND TO AIR DIRECT CONTACT HEAT EXCHANGERS AND RELATED EQUIPMENT OPERATING AT HIGH TEMPERATURE AND PRESSURE.

DETERMINE THE OPTIONS FOR EACH COMPONENT OF THE SAND TO AIR DCHX SUBSYSTEM TO BE INCLUDED IN A CONCEPTUAL DESIGN AND COST ESTIMATE.

APPROACH

CHOOSE A BASELINE SET OF COMPONENTS WHICH BEST SATISFY BASIC PERFORMANCE CRITERIA AND FOR WHICH SUFFICIENT INFORMATION EXISTS TO DEVELOP AN OPTIMIZED DESIGN FROM WHICH COST MAY BE ESTIMATED.

IF POSSIBLE, IDENTIFY AN OPTION FOR EACH COMPONENT OF THE BASELINE WHICH HOLDS THE POTENTIAL FOR IMPROVED PERFORMANCE.



CONCEPTUAL DESIGN OF A SOLID PARTICLE CENTRAL RECEIVER APPLICATION

Paper 2.7.1
B. R. Steele
Sandia National Laboratories

RADIANT HEAT FACILITY EXPERIMENT OVERVIEW

Background

The radiant heat facility experiment is the culmination of several experiments conducted previously. These tests were designed to study cold flow characteristics of particles such as mass flow, flow patterns, particle velocity and volume fraction. In addition, the heated hopper or bin was designed to preheat the particles in order to study convective loss processes.

During these preliminary studies, we developed a portable system to measure particle velocity using laser Doppler velocimetry. This system can be moved and operated anywhere that cooling water and 115 volt electricity is available.

Proposed Heating Tests

Engineering tests to verify solar heating of particles were desired. Prior to the decision to run the radiant heat facility experiment, several smaller scale tests and one very large test were considered and rejected. The small scale tests would have been run at the SNLA Central Receiver Test Facility (CRTF) solar furnace and the large test at the CRTF tower itself.

Three furnace test configurations were considered. The first test considered was a single suspended particle. This test was ruled out because of an inability to suspend the particle and to measure the particle temperature. A second method was to suspend particles between two pieces of fuzed silica glass. This test had similar problems with temperature measurements and, in addition, convective losses could not be studied. A third method considered was a wheel of particles similar to a water wheel with fuzed silica sides. The wheel would be turned and the particles allowed to fall through the solar furnace beam, be collected at the bottom of the wheel and passed repeatedly through the beam each time the wheel turned. This method had some potential, but particle to particle conduction on the back side of the cycle would make calculations and modeling difficult, if not impossible.

The large scale test considered was a 1 meter wide by 10 meters high particle curtain on the CRTF tower irradiated by the heliostat field. However, calculations indicated particle temperatures would only reach 250°C because of significant radiative losses. In addition, this test would result in significant cost to shield the facility from the spillage flux.

A non-solar experiment at the radiant heat facility in which tungsten filament quartz lamps would provide the incident flux was considered next.

Limitations of this experiment included the fact that the lamp flux does not spectrally match the solar spectrum, that the aerodynamics would not be simulated because of a small chute arrangement instead of a cavity, and that the cavity-dependent losses would not be simulated for analytical purposes. However, since the heating of a falling ensemble of particles is the critical technical element of the solid particle receiver concept, positive features included the fact that the flux level attainable at the radiant heat facility (0.1 to 0.6 MW/m^2) is reasonable and is distributed uniformly over the curtain. Also, the fall height and residence time is reasonable, and above all the basic facility was available from the 1979 5-Tube Test.

Objective

The radiant heat facility experiment was selected with the principal objective to "demonstrate the technical feasibility of the solid particle receiver concept by examining the absorption of radiant energy in a falling ensemble of particles."

Test Data

Success criteria for this test include measurements of the following:

A. Temperature change of particles while falling through controlled radiative flux. This will be accomplished using thermocouples in the catcher bin when the particles are recovered. An in-situ method of measuring the temperature of falling particles using a laser technique will be attempted.

