HEAT PIPES

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Controllable heat pipes, and designs for automatically maintaining a selected constant temperature would add significantly to the versatility and usefulness of heat pipes in industrial processing, manufacture of integrated circuits, and in temperature stabilization of electronics.

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- Heat transfer
- Heat Pipes
- Heat sink
- Heat flux transformation

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# HEAT PIPES

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INTRODUCTION

How does new knowledge, acquired for one purpose, develop into useful technology having significant impact and benefits to society? This is one case study in a series of detailed investigations tracing the origins of new knowledge developed to solve specific problems of manned space exploration, and its subsequent modification and application to commercial needs.

What differences exist between the technology required for space exploration and the requirements for application to earthly problems? What factors determine the time required to convert new knowledge into viable economic benefits? Various case examples disclose differing patterns of technological development. By comparing the common and contrasting findings it may be possible to understand better how new knowledge generates real benefits.

Starting from a specific "knowledge contribution" previously identified from an analysis of astronaut life support requirements, the origins, adaptations, and eventual significance of the new technology are presented.
HEAT PIPES

Knowledge Contribution Previously Identified

Vapor chamber heat transfer systems using capillary wick pumping had been investigated for thermal control of spacecraft.

As soon as the modern heat pipe was described, space scientists adapted the principle to the cooling of space suits. Metabolic heat could be transferred through the walls of pressure suits and into space. Several innovations were achieved: A controllable heat pipe or "thermal switch" was devised, permitting heat flow to be regulated; flexible heat pipes were developed to maintain contact with the astronaut's skin, yet permit normal body movement inside "hard" suits. Heat pipe wick materials and performance were improved, and techniques were devised to prevent freeze-up of the heat transfer fluid, and permit restarting of heat pipes after solidification of the working fluid.

NASA scientists indicated that controllable heat pipes, and designs for automatically maintaining a selected constant temperature would add significantly to the versatility and usefulness of heat pipes in industrial processing, manufacture of integrated circuits, and in temperature stabilization of electronics.

I. What They Are

The heat pipe is a high-performance heat transfer device, able to transfer heat at high rates, over considerable distances, with almost no temperature drop. The principle of the heat pipe is an amazingly simple one. In its basic form, the heat pipe consists of a sealed tube, lined with a porous capillary wick that is saturated with a volatile fluid as shown in Figure 1. Heat absorbed by the evaporator zone at one end, vaporizes the fluid; vapor flows to the other end where it condenses, giving up heat. The condensed liquid then flows back through the wick to the evaporator.
Figure 1 - Parts and Functions of the Basic Heat Pipe
The heat pipe has been called a thermal "superconductor"—since it can transfer 500 to 1,000 times as much heat as a solid copper conductor of the same size. By using various fluids, heat pipes have been designed to operate at temperatures from glowing incandescence at 3500° F, down to the ultracold, cryogenic region.

Any device that can heat or cool with high efficiency, yet has no moving parts, is completely self-contained, does not rely on gravity, and has extremely fast response time, is ideally suited for thermal control in space—where it has been widely used. Today, heat pipes are also used in scores of ways on earth—in air conditioning, industrial processes, nuclear power generators, electric motors, automobile engines, hot water heaters, and in the roasting of meats. It is particularly significant that uses virtually unrecognized 10 years ago comprise today's most important and rapidly growing areas of application: energy conservation, protecting the environment, manufacturing integrated circuits, reducing noise pollution, and cryosurgery.

II. Development History of Heat Pipes

In retrospect, the development of heat pipe technology exhibits many of the characteristics which typify other technical advances. Yet the pattern of development shows several distinguishing characteristics which set it apart from the progression that typifies transformation of new knowledge into economic and social benefits. The most important differences are due to a lack of historical roots—there was no equivalent earlier technology. The heat pipe concept introduced basically new functions and effects, and was not simply an improvement on earlier heat transfer technology. Radical innovations thread a more difficult maze toward widespread applications.

The major discoveries and principal pathways of research in heat pipe development are shown in Figure 2. Key events of major significance, which influenced subsequent development and application of heat pipes, are highlighted for emphasis. The four sections of the chart illustrate: (a) development of an adequate theory and analytical techniques for prefabricating and testing of heat pipe devices; (c) adapting heat pipe principles and designs to specific applications and markets; and (d) devising
A. Effective Invention - Not Put to Use

For centuries, heat has been the commodity most widely produced, transferred, controlled, and used in all walks of life. What more could there be to learn about heat transfer? Yet not once, but twice since 1940, the principle of the heat pipe has been discovered. Although the effectiveness of vapor heat transfer was well known, the vacuum-vapor heating systems introduced about 1910, did not anticipate the heat pipe; vapor heating systems always require that the boiler be located below the radiators, and depend on some outside force--pumps or gravity--to return the condensate.

The true capillary heat pipe was first developed in the 1940's for use in household refrigerators. R. S. Gaugler, in the General Motors research laboratories, sought a simple and reliable means of coupling thermally the main food compartment and the frozen food storage chest located below the main chamber. His patent describes tubes containing fine fiber glass wicks and a volatile fluid such as ammonia, capable of transferring heat downwardly from the food compartment to the primary evaporator near the freezer. However, this development was never carried to the production stage. The patents expired, and the work done by Gaugler lay dormant and largely unknown for nearly 20 years.

Gaugler correctly observed the effect of an inert, noncondensable gas introduced in the heat pipe, describing the use of this "buffer" gas to control thermal conductance, thus preventing over-cooling of the upper food compartment. Such control and modulation of heat pipes was destined to become one of the most important areas of development in the late 1960's.

B. Rediscovery

The modern form of the heat pipe was independently reinvented in 1963 to meet requirements of the nuclear and space power program. At the Los Alamos Scientific Laboratory of the University of California, Dr. George Grover and others were engaged in developing high temperature energy conversion technology using radioisotope heat sources. Thermionic and thermoelectric nuclear power systems required a heat transfer device having extremely high effective thermal conductance. The device developed to meet this need was what Dr. Grover called the "heat pipe."

The first description of the heat pipe in the open literature appeared in June 1964. Grover and Cotter disclosed the principles of the capillary heat pipe, and its exceptional thermal performance. It is significant that this key paper was entitled, "Structures of Very High Thermal Conductivity." During the first few years, the attention devoted to heat pipes focused almost exclusively on this one property--an effective thermal
conductance more than 1,000 times better than any known metal. Only after more experience had been gained with heat pipes did it become apparent that additional characteristics of these devices were at least as important, and often more useful, than the amount of heat transmitted.

