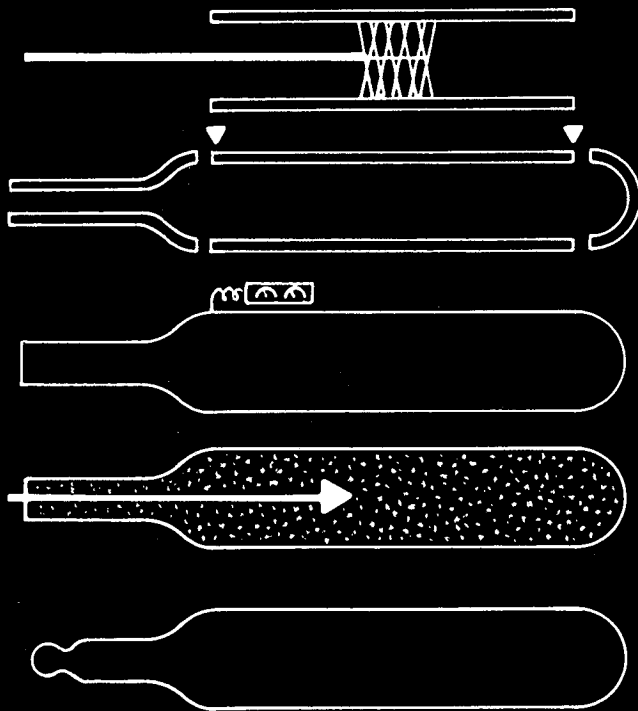


HEAT PIPE



**FINAL
REPORT**



HEAT PIPE MANUFACTURING STUDY

FINAL REPORT

AUGUST 1974

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

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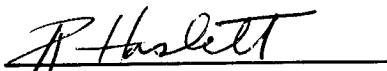
Contract No. NAS 5-23156

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FOREWORD

This report was prepared by Grumman Aerospace Corporation for the Goddard Space Flight Center of the National Aeronautics and Space Administration. The work was done under Contract NAS 5-23156 and was administered by the Thermal Systems Branch of the Systems Division with Mr. R. McIntosh serving as Technical Monitor.

The program was conducted under the direction of Mr. R. Haslett, who served as Program Manager and Mr. F. Edelstein, as Project Engineer. Contributions were made by Mr. L. Brown, Structural Analysis; Mr. J. Maciora, Advanced Materials and Processes; and Mr. W. Whitman, Chemical Engineering. Special thanks go to members of the Heat Pipe group, whose aid in preparing this text is greatly appreciated, in particular, Mr. A. Ferrara, Mr. J. Alario, Mr. W. Harwell, and Dr. R. Kosson.

ABSTRACT

Heat pipe manufacturing methods are examined with the goal of establishing cost effective procedures that will ultimately result in cheaper more reliable heat pipes. Those methods which are commonly used by all heat pipe manufacturers have been considered, including: envelope and wick cleaning, end closure and welding, mechanical verification, evacuation and charging, working fluid purity, and charge tube pinch off. The study is limited to moderate temperature aluminum and stainless steel heat pipes with ammonia, Freon-21 and methanol working fluids. Review and evaluation of available manufacturers techniques and procedures together with the results of specific manufacturing oriented tests have yielded a set of recommended cost-effective specifications which can be used by all manufacturers.

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UNITS

This report uses both engineering and SI units. In some cases, engineering units are used to preserve the usefulness and improve communication of certain material.

For reader convenience, the following list converts cgs or engineering units into SI units.