B. Aerodynamic data for particles in size 0.1 to 1 mm. This data will be gathered as velocity profiles at different heights during cold particle flow, hot particle flow and while heating the particles. This will be accomplished using the portable laser Doppler velocimetry techniques developed earlier.

C. Flux profile including spectral distribution. This will be accomplished by measuring the flux level and spectral distribution of the flux in a test section without particle flow. In addition, the flux will be measured at 4 places during the particle tests.

D. Mass flow rates will be measured by suspending the bin from three load cells and recording the change in weight during the test.

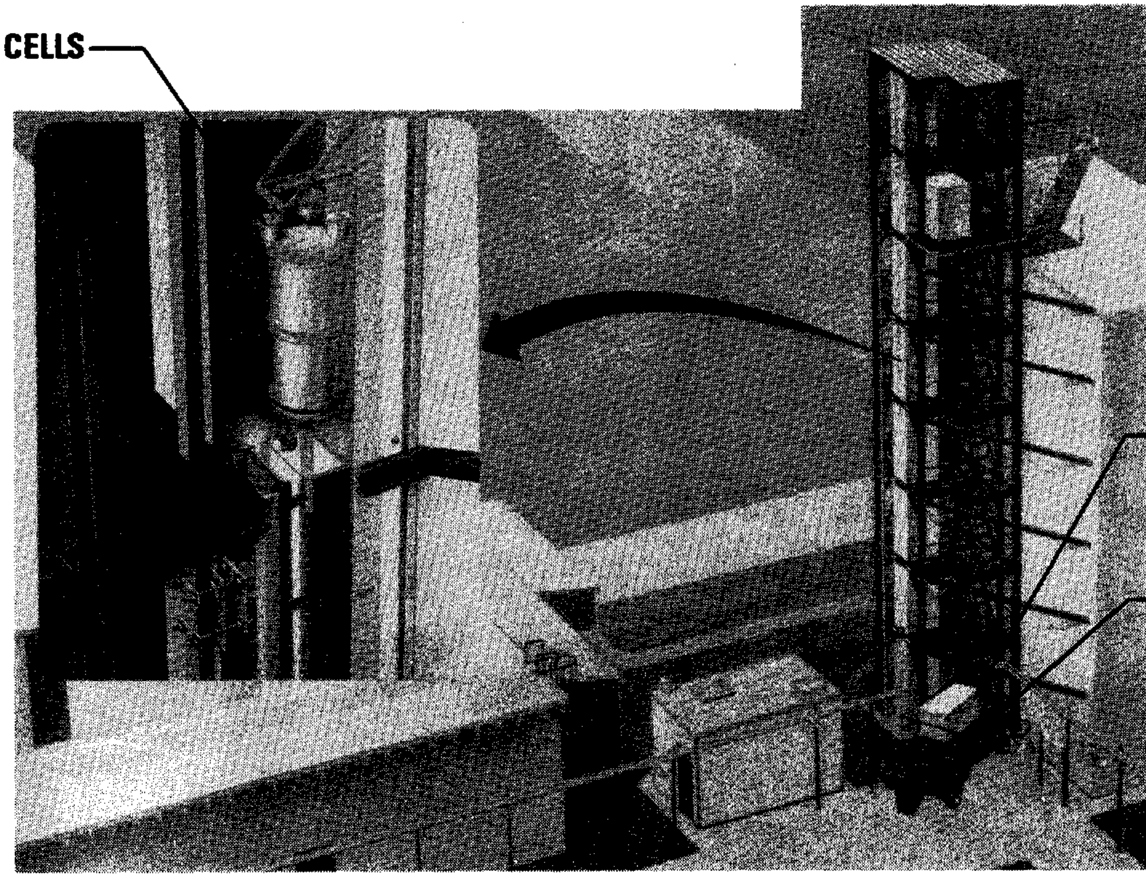
E. The effect of optical properties will be studied by using at least 2 different particles with extremely different absorption characteristics.