C. Commercial Production

The thermal conductivity of the Grover heat pipe was so extraordinary that within a few months, the first commercial venture was launched. RCA became the pioneer heat pipe company, starting work in December 1963. The Direct Energy Conversion Department, headed by G. Yale Eastman, developed a broad marketing approach, specializing in thermionic power generators and electronic device cooling systems. RCA worked with NASA, the AEC, and industrial organizations for more than 7 years. During this time, they built and tested several thousand heat pipes, in more than 60 different design configurations. RCA's heat pipes were of high quality, and were well adapted for specific uses, but the market was slow to develop because the idea was new. During the recession of 1970, the company ceased external marketing, and today manufacture and use heat pipes only in special RCA electronic devices.

Elsewhere in the space program, other workers had also been developing capillary heat transfer systems. At Jet Propulsion Laboratory, Laub and McGinness had investigated a Freon evaporator boiler to supply gas bearings on unmanned spacecraft. Laub used the capillary pumping principle to return the condensate back to the evaporator section under weightless conditions. Detailed analysis of this two-phase flow, and the first screen capillary pump, followed 1 year later by Thostesen at JPL. For the passive control of space suit temperature and humidity, Shlosinger developed wick-fed water evaporators as heat sinks. At NASA's Lewis Research Center, Haller and his associates developed the fin-tube radiator concept using capillary wicks to maintain fluid flow under zero-G conditions. Spacecraft thermal control systems, and devices for cooling on-board electronic components, were developed by Kaczor at Langley Research Center. Important contributions were made to the theory of heat pipe operation, and the design and performance of wick structures were significantly advanced. The first artery wicks were developed at Langley. These pioneering studies of screen arteries and spiral arteries helped make possible many of the high-performance heat pipes that would be developed in later years.

There was sufficient worldwide interest in heat pipes for spacecraft and nuclear applications to prompt a conference bringing together workers from Europe and the United States. The AEC/Sandia Heat Pipe Conference in 1966, focused attention on the versatility and wide range of applications for these new heat transfer devices. In comparing experimental results with the theoretical predictions, experts found that heat pipes did
not always perform as expected. The Sandia Conference pointed out the need for better understanding of heat pipe mechanisms and dynamic theory, as well as the need for compatible materials, better wicks, practical fabrication methods, and information concerning operating lifetimes. In addition to extremely high thermal conductance, operating characteristics such as temperature uniformity and heat-flux transformation began to receive more attention.

D. Theory, Analysis and Prediction

An important difference between heat pipe development and many other innovations was the need to develop fundamental theories capable of explaining the operation of this deceptively simple device. Most technical developments represent some significant improvement over a previous technology. There is often a smooth transition from the prior art, allowing incorporation of the innovation in advanced engineering, without requiring the development of new theories. In the case of heat pipe development, the order of the day was: Back to basics. Fundamentals of thermodynamics, fluid flow, capillary action, and gas dynamics of two-phase flow were invoked to develop an equilibrium theory of heat pipes. Cotter, Katzoff, Marcus, and Busse in Europe, among others, made important contributions to the theory and functional analysis of heat pipes.

With increasing experience, it became clear that while heat pipes were at first considered a thermal superconductor, their behavior was sufficiently complex that they could not be characterized by any single property such as equivalent thermal conductance. Nor could heat pipe operation be fully explained or predicted from the steady-state equations. What had been considered as a passive thermal device was--inside its shell--a highly dynamic and complex system, with transient behavior and sometimes troublesome start-up dynamics. Evaporation of the working fluid altered surface energy and capillary flow behavior of the fluid. The best wick action was not always obtained with small capillaries. Loosely bonded wicks (essentially artery wicks) showed higher performance than tightly fitted wicks. As heat pipes were pushed to higher levels of heat transport, abrupt changes indicated the existence of different regimes of operation. "Amazingly simple principle," indeed!

E. First Uses in Space

The first orbital test demonstrating heat pipe operation under zero-G conditions took place in 1967. The launch vehicle for the ATS-A satellite carried a heat pipe with thermocouples to determine its temperature uniformity and performance under varying heat loads throughout different portions of its earth orbit. This successful demonstration was followed 1 year later by the launching of GEOS-2, using heat pipes designed
by Johns Hopkins. GEOS-2 was the first satellite designed to use heat pipes as an integral part of its overall thermal control system.

F. Initial Emphasis on High Thermal Capacity

Until the late 1960's, surprisingly little attention was given to modification of the basic heat pipe. Many of the first uses were for high-temperature applications, involving nuclear reactors, radioisotope power packages for space applications, and thermoionic or thermoelectric power generators. Considerable emphasis was devoted to designing heat pipes having high thermal capacity.

From 1963 through 1968, technical articles on heat pipes reflect this concern for maximum thermal performance, with virtually no attention to different operating modes or special functions. As late as May 1968, when Scientific American featured a cover article on the heat pipe by Eastman, interest focused on the four primary characteristics of heat pipes:

1. Extremely high thermal conductance: many times the transfer capacity of metals.

2. Ability to separate the heat source and heat sink at considerable distance.

3. "Temperature flattening." Maintaining virtually uniform temperature conditions over a large surface area, despite point-to-point variations in the temperatures of the heat source.

4. Heat-flux transformation. Heat can be concentrated or dispersed, either being added over a small area at high flux and removed over a large area at low flux, or vice versa.

These were the characteristics and advantages of heat pipes that largely dictated major applications. Although workers had previously demonstrated that heat pipes could perform many other functions, there seemed to be little need at that time, for heat pipes that could operate as switches, thermal diodes, heat shields, or automatically maintain a constant temperature.

G. Space Applications Require New Functions

Space programs played a major role in extending heat pipe technology into new regimes—moderate temperatures, controlled heat pipes, and cryogenic heat pipe devices.
During the period 1967 through 1970, there was increasing interest in heat pipes for lower temperatures (0°F to 200°F) suitable for cooling electronic packages, or maintaining environmental control aboard satellites. Among the largest heat pipes ever constructed, were two 50-foot circumferential hoops built to maintain constant temperature conditions in the 40 x 15-foot thermal chamber at Manned Spacecraft Center, Houston. Methods for controlling heat transfer and holding temperatures within a desired narrow range began to assume greater importance.

H. Control of Space Suit Temperature

The art of regulating the temperature and thermal transport properties of heat pipes received new stimulus from an unexpected quarter—the need for controlling the temperature in extravehicular space suits.

In 1964, the Manned Spacecraft Center drew up specifications for the Gemini space suit. One of the goals of the Gemini program was to perform the first extravehicular space walks, and this activity would require the removal of metabolic heat—about 1,200 Btu per hour—from the thermal garment. Early tests showed that this was more heat than could be handled by gas-flow cooling; a more effective heat rejection mean was required. When the first articles on heat pipes appeared, engineers working on space suits recognized a new way to transfer heat through the multilayer suits without using any moving parts.

