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HEAT PIPES FOR SPACECRAFT TEMPERATURE CONTROL -- AN ASSESSMENT OF THE STATE-OF-THE-ART

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16. Abstract

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ABSTRACT

Spacecraft applications that require the efficient cooling of high-powered components, the precise temperature control of sensitive electronic and optical components, and the protection of cooled components from temporary, adverse environmental conditions are increasing. Heat pipes using gas, vapor, liquid, or voltage control to provide variable conductance or diode thermal behavior have been and are continuing to be developed to meet increasingly difficult requirements. The various control techniques are critically evaluated using characteristic features and properties, including heat transport capability, volume and mass requirements, complexity and ease of fabrication, reliability, and control characteristics. As a result, advantages and disadvantages of specific approaches are derived and discussed. Using four development levels, the state-of-the-art of the various heat pipe temperature control techniques is assessed. Finally, the need for further research and development is discussed and suggested future efforts are projected.

INTRODUCTION

Heat pipes are gaining increasing acceptance as efficient thermal control tools in various spacecraft applications. They are competitive in many applications with other thermal control methods such as pumped-loops, louver systems, and heaters, and sometimes can be used advantageously in conjunction with these other methods. Depending on the working fluids used, heat pipes can cover the extremely wide temperature range from ca. 4 K (helium) to ca. 2200 K (silver). However, most spacecraft temperature control applications have been near-room temperature and considerable experience now exists with fluids such as water, methanol, ammonia, and some Freons. Growing attention is being given to the cryogenic temperature range, mainly for the temperature control requirements of infrared sensors and optical systems. Some experience has already been gained with methane, ethane, nitrogen, and oxygen as cryogenic working fluids, but still more technological development is required. There also is a significant trend toward even lower temperatures which require hydrogen and helium as working fluids.

Heat pipes offer several advantages in spacecraft temperature control:

Design flexibility - Heat pipes can be built in various geometries, they can be bent and they can be made with flexible sections. Since they are able to transport a relatively high heat flux at a low temperature drop through a small cross-sectional area and over a long and complicated path, the heat

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source and heat sink can be separated. Consequently, sources and sinks can be optimized independently and with minimal constraints on the overall design of the spacecraft.

Temperature control - In addition to providing very efficient heat transfer or isothermalization, or both, heat pipes can also be designed for the close temperature control of a heat source when its power dissipation or sink temperature varies. Several techniques have been developed, ranging from passive to active feedback control, that can provide temperature control of ± 5 K to ± 0.1 K, for most applications.

Thermal protection and switching of heat fluxes - Heat pipes can be designed to operate as thermal diodes or thermal switches, transporting heat only in the desired direction. For example, a thermal diode may protect a component from overheating during critical periods such as reentry, orientation maneuvers, and prelaunch operations. Moreover, a heat pipe designed as a thermal switch could be used to transport thermal energy to one of several heat sinks selected at will.

TEMPERATURE CONTROL HEAT PIPES

Although temperature control heat pipes employ the same or similar wick structures as fixed conductance heat pipes, the specific control technique used may introduce additional hydrodynamic considerations. These considerations are discussed below; a discussion of the various control techniques follows.

Hydrodynamic Considerations

Cross sections of the major classifications of wick designs most likely to be used in temperature control applications are shown in Fig. 1. It is recognized that the designs shown are not all-inclusive, but the variety presented is sufficient to illustrate the various hydrodynamic considerations. Nine characteristics, which should be evaluated in selecting a wick design for a specific application, have also been identified. An evaluation of the wicks shown in Fig. 1 is given in Table 1. The nine characteristics are discussed below.

1. Temperature range - Because fluid properties can change significantly with temperature, the characteristics of a given wick might make it more suitable for the temperature range of a specific application. It also should be recognized that the use of gas and liquid control (discussed later) may result in large temperature gradients in the condenser section of the heat pipe.

2. Heat transport - The heat transport capability becomes important when the source and sink are separated by a long distance or when the axial heat flux is high. As will be discussed later, high heat transport capability may be difficult to achieve reliably with some control techniques. Therefore, it is sometimes advisable to reduce the required capability by using parallel heat pipes or by using a shorter control heat pipe in series with a fixed conductance heat pipe.

TABLE 1: Evaluation of Wick Designs.

WICK DESIGN \ CRITERION FOR COMPARISON	TEMPERATURE RANGE[1]	HEAT TRANSPORT CAPABILITY[2]	TEMPERATURE DROPS[2]	1G TESTING[2]	FLUID INVENTORY[3]	TEMPERATURE CONTROL POTENTIAL[2]: GAS VCHP	LIQ TRAP DIODE	BLOCKAGE DIODE	EASE OF FABRICATION[2]	RELIABILITY[2]	STATE OF THE ART[4]	SPACECRAFT
(1) SCREEN	RT, SC	P	P TO F	F TO G	L	G	G	P	G	G TO VG	4	ATS 1
(2) SINTERED STRUCTURE	RT SC	P	P TO F	F TO G	L	G	G	P	G	G TO VG	2	
(3a) STANDARD AXIAL GROOVE	RT, SC, HC	F	F	P	L TO I	G	G[6]	P	VG[8]	G TO VG	4	ATS 6 OAO 3
(3b) IMPROVED AXIAL GROOVE	RT, SC, HC	F TO G	F	F	L TO I	G	G[6]	P	G[8]	G	1	
(4a) SLAB WICK	RT, SC, HC	F	G	G	I	VG	F	P TO F	G	G	4	ATS 6
(4b) GRADED POROSITY SLAB WICK	RT, SC, HC	F TO G	G	G	I	VG	F	P TO F	G	G	2	
(5) INVERTED MENISCUS CONCEPT	RT, SC, HC	F TO G	VG	G	I	G	P TO F	P TO F	F	G	1	
(6) FILLED ARTERY (NO TUNNEL)	RT, SC, HC	F TO G	G	G	I	G TO VG	F	G	F	G	4	OAO 3
(7) SCREEN COVERED GROOVE	FOR LIQUID METALS ONLY	VG	G	G	I	F TO G	G	P	G[9]	G	2	
(8) ANNULUS GAP		VG	G	G	H	P[7]	G	P	F[9]	F TO G	2	
(9) PEDESTAL ARTERY	RT, SC, HC	VG	G	G[5]	H	P[7]	G	P[10]	F	P	4	OAO 3, ATS 2
(10a) SPIRAL ARTERY (NO TUNNEL)	RT, SC, HC	G	G	G[5]	I TO H	G	P TO F	G	P TO F	G	4	OAO 3
(10b) TUNNEL WICK	RT, SC, HC	VG	G	G[5]	H	P[7]	P TO F	G	P TO F	F TO G	4	ATS 6
(11) FILLED ARTERY WITH TUNNEL	RT, SC, HC	G	G	G[5]	H	P[7]	P TO F	G	F	F TO G	1	
(12) MODULAR ARTERY	RT SC HC	G	G	G[5]	H	G	P TO F	G	F	G	2	
(13) ARTERIAL SLAB WICK	RT, SC, HC	G	G	G[5]	H	P[7]	P TO F	P TO F	F	F TO G	4	CTS

