[redacted]

SAND78-8702
Unlimited Release

UC-62

[redacted]

Status Report on the Direct Absorption Receiver

(Summary of presentation at the Semiannual Review, Advanced Solar Thermal Technology, May 9-11, Golden, Colorado)

T. D. Brumleve

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Department of Energy under Contract AT (29-1)-789.

Printed July 1978.

[redacted]

[redacted]

[redacted]

Sandia Laboratories
energy report

Issued by Sandia Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $4.00; Microfiche $3.00

SAND78-8702
Unlimited Release
Printed July 1978

UC-62

STATUS REPORT
ON THE
DIRECT ABSORPTION RECEIVER

T. D. Brumleve
Solar Technology Division 8451
Sandia Laboratories, Livermore

ABSTRACT

A novel receiver concept is described in which concentrated solar energy is absorbed directly in a black, high-temperature, heat transport fluid. Advantages and disadvantages of the method are reviewed, and a summary is presented of the results of investigations on materials stability and corrosion, fluid flow, absorption characteristics, wind effects, and various design studies. Also described are recent high solar flux tests in which levels exceeding 6 MW/m^2 were directly absorbed in the fluid.

CONTENTS

ILLUSTRATIONS

Direct Absorption Receiver

T. D. Brumleve

Sandia Laboratories
Livermore, California

Background

Research on a rather novel direct absorption central receiver concept has been under way at SLL since 1973.[1,2] Unlike more conventional receiver designs, where the energy is first absorbed on a metal or ceramic surface and then conducted to a heat transport fluid, the concentrated light is absorbed directly into a black liquid flowing down the walls of the receiver. Figure 1A shows a cavity version of a direct absorption receiver with a downward facing aperture for a central heliostat field. Figure 1B shows an external configuration for an off-set field with the vertical dimensions trimmed to match the smaller diameter beams from the southern region of the field. In both cases, the fluid is a blackened, low vapor pressure, molten salt which can be exposed to the atmosphere.

Direct absorption is one of several advanced concepts currently under investigation; the others include sodium or salt-in-tube receivers for steam-rankine systems and metal or ceramic receivers for high temperature Brayton systems. The direct absorption work has been primarily in the temperature range suitable for operation of a modern, high-efficiency steam-rankine cycle (2400 psi/1000/1000°F, 43-45% gross cycle efficiency). The thermal storage and electrical power generation subsystems are similar to those currently being investigated for the salt-in-tube system. In several respects, direct absorption embodies the best of the sodium and the salt-in-tube systems; it achieves the high flux capability of sodium while maintaining the safety and lower cost attributes of the salt system.

The following is a brief summary of the potential advantages and disadvantages of direct absorption. Objectives, results to date, and future plans are then discussed.

Advantages

1. No limitation on flux density - Since the energy is absorbed directly in the heat transfer fluid, flux density is not limited by heat transfer and thermal stress constraints. Full advantage can thus be taken of the high concentration capability of central receiver configurations. The only other system currently under investigation which may also be able to handle peak producible flux is the liquid sodium system.

2. Absorber surface area can be minimized - This reduction is possible because of the high flux capability and results in the following:
   (a) Radiation and convective losses are reduced (in proportion to area reduction), and thereby receiver efficiency is improved.
   (b) Receiver weight and cost are reduced in relation to area.