Dr. Arnold Shlosinger, having joined TRW to continue his work with capillary evaporators for cooling space suits, suggested using part of the suit exterior surface as a thermal radiator. For advanced space suits, such as the "arc suits" being investigated by Vykukal at Ames Research Center, this was an attractive concept, since nearly 35 square feet of suit surface was potentially available—if some means of transferring heat through the suit and spreading it uniformly over the radiator surface could be devised.

Soon after development of space suit thermal control devices began, it was learned that heat pipes had more than the necessary heat transfer capability. The problem was excessive variation in the heat sink temperature. When the external radiator faced away from the sun, heat rejection was too rapid; when it faced the sun, little or no heat was rejected. Some method of regulating or controlling the conductance of the heat pipes was required.
Numerous heat pipe control methods were investigated for space suit thermal balance. The key development was a controlled conductance heat pipe: a thermal switching device using vapor flow control. Other innovations stemming from this work included:

- Flexible heat pipes.
- Dual chamber heat pipes.
- Bonded wick structures.
- Methods for avoiding freeze-up.
- Techniques for restarting frozen heat pipes.

Because this knowledge had applications outside and beyond the space suit program, these contributions were summarized in a separate report (NASA-CR-1400)—one of the rare instances in which mission-oriented research results were deliberately separated from their original context in order to broaden and to accelerate application.

I. Variable Conductance and Constant Temperature Heat Pipes

One unique and valuable property—the ability of heat pipes to automatically maintain constant temperature—was not widely appreciated for several years. As early as 1964, various workers including Hall of RCA, Wyatt and Anand of Johns Hopkins, and Kirkpatrick at TRW experimented with various heat pipe control methods including several variable conductance designs. The variable conductance heat pipe principle was at first called "power flattening" when introduced for use with radioisotope sources that decayed with time. Temperature variations of less than 1 percent were achieved with changes in input power by a factor of 10. Because certain aspects of isotope temperature control were classified, knowledge concerning these modified heat pipe designs was restricted. The concept and terminology of constant temperature heat pipes did not become widespread for several more years.

During the late 1960's, the theory and design of variable conductance heat pipe control methods was carried forward by Marcus, Kirkpatrick, and others at TRW, and by Bienert at Dynatherm, under sponsorship of NASA's Ames Research Center. The variable conductance principle has been extensively developed since 1969, and providing automatic temperature stabilization is now one of the most important uses of heat pipes. Minimizing temperature variation is highly desirable in electronics, chemical processes, electroplating, the coating of films and papers, and numerous other applications.
The conventional heat pipe transports heat with a negligible temperature drop between evaporator and condenser, so that the midsection is nearly isothermal over its entire length. However, the heat pipe does not have any particular operating temperature. Instead, it automatically adjusts its temperature to match the heat-source and heat-sink conditions.

In numerous applications, it is desirable to maintain some selected narrow temperature range along the midsection of the heat pipe, despite variations in source or sink conditions. For these uses, it is necessary to actively or positively control heat pipe conductance so that it holds the desired temperature range—the so-called constant temperature heat pipe. Many different control methods have been investigated, with control by means of noncondensible gas receiving the greatest attention. Major control approaches include:

- Condenser flooding with excess working fluid
- Vapor flow modulation
- Liquid flow control
- Gas control
  - heater controlled reservoir
  - fluid actuated bellows
- Thermal diodes (one-way heat pipes)
- Phase change material thermal accumulator

The first gas controlled variable conductance heat pipe to fly was launched in August 1972, on the Orbiting Astronomical Observatory, (OAO-C). The gas controlled heat pipe maintained the on-board data processing electronics at 65 ± 5°F for changes in power dissipation from 15 to 35 watts as shown in Figure 3. Thermal control methods previously used had resulted in temperatures varying from 0°F to 140°F.

J. Cryogenic Heat Pipes

The temperature range of interest gradually progressed from +3000°F down to the subzero range. Cryogenic heat pipes present special problems. Because liquefied gases are not very good working fluids for heat transfer, the early cryo-pipes studied by the U.S. Air Force were rather low-performance devices, extremely sensitive to gravity fields, and not working effectively with the usual wick structures. More extensive research, starting in 1970, has dramatically improved both the theory and practical arts of cryogenic
Figure 3

Source: Ames Research Center
heat pipe technology. The axial-grooved wick and the pressure-primed tunnel artery have increased heat flux capacity by a factor of 10. The Integrated Cryogenic Isotope Cooling Engine System (ICICLE) developed for Goddard, uses high-performance cryogenic heat pipes. Today, sensors and electronic components can be efficiently cooled; operation against gravity or in rotating systems is practical; and thermal capacities in excess of 4,000 watt-inches (power times length) are readily attainable. Cryogenic refrigeration systems on earth, as well as in space application, can make use of these principles.

III. Space Requirements and Contributions

Heat pipe technology has been almost totally developed through government funded research. The initial industrial concept did not lead to use; the urgent requirements of the nuclear and aerospace programs provided the stimulus to advance the state of the art. From 1963 to 1969, virtually all of the key developments were achieved to satisfy the needs of various sponsoring agencies indicated in Table 1. Since 1968, an increasing amount of development, design, and especially adaptation to specific uses, has been conducted by private industry. The number of industrial patents issued for heat pipe applications has increased rapidly since 1969. However, most of the basic knowledge concerning heat pipe theory and operation was generated in response to requirements and opportunities for space applications. Table 2 shows the major space requirements to be satisfied, specific space programs, and typical contributions. Several requirements were intrinsically achieved by the basic operating characteristics of the heat pipe, thus needing only optimization and demonstration of these capabilities.

One particular space contribution not shown in this table needs separate comment—dissemination of this new technology. It was essential to develop, improve, and modify the basic heat pipe to satisfy numerous space needs. The widest possible sharing of knowledge would help accelerate those developments, encourage utilization, improve quality and reliability, and, ultimately reduce costs by making heat pipes relatively standard, familiar components.

