UCRL- 15321-V-1

MASTER

REVIEW OF CURRENT STATUS
OF
HIGH FLUX HEAT TRANSFER TECHNIQUES

Volume I
(Text + Appendix A)

Prepared for
FUSION ENERGY DIVISION
LAWRENCE LIVERMORE NATIONAL LABORATORY
LIVERMORE, CALIFORNIA

NOTICE
PORTIONS OF THIS REPORT ARE RELEASABLE
It has been reproduced from the best
available copy to permit the broadest
possible availability.

September 1980

WMB&A Report No. 4500-95-27.20-R1

WILLIAM M. BROBECK & ASSOCIATES

1235 Tenth Street
Berkeley, California 94710
(415) 524-8664

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

REVIEW OF CURRENT STATUS
OF
HIGH FLUX HEAT TRANSFER TECHNIQUES

Prepared for:
FUSION ENERGY DIVISION
LAWRENCE LIVERMORE NATIONAL LABORATORY
LIVERMORE, CALIFORNIA

By:
William M. Brobeck & Associates
1235 Tenth Street
Berkeley, California 94710

NOTICE
PORTIONS OF THIS REPORT ARE REPRODUCIBLE.
It has been reproduced in the best
available copy to permit the broadest
possible availability.

September, 1980
WMB&A Report No. 4500-95-27.20-R1

APPROVALS

<u>ISSUE</u>	<u>CONTENTS</u>	<u>PREPARED BY</u>	<u>APPROVED BY</u>
Original	3 + 282 pages Including Appendices	William H. Bauer Hayden S. Gordon Heinz Lackner J. Richard Mettling James E. Miller	Francis C. Younger

CHECKED BY

Albert M. Weston

TABLE OF CONTENTS

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
1	Introduction	1-1
2	Summary of Plant Visit Information	2-1
3	Summary of Telephone Call Information	3-1
4	Discussion of Findings	4-1
5	Recommendations and Conclusions	5-1

LIST OF APPENDICES

A	Report of Visits to Selected Industrial Firms	A-1
B	Report of Telephone Contacts	B-1
C	A Baseline Beam Dump for Cost Comparison Purposes	C-1
D	Beam Dump Manufacturing Schedule	D-2

1. INTRODUCTION

William M. Brobeck & Associates was engaged by the Lawrence Livermore National Laboratory (LLNL) to review the current state-of-the-art in high heat flux absorption, including calls and visits to commercial organizations prepared to participate in the program, and to recommend means whereby the large systems required for MFTF-B ion and neutral beam dumps might be provided.

The development of neutral-beam injectors for plasma heating in fusion research machines has been underway at the Lawrence Berkeley Laboratory (LBL) and the Oak Ridge National Laboratory (ORNL) for a number of years. Although pulse-peak, beam-power-levels could be as high as ten megawatts, the pulse lengths were short enough and the duty factor low enough that the thermal capacity of thick, water-cooled copper plates could accept the peak power and dissipate the average power. However, the neutral-beam development programs were aimed at pulse lengths long enough to necessitate operation of the beam dumps under steady-state conditions.

Estimates made to date on the power density distribution on the MFTF-B beam dump are shown graphically on Figures 1 and 2 for the orthogonal dump surface coordinates. These values assume that for initial tune-up the analyzing magnet in the beam line is not in use and both unneutralized ions and neutralized particles are being deposited on the dump surface. Inasmuch as these estimates of peak values and distribution have not been confirmed by measurement, a Gaussian distribution of higher peak and integrated values has been derived

(See Appendix C, page C-12) for purposes of analysis. A plot of the iso-energy contours is shown in Figure 3.

Briefly, the problem became one of surveying the state-of-the-art in high heat flux dissipation technology and of recommending design approaches that are reliable, economical, and readily fabricated by existing industrial facilities.

The scope of work comprised two tasks. The first was to review high heat flux technology with consideration given to heat transfer panel configuration, diagnostics techniques and coolant supply. The second task was to prepare a report describing the findings of the review, to recommend the technology offering the least uncertainty for scale-up for the MFTF-B requirement and to recommend any new or perceived requirements for R&D effort.

MFTF 10 x 45, 80 KV Source

1.2	0.4 - 90%	4.8 MW
5.0	0.5 - 100%	
1.4	0.4 - 90%	4.8 MW
5.0	0.5 - 100%	
2.0	0.5 - 100%	2.4 MW

ASSUMED IN ANALYSIS 6.14 MW

* DATA FURNISHED BY MFTF GROUP

Figure 1. POWER DENSITY VS NARROW SOURCE DIMENSION (Z).

Figure 2. POWER DENSITY VS LONG SOURCE DIMENSIONS (Y).

Figure 3. ISO-ENERGY CONTOURS

ISO-ENERGY CONTOURS FOR ASSUMED DISTRIBUTION

Scale: One-Fourth

2. SUMMARY OF PLANT VISIT INFORMATION

High-thermal-flux technology has been developed for and applied to liquid-rocket nozzles, electron tube anodes and to some extent—albeit on a developmental basis—in fusion research machines and ion beam targets. It was clear, therefore, that these sources should be contacted and perhaps be visited. As a result, visits were made to eight companies. The name and phone number of the leading contact at each and a brief summary of the findings are listed below in chronological order. Appendix A comprises an expanded report upon each visit supplemented, where available, with documentary material obtained at the time of the visit and with names of additional contacts.

June 25, 1980	Rocketdyne 6633 Canoga Avenue Canoga Park, CA 91304	Dr. Stanley V. Gunn, Manager Special Products (213) 709-7250
---------------	---	--

Rocketdyne experience in high-heat-flux cooling has been obtained from their development of rocket nozzles for the Apollo and Shuttle programs. Current engine systems studies (ca. 1978) have addressed heat flux levels in excess of 33 kW/cm^2 and operating values of 20 to 24 kW/cm^2 are normal practice. A multitude of continuous channels several feet in length and of varying depth and width are machined on the backside (outside) of the converging section of the combustion chamber, the throat section and the initial expansion section of the nozzle. The channels are closed by an electroformed jacket bonded to the copper used for the nozzle section. Cryogenic hydrogen at 7000 psi and 2000 psi pressure drop is pumped through the machined channels obtaining 500 to 800 fps flow velocity. At 6 kW/cm^2 they estimate a water coolant inlet pressure of 2500 psi with a 1500 psi drop and a velocity of 200 ft/sec. would suffice.

Rocketdyne has laser test facilities that could heat a 4 in. x 4 in. area at a rate of $\sim 10 \text{ kW/cm}^2$. They also have good fatigue data for copper subjected to intermittent high thermal flux loading and cooled in the manner described above. They are confident that they can handle the cooling problem but do not have any experience with the sputtering problem.

June 24, 1980	Aerojet Electro Systems P.O. Box 296 Azusa, CA 91702	J. F. Keville, Manager Mechanical Engineering (213) 334-6211, Ext. 6140
---------------	--	---

Aerojet is not familiar with the beam dump problem but has extensive experience with high heat flux problems in rocket nozzles. Although no thermal-flux intensities were stated the impression was given that the values were comparable to those obtained by others. However, allusions to solid-propellant rockets and graphite nozzles implied that cooling may not have been used. They are well qualified in analytical, materials and testing areas. Aerojet has no experience with the sputtering problem.

June 26, 1980	TRW One Space Park Redondo Beach, CA 90278	Dr. Robert Bromberg Vice President (213) 536-3813
---------------	--	---

TRW has experience in rocket engine and laser problems and has facilities to test a heat flux of 10 kW/cm^2 over a 10 cm^2 area.

In addition to high heat flux experience, TRW is knowledgeable about the sputtering problem. They have design capabilities with refractories and they suggested that a design using such material be considered.

June 26, 1980	Geoscience, Ltd. 410 Cedros Avenue Solano Beach, CA 92075	Dr. Heinz Poppendiek President (714) 755-9396
---------------	---	---

Geoscience is a small R&D company specializing in heat transfer and fluid dynamics among other disciplines. They could design, fabricate and test a small

sample for heat transfer. Up to 50 kW of electric resistance heating would be used to generate the heat input.

Dr. Poppendiek also suggested that materials other than copper be considered when all the requirements were better defined to determine if OFHC copper represented the optimum combination of properties for the beam dump application. Properties to be considered would be thermal expansion and conductivity, elevated temperature strength and fatigue characteristics, melting point, perhaps sputtering characteristics and combinations of properties obtained by alloying, and fabricability. They have no experience with the sputtering problem.

July 23, 1980

Hughes Aircraft Company
Electron Dynamics Division
3100 West Lomita Avenue
Torrance, CA 90509

Dr. Al Basiulis
Assistant Manager
Thermal Products
(213) 534-2121

It was stated that heat pipes have been successfully tested at heat fluxes up to 0.5 kW/cm^2 . If lithium were used as the working fluid, it is estimated that a normal flux of 2 or 3 kW/cm^2 could be obtained. The pipe material would be molybdenum, tungsten-rhenium or TZM. Operating temperature could be as high as 1600°C .

High temperature heat pipes were claimed to have the following advantages:

1. The cooling water is kept outside the vacuum vessel.
2. The heat pipe material is a refractory metal.
3. The working fluid, lithium, has a low Z.
4. The flow rate and pressure of the cooling water can be fairly low.

Electron guns are available for providing the 10 kW/cm^2 flux required for testing on sample of some 10 cm^2 .

July 30, 1980

United Technologies
Research Center
Silver Lane
East Hartford, CT 06108

Tom Latham
(203) 727-7000

UT has a plasma physics division within the Research Center. They have extensive experimental facilities including a small mirror machine and a neutral beam source although not currently operational. They fabricated many of the components of the Texas Tokamak.

UT has tested a tangentially-fed, water-cooled swirl tube to a thermal flux intensity of 14 kW/cm^2 which Latham believes is the highest flux level achieved in a simple system.

UT also has developed a proprietary process for fabricating "Thermal Skin[®]" which comprises photo-etched coolant passages of specified shape, size and layout within a furnace-brazed metal sandwich. Thermal Skin[®] can handle 2 kW/cm^2 and studies have been made which predict thermal flux level capability as high as 7 kW/cm^2 for flow channels 10×20 thousandths of an inch ($0.25 \times 0.50 \text{ mm}$).

July 31, 1980

Westinghouse
Research & Development
Center
1310 Beulah Road
Pittsburgh, PA 15235

Dr. Martin D. Nehemow
Senior Engineer
(412) 256-7000, Ext. 3079

Included within the extensive theoretical and experimental facilities of the Westinghouse R&D Centers are several systems which could be used to study the problems at hand.

One is an electron bombardment source providing 40 to 50 kW at 150 to 200 kV which can be rastered and modulated over an area up to $10 \times 10 \text{ cm}$ to simulate a specified distribution on the target surface. Target samples are cooled by a

system capable of operating over an extended range of choices of pressure and velocities. Westinghouse is also preparing to build ion beam facilities of 1.5 kW at 150 keV to compare the effects of electron and ion beams on materials and sputtering which could provide data of value in the design of the beam dumps.

August 1, 1980

McDonnell Douglas
Astronautics Company
969 Executive Parkway Drive
St. Louis, MO 63141

Dr. Donald Kummer
Director
Fusion Energy Division
(314) 576-8253

The fusion energy division, in existence some six years, does work in support of ORNL, ANL, LBL, LLNL, EPRI and others. Included is ion source fabrication, analytical work on first wall problems, and laboratory experimental work.

3. SUMMARY OF TELEPHONE CALL INFORMATION

Telephone calls were made to each of the companies visited to make travel plans and set schedules. Often these calls developed new information which has been incorporated in the reports of visits. Calls to companies or individuals which did not lead to visits often produced information of interest.

The contacts and a summary of the findings, again in chronological order, are listed below, and expanded, where needed, in Appendix B.

June 18, 1980	Stanford University Stanford, CA 94305	Professor A. L. London (415) 497-4022
---------------	---	--

Professor London had published a report on an experimental program done under contract with Varian Associates which he believed to represent the highest thermal flux levels for equipment in commercial production at that time. The reference is London, A. L., "Coolant Path Hydraulic Design for High Power Twystron Tubes," Varian Associates, Stanford, USA, 1971.

Professor London expressed the opinion that a good data base exists but needs collation and possible R&D work to bridge any gaps which may be found. He also suggested contacting Professor Kraus at the University of Southern Florida.

June 19, 1980	University of Southern Florida Tampa, FL 33620	Professor Alan D. Kraus (813) 974-2581
---------------	---	---

Professor Kraus's work has been in the area of electronic equipment cooling such as klystrons and traveling-wave tubes. The most recent report of his work appeared in a publication entitled "Directions of Heat Transfer

in Electronic Equipment" which resulted from a research workshop supported by NSF grant ENG-7701297, hosted by the College of Engineering, University of Southern Florida, Tampa, and held at Atlanta, Georgia, October 17, 18 and 19, 1977.

Professor Kraus has also authored several books including "Cooling Electronic Equipment," McGraw-Hill but now out-of-print. Another book, also out-of-print, was addressed to extended surface cooling but not applicable to the levels of interest to us.

June 24, 1980

Convair Division
General Dynamics Corp.
P.O. Box 80847
San Diego, CA 92130

R. E. Tatro
(714) 277-8900
Ext. 3818

Emmet Christensen
Ext. 1110

Dick Pleasant
Ext. 1701

Mr. Tatro is working on the LLNL MFTF program but on subjects other than high-flux heat transfer.

Emmet Christensen in the Thermodynamics group said they had no experimental program. However, the group has in the past, done finite-element transient analysis on graphite throat blocks for solid-propellant rockets using material properties supplied by their material research group.

Dick Pleasant in the laser group said they had submitted a proposal to do experiments with a one-inch diameter target heated by an electron beam from an EB welder and cooled by phase change of a water jet directed against the back side. They did not win the award. Their work on laser mirrors is directed to the achievement of high reflectance surfaces carried on a low-thermal expansion substrate without special cooling.

July 16, 1980

Hughes Research Laboratories
3011 Canyon Road
Malibu, CA 90265

Dr. Harry King
(213) 456-6411

Dr. King is familiar with the MFTF program since Hughes has built ion sources for the neutral beam program. Hughes would be interested in doing funded studies or proposals and would furnish statements of capabilities in response to questionnaires. Also, Dr. King would suggest divisions of the company where work of interest to the MFTF program could be done, such as the laser mirror facilities where liquid cooled surfaces capable of handling high heat flux had been fabricated.

July 17, 1980

Grumman Aerospace Corporation
Bethpage, (L.I.) NY 11714

Robert Botwin
Assistant Director
Advanced Energy Systems
(516) 575-0574

At the present time, Grumman is doing no work on high-heat-flux cooling. However, Robert Botwin sent reprints of papers covering studies on plasma limiter design, on material and environment interaction and first-wall thermostructural and material considerations and on vacuum vessel protective plates for the Tokamak Fusion Test Reactor. Also included was a copy of their "Proposal for Use of Heat Pipe Technology in the Neutral Beam Injection System" submitted to LBL, April 18, 1977, which is also in the MFTF files. This proposal references the Princeton Plasma Physics Laboratory report "An Experimental Evaluation of Material for Use as Limiters, Wall Armor or Beam Dumps" by M. Ulrickson. The reprints and the PPPL reference are reproduced in Appendix B.

July 18, 1980

RCA Corporation
Lancaster, PA 17604
(717) 397-7661

Mr. Don Fleckenstein
Contact Administrator
Ext. 3270

RCA has done no further work on the beam dump problem since the report for LLNL by Harbaugh, Bauder, and Novajovsky and the call to Novajovsky was

referred to Don Fleckenstein who had the call returned by Don Carter.

RCA is producing switch tubes for TFTR which have pulse peak power densities normal to beam axis of 10 kW/cm^2 but by geometrical artifice reduces this to 600 w/cm^2 normal to anode surface. This conservative value is deemed necessary to limit thermal stresses during the pulse to ensure longevity of the anode surface for 1/2 second long pulses.

RCA has used tungsten-faced copper anodes for tubes with very short pulse length and high density power levels, but have done no work on sputtering.

Dick Bauder is the member of the group who does the finite-element heat flow and thermal stress analysis calculations.

July 25, 1980 Packer Engineering
 Naperville, IL 60640
 (312) 355-5722

Dr. James Slater

Packer Engineering had submitted to LLNL, in response to an earlier inquiry, a paper on heat pipes authored by Dr. Charles C. Roberts. Dr. Slater explained that Packer was a mechanical and materials consulting engineering firm with very limited shop facilities. Also that Dr. Roberts was no longer with the firm so their interest was minimal.

However, Dr. Roberts was continuing to consult on the subject. He could be contacted at:

27 West 776 Greenview
Warrenville, IL 60555
(312) 393-1108

Also, Packer had worked with a heat pipe fabricator, B&K Engineering, Inc., who has production facilities, makes equipment covering a wide range of operating conditions and is well recommended by Slater.

September 4, 1980 B&K Engineering, Inc.
Suite 825
One Investment Place
Towson, MD 21204

Mr. Patrick Brennan
(301) 296-7719

A call to B&K Engineering, Inc. elicited the information that they used internally-fluted tubular extrusions in heat-pipe fabrication. Their product is apparently for modest temperature applications although Patrick Brennan expressed a strong desire to be offered an opportunity to bid on LLNL work including high-temperature and high-flux systems.

B&K Engineering, Inc. has no brochures or product information for distribution but would respond to specific requests.

September 12, 1980 General Electric Corporation
Research & Development Center
P.O. Box 43
Schenectady, NY 12301

Dr. Fred W. Staub, Manager
Heat Transfer Unit
Building 37
(518) 385-4483

The call was made to Dr. Fred W. Staub, manager of the Heat Transfer Unit. He is on sabbatical leave and will not return until October, so we talked with Dr. B. Kermati the acting manager. The Unit is conducting several programs on high-flux heat transfer mostly employing two-phase flow. High-power thyristor cooling employs freon because of water-treating problems but turbine-blade cooling uses water with, in some cases, the outflow caught in stationary, circumferential channels. These are development projects only. However, GE is very interested in being considered for work in support of the fusion program in both heat transfer and other areas such as beam dump sputtering and surface-coating experiments. Inquiries and RFP's should be addressed to Dr. Staub, Unit Manager. Meanwhile, Dr. Kermati will ask the Public Relations department to mail general descriptive material on the work and facilities of the R&D Center.

In addition to the 1979 General Electric Annual Report, which shows \$22,460,600,000 in sales to customers with 405,000 employees, average world wide, (\$55,458 sales per employee) a descriptive brochure on the R&D Center was included in the material received. This material is available from the central file of collected material on the Review of Current Status of High Heat Flux Transfer Techniques.

A one-page description of the Mechanical Systems and Technology Laboratory, Thermal Branch, is reproduced in Appendix B.

The description emphasizes the application of the work of the Thermal Branch in support of the Corporation goals but inferences may be drawn to broaden applications of their work.

4. DISCUSSION OF FINDINGS

General

The three areas of interest found in the survey of existing technology applicable to the MFTF-B beam dumps comprise material properties, heat transfer film factors and diagnostics. Materials properties involve not only melting point, thermal conductivity and strength but also properties relevant to cyclic fatigue, and the surface effects of sputtering, erosion and blistering by embedment from impinging particles. Heat transfer film factors are a function of cooling fluid properties and velocity as well as mechanical design of fluid channels. Diagnostics for the MFTF-B beam dumps may be limited to gross calorimetry and detection of incipient failure. Beam power distribution is assumed to have been determined by measurements made in a teststand using multiple calorimetric targets.

Materials Considerations

The front surface material, shape and thickness must be such that requirements imposed on the surface are maintained within acceptable metallurgical limits, that cyclical thermal stresses do not lead to early failure and that coolant pressure stresses are consistent with strength at operating temperatures. The most sophisticated application of this approach that was observed was in the design of the space-shuttle, rocket-engine nozzles using liquid hydrogen coolant at 7000 psi inlet pressure with a 2000 psi pressure drop and 600-700 ft/sec channel velocity in machined eternally-fluted copper throat sections.

Heat Transfer Considerations

Current engine systems studies (ca. 1978) have addressed heat flux levels in excess of 33 kW/cm^2 . In the shuttle engines 60,000 hp turbine driven pumps are used for the fuel and for the oxidant. A similar design using water as a coolant at an inlet pressure of 2500 psi, a pressure drop of 1500 psi and a channel velocity of 200 ft/sec. is estimated to be capable of handling 6 kW/cm^2 .

Klystron beam catchers using a similar approach of external flutes jacketed with cylinders and cones are used at operating thermal-flux levels of 2 kW/cm^2 —with burnout estimated at 4 kW/cm^2 —at more modest cooling parameters and with an extended service life.

Another high-thermal flux technique is to use some form of "swirl" tube. The swirl effect may be obtained by inserting a twisted, flat strip into a round tube and securing it by drawing the tube to a slightly smaller diameter thus locking the strip into the tube. Tubes with internal, spiral fins are a commercially available alternate. Injecting the coolant at a high velocity tangentially to the tube inner-wall surface produces a spiral flow with the ratio of tangential to axial velocity decreasing with length. Thermal fluxes of 14 kW/cm^2 have been measured. However, pumping power is high as an 800 psi pressure drop across the injection slot was used. Swirl tubes have unique merit in that they can be curved and if attached only at the ends can bow to accommodate differential thermal expansion without creating stresses in neighboring tubes. However, the pattern must be double-layered to intercept beam passing through interstices between adjacent tubes. In any of several alternate design approaches, a relatively direct relationship exists between achievable thermal-flux levels and pumping power.

