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ADVANCED CRYOGENIC HEAT PIPE DEVELOPMENT PROGRAM

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April 1994

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Final Report

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13. Supplementary Notes

14. Abstract The Phase I effort for the development of advanced cryogenic heat pipe technology demonstrated the feasibility of a high performance cryogenic flexible heat pipe (CFHP). The CFHP's design incorporates a circular stainless steel fibrous wick which is homogeneous over the length of the heat pipe and which permits flexibility in any direction. A 400-mesh sleeve covers the fibrous wick core to provide increased capillary pumping and transport. This permits reducing the wick's cross section and the corresponding fluid inventory which reduces pressure containment requirements and the sutdown energy in liquid trap diode designs. Stainless steel bellows and Hastalloy C evaporator and condenser sections make up the heat pipe envelope. The CFHP was tested with oxygen at 120K and demonstrated repeatable composite pumping with an extrapolated 0-g transport capability of 680 watt-in with applied heat loads of up to 16 watts at a 0.375-in adverse tilt.

15. Subject Terms Cryogenic heat pipe, Flexible heat pipe, Cryogenic diode heat pipe

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1.0 INTRODUCTION

Cryogenic components and subsystems introduce problems that are typically not experienced with ambient temperature devices and this is true for both aerospace and ground based applications. In all cases heat leaks must be minimized, pressure containment and safety requirements must be satisfied, and mechanical compliance or flexibility must exist.

A schematic of a future aerospace sensor cryogenic cooling system is presented in Figure 1-1. This system incorporates a diode and a fixed conductance heat pipe, flexible sections for compliance, and a thermal storage unit. A telescope assembly which has similar cryogenic thermal control requirements is shown in Figure 1-2. Generally, all studies conclude that there are several elements or requirements that are common to sensor thermal control systems and they are:

1. Compliance joints to accommodate differential thermal contraction and expansion.
2. Vibration damping isolators to minimize noise and vibration effects on the sensor.
3. One way heat transfer to isolate the sensor from energy back flow.
4. Thermal energy storage to provide temperature stability and vibration free sensing.

A cryogenic flexible diode heat pipe (CFDHP) accommodates the first three requirements and properly designed it is readily integrated with a thermal storage unit. In addition to solving the three issues listed above, a flexible diode heat pipe also provides the following advantages and systems' accommodations:

1. Ease of alignment during integration.
2. Sensor pointing and scanning.
3. Radiator deployment in passive cooler applications.
4. Independent location of cooler and sensor which could reduce size and weight as well as lowering environmental heat loads and dynamic loads.
5. Co-planar component heat pipe ground testing is a secondary benefit.

The Phase I effort for the Development of Advanced Cryogenic Heat Pipes had three major objectives:

a. Develop reliable cryogenic heat pipe designs for temperature control applications that range from 10 K to 150 K.
b. Heat pipe designs shall accommodate flexible and rotating joints.
c. Heat pipe designs shall be capable of diode operations.

