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Proceedings of the Annual Solar Thermal Technology Research and Development Conference

March 8 and 9, 1989

W. A. Couch, Editor

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Proceedings of the Annual Solar Thermal Technology Research and Development Conference

March 8 - 9, 1989

Arlington, Virginia

Sponsored by the U.S. Department of Energy
Organized and Hosted by Sandia National Laboratories and
The Solar Energy Research Institute

ABSTRACT

The Annual Solar Thermal Technology Research and Development Conference is being held at the Holiday Inn Crowne Plaza in Arlington, Virgina, March 8 and 9, 1989. This year the conference is meeting in conjunction with SOLTECH '89. SOLTECH '89 is a jointly sponsored meeting of the Solar Energy Industries Association, Interstate Solar Coordination Council, Sandia National Laboratories and the Solar Energy Research Institute. This report contains the agenda, extended abstracts and most significant visual aids used by the speakers during the Solar Thermal Technology research and development sessions. The program is divided into three sessions: Solar Electric Technology, Non-Electric Research and Development and Applications, and Concentrators.

ACKNOWLEDGMENTS

I would like to acknowledge and express my appreciation for the support provided by many individuals whose contributions were essential to the success of the conference. Special recognition and thanks are due to Russell Hewett who was instrumental in helping to organize te conference. Thanks are also expended to the Session Chairpersons: Paul Klimas, Bim Gupta, John Thornton, and John Holmes, for securing speakers and organizing and conducting their sessions.

William A. Couch

AGENDA
SOLAR THERMAL TECHNOLOGY PROGRAM ANNUAL R&D REVIEW

REGISTRATION - 10:00 a.m. - 1:00 p.m.

Session 1: SOLAR ELECTRIC TECHNOLOGY
(March 8, 1989, 1:00 - 5:00 p.m.)

- SESSION 1 CHAIRMAN: Paul Klimas (SNLA)

OVERVIEW PRESENTATIONS	SPEAKERS	TIME
(1) *Welcome and Announcements*	*H. Coleman (DOE/HQ)*	*1:00 - 1:10*
(2) *DOE Cooperative Programs: Overview*	*J. Otts (SNLA)*	*1:10 - 1:20*
(3) *Cummins Free Piston Stirling Engine*	*J. Davis (Cummins Engine Co.)*	*1:20 - 1:35*
(4) *Solar Thermal Electric Systems:Overview*		
• *Utility Study Activities*	*T. Hillesland, Jr. (Pacific Gas & Electric)*	*1:35 - 1:55*
• *Advanced Electric Generation Technology*	*P. Klimas (SNLA)*	*1:55 - 2:15*
(5) *Solar Concentrators Development Overview*	*J. Holmes (SNLA)*	*2:15 - 2:35*
(6) *Photochemical Systems and Emerging Applications Overview*	*B. Gupta (SERI)*	*2:35 - 2:55*
(7) *Status of Receivers: Overview*		
• *Reflux Distributed Receivers*	*R. Diver (SNLA)*	*2:55 - 3:10*
• *Advanced Central Receivers*	*J. Chavez (SNLA)*	*3:10 - 3:30*
BREAK		*3:30 - 3:45*

AGENDA
SOLAR THERMAL TECHNOLOGY PROGRAM ANNUAL R&D REVIEW

Session 1: SOLAR ELECTRIC TECHNOLOGY (continued...)

TECHNICAL PRESENTATIONS	SPEAKERS	TIME
(8) Dish Conversion Systems		
• *Heat Pipe Solar Receivers for Stirling Engines*	*D. Adkins (SNLA)*	*3:45 - 4:00*
• *Pool Boiler Receiver Bench Test Results*	*C. Andraka (SNLA)*	*4:00 - 4:15*
• *Kinematic Stirling Engines for Solar Thermal Electric Systems*	*K. Linker (SNLA)*	*4:15 - 4:30*
• *Status of DOE/NASA Advanced Stirling Conversion System Program*	*R. Shaltens (NASA)*	*4:30 - 4:45*
(9) Fluid and Thermal Behavior of the Direct Absorption Receiver	*M. Bohn (SERI)*	*4:45 - 5:00*
ADJOURN		

SOLTECH '89 RECEPTION in the Exhibition Hall	5:00 p.m.

AGENDA
SOLAR THERMAL TECHNOLOGY PROGRAM ANNUAL R&D REVIEW

SESSION 2: NON-ELECTRIC R&D AND APPLICATIONS
(March 9, 1989, 8:00 a.m. - 11:40)

- SESSION 2 CO-CHAIRMEN: Bim Gupta (SERI) & John Thornton (SERI)

TECHNICAL PRESENTATIONS	SPEAKERS	TIME
(1) Opportunities for the Solar Processing of Toxic Wastes	*J. Thornton (SERI)*	*8:00 - 8:20*
(2) High Flux/High Temperature Solar Destruction of Hazardous Waste		
• Laboratory Experiments	*B. Dellinger (U of Dayton)*	*8:20 - 8:40*
• Solar Furnace Experiments - I	*G. Nix (SERI)*	*8:40 - 9:00*
• High-Temperature Solar Destruction of Hazardous Wastes	*J. Fish (SNLA)*	*9:00 - 9:20*
(3) Solar Detoxification of Organics in Water		
• Research on Destruction of Organics in Dilute Aqueous Solutions	*J. Webb (SERI)*	*9:20 - 9:40*
• Engineering Studies of the Photocatalytic Destruction of Organics in Water	*C. Tyner (SNLA)*	*9:40 - 10:00*
BREAK		*10:00 - 10:20*

AGENDA
SOLAR THERMAL TECHNOLOGY PROGRAM ANNUAL R&D REVIEW

SESSION 2: NON-ELECTRIC R&D AND APPLICATIONS
(Continued...)

TECHNICAL PRESENTATIONS	SPEAKERS	TIME
(4) High Concentration Optics		
• *Approaching the Irradiance of the Sun Through the Application of Nonimaging Optics*	*R. Winston (U of Chicago)*	*10:20 - 10:40*
(5) Emerging Ideas and Concepts		
• *Solar Induced Surface Transformation of Materials (SISTM)*	*R. Pitts (SERI)*	*10:40 - 11:00*
• *Solar Treatment of Carbon Fibers*	*D. O'Neil (GTRI)*	*11:00 - 11:20*
• *Photo-Assisted Solar Thermal Reactions*	*W. Wentworth (U of Houston)*	*11:20 - 11:40*
ADJOURN		

LUNCH (on your own) and Free Time for Viewing SOLTECH '89 Displays in the Exhibition Hall	*12:00 noon*

AGENDA
SOLAR THERMAL TECHNOLOGY PROGRAM ANNUAL R&D REVIEW

SESSION 3: CONCENTRATORS
(March 9, 1989, 1:30 - 4:00 p.m.)

- SESSION 3 CHAIRMAN: John Holmes (SNLA)

TECHNICAL PRESENTATIONS	SPEAKERS	TIME
(1) *Introduction*	*J. Holmes (SNLA)*	*1:30 - 1:40*
(2) *Membrane Concentrators*		
• *Stretched Membrane Heliostats*	*A. Konnerth, III (Solar Kinetics, Inc.)*	*1:40 - 2:00*
• *An Improved Stretched Membrane Heliostat Mirror Module*	*K. Beninga (SAIC)*	*2:00 - 2:20*
• *Development of a Stretched Membrane Point Focus Concentrator*	*G. Hutchison (SKI)*	*2:20 - 2:40*
• *Structural and Optical Modeling of Non-Axisymmetrically Deformed Membrane Dish Concentrators*	*T.J. Wendelin (SERI)*	*2:40 - 3:00*
BREAK		*3:00 - 3:20*
(3) *Structural Issues*		
• *Development of a Low Cost Heliostat Drive*	*W. Heller (Peerless Winsmith)*	*3:20 - 3:40*
(4) *Materials*		
• *Optical Performance and Durability of Silvered Polymer Mirrors*	*P. Schissel (SERI)*	*3:40 - 4:00*

ADJOURN

Annual Solar Thermal Technology R&D Conference

Conference Objectives

The Annual Solar Thermal Technology R&D Conference provides a review and status update of Sandia's and SERI's work in Solar Electric Technology, Non-Electric R&D Applications, and Concentrators. This project is sponsored by the United States Department of Energy as part of its Solar Thermal Technology Program. The objectives of the meeting are:

- Publicize and increase the awareness of recent R&D results
- Provide a forum for discussion among university, industry and federal scientists and engineers
- Publicize potentially promising emerging and innovative new applications of the solar thermal technologies
- Solicit input from present and potential users of the technologies for inclusion in the near- and long-range R&D program plans

CONTENTS

SESSION 1 - SOLAR ELECTRIC TECHNOLOGY

Dish Conversion Systems

SESSION 2 - NON-ELECTRIC R&D AND APPLICATIONS

Introduction

High Flux/High Temperature Solar Destruction of Hazardous Waste

Solar Detoxification of Organics in Water

High Concentration Optics

SESSION 2 - NON-ELECTRIC R&D AND APPLICATIONS (cont'd)

Emerging Ideas and Concepts

SESSION 3 - CONCENTRATORS

Membrane Concentrators

Structural Issues

Materials

FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

To provide the most current and significant research and development information from the Solar Thermal Technology Program, an annual review features invited technical presentations and reviews of scientific and engineering progress. It provides participants with an opportunity to appraise the full range of R&D paths being pursued in the federal and private sectors to achieve long-term program goals. In addition, the annual review provides a forum on recent achievements in various disciplines that are relevant and directly applicable to solar thermal technology. Speakers from private industries, universities and federal laboratories highlight recent achievements, new and innovative approaches and future plans.

The 1989 Annual Review is being held in conjunction with SOLTECH '89 -- the solar technology trade show and exhibition sponsored by the Solar Energy Industries (SEIA); the show encompasses all solar technologies. The Solar Thermal Technology position of the Conference is March 8 and 9 in Washington, D.C.

THE REFLUX HEAT-PIPE SOLAR RECEIVER DEVELOPMENT PROGRAM

Richard B. Diver

Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Stirling dish-electric systems have been identified as having potential for meeting the Department of Energy (DOE) long-term levelized energy cost goals. Dish-electric systems based on Stirling engine technology were successfully demonstrated by Advanco Corp. and McDonnell Douglas Corp. and showed the potential for high efficiency.

A shortcoming of the Advanco and McDonnell Douglas modules (both used United Stirling Engines) was the directly illuminated tube receiver. Because of the inherent nonuniformities of concentrated sunlight, the directly illuminated Stirling engine heater tubes experience temperature gradients that degrade performance and limit life. In addition, directly heated tube receivers require highly accurate concentrators to produce reasonably uniform incident solar flux distributions, and generally result in performance compromises in the engine and receiver designs. Another shortcoming of the Stirling tube receiver is that it cannot be readily hybridized with fossil fuels.

The reflux heat-pipe receiver represents the next step in the evolution of Stirling receiver technology and has the potential to address all of the tube receiver shortcomings outlined above. In the reflux heat-pipe solar receiver sodium and/or potassium is used as an intermediate heat transfer fluid between the heater tubes of a Stirling engine and a solar receiver/absorber. The liquid metal is evaporated from the backside of the solar absorber (the evaporator) and flows to the Stirling engine's heater where it condenses (condenser). The liquid is passively returned to and distributed over the evaporator by gravity (refluxing), capillary forces in a wick, or by a combination of the two effects.

The liquid metal intermediate heat transfer fluid permits, to a large extent, the independent optimization of the receiver and the Stirling engine's heater tubes. In addition, the high heat transfer and isothermal nature of evaporating and condensing metals is ideally suited to the thermodynamic requirements of Stirling engines and to the design of solar receivers. Isothermal operation has the important advantage of reducing thermal stresses and increasing life. Furthermore fossil-fuel-fired heat pipes can in principle be readily combined with a reflux heat-pipe solar receiver to utilize solar and fossil fuel in any proportion.

Heat pipe solar receivers using conventional cylindrical heat pipes have been proposed and partially developed in the past. The current approach uses spherical geometry evaporators to capture concentrated sunlight more effectively and to reduce receiver cost and complexity. The inherently simple pool boiler reflux receiver concept is also being considered.

The objective of the reflux heat-pipe receiver program is to develop the tools and expertise to design and build long-lived, reliable, cost-effective receivers. An essential part of this effort is the development of reflux heat-pipe receiver technology, including the tools to design and optimize these receivers. The program is intended to complement and support industry sponsored reflux heat-pipe receiver development, and the DOE/NASA free-piston Stirling Advanced Solar Conversion System (ASCS) program.

The reflux heat-pipe solar receiver program is being conducted in two phases. Three projects are currently under way in Phase 1: (1) Stirling Thermal Motors screen wick heat-pipe receiver, (2) Reflux Pool Boiler Receiver, and (3) Alternative Wick Heat-Pipe Receiver. Each project involves the testing of one or more full-scale receivers on a Test Bed Concentrator in Albuquerque, NM. Gas-gap calorimeters will be used to simulate an engine and to quantify receiver performance. Laboratory scale "bench tests" with quartz lamp arrays will also be used for proof-of-concept tests. In Phase II a "best" receiver design will be identified, hybridized, and constructed, and made available for long-term testing. This will become the baseline receiver design that will hopefully be used in Stirling dish-electric systems of the future.

DIRECTLY ILLUMINATED STIRLING TUBE RECEIVERS

- United Stirling - Advanco & McDonnell Douglas Modules set world solar-to-electric efficiency records and showed the promise of Stirling dish-electric systems

<u>However:</u>

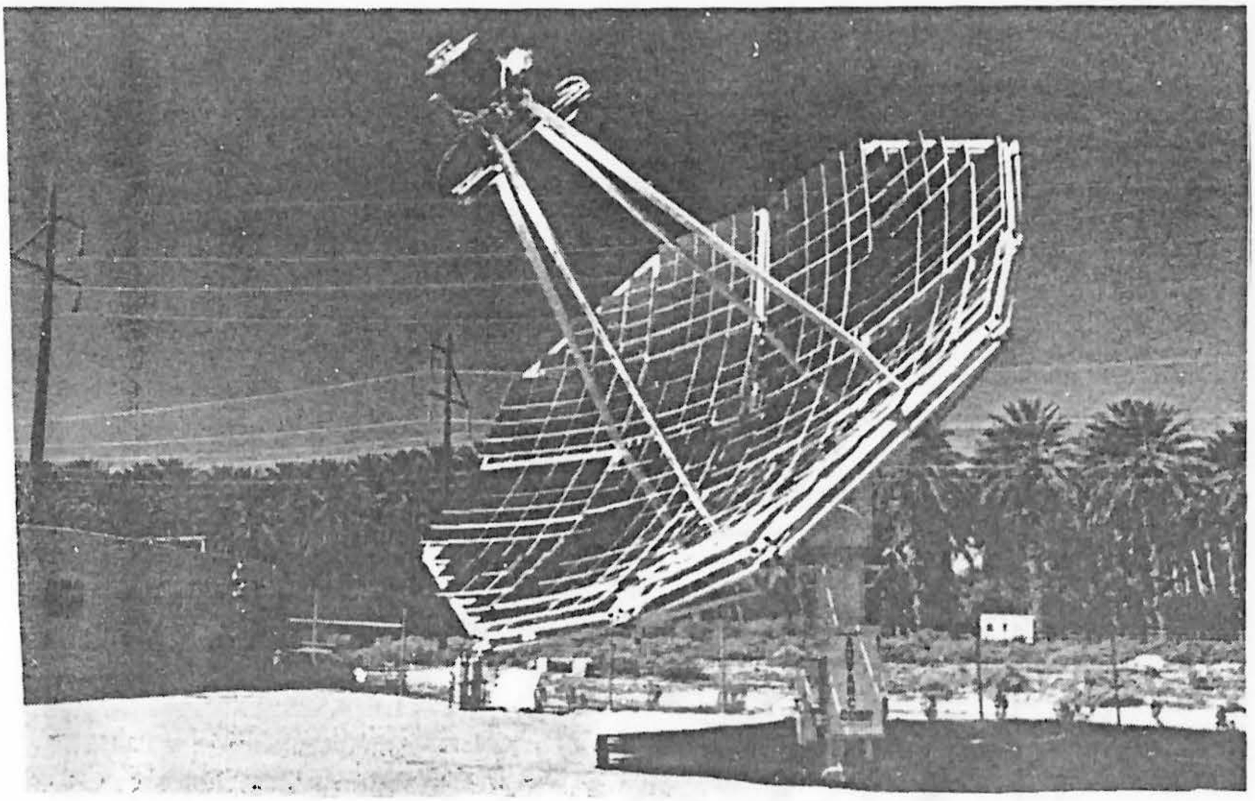
- Directly Illuminated Tube Receivers. . . .
  - Have limited life, approximately 16,000 hrs at 720°C
  - Require an accurate, high-quality dish
  - Compromise engine performance
  - Are not easily hybridized

THE REFLUX HEAT-PIPE SOLAR RECEIVER

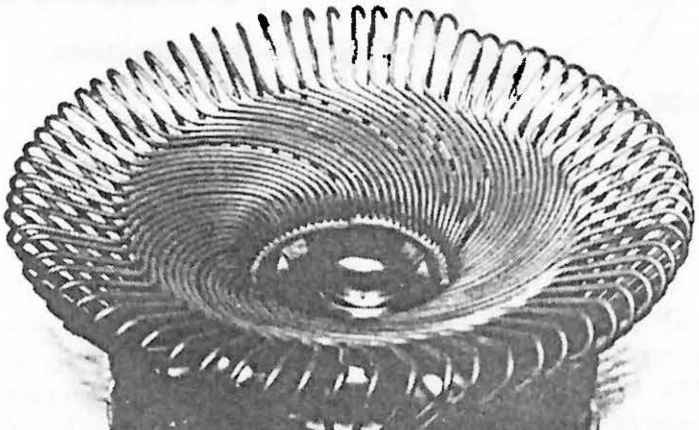
- Adaptation of liquid metal heat-pipe technology to the unique requirements of solar energy
  - Evaporator is shaped to efficiently collect solar energy
  - Condenser is the heater tubes of a Stirling engine

- Liquid metal is passively recirculated to the solar absorber/evaporator
  - Gravity (refluxing)
  - Capillary forces in a wick

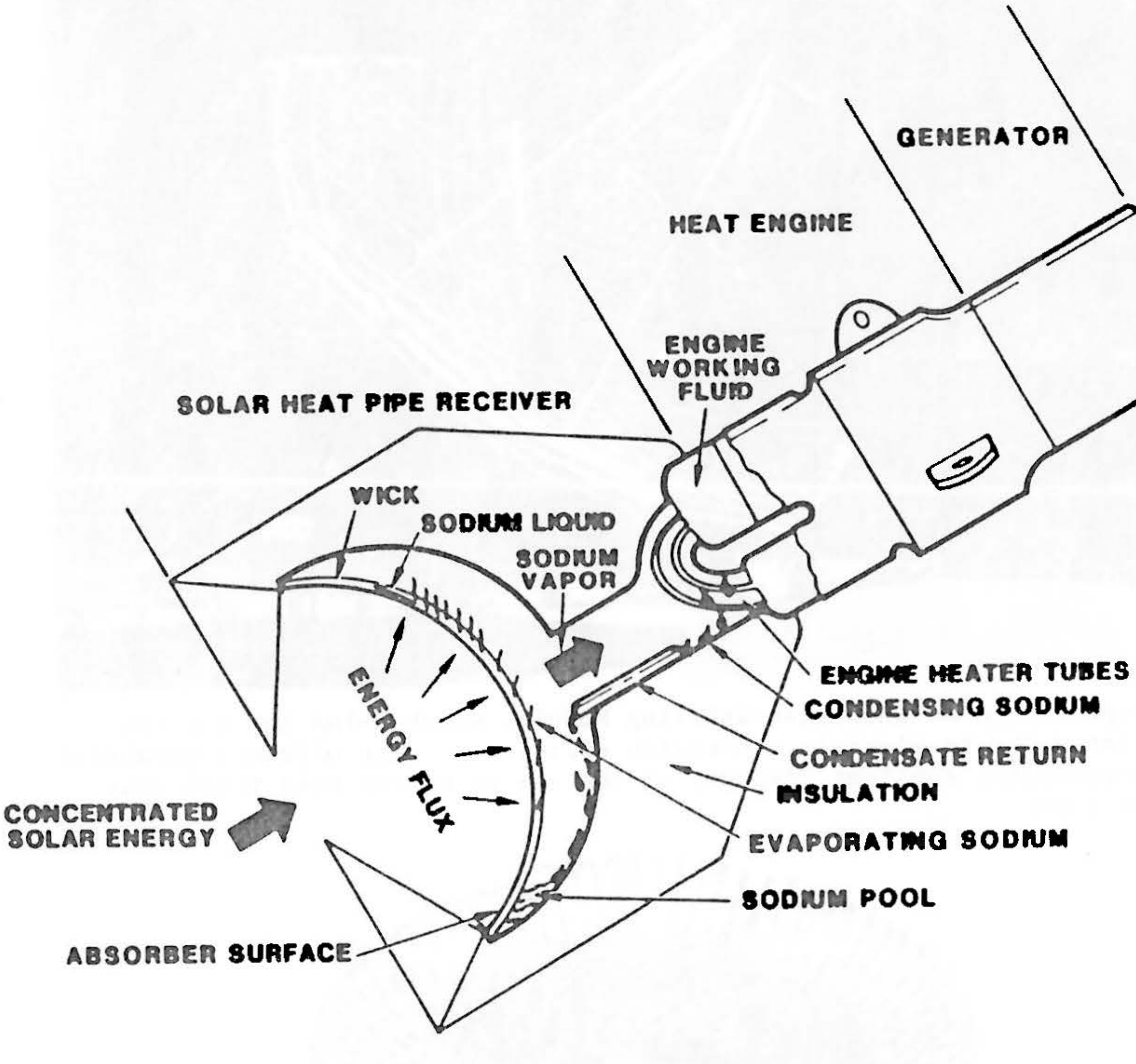
- Intermediate evaporating and condensing liquid metal
  - Leads to low ΔTs and isothermal behavior ideally suited to solar receivers and Stirling engines
  - High flux capability (as high as 8 MW/m^2)
  - Permits independent optimization of the receiver and engine
  - Leads to low thermal stresses and potentially long life
  - Readily hybridized



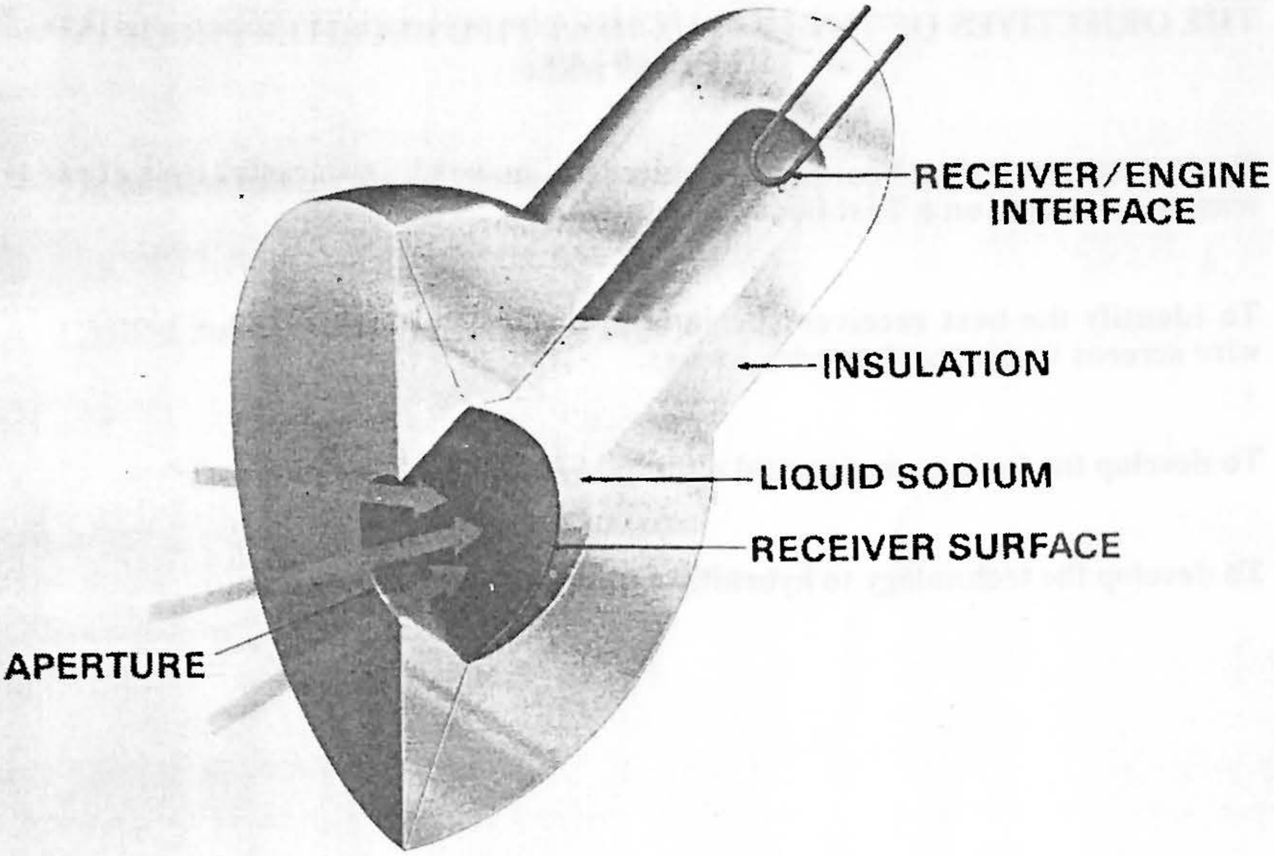
Photograph of the Advanco Dish-Stirling Module, which holds the current record for solar-to-electric conversion efficiency. The mirrored parabolic dish concentrates sunlight directly on the engine heater head tubes near the dish focus.



United Stirling ESOR-IIB heater head used on the Advanco Dish-Stirling Module. The oversized heater head tubes are spread out to improve the flux distribution and reduce thermal stress, but engine and receiver performance are compromised.



Conceptual drawing of a heat-pipe receiver and Stirling engine. The receiver's absorber surface absorbs concentrated solar flux causing sodium to evaporate from the wicks. The sodium vapor is transported to the Stirling engine's heater tubes, where it condenses and liberates heat to the engine. The liquid sodium is returned to the receiver absorber by gravity and distributed by capillary forces in the wick.



Artist's rendering of a reflux pool boiler receiver. Liquid metal is boiled from the backside of the receiver absorber and is transported as a vapor to the heater tubes of a Stirling engine. Liquid metal return to the absorber is assured by an inventory sufficient to submerge the absorber in orientations from vertical to horizontal. The engine heater tubes are always located in the vapor space above the pool.