To promote awareness and use of heat pipe technology, a variety of special methods have been used to provide effective dissemination of current knowledge:

- Design handbooks
- Bibliographies (with continuing updates)
- Conferences
TABLE 1

MAJOR GOVERNMENT FUNDED HEAT PIPE DEVELOPMENT PROGRAMS

- NASA
  - AMES RESEARCH CENTER
  - GODDARD SPACE FLIGHT CENTER
  - MANNED SPACECRAFT CENTER
  - MARSHALL SPACE FLIGHT CENTER
  - LEWIS RESEARCH CENTER
  - LANGLEY RESEARCH CENTER
  - JET PROPULSION LABORATORY
- AEC
  - LOS ALAMOS SCIENTIFIC LABORATORY
  - LAWRENCE LIVERMORE LABORATORY
- AIR FORCE
- NAVY
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<th>REQUIREMENTS</th>
<th>SPACE PROGRAM · CONTRIBUTIONS</th>
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<td>HIGH THERMAL POWER SEPARATION OF HEAT SOURCE HEAT SINK</td>
<td>• SOLAR CONCENTRATORS  SNAP  THERMIONIC CONVERTERS</td>
<td>LIQUID METAL HEAT PIPES LENGTH UP TO 70 FEET</td>
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<tr>
<td>ZERO-G-OPERATION COUNTER-G-OPERATION</td>
<td>• ORBITAL WORKSHOP COMMUNICATION SATELLITES</td>
<td>MANY WICK DESIGNS, THREAD ARTERY, EHD AUGMENTATION</td>
</tr>
<tr>
<td>LIGHTWEIGHT NO EXTERNAL POWER NO MOVING PARTS</td>
<td>• ALL</td>
<td>DESIGN OPTIMIZATION</td>
</tr>
<tr>
<td>LONG LIFE/RELIABILITY</td>
<td>• ALL</td>
<td>COMPATIBLE MATERIALS LIFE TEST SCALING</td>
</tr>
<tr>
<td>HEAT FLUX TRANSFORMATION</td>
<td>• LUNAR SURFACE MAGNETOMETER TWT COOLING</td>
<td>(INTRINSIC PROPERTY OF H.P.)</td>
</tr>
<tr>
<td>ISOTHERMALIZE LARGE AREA TEMPERATURE FLATTEN’ING</td>
<td>• GEOS-2 OAO-C</td>
<td>(INTRINSIC PROPERTY OF H.P.)</td>
</tr>
<tr>
<td>MAINTAIN CONSTANT TEMPERATURE</td>
<td>• ON-BOARD PROCESSOR Ames H.P. EXPERIMENT</td>
<td>NUMEROUS VARIABLE CONDUCTANCE DESIGNS FEEDBACK CONTROL</td>
</tr>
<tr>
<td>SPECIAL OPERATION</td>
<td>• SPACE SUIT RECTIFIERS</td>
<td>THERMAL SWITCH THERMAL DIODE THERMAL ACCUMULATOR EHD PUMPING AXIAL GROOVE WICK PRESSURE PRIMED ARTERY</td>
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Representative of these special information resources is the Heat Pipe Technology bibliography and abstracts prepared by NASA's Technology Applications Center at the University of New Mexico. Several companies now engaged in marketing commercial heat pipe devices indicated that their decision to enter the field was influenced to a major degree by the information obtained through these sources.

IV. Significance and Impact

Ten years have passed since the heat pipe principle was rediscovered. What assessments of the significance of these devices can be made at this time?

One measure of activity in the field is reflected in the growth of the technical literature. Figure 4 shows the rapid increase in the number of articles, books and patents covering heat pipe applications. New findings are appearing at a current rate of nearly 200 publications annually. Several thousand engineers and scientists around the world are working to exploit the properties of heat pipe. Approximately 40 U.S. organizations and a score of universities currently maintain active heat pipe research and development programs. The interest is worldwide; more than 30 foreign companies and governmental organizations have acquired the new technology and are vigorously exploiting applications. A listing of present factors in the United States and Europe follows the chronology sections, and indicates the principal fields of specialization.

It should be noted that heat pipe technology has not been fully assimilated into traditional manufacturing industries. Thus far, heat pipes continue to be manufactured and sold by highly specialized firms.

The principal U.S. producers include:

Q-Dot Corporation - Dallas, Texas
Isothermics, Inc. - Clifton, New Jersey
Heat Pipe Corporation of America - Newark, New Jersey
Noren Products - Redwood City, California
GROWTH OF HEAT PIPE LITERATURE

Figure 4

Source: Midwest Research Institute; derived from "Heat Pipe Technology" - Bibliography.
In addition, about a dozen firms offer the special tubing and wick materials used in the fabrication of heat pipe devices.

Only within the past few years have heat pipes started to gain commercial acceptance. The first two commercial ventures found that the market was not yet developed, or that special applications did not match their marketing capabilities. RCA has ceased external marketing both in the U.S. and in Britain. Energy Conversion Systems, Inc. began in 1966 as a spin-off from the mechanical engineering department at the University of New Mexico. This company specialized in industrial applications, primarily electronics cooling. However, their best known product was the "Thermal Magic" cooking pin, a heat pipe that cut the cooking time for large pieces of meat to one-half the usual period. Some 20,000 units were sold, and independent tests have proven the efficiency of the device. However, the household and commercial food preparation market did not prove particularly profitable. The company continues to market stock sizes of heat pipes for use in equipment made by other firms.

Viable commercial markets for heat pipes began to emerge after 1970. The heat pipe has replaced many conventional heat transfer systems, and effective use of heat pipe characteristics often makes otherwise marginal devices highly practical. Numerous different shapes and sizes of heat pipes have been introduced. Some heat pipe devices such as the vapor chamber griddle shown in Figure 5 bear scant resemblance to the more familiar tubular designs. The great number and extreme diversity of present uses makes it helpful to classify applications according to the primary heat transfer function; or according to the field of use. Table 3 summarizes some of the growing list of heat pipe applications.

The important role of new and nontraditional applications deserves
Figure 5 - Vapor Chamber Griddle Provides Uniform Surface Temperature and Quick Warm-up

Source: Hughes Electron Dynamics Division
# TABLE 3

**HEAT PIPE APPLICATIONS**

By Major Heat Transfer Function

## Heating
- Thermal recovery units, winter heating
- Space heating from flue-gas, fireplaces
- Industrial process heat recycle
- Aircraft wing deicing
- Warming carburetors, air intakes
- Stirling engines, Brayton cycle engines
- Deicing highway bridges, intersections
- Solar energy collectors
- Geothermal energy recovery
- Thermoelectric hot shoes
- Thermionic emitters
- Coal gasification
- Chemical reaction vessels
- Heat recuperators, air preheaters
- Mobile home furnace/hot water heater combination units

## Cooling
- Air conditioning precoolers
- Electric motors, transformers
- Switchgear, circuit breakers, starters
- Electric bus bars
- Storage batteries, fuel cells
- High power electron tubes, TWT's
- Power rectifiers, SCR's, transalient rectifiers
- Electronic rack cooling, high density packaging
- Turbine shafts and blades
- Lathe cutting tools, drills
- Foundry and die casting molds
- Injection molding machines and dies
- Disc brakes, auto and aircraft
- Motorcycle crankcase cooling
- Fission product storage vaults
- Space suit temperature control
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<th><strong>TABLE 3 (Concluded)</strong></th>
<th><strong>Temperature Control, Isothermalization, Other</strong></th>
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<tr>
<td>Crystal oscillator ovens</td>
<td><strong>Inertial guidance gyros</strong></td>
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<tr>
<td>Electroplating baths</td>
<td><strong>Temperature regulation for data processing electronics</strong></td>
</tr>
<tr>
<td>Coating rolls and doctor blades</td>
<td><strong>Isothermal furnaces, semiconductor diffusion</strong></td>
</tr>
<tr>
<td>Black-body radiation cavities</td>
<td><strong>Spacecraft structures, isothermalization</strong></td>
</tr>
<tr>
<td>Isothermal mounting plates for electronics</td>
<td><strong>Telescopes, optical equipment</strong></td>
</tr>
<tr>
<td>Surgical cryoprobe, dermatology, etc.</td>
<td><strong>Infra-red detector cryogenic cooling</strong></td>
</tr>
<tr>
<td>Laser mirror cooling, laser tuning</td>
<td><strong>Directional casting, heat treating</strong></td>
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practical benefits provided by heat pipe technology. Selected uses of heat pipes to satisfy requirements that were largely unforeseen in 1963 will be described briefly.