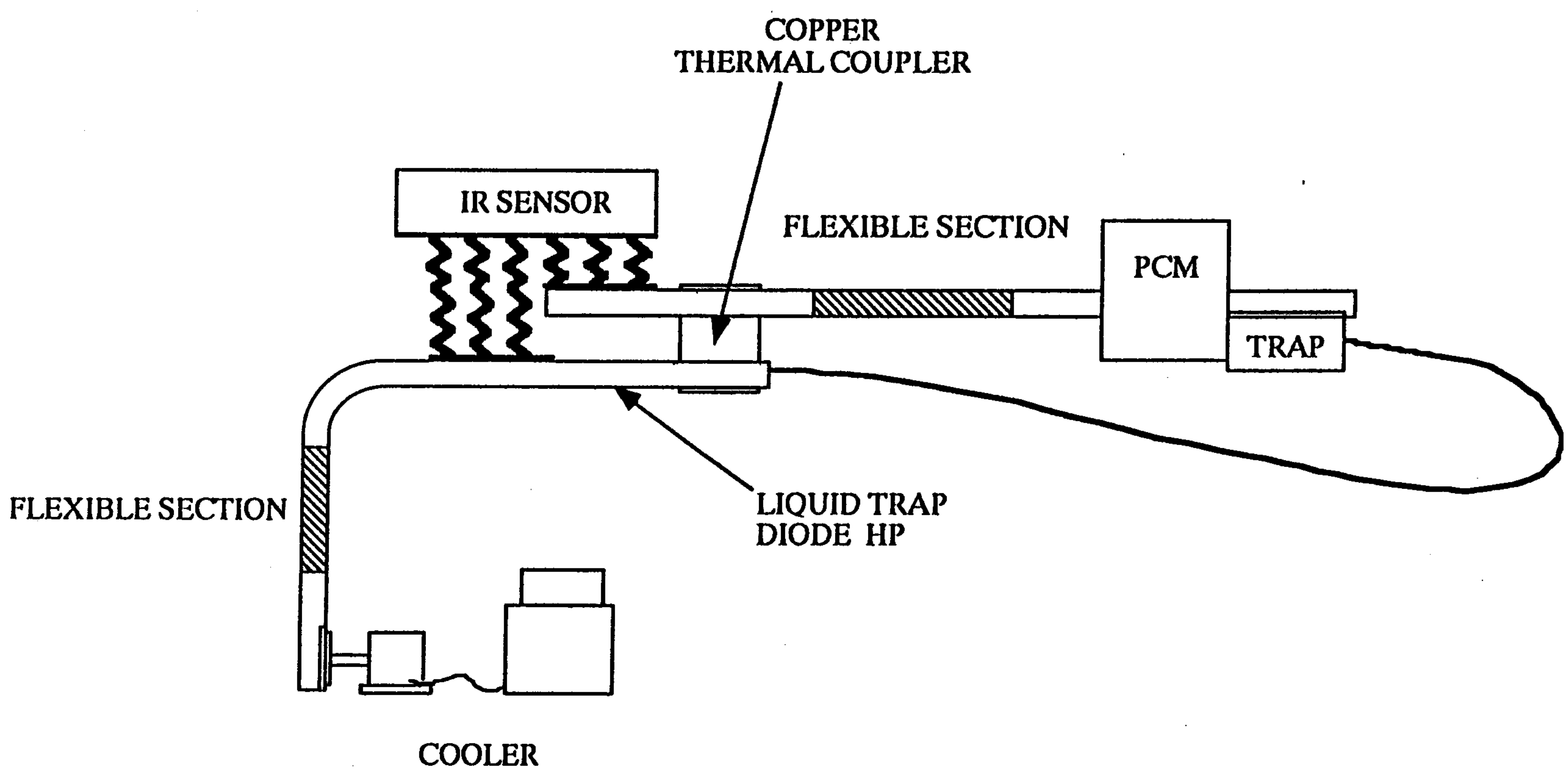

Figure 1-1. Cryogenic Thermal Control System for an Infrared Detector

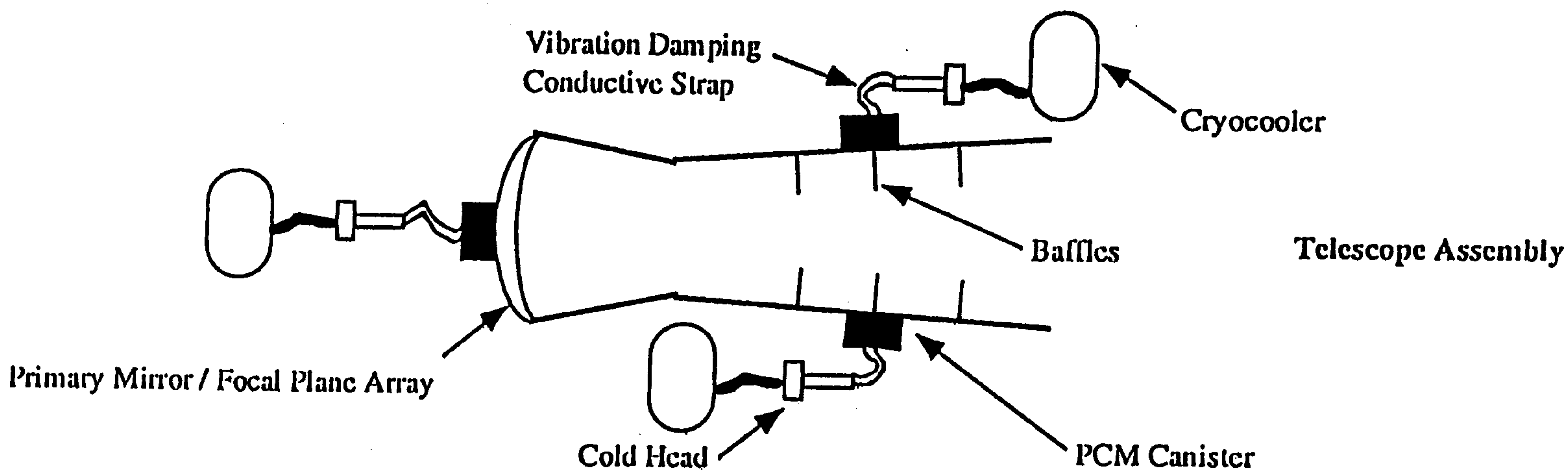

Figure 1-2. Cryogenic Telescope Assembly

Fibrous wick* heat pipes with flexible braided metal bellows were selected to accomplish these objectives. The Phase I effort for the development of advanced cryogenic heat pipe technology demonstrated the feasibility of a high performance cryogenic flexible heat pipe (CFHP). Diode operation was beyond the scope of this effort and is recommended for development in Phase II. The CFHP's design is illustrated in Figure 1-3 with basic design and performance parameters summarized in Table 1-1. A picture of the CFHP unit with the transport wick material and a wick development sample is presented in Figure 1-4. The design incorporates a circular fibrous wick which is homogenous over the length of the pipe. A fine mesh wire cloth was wrapped around the fibrous wick to provide a high capillary pumping head once the fibrous wick self-primes. A circular cross section was chosen to permit flexibility in any direction. The development heat pipe has an overall length of 35.7-in with a 0.25-in ID flexible metal bellows section and 0.5-in OD high strength Hastalloy C steel tubing.

The following sections present a summary of the design trade-off and design selection including the parametric transport analysis and the detailed design of a flexible oxygen heat pipe. Measured performance with oxygen at 120 K is compared to theoretical performance. Theoretical performance of optimized designs which are based on the test results is also included for hydrogen, oxygen and methane designs.

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* M. Groll, et.al. "Parametric Performance of Circumferentially Grooved Heat Pipes with Homogeneous and Graded - Porosity Slab Wicks at Cryogenic Temperatures." 2nd International Heat Pipe Conference, March 1976.