1) RT NEAR ROOM TEMP (300K - 200K)
SC SOFT CRYOGENIC TEMP (200K - 80K)
HC HARD CRYOGENIC TEMP (< 80K)

2) VG VERY GOOD
G GOOD
F FAIR
P POOR

3) L LOW
I INTERMEDIATE
H HIGH

4) 1 RESEARCH
2 LABORATORY PROTOTYPE
3 FLIGHT HARDWARE
4 FLIGHT DEMONSTRATION

5) IF ARTERIES ARE PRIMED
6) IF STAINLESS STEEL TUBES ARE USED
7) IF GAP OR ARTERY DOES NOT PRIME
8) NOT IF STAINLESS STEEL TUBES ARE USED
9) DIFFERENT TECHNOLOGY REQUIRED FOR LIQUID METAL HEAT PIPES
10) IF NO BLOCKING ORIFICE IS USED

3. Temperature drops - Low overall temperature drops are generally desirable. In low temperature applications, unduly large temperature drops may significantly increase radiator size. The evaporator/condenser temperature drop is inversely proportional to the evaporator/condenser heat transfer coefficient and to the wall conductance, and is proportional to the radial heat flux. Temperature control heat pipes may have short evaporators (compact sources) and, thus, high radial heat fluxes. The tendency of the wick structure to fail at the boiling limit is also considered in this category.

4. Influence of gravity - Heat pipes or systems employing heat pipes generally have to be tested in a 1-g field. If the heat pipes are very sensitive to gravity, for example, if the wicking height is small, 1-g tests can become extremely difficult, time consuming, and expensive. The effect of a gas or liquid storage reservoir on the 1-g wicking height must be considered. To simplify this evaluation, all arteries are assumed to be primed.

5. Fluid inventory - Besides the mass of the fluid itself, the fluid inventory adds to the weight of a heat pipe in other ways. This is especially true when the fluid is in a supercritical state at storage or handling temperatures and the internal pressure requires thick walls for pressure containment. The fluid inventory also influences such control characteristics as reverse heat leaks, recovery times, shutdown times and shutdown energies. The sensitivity of a wick structure to over- or underfill has been included under 'Reliability' (item 8 in this list).

6. Temperature control potential - It might become advantageous during the development of a project to switch from fixed conductance to variable conductance heat pipes, or one might want to employ the same baseline design for both fixed conductance and variable conductance heat pipes in the same project.

In either case, a good temperature control potential should result in a less expensive and faster development.

7. Ease of fabrication - This category indicates the relative cost of manufacturing and the potential of a standardized design. In general, the simpler a design, the easier, cheaper, and less time consuming will be the machining, cleaning, component testing, and assembling processes. Standardized designs will significantly contribute to low cost. Ease of fabrication becomes an important factor when large numbers of heat pipes are being considered.

8. Reliability - There are various considerations that may permit a given design to be used despite the fact that its performance is not completely reliable. For example, redundancy can be built into the system, or individual heat pipes can be overdesigned in order to provide a sufficiently high safety margin. Reliable startup and arterial priming, predictable performance, undegraded long-term performance, sensitivity to over- or underfill, and sensitivity to gas and other impurities are the major concerns.

9. State-of-the-art - This category might become decisive when the use of a heat pipe as a thermal control element in a spacecraft is considered. It represents the amount of successful effort invested to make a heat pipe usable for, and demonstrable in, flight applications.

It should be emphasized that the evaluations shown in Table 1 reflect the authors' opinions and do not necessarily represent the views of others in the heat pipe field.

Control Techniques

When answering the questions - How do we want a thermal control heat pipe to perform? What shall its control characteristics be? - the following classifications apply:

1. Variable conductance heat pipes (VCHP) - These control the vapor, evaporator, or source temperature within certain limits despite the fact that the heat throughput or the sink temperature vary considerably.

2. Diode heat pipes - These allow heat to flow in one direction only; they block the heat flow in the reverse direction, if the condenser temperature rises above the evaporator temperature.

3. Heat pipe thermal switches - This technique can be applied to shutdown an adverse heat flow from a normal condenser to the normal evaporator and at the same time sustain a heat flow from the normal evaporator to a second condenser.

4. Combination or hybrid control systems - These systems combine VCHP and diode control, controlling heat pipe temperature and preventing reverse heat flow. A VCHP and thermal switch might also be combined.

On the other hand, one might ask: How can thermal control be achieved? What has to be done physically to the heat pipe to make it a VCHP, diode, etc.? Accordingly, the following basic control techniques can be identified: (1) gas control, (2) vapor control, (3) liquid control, and (4) voltage control.

Based on these techniques, Table 2 has been developed. Thermal switches have been omitted from this table as their range of applicability seems to be narrower than that of VCHPs and diodes. The control techniques outlined in Table 2 will now be discussed. In cases of well-established technology, the reader is referred to the available literature; recent developments are described in more detail.

Table 2: Classification of Heat Pipe Temperature Control Techniques.

GAS CONTROL	VAPOR CONTROL	LIQUID CONTROL	VOLTAGE CONTROL
• WICKED (COLD) RESERVOIR • WICKED CONST. TEMP. RESERVOIR (AUXILIARY HEATER) • NON WICKED (HOT) RESERVOIR • CASCADED VCHP SYSTEM • MECHANICAL FEEDBACK CONTROL (NON WICKED VARIABLE VOLUME RESERVOIR) • ELECTRICAL FEEDBACK CONTROL (WICKED HEATED RESERVOIR)	• VAPOR FLOW RATE CONTROL (FCHP) • INDUCED WICK/GROOVE DRY OUT (FCHP): ONE, TWO, OR THREE HEAT PIPE SYSTEM	• LIQUID BLOCKAGE OF CONDENSER MECHANICAL FEEDBACK BELLOWS SYSTEM, ELECTRICAL FEEDBACK HEATED RESERVOIR SYSTEM	• ELECTROHYDRODYNAMIC PUMPING • ELECTRO OSMOTIC PUMPING
VARIABLE CONDUCTANCE HEAT PIPE (VCHP) AND FEEDBACK CONTROL HEAT PIPE (FCHP) TECHNIQUES			