**B. Permafrost Stabilization**

The largest single market currently for heat pipes is for environmental protection along the trans-Alaska pipeline. The warm pipeline will be supported above the arctic tundra by thermal piles with internal heat pipes extending many feet into the permafrost layer. Operating as a thermal diode, the heat pipes will help freeze and subcool the soil to full depth in winter when air temperatures are low. In the summer, the heat pipe thermal piles will be inactive and the permafrost will thaw only near the surface. By maintaining a solid mass of permafrost around each supporting pile, heaving and shifting of the soil will be reduced and pipeline settling can be avoided. Without this thermal protection, uncontrolled freezing and thawing of the soil could stress the crude oil line to the point of rupture. Protecting the delicate tundra environmentally by keeping the permafrost frozen was a significant consideration in assessing the environmental impact of the project.

Several aerospace contractors are involved in the design and life testing of heat pipes for Alyskea. Nearly 110,000 heat pipes using ammonia fluid and steel tubes, up to 50 feet in length, will be required, with a total cost of approximately $40 million. Figure 6 shows heat pipes being tested to determine performance and reliability. Among the most challenging aspects of the design of these heat pipes was the scaling of conditions for accelerated life test and reliability prediction. The pipeline is designed to have an operating life of 30 years. Accelerated life tests at high temperatures were accomplished in approximately 4 months to demonstrate that heat pipes will function properly for 30 years.

**C. Energy and Fuel Conservation**

Heat pipes are now helping homeowners to stretch scarce fuel oil supplies. In many oil-fired furnaces, 25 to 30 percent of available heat is lost in hot flue gas up the stack. The Air-O-Space heater introduced by Isothermics, Inc., uses heat pipes to extract flue gas waste heat, and can normally recover from 7,000 to 10,000 Btu per hour. Figure 7 shows a typical installation that can increase heating system efficiency approximately 10 percent, thus reducing domestic heating oil consumption.

Industry is rapidly adopting heat pipe thermal recovery units that can dramatically reduce energy consumption and operating costs. The first industrial units to recycle waste heat were introduced in 1971 by Q-Dot Corporation, founded by George Grover, discoverer of the modern heat
Figure 6 - Testing Heat Pipes for Trans-Alaska Pipeline.
Each pipe removes 400 watts of heat.

Source: Hughes Electron Dynamics Division
Figure 8 shows how a thermal recovery unit captures 60 to 80 percent of waste heat from a kiln dryer and returns the heat directly back to the processing kiln.

Energy conservation through heat recovery is becoming essential for industries that need to expand production and are not able to obtain additional supplies of natural gas or other fuels. In addition, the savings from process heat recycling can often pay for the heat pipe recovery system in the first operating year. The widest use of process heat recovery units to date has been in foundries, rubber vulcanizing, paint drying ovens, coffee roasting and spray drying of detergents. In many other industrial plants, waste heat is recovered and used to provide comfort heating for the factory.

Commercial and institutional buildings are obtaining substantial energy and equipment cost savings through the use of heat pipe recovery units in air conditioning, heating and ventilating systems. The heat pipe exchangers work both winter and summer. In winter, heat is transferred from warm building exhaust air to preheat cold incoming fresh air. In summer, the incoming hot air is precooled ahead of the main air conditioner. The heat transfer can be controlled by tilting the thermal recovery unit a few inches, permitting gravity to aid or retard fluid flow in the axial capillary grooves that serve as the wick. Separation of the two air streams by a sealed partition insures that no contamination of the fresh air supply will occur, an important consideration in hospitals and schools. The recovery of waste heat makes it practical to use 25 to 30 percent smaller air conditioning systems, and to reduce heating costs significantly.

D. Cryogenic Surgery

Recent advances in cryogenic heat pipes have made possible a simple cryosurgery instrument. This open-loop heat pipe cooled by liquid nitrogen is a small, hand held, self-contained surgical probe developed by Hughes Electron Dynamics Division, and shown in Figure 9. It brings extreme cold directly to the surgical area at the tip of the instrument. Equally important, the simplicity and modest cost of the unit is bringing cryosurgery into doctors' offices and outpatient clinics rather than requiring elaborate operating room equipment. The "Kryostik" is being marketed for Hughes by the Ritter Company, a medical equipment manufacturer and supplier.

E. Isothermal Furnaces

The isothermal or uniform temperature property of heat pipes has been used in precision furnaces for treating integrated circuits, and jet engine turbine blades. An annular heat pipe can conduct externally applied
THERMAL RECOVERY UNIT

INDUSTRIAL HEAT RECOVERY

Unit transforming waste heat from a process exhaust directly back into the process.

Figure 8
Figure 9 - Open-Loop Surgical Cryoprobe

Source: Hughes Electron Dynamics Division
heat--even nonuniform heating--to the inner surface, so that the temperature of the inner wall is held constant over its entire surface. For scientific purposes, isothermal furnaces are used as "black-body" radiation cavities for calibrating radiation measuring devices and measuring thermal radiation properties of materials.

One of the greatest needs for a truly isothermal furnace is in the diffusion of semiconductor materials used for transistor and integrated circuits. For complex circuit chips, it is essential that all of the semiconductor wafers being processed get exactly the same heat treatment, requiring furnaces having extreme temperature uniformity. The heat pipe principle assures uniform furnace temperatures with greatly simplified controls. An important bonus lies in the ability of the heat pipe furnace to provide uniform temperature while operating in a vertical mode. Isothermal operation of vertical furnaces is difficult, if not impossible, to achieve using normal furnace construction.

F. Noise Abatement

New industrial safety and noise abatement codes under the Occupational Safety and Health Administration (OSHA) often require building an acoustic enclosure around noisy machines such as grinders. Without some means of cooling the machine and its motors, overheating can easily occur. Heat pipe exchangers, which penetrate into the sealed enclosure, are ideally suited for such cooling applications because they are small, efficient, automatic in operation, and need no external connections or power.