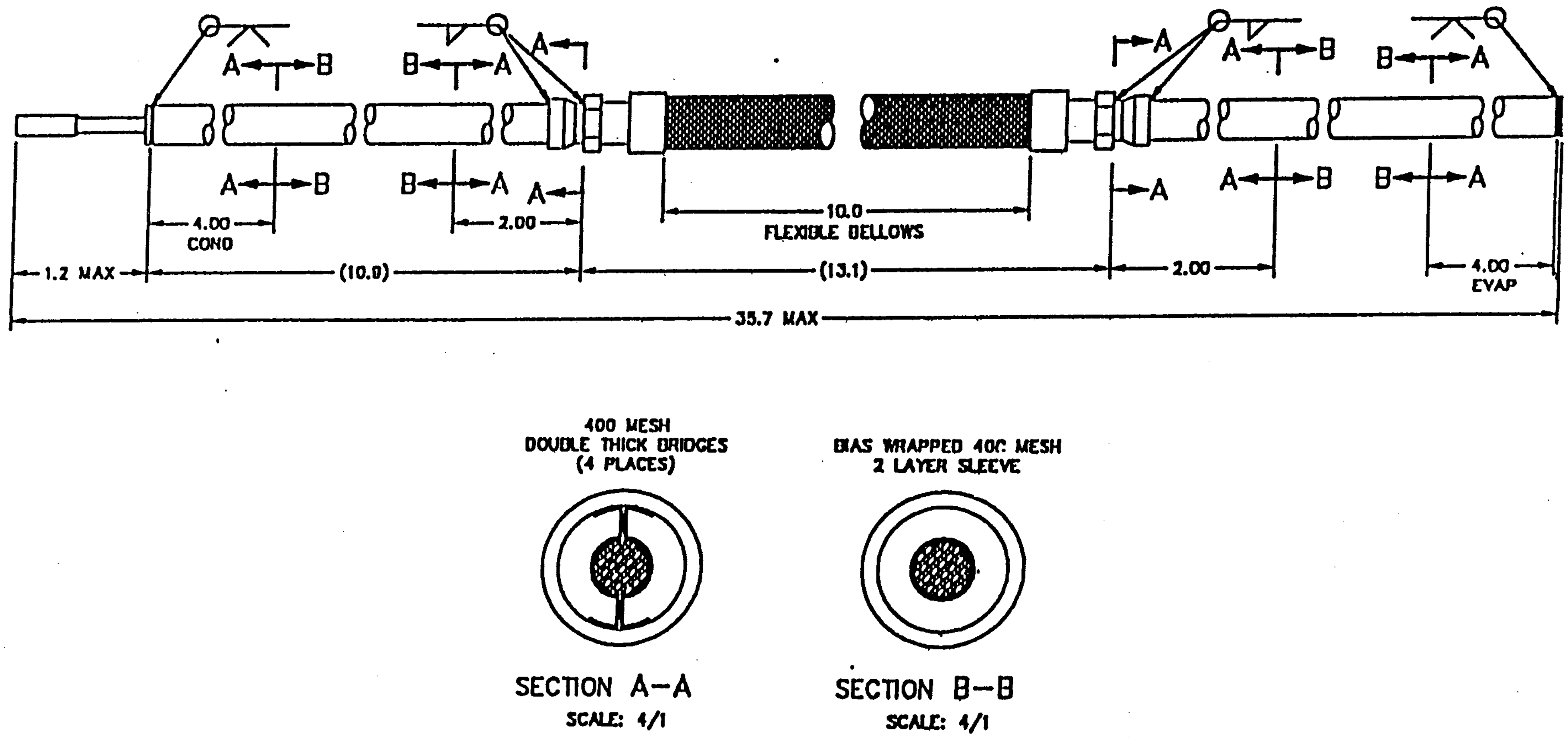


Figure 1-3. Cryogenic Flexible Heat Pipe Development Unit Design

Table 1-1. Cryogenic Flexible Heat Pipe Design Summary

TUBING

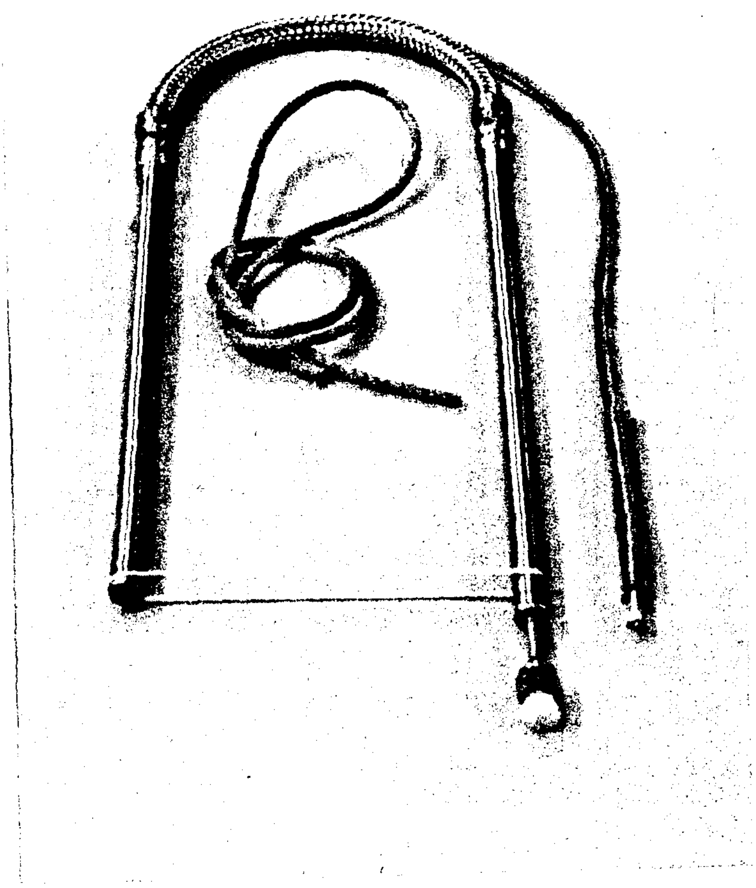
Tubing	Length (Inches)	ID (Inches)	OD (Inches)
Evaporator	4	0.402	0.5
Flexible Hose[1]	10	0.25	0.55
Condenser	4	0.402	0.5
Overall[2]	35.7	N/A	N/A
Effective Length	30.5	N/A	N/A

WICK DESIGN

Transport Wick	Circular Cross-Section of Woven Fibrous Wire
Wire Diameter	0.006-in
Porosity	0.81
Wick Diameter	0.195-in
Length	34.5-in
Theoretical Pumping Radius	0.012-in
Theoretical Permeability	1.72E-6-in^2
Pumping Wick	Two (2) Double layer sleeves of 400 mesh screen
	Each sleeve individually slipped over the transport wick. The outer sleeve is spot welded to form a closed seam along its length.
Theoretical Pumping Radius	0.00125-in

INTERFACE WICKS Evaporator and condenser bridge wick.	4 layers of 400 mesh wire cloth, 4-in long at evaporator and condenser ends, 2-in long at bellows ends. See Figure 3-3.
TUBING CIRCUMFERENTIAL WICK	Tubing is threaded over 8 -inches from evaporator and condenser ends. Threads are .004-in deep x 60° x 100 / Inch.
MATERIALS	Wicks, endcaps and flexible bellows - 316 stainless steel, tubing - C-276 (Hastalloy C) steel.

Notes: 1. *Swagelok flexible metal bellows and metal braid (Part No. SS-4HO-1-4-S4), 10-in working length*
2. *Overall length includes 1.0-in fill tube and 0.2-in end cap zones.*



