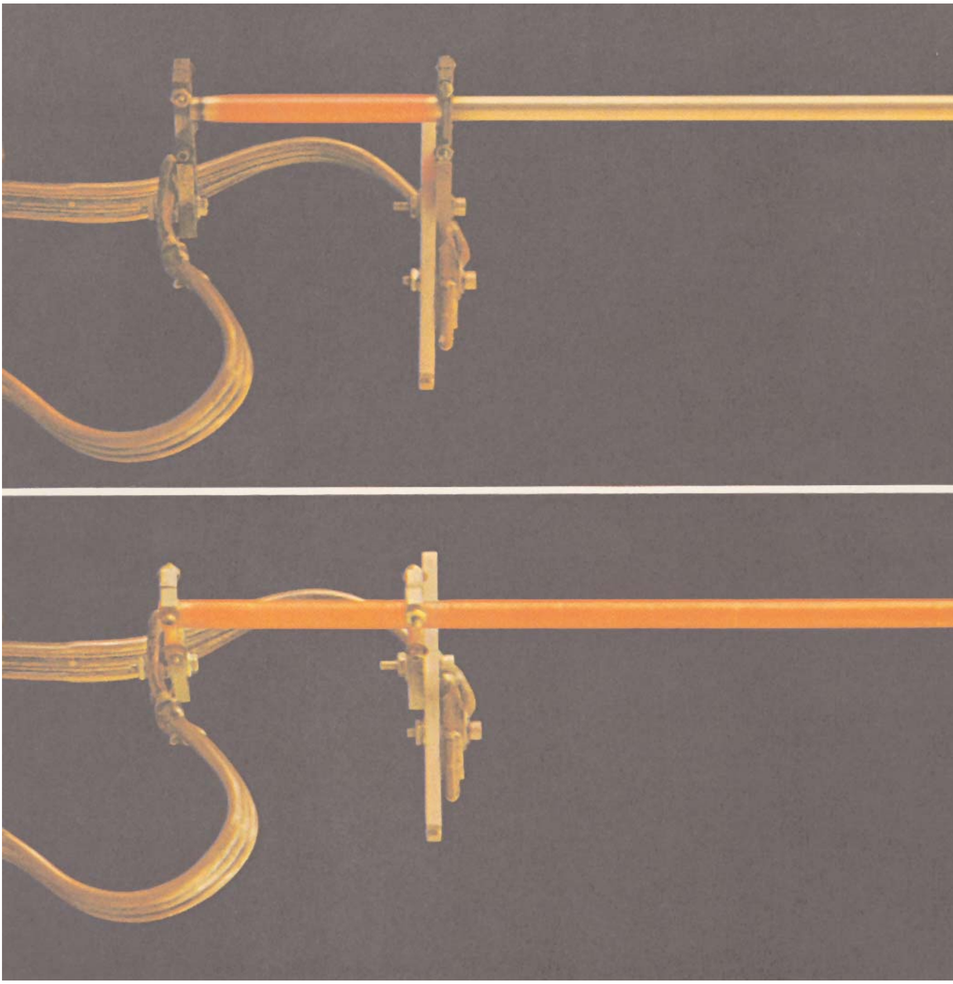


THE HEAT PIPE

by G. YALE EASTMAN

REPRINTED FROM
SCIENTIFIC AMERICAN
MAY 1968
VOL. 218, NO. 5
PP. 38-46

THE HEAT PIPE

This new device can be several thousand times as effective in transporting heat as the best metals. It shows promise of being immediately useful in many areas of technology.

The transportation of heat plays an increasingly important role in many areas of modern technology. For example, a nuclear power station produces energy in the form of heat, which must be brought out of the core of the reactor before it can be converted into useful electric power. Similarly, almost all electrical devices, including solid-state electronic components, generate heat as a useless by-product, which must be removed from the immediate environment and disposed of in some suitable heat "sink."

It is hardly surprising, therefore, that a major research effort has been mounted to find more efficient means of moving heat from one place to another. The trouble is that metals, even though they conduct heat much better than other substances, are poor conductors of heat. Copper, for instance, is usually regarded as one of the best conductors of heat. Yet if a thermal power of 10,000 watts were applied to one end of a solid copper bar one inch in diameter and one foot long, the temperature difference along the bar could theoretically exceed 30,000 degrees Fahrenheit. That is, one end could become a vapor hotter than the sun's surface, while the other end remained at room temperature! Thus it is quite remarkable that a device just emerging from the laboratory can transfer this amount of heat with a temperature difference of only a few degrees. This new device, called the "heat pipe," can be several thousand times more effective in transporting heat than the best metallic conductors.