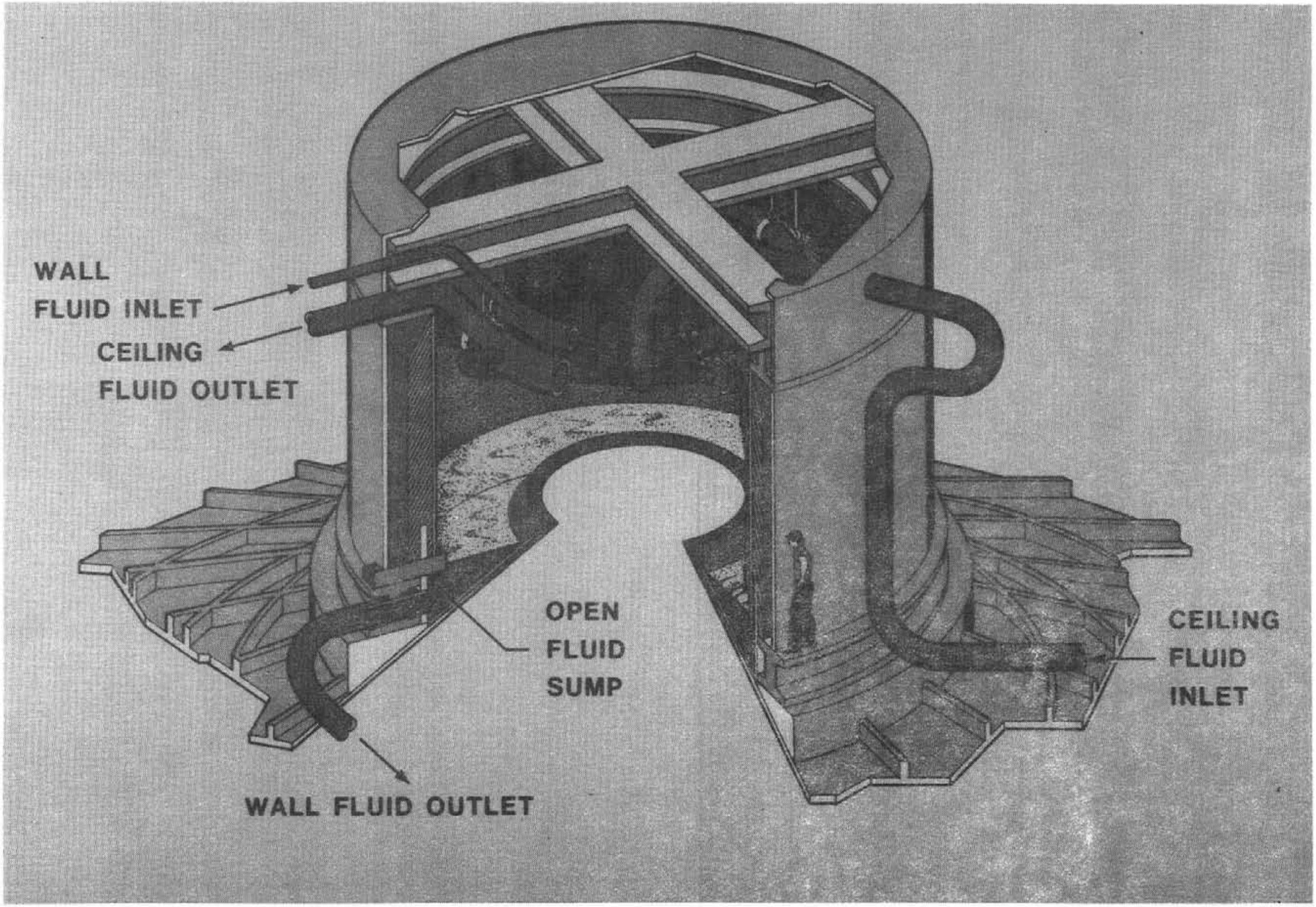
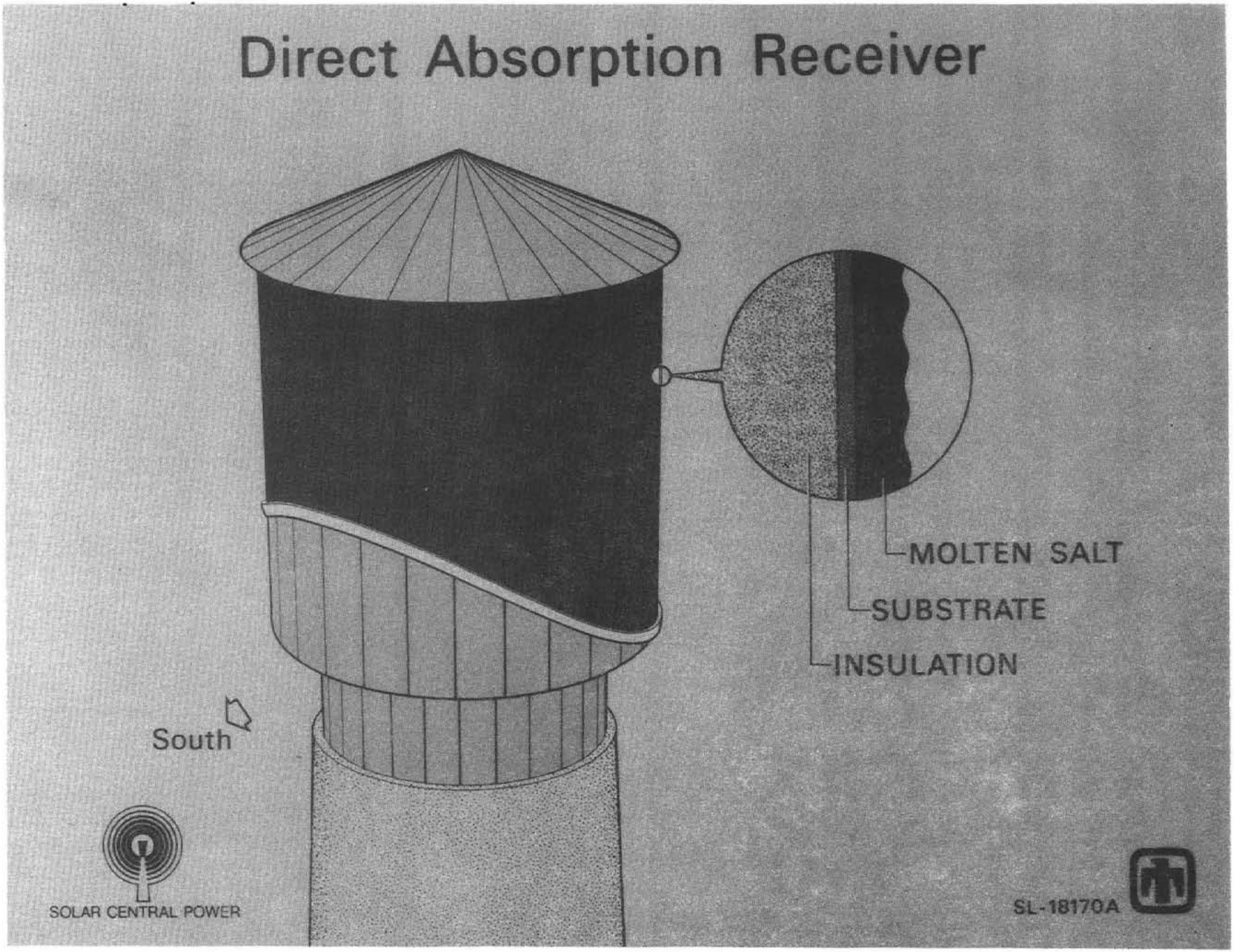