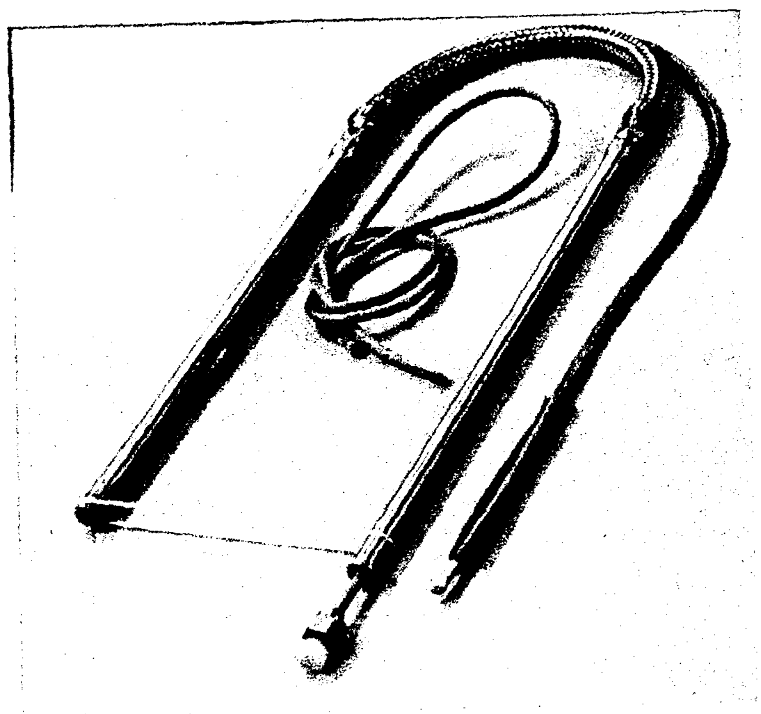


Figure 1-4. Cryogenic Flexible Heat Pipe Burst Unit and Sample Wick

2.0 CRYOGENIC FLEXIBLE HEAT PIPE (CFHP) DEVELOPMENT PROGRAM

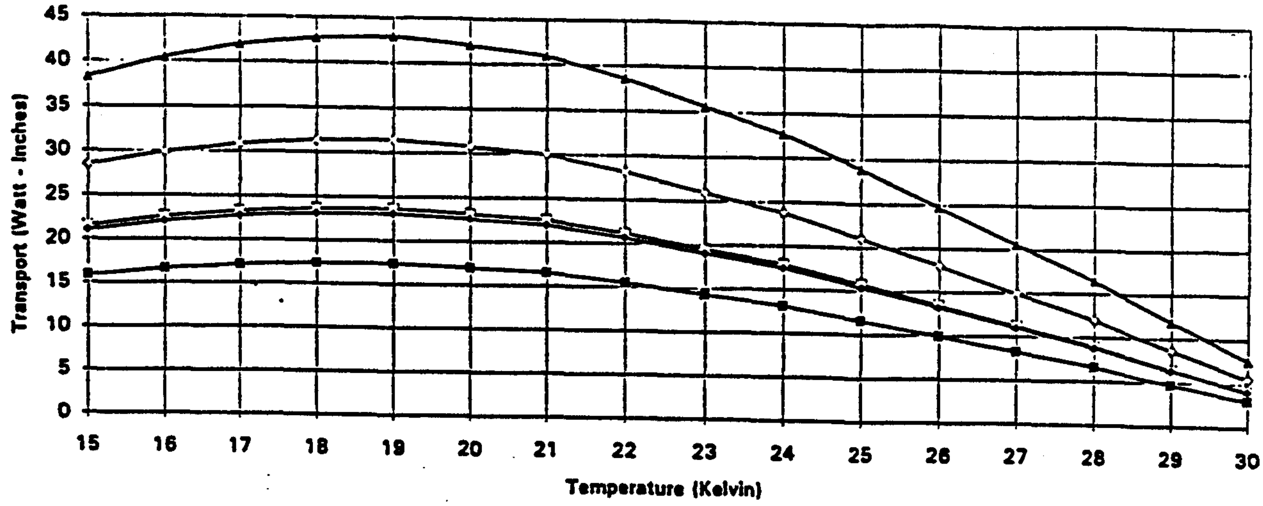
2.1 CFHP DESIGN AND ANALYSIS

The requirement for flexible and rotating joints tends to dictate the heat pipe wick design. Flexible wicks can be achieved by fabricating fibrous wicks that are woven on a 45° bias. A circular cross section (e.g. Figure 1-3) centrally located provides maximum flexibility in all directions. Flexible 316 stainless steel (SS) braided metal bellows were chosen since they provide flexibility up to 180° in any direction, they have good strength for containing the relatively high pressure cryogenic fluids, and they are "off-the-shelf" hardware. High strength C-276 (Hastalloy C) steel was selected for the evaporator and condenser sections. In addition to its high strength, this alloy can be welded to 316 SS and it has a low conductivity for diode operation.

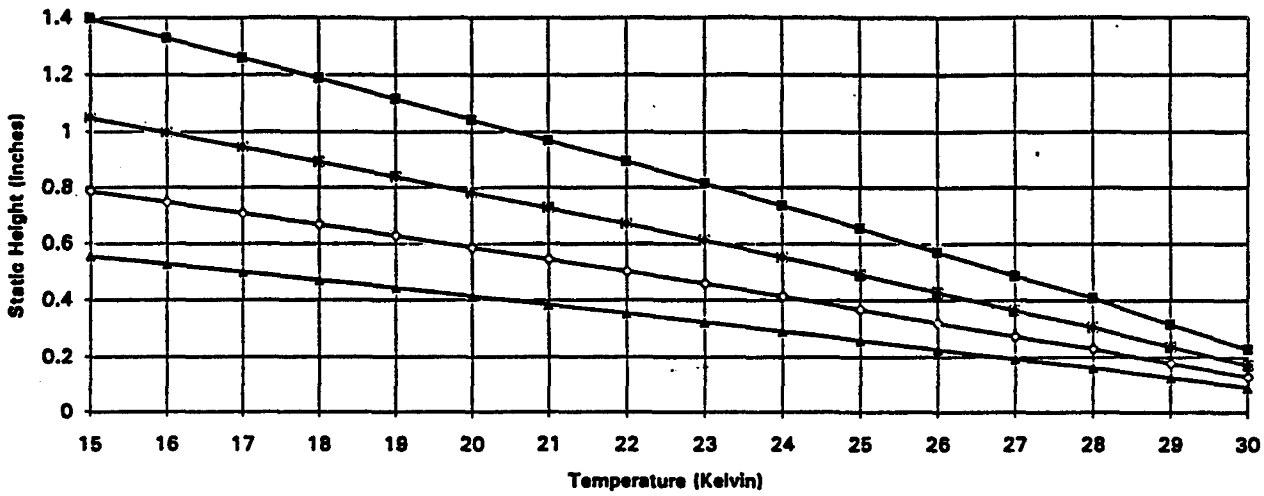
Diode requirements and cryogenic startup as well as pressure containment and weight dictate the need for minimizing the fluid inventory consistent with startup transport requirements. One means to accomplish this is to utilize the high capillary pumping that can be obtained from a fine pore wick and therein compensate for the area reduction needed to minimize the fluid inventory to minimize pressure containment requirements and shutdown energy in liquid trap configurations.