Design Approach

To obtain surfaces capable of handling high thermal fluxes, requires a solution balancing several antithetical requirements. If one neglects the front surface (input side) resistance by defining the surface thermal flux—as would be the case for impinging particles—leaves two resistances in series. The first is the reciprocal of the thermal conductivity of the structural material. The second is the film resistance at the interface between the material and the coolant. Thermal conductivity is a material's property, but the film resistance varies with the velocity and nature of the coolant fluid. This resistance is lowered by the onset of nucleate boiling.

Reducing the film resistance can be accomplished in several ways. A laminar boundary layer at the material-liquid interface is the source of the major resistance as the thermal conductivity of the coolant—usually water—is low compared to its heat capacity. The thinner the boundary layer, the lower the resistance since in turbulent flow regime the mixing of the heated coolant with the total flow volume ensures a relatively uniform temperature distribution throughout the entire flow channel. Decreasing the boundary layer thickness may be accomplished in several ways. One is to increase the velocity of flow, and another is to introduce "turbulators" which interrupt the boundary layer build-up and start the process anew. Still another is to produce "swirl" flow by inserting a twisted metal strip—sometimes internal fins integral with an extruded tube—in a circular flow passage which introduces a tangential flow component to increase the local velocity. The technique to be proposed, based upon our findings, is to use small, machined flow passages and relatively moderate velocities and to limit the thermal flux normal to the target surface by setting the surface at a reduced angle of incidence to the particle beam in

areas of high intensity. This choice is made to minimize production costs and coolant pumping power and to enhance reliability.

Diagnostics Techniques

Certain companies are using interesting diagnostic techniques.

United Technologies employs thin film sensors to measure temperatures close to the heated surface. These sensors are sputtered onto the surface in thin layers (less than .001 inch). For a beam dump application, the sensor must be located below the surface. Parent material is applied over the sensor to protect it from sputtering. Some illustrations of this technique are shown in the United Technologies section of Appendix A.

Westinghouse can place thermocouples .005 to .010 inch below the cooled surface. They braze the thermocouple into a groove and then grind the surface smooth. They are also investigating the use of ultrasonic detection equipment to detect the onset of nucleate boiling.

The McDonnell-Douglas Arc Heater Laboratory employs an infrared television scanner system to determine temperature profiles. The response of the system is too slow to be used to detect impending burnout, however, it could be used to determine beam profile. Information concerning this equipment is included in the McDonnell-Douglas section of Appendix A.

5. CONCLUSIONS AND RECOMMENDATIONS

Heat Transfer

No significant improvements in the state-of-the-art of handling high thermal flux came to our attention. The capability of achieving flux levels of 10, 15, 20, 25 or 30 kW/cm² does exist but the methods become increasingly esoteric and increasingly expensive. The industrial approach, where feasible, has been to reduce the flux normal to a collector surface by reducing the angle of incidence from 90° (i.e. normal to the surface) to 10° to 15°, or to 17 percent to 25 percent of the normally incident flux respectively. One example quoted by RCA for switch-tube-anode cooling would be the equivalent of reducing the angle to about 3.5°. By working at lower flux levels the operating stresses and cyclical thermal stresses are lowered, the onset of thermal stress cracking is delayed or prevented and greater material thicknesses are permitted. Inasmuch as the objective in the design of the MFTF-B beam dump is to obtain a long-lived, reliable and economical beam dump system this is the approach recommended.

Surface Damage

A second, but less well understood problem, is that of the effect of the impinging nuclei upon the dump front surface. The sputtering of material from the front surface appears to constitute one limit to the lifetime of the dump in terms of the number of equivalent full-power pulses. This cannot be solved by increasing the thickness of the surface because of the increased temperature difference between the bombarded surface and the coolant and

the increased thermal stressing. The implantation of the nuclei near the surface will create a high-pressure gas giving rise to surface blistering with resulting adverse effects upon heat transfer. The resolution of these surface phenomena constitutes the most pressing requirement for an R&D program. Appendix C presents a preliminary estimate of the loss of front surface material from sputtering only, amounting to about 0.2 mm (0.008 in.) thickness of copper in 1000 - 30 second pulses for the area of the beam pattern at and above 9 kW/cm^2 . No data have been found to permit any estimates of loss of material by blistering.

Proposed Dump Configuration

Pending a resolution of the sputtering and blistering problems, the most promising beam dump configuration appears to be one in which a flat plate design capable of safely absorbing a few kW/cm^2 be used as the basic element. Where thermal flux exceeds the selected level the flat plate is tilted by an amount necessary to reduce the flux normal to the surface to the selected design limit. For example, if 2 kW/cm^2 is selected as the criterion for design, a flux of 10 kW/cm^2 can be accommodated by tilting the surface by $90^\circ - 11.5^\circ$ or 78.5° from the normal. In a trumpet-bell-shaped configuration this would be the maximum tilt and the total area projected normal to the beam would be less than 1000 cm^2 of an expected beam footprint area of more than 3000 cm^2 . Iso-energy contours for the assumed beam profile are shown in Section 1, Figure 3. Copper plates with milled flow channels on the back side can readily accommodate the 2 kW/cm^2 with a water-flow pressure drop of less than 100 psi depending upon length of flow passage. If all flow passages were optimized to achieve the same

temperature rise irrespective of incident flux the water flow rate during the pulse would be 1160 gpm for a 20°C rise or twice this amount for a 10°C rise assuming a 6.14 MW beam power input. Because of beam power distribution uncertainty the flow rate should be higher. The preliminary configuration assumed for the cost estimates given in Appendix C, page C-30 is based upon such assumptions.

Beam Dump Manufacturing Schedule

Figure 4 is based upon the estimated cost and related effort for designing, fabricating and installing the beam dumps. The assumptions and estimating bases are given in Appendix D.

R&D Requirements

It is clear by examination of Figure 4 that no time is available for an extended R&D program preceding the prototype testing and development. Thus no R&D schedule can be proposed to precede the manufacturing schedule.

For thermal flux intensities of 2 to 2.5 kW/cm^2 it is not obvious that R&D work is required. Engineering modeling and testing is assumed to be within the scope of work envisioned for prototype testing and development.

For thermal flux levels in the 4 to 10 kW/cm^2 range it is again not obvious that solutions do not exist within present state-of-the-art. Optimization and model testing is needed when requirements have been fully defined.

The need to determine as quickly as possible the importance of the suspected surface effects does demand immediate attention. Experiments may be needed, if data are not already available on sputtering, erosion and blistering with the particles and at the energy used on the MTF-B beam

MFTF-B BEAM DUMP SCHEDULE

WMB&A
9/29/80

FIGURE 4

* MONTHS DURATION

dumps. The effects on the plasma of sputtered particles needs definition of the kinds and amounts acceptable. Such definition may suggest the use of alternate dump surface materials applied as laminates or coatings which should be tested.

Appendix A
Report of Visits to Selected Industrial Firms

TABLE OF CONTENTS

SECTION	COMPANY	PAGE
I	Rockwell International Rocketdyne Division	A-3
II	Aerojet Electro Systems	A-5
III	Defense and Space Systems Group of TRW, Inc.	A-7
IV	Geoscience Ltd.	A-9
V	Hughes Aircraft Company Electron Dynamics Division	A-29
VI	United Technologies Research Center	A-64
VII	Westinghouse Electric Corporation Research and Development Center	A-79
VIII	McDonnell Douglas Astronautics Company	A-116

Organization: Rockwell International
Rocketdyne Division

Address: 6633 Canoga Avenue
Canoga Park, CA 91304

Phone: (213) 709-7250

Contacts: Dr. Stanley V. Gunn, Manager
Special Programs

William R. Wagner, Project Engineer
(213) 884-2655

H. H. Ratekin

Reference: RI/RD 78-273P
Engineering Study on Neutral Beam Dump for the MFTF
Technical Proposal dated November 28, 1980

Apert From general discussions with the above-named contacts and other staff ~~notes~~ on the shuttle engine design, no new information supplementing the ~~reference~~ proposal was obtained. The shuttle engine operating parameter are ~~discussed~~ in the preceding text of this review report.

The ~~reference~~ proposal is in the MFTF files.

Organization: Aerojet Electro Systems

Address: 1100 West Hollyvale Street
P.O. Box 296
Azusa, CA 91702

Phone: (213) 334-6211

Contacts: *J. F. "Bud" Keville, Manager
Mechanical Engineering
Extension 6140

*Dr. Max K. Barsh
Senior Specialist, Technical Staff
Materials Engineering and Special Design
Extension 4231

Truman Lawson
Technical Specialist, Heat Transfer and Thermodynamics

*Forrest R. Cleveland
Technical Specialist

*Richard J. Williams
Supervisor, Thermal and Fluids Group

John Ahern
Senior Technical Specialist
Fluids and Thermacs Group

Thomas Jackson
Technical Marketing
(Formerly Supervisor, Fluids and Thermal Group)

The list of the discussions has been given in the preceding text of this review.

Professional resumes of those present at the meeting, with the exception of Dr. Barsh, and of two of the staff on vacation are available from the MFTF files.

Thomas Jackson, Technical Marketing, is the contact for Requests for Bids or Proposals.

*Present at the meeting.

Organization: Defense and Space Systems
Group of TRW Inc.

Address: One Space Park
Redondo Beach, CA 90278

Contacts: Dr. Robert Bromberg, Vice President
(213) 536-3813

James Gordon

Wesley Steele

Dr. Kenneth W. Arnold
Senior Scientist
Advanced Systems Department
(213) 535-1040

Vlad Van
Scientist
Advanced Systems Department
(213) 536-2366

No supplemental material was obtained from TRW. The discussions have
been summarized in the preceding text.

Organization: Geoscience, Ltd.

Address: 410 South Cedros Avenue
Solano Beach, CA 92075

(714) 755-9396

Contact: Dr. Heinz F. Poppendiek, President

General Remarks:

The work of Geoscience is described in the two brochures which are reproduced on the following pages. An original copy of each is available from the MFTF file.

Geoscience Ltd was founded as a California Corporation in June 1961 for the purpose of performing contract research and development in a number of applied physical and biomedical science areas.

Members of the staff specialize in heat transfer, fluid dynamics, mass transfer, neutron diffusion, atmospheric turbulence, rarefied gas dynamics, electromagnetics, physical chemistry, properties of materials, biology and medical physics.

About Geoscience

Geoscience is made up of three divisions. The first one, Research and Development, is responsible for the primary company activity, namely, contract research and development; both theoretical and experimental efforts are pursued. The second division, Laboratory Testing, performs thermal and acoustic insulation testing and measures thermal properties of gases, liquids and solids over wide temperature ranges. The third division, Geosystems, is responsible for the design, fabrication and sale of prototype heat exchange components. The work done by the three divisions is performed for governmental, institutional and industrial organizations.

Heat Transfer Laboratory

A number of heat transfer facilities including forced convection, forced flow boiling, forced flow condensation, and droplet vaporization systems are available in the company's heat transfer laboratory. Cryogenic fluids, organics, refrigerants, and liquid metals, in addition to water, are the working fluids used in these systems. Computer and analog flux plotting systems are also available for steady state and transient analysis of complex heat transfer systems.

Fluid Flow Laboratory

The fluid flow laboratory contains two principal research facilities. One consists of a water tunnel that is used to study the turbulence structure in large scale models of finned tube heat exchangers. A second facility consists of a heat transfer wind tunnel wherein full scale heat exchanger modules are investigated for their heat transfer and pressure drop performance characteristics.

Research and Development Facilities

Biophysics Laboratory

This laboratory contains special instrumentation for use in hematology and extra-corporeal circulation; equipment for the measurement of thermal and electrical properties of biological fluids and tissues is also available. Another facility in this laboratory is an electromagnetic force field system which is used for experiments with aqueous biological systems. Calorimeter systems are also available so that metabolic heat releases from laboratory animals can be measured including the convective, radiative, and evaporative energy transport terms.

Field Measurement Equipment

Geoscience performs field measurement programs in energy and conservation for the government and industry. Waste heat loss studies for industrial systems; micrometeorological surveys under a range of climatic conditions; geothermal heat flux measurement near the earth's surface as well as in exploration holes and at lake and ocean bottoms; and acoustic surveys for the building industry are conducted. The company has available a wide range of thermal and acoustic sensors and recording equipment for such field studies.

Certified Laboratory Testing

For the past ten years the company has studied the effectiveness of the major building insulation candidates, namely, batt, loose fill, foam, reflective foil, as well as composite wall, roof and floor structures. It utilizes ASTM C-236, C-177, and C-518 test apparatus of various sizes to cover insulation thicknesses ranging from one-quarter of an inch to twelve inches. Geoscience performs R and K value studies for insulation manufacturers and distributors as well as governmental organizations. The company has been certified by both government and state agencies as a qualified testing laboratory.

Physical Properties Laboratory

Thermal conductivity, thermal expansion coefficient, specific heat, electrical conductivity, viscosity, density, surface tension, vapor pressure, sound intensity, emissivity and heats of reaction are measured by Geoscience for governmental and industrial organizations for a wide range of materials and temperatures. The equipment used to make these measurements is mostly absolute in character; however, material standards are also used by the company to continuously check its measurements.

Laboratory Testing Facilities

Heat Exchanger Fabrication

Geoscience fabricates special heat exchangers (gas-to-gas, gas-to-liquid, boilers and condensers) for a number of working fluids including cryogenics, organics, fused salts, liquid metals, air and water. The heat exchangers are designed at Geoscience. Components are fabricated by subcontractors in the San Diego and Los Angeles areas; the heat exchangers are assembled and tested at Geoscience prior to delivery.

System Component Fabrication

Geoscience also designs and fabricates a range of components other than heat exchangers for its clients. Examples are special cold traps for vacuum systems, thermal property apparatus, solar panels for water and house heating and thermal energy storage modules for low and high temperature system applications.

Special metal working facilities and techniques have been developed by Geoscience for the heat exchanger and system component work outlined here.

Geosystems Facilities

High Flux Heat Transfer in Rankine Cycle Power Systems

Geoscience has developed new cooling methods involving helical flow which increase heat fluxes by large factors. Consequently, high exit vapor qualities required in Rankine cycle systems are now achievable in compact vapor generator systems.

Rankine Cycle System Dynamics

Analytical descriptions of the startup and transient state performance characteristics of Rankine cycle systems are prepared for power plant operators. Closed form and finite difference solutions are performed. Computer support is also available at Geoscience.

Reactor Safeguard Analyses

Problems dealing with the safety of nuclear power reactors are analyzed. Atmospheric diffusion of gaseous fission products, transient temperature variations of the reactor fuel elements during prompt critical excursions and after-heat periods, and fission product diffusion through the fuel and cladding are studied.

Atmospheric Diffusion Studies

Atmospheric diffusion processes control air pollution, heat and mass transfer in agriculture, and the distribution of gases and smoke screens in chemical warfare. Geoscience conducts fundamental studies of the controlling atmospheric transport mechanisms.

Programs

Classified Governmental Projects

Geoscience has contributed significantly to classified military and intelligence community programs since the company's inception.

Power Generation and Conversion Demonstration Programs

It has been Geoscience's position that in order to make greater progress in power generation and conversion, more demonstration programs must be initiated by government and industry; some past and current demonstration programs in which Geoscience has participated are: (1) thermal energy storage in latent heat reservoirs; (2) high performance vapor generators and condensers for steam

cars; (3) low power level Rankine cycle systems for geothermal hot springs; (4) heat generation and conversion by the incineration of municipal wastes; and (5) high temperature economizers in the process industry.

Ocean Thermal Energy Systems

Fundamental ammonia boiling and condensing heat transfer as well as water side convective cooling and pressure drop data have been determined by Geoscience for the government's OTEC project. The results have made it possible to optimize system performance and reduce sizes and capital costs.

Geothermal Energy Exploration and Applications

Two geothermal heat flux transducers have been developed for the government that can be used to make measurements in observation or test holes without the need of core sample thermal conductivity measurements. Geoscience has also conducted geothermal system cycle analyses and heat exchange component designs for the purpose of getting practical power systems on line.

Electromagnetic Blood Pump Research

Studies have been conducted to verify the possibility of circulating blood electromagnetically. This method yields low hemolysis values because

mechanical pumping turbulence is absent.

Thermal and Electrical Conductivity Studies of Biological Materials

With specially designed thermal and electrical conductivity equipment, Geoscience measured the conductivities of biological fluids and tissues. These results are used to establish damage criteria for biological materials exposed to freezing and thawing in connection with whole organ and blood storage.

Physical Force Field Studies Under Space Environmental Conditions

Studies have been made of the influence of various physical force

Programs

field parameters on the growth of selected biological species in enclosed environments simulating conditions in spacecraft. Such parameters as electromagnetic and magnetic fields and temperature distribution through biological media have been investigated with respect to growth rate.

Metabolic Heat Release Studies

Medical researchers at times require knowledge on metabolic heat releases for patient treatment and drug administration. The company has made such heat release measurements from animals and humans utilizing new calorimetric sensing systems that are also capable

of breaking down the metabolic term into the convective, radiative and evaporative fractions.

Space Vehicle Systems

Zero gravity fluid flow measurement systems and heat exchangers have been developed for space vehicles.

Text Books

Geoscience staff members have written a number of text books and handbooks for governmental agencies. These documents contain fundamental analytical and experimental heat transfer and fluid flow information with special application to new technologies of current national interest.

Geoscience has been following the rapid technological and economic changes that are taking place in the world and, consequently, has become involved in new programs that it is hoped will be responsive to the new national needs. Examples of areas in which Geoscience has started to work are:

New Programs for National Needs

Heat recovery from municipal wastes
 Fuel generation from biomass
 Fuel generation from solar energy
 Radioactive and organic waste
 monitoring
 Heat transfer in fusion system
 components
 Firefighting research and
 development.

The technical and financial success of Geoscience can be traced to three important policies that have been in force since the inception of the company. First of all, Geoscience believes that its mainstay is a strong, technically-oriented staff which has the technical disciplines required to carry out research and development, thermal testing, and systems activities. The company's technical strength is reflected in its publications in the open literature.

Secondly, Geoscience has been involved in applied programs in which economics is an important factor. National needs require that advances in energy, conservation, and biomedicine include the cost of the technology.

The third policy is that the company is responsive to the needs of its clients. Progress reports and conferences as the work is performed ensure the most profitable results for the customer. Industrial work is performed on a confidential basis so that proprietary information is protected.

In the coming years, the United States will require organizations with proven records of performance to make the needed contributions in energy, conservation, and biomedicine. Geoscience Ltd is such an organization.

Officers and Directors

Heinz F. Poppendiek
President, Director
Cullen M. Sabin
Vice President, Director
A. Stanley Thompson
Director
Louis Possner
Director

Atomic Energy Commission
ERDA
Department of Energy
Office of Naval Research
Port Hueneme Naval Civil Engineering
Laboratory
China Lake Naval Weapons Center
NOSC
Andrews Air Force Base
Brooks Air Force Base
Patrick Air Force Base
Fort Rucker
Fort Belvoir
Intelligence Community
Johnson Spacecraft Center (NASA)
Lewis Research Center (NASA)
Ames Research Center (NASA)

Jet Propulsion Laboratory
Aerospace Corporation
Oak Ridge National Laboratory
Stanford Research Institute
University of California, Davis
University of California, Los Angeles
University of Notre Dame
University of Hawaii
California Heart Association
American Cancer Society
National Institutes of Health

Clients

The list of clients who have had confidence in Geoscience is a long one; because of space limitations, partial governmental, institutional and industrial lists are given here

Aerojet Electro Systems Company
Aeronutronic-Ford Corp
AiResearch Mfg Co
Alfol, Inc
Amax Exploration Co
American Brick and Tile Co
Ameron
Babcock & Wilcox
Borg-Warner, York Division
Celotex Corp
Eaton Corp
Fairchild Hiller Stratos-Western
Ford Motor Co
Foilpleat Insulation Inc
Fugro Consulting Engineers & Geologists
General Atomic
General Dynamics
General Electric Co
General Electric Space Systems
General Pumice Corp
Glasteel Inc
W. R. Grace & Co
Ernest W. Hahn Inc
Hughes Aircraft Co
Infra Insulation Mfg Co
International United Chemical Co
Kaiser Aerospace & Electronics Corp
Kelco Co
Lockheed Missiles & Space Co, Inc.
Marquardt Corp
McDonnell Douglas Corp
Northrop Corp, NORAIR Div
Pacific Clay Products Inc
The Ralph M. Parsons Co
Petrolite Corp
Permanent Pipe Products
Polymer Industries

Premiere Aluminum Products, Inc
Reichhold Chemicals Inc
Rockwell International, Rocketdyne Div
Roy & Sons Inc
Sierracin Corp
Solar Division International
Harvester Co
Solarguard Reflective Products Inc
Southern California Gas Co
Steam Power Systems
Superior Aluminum Insulation Inc
Teledyne-Kinetics
Truesdail Laboratory Inc
U. S. Borax Research Corp
U. S. Testing Co, Inc
Union Carbide Corp
United Foam Corp
Varian Associates, EIMAC Div
Weyerhaeuser Co

LABORATORY TESTING DIVISION

CIRCLE 101
4415 Canyon Avenue
Buena Park, California 92621
(714) 765-5100

- Physical Property Measurement
- Thermal Insulation Testing
- Acoustic Insulation Testing
- Controlled Environment Testing
- Solar Equipment Testing
- Heat Exchanger Testing
- Accident Investigations

The Laboratory Testing Division of Circle 101 performs the following property measurements: thermal and acoustic insulation testing, controlled environment testing, solar equipment testing, heat exchanger testing and accident investigations. The company has performed such work as was part of the customer's test facility. The Laboratory Testing Division assists its clients in establishing a liaison between a design and a test facility and testing that involves description and of the application of the test facility and the test facility and the test facility. The company also is involved in cooperative efforts with other testing laboratories and equipment suppliers.