G. Future Markets and Growth

No complete estimates are available to measure the present size and rate of growth in commercial heat pipe devices. All manufacturers reported substantial recent increases in production. Several firms expressed amazement at the number and variety of new uses devised by their customers. With many of the large volume applications stemming from relatively new needs--such as energy conservation--it is difficult to predict the extent of growth even over the next few years.

By combining estimates furnished by established heat pipe makers in Europe and the U.S., some consensus was obtained regarding present market size and anticipated growth over the next few years. These estimates are summarized in Table 4. British production is currently small but is expected to exceed $1.2 million by 1976. Western Europe represents a somewhat more developed market. In the United States, the demand for heat pipe devices is expected to double or triple by 1976. The heat pipes that will
be used for the Alaska pipeline, will mean an additional $15 to $20 million per year during 1975 and 1976. A continuing market for soil stabilization and foundations in the arctic regions is foreseen. Virtually all of the commercial markets have emerged since 1970, so that it is hardly possible to estimate the ultimate significance and impact of this burgeoning new technology.

**TABLE 4**

**ESTIMATED SALES OF HEAT PIPE DEVICES**

<table>
<thead>
<tr>
<th>Region</th>
<th>1973</th>
<th>1976</th>
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<tr>
<td>Great Britain</td>
<td>$36,000</td>
<td>$1.2 million</td>
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<tr>
<td>Continental Europe</td>
<td>$135,000</td>
<td>$2.3 million</td>
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<tr>
<td>United States</td>
<td>$8 to $10 million</td>
<td>$18 to $25 million</td>
</tr>
<tr>
<td>Alaska</td>
<td>-----</td>
<td>$20 million</td>
</tr>
</tbody>
</table>
CHRONOLOGY

DEVELOPMENT OF HEAT PIPES

1899: James A. Trane introduced the vapor heating system which gained acceptance by 1920. Vapor heat transfer provided high thermal capacity and fast response. Typically required vacuum pump, air eliminator, steam traps, condensate return lines, and the boiler was below the radiators for gravity flow return.

1945-1948: R. S. Gaugler (General Motors), "Capillary Heat Transfer Device for Refrigerating Apparatus." Describes use of fiber glass strands enclosed in braided fiber glass sleeve as an improved, flexible wick that permits bending metal heat pipes. Density of wick packing varied from low at bottom to high density at top of tube. Glass wick and anhydrous ammonia were the preferred combination, although water or alcohols may also be used. Fibrous wicks claimed superior to the previously used sintered iron powder, which was brittle and difficult to fabricate. Note: Mentions the use of inert gas such as nitrogen introduced into pipe to block off the header and prevent cooling the upper food chamber more than desired. U. S. Patent No. 2,448,261.


1962: L. Trefethen (Tufts University/General Electric), "On Surface Tension Pumping of Liquids, As a Possible Role of the Candlewick in Space Exploration." Speculation proposing the use of evaporation-condensation and capillary pumping concept in the space program. Author commented: "How well this idea would perform in space is apparently not known." (February 1962).
1962-


1963-


1963-


1963-


1964: Manned spacecraft Gemini space suit RFP. Thermal target was rejection of 1,200 Btu per hour. (More than could be removed by gas cooling.)

1964: Campana and Holland (Gulf-General Atomics). Description of heat pipes operating as radiating fins. The six functions of a heat pipe are examined to identify the factors that influence heat pipe design and which determine their minimum size and weight. GA-5676 (September 17, 1964).
1964: Wm. Hall (RCA), "Constant Temperature Output Heat Pipe." Patent covering the "power flattening" heat pipe designed to control heat flux from isotope sources to electric power converters. Heat pipe is provided with a noncondensible gas reservoir at the condenser end to prevent large changes in operating temperature as the isotope decays. U.S. Patent No. 3,613,773 (October 19, 1971), application filed December 7, 1964.


1965: T. Wyatt (Johns Hopkins/Applied Physics Lab), "A Controllable Heat Pipe Experiment for the SE-4 Satellite." Observation of unwanted hydrogen in an early heat pipe trial led to pioneering study of gas controllable heat pipes in which the amount of heat liberated is proportional to the amount of noncondensible gas present. APL-SDO-1134 (March 9, 1965).


1965-


1966: Shlosinger (TRW). Development of heat pipes for thermal control of space suits. Several innovations:
- flexible heat pipes
- thermal switch
- fabrication methods
- vapor flow control
- avoidance of freeze-up
- startup dynamics
NASA-CR-73168 (September 1967); NASA-CR-73270 (September 1968);


1966-

1970: Ferrell, Cosgrove, et al., (North Carolina State University). A study of the operating characteristics of the heat pipe:
- Analytical model for predicting limits of operation
- Capillarity in porous media
- Vaporization from flooded wick
- Heat transfer in evaporator zone
U.S. Patent No. 3,279,759 (January 18, 1966), assigned to AEC.
Application filed December 2, 1963.

1966: Energy Conversion Systems, Inc. First independent heat pipe concern
founded as a spin off from work in the mechanical engineering department at the University of New Mexico. Produced heat pipes for electronics. Introduced the first consumer heat pipe device called "Thermal Magic" cooking pin, designed for roasting meats.

1966-


1967: S. Frank (Martin-Marietta), "Heat Pipe Design Manual." First compilation of materials properties and parameters in a form directly useful to the heat pipe designers. Emphasis was largely on the properties of working fluids. WND-3288 (1967).


1967-


1968: (Johns Hopkins/Applied Physics Lab), "GECS-2 Heat Pipe System." The GEOS-2 spacecraft was the first satellite to use a heat pipe as an integral part of its thermal design. NASA-CR-94585 (April 1968).


1968: Noren Products Company established to market electronic cooling devices for high density electronics.

1968: Conway (General Electric), and WilmARTH (NASA-ERC). Cooling of high power electron tubes in a space vehicle. IEEE, 9th Conference on Tube Techniques, p. 182-190 (1968).

1968-1974: K. T. Feldman (University of New Mexico). Workshop on Heat Pipe Design and Analysis (April 19-20, 1968). The first in a continuing series of short courses and workshops to provide theory, design, analysis and applications technology to persons wishing to acquire up-to-date heat pipe technology.


1969: Dynatherm Corporation established by an active heat pipe group at Martin, after Teledyne acquired Martin Nuclear Corporation.


1970: Q-Dot Corporation formed by Dr. George Grover, the inventor of modern heat pipes, and H. Bärkmann. Specialize in exchangers for energy conservation in buildings and for industrial process heat recovery.