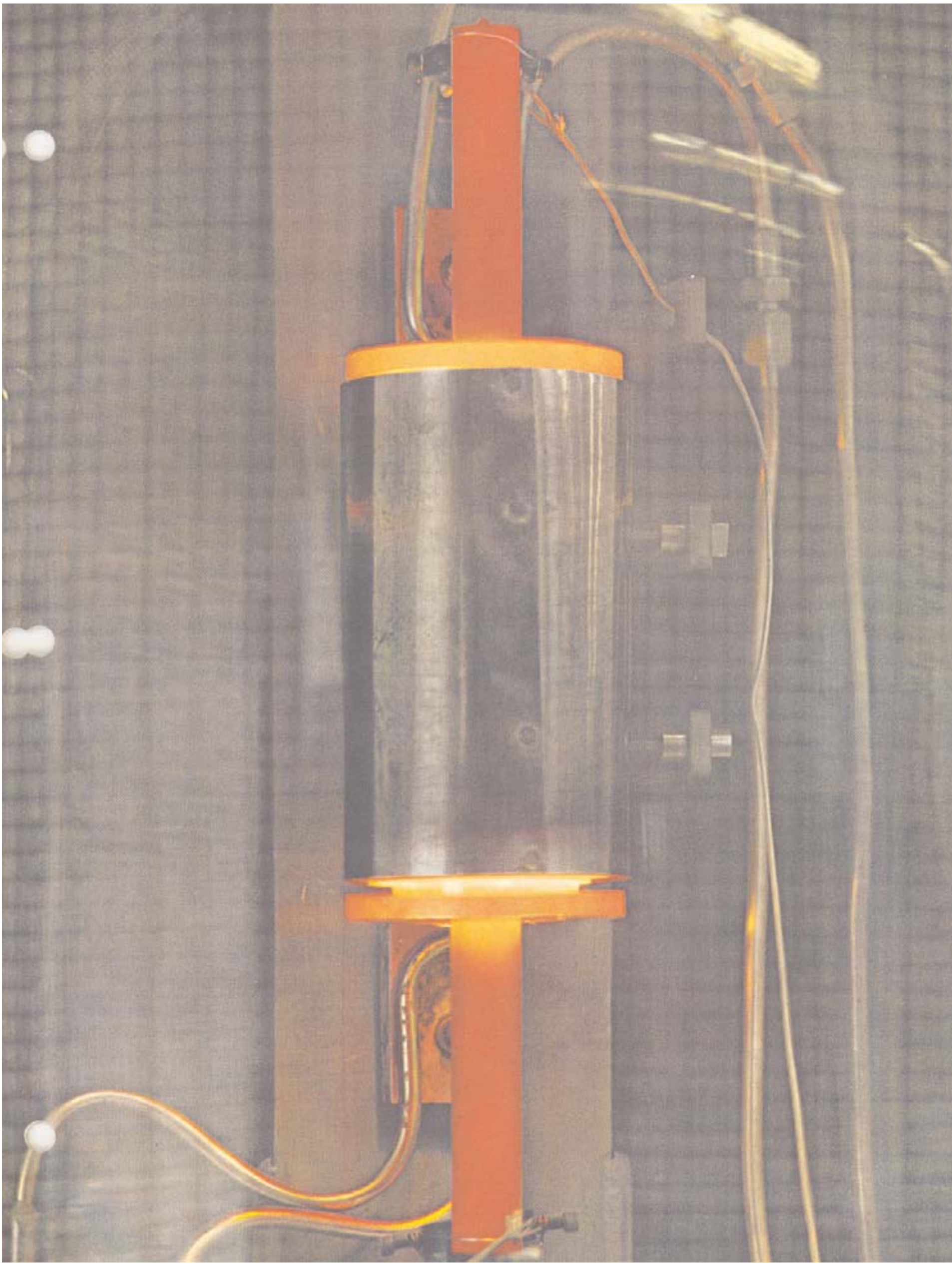
The principle of the heat pipe was first put forward in 1942 by Richard S. Gaugler of the General Motors Corporation. Gaugler's device was not effectively put into use, however, and as a result his proposal was not widely known in 1963, when George M. Grover of the Los Alamos Scientific Laboratory independently hit on a similar device and coined the name "heat pipe" to describe it. Grover and his colleagues originally developed the heat pipe for use in highly specialized power-generating systems for spacecraft. The heat pipe is one of the first such space components to show promise of immediate application in other areas. Since 1963 the development of the heat pipe for a wide range of industrial applications has been taken up by a number of research groups, including our own at the Radio Corporation of America.