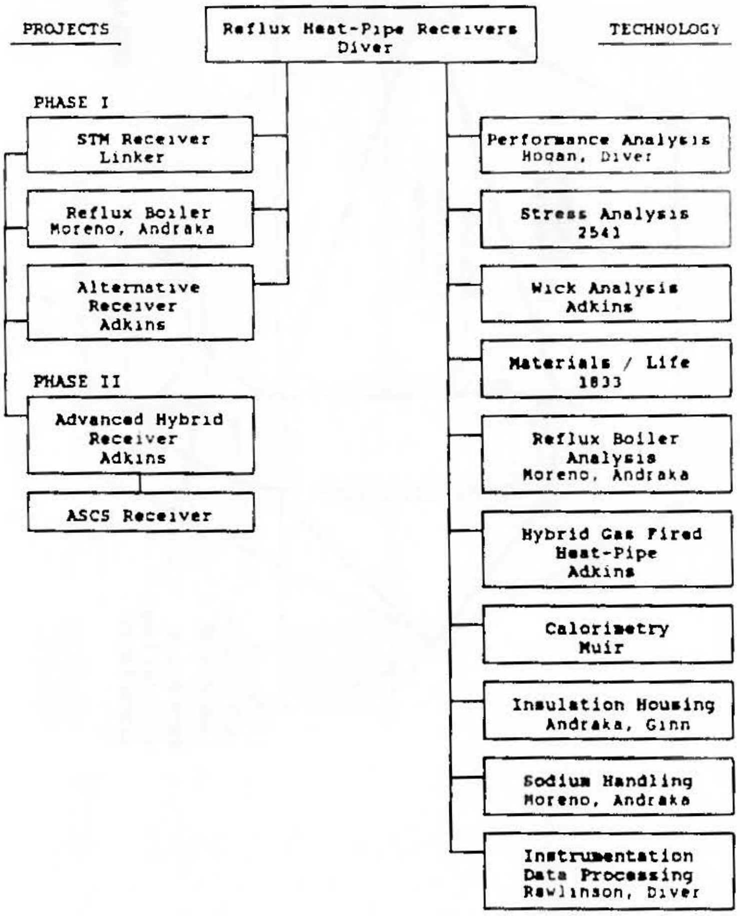
THE OBJECTIVES OF THE REFLUX HEAT-PIPE RECEIVER PROGRAM IN FY88-89 ARE:

- **To demonstrate reflux heat-pipe receiver technology by successful tests of at least one receiver on a Test Bed Concentrator.**
- **To identify the best receiver design approach--heat-pipe vs. reflux boiler, wire screens vs. sintered powder wicks.**
- **To develop the tools to design and optimize reflux heat-pipe receivers.**
- **To develop the technology to hybridize reflux heat-pipe receivers.**

THE REFLUX HEAT-PIPE RECEIVER PROGRAM WILL EMPHASIZE HARDWARE TESTING

- **Tests will be performed on the Test Bed Concentrators (TBC)**
- **The first phase of testing will establish hardware limitations (test to failure)**
- **The second phase of testing will determine performance characteristics**

REFLUX HEAT-PIPE SOLAR RECEIVER PROGRAM ORGANIZATION



PROJECTS

Reflux Heat-Pipe Receivers
Diver

TECHNOLOGY

PHASE I

STM Receiver
Linker

Reflux Boiler
Moreno, Andraka

Alternative
Receiver
Adkins

PHASE II

Advanced Hybrid
Receiver
Adkins

ASCS Receiver

Performance Analysis
Hogan, Diver

Stress Analysis
2541

Wick Analysis
Adkins

Materials / Life
1833

Reflux Boiler
Analysis
Moreno, Andraka

Hybrid Gas Fired
Heat-Pipe
Adkins

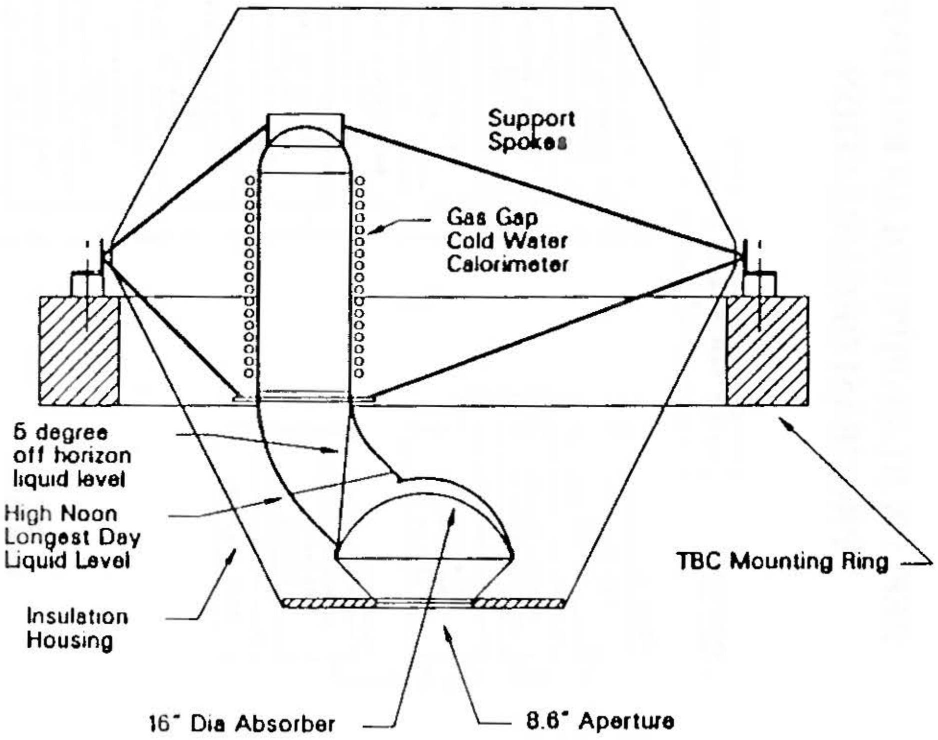
Calorimetry
Muir

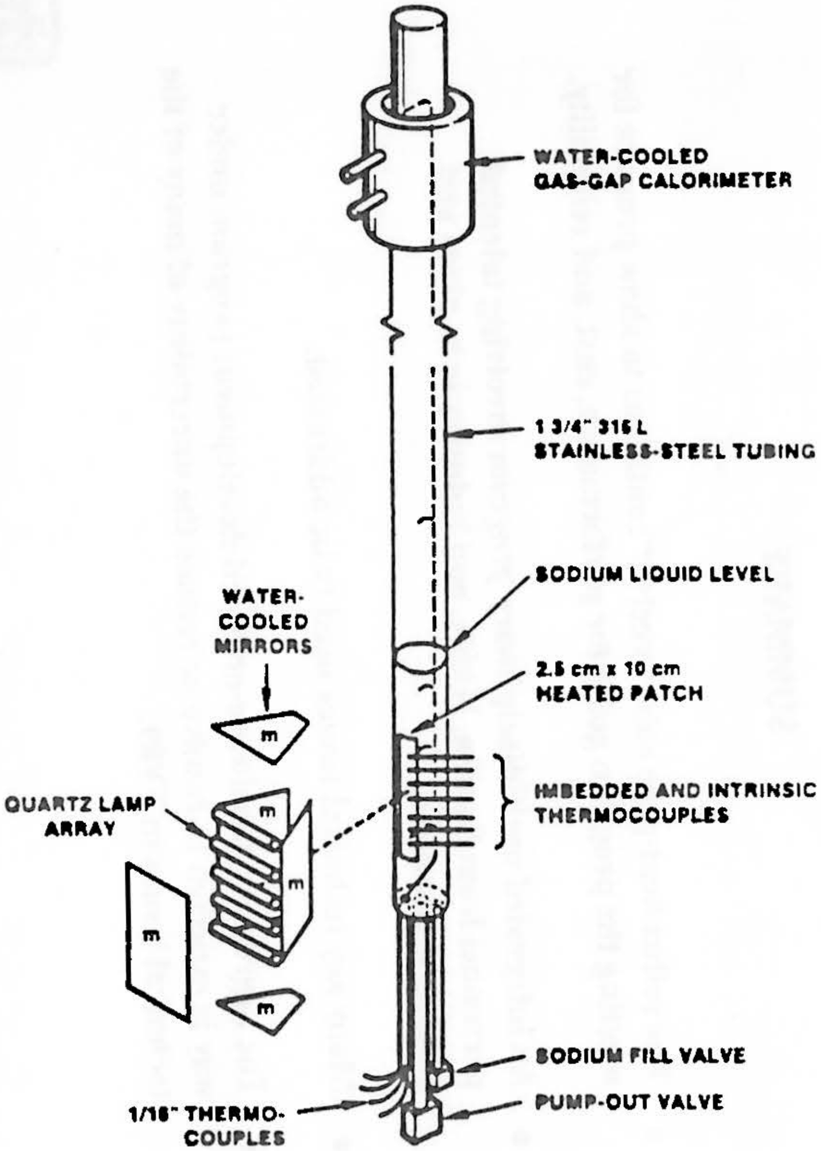
Insulation Housing
Andraka, Ginn

Sodium Handling
Moreno, Andraka

Instrumentation
Data Processing
Rawlinson, Diver

Sandia Heat–Pipe/Pool Boiler Receiver





Pool Boiler Bench Test

SUMMARY

- The reflux heat-pipe solar receiver continues to show promise for meeting the program goals for performance, cost, and reliability.
- An integrated multidisciplinary program involving talented personnel from Sandia, NASA, and industry is in place and gaining momentum.
- Many key technical issues need to be addressed.
- The aggressive, hardware-oriented development program under way is expected to resolve or reduce the uncertainty of many of the technical issues in FY89.

HEAT-PIPE SOLAR RECEIVERS FOR STIRLING ENGINES*

Douglas R. Adkins
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

Solar thermal dish-electric systems that are currently being developed will use heat pipes to transfer solar energy from the focal point of a parabolic dish concentrator to the working fluid of a Stirling engine. In a heat-pipe receiver, concentrated solar energy collected on the front (concave) surface of a dome is removed by the evaporation of liquid sodium on the back side of the dome. The sodium vapor then condenses on the heater tubes of a Stirling engine and transfers energy to the working fluid of the engine. Under the influence of gravity, the condensed sodium flows back to the evaporator surface where it is redistributed across the surface by the capillary action of a wick.

In the present program, heat-pipe solar receivers will be required to operate at sodium vapor temperatures of up to 800°C and transfer nominally 75-kW of thermal energy from the absorber surface to an engine's heater tubes. Peak fluxes on the absorber dome are on the order of 100 W/cm^2, and, without an adequate supply of sodium to the wick, the heat flux could burn a hole through the absorber dome in a few seconds. This situation places some rather stringent design requirements on the wick, and designing the wick-covered absorber dome has been one of the more critical elements of the receiver development task. Work is now being conducted at Sandia National Laboratories to develop and transfer the technology required to design, fabricate, and test heat-pipe solar receivers and their associated components.

For a heat pipe to work properly, the wick's capillary pumping capabilities must overcome both body forces (gravity and acceleration loading) and flow losses that are developed as the liquid passes through the porous matrix of the wick. Models have been developed at Sandia to predict pressure drops in wicks covering dome-shaped absorber surfaces. These models are used to explore various options of arranging wick materials across the absorber domes, and they have also been used in investigating artery systems to reduce flow losses in the wick.

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* This work was performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under contract number DE-AC04-76DP000789.

Various methods of fabricating and attaching wick structures to absorber domes are also being explored. Current efforts at Sandia are focused on constructing wicks from stainless steel screens. Steel screens are available in a variety of mesh sizes and they can be easily formed into domed-shapes, sintered into porous plates, and welded to an absorber dome. Methods of forming wicks directly on the absorber surface by plasma spraying or sintering metal powders are also being studied.

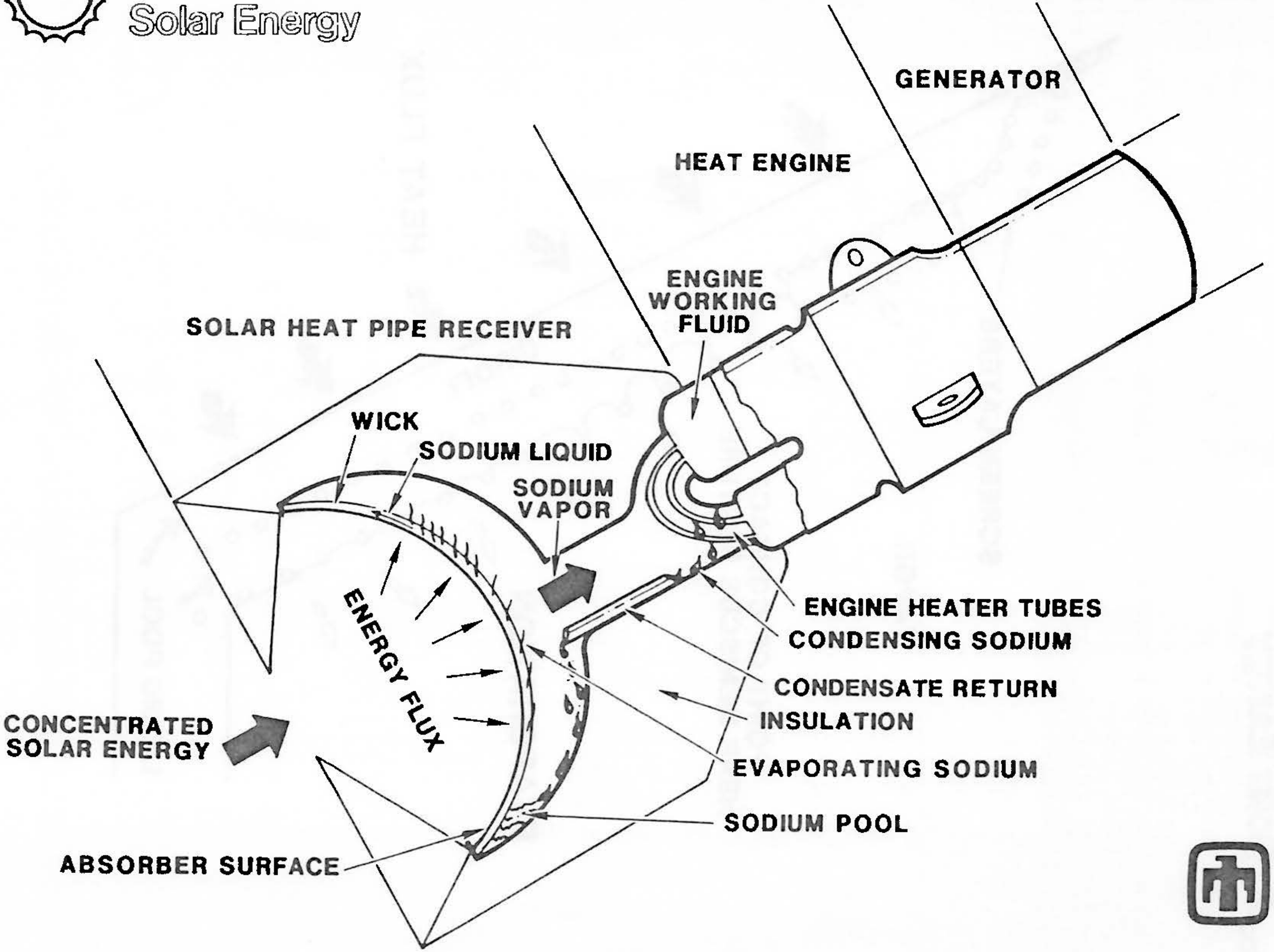
In addition to the fabrication and modeling efforts, techniques have been developed to measure the flow characteristics of wick materials. Properties such as flow resistance and surface pore size (pore size is important in determining capillary pumping capabilities) can be measured in both component and assembled wick configurations. Measuring the properties of wick components provides the data required for wick modeling tasks, and measuring the flow characteristics of fabricated evaporator domes is a useful quality assurance procedure that allows expensive and lengthy testing to be avoided in many cases. Heat-pipe receiver developers can also establish their own wick testing capabilities using the simple and inexpensive test procedures developed at Sandia.

Sandia is now preparing to conduct bench-scale and full-scale tests of heat-pipe solar receivers. In the bench-scale test, a wick covered section of a 3-foot long, 1 3/4-inch diameter pipe will be illuminated by quartz lamps. This bench-test will answer important questions about designing heat pipe wicks for the high flux encountered in solar thermal systems. Information that is gathered in the bench-scale test will be transferred into the design of full-scale heat-pipe solar receivers for 25-kWe dish-electric systems.

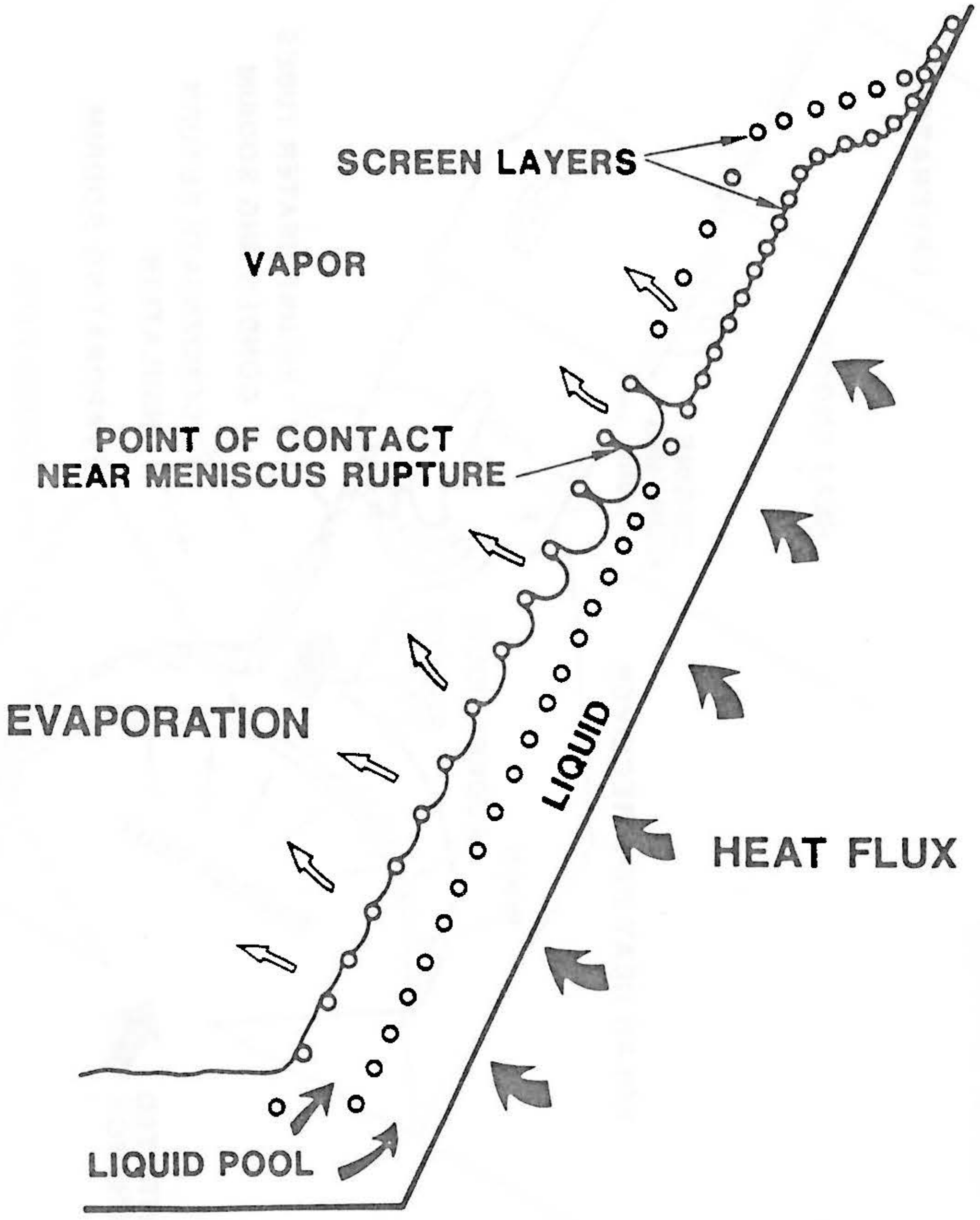
Sandia National Laboratories

Solar Energy

OPERATION OF A HEAT-PIPE SOLAR RECEIVER



OPERATION OF A WICK



WICK REQUIREMENTS

HIGH CAPILLARY PUMPING CAPABILITIES

SMALL SURFACE PORES (≈30 μm)

NO IMPERFECTIONS AT ATTACHMENT POINTS

LOW PUMPING REQUIREMENTS

LOW VERTICAL RISE

HIGH PERMEABILITY (≈80% POROSITY w/o ARTERIES)

LOW TEMPERATURE DROP

THIN WICK (≈1 mm)

REDUCE HEAT FLUX

WICK MATERIALS
SCREENS
POWDERED METALS
METAL FELTS
GROOVED SUBSTRATE

Forming Techniques

Screens:
- Bias Stretching
- Spin-Forming
- Hydro-Forming

Metal Powders:
- Retaining Dams
- Slurry Application

Metal Felts:
- (Questionable)

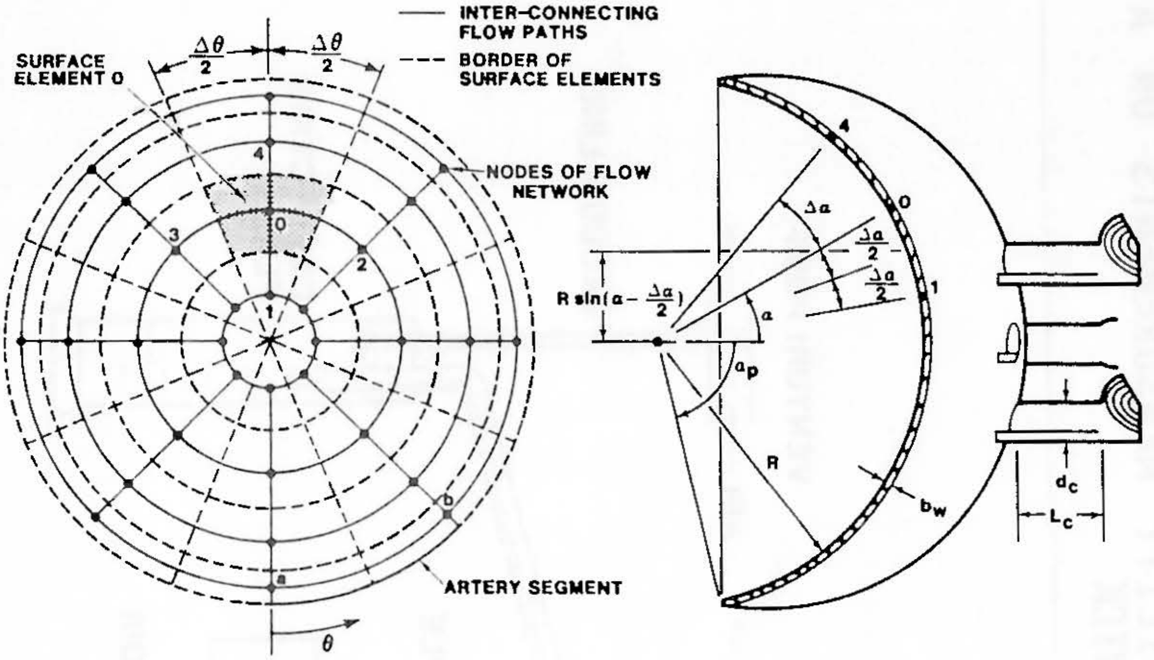
Grooved Substrate:
- Machining
- Chemical Etching

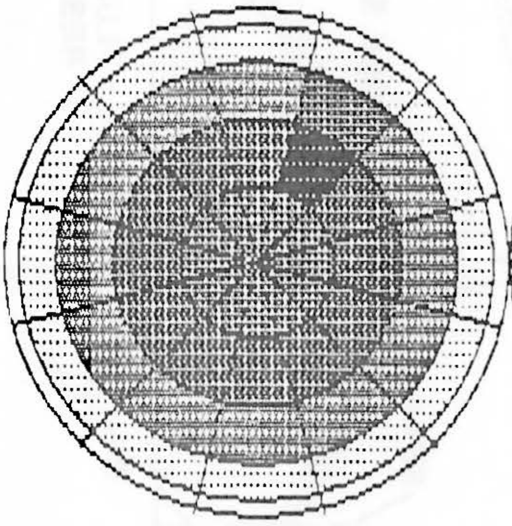
Fastening Techniques

Screens:
- Resistance Welding
- E-Beam Welding
- Sintering
- Brazing
- Mechanical Force

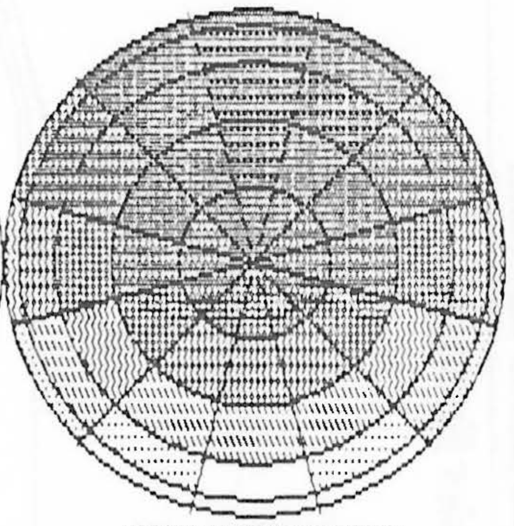
Metal Powders:
- Sintering
- Plasma Spraying
- Flame Spraying

DISCRETIZED WICK MODEL





FLUX DISTRIBUTION



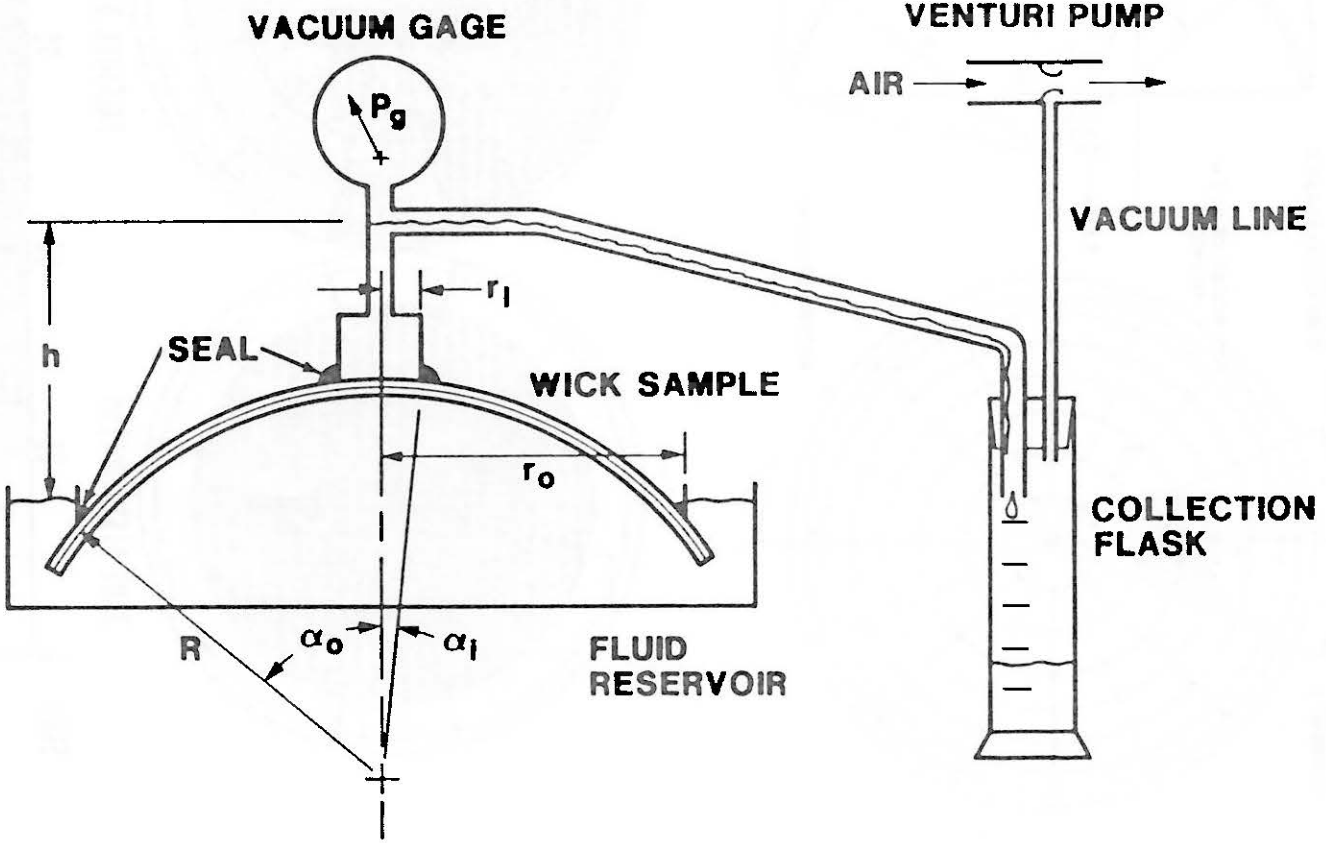
PRESSURE DISTRIBUTION

FLUX 0 25 50 75 100 W/cm^2

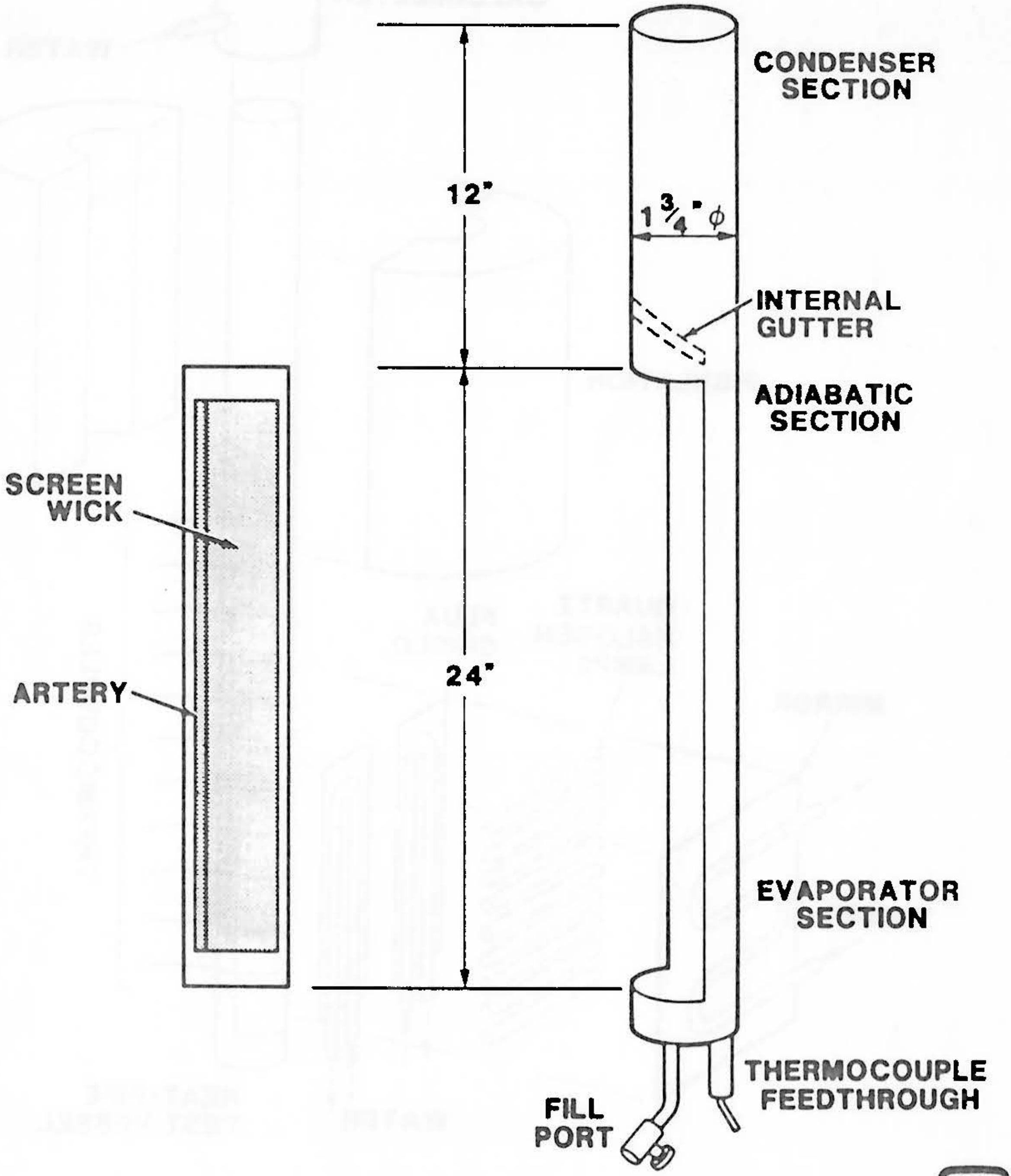
PRESSURE 0 25 50 75 100% Pmax

Pmax = Maximum capillary pressure for a given wick

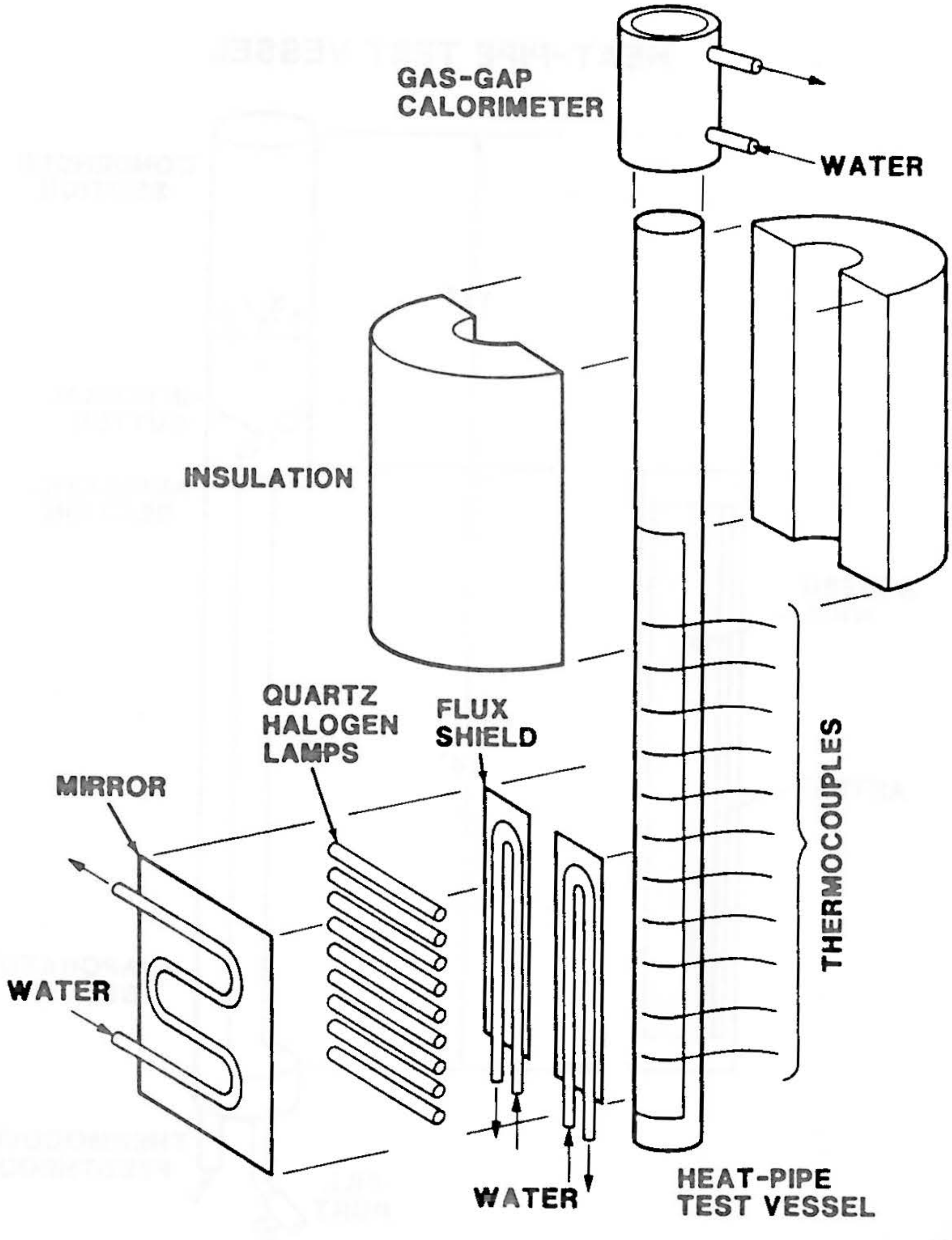
PERMEABILITY MEASUREMENTS ON A FORMED WICK