F. Particle size effects will be determined by using several different particle sizes in controlled tests.

Experimental Apparatus

The experimental apparatus is depicted in Figure 1. It consists of the steel structure and lamp arrays fabricated several years ago for the 5 tube test. The lifting platform lifts the laser for measuring particle velocity at different distances from the hopper. The inset shows the load cells for measuring mass flow.

Figure 2 is a blowup of the inset from Figure 1 and shows the details of the experimental setup. The hopper contains the particles and distributes them to form the particle curtain. The particle curtain is confined in the chute by the glass to protect the lamps. The lamp panels are water cooled.



SOLID PARTICLE RECEIVER RADIANT HEAT TEST SETUP

Figure 1

Paper 2.7.2
P. L. Class
Sandia National Laboratories

RADIANT HEAT FACILITY

SNLA's Radiant Heat Facility (VG 1) was built to provide laboratory simulation of high-temperature environments and their effects on materials, components, and major assemblies. A wide range of thermal environments has been simulated from aerodynamic heating inputs to a missile or externally carried weapon to long-duration tests simulating JP-4 fuel fires or concentrated solar radiation.

Our involvement with the solid particle receiver program is out-lined in the accompanying viewgraph (VG 2).

Our first activity, which paralleled site preparation outside Building 6536 for the solid particle radiant heat experiment, was to set up a 1/4-length version of the test inside Building 6536, utilizing the same array panels, lamps, receiver chute, and cooling fan as would be used on the full-size experiment. The purpose of this test was to characterize the flux distribution inside the receiver chute. A secondary benefit was to evaluate all the hardware designed for the full experiment, including the air deflector design and the quartz glass window and supporting frame durability.

As we accumulated operating experience, we found that one major weakness of our design was the support frames for the quartz glass windows. The frames were originally fabricated from 304 stainless. These frames oxidized and warped. Thermocouples attached to the frame pieces during testing indicated temperatures approaching 2000°F. A higher temperature material was clearly needed for this application. A search of high temperature properties of alloys narrowed to Hastelloy X and an Inconel alloy. The Hastelloy X was available in the size needed, so we chose that material and later had a complete set of support hardware fabricated.

During the calibration testing, the lamp voltage was measured at various flux levels. This information is utilized as a transfer function for computer control of the ac test power during testing.

The particle receiver radiant heat test was being set up during the calibration effort. The experiment utilized the existing five tube test tower. Eight lamp panels, each with about 42 lamps, were employed on the tower to achieve a radiant source 10 m high.

Division 8453 and 7531 personnel share in the responsibilities during a typical test run.

RADIANT HEAT

FACILITY	Range of Environment Parameters: Test Object Size (ft^2)	Temperature Range (°F)	Heat Flux Range (Btu/ft^2-s)	Minimum Rise Time (seconds)	Data Acquisition Capability: Total Electric Power Capability (kW)	Typical Data Scan Rate (seconds)	Thermocouple Capacity (type K)	High Level Input (0 ± 10V)	Low Level Input (0 ± 800mV)	Current Input (0-20mA)	Explosive Limits
Bldg 6536	250	0-2,800	0-400	2-5	5,000	5[3]	240	64	32	16	(1)
Bldg 6538	132	0-2,800	0-120	2-5	3,000	5[3]	216	32	16	16	(1)
Outside 6536/6538	No Limit	0-2,800	0-120	2-5	3,000	5[3]	176	32	16	16	(1)
Remote HE. Test Facility	100	0-2,000	0-120	2-5	500	5[3]	176	32	32	16	(2)

Note 1 Only self-contained HE units allowed
Note 2 Units containing up to 40 lb of HE allowed
Note 3 Data scan rate is a function of number and type of channels, data display requirements during test, and test run time.