Parametric studies were performed which considered heat pipe tubing and flexible hose diameters, as well as fibrous wick properties including wire diameters (δ), porosity (ε) and cross-sectional area (Aw). Performance with hydrogen, oxygen and methane was calculated since these are the fluids of choice for operation in the range of 10 to 150 K. The theoretical noncomposite 0-g transport capabilities and static wicking heights are presented in Figures 2-1 through 2-3 versus operating temperature for each of the three fluids for a 0.25-in flexible bellows design with a 0.175-in wick diameter. This wick diameter represents a compromise to provide adequate startup transport without an excessive fluid inventory. The 0.25-in bellows represents the smallest diameter off-the-shelf unit and its bend radius and strength are more than adequate for most cryogenic applications. These figures illustrate the general effect of the wick design on performance. An increase in the wire diameter and porosity either independently or together increases the transport but decreases the static wicking height and therefore the 1-g transport.

The high pumping afforded by the fine mesh wire cloth sleeve was not used in the parametrics because it is first necessary to establish noncomposite performance since this is the measure of a fibrous wick's ability to prime in 1-g and 0-g under parasitic heat inputs. Based on the results of this analysis a fibrous wick design that has a porosity of 0.75 and utilizes a 0.006-in wire diameter was selected as a reasonable compromise for self-priming in 1-g.



Transport Capability versus Operating Temperature



Wicking Height versus Operating Temperature

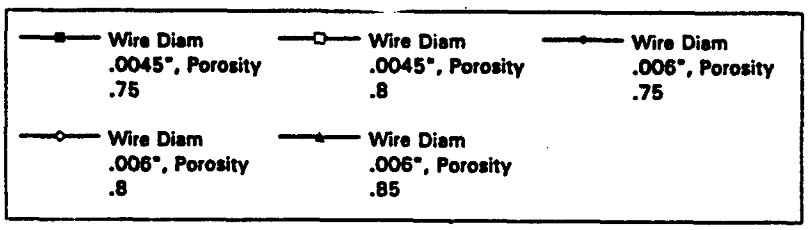
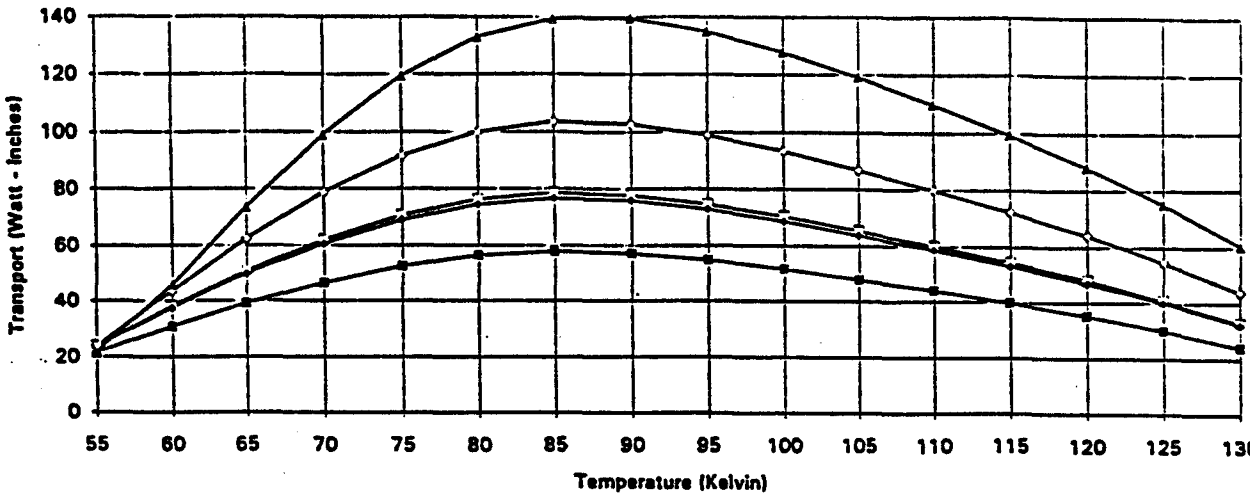
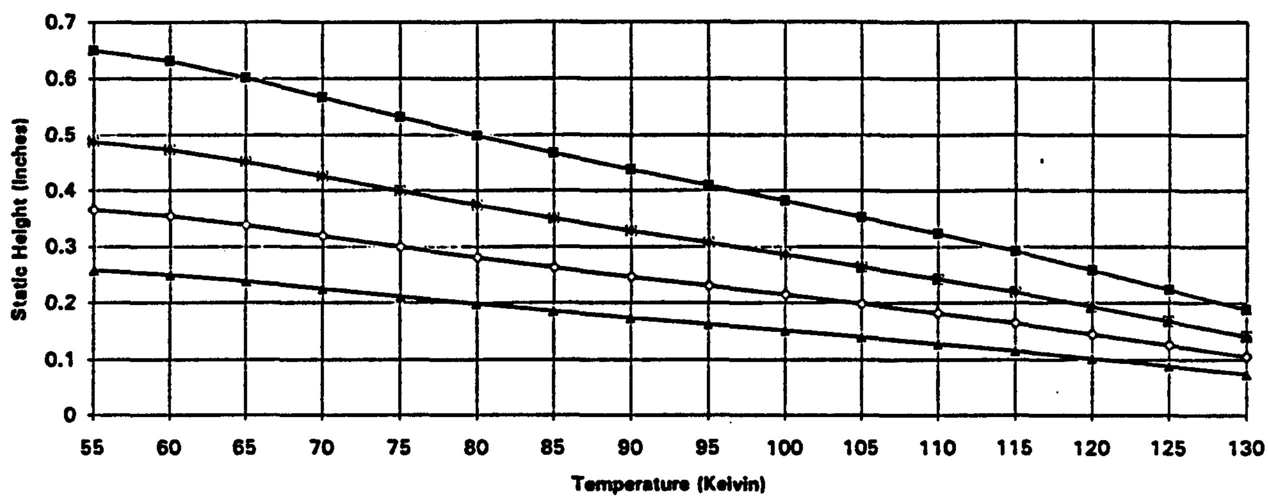