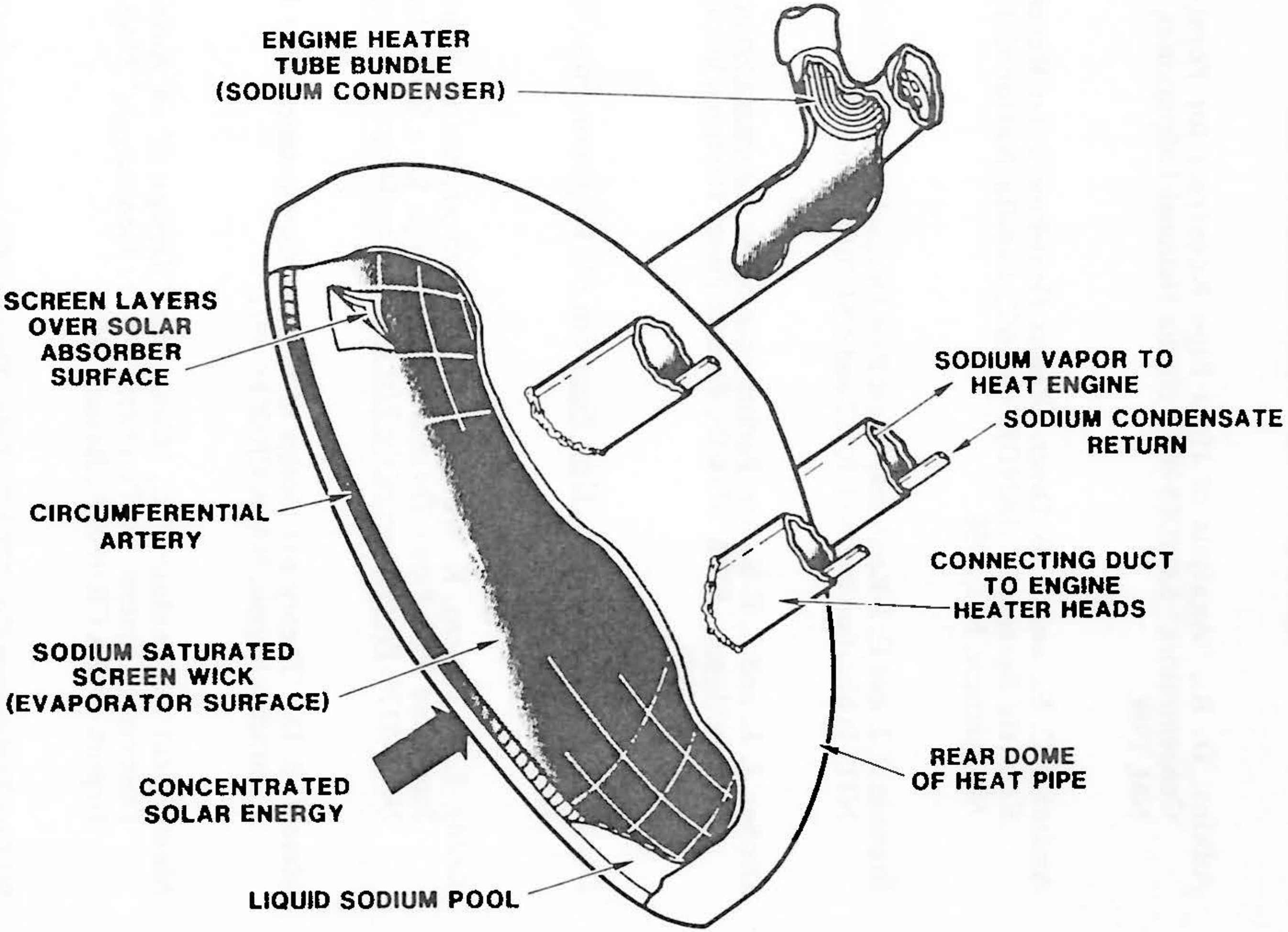
HEAT-PIPE TEST VESSEL



HEAT-PIPE TEST APPARATUS



HEAT-PIPE SOLAR RECEIVER WITH A SCREEN WICK



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POOL BOILER RECEIVER
BENCH TEST RESULTS*

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Charles E. Andraka

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Albuquerque, New Mexico 87185

ABSTRACT

The feasibility of competitive modular bulk electric power from the sun may be greatly enhanced by the use of a reflux heat pipe receiver to combine a heat engine such as Stirling with a paraboloidal dish concentrator. This combination represents a potential improvement over previous successful demonstrations of dish-electric technology in terms of enhanced performance, lower cost, longer life, and greater flexibility in engine design. There are, however, important issues and unknowns which must be addressed to determine engineering feasibility of these devices.

In the pool boiler reflux receiver, concentrated solar radiation causes liquid metal (sodium or potassium) to boil. The vapor flows to the engine heater heads, where it condenses and releases the latent heat. The condensate is returned to the receiver absorber pool by gravity (refluxing). This is essentially an adaptation of heat pipe technology to the peculiar requirements of concentrated solar flux, and provides many advantages over conventional heated tube receiver technology.

A pool boiler bench test program was initiated at Sandia National Labs in order to address several pool boiler concerns before proceeding to on-sun testing. The first of these concerns was that nucleate boiling initiation with liquid metals might require unacceptably high incipient superheats due to the high thermal conductivity of the fluid and its surface wetting characteristics. In addition, once boiling starts, for similar reasons, the boiling might be unstable, continually starting and stopping. Due to the high heat fluxes involved, approaching 100 W/cm^2, transition to film boiling during startup was also a concern. Finally, once stable boiling is accomplished, the surface cyclic thermal stress caused by bubble departure might quickly fatigue the surface.

A bench test was designed with a 1-3/4" dia 316L stainless tube with a 12 inch pool of sodium. Heat was provided by a quartz lamp array, with a net flux into the sodium of about 70 W/cm^2. The condenser end was cooled with a gas-gap cold water calorimeter, with which the heat rejection rate could be controlled by a variable ratio mixture of helium and argon. The device was extensively instrumented with thermocouples for safety and data.

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* This work was performed at Sandia National Laboratories which is operated for the U.S. Department of Energy under contract number DE-AC04-76DP000789.

The first attempts at operation resulted in unstable boiling. The boiling would occur for fractions of a minute, and then boiling would simply stop. As the superheat increased, at some point a bubble would inflate and boiling would initiate again. This resulted in rapid temperature fluctuations in excess of 100°C, and frequent automatic safety shutdowns.

An artificial cavity was added to the sodium side of the heated wall. Boiling stability theory suggests that if the cavity is deep enough, then, due to the thermal gradient through the wall, liquid sodium will not penetrate to the bottom of the cavity. The cavity will then remain an active nucleation site, and boiling will be stabilized. Upon operation, it was apparent that the modification greatly improved boiling stability. The cavity was placed near the top of the heated area in order to determine if the boiling would propagate down the surface. The imbedded thermocouples verified that stable boiling covered the entire heated area.

Boiling initiation typically involved a single large transient wall superheat ("bump") at about 600°C, followed by stable boiling. The device was operated for 100 hours at 800°C with about 20 cycles to ambient temperature, simulating 1 month of on-sun testing. In addition, stable boiling was verified at reduced power levels and at 700°C. One area of concern is a hot restart. If the power is removed long enough for the pool to cool to 700°C, and then power is returned, the incipient boiling superheat needed to restart produces extremely-high wall temperature superheat. If the power is not re-applied until the pool drops to 600°C, the superheat produces much less-severe wall temperatures.

The pool boiler bench test demonstrated stable boiling for 100 hours with 20 cycles to ambient. In addition, a safety shutdown and data system was developed that can be applied to the on-sun testing. Once on-sun operation is demonstrated, further development work must be pursued. Long term materials compatibility, life, and stress issues must be addressed before the pool boiler can be a commercial reality.

Reflux Receiver Development Issues

Pool Boiler Concerns

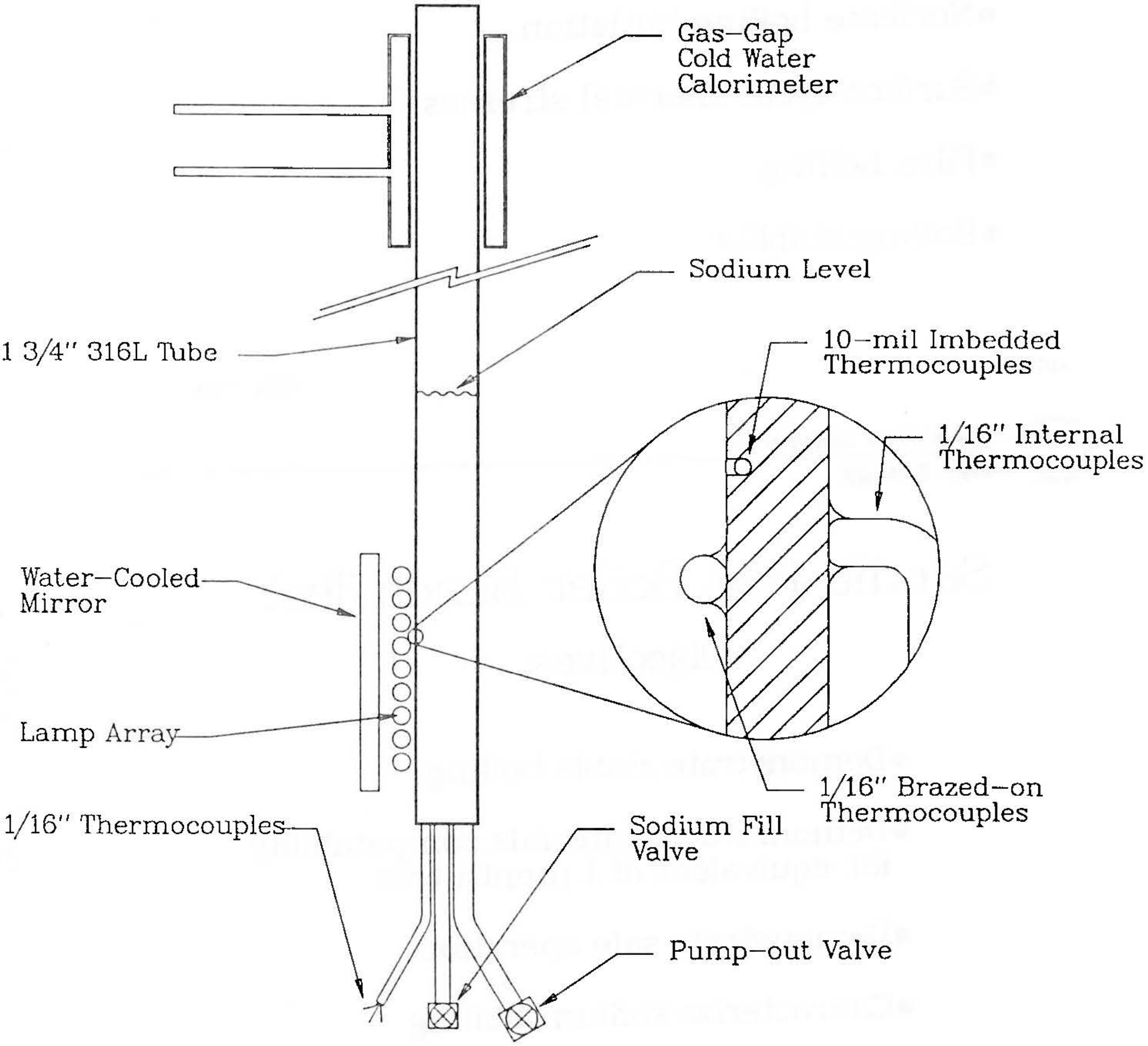
- Nucleate boiling initiation
- Surface cyclic thermal stresses
- Film boiling
- Boiling stablity

Sandia Pool Boiler Bench Test

Objectives:

- Demonstrate stable boiling
- Demonstrate materials compatability for equivalent of 1 month test
- Demonstrate safe operation
- Characterize sodium boiling

Boiling Test Module



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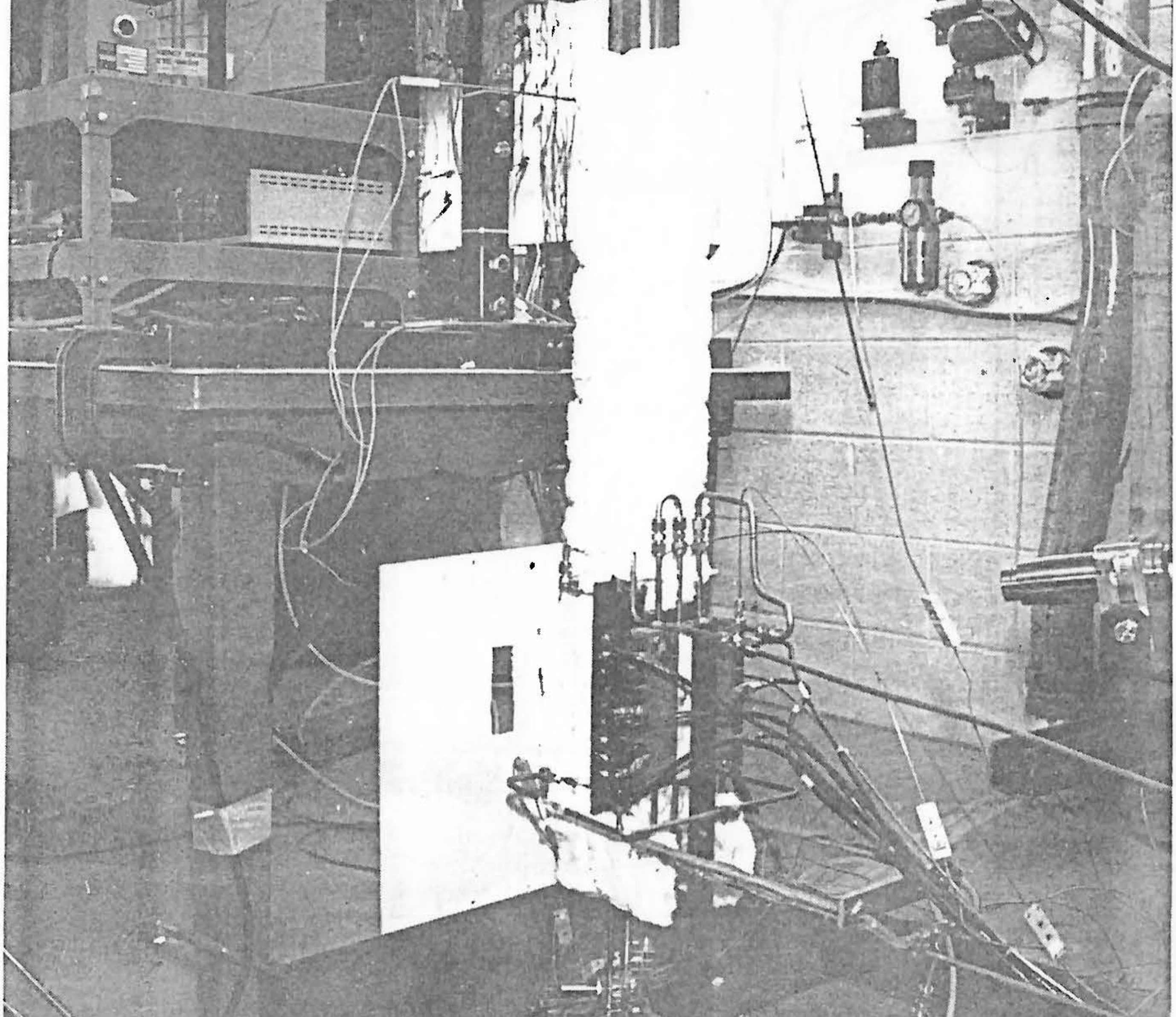
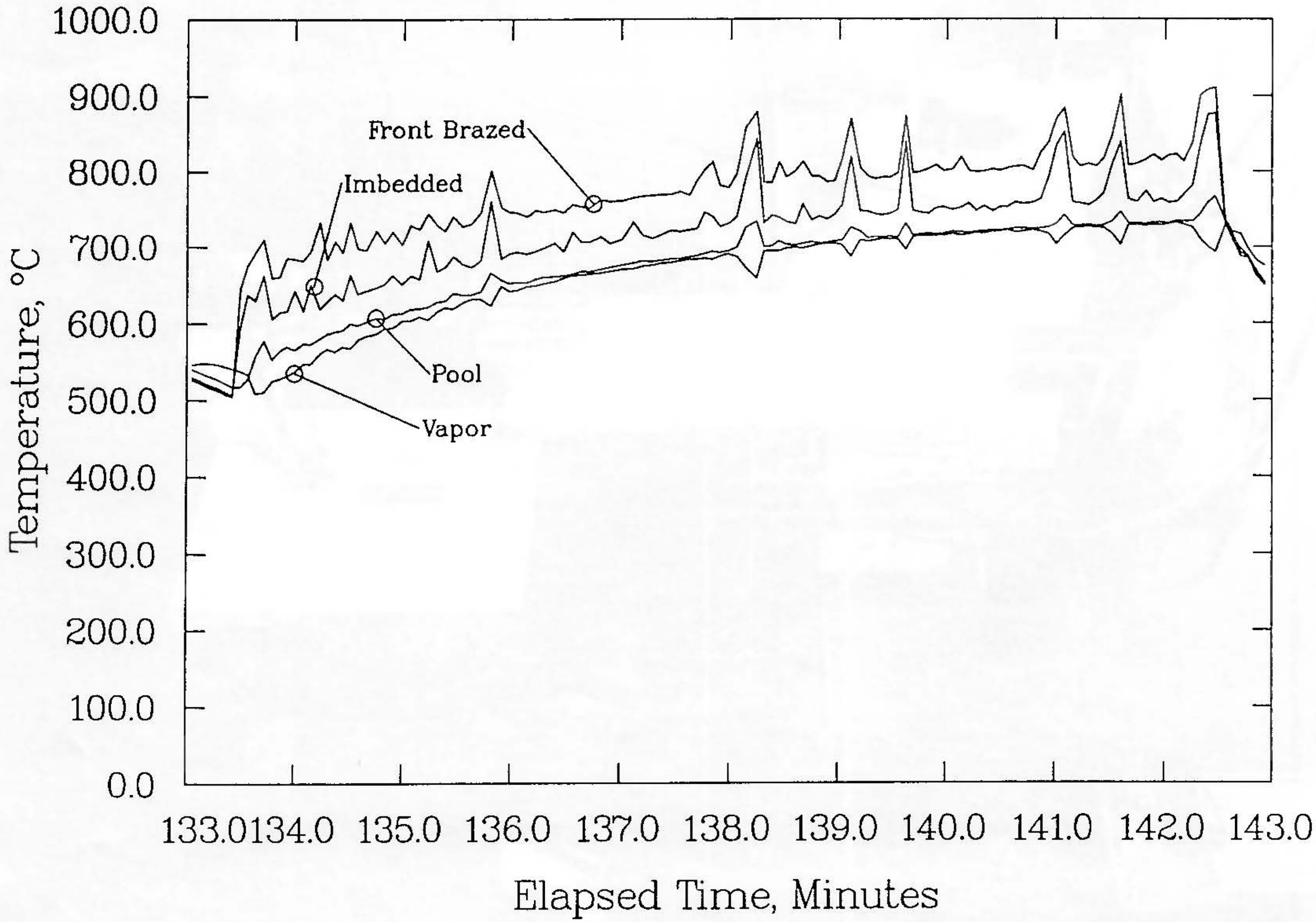


Unstable Boiling



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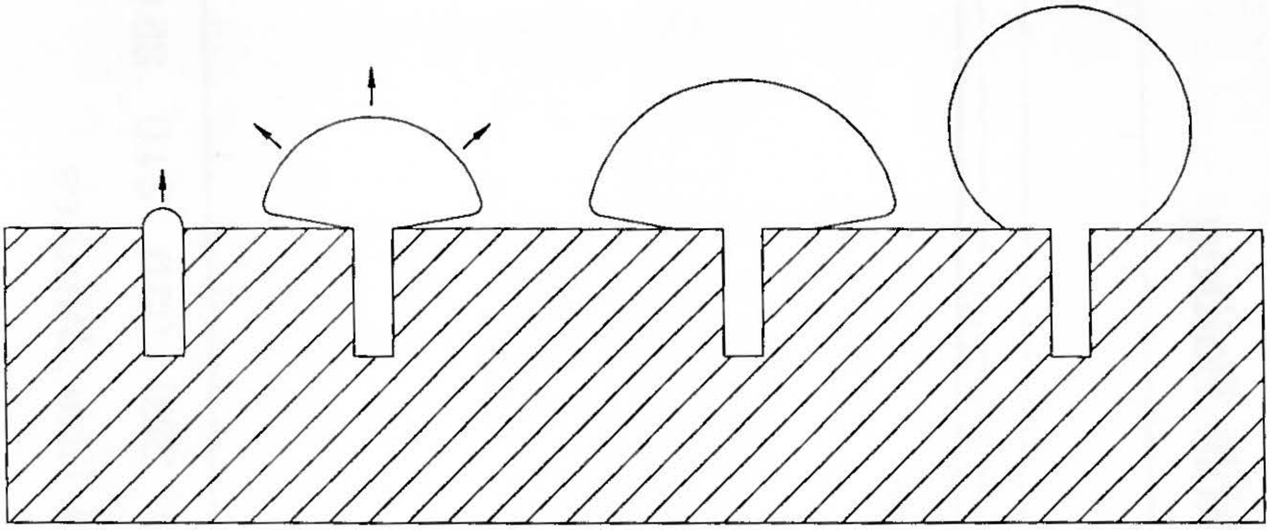
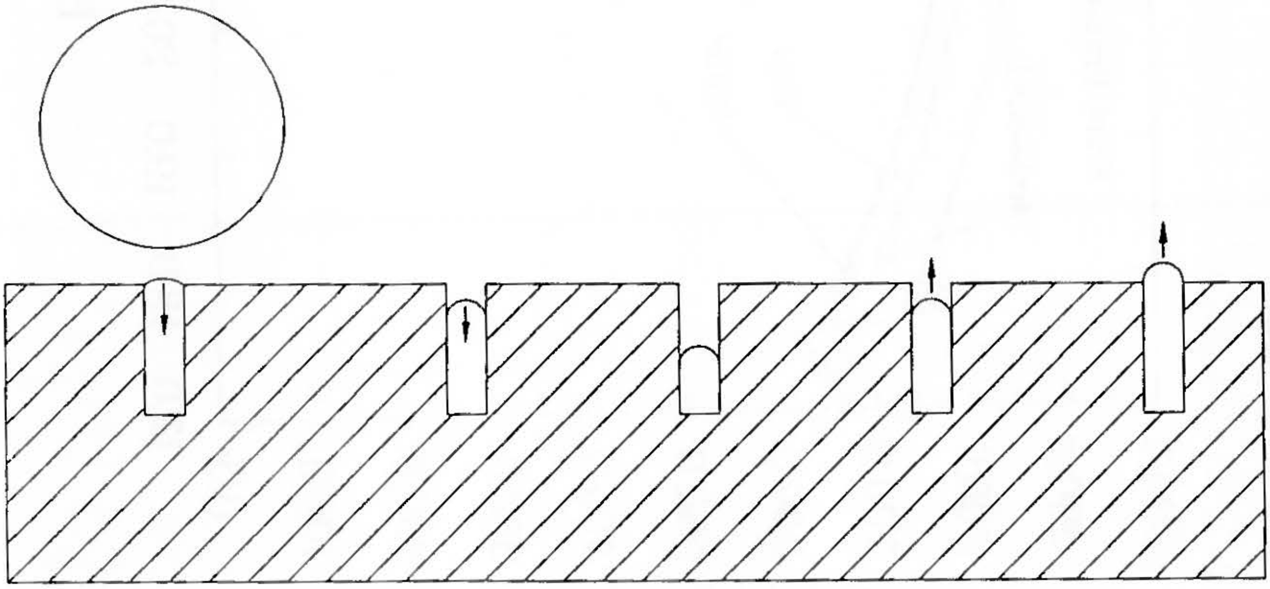
Nucleate Boiling