FOR MORE INFORMATION PLEASE CALL: (505) 844-3169

Vugraph 1

R803080

SOLID PARTICLE RECEIVER RADIANT HEAT TEST

DIVISION 7531 RESPONSIBILITIES

1. HEATER ARRAYS

2. GLASS WINDOWS AND SUPPORT FRAMES

3. HEAT FLUX MAPPING OF RECEIVER

4. INSTRUMENTATION

5. SOFTWARE GENERATION FOR DATA ACQUISITION AND AC TEST POWER CONTROL

6. UTILITIES AND WEATHER PROTECTION

7. SOP AND PERIODIC REPORT (COST & SCHEDULE)

8. OPERATE DAS (EXCLUSIVE OF LVD SYSTEM) AND AC TEST POWER CONTROL

Paper 2.7.3
V. P. Burolla
Sandia National Laboratories

SOLID PARTICLE RECEIVER

TEST PLAN

The primary objectives of the test are to verify that solid particles can absorb heat from a radiant flux and to complete enough tests and gather enough data to further the ongoing modeling efforts in the program. The verification of particle heating is necessary because of the simplifying assumptions made in preliminary calculations of the particle heating phenomenon.

Activities directed by the plan are designed to yield information on the effects of particle flow rate, particle size, particle preheat, particle optical properties, chute preheat and radiant flux, on the particle temperature change and on particle average velocity. Particle velocity information will also be used to estimate the convective currents created by the particles and by the chute walls. The attached summary contains the essentials of the test plan as originally written. Tests to be conducted as of 1 February 1984 will investigate the effects of varying particle optical properties, particle preheat and still higher fluxes. Some testing also remains to fill in gaps in the existing test data.

RADIANT HEAT FACILITY, SOLID PARTICLE TEST SUMMARY

SERIES	TEST PURPOSE	CONDITIONS	MATERIAL	DIAGNOSTICS
000	Chute bake out, Thermal expansion test--Thermocouple & misc. instrumentation check	Flux only	None	Thermocouples Visual observation
100	Evaluate particle curtain to determine flow rates and and slit geometries necessary for a good test	Particle flow only with varying slits	SiC 300 microns	Visual observation of flow in chute
200	Determine velocity development under zero flux conditions	Particle flow only with optimum slit determined in 100	SiC 300 microns	Part. vel. at 5 or 10 levels
300	Determine spectral distribution of flux	.3MW/m^2 flux no particle flow	None	Radiometer and Filters
400	Determine the appropriate flux level for reasonable delta temperature	variable flux w/fans no particle preheat, no chute preheat	SiC 300 microns	Inlet and outlet temperatures and total flux
450	Determine if chute preheat is essential to approach steady state conditions for duration of test run	Flux (from 400) w/fans, no particle pre-heat, optimum slit, w/ & w/o chute preheat	SiC 300 microns	Temperature of chute walls and inlet and outlet particle temperature
500	Measure aerodynamic effects and thermal effects for baseline conditions	Flux (from 400) w/fans no particle pre-heat other conditions as determined by 100-400	Sic 300 microns	Part. velocity as f(H) Temperature as f(H) Total flux Air velocity inlet and outlet

SERIES	TEST PURPOSE	CONDITIONS	MATERIAL	DIAGNOSTICS
600	Determine the thermal effects associated with initial particle temperatures greater than ambient	Same as in 500 with varying particle preheat	SiC 300 micron	Temperature as f(H) Total flux Air velocities Part. vel. outlet
700	Evaluate the effect of different optical properties on thermal absorption	Same as in 500	Sand 300 micron	Part. vel. outlet Part. temp. outlet Air vel. inlet and outlet Total flux
800	Evaluate the effect of different optical properties and different particle size on thermal absorption	Same as in 500	Rutile (TiO_2) 100 micron	Same as 700
900	Same as 800	Same as in 500	SiC 500 micron	Same as 700
1000	Evaluate the effects measured previously, now under maximum flux	Same as in 500 except maximum flux	SiC 300 micron	Same as 700

Paper 2.7.4
V. P. Burolla
Sandia National Laboratories

SOLID PARTICLE RECEIVER RADIANT HEAT TEST

DIAGNOSTIC CAPABILITIES

One of the primary goals of the radiant heat tests is the acquisition of a complete set of accurate data that will enable a thorough analysis of the tests, and provide meaningful information for ongoing modeling efforts. The following is a description of the instruments and techniques used:

Radiant flux

Flux measurements within the chute are critical for radiation modeling of the energy absorbing process. Since the particles have absorption properties that vary with wavelength, the spectral distribution of the radiant lamps must be verified. In addition the total flux entering the chute and within the chute must also be measured. The spectral measurements were conducted on a separate chute section installed in a laboratory near the outdoor tests. A Molectron Corp. PR 200 pyroelectric radiometer with a flat response between .3μm and 50μm measured the flux entering a cutout in the rear wall of the chute after passing through one of twelve, narrow band infra-red interference filters. Dividing the measured incident radiation by the bandwidth of the particular filter generates a relative frequency reponse curve. The bandpass of the filters was verified by R. Pettit of SNLA.

Total flux measurements within the chute was also accomplished on this laboratory setup using a circular foil heat flux gage. The gage was mounted on a probe so that it could be located in three dimensions within the chute cavity. Total flux profiles across the width and through the depth of the chute were completed along with total flux as a function of vertical position relative to the lamps. The full scale test chute is instrumented with four heat flux gages located at the rear wall and centered within each section. This allows measurements during particle flow. Personnel from 7531 were responsible for these data.

Temperature

Ungrounded, sheathed chromel-alumel thermocouples are used for all temperature measurements in the test. Thermocouples are located in the distribution bin at the top, on the inside of the chute walls, within the insulation on the chute, on the outside metal skin of the chute and in the collection bin at the bottom. In many cases redundant thermocouples are positioned to guarantee a complete set of data even if some thermocouples failed. SNLA personnel are responsible for all temperature data collection.

In addition to thermocouple data, attempts will be made to measure particle temperature within the chute using optical techniques. Because of the high flux within the chute, the chute wall temperatures and the scarcity of particles, this technique requires special instrumentation that may not overcome all problems. The technique uses an expanded HeNe laser beam passing through the particle curtain to measure the viewed area covered by particles. By measuring the radiant flux from this area only (with a zero radiating background) one can extrapolate the total flux as if the entire area were covered by particles. One can then calculate the temperature of the particles given their emissivity.

Particle velocity

Particle velocity information is necessary to determine the average particle residence time in the flux and to evaluate the magnitude of convective currents within the chute generated by either the particles or the chute walls.

A laser velocimetry system consisting of a 4 Watt Argon Ion laser, and TSI Inc. system optics for measurements in the backscatter mode is used to measure particle velocity. By mounting the entire system on a lifting platform, velocity data can be acquired over the entire ten meters of fall. The focusing lens has a 2.2 m focal length which allows the laser and optics to be far enough away from the radiant flux to preclude damage. The signal from the LDV system is fed to a TSI counter located in a data shack at ground level. Raw data from the counter is fed over a custom made interface to an HP 9826 computer for real time analysis and graphical output. The HP 9826 computer is synchronized with the main data acquisition system just prior to a test so that velocity data can be compared in time to all the other measurements.

Particle mass flow

Although the flow of particles from the discharge hopper should be constant with time (an air operated vibrator helps to assure that it is) real time mass flow data was considered essential to verify the mass flow rates. Three strain gage style load cells are used to support the distribution bin at the top. The signal from these cells is fed to the main data acquisition system. To prevent signal drift due to temperature variations, the cells and signal cables were wrapped in insulation and cooled with a fan. As a final precaution, the load cells were instrumented with type K thermocouples.

Optical depth

Optical depth is a measure of the ability of the radiant flux to pass through the particle curtain and can be a valuable tool to verify radiative modeling. To measure optical depth, the beam from a Helium Neon laser is passed through a beam expander to form a 3.0 cm diameter collimated beam. This beam passes through the chute and illuminates a photodiode on the opposite side. The photodiode is equipped with a laser line filter to preclude energy from the lamps and a neutral density filter to prevent saturation of the diode. As the curtain density varies so will the output of the photodiode. This system is the same that will be used for attempts at in-situ particle temperature measurements.