1971: R. Pessolano (Isothermics, Inc.). Began manufacture and marketing of heat pipes following workshop course at University of New Mexico. Specialize in HVAC exchangers ("Air-O-Space Heater"), industrial devices, water heaters.


1969-


1972-

1972-

HEAT PIPE SPECIALISTS--PRODUCERS AND USERS

A. Suppliers of Materials

Metal Foams

Astro Met Associates, Inc.
95 Barron Drive
Cincinnati, Ohio 45215

General Electric Company
Metallurgical Products Department
Box 237, General Post Office
Detroit, Michigan 48238

Gould, Inc.
Gould Laboratories
540 East 105th Street
Cleveland, Ohio 44108

Union Carbide Corporation
12900 Snow Road
Parma, Ohio

Metal Felts

Astro Met Associates, Inc.
95 Barron Drive
Cincinnati, Ohio 45215

Brunswick Corporation*
Technical Division
1 Brunswick Place
Skokie, Illinois
*Formerly Huyck Metals Company

Screen

Cambridge Wire Cloth
P. O. Box 399
Cambridge, Maryland 21613

Michigan Wire Cloth Company, Inc.
2100 Howard Street
Detroit, Michigan 48216

Screen (concluded)

Newark Wire Cloth Company
351 Vernon Avenue
Newark, New Jersey 07104

Tobler, Ernst and Traver, Inc.
420 Saw Mill River Road
Elmsford, New York 10523

Composite Screen

Aircraft Porous Media, Inc.
32 Sea Cliff Avenue
Glen Cove, New York 11542

Finned Tubing

Noranda Metal Industries, Inc.
French Tube Division
P. O. Box 558
Newtown, Connecticut 06470

Porous Metals

Union Carbide Corporation
Stellite Division
1020 West Park Avenue
Kokomo, Indiana 46901
B. Fabricators and Vendors

Donald W. Douglas Labs
Richland, Washington

Dynatherm Corporation
Cockeysville, Maryland

Grumman Aerospace Corporation
Bethpage, New York

Hughes Electron Dynamics Division
Torrance, California

TRW Systems Group
Redondo Beach, California

Thermoelectron Corporation
Waltham, Massachusetts

Energy Conversion Systems, Inc.
Albuquerque, New Mexico

Heat Pipe Corporation of America
Newark, New Jersey

Isothermics, Inc.
Clifton, New Jersey

Jermyn Industries
San Francisco, California

Noren Products
Redwood City, California

Q-Dot Corporation
Dallas, Texas
C. Heat Pipe Users

Buy or make heat pipes for their own equipment without selling the finished product (incomplete list).

<table>
<thead>
<tr>
<th>U.S. Organizations</th>
<th>Product or Application</th>
</tr>
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<tbody>
<tr>
<td>Los Alamos Scientific Lab (AEC), N.M.</td>
<td>Thermal control of Reactor's, Irradiation capsules, theory, and other applications</td>
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<tr>
<td>Oak Ridge National Lab, Tennessee</td>
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</tr>
<tr>
<td>Argonne National Lab, Illinois</td>
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</tr>
<tr>
<td>NASA Research Centers</td>
<td>Temperature control of electronic systems and other applications</td>
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<tr>
<td>Ames, Lewis, Goddard, Marshall, Langley</td>
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<tr>
<td>Jet Propulsion Laboratory</td>
<td>Electronics cooling, and other applications</td>
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<tr>
<td>Pasadena, California</td>
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<tr>
<td>National Bureau of Standards</td>
<td>Black body cavities, vapor laser cavities</td>
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<tr>
<td>Boulder, Colorado</td>
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<tr>
<td>Sandia Labs, Albuquerque, N.M. (AEC Lab)</td>
<td>Electronic cooling</td>
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<tr>
<td>Wright Patterson Air Force Base, Ohio</td>
<td>Electronic cooling, cryogenic heat pipe</td>
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<tr>
<td>U.S. Army, Fort Belvoir, Virginia</td>
<td>Electronic cooling</td>
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<tr>
<td>Lawrence Livermore Lab, California</td>
<td>Experiments, fusion reactor cooling study</td>
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<tr>
<td>Battelle Memorial Institute</td>
<td>Basic studies</td>
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<td>Columbus, Ohio</td>
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<tr>
<td>U.S. Navy, Office of Naval Research</td>
<td>Research support</td>
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<td>Raytheon Company</td>
<td>Electronic cooling</td>
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<td>Bedford, Massachusetts</td>
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<td>AirResearch Manufacturing Company, Los Angeles, California</td>
<td>Experiments</td>
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<td>Electronic Communications, Inc., St. Petersburg, Florida</td>
<td>Electronic cooling</td>
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</table>
C. Heat Pipe Users (Continued)

<table>
<thead>
<tr>
<th>U.S. Organizations</th>
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<td>Bendix Corporation</td>
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<td>Navigation and Control</td>
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<td>Gulf General Atomica</td>
<td>Survey for fin cooling</td>
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<td>San Diego, California</td>
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<td>Martin Marietta Corporation</td>
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<td>Baltimore, Maryland, Denver, Colorado</td>
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<tr>
<td>Pratt and Whitney Aircraft</td>
<td>Basic theory and experiments</td>
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<td>East Hartford, Connecticut</td>
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<td>Aerospace Corporation</td>
<td>Basic experiments</td>
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<td>El Segundo, California</td>
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<td>Sanders Association, Inc.</td>
<td>Electronics cooling</td>
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<td>Nashua, New Hampshire</td>
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<td>Collins Radio</td>
<td>Experiments</td>
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<td>Cedar Rapids, Iowa</td>
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<td>Philco-Ford, Space Division</td>
<td>Electron tube cooling, avionics cooling</td>
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<td>Palo Alto, California</td>
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<td>Brown Engineering, Inc.</td>
<td>Spacecraft thermal control study</td>
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<tr>
<td>Huntsville, Alabama</td>
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<td>Fairchild Hiller Corporation</td>
<td>Satellite thermal control, thermionic converters</td>
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<td>Farmingdale, New York</td>
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<td>Aerojet Liquid Rocket Company</td>
<td>Rocket motor cooling study</td>
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<td>Sacramento, California</td>
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<tr>
<td>Aerojet General, Nucleonics</td>
<td>Liquid metal studies</td>
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<td>San Ramon, California</td>
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<td>Teledyne, Inc.</td>
<td>Thermoelectric converter cooling</td>
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<td>Perkin-Elmer Corporation Danbury, Connecticut</td>
<td>Cryogenic heat pipe for IR cooling</td>
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<td>Bell Laboratories Naperville, Illinois</td>
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<td>Whippany, New Jersey</td>
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<td>Murray Hill, New Jersey</td>
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<td>North American Rockwell Corporation Space Division, Downey, California</td>
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<tr>
<td>Northrop Corporate Laboratories Hawthorne, California</td>
<td>Basic studies, electronic cooling</td>
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<td>Sperry Rand, Space Support Division Huntsville, Alabama</td>
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<td>Battelle-Northwest Richland, Washington</td>
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C. Heat Pipe Users (Continued)