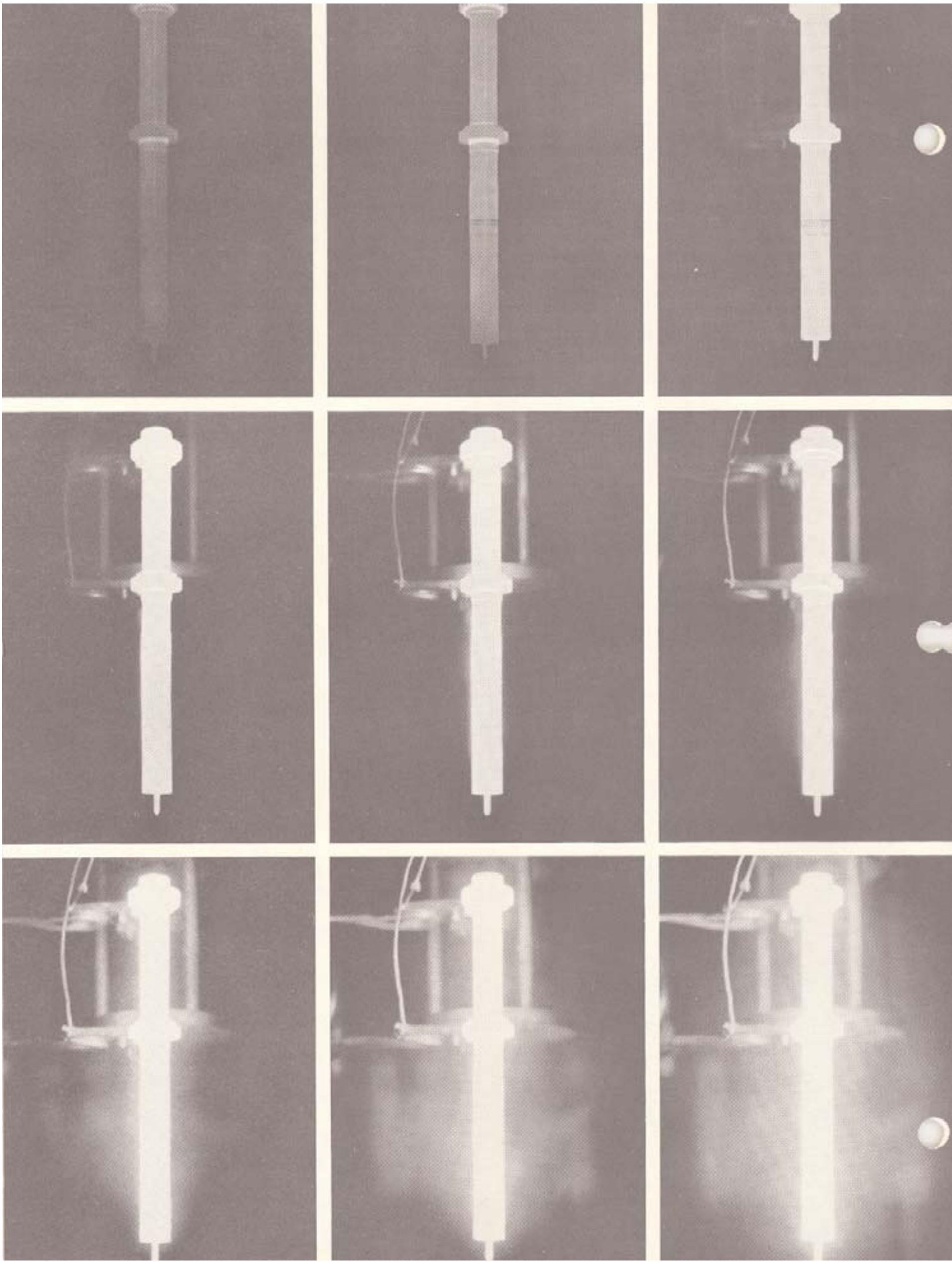
The heat pipe is essentially a closed, evacuated chamber whose inside walls are lined with a capillary structure, or wick, that is saturated with a volatile fluid [see top illustration on page 6]. The operation of a heat pipe combines two familiar principles of physics: vapor heat transfer and capillary action. Vapor heat transfer is responsible for transporting the heat energy from the evaporator section at one end of the pipe to the condenser section at the other end. This principle is of course the same as that used in conventional steam-heating systems. What distinguishes the heat pipe from such systems is that in the heat pipe capillary action is responsible for returning the condensed working fluid back to the evaporator section to complete the cycle. (Capillary action is the process by which moisture rises in a bath towel when one end is dipped in water.)

The function of the working fluid within the heat pipe is to absorb the heat energy received at the evaporator section, transport it through the pipe and release this energy at the condenser end. It is this process that is called vapor heat transfer. When a liquid vaporizes, two things happen. First, a large quantity of heat is absorbed from the heated area. This change takes place because energy is needed to separate molecules that are in contact in the liquid state. The quantity of energy required to evaporate a unit mass of liquid at a given temperature is called the latent heat of vaporization.

Second, as the working fluid vaporizes, the pressure at the evaporator end of the pipe increases. The pressure is caused by the thermal excitation of the molecules comprising the newly created vapor. The vapor pressure sets up a pressure difference between the ends of the pipe, and this pressure difference causes the vapor, and thus the heat energy, to move toward the condenser section. When the vapor arrives at the condenser section, it encounters a temperature lower than that of the evaporator. As a consequence the vapor turns back to a liquid and thereby releases the thermal energy stored in its heat of vaporization.

EFFECT OF GRAVITY on the operation of a heat pipe is shown to be negligible in this demonstration in which the heat pipe is being heated in its middle by an electric coil inside the metal sleeve at center. The uniform orange color of the heat pipe indicates that heat is being transferred equally upward and downward by the flow of vapor through the core of the pipe. Heat is being removed by radiation from the surface of the pipe, accompanied by condensation of the vapor inside the pipe. The cycle is completed by the return flow of liquid through the capillary structure, or wick, that lines the inside surface of the pipe. The heat pipe here was developed for the Air Force by the Radio Corporation of America.





In addition, as the fluid condenses, the vapor pressure created by the molecules decreases, so that the necessary pressure difference for continual vapor heat flow is maintained.

It is important to note that the vaporized fluid stores heat energy at the temperature at which the vapor was created, and that it will retain the energy at that temperature until it meets a colder surface. The result is that the temperature along the entire length of the heat pipe tends to remain constant. It is this tendency to resist any difference in temperature within the heat pipe that is responsible for the device's high thermal conductance.

One of the requirements of any self-contained vapor heat-transfer system is a means of returning the condensed liquid to the evaporator to replenish the supply. In older systems this return was accomplished either by gravity or by a pump. Each of these methods has disadvantages. The use of gravity requires that the boiler always be located below the condenser, and this arrangement is not always convenient. A separate pump eliminates the gravity restriction, but it requires outside energy for its operation. Such a system depends on a second source of energy, with the attendant complexity of control and reduced reliability.