Paper 2.7.5
J. M. Hruby
Sandia National Laboratories

Radiant Heat Facility Experiment: Test Results

The first experiments performed at the Radiant Heat Facility employed 300 micron diameter SiC particles and a radiant flux of 0.25 MW/m^2. The convective currents present as the particles and the chute heated were strong enough to overcome the velocity of the particles, and cause flow reversal. This resulted in 90% of the particles being thrown from the top of the chute, and 10% being captured in the catch bin.

In an effort to overcome such convective effects, larger diameter particles were tried. Large diameter particles resist convective effects because they have both an increased velocity and less convective heat transfer from their surface. Successful experiments were performed with 500 and 1000 micron SiC with a radiant flux of 0.25 MW/m^2. The results from these experiments are presented in Tables 1 and 2 respectively.

The results of the 500 micron particles indicate that an equilibrium temperature is obtained within three seconds. This is an important result because it indicates fall heights of less than ten meters are appropriate for a solar receiver which employs 500 micron particles. In addition, the effects of convection on particle velocity can be determined. It appears that convective effects due to the hot particles themselves account for a decrease in particle velocity from 7.5 to 4.0 m/s. This is attributed to particle convective effects not chute convective effects because the chute walls were not preheated and consequently do not reach a high temperature. However, chute convective effects are apparent when chute preheat occurs. In the preheat case, chute convection appears to be responsible for a velocity drop from 4.0 to 2.2 m/s.

Equilibrium temperature was not reached when 1000 micron particles were used. The final temperature recorded was 650 C compared to 850 C for the 500 micron particles. This can be explained by examining the residence time of the particles in the radiant flux and considering the thermal capacitance of the particles. Convective effects seem less significant for the larger particles. A decrease by a factor of 2 in the velocity is seen when the chute is preheated. The 500 micron particles experienced a decrease by a factor of 3.5.

The data just discussed is information very recently gathered. Many other interesting results have occured but have not been fully analyzed. There are plans to complete the data sets and expand the data set to include different particle materials. These experiments should be complete by the end of March, 1984.

Spectral flux mapping was accomplished on a laboratory mock-up of one chute section. The measured spectral flux distribution is shown in Figure 1. These results indicate that the lamps appear to be a blackbody of about 2400 K (the sun is a blackbody of 6000 K). With this information, the performance of particles in this infrared flux can be compared to their performance in a solar flux if the spectral characteristics of the particles are understood.

500 MICRON PARTICLES

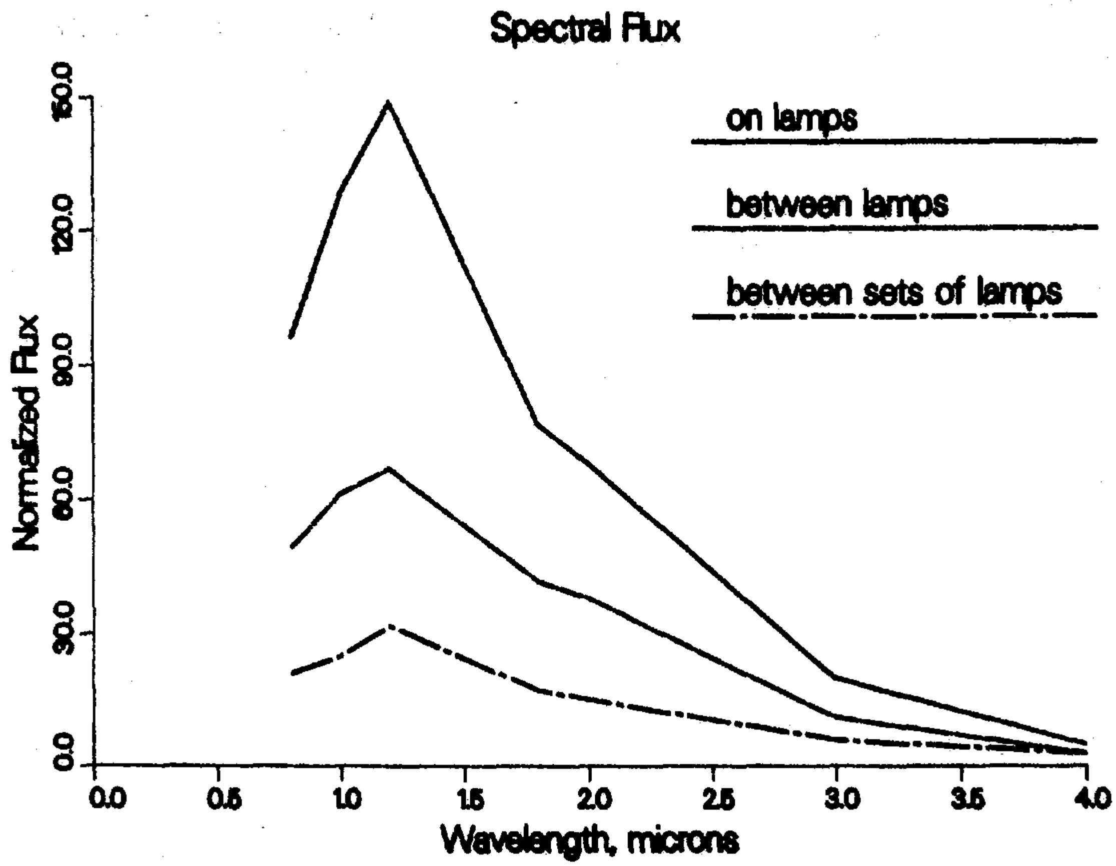
FLOW CONDITION	VELOCITY (m/s) AT			RESIDENCE TIME (sec)	FINAL TEMPERATURE(°C)
	1.70m	4.11m	6.66m		
COLD FLOW	4.9	6.9	7.5	2.2	AMBIENT
HOT FLOW - NO PREHEAT, FLUX = 0.25 MW/m^2	--	--	4.0	3.1	850
HOT FLOW - CHUTE PREHEAT, FLUX = 0.25 MW/m^2	4.5	--	2.2	4.2	850