Figure 1A. Direct Absorption Cavity Receiver



Direct Absorption Receiver

Figure 1B. Direct Absorption External Receiver

3. Peak and average receiver temperatures are minimized - Unlike all other concepts, wherein the energy is first absorbed on a surface and then conducted to a lower temperature heat transfer fluid, the highest temperature in the direct absorption receiver is that of the fluid itself. Temperatures are typically 40-150°C lower and this results in a further reduction of radiative and convective heat losses.

4. Thermal stress and creep-fatigue problems are avoided - Because there are no absorber tubes, this major constraint on receiver design and lifetime is removed. In addition, the following operational advantages result:
   (a) Since the receiver can tolerate the high rates-of-change of flux which can occur during cloud passage, no special heliostat array controls are needed to limit flux rates of change.
   (b) Because of low thermal mass and inherently fast response, energy losses during startup, shutdown, and cloud transients are minimized.

5. Design and fabrication of the absorber surface is greatly simplified - The absorber is reduced to a simple substrate (such as sheet metal or chain mesh) whose only function is to provide a surface down which the fluid can flow. Complex welded tube arrays and manifolds tailored to flux distribution, requirements for pressure integrity, and concerns about scale buildup are thus avoided. The resulting reduced cost and weight per unit area of absorber surface, when coupled with the minimized total area, substantially reduces receiver cost and weight.

6. Design of tower and piping is simpler and less costly -
   (a) Because the receiver is open to the atmosphere, and because the riser is decoupled from the downcomer, provisions can readily be made for changes in pipe length due to thermal expansion, thereby eliminating the need for thermal expansion loops.
   (b) Certain tower design requirements can be relaxed because of reduced receiver and piping weight and because of less stringent seismic concerns.

Disadvantages

At this point in development, the principal disadvantages of the concept are not system disadvantages but rather the R&D which is yet to be completed. Uncertainties about high-temperature stability and corrosion are not fully resolved, and overall feasibility has yet to be demonstrated. More specifically:

1. High-temperature stability of the direct absorption fluid is not well established. Mixtures of sodium nitrate and potassium nitrate look promising, but stability data at the temperatures of interest is presently limited.

2. Corrosion rates and effects on candidate containment materials are also not well established for the high-temperature portions of the system. Only limited data is available for materials of interest (e.g. stainless steels) under the envisioned use conditions.

3. Because of uncertainties on stability and corrosion, the nature and magnitude of fluid maintenance which may be required is not determined

4. The feasibility of the direct absorption process has yet to be demonstrated on a meaningful scale under representative conditions.

Objectives

Sandia's objectives are to answer the principal questions pertaining to the direct absorption concept and to demonstrate the feasibility of a direct absorption receiver. This is one of several Sandia efforts aimed at devising ways to improve the cost-effectiveness of central receiver systems.

It is anticipated that if the concept continues to look promising, R&D participation by one or more industrial contractors will be solicited.

Results to Date

The following summarizes the work which has been completed or is currently under way to answer questions which have been identified.

1. An analytical model of the direct absorption process has been developed, and a variety of parametric studies has been completed.[3] For any specified incident flux distribution (i.e., intensity, specular or diffuse, spectral composition) the model determines absorption, reflection, reradiation, and temperatures of the fluid stream and along the substrate for given optical, heat transfer, and other physical properties of the fluid and substrate.

2. The direct absorption properties of some representative doped molten salts have been experimentally determined.[4] The presently preferred fluid is a mixture of sodium nitrate and potassium nitrate (with small amounts of nitrites) with a melting point of about 257C. Since the salt is nearly transparent to the solar spectrum in its molten state, its absorptivity is increased by adding a small amount of hydrated cobalt nitrate to form a finely divided cobalt oxide suspension (particle size $\sim 1\mu m$). The experiments successfully characterized the absorption coefficient of the fluid as a function of dopant concentration. At the film thicknesses of interest (1-5 mm), less than 1 wt percent of dopant is sufficient to raise the bulk absorptivity of the fluid to greater than 0.95.