• Physical Property Measurements

The company performs physical property tests for a variety of materials and a range of temperatures and conditions. Some of the properties, methods, materials and standards used are as follows:

Property	Method and Standard	Property	Method and Standard
Thermal Conductivity	guarded hot plate ASTM E-177 heatmeter ASTM E-177	Specific Heat	guarded hot plate calorimeter
Coefficient of Thermal Expansion	guarded hot plate ASTM E-177	Emissivity	heat meters heat balance
Heat of Fusion	guarded hot plate calorimeter	Transmissivity	heat meter
Freezing (Phase Change) Heat	guarded hot plate	Thermal Stability	heatmeter calorimeter
Surface and Interfacial Tension	surface durometer	Heat of Adsorption	guarded hot plate calorimeter
Density	weighing method ASTM D-153 density column	Viscosity	viscosity method ASTM D-445 rotary
Electrical Conductivity	Wheatstone bridge	Moisture Content in Absorption	gravimetric method ASTM D-153

● Thermal Insulation Testing

Thermal insulation test ranges from systems to high temperature applications. Dynamic temperature insulation requirements usually stipulate in maritime and aerospace environments. Normal temperature insulation applications are found in the heating and ventilating fields, and high temperature insulation requirements usually arise in furnace, incinerators, gas turbine exhausters, or nuclear reactor components.

General Electric covers ASTM full standard test cell test systems, models K1, K2, K3, K4, K5, K6, and K7, and B1, B2, and B3. The company also has a number of ASTM full standard test plate test systems, models K1, K2, K3, K4, K5, K6, and K7, and B1, B2, and B3. These systems are also instrumented with calibrated test flux sensors. It is noted that independent groups of the steady state thermal fluxes can be obtained. Several ASTM multi temperature systems are also available.

● Radiation Coefficient Testing

The primary feature of this is a profile tests of radiant heat exposures to determine their emission and absorption characteristics. The tests are performed by measuring the heat of an object between two rooms. A diffuse white fluid is used in the room and the solid panel is exposed to the radiant energy with and without the presence of the test panel. The results are used to make measurements in heat transfer calculations and analysis.

● Combined Thermal Insulation Testing

The combined testing facilities include a range of high pressure and high temperature chambers with test samples in small, medium, and large size test temperature levels. The test gases are also controlled in these

facilities. The test gases are controlled in these facilities. The test gases are controlled in these facilities.

● High Pressure Testing

The high pressure testing facilities include a range of high pressure and high temperature chambers with test samples in small, medium, and large size test temperature levels.

● High Temperature Testing

The high temperature testing facilities include a range of high temperature and high pressure chambers with test samples in small, medium, and large size test temperature levels. The test gases are controlled in these facilities. The test gases are controlled in these facilities.

● High Pressure Testing

The high pressure testing facilities include a range of high pressure and high temperature chambers with test samples in small, medium, and large size test temperature levels. The test gases are controlled in these facilities. The test gases are controlled in these facilities.

Organization: Hughes Aircraft Company
Electron Dynamics Division

Address: 3100 West Lomita Boulevard
Torrance, CA 90509

Phone: (213) 534-2121

Contacts: Al Basiulis, Assistant Manager
Thermal Products

R. M. Rall
Cryo Programs Liaison Manager

General Remarks:

In addition to the information obtained from the visit and summarized in the text of this review, four technical papers on heat pipes were obtained.

These are the following and are reproduced in the following pages.

Basiulis, A. and P. C. Prager, "Compatibility and Reliability of Heat-Pipe Materials."

Ewell, G. J., A. Basiulis and T. R. Lamp, "Reliability of Low Cost Liquid Metal Heat Pipes."

Basiulis, A. and D. J. Formiller, "Emerging Heat Pipe Applications."

Basiulis, A., G. L. Fleischman and C. P. Minning, "Design, Development and Test of a 1000-watt Osmotic Heat Pipe."

COMPATIBILITY AND RELIABILITY OF HEAT-PIPE MATERIALS

A. Basiulis* and R. C. Prager†

Hughes Aircraft Company, Torrance, Calif.

Abstract

**Radiative Transfer
and Thermal Control**

Progress in
Astronautics and Aeronautics

Volume 49

Smith, editor

1976

American Institute of
Aeronautics and Astronautics
New York, New York

COMPATIBILITY AND RELIABILITY OF HEAT-PIPE MATERIALS

A. Basiulis* and R. C. Prager†

Hughes Aircraft Company, Torrance, Calif.

Abstract

To predict the long-life capabilities of heat pipes, a life-test program was begun eight years ago to evaluate potential heat-pipe fluids. Fluids tested range from those suitable in cryogenic applications to those of use in high-temperature heat pipes. Stainless steel proved to be acceptable for long-term use with all common low-temperature fluids except water, which requires copper or monel. Failures usually were caused by material incompatibility or improper cleaning and processing, although breakdown of some high molecular weight organic fluids under heat-pipe operating conditions was encountered.

I. Introduction

Heat pipes slowly are gaining acceptance in industry, and we are beginning to find them used in a variety of applications from electronic-component cooling to waste-heat recovery. In most cases, the choice of heat-pipe materials is dictated by the application; the choice of heat-pipe envelope is controlled by the environment in which the heat pipe will have to operate, the choice of working fluid usually is controlled by the operating temperature, and the wicking structure must be compatible with both the heat-pipe envelope and working fluid.

A good heat-pipe working fluid will have desirable transport properties in the temperature range in which it will be

Presented as Paper 75-660 at the AIAA 10th Thermophysics Conference, Denver, Colo., May 27-29, 1975.

*Assistant Manager, Thermal Products, Electron Dynamics Division.

†Member of the Technical Staff, Electron Dynamics Division.

employed: high liquid and vapor densities, a high latent heat of vaporization, a high surface tension, and low-liquid and vapor viscosities. The ideal fluid is "well-behaved", it wets wicks and walls nicely, it is compatible with common engineering materials, it is not contaminated easily in storage, and is readily available (and inexpensive!). In addition, special requirements as defined by the application may have to be met; for example, the fluid might be required to be dielectric or completely nontoxic.

Obviously, any fluid available is a compromise. In order to investigate their relative merits and to predict their long-life compatibility with heat-pipe materials, eight years ago Hughes initiated a life-test program to evaluate potential heat-pipe fluids. The program initially included fluids and materials that had potential in electron tube cooling applications, but as the range of applications expanded, so did the choice of fluids and materials. The life-test program now includes fluids from cryogenic to liquid metals. In addition to the in-house life-test program, materials literature and especially heat-pipe literature is searched periodically for compatibility information. This information is tabulated and updated and compared to the in-house data. As new information becomes available, and confidence is gained, the compatibility tables are revised.

II. Test Vehicles

Heat pipes, in addition to having good heat transfer characteristics and reliability, must be inexpensive in order to be competitive with conventional heat transfer devices. For this reason, when possible, commercially available working fluids and wicking structures were utilized. The envelopes were selected primarily by the working environment and cost. The wicking structure, when possible, is fabricated from the same material as the envelope. The integral wicks either can be extruded, forged, or machined and are part of the basic envelope material. The fabricated wicks either are formed wicks, screen, felt metal, fiber metal, foam metal, or cloth. These wicks either have pressure contact with the envelope or are bonded to the envelope by diffusion or brazing. Working fluids were selected primarily for operating temperature and predicted compatibility with the heat-pipe envelope. The size of the test vehicles varied with potential applications, thus the life-test vehicle diameter varies from 0.48 cm (0.19 in.) to 5.1 cm (2 in.), and the length varies from 10 cm (4 in.) to 18.9 m (40 ft.).

Heat pipes containing homogenous wicks are tested either horizontally or against gravity in order to detect wick decom-

position. Large heat pipes and heat pipes with cut grooves or channels are tested horizontally or in a gravity aiding mode of operation. Power is supplied by using electrical resistance heaters, and ambient air is employed as the heat sink. Temperatures are monitored using types T, J, or K thermocouples. Periodically, heat pipes are removed from the test rack and tested at lower temperatures to determine whether any noncondensable gas is present.

None of the heat pipes being tested are valved; all have conventional charge tubes and are sealed. This life-test setup was devised to test heat pipes, not to engage in basic materials research, and the long-term performance of the sealing technique also was being investigated. A list of heat pipes currently on life test is presented as Table 1.

III. Life Test Results

Although several test vehicles have been built using a number of exotic organic substances as working fluids, most work performed at Hughes or reported by other researchers has been restricted to ammonia, methanol, acetone, water, Dowtherm A^R (a eutectic mixture of diphenyl and naphenyl oxide), potassium, and sodium.

Initial work at Hughes was conducted to find working fluids suitable for cooling electronic equipment between 60 and 260°C. Although water or methanol are suitable at the lower end of this range, most applications were encountered at the high end, and an additional requirement was imposed: the fluid had to be dielectric.

After a series of tests on commercial heat-transfer fluids, Dowtherm A^R was decided upon, and still is being used successfully in this application. This fluid has a melting point of 12°C and a boiling point of 258°C. It was developed by the Dow Chemical Company for high-temperature heat-transfer applications in pumped systems and in evaporative systems. Results from our life-test program have been mixed; the temperature drop along pipes charged with this fluid increases slowly with time, although no cold zone indicative of copious gas generation appears to be present.

Copper/Refrasil^R/Dowtherm A^R heat pipes running since February 1969 at about 140°C have shown an increase in temperature drop to date from an initial 14 to 37°C, indicating that something is taking place; but whatever it is, the process (with this combination of materials) is a slow one. To investigate the possibilities of this fluid at higher

Table 1 Heat pipes on life test as of April 15, 1975

Body	Wick	Materials	Fluid	Dimensions, CM		Approx Operating Temp. °C	Hr of Operation	Date life test began
				Length	Diam			
SS/Cu	Sintered Cu		Dow ER	10	5.75	145	68,932	June '67
Cu	SS mesh		Dow ER	15	2.5	100	67,188	June '67
Cu	Sintered Cu		Dow 209	15	2.5	90	66,142	Sept. '67
Cu	Refrasil ^R		CP-9	15	2.5	135	59,188	June '68
Cu	Refrasil ^R		Dow A	15	2.5	130	52,372	Feb. '69
SS	Refrasil ^R		Dow A	30	2.5	90	46,080	July '69
Cu	Refrasil ^R		C ₆ F ₆	15	2.5	85	50,708	June '69
Cu	Refrasil ^R		Methanol	15	2.5	75	47,664	Nov. '69
Cu	Carbon Felt		Methanol	15	2.5	85	47,664	Nov. '69
Cu	Refrasil ^R		DC-200 ^R	15	2.5	80	43,748	March '70
Cu	Refrasil ^R		C ₂ Cl ₄	15	2.5	80	42,398	May '70
Cu	Refrasil ^R		Methanol	15	2.5	70	49,886	July '69
Cu	Refrasil ^R		Acetone	15	2.5	70	49,886	July '69
SS	SS mesh		Ammonia	15	2.5	40	44,628	Feb. '70
Al	Ni Felt		Ammonia	15	2.5	50	43,848	Apr. '70
Al	Al Felt		Ammonia	15	2.5	50	43,848	Apr. '70
Cu	Refrasil ^R		Di Methyl Sulfide	15	2.5	80	41,367	June '70
Cu	Cu Felt		CP-32 ^R	15	2.5	80	36,538	Jan. '71
SS	SS Felt		Methanol	12.5	0.64	110	21,792	Nov. '72
Cu	Sintered Cu/ Refrasil ^R		Dow A ^R	9	2.5	130	21,164	Nov. '72
Cu	Monel mesh		Water	20	1.6x0.3	70	22,655	Sept. '72
SS	SS mesh		Water	60	1.25	90	22,776	Sept. '72
Cu	Sintered Cu/ Refrasil ^R		DC-200 ^R	9	2.5	90	17,664	Apr. '73

518

A. BASTIUS AND R. C. PRAGER

Body	Wick	Materials	Fluid	Dimensions, CM		Approx Operating Temp °C	Hr of Operation	Date life test began
				Length	Diam			
Cu	Cu Felt		Water	15	2.5	75	17,520	March '73
Cold	Refrasil ^R		Dow A ^R	15	2.5	80	17,496	Apr. '73
Rolled Steel								
SS	Cu mesh		Dow A ^R	60	1.25	200	17,016	May '73
SS	SS mesh		Dow A ^R	60	1.25	200	17,016	May '73
Monel	Monel mesh		Water	45	1.65	105	13,320	Oct. '73
Cu	Cu mesh		Water	30	0.95	115	13,032	Oct. '73
347 SS	Cu mesh		Water	75	2.5	165	9,376	Dec. '73
Cu	Cu foam		Water	25	1.25	60	8,736	Apr. '74
Cu	Sintered Cu		Water	30	1.25	60	8,736	Apr. '74
Monel	Monel mesh		Water	30	2.5	100	6,576	July '74
Cold	(None)		Ammonia	1220	5	45	5,503 ^a	Jan. '74
Rolled Steel								
Cold	(None)		Ammonia	1220	5	45	5,503 ^a	Jan. '74
Rolled Steel								
Cold	(None)		Ammonia	1220	5	45	5,503 ^a	Jan. '74
Rolled Steel								
Cu	Cu Felt		Water	30	1.25	60	5,688	Aug. '74
Al	(Wall grooves)		Ammonia	45	1.65	50	5,688	Aug. '74
SS	SS screen		Ammonia	10	0.48	60	5,688	Aug. '74
SS	SS felt		Ammonia	15	0.48	50	5,688	Aug. '74
SS	SS felt		Potassium	15	1.25	650	5,528 ^a	Aug. '74
SS	SS felt		Sodium	15	1.25	650	2,380 ^a	Aug. '74

temperatures, a series of stainless steel heat pipes with stainless steel wicks were built. These pipes were charged with Dowtherm A^R, and run for several weeks at 180°C. The temperature drop increased from 5 to as much as 40°C in two weeks. If this increase in temperature drop were due to the presence of noncondensable gas, "burping" the heat pipes from the condenser to vent gas while the internal pressure is above atmospheric pressure should restore the heat pipe to its original state, and, according to the results obtained by Petrick,¹ it even might show a decrease in the rate of degradation.

This procedure was tried repeatedly on one heat pipe, and within 1 hr each time, the original pattern had re-established itself; a slight temperature difference had grown to a large temperature difference (although a smaller temperature difference than that prevailing after several weeks).

One such pipe was cut open, and the evaporator contained some form of black discoloration, indicating that the working fluid may have broken-down. Scanning Electron Microscope (SEM) photographs were taken of evaporator and condenser wick samples, but no traces of buildup or corrosion of the wick could be seen. After cracking the components of Dowtherm A^R, benzene, short aliphatic compounds, and water could be present in the pipe. Some of these products are condensible, and so, even after the venting process just described, we still had a two- (or multi-) component heat pipe in which, according to the results of Tien and Rohani,² and Brommer,³ all components would be distributed in varying concentrations throughout the pipe. Some of this increase in temperature drop might be explained by the fact that Dowtherm A^R consists of two separate fluids, but the liquid-vapor equilibrium curve for mixtures of the two compounds are so close together⁴ that very little separation actually will take place.

Kreeb et al.⁵ list a "Diphyl"/mild steel heat pipe (by which they may mean diphenyl) run for 6200 hr at 130°C. The temperature drop in this pipe rose over this time period from 68 to 90°C. When this pipe was opened, "slight attack" was noticed on interior surfaces. In summary, Dowtherm A^R can be used in a copper heat pipe where a significant (and growing) temperature drop is tolerable. At high temperatures (i.e., 200°C and up) it tends to decompose slowly, a problem it shares with most high-boiling-point organic fluids.

Other high-boiling-point fluids tried in this early study⁶ were Dowtherm E^R (o-dichlorobenzene) from the Dow Chemical Company, DC-200^R (a dimethyl polysiloxane) from Dow Corning Corporation, CP-9^R (unknown) and CP-32^R (pyridine)

from Monsanto, Dow 209^R (a methoxy-propanol/water azeotrope) from the Dow Chemical Company, perchloroethylene, hexafluorobenzene, and dimethyl sulfide. The greatest effort was placed on DC-200 because, like Dowtherm A^R, this fluid has good dielectric properties. The formulation with a kinematic viscosity of 0.65 cs is a pure fluid, and has been used successfully as a heat-pipe working fluid, but its latent heat and boiling point are lower than that of Dowtherm A^R, making the latter a superior high-temperature fluid for the application under consideration at the time. A DC-200 heat pipe was cut open after 23,000 hr of operation, and photographs of samples of the stainless steel mesh wick for the evaporator and condenser are shown in Figs. 1 and 2. A non-uniform deposit up to 3×10^{-4} in.-thick can be seen in the evaporator, and a uniform deteriorated layer in the condenser 6×10^{-5} in.-thick is visible. No evidence of corrosion was found on the copper wall of the heat pipe. A pure fluid DC-200 therefore can be used in a copper heat pipe.

A copper/perchloroethylene heat pipe performed essentially isothermally for several months, but at this point the heat pipe failed. When the pipe was opened and examined, the wick was found to be clogged with CuCl_2 deposits. This combination therefore is not recommended.

Water is attractive as a heat pipe fluid because of its familiarity to potential users and its high latent heat and surface tension. Unfortunately, water is also highly corrosive to most materials which one would like to use in heat pipe construction.

The incompatibility of aluminum and water long has been well known, but many researchers have built water heat pipes utilizing stainless steel and have reported their results^{1,7-9}. The usual alloys employed have been 304, 316, and 321, all of which generate large amounts of hydrogen gas. Stainless steel alloy 347 differs from the very similar 321 only in the addition of Tantalum (a known hydrogen getter) and the removal of Titanium. A 347 stainless steel heat pipe with a copper screen wick on the wall has been running continuously since December 1973 with no traces of gas generation. A bare 347 tube run as a reflux boiler showed some gas generation, whereas 347 pipes with 347 felt-metal wicks generated gas plugs very rapidly, even after repeated venting. Thus, 347 stainless steel can be used as a heat-pipe envelope material in a water heat pipe, particularly with a copper wall-mounted wick to protect it, but the use of this material in a wick structure definitely is not recommended.

Fig. 1 Evaporator wick, DC-200 heat pipe (400X).

Fig. 2 Condenser wick, DC-200 heat pipe (400X).

A C1015 carbon steel reflux boiler was built by the authors, but after 5 months of operating it had developed a 40°C temperature drop along the condenser. This material also is not recommended.

Nickel-water heat pipes were used by Anderson in his investigation of scaling laws for accelerated-life testing,¹⁰

and under certain operating conditions, extensive amounts of gas were generated. The traditional heat-pipe envelope and wick material for use with water has been copper, with many references in the literature. The authors have used OFHC copper as the envelope material almost exclusively, with no sign of gas generation, although one heat pipe was built using refrigeration tubing as the wall and commercial copper screen as the wick, again with no problem. A Monel 400 water heat pipe with a Monel screen wick has been running at Hughes since October 1973 without gas generation.

There are many advantages to having an extremely flexible wick material; Refrasil^R, a cloth composed of glass fibers, seemed ideal. Copper-walled heat pipes with Refrasil^R wicks were made up, and although no gas seemed to be generated, the wicks failed repeatedly. When the heat pipes were sectioned and the wicks examined, quartz crystals were found to be growing in the wick, completely blocking it.

Methanol is a useful working fluid in the temperature range from -40 to +120°C, as the melting point is -97.8°C, the boiling point is 64.7°C, and the critical temperature is 239.4°C. A stainless steel heat pipe with methanol as the working fluid has been run at Hughes for 20,000 hr at 115°C with a slight increase in temperature drop down the heat pipe from 3 to 5°C. It is not certain whether this change is significant, as the life-test station has been moved about the lab several times in the interim, and ambient air conditions are different. (Prior to going on life tests, this pipe was tested thoroughly, including 8 hr of operation above 200°C.) Kreeb, Groll, and Zimmermann built a series of such heat pipes⁵ and noticed no change in temperature drop after several thousand hours. However, upon sectioning and examining the wall, "slight corrosion" was detected, and when the gas was analyzed, traces of H₂, H₂O and CO were found, presumably products of slow decomposition of methanol, with the stainless steel wall acting as a catalyst.