TABLE 1

1000 MICRON PARTICLES

FLOW CONDITION	VELOCITY (m/s) AT			RESIDENCE TIME (sec)	FINAL TEMPERATURE(°C)
	1.70m	4.11m	6.66m		
COLD FLOW	5.34	7.37	8.35	2.1	AMBIENT
HOT FLOW - CHUTE PREHEAT	5.30	--	4.20	2.8	650

TABLE 2



Spectral Flux
on lamps
between lamps
between sets of lamps
Normalized Flux
0.0
30.0
60.0
90.0
120.0
150.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Wavelength, microns

Figure 1

APPENDIX A--MEETING AGENDA
Solid Particle Receiver Review
January 25-26, 1984
SNLL, 921 Conference Room

Wednesday, January 25, 1984

8:30	Welcome	P. K. Falcone, 8453
8:40	Overview of Central Receiver Program	W. G. Wilson, 8453
9:00	Overview of Solid Particle Receiver Work	P. K. Falcone, 8453
9:30	Aerodynamics Modeling/Experiments	J. M. Hruby, 8124
10:00	BREAK	
10:30	Radiation Modeling	W. G. Houf, 8124
11:00	Optical Properties Measurements	R. B. Pettit, 1824 J. W. Griffin, PNL
11:30	Discussion	
12:00	LUNCH	
1:00	Particle Materials Overview	J. R. Hellman, 1845 T. A. Michalske, 1845
1:20	Sintering Study	G. L. Messing, PSU
1:50	Fracture Study	S. M. Wiederhorn, NBS
2:20	BREAK	
2:40	Ethylene Reactor Design Not Presented	P. K. Falcone, 8453
3:00	Hot Air Heat Exchanger Design	B. Fisher, SERI
3:20	Discussion	
3:45	ADJOURN	

Thursday, January 26, 1984

8:30	Radiant Heat Facility Experiment Overview	B. R. Steele, 8453
9:00	Radiant Heat Facility	P. L. Class, 7531
9:15	Experimental Apparatus	B. R. Steele, 8453
9:30	Diagnostics	V. P. Burolla, 8313
10:00	BREAK	
10:30	Test Plan	V. P. Burolla, 8313
11:00	Test Results	J. M. Hruby, 8124
11:30	Discussion	
11:45	Action Items and Summary	P. K. Falcone, 8453
12:00	ADJOURN	