Figure 2-1. Noncomposite Heat Pipe Performance with Hydrogen



Transport Capability versus Operating Temperature



Wicking Height versus Operating Temperature

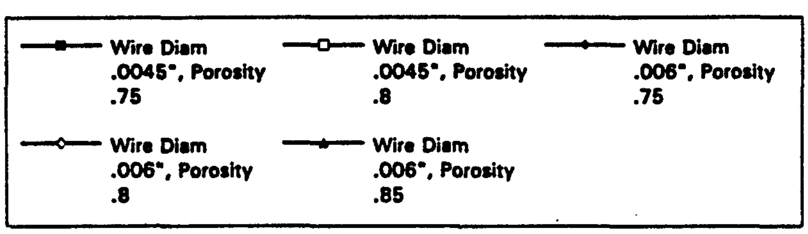
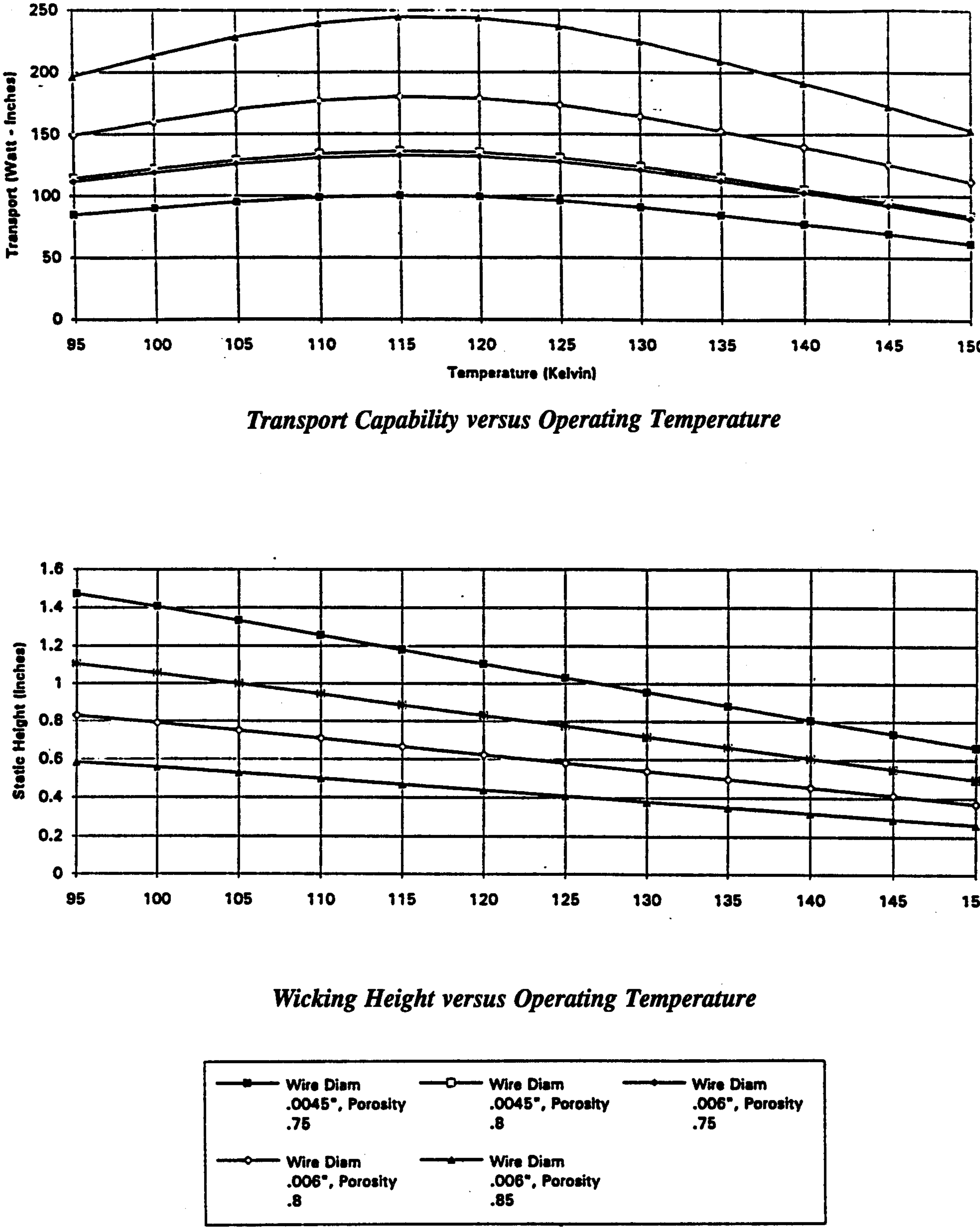


Figure 2-2. Noncomposite Heat Pipe Performance with Oxygen



Transport Capability versus Operating Temperature

Wicking Height versus Operating Temperature

Figure 2-3. Noncomposite Heat Pipe Performance with Methane

2.2 CFHP DEVELOPMENT HARDWARE

A Cryogenic Flexible Heat Pipe (CFHP) unit was fabricated per the design presented in Figure 1-3 and Table 1-1. Weight measurements of the fibrous wick indicated that its "as-fabricated" porosity was 0.81 versus 0.75 that was specified. The wick diameter was also larger and measured 0.195-in versus the 0.175-in that was specified. The higher porosity and larger cross section gives a higher 0-g transport but a lower static height which results in slower 1-g startup. A liquid nitrogen reservoir was used as the heat sink for testing and it provided a minimum priming temperature of 80 K. The heat pipe had to be oriented at a slight positive tilt of 0.10-in to permit overnite priming with the development heat pipe. The porosity will neeed to be controlled better in future designs to guarantee sufficient noncomposite pumping to permit startup at an adverse tilt on the ground. The addition of small diameter (less than 0.030-in) arteries can also be used to improve the noncomposite transport and priming.

2.3 CFHP TEST RESULTS

The heat pipe was flexed into an "L" configuration for thermal vacuum tests and setup and instrumented as shown in Figure 2-4. A liquid nitrogen reservoir was mounted to an aluminum cold plate to provide the heat sink. A foil heater was attached to an aluminum saddle that was clamped to the evaporator. A similiar 4-in long saddle was clamped to the condenser end of the heat pipe. This saddle was in turn bolted to the aluminum cold plate. Carbon felt was used at the heat pipe / saddle interfaces and also between the saddle and cold plate and cold plate and reservoir.