A copper/methanol/Refrasil^R wick heat pipe was put on life test in July 1969. To date (Spring 1975), the temperature drop has increased from 2 to 8°C, but other than that the heat pipe is functioning normally. Kreeb et al. reported no corrosion worth mentioning in copper/methanol heat pipes with copper-bronze screen wicks, and this combination of materials was recommended.

Aluminum is attacked by methanol, and this combination has been rejected as potential heat-pipe materials when used together. A series of acetone/aluminum and acetone/stainless

Fig. 3 Stainless steel felt-met. wick "as received" (400X).

steel heat pipes with stainless steel wicks were built in 1970 and the fluid analyzed after varying periods of operation. The only significant contaminant was Mesityl Oxide, at an average concentration of 0.16%.

For wick comparison purposes, a photograph of the stainless steel wick material in the "as received" condition, and a photograph of the wick as it was removed from the heat pipe after 1032 hr of operation are shown as Figs. 3 and 4. These heat pipes were run as hot as 110°C. (The boiling point of acetone is 56°C; its critical temperature is 235°C.) In all cases, the temperature drop down the heat pipe increased. Some of them stopped working completely, even with the evaporator directly below the condenser.

These results still are unexplained and the program was dropped, since methanol can do the same job reliably in a stainless steel heat pipe. Kreeb et al. report only a "slight attack at the metal surface" in an all-stainless steel (types 304, 316) heat pipe, and recommends this combination. It is possible that the problem was in our filling technique, and contaminants were introduced. If these hypothetical contaminants were consumed completely, forming gaseous reaction products, no trace of them would have been found in the analysis, since only the liquid was analyzed.

Fig. 4 Sample of stainless steel felt-metal wick after 1032 hr in condenser of acetone heat pipe, aluminum envelope (400X).

A copper/acetone heat pipe with a Refrasil^R wick has been running since July 1969 with a slight increase in temperature drop along the pipe from 3 to 6°C. This pipe is running at about 75°C. In analysis performed on an all-copper heat pipe, Kreeb reports no visible corrosion and no gas generation after up to 15,000 hr, although the acetone was reported to have changed color, possibly due to dissolved metal ions. This combination, copper with acetone, apparently is reliable in a heat pipe.

Ammonia long has been utilized successfully in heat pipes for low-temperature applications. During life tests at Hughes, no gas generation or performance degradation indicating internal corrosion has been observed in ammonia heat pipes using 304 stainless steel with 304 stainless steel screen or felt metal wicks, 6063 aluminum with axial grooves or nickel or aluminum felt metal, or carbon steel (C1015) run as a reflux boiler.

The wickless carbon steel/ammonia heat pipes were run for 2400 hr at 60°C and sacrificed. A deposit was found on the wall; but, upon analysis, the species identified in the deposit were residuals from cleaning solutions left due to incomplete rinsing. Metallographic analysis of the carbon-steel wall showed no trace of attack: the surface was identical to that of similar pipe in the "as cleaned" condition.

Gas and liquid samples were taken from several test vehicles and analyzed using a mass spectrograph. The analysis showed only two constituents above the limits of detection of the spectrograph: hydrogen (H_2), ranging from the limits of detection (less than 0.1 ppm) to 0.5 ppm, and nitrogen, ranging from the limits of detection (less than 0.1 ppm) to 5.0 ppm. No gas slug was observed in any of these pipes when operated at $-15^\circ C$.

Some researchers have reported difficulties in aluminum-walled ammonia heat pipes with stainless steel wicks, so this combination should be used with caution. Kreeb⁹ reported results from a stainless steel heat pipe with an aluminum wick, and after 12,000 hr of operation at $50^\circ C$, the temperature drop down the pipe had increased from 2 to $2.5^\circ C$, not really a substantial change. Ammonia, of course, is not compatible with copper.

For higher operating temperatures, liquid metals are used as working fluids. Sodium and potassium heat pipes have been made and operated successfully for several thousand hours using 304 stainless envelopes and screen wick. No gas generation or change in the temperature drop along the heat pipe has been observed. Much more extensive data on this combination are available in the literature. For example, in the Materials Compatibility chapter of Skrabek and Bienert¹¹, results of 11,500 hr of operation of a sodium/304 stainless steel heat pipe by Bienert are cited. No signs of failure were observed. In the same work, results originally published by Kemme show no failure in a potassium/347 stainless steel heat pipe after 6500 hr of operation at $510^\circ C$.

For heat pipes running at still higher temperatures, a fluid such as lithium must be used. At $1600 - 1800^\circ C$, Quataert, Busse, and Geiger¹² reported on extended-life tests of lithium heat pipes of Tungsten and 26% Rhenium. They found that extended life (i.e., many years of successful operating prior to failure) could be attained at $1600^\circ C$, whereas at $1700^\circ C$, "significant corrosion" was observed after one year, and at $1800^\circ C$, the pipes failed after about one month of operation. Eastman¹³ reported on several lithium heat pipes of TZM, all of which failed shortly after 10,000 hr at $1500^\circ C$.

Several¹⁴ report a mercury/stainless steel (347 tube, 304 screen wick) heat pipe run for 10,000 hr and then opened up. At this time, the heat pipe still was running isothermally. Some corrosion and mass transfer had occurred, with

Table 2 Summary of results

	Recommended	Not recommended
Ammonia	Aluminum Carbon steel Nickel Stainless steel	Copper
Acetone	Copper Silica Aluminum ^a Stainless steel ^a	
Methanol	Copper Stainless steel Silica	Aluminum
Water	Copper Monel 347 stainless steel ^b	Stainless steel Aluminum Silica Inconel Nickel Carbon steel
Dowtherm A ^R	Copper Silica Stainless steel ^c	
Potassium	Stainless steel Inconel	Titanium
Sodium	Stainless steel Inconel	Titanium

a. The use of acetone with aluminum/and or stainless presented problems to the authors, but others have had good results with these materials. The problem may be temperature-related; use with caution.

b. Recommended with reservations. Investigation of the suitability of the water-347SS combination is continuing.

c. This combination should be used only where some non-condensable gas in the heat pipe is tolerable, particularly at higher temperatures.

deposits on the wick and the walls, and stress corrosion at intersections of wires in the mesh wick, although operation of the heat pipe had not been affected. Other pure materials also are being tested by many workers for use in these higher-temperature ranges, usually for special applications such as reactor cooling.

III. Conclusion

Table 2 summarizes the results reported in this paper, which were obtained either from test results at Hughes or from literature cited in the body of the paper. Although good results have been reported with these materials, caution must be observed in using metallic wicking material inside an envelope of a different material. Proper cleaning also is important, as is thorough rinsing of cleaning agents from the heat pipe, particularly from wick structures. With proper choice of materials, it is possible to build heat pipes that have an indefinitely long operational life-time.

References

- ¹Petrick, S. W., "Hydrogen Generation in Water/Stainless-Steel Heat Pipes," ASME Paper 72-WA/HT-37, Nov. 1972, New York, N.Y.
- ²Tien, D. L. and Rohani, A. R., "Theory of Two-Component Heat Pipes," ASME Paper 71-WA/HT-30, Nov.-Dec. 1971, Washington, D.C.
- ³Brommer, H. J., "Theoretical and Experimental Investigation of Two-Component Heat Pipes," AIAA Paper 74-720; also, AIAA Progress in Astronautics and Aeronautics: Heat Transfer with Thermal Control Applications, Vol. 39, edited by M. M. Yovanovich, New York, 1975, pp. 145-165.
- ⁴"Dowtherm Heat Transfer Fluids," Dow Chemical Co., Midland, Mich., 1971.
- ⁵Kreeb, H., Groll, N., and Zimmermann, P., "Lifetest Investigations With Low Temperature Heat Pipes," International Heat Pipe Conference, Oct. 1973, Stuttgart, Federal Republic of Germany.
- ⁶Bastulis, A. and Filler, M., "Operating Characteristics and Long Life Capabilities of Organic Fluid Heat Pipes," AIAA

Paper 71-408; also, AIAA Progress in Astronautics and Aeronautics and Aeronautics: Fundamentals of Spacecraft Thermal Design, Vol. 29, edited by J. W. Lucas, The MIT Press, Cambridge, Mass., 1972, pp. 431-444.

⁷Schwartz, J., "Performance Map of the Water Heat Pipe and the Phenomenon of Noncondensible Gas Generation," ASME Paper 69-HT-15, 1969, Minneapolis, Minn.

⁸Kreab, E., "Zur Wahl von Werkstoff und Wärmeträger bei Niedertemperatur-Wärmeröhren," dissertation, Institut für Kernenergetik, University of Stuttgart, Federal Republic of Germany, 1972.

⁹Busse, C. A., Loens, J., and Campanile, A., "Hydrogen Generation in Water Heat Pipes at 250°C," International Heat Pipe Conference, 1973, Stuttgart, Federal Republic of Germany.

¹⁰Anderson, W. T., "Hydrogen Evolution in Nickel-Water Heat Pipes," AIAA Paper 73-726, July 1973, Palm Springs, Calif.

¹¹Skrabek, E. A. and Bienert, W. B., Heat Pipe Design Handbook, Vol. I, Final Rep. for NASA Contract NAS9-11927, Dynatherm Corporation, Cockeysville, N. Dak., Aug. 1972.

¹²Quataert, D., Busse, C. A., and Geiger, F., "Long-Time Behavior of High Temperature Tungsten-Rhenium Heat Pipes with Lithium or Silver as Working Fluid," International Heat Pipe Conference, Oct. 1973, Stuttgart, Federal Republic of Germany.

¹³Eastman, G. Y., "The Heat Pipe - A Progress Report," 4th Intersociety Energy Conversion Engineering Conference, Sept. 1969, Washington, D.C.

¹⁴Deverall, J. E., "Mercury as a Heat Pipe Fluid," Rep. LA-4300-MS, Jan. 1970, Los Alamos Scientific Laboratory, Los Alamos, N. Mex.

RELIABILITY OF LOW-COST LIQUID METAL HEAT PIPES

G. J. Ewell, A. Basulua, and T. R. Lamp
Hughes Aircraft Company
Torrance, California

Abstract

Low-cost stainless steel heat pipes containing sodium or potassium working fluids have been proven to have long-term reliability. Heat pipes fabricated from 304 stainless steel with wicks of the same material have exhibited over 10,000 hours of reliable operation at 600°C (potassium) and 700°C (sodium) in ambient environments. Temperature stability was maintained to within 5°C over the test period. Extensive metallurgical analyses of inner and outer surfaces of the heat pipes and of the wicks have shown only minor amounts of material transport and of leaching from inner surfaces. External oxidation was negligible and there were no indications of electrolytic corrosion. The depth of inner surface attack was only 0.001 to 0.003 cm in thickness after 10,000 hours of operation. From this information lifetimes in excess of 50,000 hours can be reliably predicted.

Introduction

In energy conservation and energy generation applications, there is always a requirement for heat exchangers. For low temperatures, there is a large variety of heat exchangers available, such as rotary recuperators, tube-and-shell, secondary loop, plate fin, and heat pipes. In high-temperature applications, above 600°C, the availability of reliable and efficient heat exchangers drastically decreases with increasing temperature. Reliable heat exchangers, however, are needed for energy conservation applications, such as topping cycles, incinerators, and process control applications.

Heat pipe heat exchangers, because of their inherent reliability and design flexibility, offer an attractive alternative to more conventional heat exchangers. The major drawback in employing heat pipe heat exchangers has been the cost. The cost is high, not because heat pipes are expensive to build, but because high-temperature heat pipes use liquid metals as working fluids and liquid metal heat pipes are customarily built from very expensive superalloys. If liquid metal heat pipes could be reliably fabricated from stainless steel, a relatively inexpensive heat pipe heat recovery unit would be a reality.

A program was initiated to demonstrate the reliability of low-cost liquid metal heat pipes. Potassium and sodium working fluids were selected for evaluation with stainless steel envelopes.

Test Vehicles

Test heat pipes were fabricated from certified AISI 304 stainless steel tubing of 0.8 mm thickness. The test vehicles measured 12.7 mm in diameter and 300 mm in length; heat pipe configuration is shown in Fig. 1. Wicks were formed of Dynaloy X-7 304 stainless steel sintered fiber. The heat pipes were first vapor degreased and then vacuum baked for 20 minutes at 900°C in a vacuum of

WORKING FLUID: SODIUM OR POTASSIUM

PIPE: MATERIAL: 304 SS

EVAPORATOR: 6 IN.

WALL THICKNESS: 0.020 IN.

CONDENSER: 6 IN.

OVERALL: 12 IN.

WICK: DYNALOY X-7 304 SS, SINTERED FILAMENTS

HEAT INPUT: RADIATION HEATER

COOLING: FREE CONVECTION AND CONDUCTION VIA CLAMP

Fig. 1 Heat pipe design details.

10^{-6} torr. The pipes were then loaded with either purified potassium (99.95% minimum) potassium or sodium (ACS grade) metal. All processing was done inside a high-performance vacuum system. After loading and then outgassing well above their operating temperatures, the heat pipes were individually cooled and closed by fusion welding, without loss of vacuum. After a short performance test, the heat pipes were removed from the vacuum system and placed on life test. The potassium heat pipes were tested at 600°C and the sodium pipes at 700°C.

Figure 2 shows a representative heat pipe on life test. All heat pipes contained only wicks and working fluids; no atmospheric getters were used. All life tests were in air for two reasons: first, to observe possible oxidation effects on the heat pipe's external surface and second, to test for possible diffusion of gases such as hydrogen through the heat pipe.

Test Plan

In order to determine the long-life reliability of the stainless steel heat pipes, a plan was established for the periodic analysis of the life test vehicles. Four heat pipes of each working fluid were processed at the same time for life test. A fifth was processed through cleaning and out-gassing, but without a working fluid, and set aside as a reference.

All heat pipes had thermocouples attached to their external surfaces. Temperatures were recorded once a week, or if any unusual behavior was observed. The first set of sodium and potassium heat pipes were removed after 2300 hours for

Fig. 2 Sodium heat pipe on life test at 700°C.

analysis, the second set after 6,500 hours, and the third set after 10,000 hours. The fourth set of heat pipes will be operated to 30,000 hours or to failure. As of this date (April, 1978) some 18,000 hours have accumulated without failure.

After removal from the life test fixtures, each set of pipes was cooled and carefully opened, and the working fluid removed. The pipes were then carefully inspected metallurgically for effects of stress, corrosion, erosion, mass transport, chemical attack, oxidation, and hydrogen diffusion. Metallurgical analyses consisted of optical and scanning electron microscopy (SEM) examination of external and internal surfaces and of cross-sections. Energy-dispersive x-ray equipment attached to the SEM was used for elemental analysis.

Test Results

Temperature Uniformity

Temperatures were monitored using Chromel-alumel thermocouples spot welded to the heat pipe envelopes. The thermocouples were located 0.25 cm and 14 cm from the condenser end of the heat pipe. Temperature measurements were also made using an optical pyrometer. During the course of these tests, no changes were noted in heat pipe temperature differentials, other than those caused by deteriorating thermocouple junctions.

Heat Pipe Compatibility

The first sodium and potassium stainless steel heat pipes were removed for analysis in July, 1975. Post-test material analyses indicated no signs of chemical attack or material embrittlement on either surface of the heat pipe or of the wick material.

MAGNIFICATION 170X

MAGNIFICATION 4250X

Fig. 3 SEM photographs of wick structure after 2300 hours at 700°C. Light grain boundary relief is evident.

The only changes noted in the wick material was a small amount of grain boundary relief (Fig. 3), resulting from long-time, elevated temperature exposure. A small amount of mass transport of material from the condenser to the evaporation portion of the inner surface of the heat pipe was observed, however.

The mass transport shown is quite visible and documented in SEM photographs. The condenser section is shown in Fig. 4; material was removed from the inside of grains, outlining their boundaries. The composition of the grain boundaries and grains remains the same, as shown in the x-ray spectra in Fig. 5. Material removed from the condenser was deposited in the evaporator. Evidence of deposition was found both at the pipe bottom and adjacent areas, see Fig. 6. A higher chromium concentration was found in the grain boundaries than in the grain interiors (Fig. 7). No effect of this minor amount of mass transport on heat pipe performance was noted.

MAGNIFICATION 930X

MAGNIFICATION 4700X

Fig. 4 SEM photographs showing the grain structure in the condenser section. Arrows point to areas X-ray analyzed.

The second and third set of heat pipes were removed for analysis after 6,500 and 10,000 hours, respectively. The fourth set is still operating. Analyses indicated no significant chemical attack, other than minor oxidation, on the exterior of the pipe. No scale formed, nor did the oxide layer encompass any significant fraction of the wall thickness. After 10,000 hours the wick material appeared as in Fig. 8; increased grain boundary relief and some fracturing where fibers have been bent are the only indications of exposure. The wick should easily be able to withstand 50,000 hours of exposure without significant degradation.

The change in surface appearance of the condenser is illustrated in the photographs of Fig. 9. An amorphous, chromium rich surface layer is built up over and obscures the grain structure still

AREA A

AREA B

AREA C

Fig. 5 X-ray spectra of regions in Fig. 4, 1000,000X. Note identical compositions.

visible in Fig. 4. The surface layer after 10,000 hours is dense and tenuous, except for small areas where it has flaked off. The evaporator (Fig. 10) shows increased grain boundary relief, caused by carbide exposure, and grain interior attack. The attack is sufficient to reveal the

MAGNIFICATION 47X

MAGNIFICATION 950X, AREA 2 ABOVE

Fig. 6 SEM photographs showing surface structure in the evaporator section. Arrows point to areas X-ray analyzed.

texture of the grains. Around the edge of the evaporator close-off (Fig. 11), another minor form of localized attack is evident. The extent of surface attack is illustrated in Fig. 12, where a maximum depth of attack is found to be about 0.002 cm.

Discussion

Stainless steel heat pipes have been shown to be compatible with fluids used for low temperature uses, such as ammonia, methanol, and apparently all common fluids except water.^{2,3} Use of stainless steel at elevated temperatures is infrequent. Bienert⁴ sites the successful operation of a 304 stainless steel/sodium heat for 11,500 hours and a 347 stainless steel/potassium pipe for 6,500 hours at 510°C. Bader⁵ discusses successful use of 304 stainless steel/sodium heat pipes at 720°C in wetting studies. Dunn and Reay³ also site use of 316 stainless steel/sodium heat pipes at 770°C with over 4,000 hours of successful operation.

GRAIN BOUNDARY

GRAIN INTERIOR

Fig. 7 X-ray spectra of regions in Fig. 6. 100,000X. Note increase in relative chromium content in boundary region.

MAGNIFICATION 1250X

Fig. 8 Wick appearance after 10,000 hours exposure at 700°C. Grain boundary relief and some fracture where fibers may have been bent is visible.

MAGNIFICATION 1050X

MAGNIFICATION 475X

MAGNIFICATION 900X

MAGNIFICATION 1190X

Fig. 9 SEM photographs showing buildup of material in the condenser section after 6500 hours (top) and 10,000 hours bottom. The material is primarily chromium.

Fig. 10 SEM photographs showing surface attack in the evaporator section. Grain boundary carbides and attack on grain interiors is light, but distinct.

The metallographic analyses indicated the absence of life-limiting material interactions other than mass transport. A chromium-rich, amorphous stainless steel layer is gradually formed in the evaporator region of the pipe, leaving a depleted zone in the condenser. The maximum thickness of the depletion layer is about 0.002 cm after 10,000 hours of operation. If the depletion rate remains constant or decreases with time, material removal will not result in limiting pipe life. It is possible that the chromium surface layer in the condenser will limit heat flow after longer exposures, but no indication of this has been seen in heat pipe efficiency up to 10,000 hours of operation. Reliable life-times well in excess of 50,000 hours at operating temperatures can thus be expected.

Conclusions

Initial test results indicate that liquid metal heat pipes can be constructed entirely of stainless steel and expected to operate for more than 50,000 hours in an air environment. These life test results can be used to design future experiments to study the wider applicability of stainless steel liquid metal heat pipes.

References

1. Savage, C.J., "Development of Artery Heat Pipes in Europe Under ESA Sponsorship," 2nd International Heat Pipe Conference Proceedings, 1976, European Space Agency, SP-112, Vol. 1, pp. 373-382.

MAGNIFICATION 195X

MAGNIFICATION 710X

Fig. 11 SEM photographs showing evidence of localized chemical attack adjacent to end of evaporator section.

MAGNIFICATION 100X

MAGNIFICATION 1000X

Fig. 12 Etched microstructure in evaporator weld region, 10,000 hours exposure, showing depth of surface-affected layer (arrows).