The heat pipe, on the other hand, can operate against gravity and without a second external energy source. Movement of the working fluid is accomplished by capillary action within the wick that connects the condenser to the evaporator. The driving force that causes the liquid to move through a capillary is the surface tension of the liquid. Surface tension results from the forces of attraction between the molecules of the liquid. In any liquid each molecule is surrounded by other molecules, so that the pull between adjacent molecules in one direction is balanced by an equal pull of the molecules in the other direction. The net result is that no motion occurs. At the surface, however, there is no pull from outside to balance the pull from inside the liquid. Accordingly there is a net force that tends to pull the surface molecules inward and create a shape with a minimum surface area. This tendency explains why droplets and bubbles tend to be spherical.

When a fluid is placed in a vessel composed of a material that the fluid "wets" well, there is an attractive force between the fluid and the wall of the vessel. The force combines with the surface tension in such a way as to move the liquid surface toward the unfilled portion of the vessel [see bottom illustration on page 7]. If the vessel is a capillary of small diameter (or any wick material with small continuous pores), this force, called capillary attraction, can be large compared with the mass of fluid in the capillary. Rapid motion of the fluid then results.

Thus the capillary provides a structure in which the liquid pumps itself along. This process will continue indefinitely in the absence of other forces, as in gravity-free space. If the motion is upward against a force such as gravity, a limit will be reached when the weight of the fluid column being lifted is equal to the lifting force. A high-performance heat-pipe fluid has a high latent heat of vaporization, a high surface tension and a low density. Low viscosity is also a desirable property to minimize "drag" as the liquid moves along through the wick. The heat pipe derives its unique properties, therefore, from the combination of vapor heat transfer and capillary pumping.

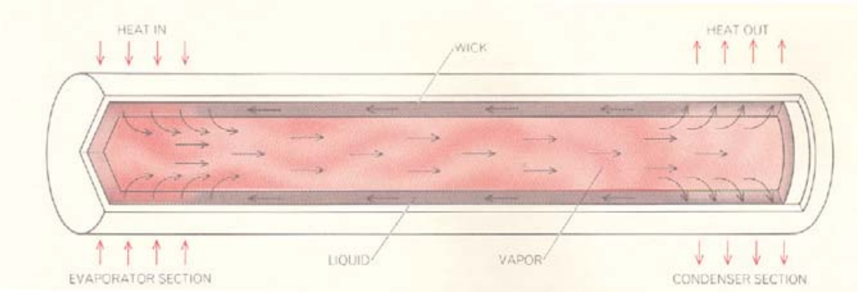
There are five properties of the heat pipe that deserve special mention because they serve to define the areas in which practical applications are to be found for the device. First, devices that operate on the principle of vapor heat transfer can have several thousand times the heat-transfer capacity of the best metallic conductors, such as silver and copper. In one case a thermal power of 11,000 watts has been carried 27 inches by a one-inch heat pipe with a temperature loss so small that it was difficult to measure accurately. By way of comparison, a copper block nine feet in diameter and weighing about 40 tons would be required to produce the same result.

A second property of the heat pipe is called "temperature flattening." There are many heat-transfer applications in which a uniform temperature over a large surface area is required. Without the heat pipe special care must be taken to ensure a uniform temperature of the heat source. A heat pipe, however, can be coupled to a nonuniform heat source to produce a uniform temperature at the output, regardless of the point-to-point variations of the heat source. This statement is true because evaporation and condensation of the working fluid take place at essentially the same temperature. Variations in source temperature affect only the rate of evaporation; an increase in the temperature of the heat source at a given point on the surface of the evaporator causes an increase in the rate of evaporation at that point without affecting the temperature of evaporation. Condensation of the working fluid at the heat-delivery zone takes place at the temperature at which the fluid was evaporated, regardless of the pattern of the heat input. In fact, the entire surface of the heat pipe is held constant within very narrow limits. The heat pipe is therefore an isothermal device for most practical engineering purposes. A demonstration of this property in conjunction with a nonuniform heat source is given when a flame is used to supply thermal power to a heat pipe. Although a flame is one of the most nonuniform of all heat sources, the heat pipe still delivers thermal power with a high degree of uniformity.

Third, the evaporation and condensation functions of a heat pipe are essentially independent operations connected only by the streams of vapor and liquid in the pipe. The patterns and area of evaporation and condensation are independent. Thus the process occurring at one end of the pipe can take place uniformly or nonuniformly, over a large or a small surface area, without significantly influencing what is going on at the other end. This separation of functions leads to one of the most valuable properties of the heat pipe: its ability to concentrate or disperse heat. This property has been called "heat-flux transformation." If thermal power is introduced to the heat pipe at a slow rate over a large surface area, the same total amount of working fluid can be evaporated as when the power is introduced at a high rate over a small surface area. Similarly, vapor can be condensed rapidly over a small area or slowly over a large area. It is the ratio of the surface area of the evaporator to the area of the condenser that determines whether heat energy is concentrated or dispersed at a constant temperature. In that way the thermal power available per unit of heat-transfer area can be either increased or decreased. This property of the heat pipe makes it possible to match sources and users of heat that were formerly incompatible because of their differing natural heat-transfer rates.

Two examples from the space-power field illustrate the use of this heat-flux-transformation property. Radioactive isotopes that could not be used previously because of their low power output are now being considered as heat sources for space-power systems.