GAS CONTROL	LIQUID CONTROL
• GAS BLOCKAGE OF EVAPORATOR	• LIQUID TRAP (DESATURATION OF WICK STRUCTURE) • LIQUID BLOCKAGE OF EVAPORATOR
DIODE HEAT PIPE TECHNIQUES	

GAS CONTROL	LIQUID CONTROL	COMBINATION GAS LIQUID CONTROL
• GAS VCHP OR FCHP AND DIODE	• LIQUID BLOCKAGE FCHP AND DIODE • LIQUID BLOCKAGE FCHP AND LIQUID TRAP DIODE	• GAS VCHP OR FCHP AND LIQUID TRAP DIODE
COMBINED VCHP/DIODE TECHNIQUES		

GAS CONTROL

The use of noncondensing gas to vary the effective condenser length has been investigated in the greatest detail /1/. Basically, the technique involves the addition of a fixed quantity of gas which is swept to the end of the condenser and into any reservoir volume that has been provided, effectively "shutting off" the portion of the condenser it fills. Consequently, variation in the length of this gas plug in response to changes in evaporator or reservoir temperature represents a variation in active condenser length and hence in heat transfer from the system. Complete blockage can also be used to protect the normal evaporator from reverse heat flow if the condenser sink temperature becomes elevated. Thus, gas control can be used to achieve VCHP, diode, and thermal switch functions.

Hydrodynamics

The following wicks are generally considered for gas controlled heat pipes:

1. axial grooves
2. slab wicks } lower capability, but insensitive to the presence of gas
3. filled arteries
4. slab wicks with arteries
5. various arterial wicks } higher capability, but sensitive to the presence of gas

Although they provide higher heat transfer capability, arterial wicks have disadvantages when used in the presence of a control gas. In fact, arteries will not prime and remain primed with high vapor-pressure fluids such as ammonia, evidently because of pressure fluctuations caused by the slight instability of the gas front /2/. With lower pressure fluids, such as methanol, priming foils /3/ can be used to vent noncondensible gas trapped in the artery, but rigid leveling requirements are necessary during test to prime the arteries. Modular arteries have been used reliably with both high and low pressure fluids, but at a considerably reduced heat transfer capability /4/.

Recently a mechanism has been investigated that offers the possibility of priming large arterial heat pipes, regardless of the working fluid. This concept utilizes a jet pump to create the suction necessary to fill the artery and keep it primed /5/. Basically, the jet pump consists of a venturi or nozzle-diffuser type constriction in the vapor passage (Fig. 2). The throat of this venturi is connected to the artery. Thus, vapor, gas, liquid, or a combination of these is pumped continuously out of the artery. As a result, the artery is always filled with liquid and an adequate supply of working fluid is provided to the evaporator of the heat pipe. A proof-of-principle experiment using water as the working fluid has been successfully conducted in a simulated heat pipe environment.

High capability nonarterial heat pipes currently are being developed by optimally varying the porosity of the wick along its length /6/. By varying the porosity, the capillary-pressure limit is only as high as required to sustain the local vapor-liquid pressure difference. Thus, the permeability is as high as possible everywhere along the length of the wick. The potential increase in capability depends on the particular application, but it is typically greater than a factor of 2. A particular goal is the development of a 1.27 cm (0.5 in.) diameter, all-aluminum heat pipe for use with ammonia that has a heat transport capability in excess of 25,400 W cm (10,000 W in.).

Types of Gas Control

A further distinction is that of the temperature that is actually controlled. Is it the vapor temperature or the source temperature? For example, a heat pipe provided with an infinitely large, constant temperature gas reservoir, can only maintain the vapor temperature constant when the heat throughput is varying. Thus, the source temperature must increase since the temperature drop between source and heat pipe vapor is proportional to the heat flux and the thermal resistance between the source and the vapor (Fig. 3(a)). To control the source temperature directly, a feedback of the source temperature to the noncondensible gas reservoir is required to activate a heater, or other control element. This heater can, in turn, modify the gas blockage of the condenser in such a way that the vapor temperature decreases with increased heat throughput, thus allowing the source temperature to remain constant (Fig. 3(b)). Mechanical feedback systems have also been developed that vary the gas reservoir volume.

The various types of gas control have been described in detail elsewhere in the literature and will be only listed here. Exceptions are the recently developed cascaded VCHP, the liquid sponge reservoir concept, and the hybrid VCHP/diode.

Non-feedback control

1. Wicked reservoir (non-heated) /7,8/

2. Wicked reservoir (heated, constant temperature) /9/

3. Non-wicked reservoir (short, wide gas feed tube, rapid diffusion /7,10/)

4. Non-wicked reservoir (long, thin gas feed tube, slow diffusion /11/)

(Both wicked and non-wicked designs can be provided with "cold or hot traps" located near the condenser end of the gas feed tube to reduce fluctuations of the condenser end temperature, which governs the vapor partial pressure in the gas reservoir /10/.)

5. Cascaded VCHP /12/ - This is a system of two or more conventional VCHPs that are connected in series as shown in Fig. 4. In this case, they are provided with extremely long, thin gas feed tubes. The series connection allows extremely close passive temperature control. The radiator-connected heat pipe operates with relatively coarse control of its evaporator temperature. The condenser end of the source-connected VCHP is coupled to this evaporator and, therefore, sees a relatively constant temperature environment that leads to precision control of the evaporator temperature of this VCHP. Source heat pipe temperature variations can be reduced by an order of magnitude from those of the coarse-controlled heat pipe. One coarse-control VCHP can act as a constant temperature heat sink for one or more fine control VCHPs. A smaller total reservoir volume is required for a cascaded system.

6. Liquid sponge reservoir /13/ - This new method makes use of the solubility of noncondensible gases in liquids. If the Ostwald coefficient, the ratio of number of gas molecules in the liquid phase to number of gas molecules in the vapor phase of this liquid, is considerably larger than 1, a small liquid volume would be sufficient to store (by dissolution) a large amount of noncondensible gas (Fig. 5). If, for example, the Ostwald coefficient of an appropriate liquid/gas combination is 10, the gas absorption reservoir could ideally be made ten times smaller than an equivalent standard gas reservoir. Fig. 6 displays the Ostwald coefficients of some gas/liquid pairs potentially applicable in the temperature range from near room temperature down to the lower end of soft cryogenic temperatures. Gas/liquid systems of potential interest in the cryogenic temperature range are: methane/ethane, argon/methane, nitrogen/methane, nitrogen/oxygen. Experiments with a laboratory heat pipe have provided encouraging results. Methanol has been used as the working fluid with nitrogen, butane, and ammonia as control gases.