2. Basiulis, J., Prager, R.C., and T.R. Lamp, "Compatibility and Reliability of Heat Pipe Materials," 2nd International Heat Pipe Conference, Proceedings, 1976, European Space Agency, SP-112, Vol. 1, pp. 357-372.
3. Dunn, P. and D.A. Reay, Heat Pipes, Pergamon Press, NY, 1976, pp. 105-113.
4. Skrabek, E.A. and W.B. Bienert, Heat Pipe Design Handbook, Volume 1, Final Report on NASA Contract NAS9-11927, Dynatherm Corp., Cockeysville, North Dakota, 1972.
5. Bader, M., "The Gas Controlled Heat Pipe As a Tool For Wetting Studies," 2nd International Heat Pipe Conference, Proceedings, 1976, European Space Agency, SP-112, Vol. 1, pp. 327-334.

EMERGING HEAT PIPE APPLICATIONS

A. Basulis and D. J. Formiller
Hughes Aircraft Company
Torrance, California

Abstract

Heat pipe thermal control devices have recently matured to full production in electronic component cooling and heat recovery. Examples are: thermal diodes used in missile electronics, cylindrical heat pipes which cool shipboard and missile electronics, heat pipe modules for heat recovery, and variable conductance heat pipes used for spacecraft components and industrial process thermal controls.

Heat pipe heat distribution devices such as isothermal vapor chambers, solar collector heat pipes, and switching heat pipes are in the prototype stage and could reach production within the next two years.

Introduction

In the past, the heat pipe was looked upon as a solution searching for a problem and then dismissed as a laboratory curiosity. Today, heat pipes are recognized as a worthy consideration in industrial, space, and military applications. Heat pipe heat recovery units are routinely specified in heating, ventilating, air conditioning, and industrial paint drying applications.^{1,2} Typical applications of the simple heat pipe include electronic component cooling in airborne systems and on spacecraft³ and are also currently being used to stabilize permafrost in Alaska's pipe line.⁴ Variable conductance heat pipes are being designed as integral components into spacecraft thermal control systems.⁵ The number of applications are continuously increasing, however not without resistance. In most cases a heat pipe system is considered only when alternate methods are too expensive, unreliable, or impossible to use. Thus, we are continuously exploring new ideas and looking ahead at emerging heat pipe applications.

Simple Cylindrical Heat Pipes

Cylindrical heat pipes with concentric homogeneous wicks have been around for years, but only in the past few years have they been produced in large quantities. Typical applications are electronic component cooling and injection mold cooling. At present it appears that real high volume production is in electronic component cooling applications. Subsystem designers have discovered that heat pipes, in addition to being an excellent heat transfer device, are good lightweight structural members that can carry a substantial load. Heat pipes designed for electronic component cooling applications are shown in Fig. 1 and are typically fabricated in lots of 200 per month. For most applications, they are made from copper with water as a working fluid with an operating range of 30°C to 100°C.

Cylindrical heat pipes have been incorporated into evacuated solar collectors. Initial tests indicate that heat pipes offer an advantage over flow-through systems when a solar collector is used as the primary source (without a secondary heat

Fig. 1 Cylindrical heat pipes for electronic component cooling applications.

exchange loop) for heating water or air. A typical solar collector heat pipe is shown in Fig. 2. This particular collector heat pipe is 5 feet long and transfers 115 watts thermal at a temperature of 300°F. Evacuated tubular collectors utilizing heat pipes were field tested and compared with counter flow tubular collectors using an identical design, and heat pipes proved more efficient.⁶

Banks of finned heat pipes with a flow separator in the center make excellent heat recovery units however, applications are mostly in the HVAC market. Industrial applications require temperatures above 300°C and we still have to find really good working fluids. In temperatures above 500°C, liquid metals such as potassium or sodium can be used. Technology

Fig. 2 Solar collector heat pipe.

in processing liquid metal heat pipes has been developed to a point where liquid metal heat pipes could be produced in high volume at a relatively low cost. However, industrial applications are few, mainly because industries do not believe in utilizing new technology or are looking toward Washington for incentives and/or direction. As a result, the industrial market for even low temperature heat recovery is decreasing in spite of the energy crisis. Industry just does not know what fuels will be available in the next few years and what capital expenditures will be required to accommodate the changeover, say from natural gas to coal.

Switching Heat Pipes and Thermal Diodes

Thermal diodes initially developed for spacecraft applications⁷ found an ideal application in thermal management of airborne missile electronics. During subsonic flight, heat pipes cool missile electronics by pumping waste heat into the skin of the missile, and then rejecting it to the atmosphere. During the supersonic flight, the heat pipe switches off, and acts as a thermal insulator, thus protecting the internal missile electronics from aerodynamic heat. Figure 3 shows a thermal diode designed for a missile application.

Switching heat pipe technology actually is an extension of liquid trap diodes which have been applied to pump heat from the automotive exhaust into the passenger compartment to provide quick heat. One prototype model has been fabricated and tested. Initial tests indicate that the switching heat pipe could provide warm air into passenger

compartment within 3 minutes. However, this fast start up heat pipe system as designed is very expensive and we expect this device probably will not see mass production because of the very high cost of materials. A heat pipe developed for a quick heating system is shown in Fig. 4.

Variable Conductance Heat Pipes

Gas controlled heat pipes found acceptance in spacecraft thermal control applications⁵ especially in controlling temperatures of electronic components. Typical VCHP's are shown in Fig. 5. A major effort has been expended at Hughes to reduce cost, weight of high performance VCHP's for space, and accumulate reliability data.⁸ In industrial applications, heat pipes are being used to control the temperature of polymers.⁹ Figure 6 shows a nozzle with variable conductance heat pipes. There are many potential applications for chemical processes, but the acceptance of these techniques are several years away. Heat pipes have been designed to evaluate materials in hostile environments, such as producer gas in a coal gasifier or condensation of corrosive liquids in sulfur plants. Figure 7 illustrates a typical heat pipe test vehicle designed to operate at 500°C.

Vapor Chambers

Two types of vapor chambers have been built: small flat heat pipes to cool electronic flat packs shown in Fig. 8, and large units such as those shown in Fig. 9 which are being used as IR targets. The units shown in Fig. 9 are 7' x 2' and are isothermal with $\pm 0.2^\circ\text{C}$ over the entire surface.

Fig. 3 Thermal diode heat pipe.

Fig. 4 "Quick Heat" heat pipe system.

Fig. 5 VCHP's designed for thermal management of space borne electronics

Fig. 7 Heat pipe designed to evaluate materials in hostile environments.

Conclusion

In the last two years, a variety of new heat pipe applications have been discovered, and unique devices have been developed. There is still a lot of resistance to use heat pipes in process control applications and in electronic systems, but objections are slowly being overcome as more and more successful applications are being reported and developed. In the coming years, we will find applications in the following areas:

Fig. 8 Heat pipe for film pack cooling.

Fig. 6 Nozzle for temperature control of flowing polymer utilizing VCHP's.

Fig. 9 Isothermal IR targets.

Electronics. Simple cylindrical heat pipes are used as heat transfer devices and structural members. In the coming years, these heat pipes will be designed into a large number of military systems. Flat heat pipes as an integral component for flat packs and circuit cards will be used only as experimental devices in the near future. The major objection will be cost and difficulty in logistics of permanently coupling electronics to the heat transfer device.

Spacecraft Thermal Control. Increase in use of VCHP's for primary thermal controls. Typically small volume, high cost, and very high performance are characteristic of these systems. Emphasis in the near future will be put on reliability and lower cost. New wicking structures will emerge to increase thermal performance, especially under adverse tilt for ground testing.

Industrial Applications. Strong market in HVAC for heat pipe heat recovery systems. Other heat recovery applications will be stagnate over the next two years, until energy policy dictates the industrial heat recovery market.

Missile Applications. Marked increase in utilization of heat pipes for thermal management of electronics in missiles. Large volume production programs within the next two years.

Vapor Chambers. Low volume, high performance, vapor chamber type heat pipes will be built to provide isothermal surfaces for a variety of space and terrestrial applications. Temperature isothermality of 0.01°C or better will be demonstrated within the next two years.

References

1. Ruch, M. A. and Grover, G. M. "Heat Pipe Thermal Recovery Unit Application" 2nd International Heat Pipe Conference, Bologna, Italy March 1976.
2. Basiulis, A., Johnson, J. H., "High Temperature Heat Pipes For Energy Conservation", 10th Intersociety Energy Conservation Engineering Conference, University of Delaware, Newark, Delaware August 1975.
3. Basiulis, A. Sekhon, K., "Heat Pipes in Electronic Component Packaging, NEPCON 1977 West/East.
4. Waters, E. D., Johnson, C. L., Wheeler, J. A., "The Application of Heat Pipes to the Trans-Alaska Pipeline", 10th Intersociety Energy Conservation Engineering Conference, University of Delaware, Newark, Delaware August 1975.
5. Olendorf, S., McIntosh, R., "Heat Pipes in Space - A NASA Summary", 2nd International Heat Pipe Conference, Bologna, Italy March 1976.
6. Ortabasi Ugur, "An Evacuated Tubular Collector Utilizing A Heat Pipe", Report No. COO-2608-3, ERDA Contract EY-76-C-Q2-2608, Corning Glass Works, Corning, N. Y. September 1977.
7. Basiulis, A., "Unidirectional Heat Pipes to Control TWT Temperature in Synchronous Orbit" Symposium on Thermodynamics and Thermophysics of Space Flight, Palo Alto, March, 1970.
8. Fleishman, G. L., Et al, "A High Reliability Variable Conductance Heat Pipe Space Radiator" to be presented at the 3rd International Heat Pipe Conference, Palo Alto, CA May 1978.
9. Sun, T. H., and Shaeffer, J. I., "Temperature Control of Polymer Fiber Spinning Process" Chemical Engineering Progress, July 1977.

DESIGN, DEVELOPMENT AND TEST OF A 1000-WATT OSMOTIC HEAT PIPE

A. Basiulis*, G.L. Fleischman* and C.P. Minning**
Hughes Aircraft Company
Torrance, California

Abstract

Osmotic heat pipes can be designed to transport high heat loads. An osmotically pumped heat pipe has been operated continuously for 500 hours with a thermal loading of 500 watts. A peak thermal transport of 1000 watts was demonstrated. At the present time, long life capabilities of osmotic membranes and stability of working fluids at elevated temperatures over prolonged periods of operation are unknowns. The narrow operating temperature range of existing membranes (25°C to 100°C) and the availability of membrane modules with very high area to module volume ratios for direct osmosis are current limitations.

Introduction

Heat pipe energy transport devices have recently matured to production in temperature control applications. Examples are: thermal control diodes in missile electronics, cylindrical heat pipes which cool shipboard and missile electronics, heat pipe modules for heat recovery, and variable conductance heat pipes for the thermal control of spacecraft components.¹ All heat pipes, however, depend on capillary forces to pump working fluid from the condenser to the evaporator and are limited in their ability to transport thermal energy long distances. Osmotic heat pipes,^{2,3} presently under development for the Air Force Flight Dynamics Laboratory under Contract F33615-77-C-3031 are not limited by capillary pumping. They show a capability of transporting energy long distances and taking over where conventional heat pipes leave off.

Principle of Operation

A conceptual drawing of a typical osmotically pumped energy transport system or osmotic heat pipe is shown in Fig. 1. When two fluids of different concentrations are separated by a semipermeable membrane, as shown in Fig. 1a, the solvent will flow into solution to attain equilibrium. As long as the concentration gradients are high between solvent and solute solution, flow will continue. If the two chambers are connected, as shown in Fig. 1b, the spontaneous pumping action will continue until the concentration of the two solutions reaches a state of equilibrium. At this point, neither solvent nor solute will flow through the membrane. By adding heat to the solution, as shown in Fig. 1c, solvent evaporates and flows to the condenser where it recondenses, giving up heat, and returns to the evaporator. Thus, the concentration difference at the membrane is constantly maintained and continuous pumping action is assured.

The thermal energy required to separate pure solvent from the solvent-solute mixture is the same energy, or waste heat, which must be transported from the evaporator region to the condenser.

Fig. 1 Principle of operation of an osmotic heat pipe

Design Considerations

Based on a literature survey, research and laboratory experiments with an osmometer, candidate membrane and working fluid systems were selected.^{4,5} Consideration was given to materials compatibility and potential failure mechanisms, which are unique in direct osmosis applications. Failure mechanisms and their effect on heat pipe performance are summarized in Table 1.

Water was selected as the optimum working fluid for the current design. It has the highest mass flow and separation properties in conjunction with current state-of-the-art membranes. Moreover, water has the highest latent heat of vaporization of any of the candidate working fluids. As in conventional heat pipes, a high latent heat of vaporization results in greater heat transport for a given mass flow or pumping rate.

Electrolytes such as those formed from salts dissolved in water offer definite advantages as solutes for osmotic pumping. First, ions are rejected by most membranes, better than non-ionic solutes. Second, the salts have extremely low vapor pressures, and consequently do not mix with the working fluid vapor. Also, they are highly soluble in water so that high osmotic pumping pressures can be easily obtained.

Organic solutes were selected, however, to avoid corrosion, and possible non-condensable gas generation in a metallic heat pipe. As in a conventional heat pipe, any non-condensable gas would be swept to the condenser surfaces, preventing efficient condensation heat transfer. Sucrose was selected as the solute, then, for the following reasons:

- Extremely soluble in water
- Non-volatile

*Electron Dynamics Division, Torrance California

**Electro Optical and Data Systems Group, Culver City, California

Table 1 Potential Failure Mechanisms

FAILURE MECHANISM	EFFECT ON HEAT PIPE PERFORMANCE
Polarization Concentration	If concentration of solvent is allowed to accumulate and block the semipermeable membrane, the pumping capacity of the osmotic membrane can go to zero.
Flow Controls	In osmotically pumped heat pipes, the liquid pumping rate is independent of the heat input. As a result, at low heat input rates, the evaporator can be flooded causing spill-over of solute into the solvent chamber.
Leakage of Solute Through the Membrane	Leakage can reduce the concentration gradient and thus the pumping capacity.
Solute Carryover in Vapor	The presence of solute in the vapor can cause contamination of the solvent.

- Good membrane separation properties
- Non-corrosive with envelope material

Copper and Monel are compatible with water in heat pipes over the design temperature range. Because a non-corrosive solute was selected, the materials compatibility problem reduces to compatibility between the solvent and the envelope material. The extensive data from conventional heat pipe life testing can be used for this purpose.

In order to provide maximum flow per unit volume of the osmotic pump, three different membrane module designs were evaluated.

Hollow Fiber Module

One of the most promising module configurations for osmotic heat pipe applications is the hollow fiber membrane module (Fig. 2). An advantage of this approach, in addition to large surface areas per unit volume, is the elimination of the need for a membrane support material. A hollow fiber module of this type can achieve a surface area of 9,000 ft²/ft³ of container volume.

Fig. 2 Hollow fiber module.

Spiral-Wrapped Module

This has been a highly successful design for obtaining large membrane surface areas in compact volumes for reverse osmosis applications. However, the module investigated for use in an osmotic heat pipe (Fig. 3), was specially designed to provide approximately 0.5 inch inter-membrane spacing on the solution side. This spacing between wraps was provided to allow adequate fluid circulation and mixing to take place.

Shell-and-Tube Module

A module consisting of three perforated stainless steel support tubes and a flange (tube sheet) was constructed as depicted in Fig. 4. Tubular cellulose acetate membranes were placed inside the support tubes and sealed at the top and bottom using epoxy. An advantage of these membranes was that the longitudinal seams, which were sealed with epoxy in the spiral-wrapped modules, were eliminated.

Component Evaluation and Testing

Experiments were designed to evaluate heat pipe components, failure mechanisms and to develop techniques to overcome effects limiting heat pipe performance. A basic test vehicle was designed to evaluate osmotic heat pipe components. It consisted of a working fluid column, membrane module compartment, solvent feed siphon and evaporator. The test apparatus is shown in Fig. 5.

Osmotic pumping rates were measured by metering solvent feed into the solvent reservoir as illustrated. Since the solvent reservoir was kept full at all times, the rate of decrease of the water level in the glass cylinder was a very accurate measure of the amount of solvent being pumped by the membranes. The solution column was maintained at a constant height by boiling off the excess liquid. This approach maintained an overall constant concentration level in the solution column.

Polarization Concentration Effect

This is a major problem in reverse osmosis. Although it was analytically predicted to be a serious problem, it did not materialize to the degree predicted

Fig. 3 Spiral wrapped membrane package.

Fig. 4 Tubular membrane module.

because of self-induced convection currents.⁶ With special flow channel designs, concentration polarization was even further reduced. Fig. 6 shows the mixing tube arrangement. In this configuration, concentrated solution returned via the central flow separator tube to the membrane, swept the membrane, and mixed with incoming solvent. Dilute solution then flowed upward through

Fig. 6 Thermal syphon experiment.

the annulus to the evaporator, where solvent evaporates and the process repeats itself.

Flow Control

Unlike the capillary wick in an ordinary heat pipe, the pumping rate across the membrane in an osmotic heat pipe does not automatically match the heat input rate. Two flow control techniques were developed to shut-off osmotic pumping, gas blockage and solvent depletion. Both techniques were effective in stopping solvent flow or in modulating the solvent flow.

The gas blockage technique is illustrated in Fig. 7. When the power was turned off, the pressure inside the heat pipe lowered and a large bubble appeared underneath the membrane, as shown. Pumping stopped immediately when the bubble appeared. When the pressure was increased by increasing the heat input, the bubble collapsed and the heat pipe started operating again. Conversely, the heater on the gas reservoir could be actuated to control the presence or absence of the bubble.

An advantage of this technique is that the flow can be stopped without special allowance for storage of the solvent in the evaporator when the heat pipe is turned off. However, it would be difficult to incorporate in the more compact membrane modules. The introduction of gas into the heat pipe could eventually saturate the solvent and enter the vapor space, thus degrading performance.

Fig. 8 illustrates the solvent depletion technique. The addition of a vent tube at the top of the membrane module provides a self-equalizing mechanism for the solvent level. When the heat pipe is turned off, all of the solvent which is needed to fill the membrane module is in the solution reservoir (evaporator). As heat is applied to the evaporator, distillation takes place and the solvent condenses in the condenser. The membrane module begins

Fig. 5 Component evaluation a, us.

Fig. 7 Gas blockage shut-off mechanism for osmotic pump.

to fill and osmotic pumping begins through the membrane. If more heat input is applied, the solvent will fill the module, wetting additional membrane area. The maximum power of the heat pipe is reached when the solvent has filled the membrane module (solvent chamber). Note that the solvent level on the condenser side is at all times equal to the height of the solvent column in the membrane module.

Fig. 8 Solvent depletion technique for shut-off and flow control of osmotic pump (condenser column height is balanced by solvent column height in membrane module).

This approach is probably the most practical since the vent tube eliminates any problems with vapor or gas bubbles blocking the membrane area at maximum power conditions. Also, the additional volume required to store solvent in the evaporator is minimized, since only the solvent required to fill the module must be stored.

Leakage Through the Membrane

During the course of the osmotic pumping experiments, samples were taken periodically from the solvent side for chemical analysis. Solutes investigated included polyethylene glycols (molecular weights of 1000 and 6750), magnesium sulfate and sucrose. The presence of solute was detected in each sample. However, the amounts were so small that quantitative values could not be obtained.

In view of the fact that leakage is a possibility, an analysis was made to evaluate the influence of the ratio of membrane area to solvent compartment volume on long term performance. This analysis was conservative in that the solvent flow was taken to be zero. It was concluded, however, that designs having small solvent volumes such as the spiral-wrapped module would be sensitive to leakage of solute through the membrane, or a microscopic leak in the seal. The shell-and-tube module, on the other hand, was relatively insensitive to solute leakage.

Solute Carryover

The carryover experiment was performed to determine how much, if any, solute was being entrained in the vapor and carried over into the solvent compartment during evaporation. Since this is a distillation process, very little contamination due to carryover was anticipated.

The experiment was performed by collecting the condensate in a clean beaker while operating the test apparatus over a period of three days. The results indicated essentially no carryover of solute in the vapor.

Module Performance

Each of the three membrane modules previously described (Figs. 2, 3 and 4) were tested for osmotic pumping performance. The best results were obtained both in reliability and flow rate tests with the shell-and-tube design.

Baseline Design

Based on the results of the experimental work described above, the following goals were established for a baseline design:

- Heat transport: 500 watts
- Evaporator temperature 50°C to 100°C
- Column Height (evaporator above condenser) 1.8m (6 feet)
- Passive flow control
- Life 1000 hours

Fig. 9 shows a cross-section of the baseline design. The heat pipe consists of five major components: 1) osmotic pump module, 2) mixing and flow separator tubes, 3) evaporator, 4) condenser, and 5) heat pipe envelope.

Fig. 9 Baseline osmotic heat pipe cross-section.

Osmotic Pump Module

The osmotic pump section of the heat pipe includes the solvent reservoir and shell-and-tube membrane module (Fig. 9). A total of eighteen perforated stainless steel tubes were used to support each of the cellulose acetate membranes, which were cast in the form of cylindrical tubes. The membranes were 2.45 cm (0.96 inch) in diameter by 30.5 cm (12 inches) long, and were sealed to the support tube walls at the top and bottom with RTV. This approach eliminated the need for lengthy seams and small volumes on the solvent side, which could be sensitive to any leakage of solute through the membrane or a microscopic leak in the seal area. In addition to this, the cylindrical membrane geometry could be adapted to the passive start-up and control technique previously discussed. The total membrane surface area was 4225 cm² (655 in.²).