TEMPERATURE UNIFORMITY is maintained over the entire surface of a heat pipe for a wide range of temperatures. In this demonstration a heat pipe is shown being heated through a range of temperatures from 1,700 degrees Fahrenheit (top left) to 2,800 degrees F. (bottom right) by means of a pair of electrodes fastened to the top and middle of the pipe. The uniform intensity of the light emitted from the incandescent surface of the pipe at each stage indicates the underlying uniformity of temperature. The containment vessel of this Air Force heat pipe was made of a molybdenum alloy; the working fluid was lithium.



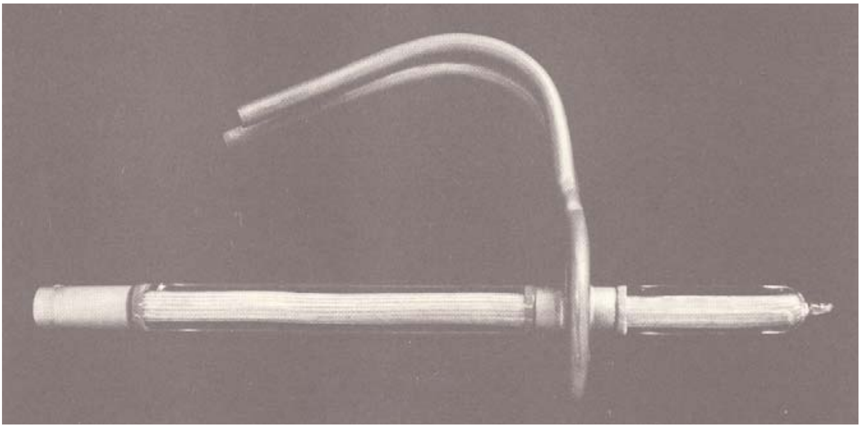
CUTAWAY DRAWING of a typical cylindrical heat pipe shows the circulatory system on which the operation of the device is based. The input of heat to one end of the pipe causes the working fluid to evaporate from the wick and also increases the vapor pressure at that end. As a result the vapor moves down the core of the pipe, carrying heat energy toward the output end. When heat is removed from the pipe, the vapor condenses and goes back into the wick. The condensate returns to the input end by capillary action. Because the fluid boils and condenses at roughly the same temperature, the temperature along the pipe tends to be uniform

Concentration of the heat by means of the heat pipe will make their use possible. As an example of the reverse process, electronic devices such as transmitting tubes and transistors generate heat at a high power density. In space, where all heat must be dissipated by radiation, this high power density far exceeds the capability of the best radiators. The concentrated heat can be effectively radiated only when spread over a large area. In order to accomplish such radiation by conventional means heat must be conducted over considerable distances with attendant temperature losses. The lower temperature requires a correspondingly larger radiator. The result can be a bulky and heavy structure. The heat pipe, however, can spread this high thermal power density, transforming it to a lower power density with a negligible temperature drop, and subsequently deliver the thermal power uniformly over the radiating surface. The fact that the heat pipe is hollow also makes it light in weight [see illustration on page 8]. The heat pipe can also be used to overcome present industrial problems.

The heat developed at the anode of a radio transmitter tube, for example, is too concentrated to be dissipated readily by the use of conventional air-cooling fans. Cooling usually requires a high-pressure, high-power blower that becomes excessively noisy. A heat pipe can accept the high power from the tube, move it a considerable distance with a negligible temperature drop and spread it over a larger area, where it can be removed quietly by a low-pressure, low-power blower.

A fourth property of the heat pipe is that it makes it possible to separate the heat source from the heat sink. It is often inconvenient or undesirable to have the heat source and the consumer of heat in close contact. In the example given above, it is generally inconvenient to locate all the electronic components of a spacecraft at the radiator in order to maximize temperature loss. In another instance it may be desired to transport heat from a nuclear reactor some distance through a radiation shield, without a drop in temperature, to the point of use, where the nuclear effects of the reactor environment can be made less troublesome. The heat pipe can carry out this function.

Fifth, the heat pipe can also be operated so that the thermal power and/or the temperature at which the power is delivered to the intended heat sink can be held constant in spite of large variations in the power input to the heat pipe. The surplus power beyond the needs of the heat sink is dissipated by means of an excess-power radiator. Temperature variations of less than 1 percent have been achieved with changes in input power of a factor of 10.
A notable feature of the heat pipe related to this last property is that once the heat pipe has been set for



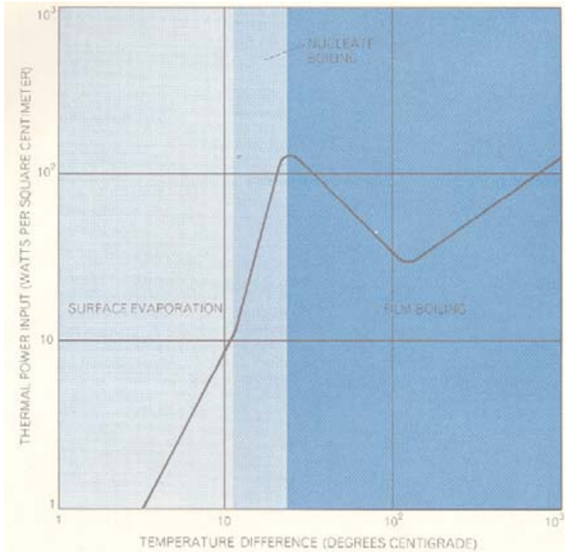
ELECTRICALLY INSULATING MATERIALS were used exclusively in the construction of this heat pipe, designed to remove large quantities of heat from high-voltage electrical circuits. The containment vessel is made of glass, the wick of fiber glass, and the working fluid is a fluoridated hydrocarbon. The two tubes extending from the pipe are employed to measure thermal conductance.

operation at a particular operating temperature no further external control is required. As a result there are no control mechanisms to fail or drift off calibration. The combination of temperature stability and self-containment can be used in conjunction with a nonuniform heat source for accurate control of the temperature of a chemical solution, a piezoelectric crystal, a heat-treating furnace or a radioactive isotope.