3. Flow characteristics of molten salts on candidate substrate materials have been checked using the test unit shown in Figure 2. Tests using nitrate salt mixtures on stainless steel have shown the flow to be well behaved. The fluid wets the substrate and spreads uniformly, and at the temperatures and mass flow rates of interest the flow is turbulent as predicted from the literature. Limited experiments have also been done on entrance configurations for distributing inlet fluid uniformly across the top of a wall panel.

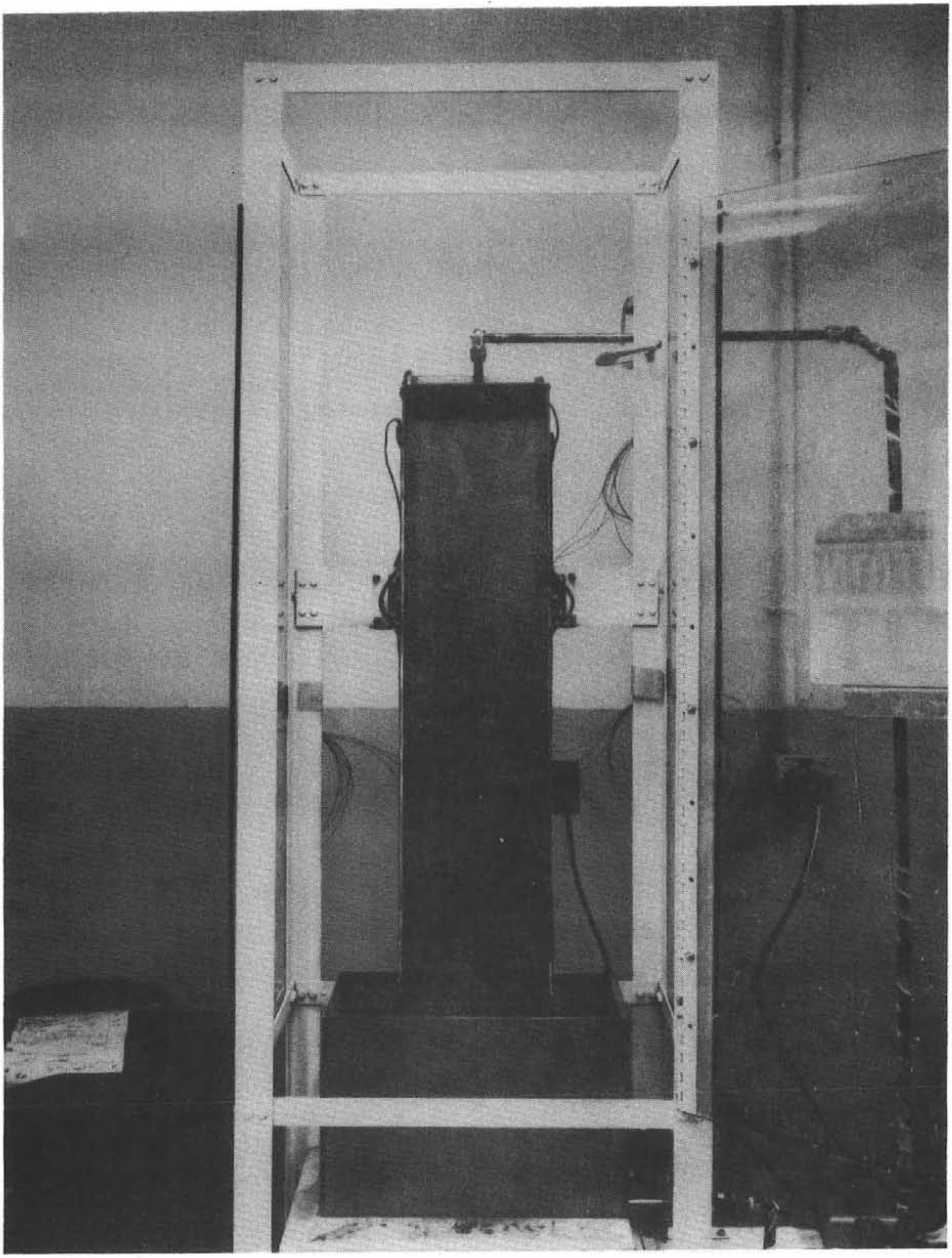


Figure 2. Direct Absorption Fluid Flow Experiment

4. The high-temperature stability of the nitrate-nitrite mixture is under investigation. Experiments have been under way for some time at SLL but they are not yet conclusive. Recent laboratory tests on the same salts at Martin Marietta, as part of their work on a salt-in-tube system, indicate that the fluid will be stable in air at temperatures of at least 565°C. Tests also indicate that reactions with atmospheric carbon dioxide and/or water vapor to form carbonates or sodium oxide proceed at a very slow rate. Some comparatively straightforward fluid maintenance alternatives have been identified which will be investigated in more detail as we gain a better understanding of these reactions and their significance in an operational system. A cooperative effort is also being arranged with Oak Ridge National Laboratory to augment current efforts at SLL and Martin Marietta and to assist in the identification and development of alternative high-temperature fluids.