Feedback control

1. Mechanical /14/ - The temperature of the source is sensed directly by a thermal expansion fluid that varies the gas reservoir volume through a control bellows. Although this system has been successfully demonstrated in the laboratory and requires no electrical power, no practical applications have been identified, because of the system's mechanical complexity.

2. Electrical /15,16/ - The temperature of the source is sensed directly by a thermistor that controls the gas reservoir temperature through a heater and electronic controller. Typical control accuracies are ±1 K. Over- or undershoots and recovery times, generally not a problem, can become significant in some applications where both rapid response and a well-insulated reservoir (minimum heater power) are required. Electrical reservoir heater power is typically only a few watts.

Diode 8

Gas control can be used to achieve diode performance; however, since this automatically provides VCHP control also, it basically results in a hybrid system as described below.

Hybrid (combined VCHP/diode) /17/

A simple non-optimized axial groove aluminum extrusion heat pipe with a stainless steel reservoir and a stainless steel to aluminum transition piece has been tested in the laboratory (Fig. 7). The gas reservoir heater was manually controlled. With this system the VCHP operation and the diode shutdown could be successfully demonstrated at cryogenic temperatures. Ethane was the working fluid and helium the control gas. The temperature control achieved was 184 K ±1 K in the active mode and 173 K ±10 K in the passive mode for power variations between 6 W and 50 W and sink temperature variations between 140 K and 172 K.

VAPOR CONTROL

By throttling the vapor flow it is possible to adjust the mass flow rate and vapor pressure drops to maintain a constant evaporator or source temperature for varying heat throughputs and sink temperatures. Unlike gas control, vapor control works well for sink temperature approaching the evaporator temperature. The vapor control technique has been successfully demonstrated for the VCHP mode. Whether it also works for diode, thermal switch, and hybrid modes has yet to be demonstrated.

Hydrodynamics

Slab wicks and arterial systems have been tested. Sufficient capillary pressure must be provided to prevent "blow through" caused by vapor pressure differences in the evaporator and condenser sections.

Types of Vapor Control

The basic vapor control technique was described years ago /7/, but has not been demonstrated until recently /18/. The throttling of the vapor flow is by a control valve activated by the thermal expansion/contraction of a control liquid in a sensor volume which is attached to the heat source. Thus, passive feedback control is achieved. One type of control directly uses the variation of the vapor flow and the resulting vapor pressure drop for temperature control. Another method utilizes the induced wick and groove dryout for control /17/.

Vapor flow rate control

A vapor flow rate control heat pipe, in which the sensor volume is inside the evaporator and thus controls the vapor temperature rather than the source temperature is shown in Fig. 8. The pressure difference required to drive the vapor flow across the valve section is provided by the differences in temperature of the evaporator and condenser. The activation of the valve is designed such that the valve opening is proportional to the deviation of the heat source temperature from the set point temperature. Thus, the heat transport through the valve exactly matches the heat input from the heat source. The maximum temperature difference between evaporator and condenser is set by the capillary pressure limit of the wick. When this limit is exceeded, vapor blows through the wick where it penetrates the valve bulkhead and heat pipe operation is terminated. The principle of vapor flow rate control has been successfully demonstrated with water. The control range achieved was 2.2 K for large variations in sink temperature and heat load /18/.

Induced wick/groove dryout

The schematic of this improved method, in which the blow through limit is used advantageously, is shown in Fig. 9. The pressure build-up when the valve is closing (due to the source temperature falling below the set point) is used to dry out parts of the external grooves at the condenser end of the input heat pipe and the transport wick in contact with them. Thereby the thermal resistance is increased and this causes the source temperature to rise again to reach the set point. For the case when the source temperature exceeds the set point, the valve opens, thus reducing the pressure and allowing the dried-out grooves and wick to rewet. This reduces the thermal resistance and causes the source temperature to fall again to the set point.

Three configurations of the induced wick/groove dryout concept are possible.

1. One heat pipe - A common wick structure extends from the source to the sink. A non-uniform evaporator temperature may result from partial dry-out of the wick.

2. Two heat pipes - A separate conventional heat input pipe is used as shown in Fig. 9.

3. Three heat pipes - Both the source and sink ends have separate conventional heat pipes, coupled by a short vapor controlled VCHP. This configuration yields the highest heat transport capability, but also produces the highest total temperature drop due to the additional interfaces.

Tests have been conducted with both the two- and three-heat-pipe configurations. The three-heat-pipe system operated at twice the 100-W design load and the source temperature was practically independent of sink conditions and increased at a rate of 0.33 K/W /19/.

The vapor modulation principle seems to be feasible for both diode operation and combined VCHP/diode operation. However, it has yet to be verified that the valve completely shuts down under adverse temperature gradients. A cleverly designed system or additional sensors to activate the control element for adverse thermal gradients could be used to accomplish the latter.

LIQUID CONTROL

The liquid in a heat pipe can be controlled by either removing it from the active portion of the pipe, thereby drying the pipe out (liquid trap), or by flooding the evaporator with excess liquid (liquid blockage) /20/. In both cases, diode operation is achieved. The dryout principle is also applied for the thermal switch /21,22/. In principle, it could be possible to achieve VCHP control by gradually and partly flooding the condenser with excess liquid /7/. This excess liquid technique, either alone or coupled with the liquid trap technique, could also be used in a hybrid system.

Hydrodynamics

Axial grooves and spiral and tunnel arteries have been used for liquid controlled heat pipes. Axial grooves offer the advantages of a small fluid inventory and high sensitivity to underfill, the latter being an advantage for the liquid trap. The large vapor space, however, makes them rather disadvantageous for liquid blockage. The arterial designs are more appropriate for liquid blockage because they have the opposite property, a small vapor space. In addition, their thermal performance is considerably higher.

Types of Liquid Control

Liquid control has been the primary technique used for diode mode operation. Its application to VCHPs has not yet been verified in the laboratory.

Liquid trap

In the reverse mode, liquid is condensed in a trap located at the evaporator end of the heat pipe, thus depleting the wick and stopping heat pipe action (Fig. 10). There is no capillary communication between trap and heat pipe, and no liquid can be transported through the wick back into the diode during shutdown.

Liquid blockage

Excess fluid is stored in a reservoir at the condenser end of the diode (Fig. 10). During the reverse mode, the liquid is evaporated into the diode, condenses and accumulates at the colder portion, thus blocking the normal evaporator. A special modification is the use of the blocking orifice concept in which an orifice is inserted into the heat pipe, between the evaporator and the adiabatic section, to hold the liquid in the blocked part, but at the same time allowing for a large evaporator vapor space /23/. The blocking orifice thus reduces the vapor pressure drop and improves 1-g fluid retention capability.