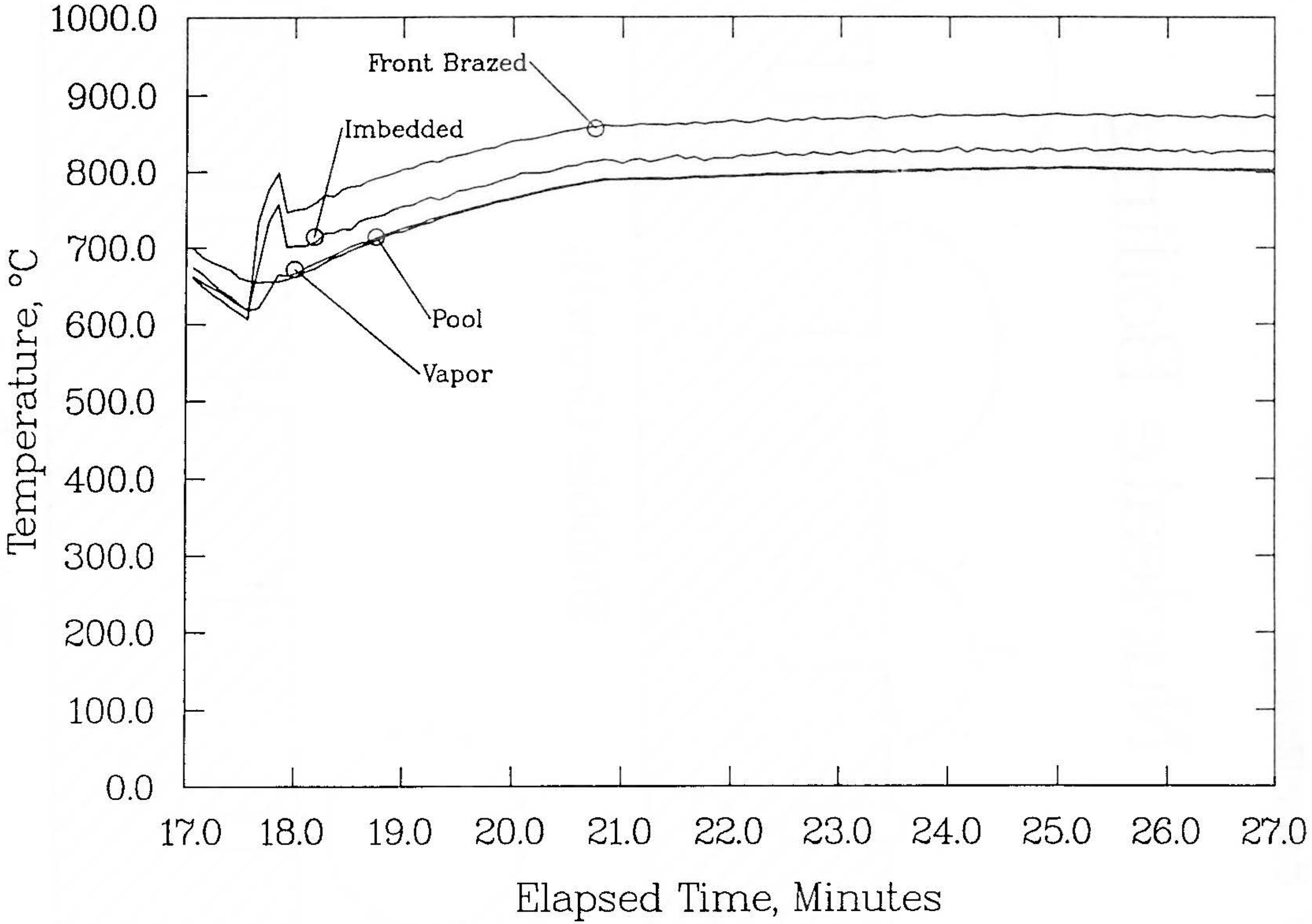
Bubble Growth



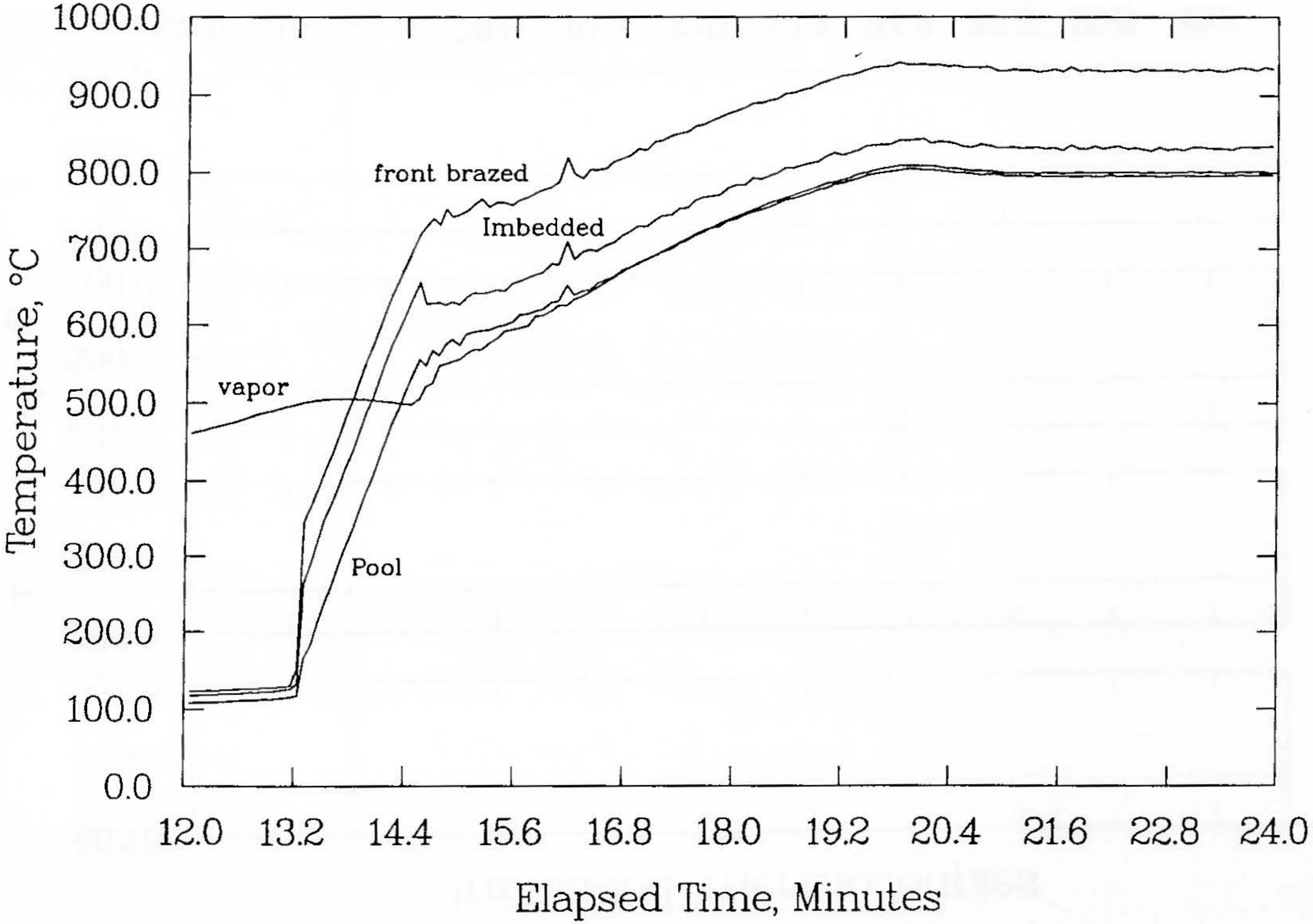
Waiting Period

After O.E. Dwyer
Boiling Liquid Metal Heat Transfer

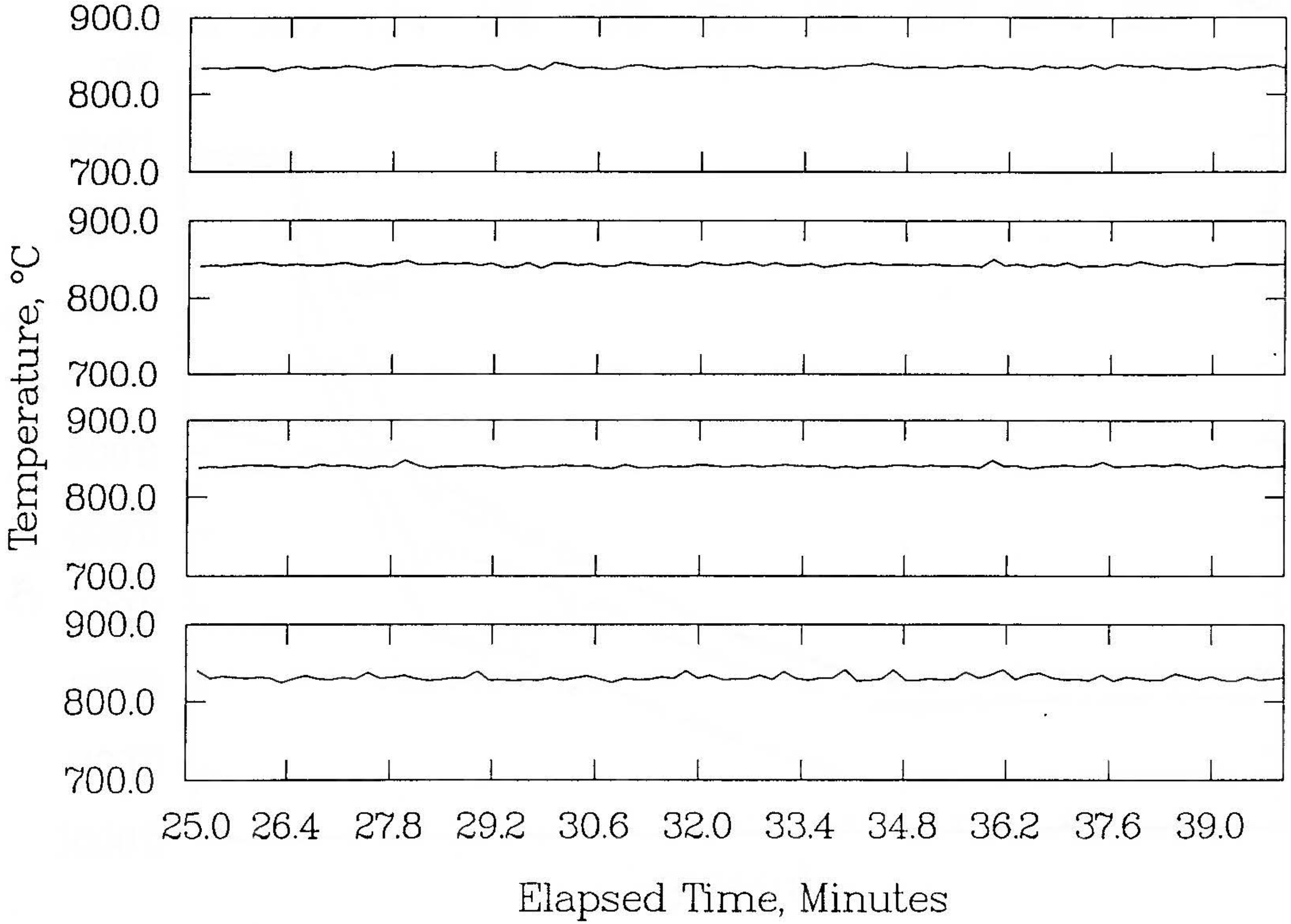
Stable Boiling



Startup


front brazed
Imbedded
vapor
Pool
Temperature, °C
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
12.0
13.2
14.4
15.6
16.8
18.0
19.2
20.4
21.6
22.8
24.0
Elapsed Time, Minutes

Imbedded Thermocouples



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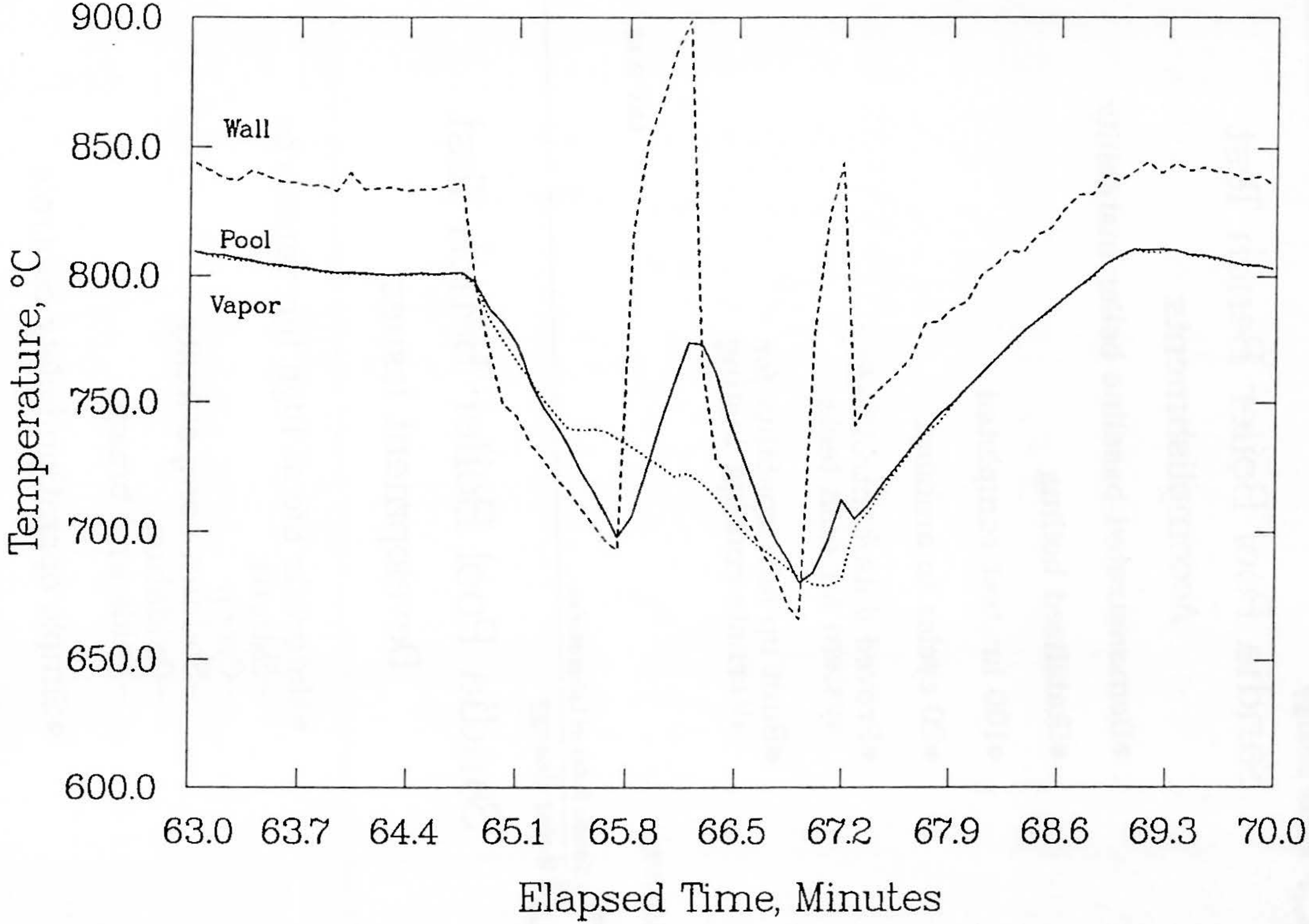
Hot Restart



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Sandia Pool Boiler Bench Test

Accomplishments:

- Demonstrated baseline boiler instability
- Stabilized boiling
- 100 hr. test completed
- 20 cycles to ambient
- Proved data/control/safety system for dish tests
- Built up lab capability for alternate concept testing

A028903

CEA 2/89

Sandia Pool Boiler Bench Test

Development Issues:

- Materials life at high temperatures
  - –Fatigue
  - –Creep
  - –Sodium compatibility
  - –Oxidation
  - –Welds and brazes
- Simple operation/safety controls
- On–sun testing

A028902

CEA 2/89

ABSTRACT

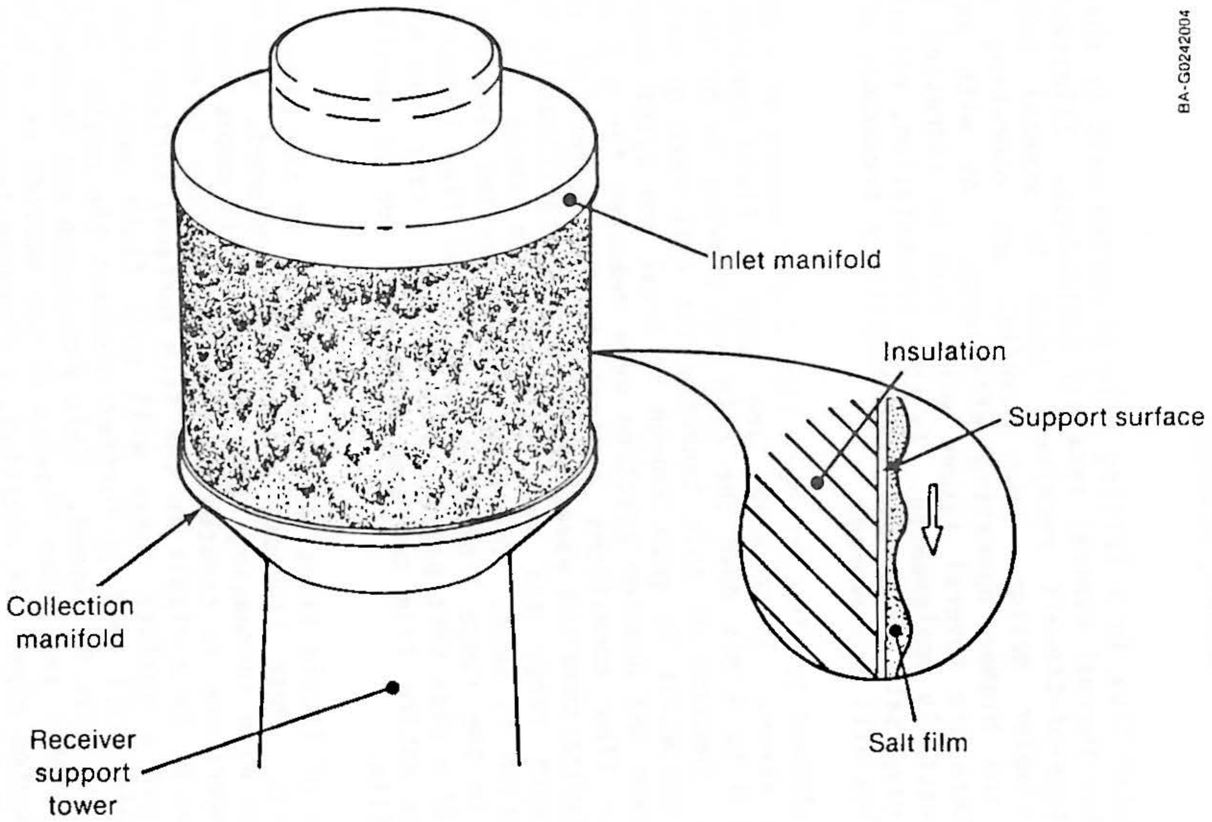
Fluid and Thermal Behavior of the Direct Absorption Receiver

Mark S. Bohn
Solar Energy Research Institute
Golden, Colorado

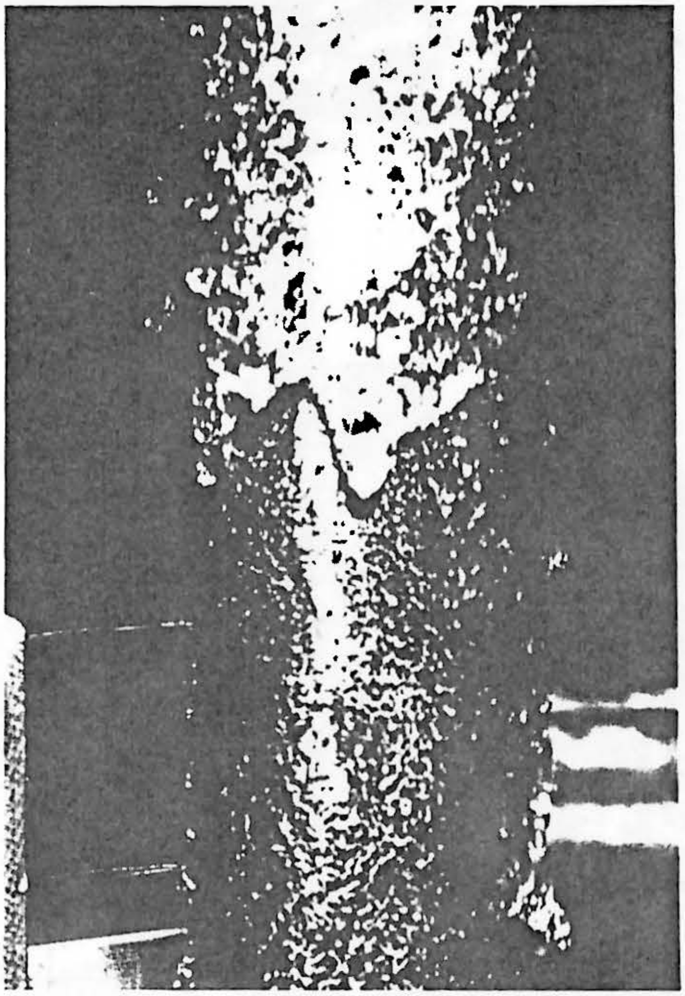
Direct absorption of solar flux in a falling film of molten salt is the basis for a promising new solar thermal central receiver technology. Elimination of the tubes used in state-of-the-art receivers leads to several potential advantages including simpler design, lower capital and operating costs, increased reliability and higher operating efficiency. As with any new technology, however, there are several issues which must be addressed before the concept can be successfully implemented. In this presentation, research on droplet ejection from wavy salt films and thermocapillary breakdown of salt films exposed to high flux will be covered.

A liquid film which is allowed to flow for more than 1 or 2 meters will develop what are known as roll waves. These waves are lumps of fluid separated by about 10 cm, moving at 3 to 4 m/s down the film and growing in height with increasing flow length. Because of this tendency for roll wave growth, the possibility exists for the waves to grow enough to break and eject droplets. In this study, wave growth and droplet ejection were measured for a 5 m long molten salt film under flow conditions typical for a commercial direct absorption receiver. Results show the waves begin to grow significantly in the 2 to 3 meter flow length range and that this is also where the first significant droplet ejection is seen. The rate of mass ejected from the film increases exponentially in the range from 1 to 4 meters of flow length up to about 1 gm/hr for the 0.27 m wide test panel. In addition, a very fine mist of salt is ejected from the entire film surface, apparently due to bursting of turbulent eddies in the film.

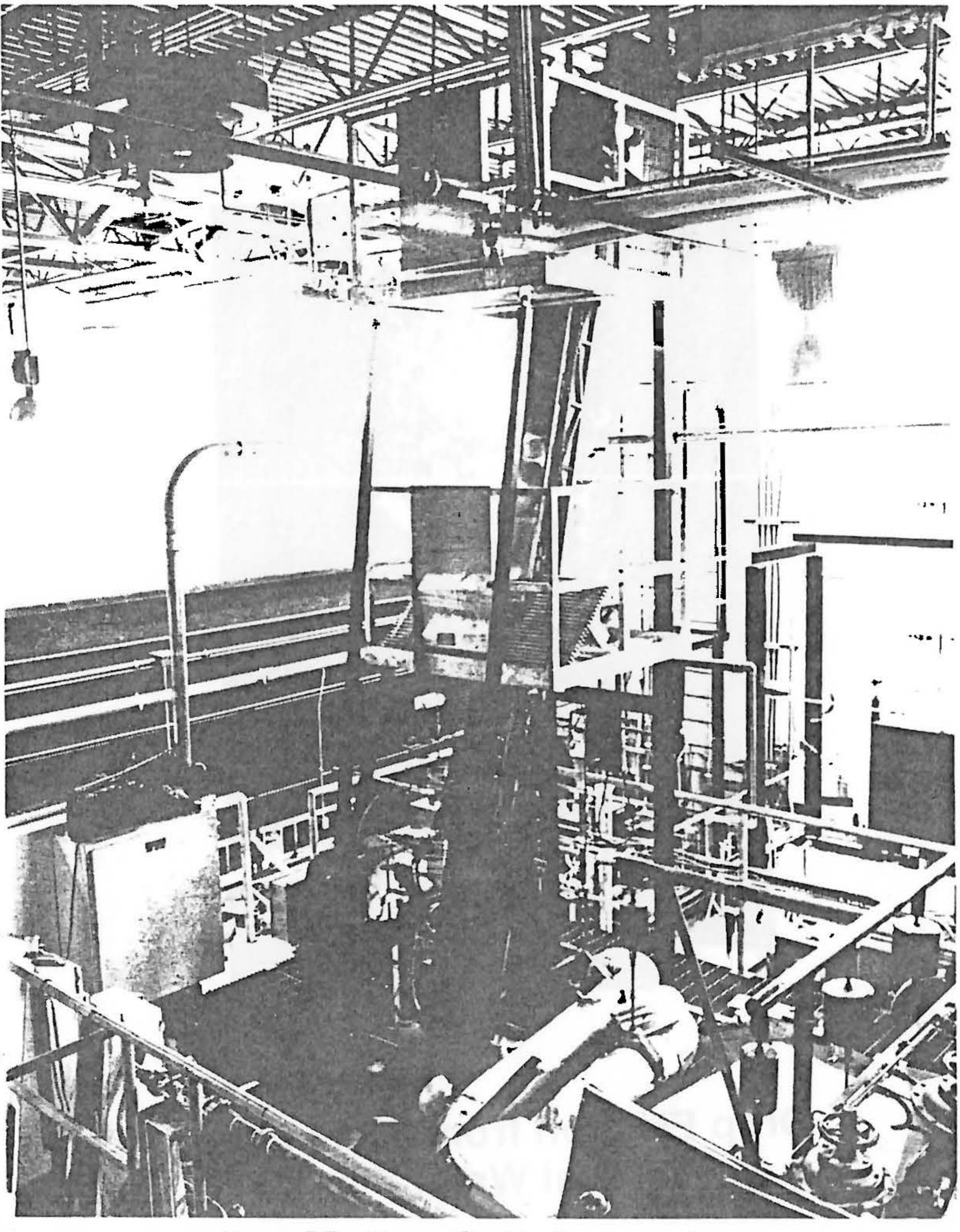
Thermocapillary breakdown of liquid films refers to rupture of the film due to surface tension gradients. Most liquids, molten salt included, exhibit a decreasing surface tension with increasing temperature. This means that if a local region of high temperature is created on the film surface (either by a local gradient in the flux or by a ripple in the film surface) surface tension will be reduced there and a surface shear will pull fluid away from the region. This local thinning will tend to further overheat the region leading to more thinning until a dry spot is formed. This phenomenon was studied with water and a mixture of glycerol and water flowing on the outside of a 2.54 cm od, 2.5 m long vertical heated pipe. In addition, a dimensionless scaling law was developed which allows data from different liquids to be compared on the same correlation plot. The experimental data covered a range of Reynolds number up to 6000 while a commercial receiver will operate in the range of 20000 to 70000. If the experimental data are extrapolated up to this higher Reynolds number range, it appears that a commercial direct absorption receiver operating with molten salt should be in the safe operating regime with regards to thermocapillary breakdown.



Molten Salt Direct Absorption Receiver

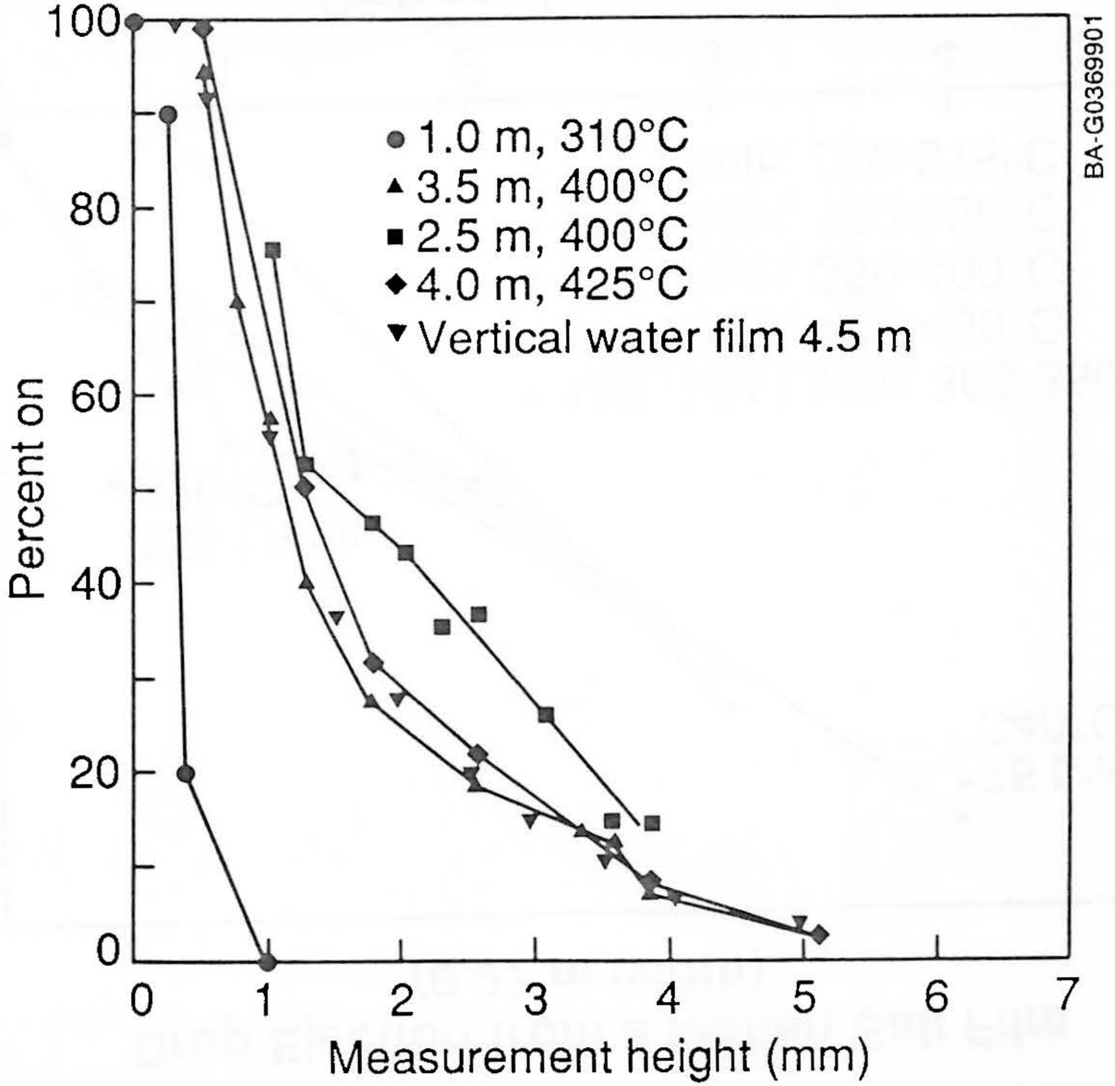


Drop Ejection from 4.5 m Long Vertical Water Film

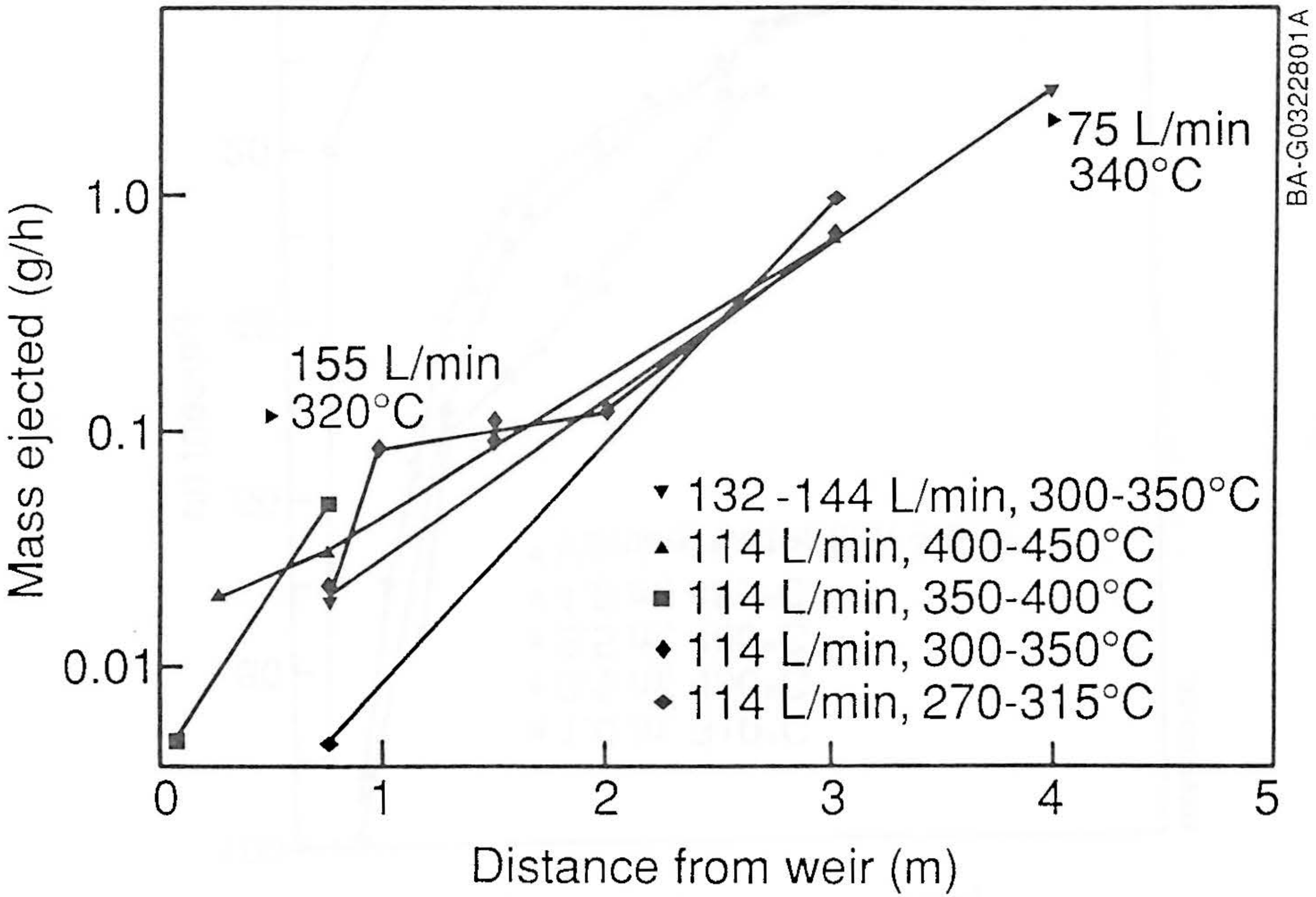


5 m Molten Salt Apparatus

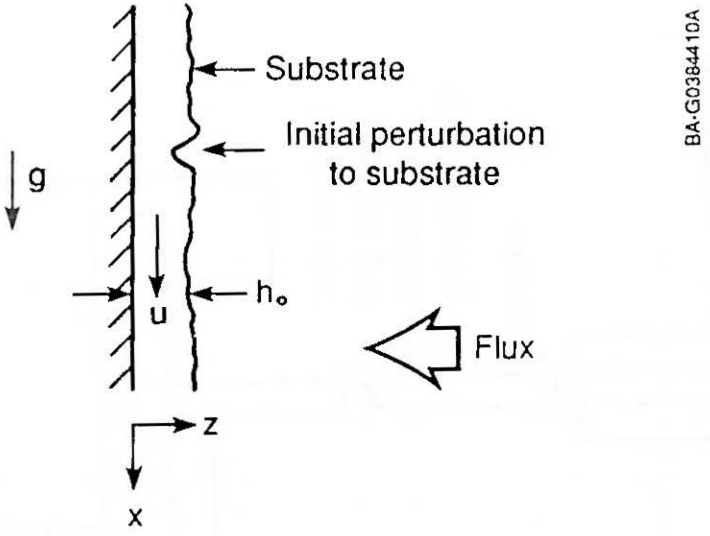
Thickness of a Molten Salt Film
(113 l/m, 0.27 m wide)