5. Corrosion samples of various candidate containment materials including low carbon steel, a range of croloys, several stainless steel alloys, and Incoloy 800 have been immersed in molten salt at SLL and Martin Marietta at temperatures of 540 to 595°C for up to six months. As expected, the low carbon steels are not suitable at these temperatures. The Incoloy 800 appears to be holding up well at 595°C in the Martin tests. Some of the stainless samples are also doing reasonably well. Tests at SLL show lower oxidation rates for alloys with increasing amounts of chrome, and that oxidation rates of most samples decreased markedly with time. Leaching of chrome from the surface layer was observed in some samples. Two issues which will bear on material selection and will require considerably more investigation are possible mass transport effects and the potential flaking of protective oxide layers. Materials review meetings are being held periodically to coordinate stability and corrosion work at Sandia and Martin Marietta. While experiments to date are encouraging, considerably more data will be needed before corrosion questions can be adequately answered.

6. A series of very interesting experiments are now being conducted at SLL using a small solar furnace to verify analytical and experimental characterizations of the direct absorption process and to confirm high flux capability. A small open receiver is positioned at the focal point of a 1.3 m diameter parabolic mirror (Figure 3) illuminated by a 1.8 x 1.8 m heliostat. Doped molten Hitec at about 315°C is pumped through the receiver at rates ranging from about 1 to 5 liters/min to provide film thicknesses ranging from 0.7 to 1.8 mm. At film thicknesses greater than 1 mm, with a dopant concentration of 1 weight percent, the substrate temperature was less than 7°C above the fluid temperature with a peak flux in excess of 6 MW/m^2 (Figure 4). The effect of dopant concentration is shown by some additional data taken under somewhat lower peak flux conditions in Figure 5. These tests are not yet completed, but data so far confirms the very high flux capability which has been predicted for direct absorption. The absorbed fluxes are well above the maximum levels expected in any central receiver application. Also, the results are generally consistent with previous analytical and experimental characterizations (tasks 1 and 2 above).