VCHP operation

The use of excess liquid to partially block the condenser, similar to a gas controlled variable conductance heat pipe, has been identified for several years /7/. This concept, which essentially replaces the non-condensing gas with excess liquid in a mechanical feedback system, has not been demonstrated due to the lack of a practical application. Another potential concept is the use of a heated liquid reservoir as a feedback control system. The liquid control technique could also be used for hybrid operation, if excess liquid is used to gradually block the condenser during VCHP operation and to completely block the evaporator during diode shutdown.

VOLTAGE CONTROL

Where a dielectric fluid is used in a heat pipe, it is possible to influence the liquid flow by application of an external electric field. Two different approaches have been explored: (1) the electrohydrodynamic heat pipe, which makes use of very high potential differences (order of several kV), and (2) the electro-osmotic heat pipe, which requires only tens of volts. Both concepts may be useful for VCHP and diode operation by simply varying the applied voltage. Since the static electric field provides both liquid pumping and the control technique, the hydrodynamics and control will not be discussed separately.

Electrohydrodynamic (EHD) Heat Pipe

An electrostatic field between the heat pipe wall and one or more electrodes is used to form one or more low-flow-resistance ducts for returning the condensed dielectric working fluid to the evaporator (Fig. 11) /24/. This principle offers an active control of heat transport by variation of applied voltage. An additional feature of EHD is that bubbles, due to nucleate boiling, are actually ejected from the liquid by the electric field. This, plus the independence from capillary forces for the major movement of the liquid, allows start-up with a superheated evaporator and stable operation under partial dryout. EHD/voltage control has been demonstrated in laboratory /25/, but has yet to be practically applied. Voltage control inherently can be used as a feedback system.

Electro-osmotic Heat Pipe

An axial electrostatic field is used to pump the dielectric working fluid through capillary tubes (Fig. 12). Only preliminary work has been done with this concept /26/. If proven feasible, it offers the potential of controlling the heat transport by variation of a low applied voltage. Again, a feedback design seems practical.

SPACE FLIGHT EXPERIENCE

Heat pipes have been or will be flown in various applications or experiments on at least the following spacecraft:

Agena (ATS-A)	ATS-6
GEOS-B (Expl. 36)	Skylab
ATS-E*	RM20*
PAC/OSO	CTS**
OAO-B*	IUE**
OAO-3	SIPS**

*Failed to achieve orbit or return satisfactory data.
**To be launched in future.

Although each flight has contributed to the understanding of and confidence in the use of heat pipes for spacecraft thermal control, the Ames Heat Pipe Experiment (AHPE) on OAO-3 and the Advanced Thermal Control Flight Experiment (ATFE) on ATS-6 have provided direct experience with controllable heat pipes; that experience is summarized briefly below. The CTS satellite, when launched, will provide additional experience with gas controlled (wicked reservoir, non-feedback) heat pipes in a critical application /27/. The SIPS is a potential shuttle facility which may depend significantly on feedback control heat pipes.

The AHPE, shown in Fig. 13, has been in orbit since August 1972. It is controlling the temperature of the spacecraft's on-board processor (OBP) and uses a non-wicked reservoir, non-feedback gas controlled heat pipe. The design 1-g and 0-g performance of the AHPE have been well-documented /10,28/. The results of recent tests, not yet published, show that the performance is still predictable and no degradation can be measured after nearly 3-1/2 years in orbit. Data from these tests (orbits 17 337-17 366) are compared with analytical predictions and previous flight data in Fig. 14.

The ATFE, shown in Fig. 15, has been in orbit since May 1974 and is providing the first flight data on the 0-g performance of a thermal diode heat pipe (liquid blockage) and an electrical feedback-controlled heat pipe. Also being evaluated is the temperature stability derived from the melting and freezing of octadecane. The design and orbital performance of the ATFE has also been well documented /15,28,29/. Basic conclusions to date are that all components are performing as predicted for the existing flight environment. The peak absorbed solar input, however, is greater than anticipated and has resulted in increased reservoir and radiator temperatures. This increase has been determined to result from contamination or degradation of the second-surface mirrors which cover the reservoir and radiator /30/.

COMPARISON OF CONTROL TECHNIQUES

Criteria for Comparison

The criteria applied for comparing the various control techniques are listed below:

1. Heat transport capability - High heat throughput in terms of the heat flux and effective length, as well as high evaporator heat fluxes, are desirable for many applications.

2. Volume and mass requirements - Low volume and mass are desirable, although in the Space Shuttle era, these requirements might rank below low-cost considerations. Only the volume and mass associated with the control technique (e.g., reservoir) are considered.

3. Complexity ease of fabrication - This criterion affects cost and reliability. A very complex design, for example, is not ideal from either a cost or reliability point of view. Again, it is the complexity of the control technique that is primarily considered.

4. Reliability - Considerations in this category are the predictability of performance, undegraded long-term performance, and problems associated with arterial structures in gas controlled heat pipes.

5. Control characteristics - Typical considerations for VCHPs are control accuracy and transient behavior, setpoint variation, active or passive control, feedback or non-feedback control. Important aspects for diodes are the reverse mode conductance and the transient shutdown characteristics. Other questions are: Can both VCHP and diode modes of operation be achieved with a single control technique or with a combination of two techniques? Can the switching function be realized with a given control technique?

6. State-of-the-art - The same four categories as described in the section on temperature control heat pipes have been used.

Evaluation of Control Techniques

The control techniques that have already been developed and demonstrated are evaluated and compared in Table 3. Thermal switching has not been included because its range of application seems to be considerably smaller than that of VCHPs and diodes. The hybrid control technique, however, has been included because there appear to be interesting applications in the cryogenic temperature range. Again, it should be emphasized that Table 3 represents the opinion of the authors and does not reflect a consensus of others in the heat pipe field.

Table 3: Comparison and Evaluation of Heat Pipe Control Techniques.