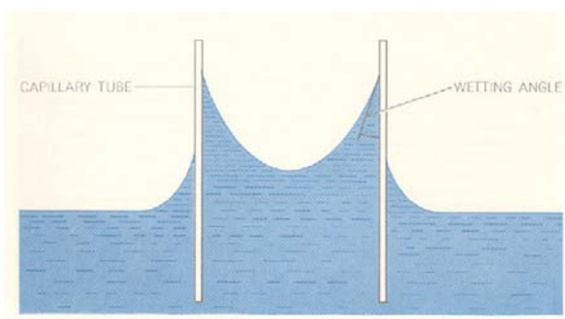
Although the heat pipe is a remarkably versatile device, it must operate within certain design limitations. Operation of the heat pipe is governed by four limiting factors: (1) the maximum total power that can be transferred in a device of a given size, (2) the maximum power per unit of evaporator area that can be handled safely, (3) the maximum and minimum useful temperature for a given working fluid, (4) the extent of operation in a gravitational field or other acceleration. Let us consider these four limiting factors separately.

The upper limit to the power-handling capacity of a given heat pipe is determined by the ultimate pumping capacity of the wick. If the heat pipe is operated above this limit, the evaporator does not receive enough working fluid to absorb the incoming heat energy from the source. Consequently the temperature of the evaporator section rises rapidly and undesirably. The ultimate pumping capacity of the wick is determined by the size and geometry of the wick, as well as by the properties of the fluid, for example its heat of vaporization, surface tension, liquid density and viscosity. This limiting value, however, is usually quite high.

In ordinary "pool" boiling, such as takes place in a kettle of water heated on a stove, the process of vaporization proceeds through three definable stages as the power input is increased, eventually reaching a critical limit [see top illustration on preceding page]. In the first stage of evaporation the input heat is just enough to cause evaporation of the liquid at the surface without disturbing the body of the fluid. The second stage involves what is called nucleate boiling, during which vapor bubbles form within the body of the fluid and rise to the surface. As the thermal power is increased and the bubbling becomes more vigorous the individual bubbles tend to form a film that covers the entire surface or large portions of it. This condition, called film boiling, is the third stage of vaporization. The effect of film boiling is that the vapor blanket sharply reduces the heat transfer from the input surface, with a resulting rise in the temperature of the surface. The onset of film boiling then represents a critical input power density that cannot be exceeded without risking damage to the container



THREE STAGES OF VAPORIZATION are apparent on this graph, which shows the temperature difference between the ontside surface of a container and the surface of a pool of liquid boiling inside the container as a function of the input power density. In the first stage (surface evaporation) the input heat is just enough to cause evaporation of the liquid at its surface. In the second stage (nucleate boiling) vapor bubbles form within the body of the fluid and rise to the surface. (There is strong evidence that nucleate boiling does not take place in a heat pipe.) In the third stage (film boiling) the individual bubbles tend to form a film that covers all or large portions of the surface. (The initial downward part of the curve corresponds to partial film boiling.) The onset of the film-boiling stage represents a critical input power density that cannot be exceeded without damaging the container.



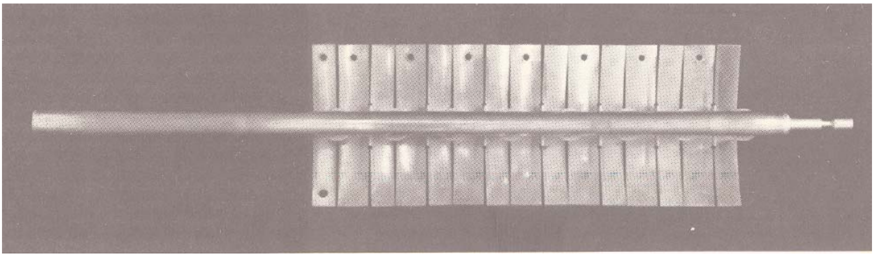
CAPILLARY ACTION within the wick that lines the inside surface of a heat pipe provides the means for returning the condensed liquid to the evaporator section in order to replenish the supply of vapor. An attractive force between the liquid and the wall of the capillary tube combines with the surface tension of the liquid to move the liquid surface toward the unfilled portion of the tube. The driving force is determined by the "wetting angle" of the liquid and the pore size of the capillary. In the absence of other forces the liquid will pump itself along indefinitely. In the presence of a force such as gravity a limit will be reached when the weight of the fluid column being lifted is equal to the lifting force.

material of the vessel. Growing evidence indicates that the high purity of the fluid, the presence of the wick and the motion of the fluid through the wick and across the heat-input surface tend to prevent the formation of bubbles and thus reduce the blanketing effect. Nevertheless, there is still a maximum input power density that cannot be exceeded, often called the critical heat-flux density. This limiting value is very high, on the order of 320,000 B.T.U.'s per hour per square foot of evaporator surface for water at 212 degrees F., or 1,600,000 B.T.U.'s per hour per square foot for lithium at 2,700 degrees F.