The heat pipe was set at a 0.10-in positive orientation to prime. Isothermalization occurred approximately 12 hours after the condenser end had cooled to 90 K. Steady-state transport test results are compared to theory in Figure 2-5. A 120 K operating temperature was required to accomodate the temperature drops through the various interfaces with up to 20 W applied. Approximately 72% of the full theoretical composite pumping of the fine pore sleeve was realized which represents a factor of 9 increase in transport over the theoretical 0-g noncomposite performance. The slope of the test data is essentially parallel to the theoretical line and this indicates that the actual flow conductance (KA) of the wick is very near the theoretical value. The less than ideal transport and static height are apparently due to a slightly larger composite pumping radius which could be due to imperfections in the fine pore sleeve. In any case, based on the limited data, the high composite pumping provides repeatable, high transport.

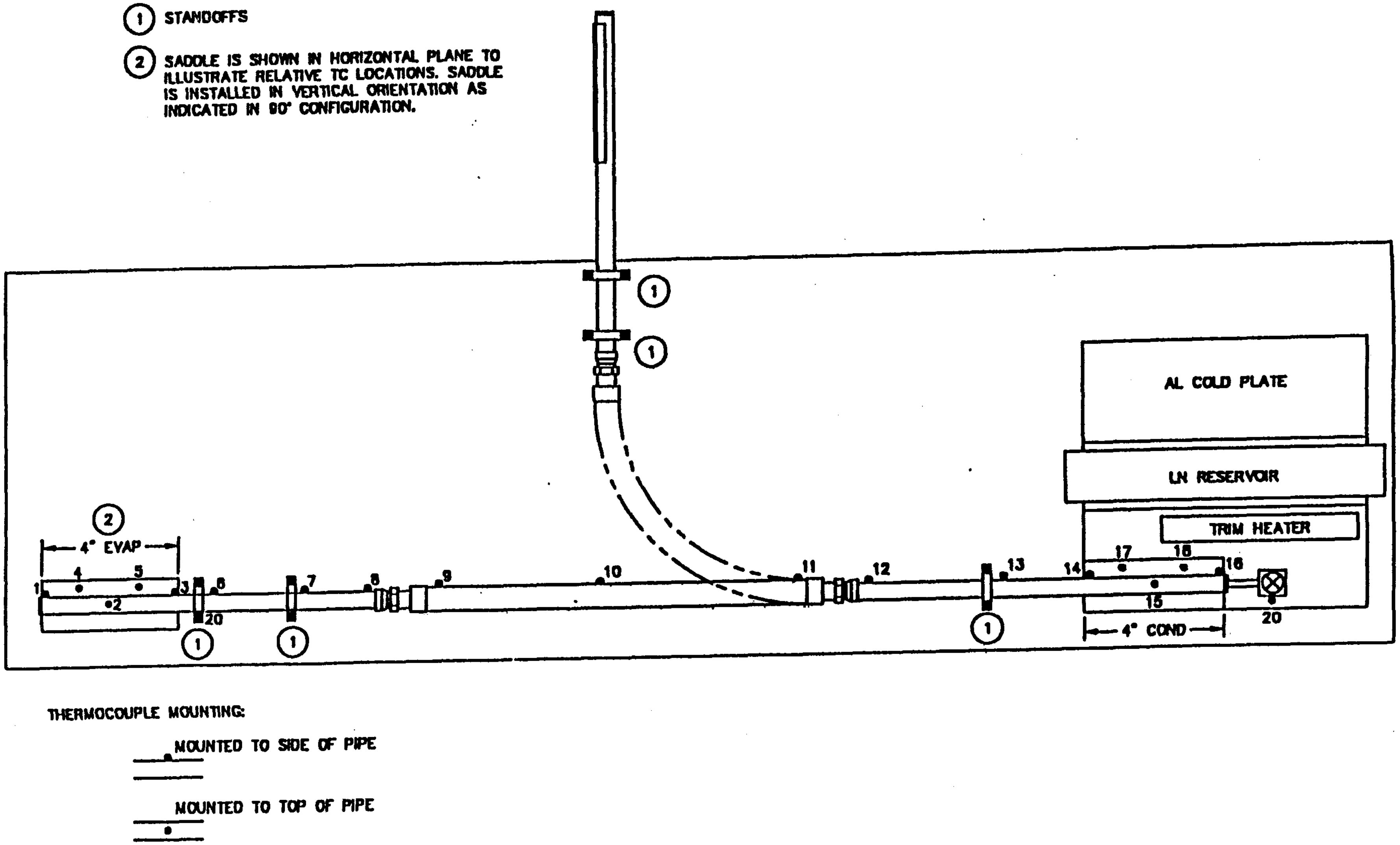


Figure 2-4. Flexible Heat Pipe's Thermal Vacuum Test Setup

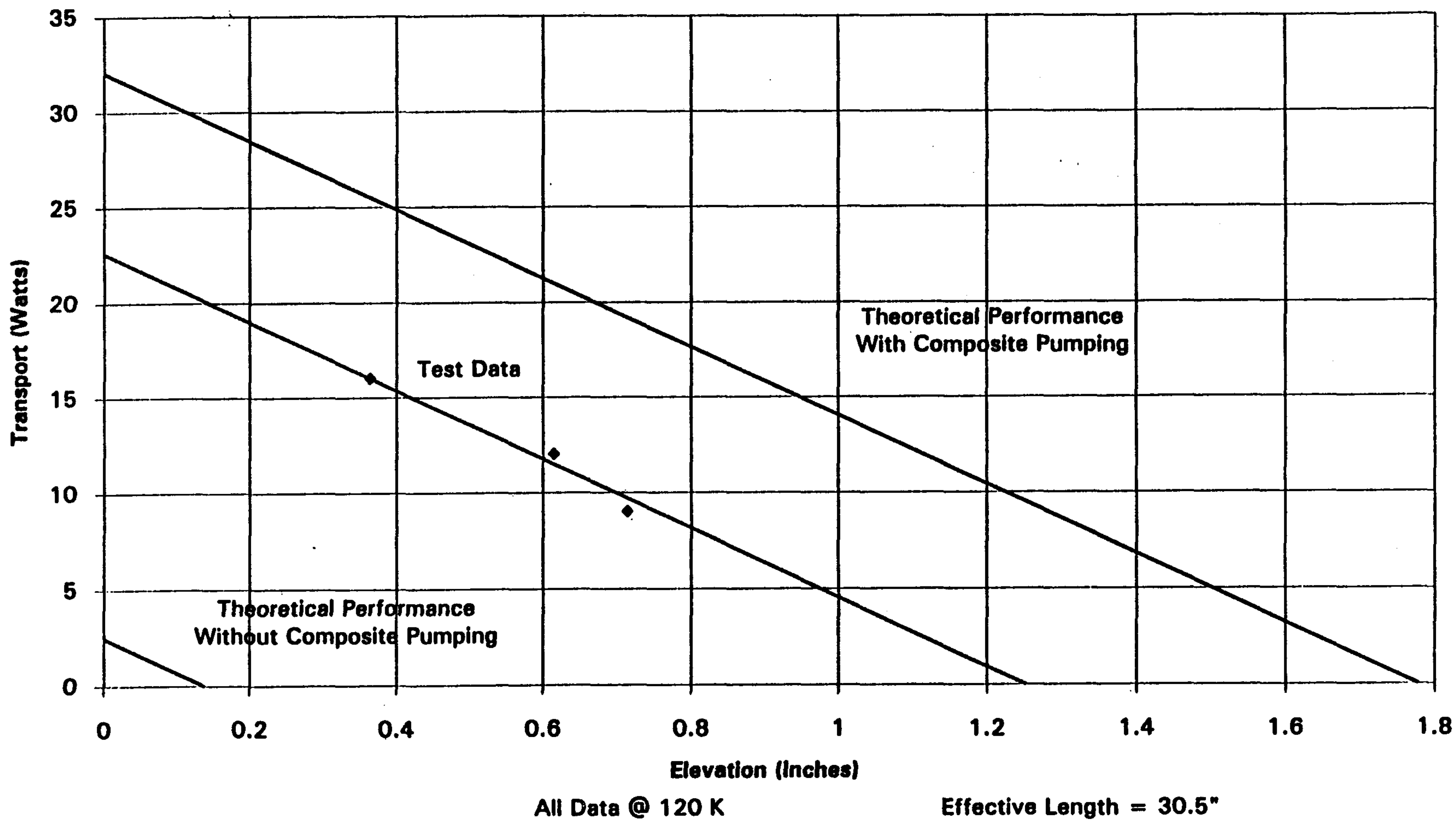


Figure 2-5. Cryogenic Flexible Heat Pipe Transport Capability

The high performance that is available with composite pumping is necessary to manage relatively high sensor heat inputs while maintaining wick areas as small as possible consistent with startup transport requirements. This minimizes fluid inventories and correspondingly the shutdown energy for liquid trap diode operation when required and helps to avoid excessive condenser blockage which can prevent 0-g startup*.

Prior to charging the heat pipe with oxygen another test unit was hydrostatically proof pressure cycled 10 times to 4500 psi. No yield was observed. Also the development unit was subjected to flexure tests to determine how much force was required to bend the unit 90° and 180°. These tests were conducted with the unit charged to a 3000 psi oxygen pressure at ambient temperature and then cooled to approximately 80 K by immersion into liquid nitrogen. The loads required to achieve the bends are listed below in Table 2-1. Very little force is needed to flex the heat pipe 90° with most of the increase in bend force being required above 135°. The results show that the cold temperature does not adversely affect the load required to bend the flexible section.

Table 2-1. Cryogenic Flexible Heat Pipe Flexure Test Results

Temperature	Bend Configuration	
	90°	180°
300 K	<4-lbf	<25-lbf
80 K	<1-lbf	<18-lbf

* Brennan, et.al. "Design and Performance of Cryogenic Two-Phase (CRYOTP) Flight Experiment." SAE Paper No. 941474, June 1994.

3.0 RECOMMENDATIONS

The results of the Phase I effort demonstrated thermal performance as well as the mechanical design and safety features of a cryogenic flexible heat pipe. It remains to optimize this basic design and to incorporate diode operation. The optimization would be based on results obtained from the Phase I tests and additional testing of the development unit at temperatures that approach the triple point of oxygen (i.e. 55.4 K). It will be necessary to operate near this temperature in order to meet requirements of Mer/Cad/Telluride sensors that operate best in the 55 to 60 K range. It is important to test and demonstrate performance with oxygen at as low a temperature as