	CRITERION FOR COMPARISON / CONTROL TECHNIQUE	HEAT TRANSP CAPABILITY	VOLUME/ MASS REQUIREMENTS	COMPLEXITY EASE OF FABRIC	RELIABILITY	CONTROL CHARACTERISTICS	STATE OF THE ART/ SPACECRAFT	
VARIABLE CONDUCTANCE TECHNIQUE	NON FEEDBACK					ONLY VAPOR TEMPERATURE CAN BE CONTROLLED		
VARIABLE CONDUCTANCE TECHNIQUE	(i) WICKED (COLD) GAS RESERVOIR	F to G[1] VG[2]	F	G	G	A[4]: PASSIVE, SIMPLE DESIGN, DIODE POTENTIAL. D[5]: VERY SENSITIVE TO SINK TEMP. VARIATIONS, ESPECIALLY WHEN SINK TEMP. IS CLOSE TO OPERATING TEMP. (CIRCUMVENT BY USE OF CONSTANT TEMP. RESERVOIR), ARTERIAL WICKS PROBLEMATIC.	4	CTS
VARIABLE CONDUCTANCE TECHNIQUE	(ii) NON-WICKED (HOT) GAS RESERVOIR	F to G[1] VG[2]	F	G	F to G	A. PASSIVE, SIMPLE DESIGN, LESS SENSITIVE TO SINK TEMP. VARIATIONS. D: SENSITIVE TO PRESENCE OF VAPOR OR LIQUID IN RESERVOIR (MINIMIZE WITH VERY SMALL OR VERY LARGE L/D GAS FEED TUBES), ARTERIAL WICKS PROBLEMATIC.	4	OAO-3
VARIABLE CONDUCTANCE TECHNIQUE	(iii) CASCADED VCHP (NON-WICKED GAS RESERVOIR)	F to G[1] VG[2]	F[6]	F to G	F to G	A: PASSIVE; EVEN LESS SENSITIVE TO SINK TEMP. VARIATIONS (IF COARSE CONTROL PIPE HAS NON-WICKED RESERVOIR) D. TWO HEAT PIPES NEEDED. LARGER TOTAL TEMP. DROP; ARTERIAL WICKS PROBLEMATIC.	2 3	
VARIABLE CONDUCTANCE TECHNIQUE	FEEDBACK					SOURCE TEMPERATURE CAN BE CONTROLLED		
VARIABLE CONDUCTANCE TECHNIQUE	(i) ELECTRICALLY HEATED WICKED GAS RESERVOIR	F to G[1] VG[2]	F to G	F to G	G	A. VERY GOOD CONTROL WITH SMALL RESERVOIRS; GOOD TRANSIENT RESPONSE, VARIABLE SET-POINT POSSIBLE, DIODE POTENTIAL. D: ELECTRICAL POWER AND CONTROLLER REQUIRED. ARTERIAL WICKS PROBLEMATIC.	4	ATS-6
VARIABLE CONDUCTANCE TECHNIQUE	(ii) BELLOWS SYSTEM ACTIVATED BY EXPANSION FLUID, NON-WICKED GAS RESERVOIR	F to G[1] VG[2]	P	P to F	F	A. GOOD CONTROL, NO ELECTRICAL POWER REQUIRED. D: MECHANICALLY COMPLEX, LARGE AND HEAVY, ARTERIAL WICKS PROBLEMATIC.	2	
VARIABLE CONDUCTANCE TECHNIQUE	(iii) VMHP[3] VAPOR FLOW RATE CONTROL	P to F	G	F	F	A: GOOD CONTROL; NO ELECTRICAL POWER REQUIRED, INSENSITIVE TO SINK TEMP VARIATIONS D: LIMITED TO LOW PRESSURE FLUIDS AND FINE CAPILLARY STRUCTURES (BLOW-THROUGH LIMIT); FREEZING PT. OF FLUID MUST BE BELOW SINK TEMP.	2	
VARIABLE CONDUCTANCE TECHNIQUE	(iv) VMHP[3]: INDUCED WICK/GROOVE DRY OUT TECHNIQUE	F[1] to VG[2]	G	F	F to G	A. SAME AS ABOVE, BUT NO RESTRICTIONS ON FLUID OR WICK DUE TO BLOW THROUGH LIMIT. D: COMPLEX (BUT COMPACT); LARGER OVERALL TEMP. DROP IN 2 AND 3 HEAT PIPE CONFIGURATIONS.	2	
DIODE TECHNIQUE	(i) EVAPORATOR BLOCKAGE BY LIQUID	G[2]	G	G	G	A: PASSIVE; SMALL LIQUID RESERVOIR (IF EVAPORATOR AND VAPOR SPACE ARE SMALL); GOOD TRANSIENT RESPONSE. D. 1 g TESTING DIFFICULT AND VAPOR PRESSURE DROPS CAN BE HIGH (IF BLOCKING ORIFICE IS NOT USED).	4	ATS 6
DIODE TECHNIQUE	(ii) EVAPORATOR BLOCKAGE BY GAS	F to G[1] VG[2]	F to G	G	G	A. PASSIVE, SIMPLE DESIGN; CAN BE USED WITH AXIAL GROOVES, CAN BE USED AS VCHP D. LARGER RESERVOIR AND POORER RESPONSE THAN LIQUID BLOCKAGE, ARTERIAL WICK PROBLEMATIC	2 3	
DIODE TECHNIQUE	(iii) TRAPPING OF WORKING FLUID	F to G[1] VG[2]	G	G	G	A: PASSIVE; SMALL TRAP AND GOOD TRANSIENT BEHAVIOR (DEPENDS ON WICK); CAN BE USED WITH GAS-VCHP IN HYBRID SYSTEM, CAN BE USED AS THERMAL SWITCH D. LARGE TRAPS REQUIRED BY ARTERIAL WICKS. ENERGY MUST BE DISSIPATED FROM TRAP DURING SHUTDOWN	2	
HYBRID TECHNIQUE	GAS CONTROL VCHP AND GAS-BLOCKAGE DIODE	F to G[1] VG[2]	F	G	G	A. PASSIVE: ONE PIPE SERVES TWO PURPOSES, SIMPLE IF AXIAL GROOVES ARE USED. MOST VCHP TECHNIQUES APPLICABLE. D. ARTERIAL WICKS MAY BE PROBLEMATIC.	1	

CLASSIFICATIONS

P = POOR 1 RESEARCH
F = FAIR 2 = LABORATORY PROTOTYPE
G = GOOD 3 FLIGHT HARDWARE
VG = VERY GOOD 4 = FLIGHT DEMONSTRATION

1) FOR NON-ARTERIAL HEAT PIPES
2) FOR ARTERIAL HEAT PIPES
3) VMHP = VAPOR FLOW MODULATED HEAT PIPE
4) A = ADVANTAGES
5) D = DISADVANTAGES
6) HOWEVER, 2 OR MORE VCHP's USED

SUMMARY

Assessment of the State-of-the-Art

Figure 16 summarizes the state-of-the-art of both conventional and temperature controlled heat pipes. Various types of heat pipes have already been successfully flown aboard spacecraft. Additional 0-g information is available from a variety of sounding rocket tests which have not been discussed in this paper. However, it can clearly be seen that much research and development remains to be done to flight-demonstrate the broader capabilities of temperature control heat pipes and, therefore, to provide the spacecraft designer with a complete set of proven, reliable thermal control components.