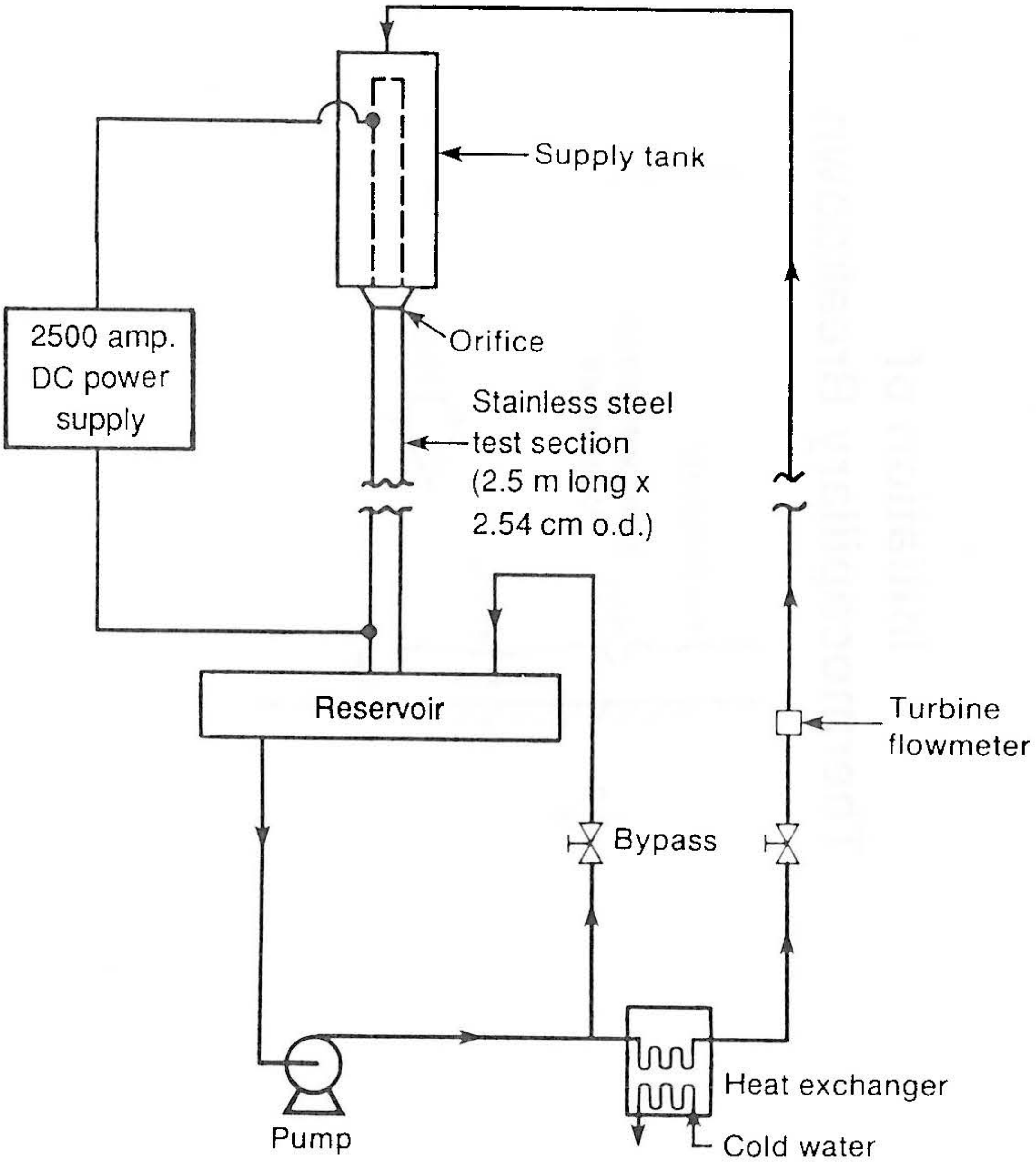
Drop Ejection from a Molten Salt Film
(0.27 m width)



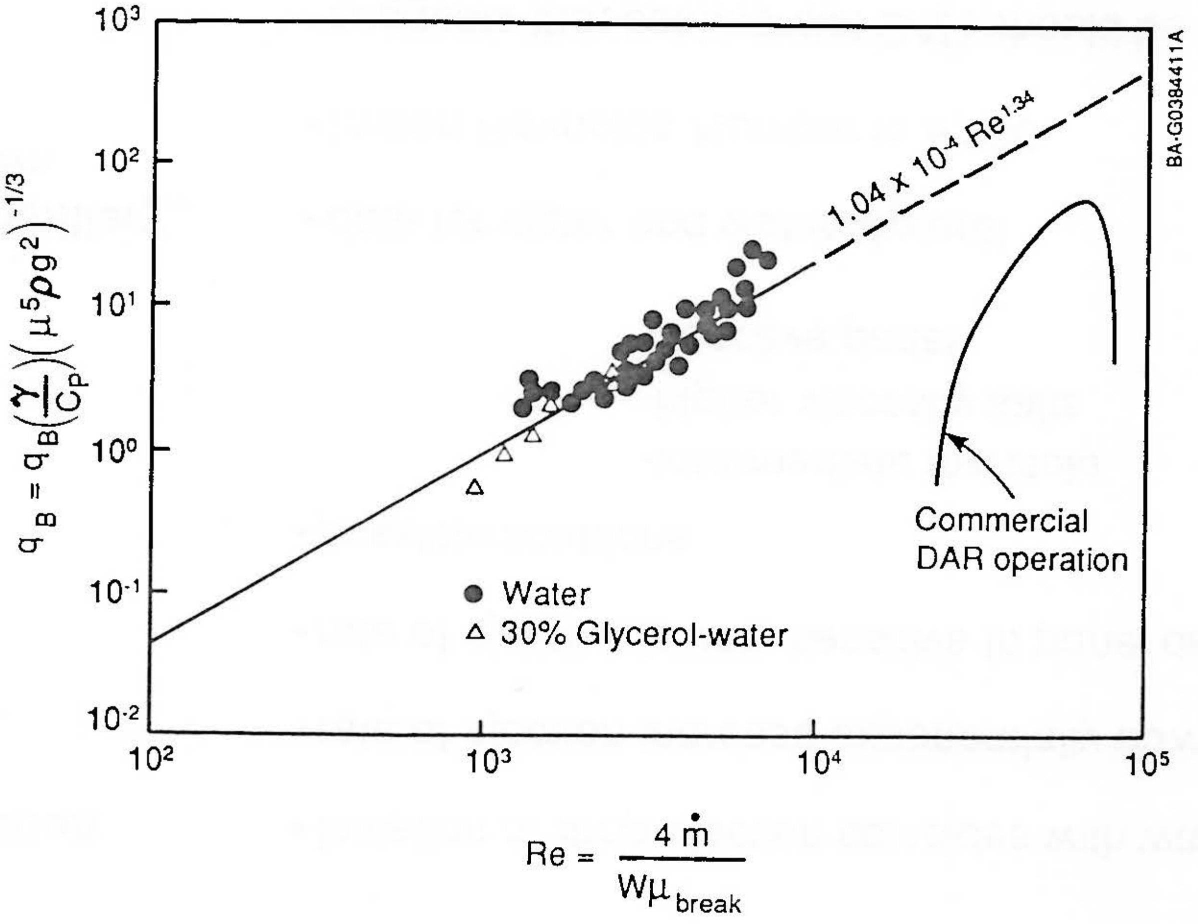
Initiation of Thermocapillary Breakdown



Apparatus Used for Measuring Thermocapillary Breakdown Flux



Thermocapillary Breakdown of Falling Liquid Films



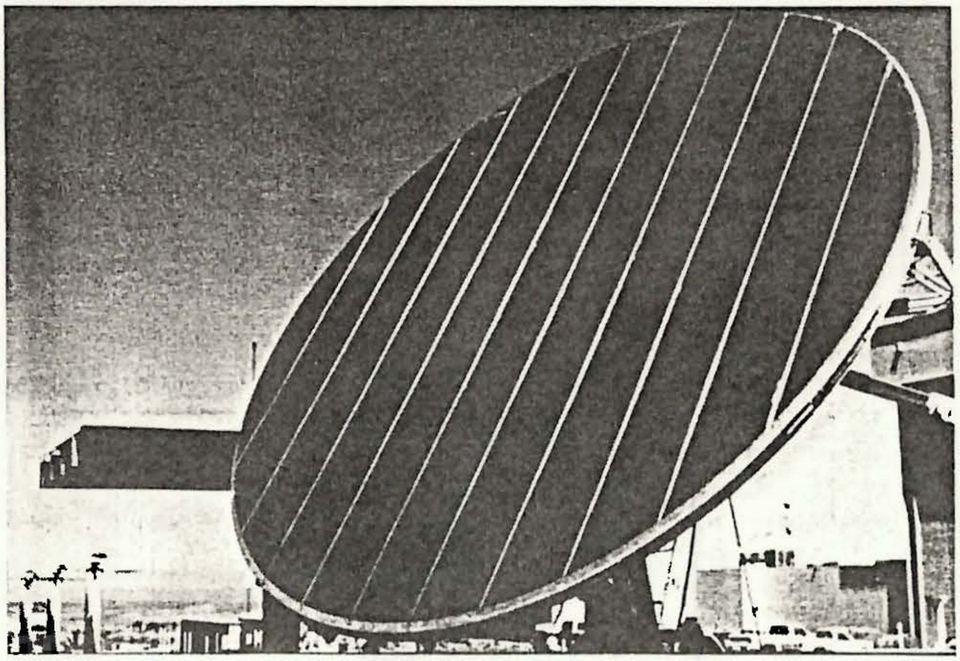
Conclusions

Drop Ejection

- initiation of drop ejection coincides with wave growth
- rate of ejection increase exponentially down the panel
- rate of ejection is very sensitive to panel deformations
- possible solutions
    - -intermediate manifold
    - -higher viscosity salts
    - -concave panel

Thermocapillary Breakdown

- data for water and water/glycerol
- limited Reynolds Number to 6,000
- suggests that commercial DAR should be safe
- data at higher Re needed



Stretched-Membrane Heliostat

By

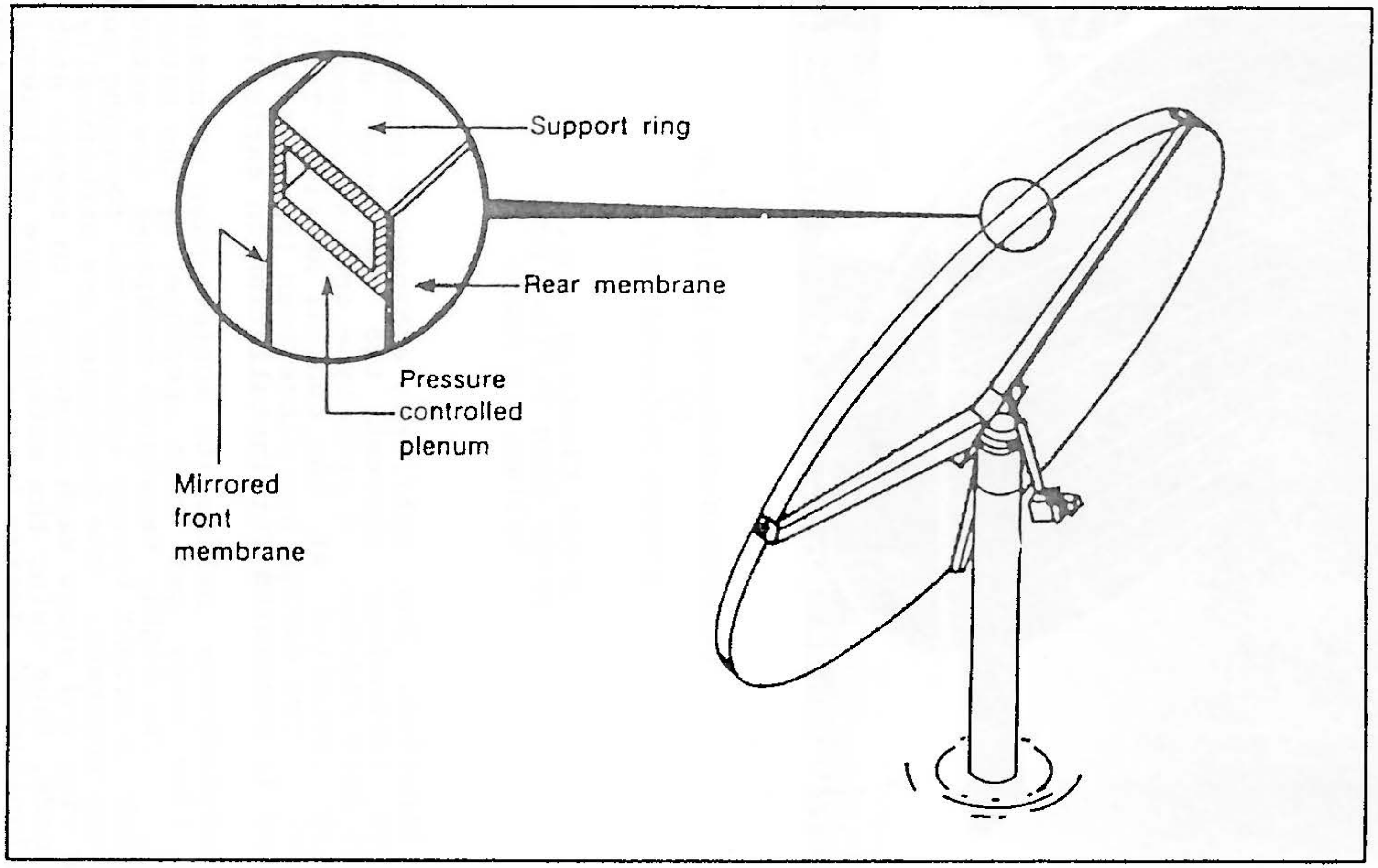
Andrew Konnerth III

Solar Kinetics, Inc.
10635 King William Dr.
Dallas, TX 75220

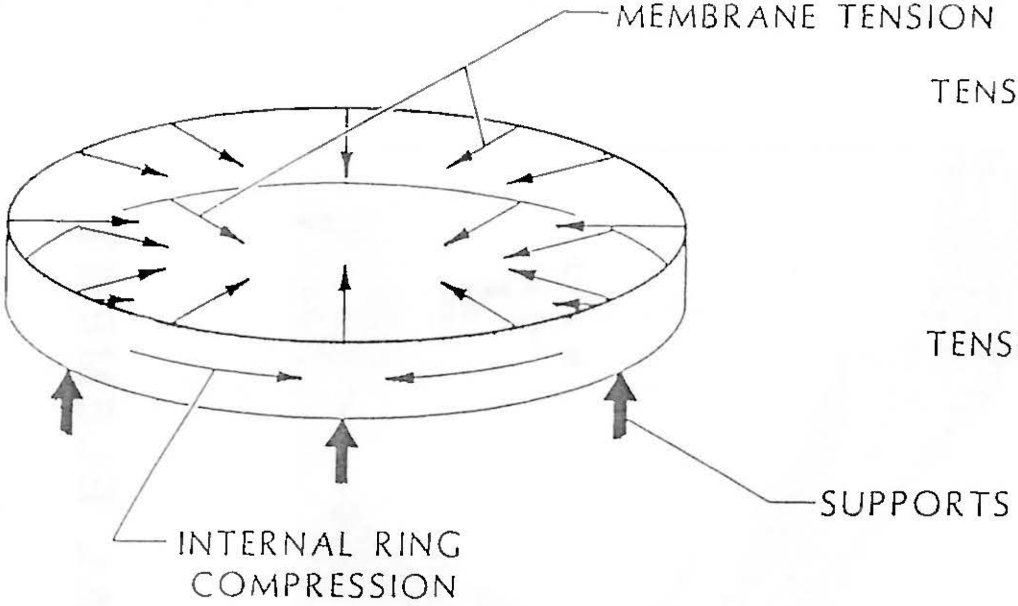
Solar Kinetics, Inc. (SKI) has enhanced stretched-membrane heliostat technology through two contracts under Sandia National Laboratories. A prototype optical element was successfully installed at the Central Receiver Test Facility in 1986. The design has since been improved and a second prototype is scheduled for installation in early 1989.

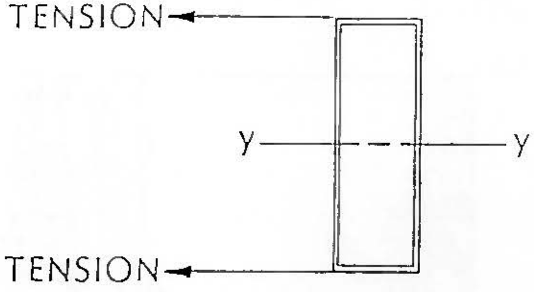
Stretched-membrane heliostats achieve high structural efficiency (low mass per unit aperture) by the nature of the concept. Two highly tensioned membranes are attached to a ring with a slight vacuum inducing the focusing contour of the front membrane. The membranes are structurally coupled to the ring and allow each component to remain stable under large loads, thus using the material more efficiently. Several significant design improvements have been implemented in the second heliostat. These improvements will increase performance and structural efficiency and decrease manufacturing complexity and cost.

STRETCHED MEMBRANE HELIOSTAT CONCEPT



STRETCHED MEMBRANE CONCEPT

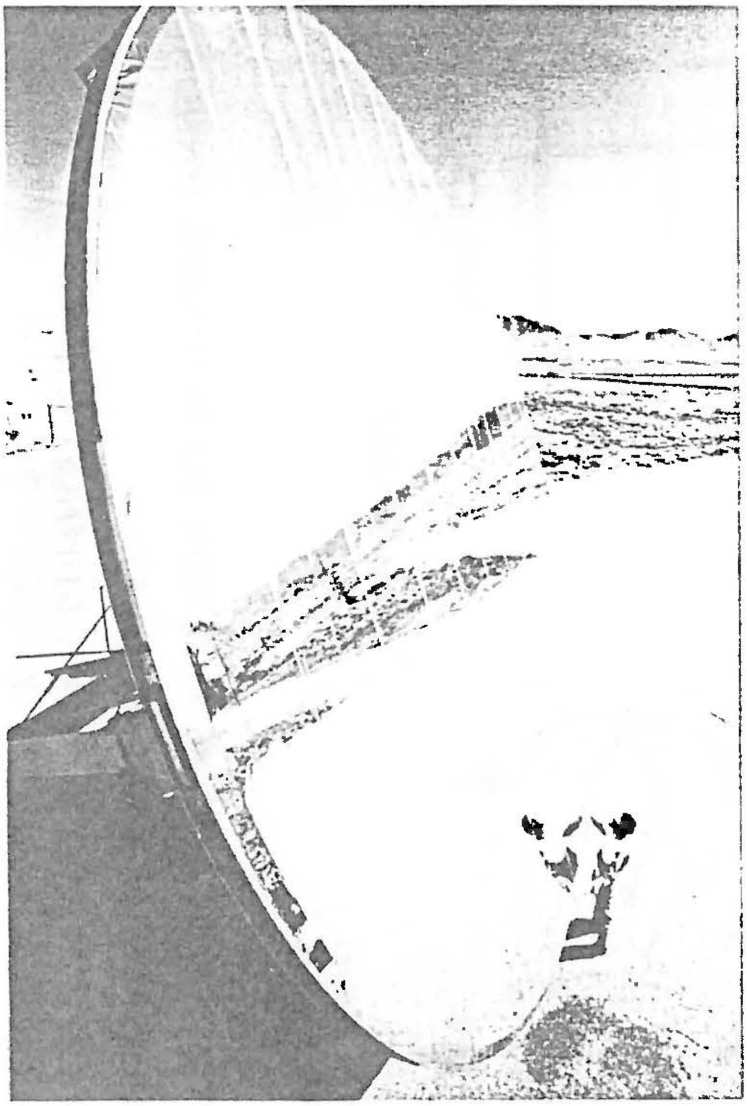




RING CROSS SECTION

- AXIAL COMPRESSION IN RING AS REACTION TO MEMBRANE TENSION
- MEMBRANE INCREASES IN-PLANE STABILITY
- MEMBRANE INCREASES OUT-OF-PLANE STIFFNESS & STABILITY
  - DEFLECTION ACCOMPANIED BY ROLL
  - ROLL RESISTED BY MEMBRANES

SOLAR KINETICS INC.



OPTICAL ELEMENT

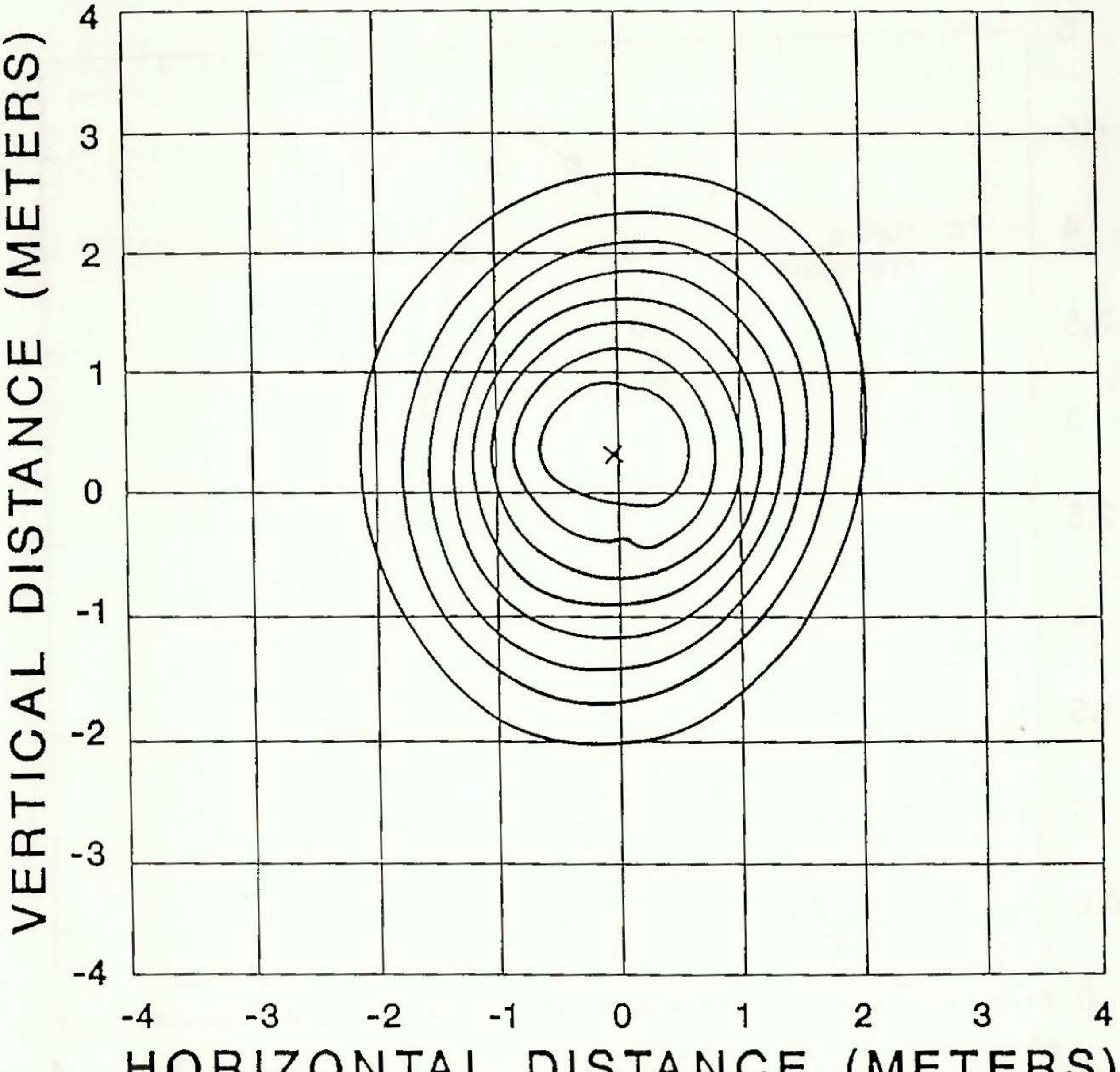


Figure 8. Example of measured flux contours of the beam spot from SKI's 50-square-meter stretched-membrane mirror module. Contour spacing is 0.5 kW/square meters. As measured by SNLA, SAND88-2620.