Universities

University of New Mexico
University of California at Los Angeles
North Carolina State University
Lehigh University
University of California at Berkeley
Colorado State University
Navy Post Graduate School
John Hopkins University, Applied Physics Lab
Case Western Reserve University
Kansas State University
Catholic University
California Tech
Massachusetts Institute of Technology
Brooklin Polytechnic Institute
University of Illinois
Texas A&M
University of Idaho
George Washington University
New York University
Fordham University
University of Missouri
Iowa State University
Purdue University
Louisiana State University
Princeton University
University of Iowa
Georgia Tech
Washington University

Product or Application
Research, testing, development studies
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<td>Eratom Lab, Ispra, Italy</td>
<td>Experiments, liquid metals for high temperature, theory, etc.</td>
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<td>IKE, University of Stuttgart, Germany</td>
<td>Experiments, development for applications.</td>
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<td>National Society for Construction of Aviation Engines, Paris, France</td>
<td>Gas turbine cooling studies</td>
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<td>Technical High School, Stuttgart, West Germany</td>
<td>Experiments</td>
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<tr>
<td>Royal Aircraft Establishment, Farnborough, England</td>
<td>Satellite heat transfer</td>
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<td>Jermyn Manufacturing, Vestry Estate, Seven Oaks, Kent, England</td>
<td>Electronics cooling devices</td>
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<td>Central Electricity Generating Board, London, England</td>
<td>Experiments</td>
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<td>National Research Council, Mechanical Engineering Division, Ottawa, Canada</td>
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<td>French Atomic Energy Commission, Grenoble, France</td>
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<td>Institute for Nuclear Physics and Reactor Technology, Karlsruhe, West Germany</td>
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<td>United Kingdom Atomic Energy Authority, Harwell, England</td>
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<td>Philips Research Labs, Eindhoven, Netherlands</td>
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<td>University of Wales, Institute of Science and Technology, Cardiff, Wales</td>
<td>Domestic heating study</td>
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<td>National Center for Space Studies</td>
<td>Space radiator</td>
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<td>(CNES), Cannes, France</td>
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<td>Reading University</td>
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<td>University of Swansea, Mechanical Engineering</td>
<td>Rotating heat pipe studies</td>
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<td>South Wales, England</td>
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<tr>
<td>Institute for Heat and Mass Transfer</td>
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<td>Soviet Academy of Sciences</td>
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<td>Heidelberg, West Germany</td>
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### C. **Heat Pipe Users (Concluded)**

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<tr>
<th>Non-U.S. Organizations</th>
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<td>Technical University, Applied Physics Department, Delft, Netherlands</td>
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<td>Technical Institute, Kiev, USSR</td>
<td>High temperature heat pipes</td>
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<tr>
<td>National Institute for Research in Science, Chilton, England</td>
<td>Nuclear/physics experiment</td>
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<td>National Gas Turbine Establishment, Pyestock, England</td>
<td>Gas turbine cooling studies</td>
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<tr>
<td>National Engineering Lab, Applied Heat Transfer Division, East Kilbride, England</td>
<td>Basic studies</td>
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<tr>
<td>University of Genoa, Genoa, Italy</td>
<td>Heat pipe plasma oven</td>
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<tr>
<td>Thomson-CSF, Electron Tube Group, Essonne, France</td>
<td>Thermionic converters</td>
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<tr>
<td>Institute for Machine Design, Thermodynamics Department, Bechovice, Prague, Czechoslovakia</td>
<td>General studies</td>
</tr>
</tbody>
</table>
D. Heat Pipe Users

Commercial device marketing.

RCA, Lancaster, Pennsylvania
Camden, New Jersey

(First commercial firm)
Electronics cooling, and other applications
(No longer active)

General Electric Company
Schnecktady, New York
Cincinnati, Ohio
Philadelphia, Pennsylvania
Valley Forge, Pennsylvania
Erie, Pennsylvania

Electronic cooling,
electric motor cooling,
transformer cooling

Westinghouse
Pittsburgh, Pennsylvania

Experiments

Dynatherm Corporation
Cockeysville, Maryland

General use, solar collectors,
electronics cooling, isothermal ovens, and other applications

TRW Systems, Inc.
Redondo Beach, California

General use, temperature control, electronics cooling,
isothermal oven, and other applications

Hughes Aircraft Company
Electron Dynamics Division
Torrance, California

General use, electronics cooling, TWT cooling,
crosurgery device, and other applications

Grumman Aerospace Corporation
Bethpage, New York

Aerospace and other applications

Donald W. Douglas Labs
Richland, Washington

General use, permafrost stabilization, other applications

Thermo Electron Engineering Corp.
Waltham, Massachusetts

Energy conversion device use, general use

Litton Industries
Electron Tube Division
San Carlos, California

Electron tube cooling
D. Heat Pipe Users (Concluded)

Energy Conversion Systems, Inc.
Albuquerque, New Mexico
General use, cooking pin, electronic cooling

Q-Dot Corporation, Dallas, Texas
Air-to-air heat exchangers

Isothermics Corp., Clifton, New Jersey
General use, heat exchangers, other

Noren Products
Redwood City, California
General use, electronics cooling

Dornier Systems, GmbH
Friedrichshafen, West Germany
Solar collector, cryogenic, others

E. Technical Specialists

Independent consultants not listed previously.

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Mechanical Engineering, Professor
Research, testing, teaches short course, consultant
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Albuquerque, New Mexico

C. C. Silverstein
Consultant
Baltimore, Maryland

D. K. Edwards, Professor
Consultant, research
Energy and Kinetics Department
University of California at Los Angeles
Los Angeles, California

C. L. Tien, Professor Mechanical Eng.
Consultant, research
University of California
Berkeley, California

E. K. Levy, Mechanical Engineering
Research
Lehigh University

J. K. Ferrell, Chemical Engineering
Research
North Carolina State University
Raleigh, North Carolina

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Mr. David Smith

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Mr. Harold Rosen

Electron Dynamics Division, Hughes Aircraft Company
Mr. Al Rabinis
Mr. Thomas Hummel

Noren Products
Mr. Don Noren

Heat Pipe Corporation of America
Mr. Robert Straley

Jermyn Industries
Mr. Ron Kemp
Mr. G. Rattcliff

Johns Hopkins University
Applied Physics Laboratory
Mr. Clarance Wingate

RCA
G. Yale Eastman

NASA Ames Research Center
Mr. J. P. Kirkpatrick