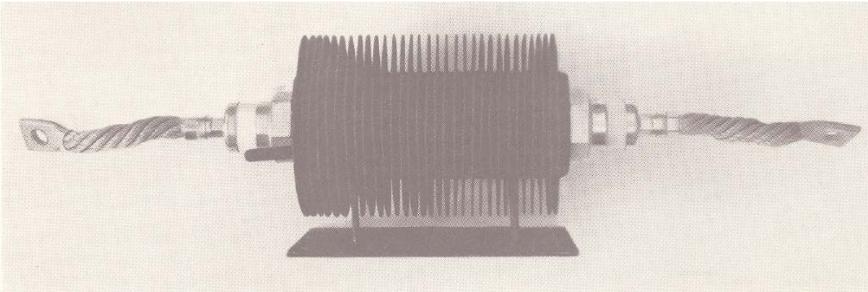
HEAT RADIATOR FOR SPACECRAFT incorporates 100 stainless-steel heat pipes {horizontal lubes) in which the working fluid is sodium. The heat pipes are designed to remove heat from the condenser section of a potassium-filled "loop" (flattened vertical tube), which in turn passes through the nuclear reactor and turbine used to power the spacecraft. The advantages of using heat pipes to dissipate unwanted heat in space include light weight, gravity-free operation and efficient dispersion of heat over a large radiating surface. This particular radiator is designed to dissipate 50,000 watts of heat energy at an operating temperature of 1,420 degrees F. The entire assembly measures 23 inches by 43 inches and weighs only 17 pounds. The device was developed for the Air Force by RCA; one of the horizontal heat pipes was used for the demonstration shown in the color photograph on page 3 .

As the temperature of the heat pipe is increased, the rate of evaporation, and consequently the vapor pressure of the working fluid, increases rapidly. The power-handling capacity of the heat pipe also increases, since it is the vaporization of the working fluid that is responsible for heat transfer. For a particular working fluid there is a minimum temperature below which the rate of evaporation becomes insufficient to effect a smooth transfer of thermal power. There is also a maximum operating temperature of the working fluid that is based on the maximum safe vapor pressure allowed within the heat pipe. As the rate of evaporation increases with temperature, the vapor pressure within the container also increases, stressing the container walls. The maximum operating temperature, therefore, is determined by the "creep" strength of the containment material of the heat pipe. Typically the pressure in a heat pipe at the operating temperature is between .03 atmosphere and 10 atmospheres (between .4 pound and 150 pounds per square inch).

To repeat, the driving force that moves the condensate through the wick to the evaporator is the surface tension of the fluid. The extent to which this force can be brought to bear on the fluid is determined by the "wetting angle" and the pore size of the capillaries. If a heat pipe is subjected to a force that is so directed as to oppose the return of the condensate (such as the acceleration of gravity or of a rocket engine), less fluid can be moved because the surface tension must divert some of its force to overcome the new opposing force. This effect reduces the total power-handling capacity of the heat pipe. In this situation the latent heat of vaporization, the liquid density and the viscosity of the fluid act to determine the extent to which proper heat-pipe operation can be sustained. The heat of vaporization determines the quantity of fluid that must be evaporated to carry the required thermal power and therefore the quantity of condensate that must be returned. The liquid density controls the mass that must be transport-



POWER DISTRIBUTOR FOR SPACECRAFT is the function of this heat pipe, which also uses sodium as its working fluid. Attached to the heat pipe are eight silicon-germanium thermoelectric conversion modules, which convert a fraction of the heat delivered by the heat pipe into electric power. The excess heat is radiated into space by means of the rectangular metal plates behind the converters.



COOLING DEVICE for use with semiconducting electronic components consists of a heat pipe that passes through the center of a series of hollow copper convective fins {black disks). The heat pipe shown here is simultaneously cooling two 250-ampere silicon rectifiers, which are located at the two ends of the heat pipe. The device is designed to dissipate 100 watts of heat at 100 degrees centigrade with natural convection or 600 watts at the same temperature with forced convection (that is, with the aid of a blower).

ed by the surface tension. The viscosity determines the amount of frictional drag that opposes fluid flow through the wick. Within limits the effects of such outside forces can be reduced by decreasing the size of the capillary pores in order to increase the surface area of the capillary structure and consequently its lifting ability. A reduction in pore size, however, also increases the viscous drag because of the increased surface area.

Since the pertinent physical properties vary widely from fluid to fluid, the effects of outside forces also vary widely. For example, operating a heat pipe against gravity (that is, in the vertical direction with the evaporator at the top) decreases the total power capability of a lithium heat pipe only about 10 percent compared with horizontal operation. On the other hand, the corresponding difference in the operation of a mercury heat pipe can be several orders of magnitude.

Heat pipes have been made to operate at various temperatures spanning the range from below freezing to over 3,600 degrees F. The power transferred ranges from a few watts to more than 17,000 watts. Working fluids have included methanol, acetone, water, fluoridated hydrocarbons, mercury, indium, cesium, potassium, sodium, lithium, lead, bismuth and a range of inorganic salts. The containment vessels have been made of glass, ceramic, copper, stainless steel, nickel, tungsten, molybdenum, tantalum and various alloys. The wicks or capillary structures have included sintered porous matrixes, woven mesh, fiber glass, longitudinal slots and combinations of these structures in various geometries. In physical size heat pipes have ranged from a quarter of an inch to more than six inches in diameter and up to several feet in length. Moreover, heat pipes can be designed in almost any configuration.