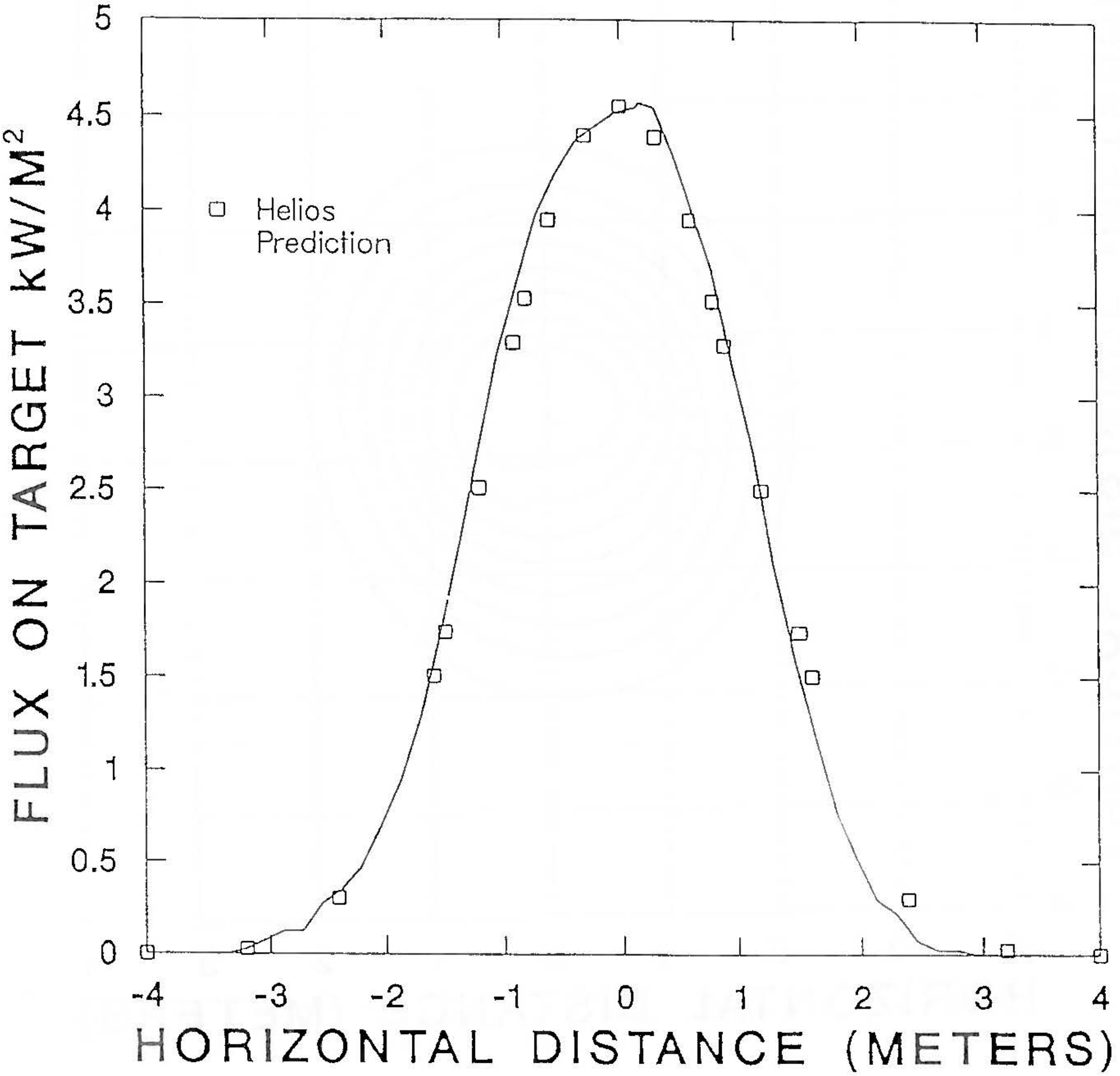
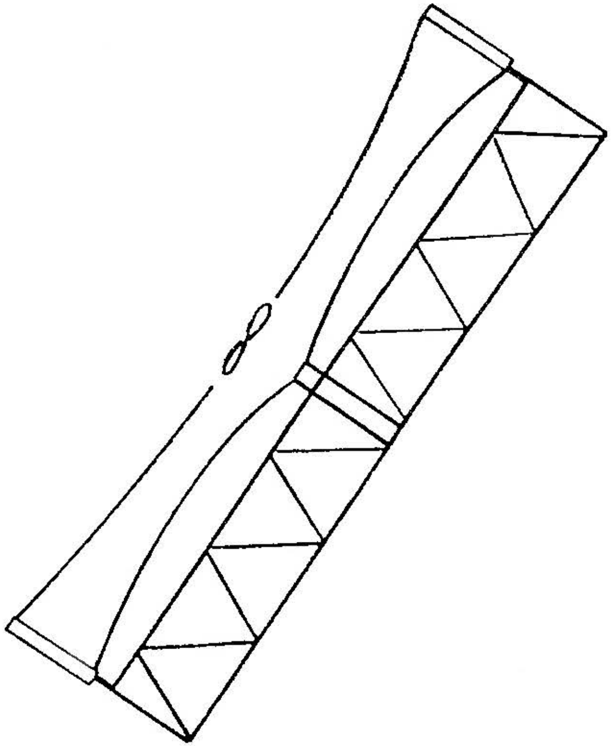


Figure 10. Measured horizontal beam profile through the centroid of Figure 7 compared with the theoretical profile calculated with HELIOS [18,19] (squares) assuming a beam-dispersion error of 2.6 mr. As measured by SNLA, SAND88-2620.

PHASE II IMPROVEMENTS

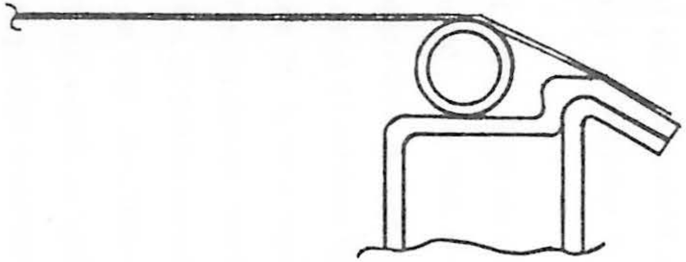
CENTRAL RESTRAINT

AND FRONT FAN REFERENCE

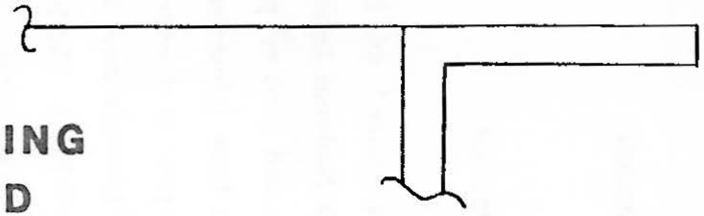


- REDUCES NORMAL LOAD OF RING
- REDUCES DIAPHRAGM STRESS
- DECREASES CONTROL RESPONSE TIME
- DECREASES WIND INDUCED TRANSIENT ERROR

PHASE II IMPROVEMENTS

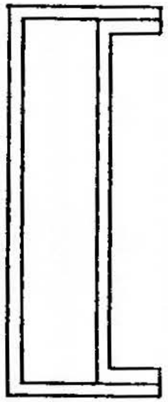


TENSIONING METHOD



REDUCE COST > $1.00/m^2

IMPROVED PERCEIVED RELIABILITY



OPEN SECTION RING

DECREASED MANUFACTURING COMPLEXITY

MORE EFFICIENT MATERIAL DISTRIBUTION

ABSTRACT

An Improved Stretched Membrane Heliostat Mirror Module

Kelly J. Beninga
Barry L. Butler

Science Applications International Corporation, San Diego, CA

Science Applications International Corporation (SAIC) has developed an improved stretched-membrane heliostat mirror module under contract to Sandia National Laboratories, Albuquerque, New Mexico. Both a 150-m^2 commercial mirror module and a 50-m^2 prototype mirror module have been designed. The prototype mirror module has been fabricated and is being tested at the Central Receiver Test Facility (CRTF) in Albuquerque. A drawing of the commercial mirror module mounted on the Peerless-Winsmith advanced low-cost drive is shown in Figure 1. The commercial mirror-module specifications are shown in Table 1. The total area of the mirror module is 150 m^2 with a diameter of 14 meters. Tensioned stainless steel foil membranes are welded to both sides of the carbon steel ring. The ring is supported by five trusses, which radiate from a central hub. The hub is mounted on a pedestal-type drive system for purposes of tracking in the azimuth and the elevation directions. In order to compensate for changes in pressure on the front reflective membrane due to wind forces, an active focus-control system is utilized. The system consists of a LVDT mechanical position indicator that measures the position of the front membrane, and a linear actuator that is attached to a pad on the rear membrane. The linear actuator modulates the position of the rear membrane in order to change the internal volume and therefore, pressure. A refocus valve is included to periodically compensate for air leaks in the mirror module.

The A500B carbon steel ring is made of rectangular tube cross-section with a height of 22.9 cm (9 in) and a width of 7.6 cm (3 in). Its wall thickness is 2.29 mm (.09 in). The dimensions of the ring were determined based on a mirror module with five truss supports and a maximum allowable deflection between supports of 4.2 mm (.165 in) under a 12 m/s (27 mph) wind load. This out-of-plane deflection corresponds to an optical slope error of .60 mrad RMS.

The .0762-mm (.003-in) thick 304L stainless steel membranes are roll-resistance lap-seam welded from 61.0-cm (24-in) wide rolls of stock. The membranes are tensioned to a 89.6 MPa (13,000 psi) stress level. The ring is pre-compressed to 44.8 MPa (6500 psi). The membranes are then welded directly to the ring on the top and bottom surface, as shown in **Figure 2.** Welding of the membranes to the ring is accomplished with a roll-resistance welding head.

The membranes are tensioned prior to welding in a manner that imparts uniform circumferential and radial stress over the surface of the membrane. The rigid attachment to the ring increases the stiffness of the overall mirror module.

The ring stiffness and tolerance achievable by conventional manufacturing methods dictate the ring distortions prior to installation of the mirror module. Once the mirror module is installed, wind loads on the heliostat exert additional out-of-plane loads. The effects of these in-plane and out-of-plane forces on the module have a critical effect on optical mirror accuracy. A comprehensive finite-element computer model of the mirror module was used for the structural design of the ring/membrane system and truss supports. A graphic of the module finite-element model is shown in **Figure 3**. A graphic of the 3-dimensional support truss under wind loading is shown in **Figure 4**. The results of the structural analysis for the commercial design are shown on **Table 2**.

Following the design of the 150-m^2 commercial mirror module, a 50-m^2 prototype mirror module was designed and fabricated. A photograph of the heliostat is shown in **Figure 5**. The prototype design replicates the commercial mirror module design to the extent that it is feasible. The support ring for the prototype module has a 7.9-m (26.0-ft) inside diameter with cross-sectional dimensions of 5.10-cm by 15.2-cm (2-in by 6-in). The membranes are fabricated from 14 strips of 61.0-cm (24-in) wide 304 stainless steel, each of which is .0762 mm (.003 in) thick. ECP-300 reflective film is laminated to the front membrane of the module. Five support trusses radiate from a central hub for support of the ring. The support truss design incorporates a triangular cross-section to provide both in-plane and out-of-plane support for the ring.

The 50-m^2 second-generation prototype stretched-membrane heliostat was assembled and installed at the Central Receiver Test Facility in July 1988. Preliminary test results from the mirror module have shown excellent optical performance and focus-control system performance under calm and gusting wind conditions. A flux contour map, as measured with a beam characterization system at the CRTF, is shown in **Figure 6**. A comparison of the measured beam shape with an analytical prediction generated by the HELIOS computer program has shown that for a reflected cone containing 90% of the reflected energy, the cone half-angle is 1.4 mRad (2.8 mRad full-angle). This indicates that the optical quality of the stretched-membrane mirror module is very good. As shown in **Figure 7**, the time to defocus the image of the mirror module is about 3 to 4 seconds. Additional optical and structural testing of the second-generation prototype mirror module will take place in the next year.

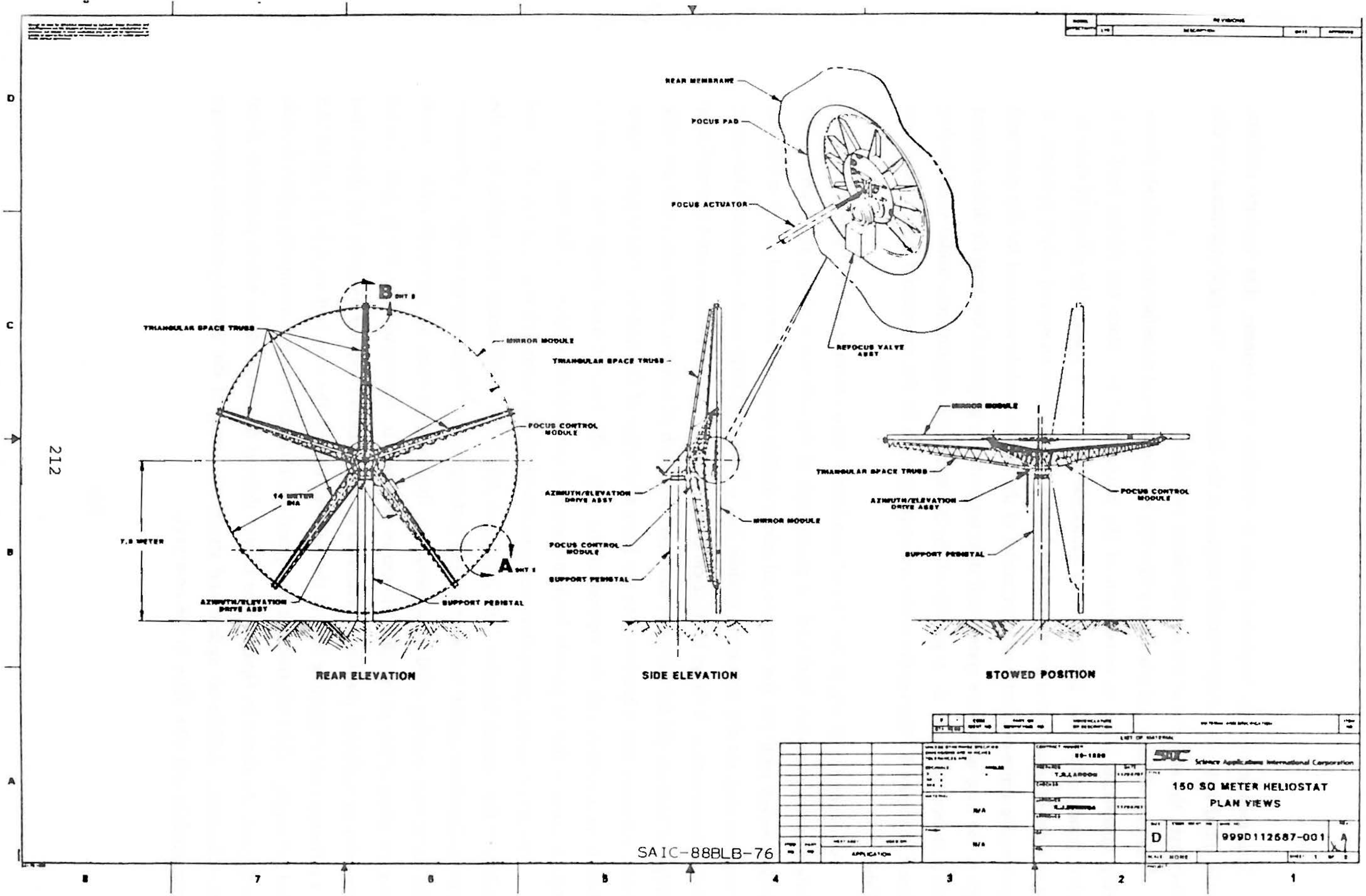


Figure 1. 150 Square Meter Heliostat Plan Views

TABLE 1. COMMERCIAL HELIOSTAT SPECIFICATIONS

Heliostat Diameter	14 m	(46 ft)
Area	154.4 m^2	(1661.9 ft^2)
Reflective Area	148.85 m^2	(1602.2 ft^2)
Support Ring Material	A500B Carbon Steel	A500B Carbon Steel
Support Ring Cross Section	7.62 cm x 22.86 cm	(3 in x 9 in)
Ring Wall Thickness	0.23 cm	(0.09 in)
Ring Cross Sectional Area	13.94 cm^2	(2.16 sq in)
Ring Moment of Inertia - Ix	875.75 cm^4	(21.01 in^4)
Ring Moment of Inertia - Iy	156.92 cm4	(3.77 in^4)
Front Membrane Material	304L Stainless Steel-Annealed	
Back Membrane Material	304L Stainless Steel-Half Hard	
Membrane Thickness	0.008 cm	(0.003 in)
Membrane Preload	6.829 nt/mm	(39 lbs/in)
Membrane Stress	89.64 m Pa	(13000 psi)
Number of Ring Supports	5 Each	5 Each
Span	7.0 m	(23 ft)
Depth of Support at Hub	0.76 m	(30 in)
Depth of Support at Outer Ring	0.305 m	12 (in)
Modulation Pad Diameter	1.83 m	(6 ft)
*Center of Gravity	56.6 cm	(22.3 in)