possible because of the limited choice of cryogenic fluids. Sensor requirements in the 55 to 65 K range can be satisfied with oxygen or fluorine and fluorine poses serious safety problems. One could also use lower temperature heat pipes such as neon or hydrogen which operate in the 20 to 40 K range, but this represents significant cooler power penalties for a 60 K sensor and these pipes remain to be developed. It will be necessary to conduct development tests with the oxygen heat pipe operating near its triple point because its performance at lower temperatures is dominated by vapor losses which tend to be less predictable, particularly in corrugated bellows sections. Also, compressibility effects could be present.

4.0 COMMERCIALIZATION OF CFHP

Several opportunities have been identified for this product and its related cryogenic heat pipe technology for the military, NASA and commercial companies. Immediate applications exist for incorporating this product with sensors in remote sensing and imaging satellites. The value of these satellites with improved high resolution sensing to provide data relative to crop growth, environmental conditions, animal migration and disease control, drug interdiction, etc., is recognized and is promoting their commercialization. Recent State Department approval to permit export of these satellites will significantly increase their market potential.

Another aerospace application that is evolving is the cryogenic cooling of solid-state electronic components to increase the speed of computers and multi-plexers in communications spacecraft. Again, flexible cryogenic or low temperature heat pipes will permit versatility in spacecraft architecture including the use of deployable passive radiators. Also, as regards aerospace applications, an immediate offshoot is the implementation of flexible heat pipes to ambient temperature deployable radiators for both military and commercial communications spacecraft.

It is also important to optimize, fabricate and test a hydrogen flexible diode heat pipe for operation in the range of 15 to 30 K, and methane for the 95 to 150 K range. A successful development program would put in place flexible diode heat pipes that will provide thermal control for sensors and their optics in the range of 15 to 150 K. Results obtained will also permit extrapolation to fluids such as neon (26 to 40 K), nitrogen (65 to 110 K), as well as propane, ethane, and butane which can be used to span the range of 100 to 300 K. In addition, this technology is also adaptable to ambient temperature heat pipes with ammonia or other working fluids and can be used to develop flexible high performance ammonia heat pipes for deployable radiator applications for Federal and Commercial Communications Spacecraft where power dissipation is exceeding available radiator envelopes.

Ultimately, CFHPs and CFDHPs will need to be flight tested to ensure that their 0-g behavior is predictable and to guarantee their flight readiness to the user community. The Cryogenic Two Phase (CRYOTP)* test bed which is flown as a shuttle - HitchHiker payload, can be used. Modifications to the CRYOTP would be minimal and the flight demonstration would be extremely cost-effective to verify the performance of an oxygen CFDHP at 58 K and a methane CFDHP at 120 K.

* Ibid page 15.

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