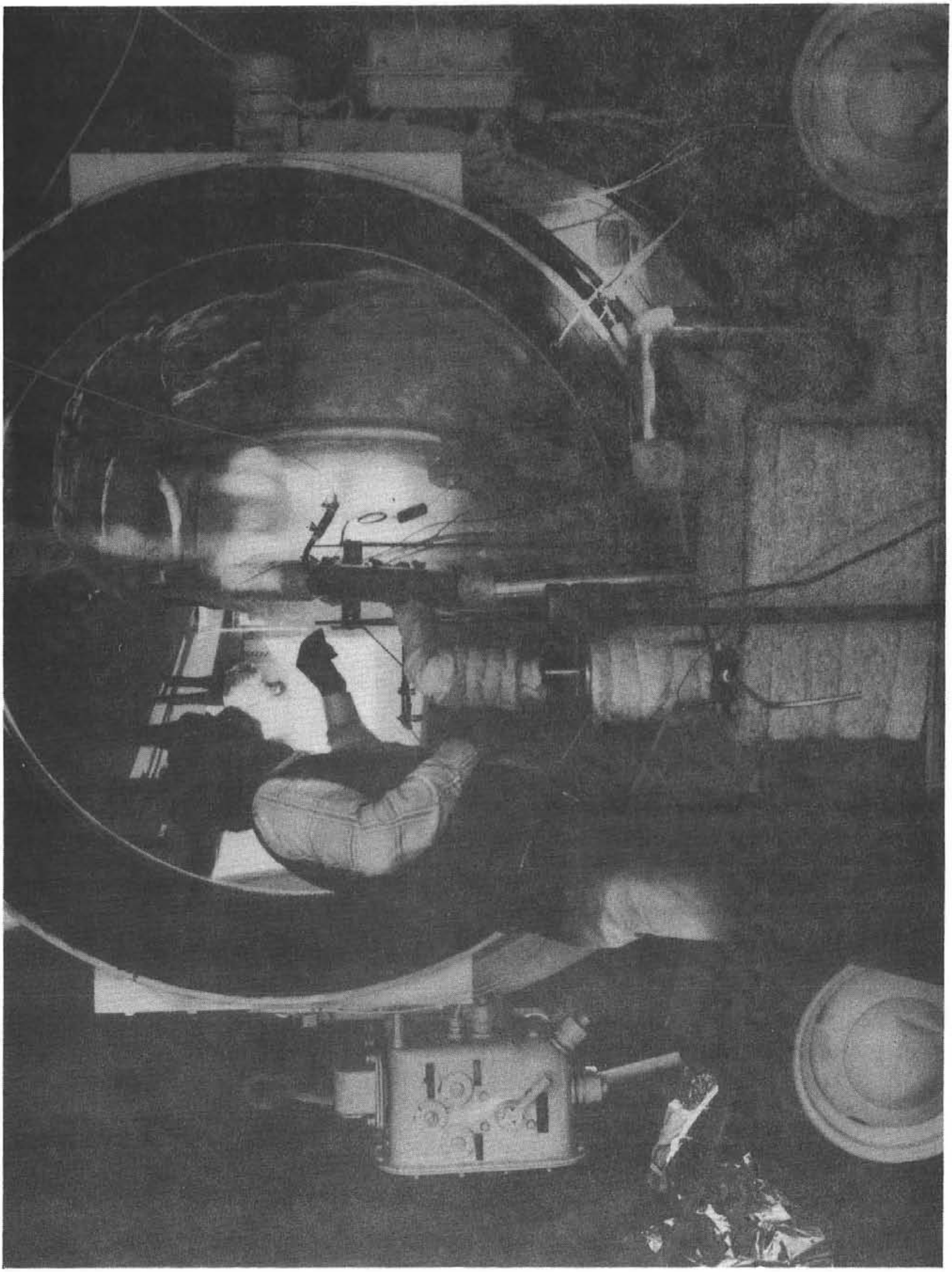


Figure 3. Direct Absorption High Flux Test Unit

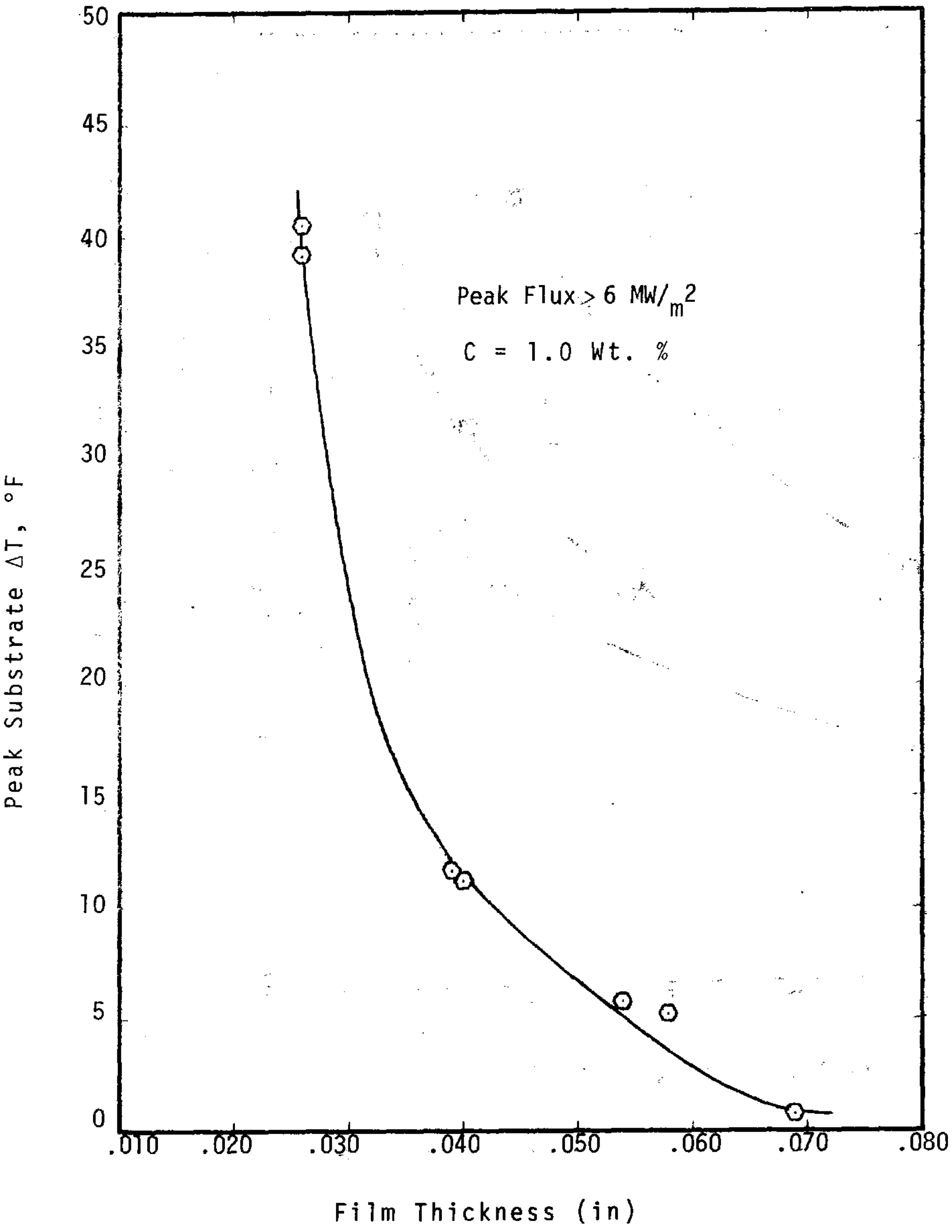


Figure 4. Peak Substrate Temperature Change vs. Film Thickness, High Flux Tests

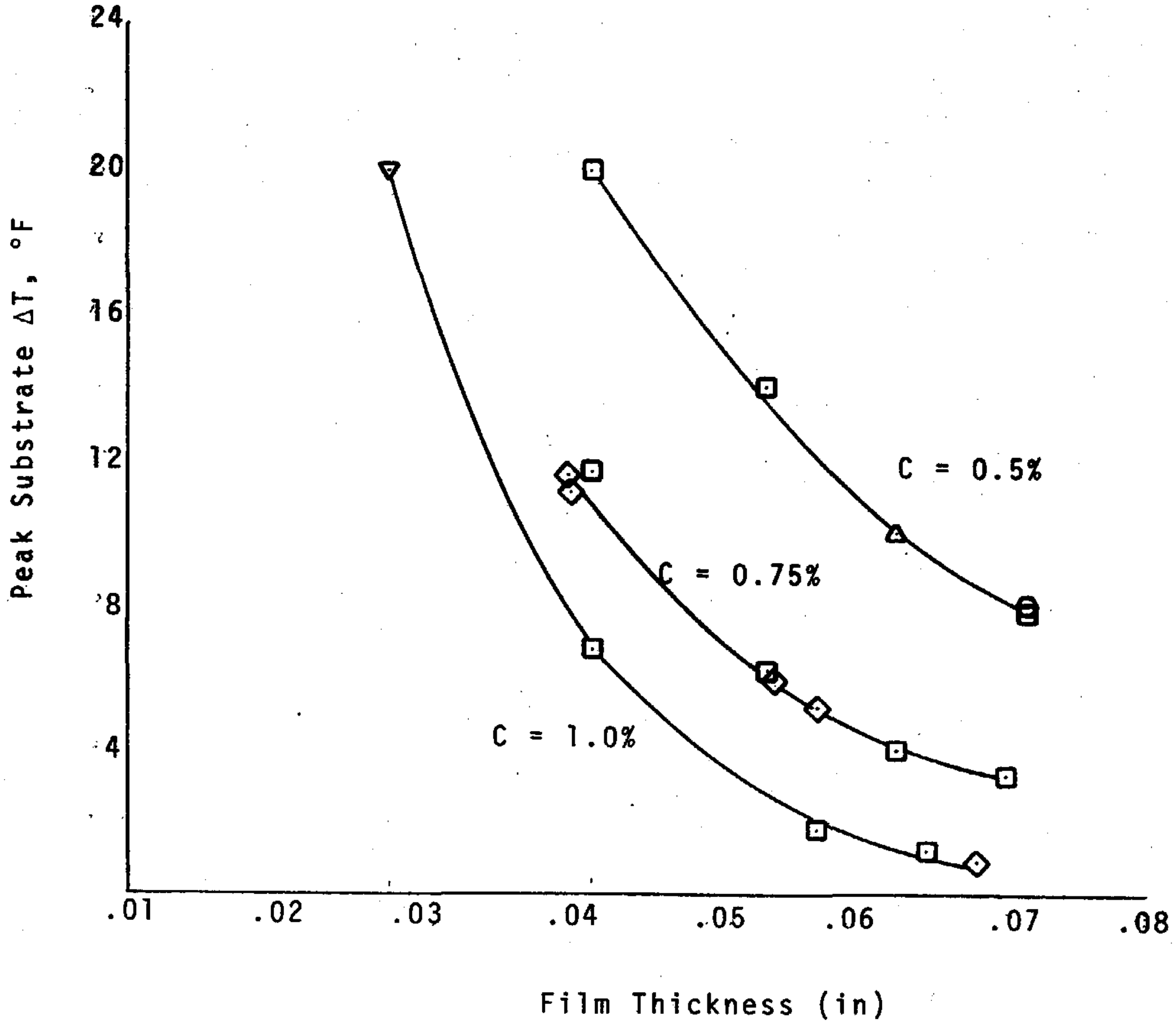


Figure 5. Peak Substrate Temperature vs. Film Thickness and Dopant Concentration, High Flux Tests

7. The initial 1973-1974 work on direct absorption was done primarily for a cavity receiver.[2] A conceptual design of an external configuration has recently been performed to allow cost and performance comparisons to a water-steam system and to second-generation salt, sodium, and Brayton designs. This is part of Sandia's continuing efforts to evaluate and improve several of the more promising advanced system concepts. Compared to a first-generation McDonnell Douglas (MDAC) type commercial receiver (for example a 0.85-MW_t peak flux design), the direct absorption receiver is about the same diameter (assuming the same heliostat array). Because peak flux need not be limited, the height is reduced to that required for single rather than three point aiming. Consequently, the absorber surface area is reduced by about 40%. Because of the reduced size and the lower weight per unit area, the weight is reduced by about 90 percent. Because of less material and simpler fabrication and installation, the direct cost is expected to be reduced by an even greater percentage.