The solvent reservoir volume consists of the volume not displaced by the membrane package. Two ports on the side at top and bottom of the reservoir are for vapor venting and solvent entering the reservoir, respectively. Note that this port represents the vent tube previously referred to in the solvent depletion control technique. An O-ring seal above and below the membrane module flange sealed the assembly into the heat pipe envelope.

Mixing and Flow Separator Tubes

There are two concentric solution transport tubes in the solution column. The inner tube transports the upward moving fresh solvent flowing through the membrane, whereas the outer annulus transports the downward moving solution concentrated by evaporation in the evaporator. The solution mixing chamber and mixing tubes (Fig. 9) direct the concentrated solution down into each

membrane cylinder. In this manner, the concentration level is maintained near the membrane surfaces to provide continuous osmotic pumping pressures over long periods of time.

Evaporator and Condenser

The evaporator was designed to be at least equal in volume to the solvent reservoir, as dictated by the solvent depletion control technique. That is, when the heater power is turned off, all of the solvent will be pumped out of the solvent reservoir, and reside in the evaporator (solution reservoir). The evaporator was 15.2 cm (6 inches) in diameter and 20.3 cm (8 inches) long. Four heating wells were installed at the bottom of the evaporator. A cartridge heater was placed inside each of the wells.

There were no wicks in the evaporator. Instead, the heater wells were completely immersed in the solution at all times to promote boiling. This eliminated problems related to unwetted surfaces of the heater wells overheating and breaking down the sucrose.

The condenser was an annular water cooled heat exchanger located on the vapor transport tube just above the membrane module. This aspect of the heat pipe is shown more clearly in Fig. 10.

Heat Pipe Envelope

A material search revealed that neither copper nor Monel were readily available in the large diameter tubes needed for the solution and solvent reservoirs. Therefore, 347 stainless steel was specified for these parts, and Monel was used for the vapor transport tube (Fig. 10) as well as the solution transport tube.

Fig. 10 Baseline osmotic heat pipe test set-up.

Table 2 Maximum Power Test Results

DATE	TIME	POWER (WATTS)	HEAT PIPE TEMPERATURE							COMMENTS
			#1	#2	#3	#4	#5	#6	#7	
8/3/79	11:00 am	168	98°F	93°F	92°F	92°F	92°F	93°F	92°F	
	11:30 am		107	102	101	102	101	102	103	
	2:40 pm		152	142	141	140	141	141	140	
	2:45 pm	265								
	3:15 pm		166	157	155	154	153	153	86	
	4:45 pm		147	135	135	135	135	134	124	
	5:00	0								
	8/13/79									
	9:15 am	160								
	9:30 am	260	129	124	124	124	124	124	124	
	9:45 am	504								
	9:55 am		59°C	56°C	56°C	56°C	56°C	56°C	56°C	
	10:30 am		69	68	67	66	66	67	63	
	11:00 am		75	74	73	72	71	72	60	
	11:01 am	442								Turned power down. Pipe is too hot. Problems with coolant pump.
	11:45 am		85	80	80	81	80	81	52	
	12:05 pm		83	80	80	80	80	81	53	
	12:10 pm	220								
	12:40 pm		83	81	82	80	73	60	49	
	2:45 pm	0								Turned off to repair coolant pump.
	2:50 pm									Burped non condensable gas.
	3:00 pm	160	61	60	59	59	59	59	57	
	3:30 pm		63	60	60	60	60	47	34	
	3:35 pm		63	60	60	60	60	60	60	Burped non condensable gas.
	3:40	378								
	3:45 pm		63	60	60	60	60	60	50	
	4:00 pm		64	61	60	60	60	60	60	
	4:15 pm		67	62	62	61	61	61	61	
	4:30 pm		68	65	65	65	65	65	65	
	4:50 pm		69	66	66	66	66	66	66	
8/14/79	5:00 pm	0								
	8:45 am	286								
	9:00 am		49	46	46	46	46	46	46	
	9:20 am		52	50	50	50	50	50	50	
	9:45 am		55	52	52	52	52	52	52	
	10:15 am		65	62	62	62	62	62	62	
	11:30 am		72	68	68	68	68	68		
	11:45 am	448								
	11:50 am		70	67	67	67	67	67	67	
	1:25 pm	448	80	75	75	75	75	75	74	
	1:35 pm	639								
	2:05 pm		84	80	80	80	80	80	86	
	2:40 pm		89	84	84	84	84	84		
	2:45 pm	739								Test had 1 E
	4:00 pm		93	87	87	87	87	87		Tested flow rate and started using tap water as coolant.
	4:05 pm	855								
	4:45 pm		63	61	61	61	61	61		
	4:50 pm	1000								
	5:15 pm		65	61	61	61	61	61		
	5:30 pm		60	56	56	56	56	56		
8/15/79	5:31 pm	0								
	8:31 am	250								
	10:00 am	1000								
	11:30 am		72	67	67	67	67	67		
	1:50 pm		75	70	70	70	70	70		End Maximum Power test.

Heat Pipe Testing

After processing, the heat pipe was instrumented for thermal testing as shown in Fig. 10. First, the maximum power or pumping capability was determined by increasing power in 100-200 watt increments, allowing the heat pipe to operate at each step for two to four hours. Table 2 is a log of the power and temperature for this test. Performance tests were terminated after the heat pipe operated successfully for four hours at 1000 watts.

After completion of the maximum power test, the heat pipe was set up for life testing. The heat pipe

operated continuously with a 500 watt heat load for 500 hours. Fig. 11 is a photograph of the osmotic heat pipe during life test.

During the test, a slight gas build-up was observed in the condenser. A sample of gas was drawn off into a cylinder, and analyzed using an Inficon IQ 200 residual gas analyzer. No nitrogen was found, indicating that the pipe was leak tight. Neglecting water vapor, which would be expected in any sample drawn from a water heat pipe, the primary constituent of the non-condensable gas was carbon dioxide, with smaller quantities of carbon monoxide, hydrogen and methane. Hydrogen was probably

Fig. 11 Baseline osmotic heat pipe with insulation for thermal testing.

caused by a slow reaction of water with the stainless steel heat pipe envelope, but the organics present could be due to the oxidation of sucrose.

Conclusions

The basic concepts of osmotic heat pipes are well understood, and components for osmotically pumped systems are available for the temperature range of 25°C to 100°C. Osmotic heat pipes can be designed to transport high heat loads.

Additional development is required to obtain more compact interbrane modules for direct osmosis. The hollow fiber module, for example, should not be rejected, based only on the results of the single test reported here. It is conceivable that with proper spacing between fibers, good performance could be obtained.

An osmotic heat pipe made entirely of OFHC copper is recommended for future studies. If the heat pipe contains no dissimilar metals, then certain solutions containing ions could be used without internal corrosion taking place. A non-metallic heat pipe would be desirable from this point of view.

It is recommended that conventional heat pipes should be used to interface with the heat source and the osmotic heat pipe evaporator. Unlike ordinary resistance-type heaters, heat pipes operate at uniform temperatures. Unwetted portions of electrical heaters become overheated resulting in pyrolysis of the solute. This approach would allow wicks to be incorporated into the evaporator for more efficient heat transfer.

Acknowledgements

This paper is based on work performed under U.S. Air Force Contract F33615-77-C-3031. The authors would like to acknowledge Mr. C.J. Feldman and Dr. L.L. Midolo of the Air Force Flight Dynamics Laboratory for helpful suggestions. Also, Mr. R.A. Anderson, for the detail design and testing of the baseline heat pipe, and Dr. J.W. McCutchan of UCLA for providing the tubular membranes and technical advice.

References

1. Basulis, A. and Formiller, D.L. "Heat Pipe Applications" Third International Heat Pipe Conference, Palo Alto, CA, 1978.
2. "The Passive Pipe in an Active Role" vectors, Hughes Aircraft Co., Volume XII, Spring 1979.
3. Midolo, Lawrence L. "Heat Transfer Apparatus with Osmotic Pumping", U.S. Patent No. 3,677,337, 18 July 1972.
4. Minning, C.P., Fleischman, G.L. "Development of an Osmotic Heat Pipe" Second International Heat Pipe Conference, Palo Alto, CA 1978.
5. Fleischman, G.L. and Anderson, R.A. "An Osmotically Pumped Heat Pipe" Proceedings on Membrane Separation Technology, Clemson University, Clemson, S.C., March 1979.
6. Minning, C.P. et al. "Design and Test of Prototype Osmotic Heat Pipe", 14th All-Union Thermophysics Conference, Paper # 1092, Orlando, FL 1979.

Organization: United Technologies Research Center (UTRC)
Address: East Hartford, CT 06108
Phone: (203) 727-7000
Contacts: Thomas Latham

David J. McFarlin
Senior Project Engineer
(213) 727-7432

General Remarks:

UTRC is actively engaged in support of fusion research. They were the industrial partner of the University of Texas, Austin, in fabrication of the Texas Tokamak. They also work with Oak Ridge (ORNL) in fabrication of ion sources for neutral-beam injection. Their own equipment includes the LITE facility, Page A-68, which is planned to be operational as a neutral-beam system by June, 1981, at power densities of $2-3 \text{ kw/cm}^2$ with an expectation of reaching 10 kw/cm^2 at some later date. Page A-69 is a chronology of their work in upgrading the performance of the 15-cm ORNL source at UTRC.

Cooling At High Heat Fluxes:

Page A-70 summarizes the UTRC experience with systems requiring cooling at surfaces subjected to high heat fluxes. These values are similar to those manufacturers using equivalent techniques and the same coolants. Page A-71 shows representative values obtained with various water-cooling methods some of which are values obtained in laser mirror systems at the UT Florida Research and Development Center where the laser systems work is concentrated. Close cooperation between the two laboratories is maintained by company shuttle service between company airports using specially-outfitted 34-passenger versions of a Boeing Model 727 and of a Model 737.

The Thermal Skin[®] system developed by UTRC as produced by: first, photo-etching a metal plate (the samples displayed were copper) with any desired pattern of small channels and distribution and collection headers and second, closing the open side of the channels by furnace brazing a smooth plate with matching configuration—holes, shape, etc.—to the channeled plate. Details of the techniques, including inspecting of the passages to insure that no blockages have developed, are proprietary. Page A-72 shows a multiaperture, ORNL duo-piggatron ion-source grid elements and an assembly of this design. The completed assembly has one water inlet connection and one outlet connection. A meritorious feature of this method of producing such sandwiches is that they can be rolled or pressed into singly- or doubly-curved surfaces to produce a desired equipotential boundary to match a varying heat-flux distribution. In an ion source the distortion of a grid by lost-particle heating is minimized by maintaining a uniform surface temperature. Similar benefits accrue in a beam dump or a calorimeter where unknown power distribution may be experienced. Thermal Skin[®] heat fluxes of 4 kW/cm^2 with water supply pressure of 500 psi are considered to be state-of-the-art.

A recent development at UTRC is the swirl tube illustrated on Page A-73. Various configurations for the inlet manifold have been tried in terms of slot shapes and sizes. The slot is so positioned that flow into the tube is at a high tangential velocity and flow through the tube is spiral with the pitch increasing toward the exit end. Tests were conducted with a CW laser beam of approximately the tube diameter normal to the tube axis. Three tests to burn-out were made at three different axial positions along the tube. A typical set of values was:

Tube material	Inconel
Tube length - in.	6
Tube diameter - in.	3/16
Tube wall thickness - in.	0.005
Water supply pressure - psi	1000
Tube inlet pressure - psi	200
Tube outlet pressure - psi	50
Water axial velocity - fps	125
Water temperature rise - °F	1½-3
Tube wall temperature drop @ (10 kW/cm²) - °F	~1200

UTRC has two concepts they believe practical for fabricating large panels from swirl tubes.

Instrumentation and Diagnostics

UTRC has developed techniques for placing thin-film thermocouples on gas-turbine blades to obtain leading edge stagnation temperatures. The build-up over the protective coating of the blade is some four ten-thousandths of an inch and cannot be sensed by feel. No disturbance of the gas flow over the blade surface occurs. The films can be restored when ablated. Pages A-74 through A-78 illustrate the details of the sensor and show a suggested application to an electrode grid.

LITE FACILITY FOR 10A INJECTION

PERFORMANCE HISTORY

15-cm ORNL source at UTRC

COOLING EXPERIENCE AT HIGH HEAT FLUXES

Program	Heat Load		Type of Cooling
	Btu/in. ² /sec	kw/cm ²	
RL10 Rkt Eng - Combustion Chamber Throat	10	1.6	Cryogenic Hydrogen
XLR129 HP Rkt Eng - Combustion Chamber Throat			
• Transpiration Cooled	60	10	Cryogenic H ₂ (Boundary Layer Bleed)
• THERMAL SKIN®	85	14	Cryogenic Hydrogen
ALL Apertures	18	3	H ₂ O Cooled

WATER COOLING CONCEPTS FOR VARIOUS HEAT FLUX LEVELS

SAMPLE THERMAL SKIN[®] MULTIAPERTURE COPPER GRID

SWIRL TUBE TEST

A-73

TYPICAL THIN-FILM SENSOR

Potential installation on a grid

A-74

ELECTRODE GRID PROBLEM/SOLUTION

Thin film instrumentation can provide accurate thermal load data

A-75

TYPICAL THIN-FILM SENSOR

Typical turbine blade installation

A-76

TEMPERATURE MEASUREMENTS

Thin film sensors have been used to measure turbine temperatures

INSTRUMENTATION EFFECTS/BENEFITS

Thin film thermocouples provide reliable data

Not instrumented

- Operational parameters unperturbed (gas flow, temperature distribution, etc.)
- No temperature data

Conventional

- Operational parameters perturbed
- Unreliable temperature data
- Instrumentation survival problem

Thin film

- Operational parameters unperturbed
- Reliable temperature data

Organization: Westinghouse Electric Corporation
Research and Development Center

Addresses: 1310 Beulah Road
Pittsburgh, Pennsylvania 15235

Phone: (412) 256-7000

Fusion Power Systems Department
P.O. Box 10864
Pittsburgh, Pennsylvania 15236

Phone: (412) 892-5600

Contacts: Dr. Martin D. Nehemow
Senior Engineer
Gas Physics & High Voltage Technology
(412) 256-3079

Dr. R. D. Haun, Manager
Applied Sciences, R&D Division

Daniel Klein
Executive Assistant to the Manager
Fusion Power Systems Department

Andy R. Allen
Marketing Representative
Marketing Programs
Fusion Power Systems Department

Clifford K. Jones

Robert W. Stooksberry

Robert Draper

Al W. Possner
Special Representative
Marketing Department
Research and Development Center
(412) 256-3552

Dr. Gordon Gibson
Fusion Power Systems Department

General Remarks:

A meeting with extensive participation by Westinghouse personnel preceded visits to several laboratories. The formal agenda comprised the following:

Welcome and Orientation—Dr. R. D. Haun

Overview of Fusion Power Systems Department—Daniel Klein

Particle Beam Activities and Interests—Cliff K. Jones

EP Thermal Simulator—Dr. Martin D. Nehemow

Heat Transfer—Steve L. Vego

Robert Draper

Theoretical Studies—Alan Lee (Chi)

The organization of the Research and Development (R&D) Center, and its relationship with the major divisions of the Westinghouse Electric Corporation is shown on Page A-84. Within each of the R&D Divisions of the R&D Center are a number of Departments as listed on Pages A-85 to A-89 inclusive. Also shown are the division programs and services as well as the division expertise. Not listed, but included in the Applied Sciences-R&D-Division, is the Fusion Power Systems Department.

Pages A-90 to A-95, inclusive, comprises selected viewgraph reproductions from introductory material on the fusion reactor design and development interests of Westinghouse. The first page lists the broad areas of interest and capability; the second covers neutral beam technology; the third a list of general experimental facilities; the fourth lists experimental lithium experience; the fifth, high heat and particle flux test program; and the sixth, plasma arc heater technology capabilities and application.

In the sections to follow, the comments and attachments have been directed to the MFTF Beam Dump problems. Westinghouse is, of course, pursuing many other avenues of fusion reactor technology. Of particular interest to the MFTF Beam Dump heat transfer study is the facility which has been built at the R&D Center to obtain data on nucleate-boiling water cooling of devices subject to high heat flux. Electron beam heating up to 300 ma at 150kV can be scanned, or concentrated, on a specimen to obtain a wide range of thermal densities. The facility has been described in a paper presented at the Eighth International Symposium on Engineering Problems of Fusion Research. Pages A-96 to A-103, inclusive, includes a copy of the paper as well as a block diagram, a hydraulic and electrical schematic, and three color photos of the facility.

The Fusion Power Systems Department is responsible for the construction of an experimental facility at the R&D Center to support research in furtherance of fusion power.

Page A-104 lists the areas in which such support will be provided. Of the four areas listed, the second and fourth are germane to the MFTF beam-dump problems. These are: first, the development of neutral beamline components including beam dumps, and second, research to provide basis data on performance of selected materials subjected to ion and electron bombardment.

The Westinghouse rotating-arc-stabilized arc heater listed on Page A-108 is capable of providing thermal fluxes of $3\text{-}5 \text{ kW/cm}^2$ over areas of $45\text{-}80 \text{ cm}^2$.

Capability for studying the effects of ion bombardment of beam dump "first wall" surfaces is particularly evident at Westinghouse. The extensive facilities and services of the Material Characterization Laboratory, Physical Metallurgy, of the Material Sciences R&D Division are listed on pages A-113 and A-115.

Studies being made on ion implantation show that light ions of 40 keV energy have a range of $2000 \text{ to } 3000 \text{ \AA}$ and that at a current of 1 ma/cm^2 will increase the material density in this layer by 10% in 3 seconds. For an angle of 78° from the normal to the surface, to obtain a 2 kW/cm^2 flux from a 10 kW/cm^2 beam, the corresponding depth is of the order of $400 \text{ to } 600 \text{ \AA}$. In addition to sputtering, blistering of the surface would be expected to occur.

The R&D Center has experimental facilities to work with liquid lithium metal as shown on page A-115. If an intermediate liquid-metal heat exchange fluid, such as the sodium-potassium eutectic, were found to have merit for the beam-dump design, such facilities could be easily adapted to any R&D program.

WESTINGHOUSE ELECTRIC CORPORATION

Dr. George F. Mechtlin
Vice President
Research & Development

Westinghouse R&D Center

To prepare to meet, and help define, the future research and development needs of the Corporation, the Westinghouse R&D Center comprises a planning group and eight R&D divisions, two of which form the Design and Development Center. The various divisions and groups are characterized on these pages by examples of current programs and services, by expertise, and by a list of departments within each of the groups.

Mr. J. H. Bechtold, Mgr.

MATERIALS SCIENCE R&D DIVISION

Typical Programs and Services

- Ceramics and metals for high-temperature gas turbines
- Corrosion-resistant materials for energy systems
- Advancement of cladding and fuel technology for commercial reactors
- Advanced extractive metallurgy processes
- New welding techniques
- New magnetic core materials and fabrication
- Formulation of new electrical active ceramics
- Development of non-destructive examination techniques
- Performance of failure analysis
- Recommendation of material usage
- Thermal and electrical insulation
- High-temperature refractories

Division Expertise

- Metallurgy
- Ceramics
- Magnetics
- Glass
- Concrete
- Remote metallography
- Optical & electron metallography
- X-ray diffraction
- Mechanical testing
- Magnetic testing
- Ultrasonic, eddy-current, and mag-particle inspection techniques
- Fractographic analysis
- Melting, casting, welding, heat-treating, coating, and processing of metals, glasses, ceramics, and concrete
- Thermodynamics and kinetics of metallurgical reactions

Departments

- Metallurgy
- Magnetics
- Ceramics & glasses
- Materials evaluation & application
- Nuclear materials
- Structural behavior of materials

Dr. G. W. Wiener, Mgr.

Departments

- Energy systems analysis
- Chemical engineering
- Mechanics
- Electrochemical energy systems
- Heat transfer and fluid dynamics

Typical Programs and Services

- Coal gasification and combustion
- Examination of gas turbine corrosion, combustion, erosion, and deposition
- Nuclear steam generation
- Uranium extraction
- Nuclear fuel processing
- Nuclear power plant radioactive waste-management systems

Dr. R. D. Haun, Mgr.