*Note: Distance From Front Membrane

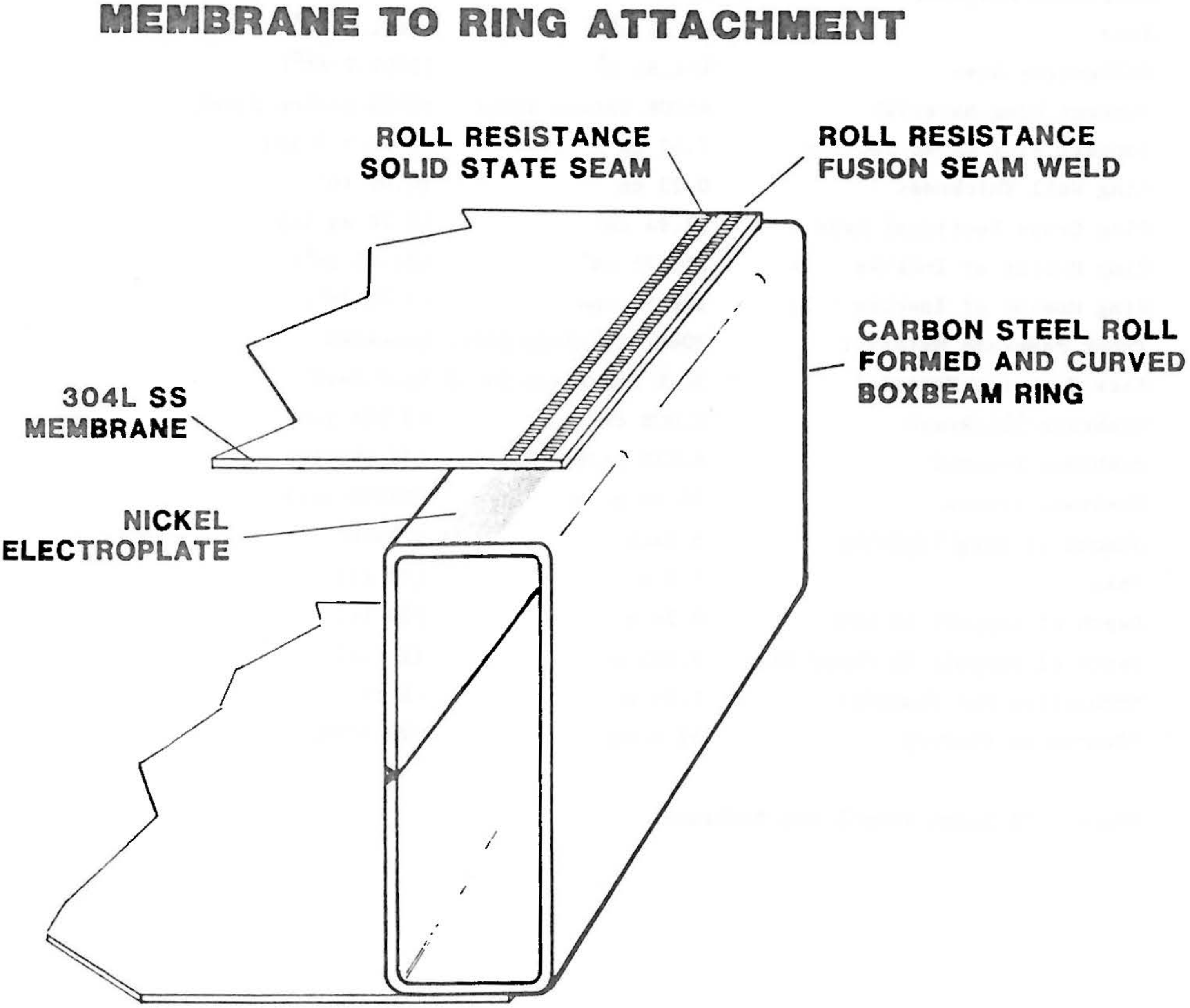


Figure 2. Membrane To Ring Attachment

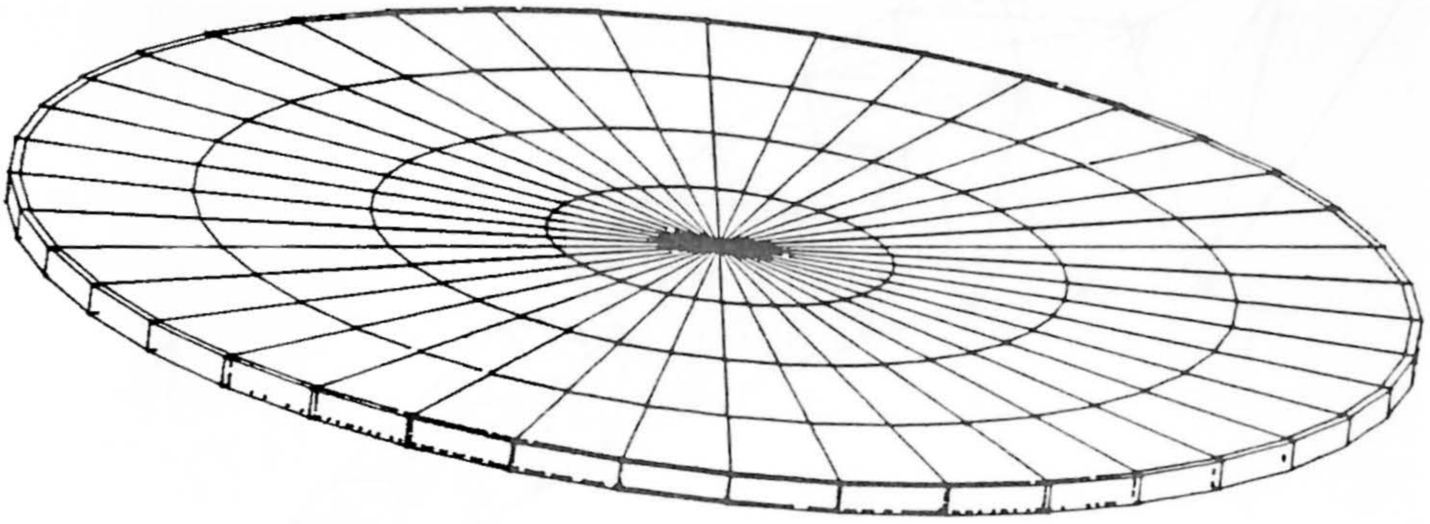


Figure 3. Mirror Module Finite Element Model

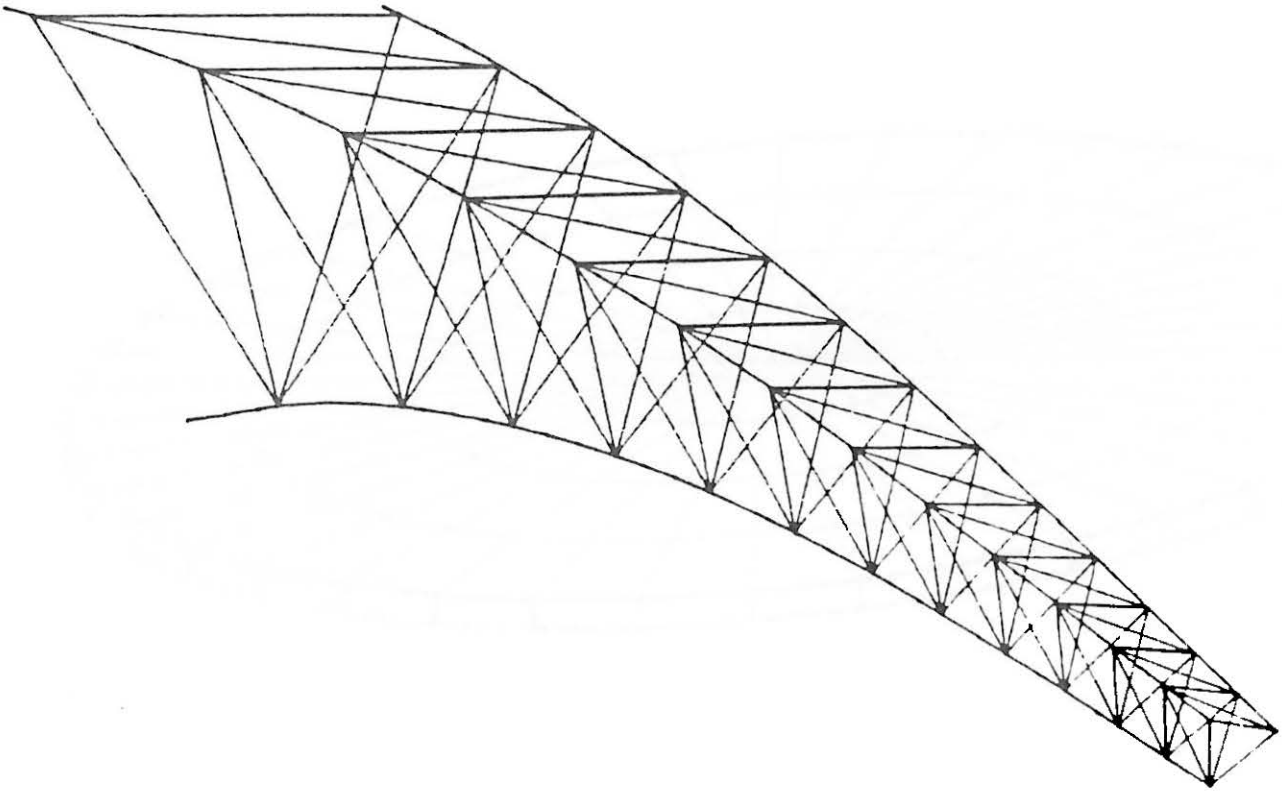


Figure 4. Commercial Design Deformed Triangular Truss

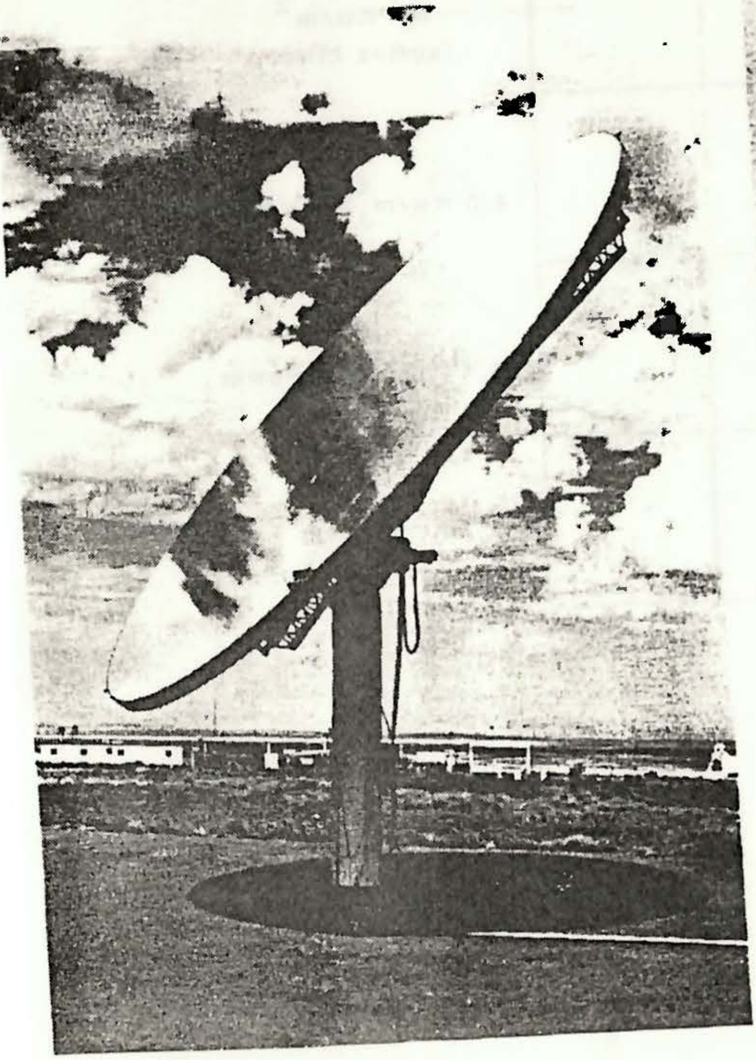


Figure 5. Prototype Heliostat Front View

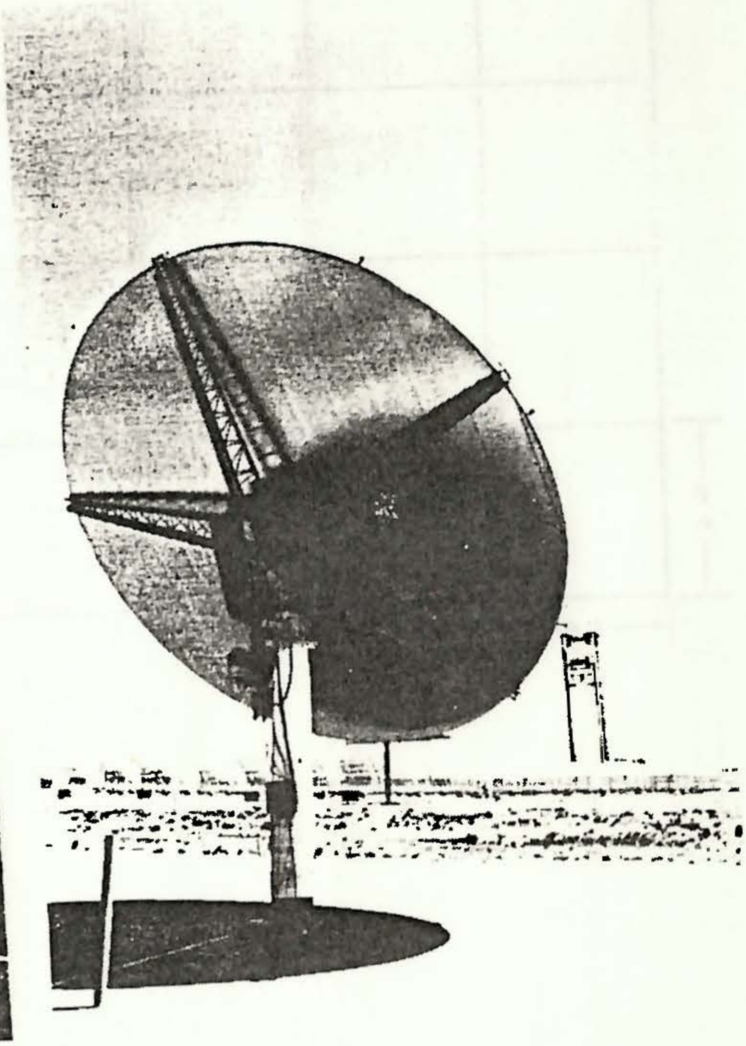


Figure 6. Prototype Heliostat Back View

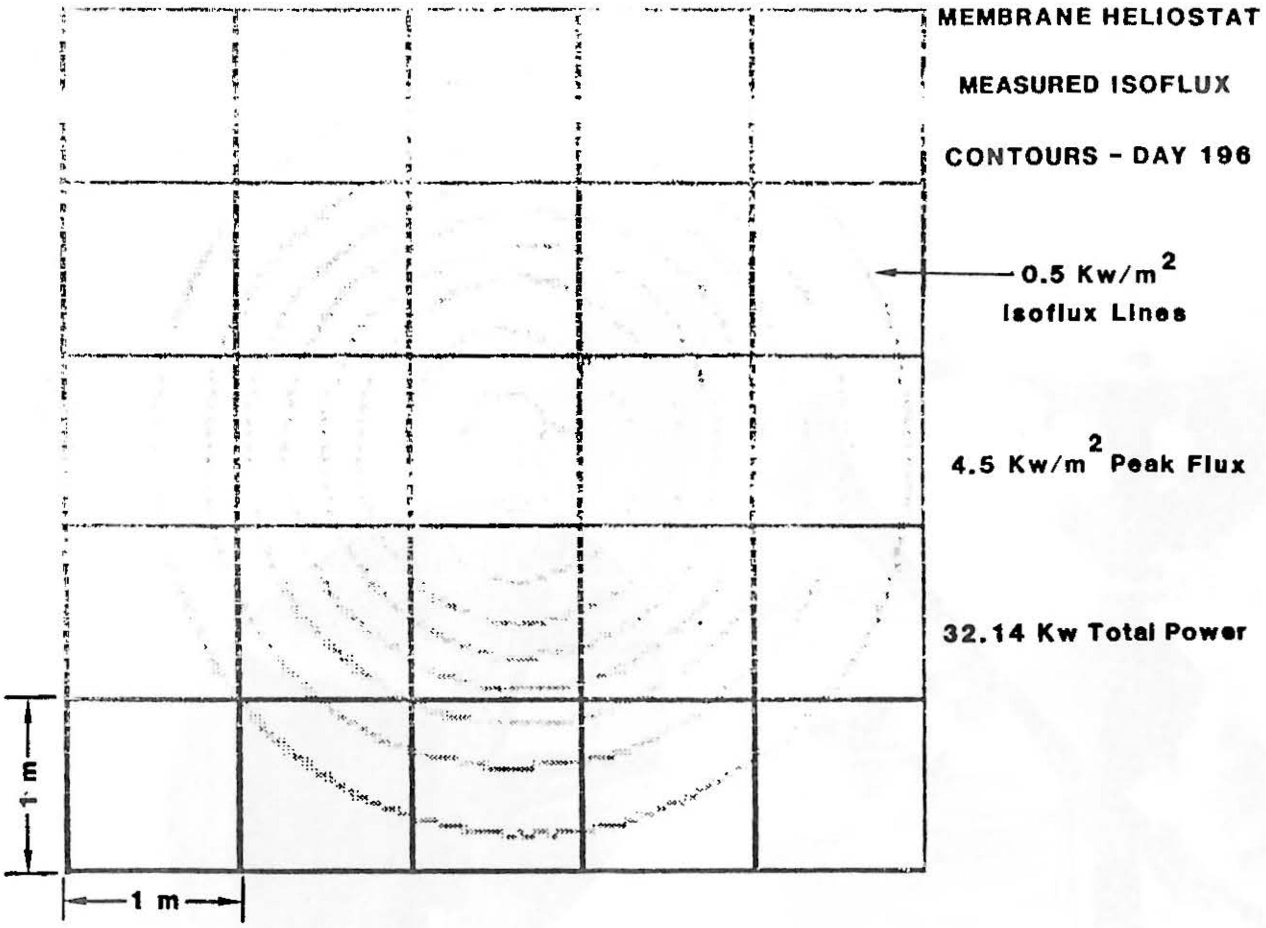


Figure 7. Membrane Heliostat Measured Isoflux Contours - Day 196

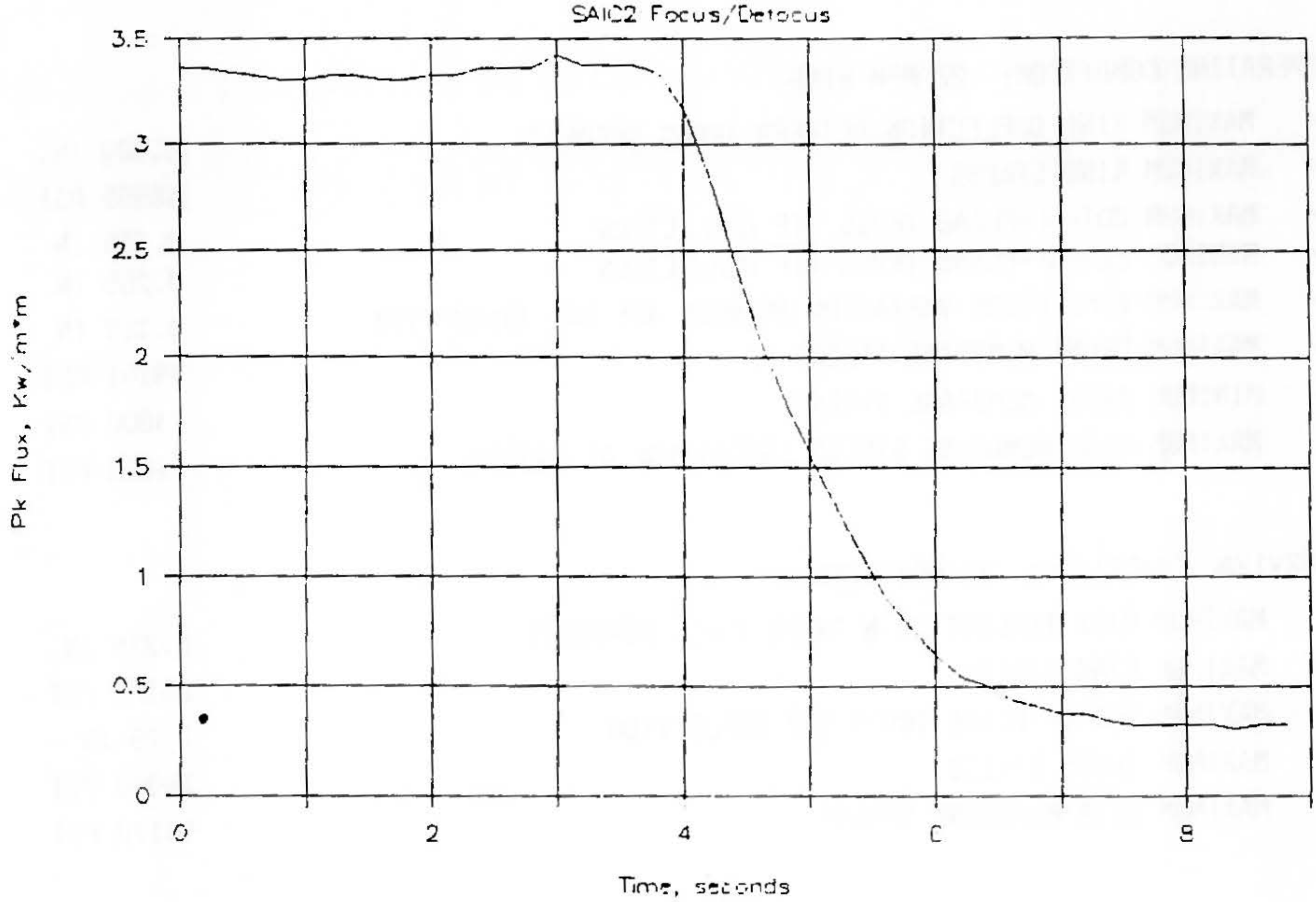


Figure 8. Defocus Time of the Membrane Heliostat

Table 2. Analysis Results for the Commercial Design

- OPERATING CONDITION: 27 MPH WIND

- MAXIMUM RING DEFLECTION BETWEEN TRUSS SUPPORTS	0.089 IN.
- MAXIMUM RING STRESS	18995 PSI
- MAXIMUM OUT-OF-PLANE TRUSS TIP DEFLECTION	0.384 IN
- MINIMUM OUT-OF-PLANE TRUSS TIP DEFLECTION	0.265 IN
- MAXIMUM DEFLECTION VARIATION BETWEEN ANY TWO TRUSS TIPS	0.119 IN
- MAXIMUM FRONT MEMBRANE STRESS	19141 PSI
- MINIMUM FRONT MEMBRANE STRESS	13000 PSI
- MAXIMUM REAR MEMBRANE STRESS (OPERATION AT 120°F)	71600 PSI

- SURVIVAL CONDITION: 50 MPH WIND

- MAXIMUM RING DEFLECTION BETWEEN TRUSS SUPPORTS	0.216 IN
- MAXIMUM RING STRESS	26373 PSI
- MAXIMUM OUT-OF-PLANE TRUSS TIP DEFLECTION	1.29 IN
- MAXIMUM TRUSS STRESS	24050 PSI
- MAXIMUM REAR MEMBRANE STRESS	93120 PSI

DEVELOPMENT OF A STRETCHED MEMBRANE POINT FOCUS CONCENTRATOR

BY

Gus Hutchison

Solar Kinetics, Inc.
10635 King William Dr.
Dallas, Texas

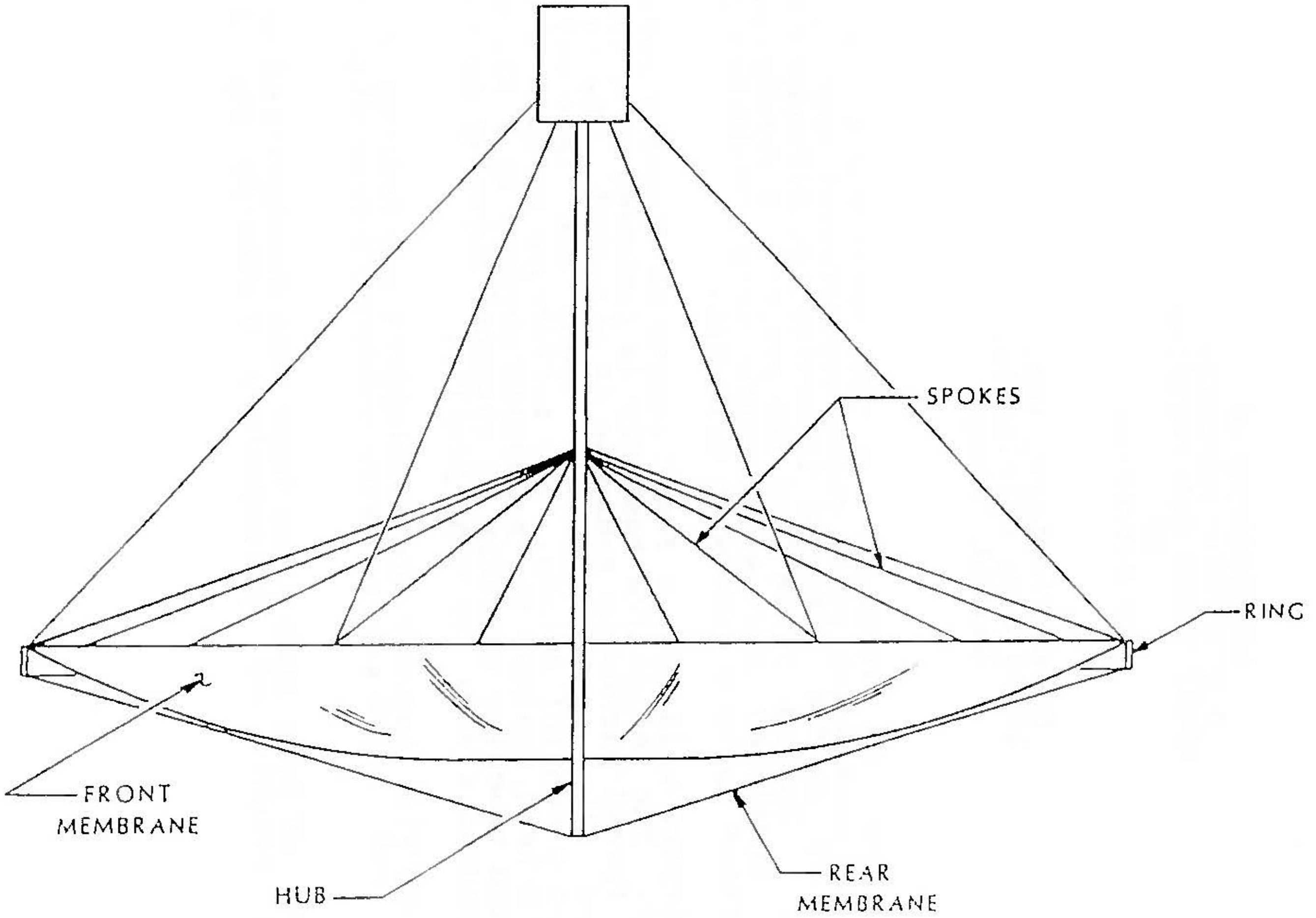
Solar Kinetics is involved in the development of a stretched membrane solar point focus concentrator under the supervision of Sandia National Laboratories, Albuquerque, New Mexico. During Phase I of the project, a conceptual design was developed and experiments were conducted on mirror membranes up to 4 meters in diameter.

The concentrator will have a focal length to diameter ratio of .6 (F/D). The reflective assembly is composed of a ring to which a formed parabolic membrane is attached. The ring is rigidized with spoke members, front and rear which terminate at a central column. The reflective surface is a polymer film held against the parabolic surface by a slight vacuum. The tracking assembly is attached directly to the ring and produces a very low wind profile.

Phase II work will include the development and testing of a full scale 100 - 150 square meter integrated concentrator assembly.

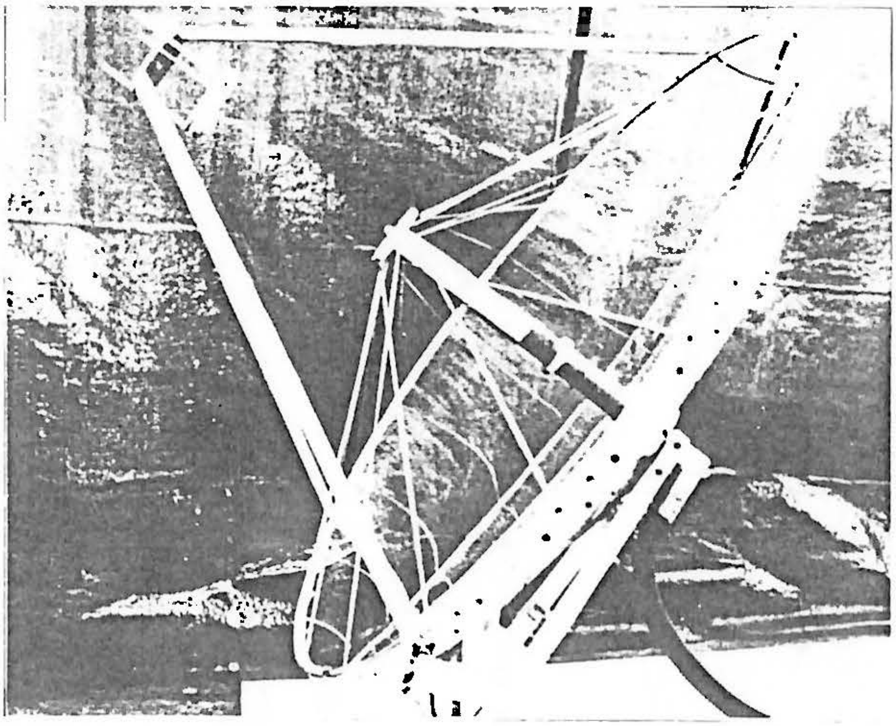
Slope errors of less than 2.5mr have been demonstrated and concentrator weights of approximately 6.6lbs/ft. sq. are anticipated.

HUB AND SPOKE SUPPORT



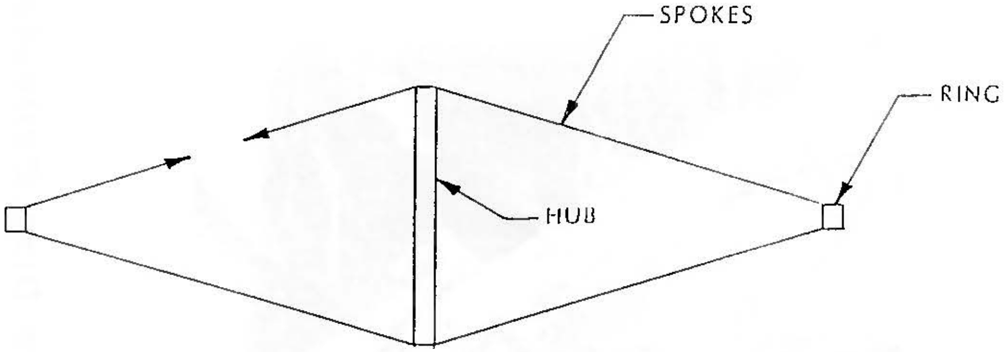
SECTION VIEW

SOLAR KINETICS INC.



Model of Stretched Membrane Dish Collector Constructed in Phase I, 1.4m Diameter

HUB AND SPOKE ENHANCEMENT OF RING



SPOKE TENSION PREVENTS: RING ROLL
OUT-OF-PLANE DEFLECTION
IN-PLANE DEFLECTION

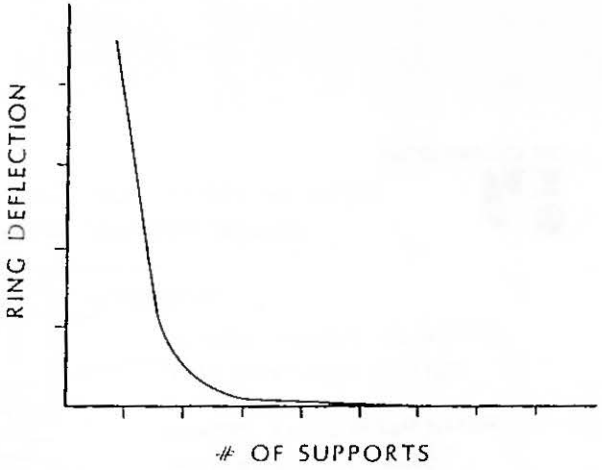
- PROVIDES RADIAL STABILITY
- PROVIDES RESISTANCE TO OUT-OF-PLANE DEFLECTION

SOLAR KINETICS INC.

HUB AND SPOKE BENEFITS

- EFFICIENTLY INCREASES NUMBER OF SUPPORTS

RING DEFLECTION $\propto \left[\text{SPAN}\right]^3$
(ERROR)



- EFFICIENTLY TRANSFERS LOADS

MOST LOADS CARRIED AS PURE TENSION

HUB CARRIES COMPRESSION WITH NO MOMENT LOADS
—AN EFFECTIVE SLENDER COLUMN—

- LOAD PICK-OFF

RING WITH CRADLE

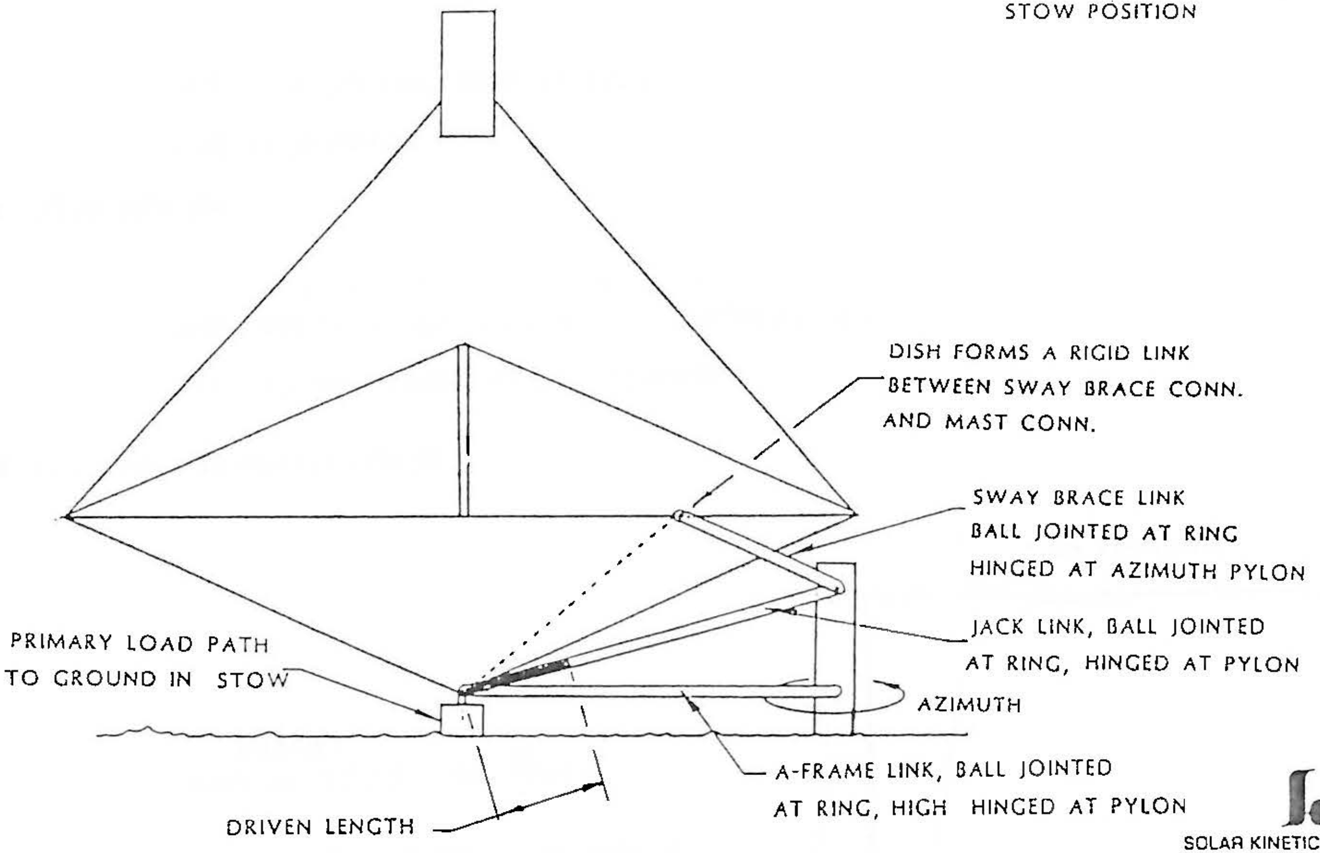
HUB WITH CONVENTIONAL PEDESTAL

SOLAR KINETICS INC.

CONCEPTUAL SUPPORT DESIGN

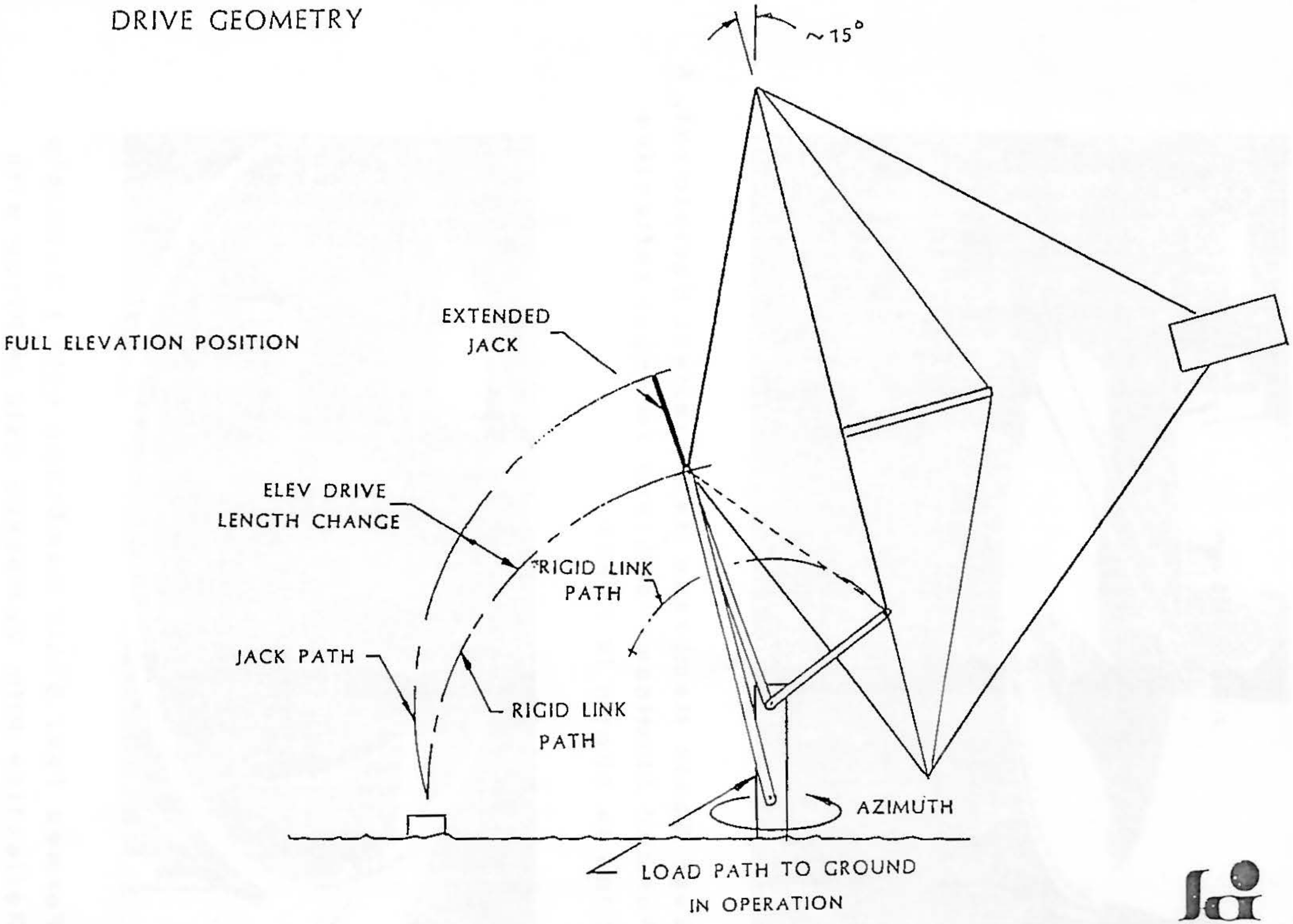
DRIVE GEOMETRY

STOW POSITION

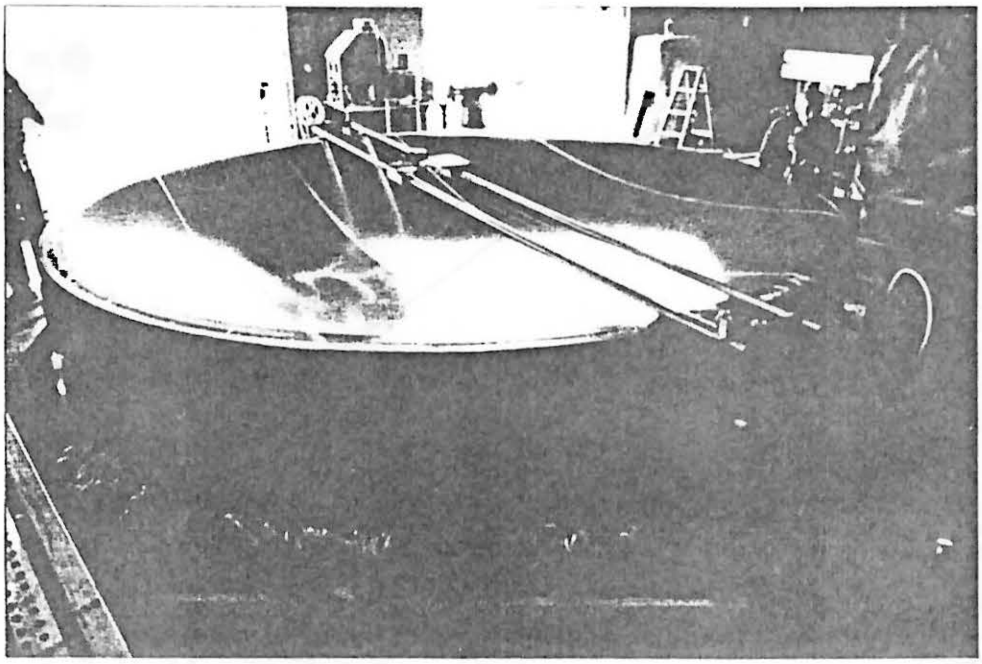


SOLAR KINETICS INC.