Outlook on Future Research and Development

Figure 17 schematically represents the efforts required to achieve flight-proven, low-cost, reliable temperature control heat pipes. Five areas have been emphasized:

1. Non-arterial and arterial VCHPs, operating at near-room and cryogenic temperatures.

2. Thermal diode heat pipes, operating at near-room and cryogenic temperatures.

3. Vapor controlled VCHPs, primarily operating at near-room temperature.

4. Voltage controlled VCHPs, operating at near-room temperature.

5. Flexible heat pipes, operating at near-room and cryogenic temperatures.

Much future effort will be directed toward cryogenic temperatures, as the demand for suitable cooling devices in this temperature range becomes more urgent.

The final goal is to develop heat pipes, especially temperature controlled heat pipes, as reliable, low-cost devices for spacecraft temperature control applications ranging from near-room to cryogenic temperatures.

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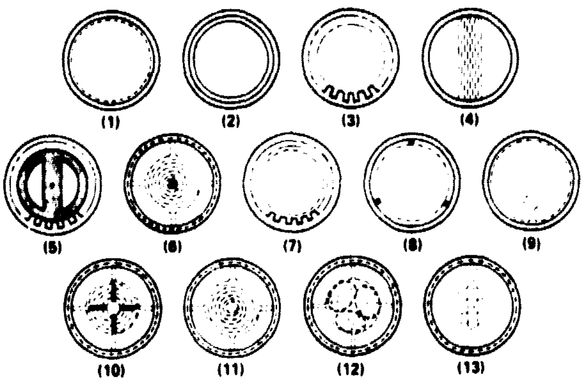

Fig. 1 Major wick designs.

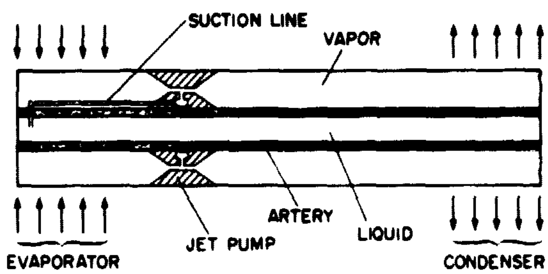

Fig. 2 Capillary jet pump.

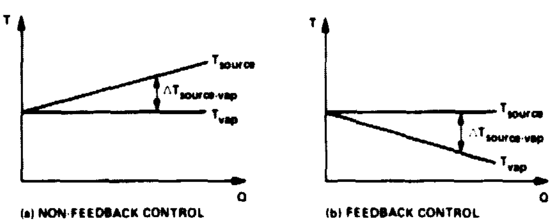

Fig. 3 Non-feedback vs feedback control.

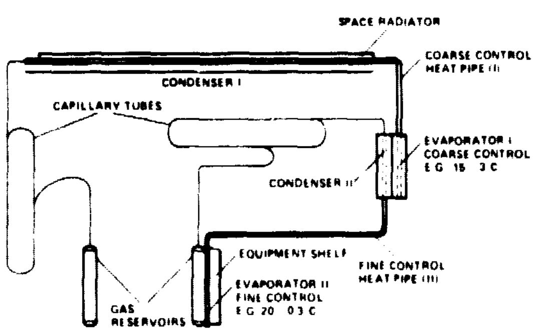

Fig. 4 Cascaded variable conductance heat pipes.

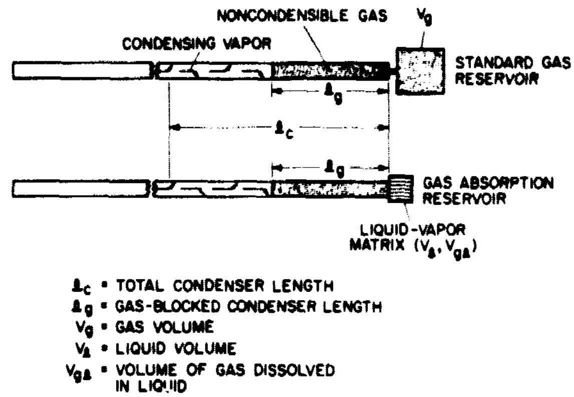

Fig. 5 Standard gas vs gas absorption reservoirs.

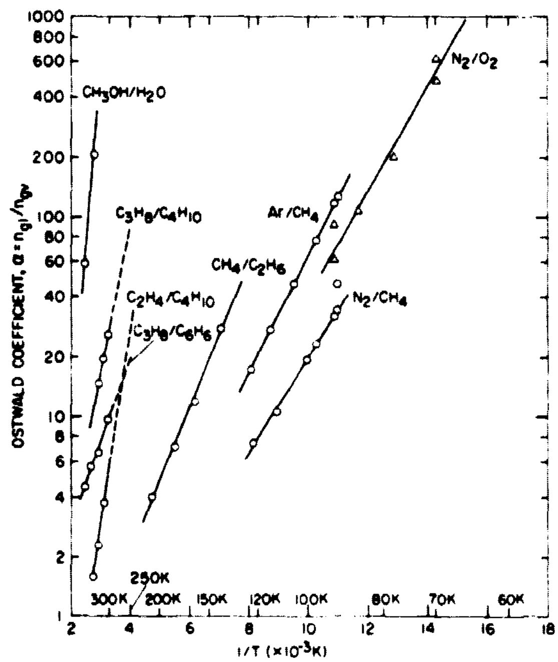

Fig. 6 Ostwald coefficients.

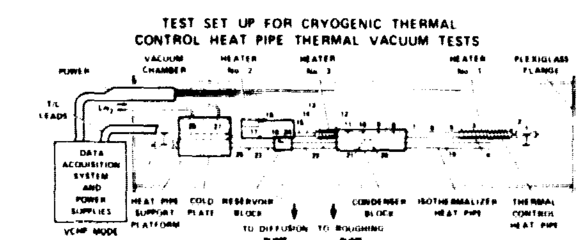

Fig. 7 Combined gas controlled VCHP/diode test setup.

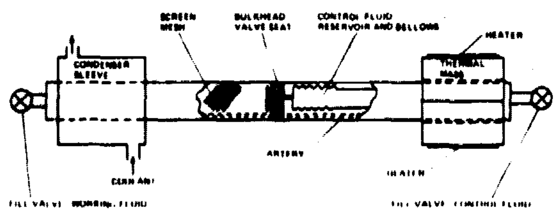

Fig. 3 Vapor flow rate control.

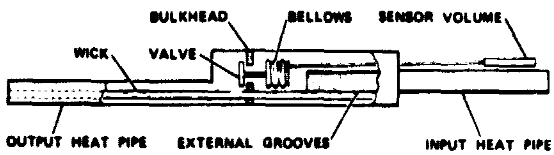

Fig. 9 Induced wick/groove dryout.