Departments

- Optical technology
- Gas lasers
- Crystal science and technology
- System sciences
- Nucleonics, gas physics, and high voltage technology
- Power interruption and lamp technology
- Special projects

ENERGY SYSTEMS R&D DIVISION

- Investigations of fluid systems
- Studies of aerodynamic noise-generation phenomena
- Studies of power and cooling cycles
- Flow-induced vibration of nuclear-reactor internals
- Seismic analysis
- Finite-element structural analysis of equipment
- Studies in wear, fretting, and fatigue
- Energy conservation studies and applications
- Solution mining hydraulics and chemistry
- Solar thermal electric power generation
- Wind power generation
- Residential and industrial heat pumps
- Hydrogen generation by electrolysis
- Basic turbomachinery research
- Heat pump research
- Heat exchange system development
- Magnetohydrodynamics research
- High-temperature fuel cells

- Load-leveling batteries for utility systems
- Batteries for electric vehicles
- Program management for energy conservation and utilization
- Creep and fatigue analysis and testing
- Solar heating and cooling of buildings

Division Expertise

- Chemical engineering
- Thermodynamics
- Process development & evaluation
- Fluid-particle interaction
- Heat transfer
- Fluid dynamics
- Shock and vibration
- Mechanics of materials
- Lubrication mechanics
- Finite-element stress analysis
- Electrochemical energy storage
- Acoustics and noise control
- Program management
- Energy systems analysis

APPLIED SCIENCES R&D DIVISION

Typical Programs and Services

- Laser isotope separation
- Laser synthesis of materials
- Optical physics and optical design
- Integrated optics
- High power lasers
- Fusion power technologies
- Charged particle beams
- Gas discharge physics
- High and low pressure vapor-lamp physics
- Current interruption
- High voltage technology
- Nucleonics
- Crystal growth
- Phosphors
- Reliability

- Optimization
- Statistics
- Mathematical modeling of fields and systems
- Economics
- Business modeling
- Technological forecasting
- Human sciences

Division Expertise

- Applied physics
- Crystal growth
- Systems science
- Mathematics
- Economics/business modeling
- Human sciences

GENERAL SCIENCES R&D DIVISION

Departments

- Materials testing and evaluation
- Analytical chemistry
- Computer sciences
- Vacuum physics
- Biology
- Instrument laboratory
- Standards laboratory
- Patent and library services
- Design/drafting
- Glassblowing and machining
- Safety and security
- Plant engineering and services
- Purchasing
- Medical

Typical Programs and Services

- Tests on materials under simulated conditions in laboratory and industrial operating conditions such as crack-growth studies on high-pressure, high-temperature water to simulate pressure-vessel conditions
- Development of novel analytical procedures such as a spectrophotometric technique to measure trace amounts of sulfur
- Design of optimization program for turbine blade geometries
- Improvement in incandescent lamp processing and gettering
- Bioassay screening tests of suspected mutagenic or carcinogenic compounds

Mr. S. A. Rosecrans, Mgr.

Division Expertise

- Materials testing
- Classical and exotic analytical chemistry
- Information storage and retrieval
- Toxicology
- Computer science
- Vacuum technology

Dr. D. R. Muss, Mgr.

SOLID STATE R&D DIVISION

Departments

- Superconductivity and cryogenics
- Devices and materials research
- Semiconductor research
- Microelectronic devices
- Thin film devices

Typical Programs and Services

- Superconducting materials growth and characterization
- Superconducting cable, transformer, coil, and machine design

- Cryogenic engineering
- Superconducting electronic devices
- Magnetic and acoustic wave studies and device development
- Ion implantation in semiconductors
- Simulation and theoretical analysis of neutron damage using high energy ion bombardment
- Infrared focal plane sensor arrays, hybrid and monolithic
- Silicon, CdS, and MIS solar cell development
- Design and development of high power semiconductor devices
- Charge coupled devices
- Silicon crystal growth
- Microwave device development
- Matrix-addressed thin film display devices
- Computer-based image analysis

Division Expertise

- Superconducting film growth and characterization
- Magnetic field theory
- Superconducting and cryogenic systems
- 180-kV ion implantation
- Radiation damage under simultaneous bombardment by He⁺ and Si⁺
- Ion beam milling, DC, RF and reactive sputtering
- Flash and electron beam evaporation of metals, dielectrics, and semiconductors
- Intermetallic semiconductor crystal and epitaxial film growth
- Complete microelectronic device fabrication
- Microwave device characterization

Dr. J. K. Hulm, Mgr.

Departments

- Electrotechnology
- Insulation chemistry
- Physical and inorganic chemistry
- Polymers and plastics
- Electrical performance of insulating materials

CHEMICAL SCIENCES R&D DIVISION

Typical Programs and Services

- Electrical insulation
- Lubricants
- Reinforced plastics
- Films
- Foams
- Elastomers
- Gases
- Paints and varnishes
- Wire enamels
- Adhesives
- Polymer synthesis
- Electrodeposition
- Liquid metal chemistry
- Accelerated aging tests
- Voltage endurance studies
- Mass spectroscopy of gases, liquids, and solids
- Corrosion protection
- Coating powders
- Casting and molding compounds

- Dielectric performance under simulated environmental conditions
- Current collection
- Laser chemistry
- Liquid metal pumps
- Homopolar machines
- Electromagnetic systems

Division Expertise

- Polymer chemistry
- Surface chemistry
- Electrochemistry
- Dielectric phenomena
- Dielectric materials
- Advanced electrical machines

R&D PLANNING

Departments

- Industry products
- Public systems
- Power systems
- Marketing and communications
- Planning administration
- Financial services

Division Expertise

- Program formulation and coordination
- Planning
- Marketing
- Communications
- Accounting
- Business systems
- Contract administration

Typical Programs and Services

- Ensure R&D program is responsive to corporate needs and is consistent with allocated resources
- Formulate and coordinate R&D programs sponsored by Westinghouse companies
- Monitor allocation of funds for all R&D projects
- Project future R&D activities and the resources needed for them
- Formulate the corporate R&D program
- Provide accounting & budgeting services
- Provide contracts management services
- Assemble strategic plans for the R&D Center

- Provide marketing services for outside funding
- Disseminate information on technical output of the R&D Center

Dr. J. W. Cottman, Director

DESIGN & DEVELOPMENT CENTER

Mr. R. G. Holdbrook, Mgr.

MECHANICAL R&D DIVISION

Division Expertise

- Electro/mechanical product design & development
- Factory automation
- Process design, development, and implementation
- Electro/mechanical/manufacturing research

Departments

- Product design
- Process design
- Manufacturing design
- Operations
- Advanced development laboratory

Typical Programs and Services

- Mechanisms and circuit breakers
- Fan and compressor development
- Heating and cooling equipment
- Factory automation equipment
- Producibility studies
- Process & method instructions

Mr. R. E. LaCroix, Mgr.,
Design & Development Center

- Plant design and layout
- Field servicing equipment and automation
- Factory energy conservation programs
- Manufacturing problem solving
- Factory tooling
- Robotics
- Automated inspection systems
- Pilot line design and operation

Dr. F. T. Thompson, Mgr.

ELECTRONICS R&D DIVISION

- Computer-aided design
- Solid-state power controls & equipment
- Power electronics applications
- Digital & analog systems
- Industrial controls
- Sensor applications
- Communications & display systems
- Sonic technology
- Electrical machine theory
- Hybrid computer simulation
- Theoretical fluid mechanics

Typical Programs and Services

- Microprocessor applications
- Automated assembly and inspection systems
- Computer-aided design for electronics systems, finite element analysis, mechanical systems
- Automated graphics systems
- High power thyristor arrays

Departments

- Automation systems lab
- Power electronics lab
- Equipment design
- Control & instrumentation lab
- Advanced systems lab
- Special projects

Division Expertise

- Project management
- Equipment design
- Manufacturing electronics
- Computer-based automation
- Control systems
- Programmable automation

- Solid-state circuit breaker controls
- Static VAR systems
- Inverters and frequency changers
- Variable speed drives
- Short circuit current limiting
- Automated distribution systems
- Solid-state elevator systems
- Solid-state metering
- Nuclear plant instrumentation & controls
- Large scale integration
- Computer design and development
- Lamp and lighting controls
- Solid-state relaying
- Compressed information storage
- Secure communications
- Sensors in manufacturing control
- Acoustic control systems
- Ultrasonic instrumentation

FUSION REACTOR DESIGN AND DEVELOPMENT

- SYSTEMS DESIGN AND INTEGRATION
- FUSION SYSTEMS CODE DEVELOPMENT
- DIVERTOR TECHNOLOGY
- HIGH HEAT AND PARTICLE FLUX TEST PROGRAM
- LIQUID METALS TECHNOLOGY PROGRAMS
- REACTOR PLANT REPAIR AND MAINTENANCE METHODOLOGY

NEUTRAL BEAM TECHNOLOGY DEVELOPMENT CAPABILITIES

- BEAM LINE SYSTEM DESIGN
ORNL-TFTR BEAM LINE SYSTEM DESIGN
- MIRROR PROGRAM NEUTRAL BEAM SUPPORT
ADVANCED CONCEPTS DEVELOPMENT
- ADVANCED FUEL NEUTRAL BEAM SYSTEM DESIGN
SAFFIRE DESIGN SUPPORT
- ION SOURCE FABRICATION
20 keV, 0.5 A, CW SOURCE FOR BNL
- WATER COOLED CATHODE DEVELOPMENT AND TEST
HIGH HEAT FLUX TEST LOOP
- MATERIALS AND COMPONENT TESTING
HIGH HEAT FLUX TEST LOOP

WESTINGHOUSE HAS A WIDE RANGE OF EXPERIMENTAL
FACILITIES AVAILABLE TO SUPPORT THE FUSION D&T PROGRAM

- SUPERCONDUCTIVITY AND CRYOGENICS
- MATERIALS DEVELOPMENT AND TEST
- LIQUID METAL TECHNOLOGY
 - FLUID FLOW AND HEAT TRANSFER
 - PURITY CONTROL AND INSTRUMENTATION
 - CHEMICAL PROCESSES AND INTERACTIONS
 - SAFETY ISSUES
 - COMPONENT DEVELOPMENT AND TEST - PUMPS, VALVES, HEAT EXCHANGERS, STEAM GENERATORS
- PARTICLE AND ENERGY FLUX TESTING
 - NEUTRAL BEAM SYSTEM COMPONENTS
 - DIVERTOR COLLECTOR COMPONENTS
 - FIRST WALL COMPONENTS
 - WAVEGUIDES AND MIRRORS
- HIGH VOLTAGE TEST FACILITIES
- VACUUM ARC RESEARCH
 - INTERRUPTERS AND SWITCHES
 - CONTACTOR EROSION AND SURFACE PHYSICS
 - UNIPOLAR ARC RESEARCH
- PLASMA DIAGNOSTICS
 - FULL RANGE OF LASER R&D
 - BOLOMETER DEVELOPMENT
 - NEUTRON DIAGNOSTICS
- HEAT TRANSPORT/CONVERSION TECHNOLOGY
 - STEAM-RANKINE CYCLE
 - LIQUID METAL RANKINE CYCLE
 - GAS-BRAYTON CYCLE
 - MHD CONVERSION

EXPERIMENTAL LITHIUM EXPERIENCE

- LITHIUM VAPOR TRANSPORT PREDICTED AND MEASURED FOR SCALED FMIT ACCELERATOR DRIFT TUBE
- LITHIUM IONIZATION DETECTOR DEVELOPED AS A SAFETY ANNUNCIATOR FOR FMIT
- LITHIUM CONCRETE REACTIONS STUDIED BY REACTION CALORIMETRY
- LITHIUM VAPOR/AEROSOL - LASER INTERACTIONS
- LITHIUM COMPATIBILITY WITH POLISHED SIC LASER MIRRORS
- MODIFIED WESTINGHOUSE COMMERCIAL ON-LINE OXYGEN AND HYDROGEN METERS SHOWN FEASIBLE FOR LITHIUM APPLICATION
- ON-LINE NITROGEN METER CONCEPTUALIZED AND SCHEDULED FOR TEST
- LITHIUM FALL EVALUATED FOR TOKAMAK POLOIDAL DIVERTOR PARTICLE TRAP
- EXPERIMENTAL MEASUREMENT OF RADIANT ENERGY DEPOSITION IN FLOWING LITHIUM

HIGH HEAT AND PARTICLE FLUX TEST PROGRAM

OBJECTIVE

TO DEVELOP A GENERAL PURPOSE EXPERIMENTAL CAPABILITY TO SCREEN AND EVALUATE POTENTIAL MATERIALS AND CONFIGURATIONS FOR APPLICATIONS INVOLVING HIGH HEAT AND PARTICLE FLUX ENVIRONMENTS.

APPLICATIONS

- NEUTRAL BEAMLINE COMPONENTS - GRIDS, CATHODES, BEAM DUMPS, CALORIMETERS, SENSORS
- DIVERTOR COLLECTOR COMPONENTS
- FIRST WALL AND LIMITER COMPONENTS
- RF ANTENNAS AND DIAGNOSTICS COMPONENTS
- BASIC MATERIALS AND HEAT TRANSFER STUDIES

TECHNIQUES AND EQUIPMENT

- ELECTRON BEAM SOURCE: 72 kW AT 150 keV
45 kW ON TARGET
- ION BEAM SOURCE: 1 kW AT 150 keV
- HIGH HEAT FLUX WATER HEAT TRANSFER LOOP
- ARC HEATER SOURCES

WESTINGHOUSE PLASMA ARC HEATER TECHNOLOGY
CAPABILITIES AND APPLICATIONS

- COMMERCIAL ARC HEATER TECHNOLOGY
STEADY-STATE POWER RATINGS: 500 TO 10,000 kW
CHEMICAL PROCESS INDUSTRY APPLICATIONS

- EXPERIMENTAL SIMULATION OF PLASMA-SURFACE EFFECTS
He - H₂ GAS MIXTURES
CAN ACHIEVE 3-5 kW/cm² ON 45-80 cm² TARGETS

M. D. Sabrow, R. Draper
Westinghouse Electric Corporation, Research Laboratories
Pittsburgh, PA 15235

F. E. McKenzie-Willson
Brookhaven National Laboratories
Upton, NY 11973

R. M. Brada
Westinghouse Electric Corporation, Industrial and Government Tube Division
Horseshoe, NY 14855

SUMMARY

This paper describes a facility built at the Westinghouse Electric Corporation Research Laboratories to study nucleated boiling water cooling of devices subject to surface heat fluxes up to 5 kW/cm^2 . Copper will radiate 24 W/cm^2 at its melting temperature, and its thermal conductivity is $4 \text{ W/cm}^2\text{C/cm}$. Thus we are in a regime where radiation is negligible and temperature gradients of the order of a 1000°C/cm are required to cool even copper. This implies that the substrate must be thin and only a narrow boundary layer in the cooling fluid is active in cooling the surface.

The cooling of surfaces subject to high heat fluxes ($1.5\text{--}5 \text{ kW/cm}^2$) is encountered in several devices important to the fusion program. Diverters, Grid Structures for Positive Ion Sources, and Cathodes for Negative Ion Sources are three such devices. The first application of the facility discussed here will be to the testing and development of cathodes to be used in the BNL surface-effect negative ion source. The design of these nucleated boiling water cooled cathodes discussed in Paper 03-10 of this Symposium

The High Flux High Pressure Nucleated Boiling Water Heat Transfer Facility consists of three main systems: the High Flux Source, the High Pressure Cooling Loop and the Control and Diagnostic System.

High Flux Source (e-beam)

The surface heat flux is simulated by an electron beam. The beam parameters are listed in Table I. If an average heat flux is simulated by scanning a focused beam across a surface the temperature rise in the deposition layer during the dwell time of the beam must be determined.

If $h_c \text{ W/cm}^2\text{C}$ are deposited in a surface layer of thickness l the temperature in the deposition layer is given by

$$T = \frac{j}{k} \frac{d\theta}{dt} \left\{ 1 - 2j^2 \operatorname{erfc} \frac{k-x}{2\sqrt{kt}} - 2j^2 \operatorname{erfc} \frac{l+x}{2\sqrt{kt}} \right\} \quad (1)$$

if $j/\sqrt{kt} \ll 1$ to first order this reduces to

$$T = \frac{j}{k} \frac{l}{\sqrt{kt}} \quad (2)$$

If an electron beam of current density j and voltage V deposits its energy in surface layer of thickness l then equation 2 can be written

$$T = \frac{jV}{k} \frac{l}{\sqrt{kt}} \quad (3)$$

where j is the beam current density in amps/cm^2

k is the thermal conductivity in $\text{W/cm}^2\text{C}$

k is the thermal diffusivity in cm^2/sec

and t is the dwell time of the beam in sec.

For copper $k = 4$; $k = 1$ with a 150 KV beam focused to $.5 \text{ A/cm}^2$ a dwell time of 25 msec results in a temperature rise of the deposition zone above ambient of 25°C . This is equivalent to scanning a $4\text{cm} \times 10\text{cm}$ surface (the BNL cathode) at an average power loading of 3 kW/cm^2 at a scan rate of 10Hz . If the beam is focused to higher current densities of the scan rate is slower the thermal ripple on the ambient temperature may be significant, but for faster scan rates the beam simulates D.C. loading well.

The electron beam system is shown in Figure 1. It consists of a 150 KV 300 ma SF_6 insulated power supply (a), an oil insulated set of auxiliary supplies for the e-beam gun (b), diffusion pumps (c), a $1\text{m} \times 2\text{m}$ vacuum chamber (d), and the e-beam gun (e). Looking into the vacuum chamber in Figure 1, at the top of the chamber is the final deflection coil for the e-beam (f). The beam can be deflected 30° at rate as high as 10kHz . The beam rests in the beam dump (g) and is deflected across the test section. The scan time can be adjusted independently of dwell time of the beam in the dump. This controls the average power to the test section for fixed beam power. The beam can be rastered I.V. style over a surface, but in the configuration shown the beam is focused to the width of the test section and scanned in one dimension. There is a mirror system (h) which allows the surface being heated to be viewed while the beam is scanning by providing sufficient attenuation of the x-rays along the viewing path. There is a low pressure water system (j) that cools the beam dump and sample mask (i) and a high pressure water system (k) for the nucleated boiling loop. Figure 3 is a view of the test surface as seen through the window showing the cathode (1) through the slot in the mask (i). Twelve electrical feedthroughs are available for diagnostic data.

High Pressure Cooling Loop

Part of the cooling loop can be seen in Figure 4. Figure 5 is a schematic diagram of the loop. The operating parameters are listed in Table I. To provide a nonpulsating flow the pump operates at constant speed. The flow rate in the main loop is controlled by the flow in the water cooled pump bypass loop. The pump provides the head for the pressure drop across the test section. The ambient pressure required to keep the coolant in the liquid phase is provided by the nitrogen pressurizer which also has its own water cooled heat exchanger. The main heat balance is provided by an electric preheater and an air cooled heat exchanger. This allows the ambient loop temperature to be independent of the heat loading of the test section. The test section can be isolated from the loop by three fast solenoid valves.

Control and Diagnostics

The loop operates under the active control of a Texas Instrument programmable controller. During startup the test section is bypassed until all ambient flow, pressure and temperature conditions are established. If during startup or during an actual test the controller cannot maintain parameters within safe limits it will shut down any part of the system necessary to maintain the integrity of the system. There are mechanical backups which will shut down or vent the system if the controller cannot hold the safe limits. If an excess pressure is detected in the vacuum chamber the e-beam shuts off, the e-beam gun is valved off from the main chamber and the high pressure loop isolates itself from the test section.

During a test the data gathered consists of beam power, scan rate, temperature profile along test section, photographs of test surface, flow rate, pressure, water temperature heat flux, and temperature rise of the water through the test section. We also plan to record the acoustical pattern of the inlet and outlet flow to try to detect the onset of thermal runaway before it actually occurs.

At the writing of this paper the system is in the process of being debugged.

Table I

High Flux High Pressure Nucleated Boiling Water Heat Transfer Facility

Present Configuration:	Cooling studies of .4cm x 10cm cathode surface loaded to 1-3 KW/cm ² Water
Working Fluid:	Water
Maximum Working Pressure:	400 psi
Maximum Head:	700 ft. H ₂ O
Working Temperature:	300°F
Maximum Temperature:	350°F
Maximum Flow Rate:	7 gpm (at 700 ft. head rise)
Maximum Heat Flux:	72 KW
Heat Inputs:	Test Section 45 KW Pre Heater 40 KW
Heat Removal:	12 KW air controlled heat exchanger Main loop Water cooled auxiliary heat exchangers for pump and pressurizer
Heat Source:	Electron beam 150 KE 5-300 ma
Input Heat Flux:	50 W/cm ² - 4.5 x 10 ⁶ W/cm ²
Maximum Scan:	20 cm X or Y
Scan Speed:	1 cm/sec to 1 cm/.sec
Rep Rate:	10Hz to 10KHz
Control:	Texas Instrument Programmable Control System

See page A-99

Figure 1 - e-beam system

See page A-100

Figure 2 - Test chamber

Figure 3 - Test section seen through chamber window

See page A-101

Figure 4 - High Flux High Pressure Nucleated Boiling
Water Heat Transfer Facility

E-BEAM SYSTEM

TEST CHAMBER

A-100

HIGH-FLUX, HIGH-PRESSURE, NUCLEATE-BOILING-WATER HEAT-TRANSFER FACILITY

A FUSION HARDWARE DEVELOPMENT FACILITY

R. W. Stooksberry and J. R. Eason
Westinghouse Fusion Power Systems

The design and development of reliable fusion system components present some formidable problems. Device first-wall, limiter, divertor collector, neutral beam dump and energy recovery elements have common or related design requirements which are governed by ion or neutral particle interaction effects. These effects include sputtering, hydrogen and impurity recycling, chemical reactions, surface heating, and thermal cycling. Plasma surface reactions observed in operating tokamaks emphasize the importance of these effects and others on the discharge characteristics and the associated useful lifetime of materials currently in use.