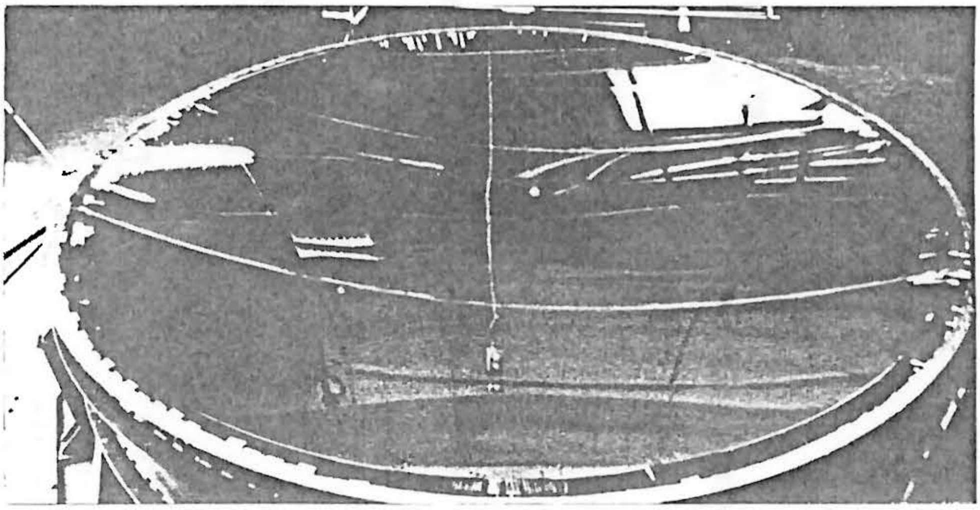
CONCEPTUAL SUPPORT DESIGN
DRIVE GEOMETRY



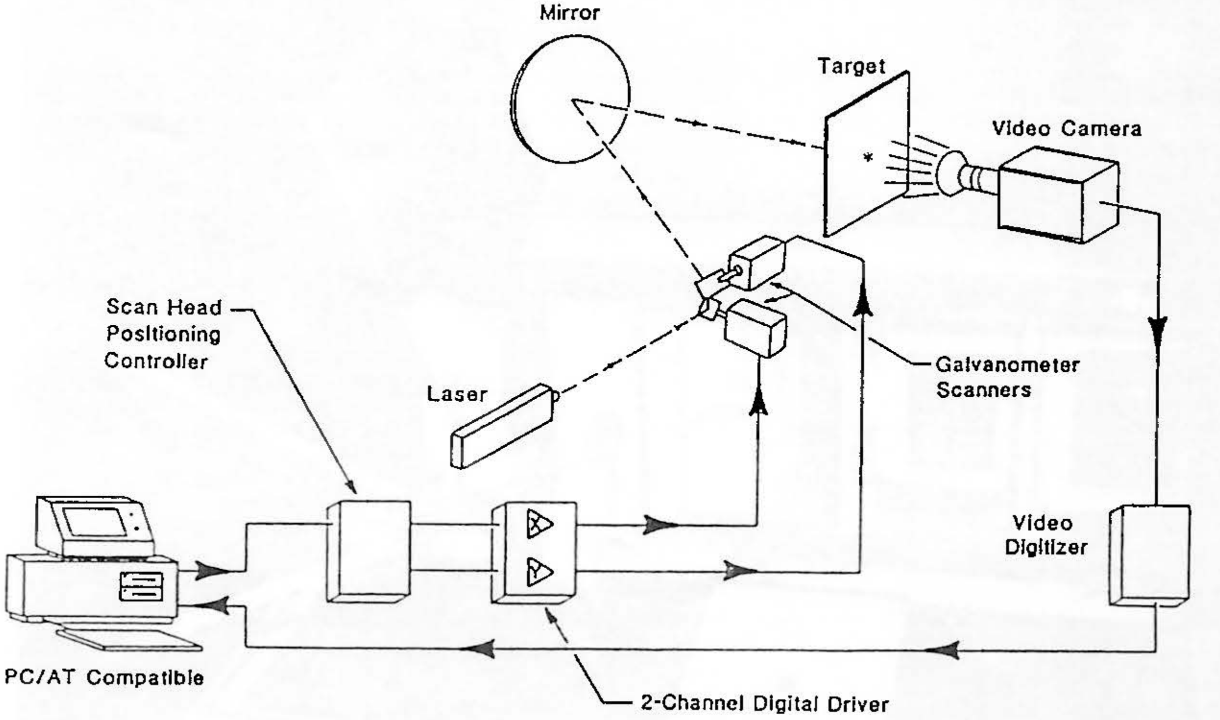
SOLAR KINETICS INC.



Test Scale Membrane Measurement Equiptment, A Formed Aluminum Membrane (without reflective film) is Shown in PLace.

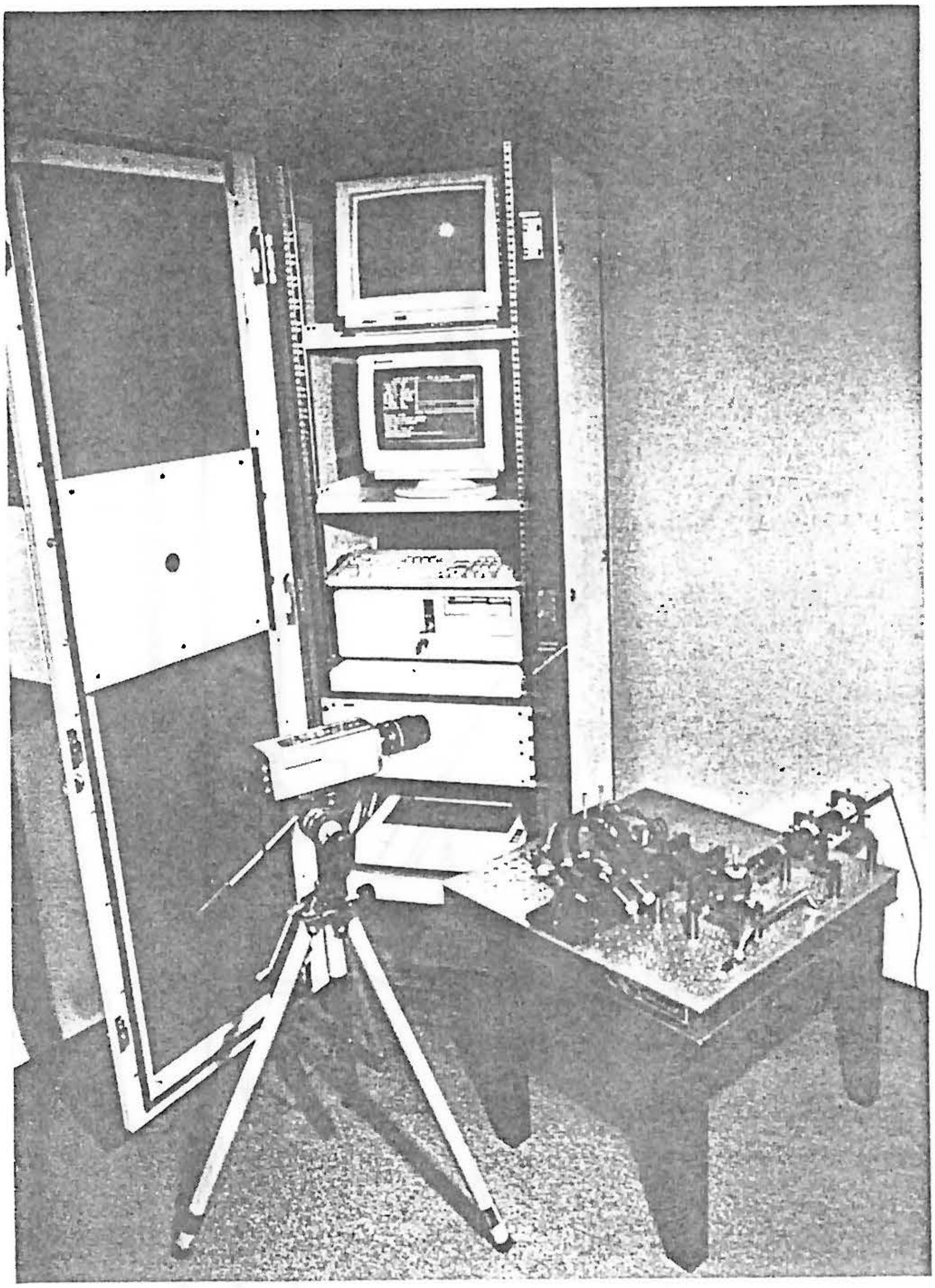


Formed Test Scale Membrane with a Separate Reflective Film Membrane Held in Place with Stabilization Pressure.

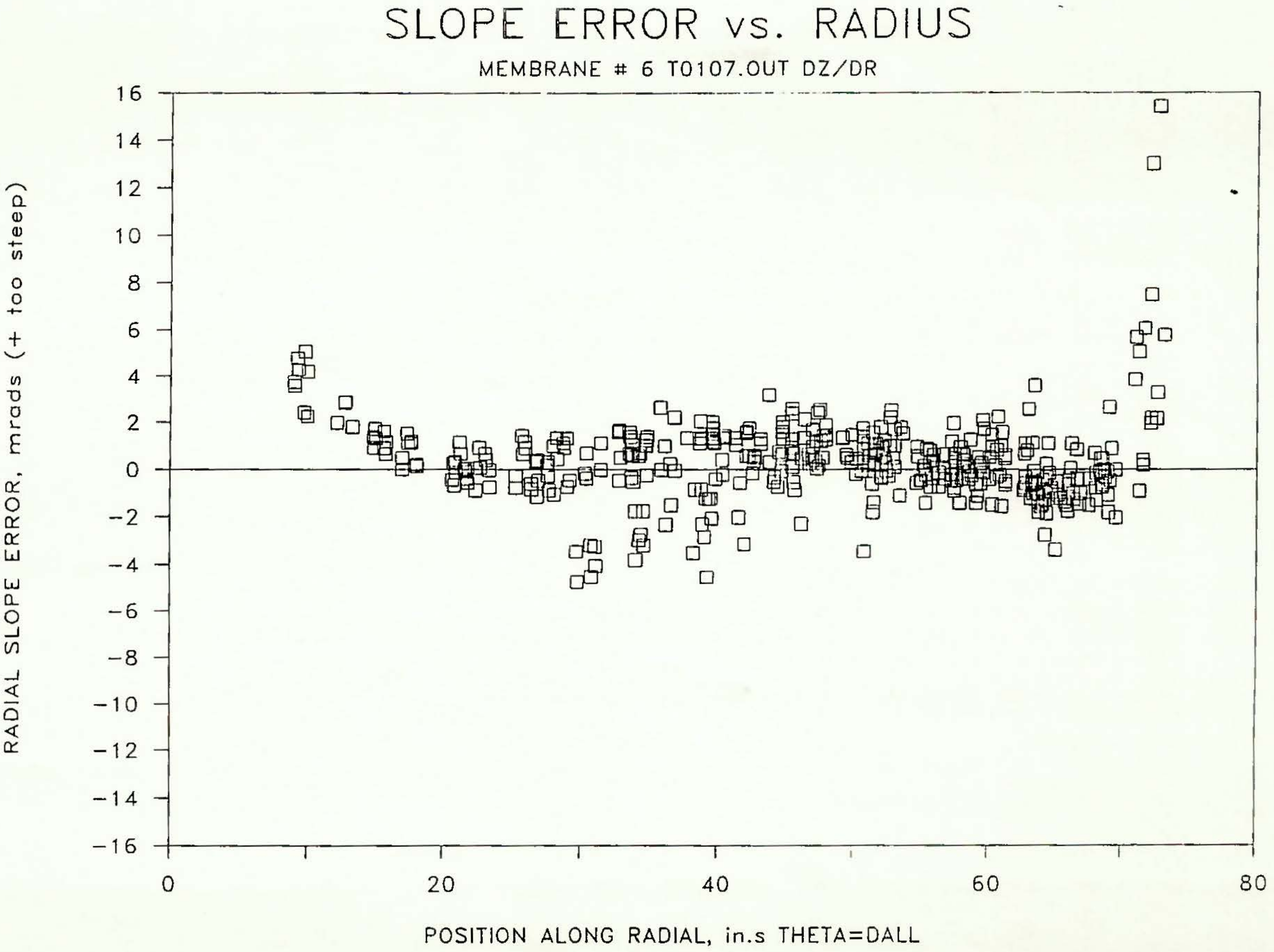


Hartmann Technique for Mirror Contour Measurements.

Figure 1

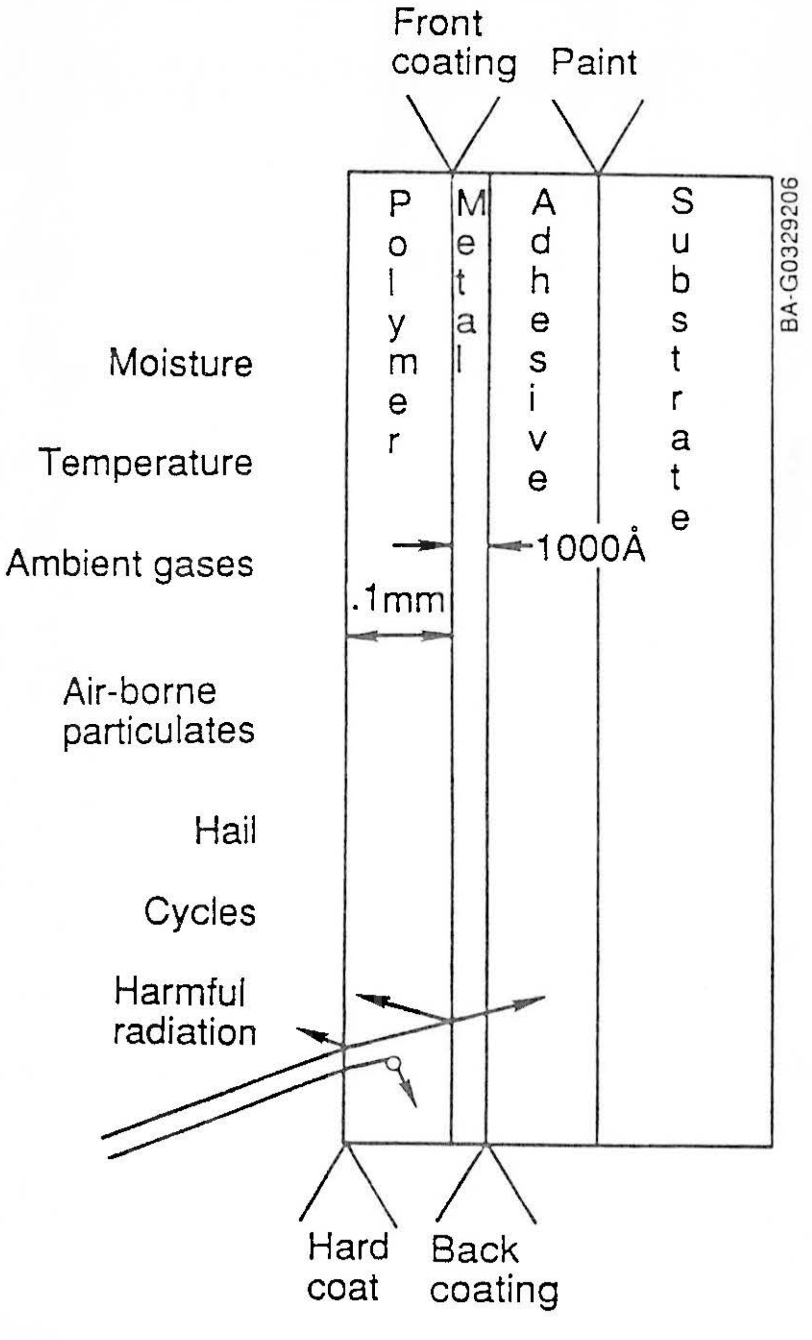


HARTMANN MEASURING SYSTEM


SLOPE ERROR vs. RADIUS
MEMBRANE # 6 T0107.OUT DZ/DR
RADIAL SLOPE ERROR, mrads (+ too steep)
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
0
20
40
60
80
POSITION ALONG RADIAL, in.s THETA=DALL

SILVERED POLYMER MIRRORS

Paul Schissel
Gary Jorgensen
Roland Pitts



Metallized Polymer Reflector Construction

Figure 1.

GOAL: MAINTAIN SPECULAR REFLECTANCE
(4 mrad FULL CONE ANGLE)
ABOVE 90% FOR 5 YEARS

PROBLEMS IDENTIFIED:

SILVER CORROSION
(SILVER/POLYMER DELAMINATION)
SOILING / CLEANING
(REPLACEMENT)

SILVER CORROSION MECHANISM STUDIES

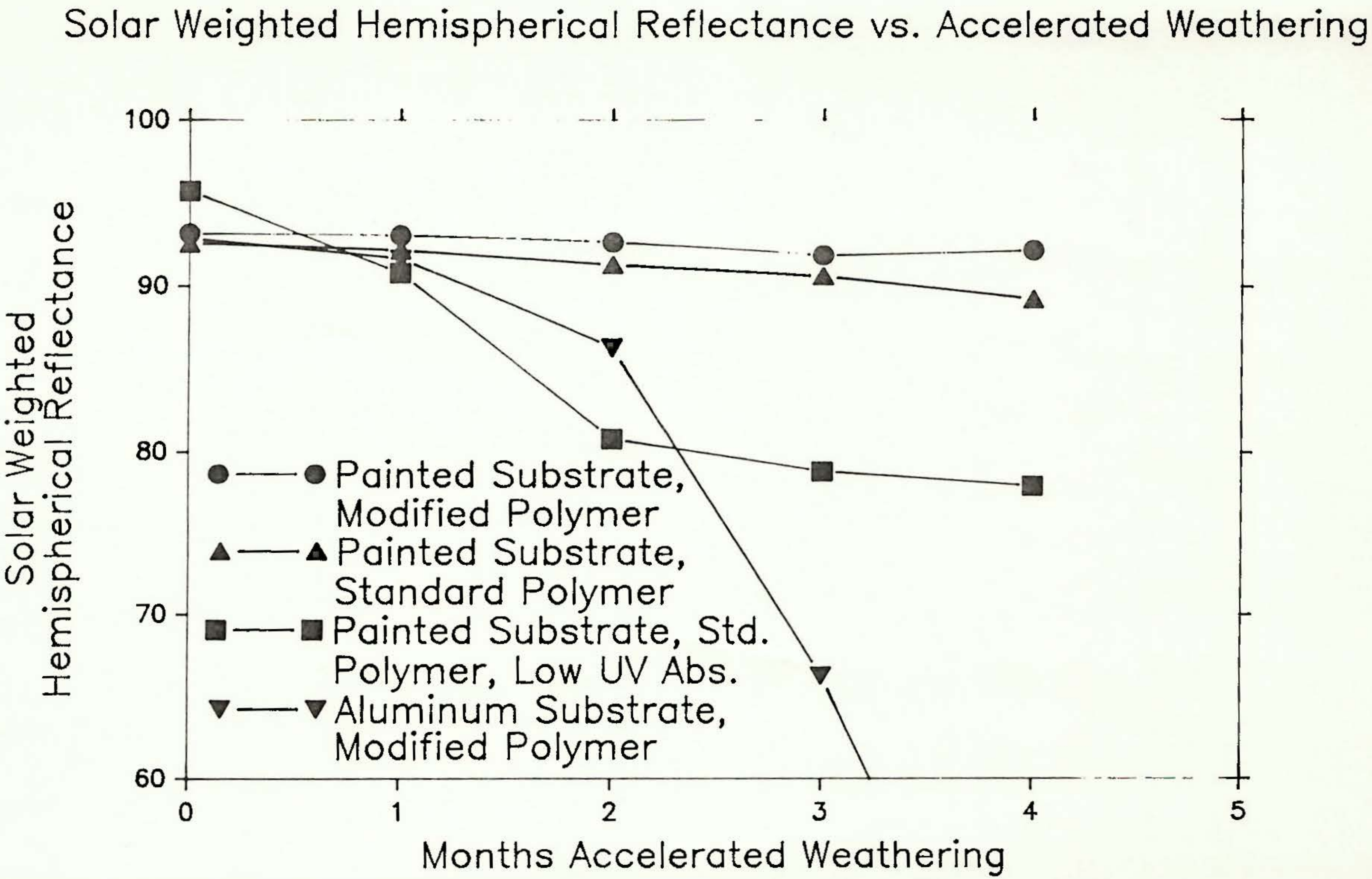
- NEAR UV LIGHT, ORGANIC ABSORBERS
- PAINTED SUBSTRATE BETTER THAN ALUMINUM OR STAINLESS STEEL
- PMMA PURITY
- UV, TEMPRATURE, SUBSTRATE, ATMOSPHERE, SYNERGISM

Outdoor Test Data

Silver Corrosion

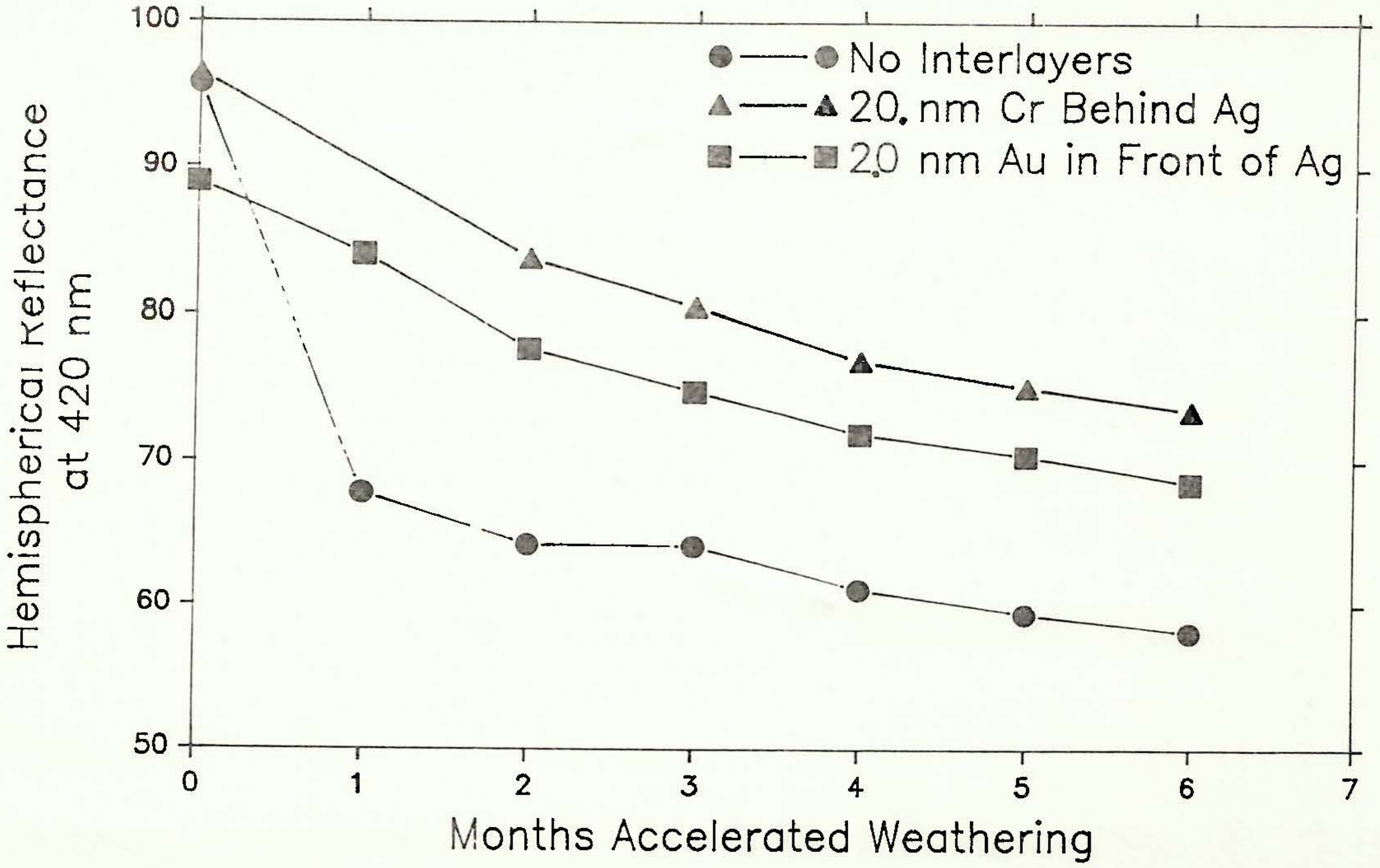
- GOLDEN/DENVER (CONTINUING)
  Hs >90% 4+ YEARS
  SPECULAR > 90% 2+ YEARS
  ECP 300 < ECP 300A, 3M Co.
  5 YEARS EXPECTED
- MIAMI 1-1/2 YEARS.....?
- PHOENIX < 90% ~1-1/2 YEARS

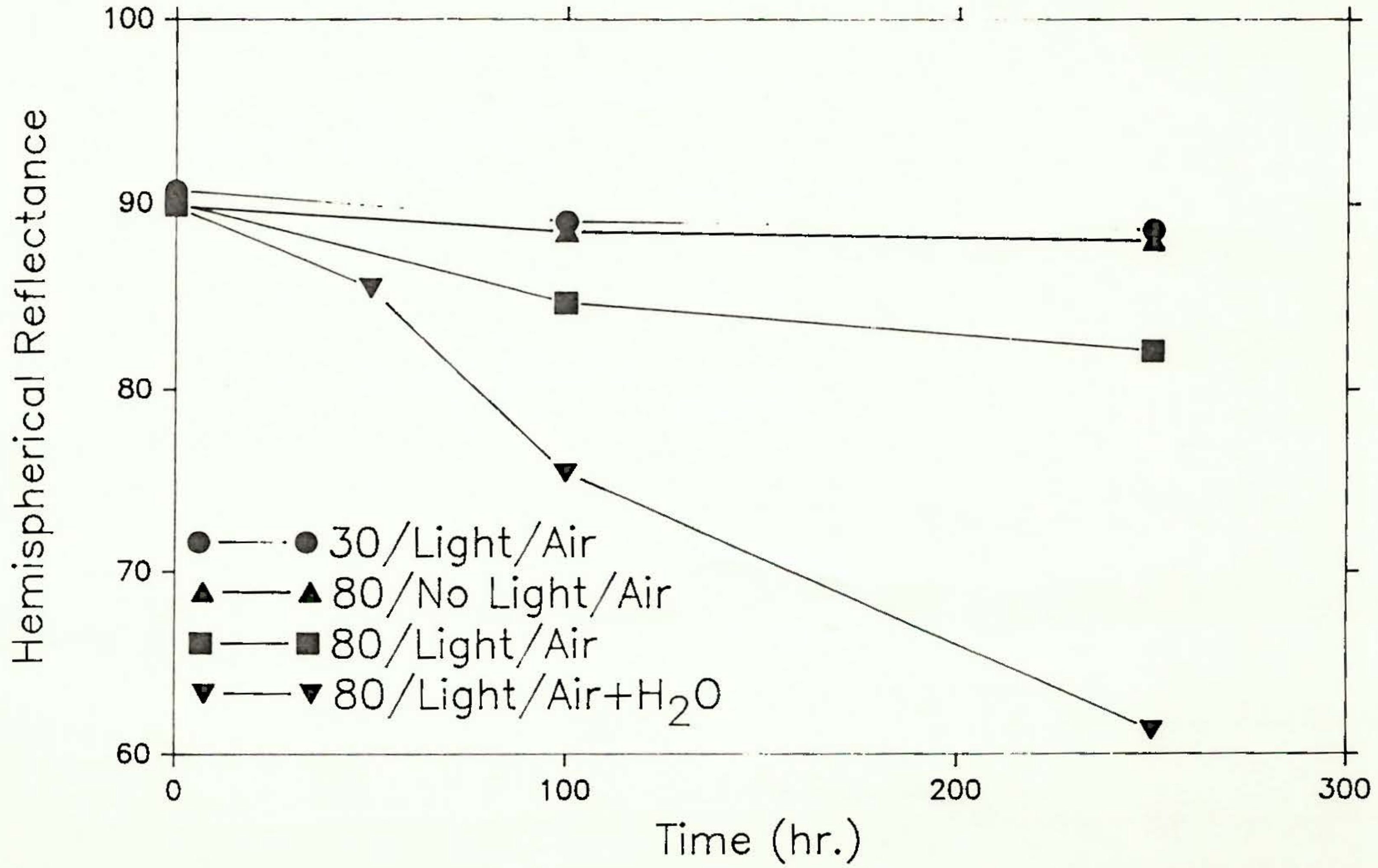
Need to slow corrosion X 4.


Solar Weighted Hemispherical Reflectance vs. Accelerated Weathering

Metal Interlayers

Hemispherical Reflectance at 420 nm vs. Accelerated Weathering





Solar Simulator Exposure of ECP−300A Lot 10 on Coil Coated Aluminum
Hemispherical Reflectance at 400 nm

NON-CONTACT CLEANING

INDUSTRIAL SOLAR TECHNOLOGY, DENVER, 6000 FT^2

MONTHLY - TWO YEARS

- 300 PSIG DI WATER RESTORES MIRRORS (85%)
  94% < PRISTINE VALUE 97%
- ABRASION RESISTANT COATS (ARC) IMPROVE
- 60 TO 500 PSIG NO DIFFERENCE OPTICALLY, MORE RAPID WITH HIGH PRESSURE, 6000 FT^2/2HOURS, 120 GALLONS
- CLEANING ADDITIVES (4) WITH/WITHOUT SHEETING AGENTS (2) NOT BETTER THAN DI WATER ALONE

CONTACT CLEANING

- LAMBSWOOL BRUSH RESTORES TO 97%
  SUBSEQUENT SOIL MORE RAPID
- ABRASION RESISTANT COATS POORER

LABORATORY CLEANING STUDIES

SERI: EXPOSE TO GM " ARIZONA ROAD DUST "

ACCELERATED WEATHERING (T, RH, UV)

NON-CONTACT CLEANING

LB FILMS > ARC POLYMER > POLYMER > 7809 GLASS
(GTRI)
TEST CORRELATES TO IST OUTDOORS, DENVER

SPRINGBORN LABORATORIES

- ANTISOIL COATS/HARDCOATS (ARC)
- BEST TO DATE
  FLUOROSILANE/ARC/POLYMER
- GOOD /ARC/POLYMER
- NOT SIMPLY RELATED TO SURFACE ENERGY

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SPRINGBORN LABORATORIES
DR. B. BAUM

GEORGIA TECH RESEARCH INSTITUTE
DR. LOIS SPEAKER

SERI MATERIALS RESEARCH BRANCH