APPENDIX B--MEETING ATTENDEES

Solid Particle Receiver Review
January 25, 1984

Affiliation	Name
Battelle Pacific Northwest Laboratories	Jeff Griffin
	Kurt Stohl
National Bureau of Standards	Sheldon Wiederhorn
Pennsylvania State University	Gary L. Messing
Sandia National Laboratories Albuquerque	Philip Class
	Bob Eagan
	Cheryl Maxwell
	Terry Michalske
	Richard Pettit
	Pete Roth
Sandia National Laboratories Livermore	Martin Abrams
	Larry Bertholf
	Vic Burolla
	Scott Faas
	Pat Falcone
	Bob Gallagher
	Jim Green
	Ralph Greif
	Bill Houf
	Jill Hruby
	Mim John
	Jon Noring
	Al Skinrood
	Rex Steele
	Bill Wilson
	Joan Woodard
	Jim Wright
Solar Energy Research Institute	Beta Fisher
	David Johnson

UNLIMITED RELEASE
INITIAL DISTRIBUTION

U. S. Department of Energy
Forrestal Building
1000 Independence Avenue
Washington, D.C. 20585
Attn: C. Carwile
H. Coleman
M. Scheve
C. Mangold

U. S. Department of Energy
P.O. Box 5400
Albuquerque, NM 87115
Attn: G. Pappas

U. S. Department of Energy
1333 Broadway
Oakland, CA 94612
Attn: R. Hughey

University of California at Berkeley
Dept. of Chemical Engineering
201 Gilman Hall
Berkeley, CA 94720
Attn: T. Cleland

University of Houston
Solar Energy Laboratory
4800 Calhoun
Houston, TX 77704
Attn: A. Hildebrandt

Pennsylvania State University
Dept. of Materials Science and Engineering
University Park, PA 16802
Attn: G. L. Messing

Battelle Pacific Northwest Laboratories
P.O. Box 999
Richland, WA 99352
Attn: J. Griffin
B. Johnson
K. Stohl

C.N.R.S.
Solar Energy Laboratory
Odeillo, B.P. 5,
66120 Font-Romeu
FRANCE
Attn: C. Royere

Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303
Attn: E. DeMeo

Georgia Institute of Technology
Atlanta, GA 30332
Attn: C. T. Brown

IEA/SSPS
Apartado 14
Tabernas, Almeria
Spain
Attn: J. Martin

National Bureau of Standards
U. S. Department of Commerce
Washington, D.C. 20234
Attn: S. M. Wiederhorn

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
Attn: J. Green
E. Fisher
D. H. Johnson

O. Walton, LLNL - 200
F. Gerstle, 1845
R. Pettit, 1824
P. Roth, 1824
T. Michalske, 1845
J. Hellman, 1845
J. Holmes, 6222
C. Maxwell, 6222
J. Leonard, 6227
P. Class, 7531
J. Nakos, 7531
R. S. Claassen, 8000; Attn: D. M. Olson, 8100
A. N. Blackwell, 8200
D. L. Hartley, 8300
C. S. Selvage, 8000A
M. Abrams, 8111
L. Bertholf, 8120
R. Gallagher, 8124
W. Houf, 8124
R. Greif, 8125
M. John, 8125
R. Gallagher, 8201
J. Vitko, 8348
8400; Attn: R. A. Baroody, 8410
A. C. Schuknecht, 8420
H. Hanser, 8440
J. F. Barham, 8460
J. B. Wright, 8450
A. C. Skinrood, 8452

S. E. Faas, 8452
P. K. Falcone, 8453 (20)
J. E. Noring, 8453
J. M. Hruby, 8453
B. R. Steele, 8453
J. C. Swearengen, 8453
J. B. Woodard, 8454
Publications Division, 8265, for TIC (27)
Publications Division 8265/Technical Library Processes Division, 3141
Technical Library Processes Division, 3141 (3)
M. A. Pound, 8424, for Central Technical Files (3)