An experimental facility is being constructed at the Westinghouse Electric Corporation which will support the fusion community's research and development activities in the following areas:

- Development of plasma limiter, divertor collector, and first-wall elements
- Development of neutral beamline components: beam dumps, ion source grids and energy recovery collectors
- Development of computer based data acquisition and control methods for large neutral beamlines
- Research to provide the basic data necessary to characterize the performance of selected materials subjected to both ion and electron beam bombardment

The objectives of this fusion component research and development project are stated below.

Neutral Beamline Elements (Positive and Negative Ion Programs)

- Evaluate cathodes for the negative ion program
- Evaluate ion beam dumps and energy recovery electrodes
- Perform research and engineering tests to support technology development in the following areas:
 - 1) Grid materials
 - 2) Power handling
 - 3) Ion/plasma sources
 - 4) Vacuum pumping
 - 5) Computerization of the beamline
- Perform electrical system simulation of a large beamline to evaluate conditioning and fault protection
- Evaluate calculational tools that are being developed for neutral beamline systems

Limiter/Divertor/First-Wall Investigations

- Perform research and engineering tests to support technology development associated with the following:
 - 1) Surface heat flux
 - 2) Ion/neutral sputtering
 - 3) Gas absorption/desorption
 - 4) Gettering techniques
 - 5) Composite material evaluation under electron and ion bombardment
- Engineering tests of candidate materials
- Development of "novel idea" techniques including:
 - 1) High power applications (e.g., moving collector concepts)
 - 2) Selective He "ash" removal with hydrogen recycle

Perform Research and Development Which Considers Both The Commonality and Uniqueness of the Various Problem Areas and Contributes to the Development of Appropriate:

- Instrumentation and diagnostic measurement techniques
- Plasma sources and ion accelerator systems which permit material evaluation and component development in the energy range of 20 eV to 150 keV

The hardware development facility utilizes the following:

1. Electron Beam Surface Heat Flux Source¹

- 45 kW electron beam (300 mA maximum at 150 keV)
- Beam area at target approximately 0.25 cm^2 (stationary beam spot)
- Magnetic beam sweeping system with scan times for a 20 cm target length down to 0.4 ms, allowing steady state flux simulation or repetitive pulsing operating modes
- Sample mounting stage with interfacing to high pressure cooling loop and diagnostics for temperature and pressure measurement
- Currently operable in conjunction with cooling loop for high heat flux removal tests
- Second beam sweeping magnet to be added, providing perpendicular scanning over 20 cm for wide or variable shape samples.

Page A-100 shows target area inside the electron beam vacuum chamber with target in place.

2. High Pressure Water Cooling Loop¹

- Achievable water temperatures to 350°F and pressures to 400 psi

- Flow rates to 7 gpm at 700 ft head H_2O
- 30 kw preheater for sample inlet temperature regulation
- Automatic control via TI-PM680 process controller for steady state heat removal or manually controllable for pulsed heat load experiments
- Currently operable in conjunction with electron beam heat source
- Future operation with 1.5 kw ion beam system is planned
- Continuous monitoring of all necessary pressures and temperatures for complete experiment interpretation.

Figure 2 shows a schematic of the cooling loop illustrating the basic functional components. Page A-99 shows the complete cooling loop and control system in place.

3. A 1.5 kw/150 keV light ion accelerator facility² under construction

- A Siemens duoplasmatron ion source capable of light ion currents ranging to 10 mA (pulse and CW operation)
- An extraction-focus-acceleration system capable of operation over a range extending to 150 keV
- A bending magnet for mass-energy selection and beam switching
- A differentially pumped (Dr-Al) scattering chamber and associated detection instrumentation (i.e., backscatter detector, residual gas analyzer, etc.)
- A direct imaging ion probe mass spectrometer for off-line target analysis
- A 565 LSI 11/23 microprocessor based data acquisition and control system interfaced via CAMAC to the instrumentation and ion accelerator. This system is designed to operate in a manner similar to the system³ now operational on the Princeton PLT neutral beam test stand

Figure 4 is a schematic of the beamline as it will be initially constructed. Figures 5 and 6 show an overall view of the facility under construction and the ion source and Einzel lens assembly respectively.

4. A Westinghouse DC and reactor facility capable of providing high heat fluxes ($10\text{--}5\text{ kW/cm}^2$) over large areas ($15\text{--}20\text{ cm}^2$). Figure 7 shows a cutaway view of a Westinghouse rotating and stabilized, and reactor.

REFERENCES

1. The Design and Testing of a Nucleated Boiling Water Cooled Diode for the BNL Negative Ion Source, M. D. Mahanow, R. Orsler, R. G. McNamee-Wilson, R. W. Brucka, 6th Symposium on Engineering Problems of Fusion Research, San Francisco CA, November 13-16, 1973.
2. A Versatile Ion Beam Facility for Fusion Research and Development, R. W. Stokksberry, J. P. Eason, R. E. Gold, W. Griffiths, 1980 IEEE International Conference on Plasma Science, May 19-21, 1980, Madison WI, p 26.
3. R. W. Stokksberry, J. E. Possmaier, M. Katz, IEEE Transactions on Nuclear Science, NS26, No. 4, (1979) p 4623.

FIGURE 2. HEAT FLUX EXPERIMENT USING ELECTRON BEAM AND HEAT DISSIPATION LOOP

Figure 4. 100 Hz/0.18 A BEAM COLLECTOR FACILITY (3.5 MeV)

Figure 6. Duplication Ion Source and Focusing Assembly

Figure 7. Westinghouse Self-Stabilizing Arc Heater.

What We Do...

• Auger Analysis

• Crystallography

• Electron Diffraction

• Electron Microprobe Analysis

• Electron Channeling

• Energy Dispersive Analysis

• Energy Loss Analysis

• Hardness Measurements

• Image Analysis

• Interface Microscopy

• Ion Milling

• Light Section Microscopy

• Light Microscopy

• Metallography

• Photomicrography

• Particle Size Analysis

• Phase Contrast Microscopy

• Residual Stress Analysis

• Replica Electron Microscopy

• Scanning Electron Microscopy

• Scanning Transmission Electron Microscopy

• Sputter Coating

• Stereo Microscopy

• Thin Film Analysis

• Transmission Electron Microscopy

• Ultraviolet Photoelectron Spectroscopy

• X-ray Diffraction

• X-ray Photoelectron Spectroscopy

...And How We Do It

Whom To Call

Dr. Ram Kossowsky
Manager - - - - - 236-3684

Dr. J. Schreurs, R. Palmquist
Auger, X-Rays, ESCA - - - - - 236-3655

Dr. M. Baron
Physics of Metals - - - - - 236-7497

C. J. Dorsch
Instrumentation - - - - - 236-7357

R. M. Slepian
Metallography - - - - - 236-3571

R. C. Kuznicki
X-Ray Diffraction - - - - - 236-7297

R. Palmquist, J. J. Haugh
Electron Microprobe - - - - - 236-7623

J. P. Yex
Quantitative Metallography - - - 236-3531

C. W. Hughes
Scanning Transmission
Microscopy - - - - - 236-3549

T. J. Mullen
Scanning Microscopy - - - - - 236-7623

Layout and Design by T.S. Petrichuk

Westinghouse R&D Center • 1310 Beulah Road • Pittsburgh, Pennsylvania 15235

EXPERIMENTAL LITHIUM EXPERIENCE AT THE WESTINGHOUSE R&D CENTER

- LITHIUM VAPOR TRANSPORT PREDICTED AND EXPERIMENTALLY MEASURED FOR SCALED FMIT ACCELERATOR DRIFT TUBE
- LITHIUM FALL EXPERIMENTALLY EVALUATED FOR TOKAMAK POLOIDAL DIVERTOR PARTICLE TRAP AND ICF FIRST WALL
- LITHIUM CONCRETE REACTIONS STUDIED BY REACTION CALORIMETRY
- LITHIUM COMPATIBILITY WITH POLISHED SiC LASER MIRRORS EVALUATED
- LITHIUM VAPOR/AEROSOL LASER INTERACTIONS STUDIED EXPERIMENTALLY
- LITHIUM IONIZATION DETECTOR DEVELOPED AS SAFETY ANNUNCIATOR FOR FMIT
- MODIFIED WESTINGHOUSE COMMERCIAL ON-LINE OXYGEN AND HYDROGEN METERS SHOWN FEASIBLE FOR LITHIUM APPLICATION
- ON-LINE TRITIUM RECOVERY SYSTEMS BEING INVESTIGATED FOR BRED FUEL EXTRACTION FOR LITHIUM COOLED CTRs
- LITHIUM WETTING OF DIVERTOR AND FIRST WALL SCREEN SURFACES STUDIED
- EXPERIMENTALLY MEASURED RADIANT ENERGY DEPOSITION IN FLOWING LITHIUM
- PRESENTLY PLANNING ICF FIRST WALL LITHIUM JET: PLASMA MOMENTUM INTERACTION STUDY
- CONDUCTED PARTICLE BEAM CESIUM TARGET AND CHARGE EXCHANGE EXPERIMENTAL STUDY FOR BNL
- CONDUCTED LIQUID METAL MIST SPRAY TESTS FOR CHEMICAL REACTANTS AND DIVERTOR CURTAINS
- EXPERIMENTALLY STUDYING CORROSION INHIBITION OF STRUCTURAL MATERIALS IN LITHIUM
- ON-LINE IMPURITY MONITORING SYSTEM TO BE SUPPLIED FOR FMIT LITHIUM TEST LOOP (ELS)

Organization: McDonnell Douglas
Astronautics Company-St. Louis

Address: P.O. Box 516
St. Louis, MO 63166

Phone: (314) 576-8253

Contacts: Donald L. Kummer, Director
Fusion Energy

Dale E. Defreese, Manager
Fusion Systems

Bill Briggs, Program Development

Clarence Trachsel, Design

Dave Morgan, Design

James H. Painter, Senior Technical Specialist
Arc Heater Laboratory
(314) 232-5443

Walter A. Rinehart, Branch Chief Technology
Arc Heater Laboratory
(314) 232-5443

General Remarks:

The McDonnell Douglas Fusion Group designed and fabricated the source on the IFI-2 neutral beam injector, now being tested at LBNL.

They have designed the following heat absorbing devices: First Wall, Beam Dump and Limiter for General Atomic D-1; Starfire Limiter for Argonne; and actively-cooled armor for INOR. These designs are described in pages A-112 through A-136.

They have the capability to test at high heat fluxes with the use of their Arc Heater Facility. They have two arc heaters: The High Impact Pressure Facility and the Large Core Arc Tunnel Facility. These heaters are usually used to simulate reentry conditions. Heat flux and target size capabilities are shown on pages A-137 and A-138.

They have an infrared television system which is used to show temperature distribution. Read out is from a color screen. A sample picture and product information are on pages A-139 through A-141.

MOAC DESIGN ACTIVITIES

- GENERAL ATOMIC TNS
- FIRST WALL, BEAM DUMP & LIMITER
- ARGONNE NATIONAL LAB
- START-UP LIMITER

CLARENCE TRACHSEC

314-441-1970

TNS ARMOR TILE

15-775

FIGURE 15-4-12 ARMOR TILE SECTION

ARMOR TILE SECTION

()

4

1

2

3

4

5

6

7

8

9

10

11

12

1

2

3

1

2

3

4

5

)

1

1

()

[The page contains extremely faint, illegible text arranged in columns, likely representing a ledger or a multi-column form.]

17 - 5

105
5.16
2.16
1.11

[illegible]

1. The first step is to identify the problem or question that needs to be answered. This involves understanding the context and the specific requirements of the task.

129

[illegible]

Table 1. Temperatures ($^{\circ}\text{C}$) in Limer Wall

Material	T_0	T_i	T_{ave}	T_g	T_{ref}	ΔT
Tantalum, 10 MW	779	193	236	26	145	91
Tantalum, 10 MW	743	192	223	201	143	150
Vanadium, 10 MW	463	191	312	242	144	168
Carbon, 10 MW	196	142	189	14	140	49

Table 2. Material Properties for Limer Wall Temperature

Material	E		ν	α	YS		US	
	$\text{Pa} \cdot 10^3$	$\text{Pa} \cdot 10^6$		$10^{-6}/^{\circ}\text{C}$	$\text{Pa} \cdot 10^3$	$\text{Pa} \cdot 10^3$	$\text{Pa} \cdot 10^3$	$\text{Pa} \cdot 10^3$
Tantalum, 10 MW	1.81	76.2	0.3	6.6	245	10	141	17
Tantalum, 10 MW	1.63	19.2	0.3	7.3	270	14	130	21
Vanadium, 10 MW	1.17	16.9	0.3	10.6	200	10	100	17
Carbon, 10 MW	0.96	13.9	0.3	20.0	141	13	100	17

(1) T_0 is the initial temperature T_{ref} .

Table 3. Stresses at Critical Points in Limer

Material	$\sigma_p^{(1)}$		$\sigma_p^{(2)}$		σ	σ/σ_y
	MPa	MPa	MPa	MPa		
Tantalum, 10 MW	-12	-38	125	142	143	0.73
Tantalum, 10 MW	12	3	0	140	171	1.00
Vanadium, 10 MW	-12	-38	108	146	137	1.19
Carbon, 10 MW	-12	-38	102	157	178	0.41

(1) Compression due to pressure.

(2) Compression due to temperature.

THIN FILM COOLANT AT FORCED SKIN COOLANT TUBES

MATERIALS		STRUCTURE	
SKIN	INTEROSTAL	SKIN	INTEROSTAL
(a) Cu	Ti	(a) Cu	Ti
(b) Ti-10Al	Cu	(b) Ti-10Al	Cu
(c) Ti	Cu	(c) Ti	Cu

FOR 5 KW/CM² PEAK HEAT FLUX:

SKIN MATERIAL	SKIN THICKNESS
Cu	250°C
Ti-10Al	650°C
Ti	400°C

CONCLUSIONS

- SKIN FORMED OVER INTEROSTAL
- THIN FILM SKIN, STRUCTURE LIMITED AS SKIN
- COOLANT COULD BE USED IN SKIN

McDONNELL DOUGLAS
CORPORATION

Page 110 per

LIGHTER CONCEPT 2: FORMED SKIN/MACHINED CHANNELS

MATERIALS

	SKIN	CHANNELS	STRUCTURE
(a)	Cu	Cu	Mo: St STL
(b)	Ta-10W	Cu	
(c)	Mo	Cu	

THERMAL PROPERTIES

FOR 5 KW/CM ² PEAK HEAT FLUX:		
COOL	SKIN MATERIAL	SKIN TEMP
H ₂ O	Cu	150°C
H ₂ O	Ta-10W	420°C
H ₂ O	Mo	260°C

MANUFACTURING

- SKIN FORMED OVER PATTERN
- RUBS MACHINED ON LATHE; OR MECHANICALLY MILLED
- SKIN WELDED TO RUBS (IF NEEDED); ASSEMBLY THEN BRAZED TOGETHER
- COATING SHOULD BE ADDED TO RUBS

McDONNELL DOUGLAS CORPORATION

RELATIVELY THERMAL/MECHANICAL ANALYSIS SUMMARY

6 MAXIMUM STEAM STATE SKIN TEMPERATURES

MATERIAL	TEMPERATURE	TEMPERATURE
Mo	400°C	400°C
Ti	400°C	400°C
Cu	250°C	150°C

7 MAXIMUM HEAT FLUX ON LIMITER SHAPE AT 1100 W/CM² (ASSUMING EXPONENTIAL FALL-OFF WITH $q = 1/10$ Q₀ ON OUTBOARD)

8 OUTBOARD FLUX > 2200 W/CM² (T-D VALUE)

9 FLOW VELOCITY IN TUBES: 20 M/S

10 INLET PRESSURE = 450 PSIA; OUTLET PRESSURE = 15 PSIA

11 TEMPERATURE = 1.9 K₂/S (36 K₂/S)

12 PUMP POWER (10 FLOW): 7.5 HP (5500 W)

McDONNELL DOUGLAS CORPORATION

ACTIVELY-COOLED ARMOR CONCEPT FOR INTOR

ACTIVELY-COOLED ARMOR CONCEPT

THE ARMOR CONCEPT CONSISTS OF GRAPHITE TILES WHICH ARE FASTENED TO WATER-COOLED FLAT STRUCTURAL PANELS. THE GRAPHITE TILE SURFACE AWAY FROM THE PLASMA IS COATED WITH FIVE MILS THICK TUNGSTEN BY CHEMICAL VAPOR DEPOSITION (CVD). THE RESULTING BOND IS WHEN THE TUNGSTEN AND GRAPHITE IS THINNER THAN THE GRAPHITE TILE. THE TUNGSTEN COATED GRAPHITE IS THEN BOND TO THE WATER-COOLED STRUCTURE USING TWO TO THREE MILS OF COPPER-SILVER OR SILVER-PAVE ALLOY. THE STRUCTURAL PANEL WOULD BE TUNGSTEN OR POLYIMIDE. TUNGSTEN IS PREFERRED BECAUSE COEFFICIENT OF EXPANSION CAN MATCH THAT OF THE COATED GRAPHITE. COEFFICIENT FOR POLYIMIDE WOULD NOT MATCH AS WELL. REFRIGERANT COOLANT TUBES WOULD BE BOND TO THE PANEL BACK FACE. THE WATER COOLANT WOULD BE LOW TEMPERATURE AND LOW PRESSURE. THE COATING OF TUNGSTEN ON GRAPHITE IS CURRENT STATE-OF-ART AS IS THE BONDING TECH. FABRICATION OF THE COOLED STRUCTURAL PANEL IS ALSO CURRENT. THERE ARE UNKNOWN PROPERTIES OF COOLING AND EFFECT OF RADIATION FROM THE PLASMA. IT IS NOT KNOWN THE TUNGSTEN ON GRAPHITE COATING AND THE EFFECT OF PLASMA CORROSION POWERS ON THE GRAPHITE TILE.

WE HAVE MADE AN INITIAL ASSESSMENT OF THE ACTIVELY COOLED GRAPHITE TILE CONCEPT IN ORDER TO DEFINE THE DESIGN, OPERATING, AND MAINTENANCE REQUIREMENTS. IF SURFACE HEAT FLUXES CAN BE MAINTAINED BELOW ABOUT 400 BTU/HR INCH² THEN THE PROBLEM OF SIGNIFICANT CHEMICAL CORROSION MAY BE AVOIDED. THE APPROXIMATION ASSUMED THAT THE TILE AGAINST PLASMA STATE TEMPERATURES EXCEEDS THE 100 DEGREE FURNACE OF THE CYCLE AND THAT THE THERMAL DISTANCE OF THE NOZZLE IS APPROXIMATE COMPARED TO THAT OF THE GRAPHITE AND THE CONDUCTIVITY. IT IS ALSO ASSUMED THAT THE SURFACE HEAT FLUXES WILL BE MAINTAINED BELOW 400 BTU/HR INCH² IN THE PLASMA STATE. LESS THAN ABOUT THREE BTU/HR INCH² AT THE 10-6 WATTS PER SQUARE CENTIMETER INFLUX. IF AS A CONSEQUENCE THEREFORE CONSIDERATION THE ACTIVELY COOLED GRAPHITE TILE CONCEPT REQUIRES A FLUX TEMPERATURE.

HEAT FLOW AND HEATER AND CONVERTER HEAT FLUXES AT VARIOUS MODEL AREAS
AND HEATER FUEL FLOW (50 KG/KG HYDROGEN)

[illegible]

61-1060-6245

MCDONNELL DOUGLAS AERONAUTICS COMPANY-ST. LOUIS DIVISION

HEAT FLUX AND TARGET SIZE CAPABILITIES OF MOG-ST. LOUIS ARC HEATER FACILITIES OPERATING ON HYDROGEN

ATA

Third Division 780

A world-wide organization.

AGA Thermovision[®] is manufactured by
AGA Infrared Systems AB. The AGA group has
subsidiaries in 28 countries, and representatives
in a further 50 countries.

HEADQUARTERS AGA Infrared Systems AB, S-141 86 Århus, Sweden
EASTERN EUROPE AGA Infrared Systems AB, S-141 86 Århus, Sweden
FRANCE AGA Infrared Systems AB, 100 Avenue de la République, 93000 Paris
ITALY AGA Infrared Systems AB, 100 Avenue de la République, 93000 Paris
UNITED KINGDOM AGA Infrared Systems AB, 100 Avenue de la République, 93000 Paris
WEST GERMANY AGA Infrared Systems AB, 100 Avenue de la République, 93000 Paris
CANADA AGA Infrared Systems AB, 100 Avenue de la République, 93000 Paris
UNITED STATES AGA Corporation, 100 County Avenue, Fairport, NY 11731
OTHER REGIONS AGA Infrared Systems AB, 100 Avenue de la République, 93000 Paris

AGA Infrared Systems AB, S-141 86 Århus, Sweden