8. For an external configuration, it is necessary to know wind velocity at which salt droplets might be entrained and carried away from the receiver. A preliminary small scale experiment was recently conducted using the flow panel described in task 3 above. A variable speed air stream was directed horizontally across downward flowing salt at 10 to 90° angles of incidence (with respect to the plane of the panel). Local wind speed was measured by a hot wire anemometer. No droplets could be carried away from the panel at wind speeds up to 60 mph at any angle of incidence. The maximum operational wind speed is expected to be well below the 60 mph. Additional experiments are planned within the next several weeks.

9. A long-term flow loop experiment is being assembled at SLL to provide data on salt stability and corrosion under representative flow and atmospheric exposure conditions. Molten, doped draw salt will be continuously circulated by means of a cantilever pump to the top of a panel and allowed to flow down the open panel to the tank. Initial operation will be at a constant temperature of 1000 or 1050°F. Provisions are being made so that temperature cycling may be added later if desired. Most of the equipment is on hand, but the panel sizing is awaiting further studies on the importance of fluid surface-to-volume ratios.

Future Plans

A rather comprehensive review of the direct absorption work is scheduled for the week of May 22, 1978 at SLL. The purpose is to objectively examine the following:

1. The potential of the overall concept relative to other central receiver systems,

2. The findings and status of the relevant efforts which have been completed or are under way within Sandia or elsewhere.

3. The principal questions which still remain, and

4. The future course of action which seems most appropriate with respect to SLL's objectives and responsibilities within the DOE Solar Central Power Program.

The review will provide a basis for a management decision to reduce, maintain, or increase our efforts toward establishing feasibility and viability of the direct absorption system.

In preparation for one of the next steps, a preliminary design is under way on a 3-MW experimental unit for testing at the Solar Thermal Test Facility at Sandia, Albuquerque. The principal objective will be to demonstrate feasibility at a scale where operational conditions can be realistically simulated. The unit is envisioned as relatively simple scaled-up version of the flow panel in use at SLL. Doped molten draw salt at 260 to 370°C will be pumped to the top of a vertical panel about 1 m wide by 3 m tall, and allowed to flow down the panel where it will be heated to 430 to 565°C (depending on flow rate) at peak fluxes up to about 2 MW/m^2. The salt will then be returned to the desired receiver inlet temperature by routing it through an air or water cooled heat exchanger. The size of the unit is large enough to provide representative flux, temperature rise, mass flow rates, and film thickness, but is still well within the capabilities of STTF.

References

1. T. D. Brumleve, A High-Temperature Solar Energy System, SAND74-8008, July 1974.

2. A. C. Skinrood, T. D. Brumleve, C. T. Schafer, C. T. Yokomizo, C. M. Leonard, Jr., Status Report on a High Temperature Solar Energy System, SAND74-8017, September 1974.

3. M. Abrams, The Temperature Distribution Along an Absorbing-Emitting Fluid Layer Flowing Over an Opaque Substrate, SAND76-8622, August 1976.

4. William D. Drotning, Solar Absorption Properties of a High Temperature Direct-Absorbing Heat Transfer Fluid, SAND-76-9104-C.

UNLIMITED RELEASE

INITIAL DISTRIBUTION:

TIC UC-62 (298)

Department of Energy
Division of Solar Technology
Washington, D.C. 20545
Attn: M. U. Gutstein
G. M. Kaplan

Department of Energy
San Francisco Operations Office
1333 Broadway, Wells Fargo Bldg.
Oakland, CA 94612
Attn: J. A. Blasy
S. D. Elliott
R. W. Hughey

J. H. Scott, 5700
G. E. Brandvold, 5710
H. J. Saxton, 5840; Attn: J. N. Sweet, 5842
T. B. Cook, Jr., 8000; Attn: A. N. Blackwell, 8010
W. J. Spencer, 8100
C. H. DeSelm, 8200
B. F. Murphey, 8300
W. E. Alzheimer, 8120; Attn: A. F. Baker, 8124
D. M. Schuster, 8310
R. W. Mar, 8313
T. S. Gold, 8320
P. J. Eicker, 8326
L. Gutierrez, 8400
R. C. Wayne, 8450
T. D. Brumleve, 8451 (50)
W. G. Wilson, 8451
A. C. Skinrood, 8452
F. J. Cupps, 8265/Technical Library Processes Division, 3141
Technical Library Processes Division, 3141 (2)
Library and Security Classification Division, 8266-2 (3)