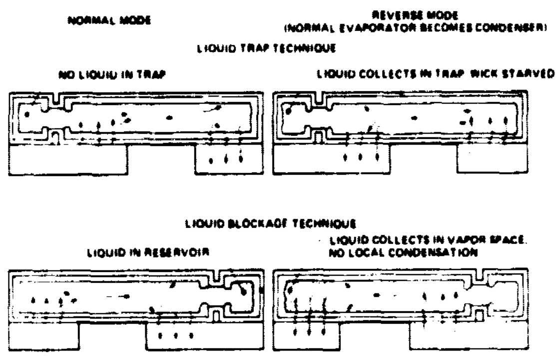

Fig. 10 Liquid controlled thermal diodes.

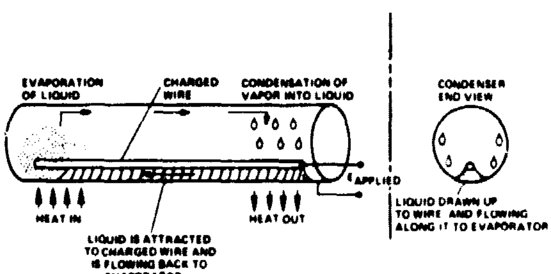

Fig. 11 Electrohydrodynamic heat pipe.

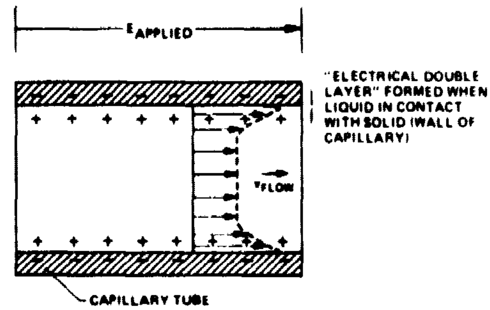

Fig. 12 Electro-osmotic heat pipe.

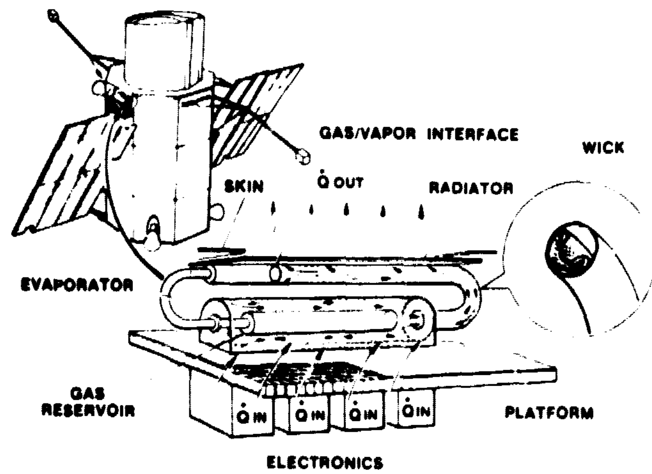

Fig. 13 Ames Heat Pipe Experiment.

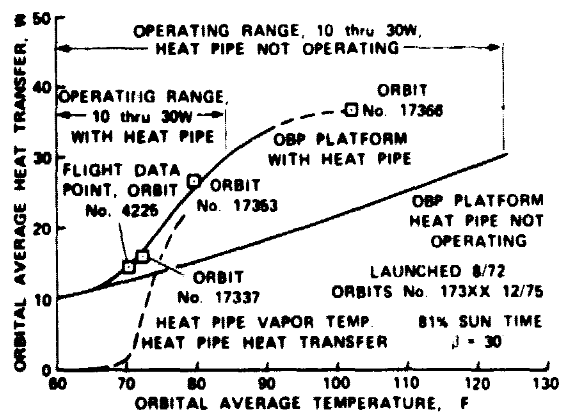

Fig. 14 Ames Heat Pipe Experiment flight performance.

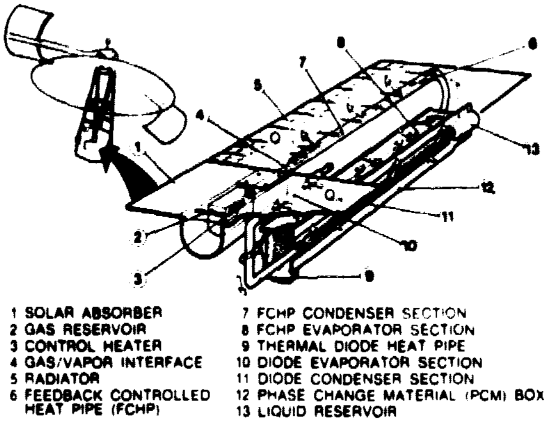

Fig. 15 Advanced Thermal Control Flight Experiment.

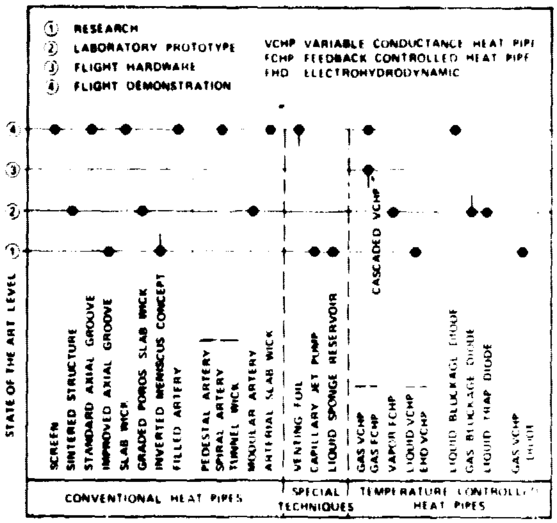

Fig. 16 State-of-the-art of heat pipes for spacecraft applications.

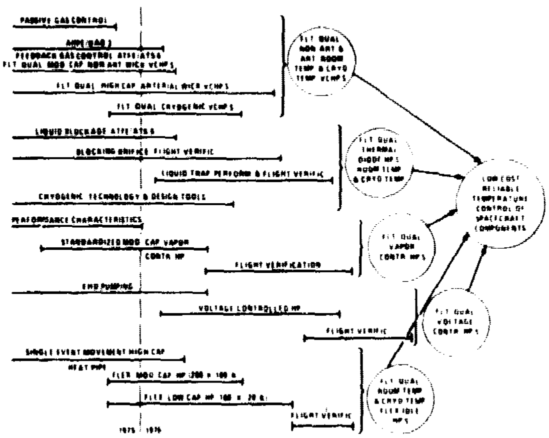

Fig. 17 Development plan for heat pipe control techniques.