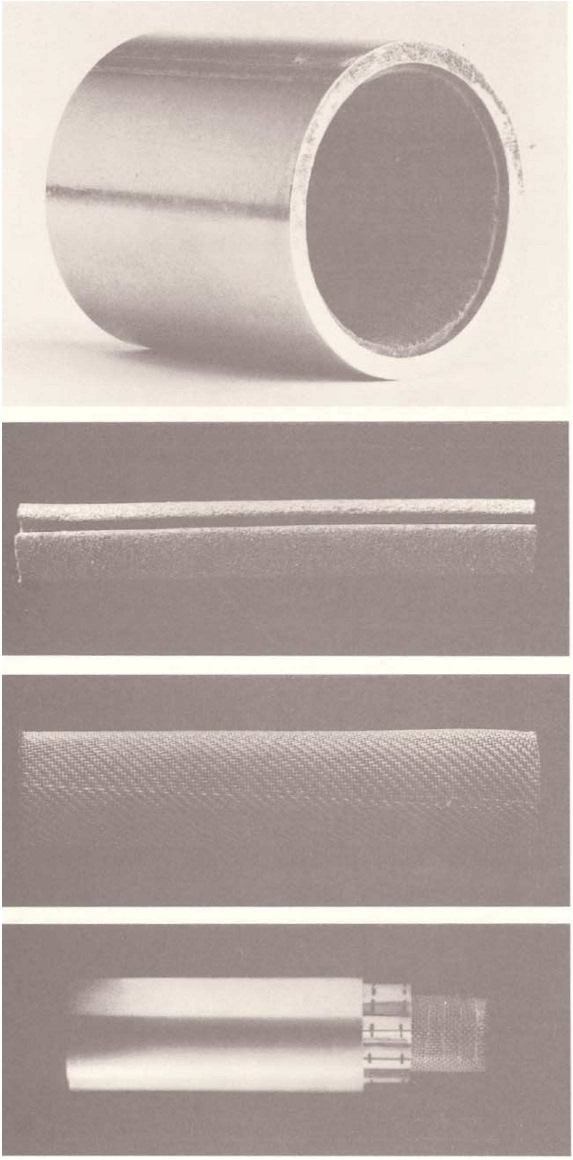
An operating life in excess of 10,000 hours without failure or detectable degradation has been achieved with a range of fluid-container systems. The longest of these tests has currently passed 16,000 hours at 1,100 degrees F., using potassium as the working fluid in a nickel containment vessel.

One interesting combination of materials involves the use of electrical insulating materials throughout the heat pipe: vessel, wick and fluid [see bottom illustration on page 6]. Such a device can move large quantities of heat from locations at high voltage. Tests to date have exceeded 5,000 volts. This unusual combination of high thermal conductance and high electrical resistance seems destined to find application in a number of electronic and electrical circuits.

In short, the heat pipe is a unique and versatile heat-transfer device. Its special properties are high thermal conductance, temperature flattening, heat-flux transformation and separation of heat source from heat sink. These properties are responsible for stimulating new developments in such varied areas as thermal-to-electrical energy conversion devices for space-power systems, heat sinks for electronic components and devices, special medical uses, coolers for electric motors and thermal-control systems for spacecraft.

The Cover

The two photographs on the cover demonstrate the extraordinary heat-transfer capacity of the heat pipe, a new device that shows promise of immediate application in many areas of technology. The photograph at top shows a hollow stainless-steel pipe being heated on one end bypassing an electric current through the section of pipe between the two electrodes at left and center. Resistance heating causes this section of the pipe to glow bright orange. Practically no heat is conducted to the part of the pipe that extends beyond the second electrode to the right, however, as is indicated by the fact that this part of the pipe does not glow. The photograph at bottom shows the same pipe, but this time with a wick, or capillary structure, lining the inside surface of the pipe. The wick is saturated with a volatile fluid that evaporates at the heat-input end and condenses at the heat-output end. The resulting circulatory system is the basis of the heat pipe's effectiveness. Although the heat pipe in the bottom photograph is heated in the same way as the hollow pipe in the top photograph, the heat pipe glows uniformly along its entire length.



WICKS FOR HEAT PIPES can come in a variety of materials and structures. At top is a ropper heat pipe with a wick of porous copper powder deposited on the inside surface. Second from top is wick consisting of a feltlike matting of nickel fibers. Third from top is a wick made of four layers of molybdenum mesh. At bottom is a heat pipe with a combination wick consisting of a molybdenum mesh layer inside a corrugated molybdenum layer.

The Author

G. YALE EASTMAN is with the Radio Corporation of America as manager of heat-transfer-device engineering in the plant at Lancaster, Pa. His group is charged with responsibility for the development of heat pipes, thermionic energy converters, alkali vapor arc lamps, vacuum components and gas lasers. Eastman has headed the group since 1966. Before that he was for seven years leader of an engineering group concerned with the development of new processes for making transmitting tubes and the materials that go into them. Eastman was graduated from Amherst College in 1950 with a degree in mathematics; he joined RCA immediately and was involved among other things in the development of picture tubes for color television.

Bibliography

THE HEAT PIPE AND ITS POTENTIALITIES. K. T. Feldman, Jr., and G. H. Whiting in Mechanical Engineering, Vol. 89, No. 2, pages 30-33; February, 1967.

STRUCTURES OF VERY HIGH THERMAL CONDUCTANCE. G. M. Grover, T. P. Cotter and G. F. Erickson in Journal of Applied Physics, Vol. 35, No. 6, pages 1990-1991; June, 1964.