Quantity	To convert from	Multiply by	To obtain	Multiply by	To convert from
Angle	degree	1.745×10^{-2}	rad		
Area (wicking height factor)	cm ²	1.0×10^{-4}	m ²	9.290×10^{-2} 6.452×10^{-4}	ft ² in. ²
Density	g cm ⁻³ g l ⁻¹	1.0×10^3 1.0	kg m ⁻³	1.602×10^1 2.768×10^4	lbm ft ⁻³ lbm in. ⁻³
Energy (work, heat)	erg calorie	1.0×10^{-7} 4.184	J	1.054×10^3	Btu
Force	dyne	1.0×10^{-5}	newt	4.448	lbf
Heat Flux (fluid transport factor)	W cm ⁻² ergs ⁻¹ cm ⁻²	1.0×10^4 1.0×10^{-3}	w m ⁻²	3.152 1.634×10^3	Btu hr ⁻¹ ft ⁻² Btu s ⁻¹ in. ⁻²
Heat transfer coefficient	W cm ⁻² K ⁻¹	1.0×10^4	w m ⁻² K ⁻¹	5.674 8.170×10^2	Btu hr ⁻¹ ft ⁻² F ⁻¹ Btu hr ⁻¹ in. ⁻² F ⁻¹
Heat of vaporization	erg g ⁻¹ cal g ⁻¹	1.0×10^{-4} 4.184×10^3	J kg ⁻¹	2.324×10^3	Btu lbm ⁻¹
Length	cm angstrom	1.0×10^{-2} 1.0×10^{-10}	m	3.048×10^{-1} 2.54×10^{-2}	ft in.
Mass	g	1.0×10^{-3}	kg	4.536×10^{-1}	lbm
Power	w	1.0	w	2.929×10^{-1} 1.757×10^1 1.054×10^3	Btu hr ⁻¹ Btu min ⁻¹ Btu s ⁻¹
Pressure	dyne cm ⁻² bar atm torr (mm Hg, O°C)	1.0×10^{-1} 1.0×10^5 1.013×10^5 1.333×10^2	newt m ⁻²	6.895×10^3	psia
Surface tension	dyne cm ⁻¹ erg cm ⁻²	1.0×10^{-3} 1.0×10^{-3}	newt m ⁻¹	1.459×10^1	lbf ft
Thermal conductivity	w cm ⁻¹ K ⁻¹ cal s ⁻¹ cm ⁻¹ K ⁻¹	1.0×10^2 4.184×10^2	w m ⁻¹ K ⁻¹	1.730 1.441×10^{-1}	Btu hr ⁻¹ ft ⁻¹ F ⁻¹ Btu in. hr ⁻¹ ft ⁻² F ⁻¹
Viscosity (dynamic)	g cm ⁻¹ s ⁻¹ (poise)	1.0×10^{-1}	newt s m ⁻²	4.134×10^{-4} 4.788×10^1	lbm hr ⁻¹ ft ⁻¹ lbf s ft ⁻²
Viscosity (kinematic)	cm ² s ⁻¹	1.0×10^{-4}	m ² s ⁻¹	2.581×10^{-5}	ft ² hr ⁻¹
Volume	cm ³	1.0×10^{-6}	m ³	2.832×10^{-2} 1.639×10^{-5}	ft ³ in. ³
Temperature	(T _C + 273.15)		T _K	(T _F + 459.67) 5/9 5/9 T _R	

SYMBOLS

A	area, in. ²	
a	crack dimension, in.	
c	crack dimension, in. ; farthest distance from neutral axis	
C	material constant	
D	diameter of pipe, in.	
E	modulus of elasticity, psi	
E _o	binding energy, ev	
e	weld efficiency factor	
F	force, lb	
F _{tu}	ultimate strength, psi	} 'A' value in MIL-HDBK-5B or minimum specification value
F _{ty}	yield strength, psi	
f	stress, psi	
f _n	natural frequency, cycles/sec	
f _s	shear stress, psi	
G	shear modulus, psi; or non-dimensional acceleration, g's	
g	gravitational acceleration, in./sec ²	
I	area moment of inertia, in. ⁴	
K	stress intensity factor, psi-in. ^{1/2}	
k	Boltzman's Constant (8.61 x 10 ⁻⁵ ev/°K)	
L	length, in. ; mean free path	
M	bending moment, in.-lb; molecular weight	
M _k	correction factor	
N	cycles	
N _A	Avogadro's number	
N _s	number of sites per cm ²	
P	force, lb	
P _u	gas pressure, micron	
p	internal pressure, psi	

SYMBOLS (Cont)

Q	constant; total flow, micron-ft ³
Q	flow rate, microns-ft ³ /sec
R	radius, in.; universal gas constant
r	radius, in.
s	displacement, in.
T	temperature, °F, or °K
t	thickness, in.
U	volumetric flow rate, ft ³ /sec
w	weight/inch of pipe; or distributed load, lb/in.
α	coefficient of thermal expansion, in./in. °F
θ	rotation, in./in. or angle, radian

SUBSCRIPTS

B	burst
m	maximum operating
O	operating condition
T	test condition
Y	yield

HEAT PIPE MANUFACTURING STUDY

By F. Edelstein

Grumman Aerospace Corporation

1 - INTRODUCTION

In recent years, the heat pipe has advanced rapidly from a laboratory test device to a viable alternate thermal control approach for spacecraft applications. NASA/Goddard has been a motivating influence in this development. One of the first spacecraft to use heat pipes not simply as an experiment, but for vehicle thermal control, was NASA's OAO. A current NASA/GSFC program, the ATS, is probably the first vehicle to make extensive use of heat pipes for equipment and structural temperature control.

However, many project engineers and engineering managers are still hesitant to commit their projects to heat pipes. This resistance will probably be overcome when the inherent reliability of heat pipes is demonstrated, and standardized manufacturing procedures are developed thus lowering their ultimate cost.

Towards this end, Grumman was contracted by NASA/GSFC to define cost-effective methods for manufacturing spacecraft heat pipes. As the title of this program implies, this effort is concerned with lowering the costs of producing heat pipes to be competitive with existing thermal control devices such as heaters, coatings, louvers, etc. A key goal of the program was to develop standardized manufacturing procedures which would assure the reliability of the final product. By evaluating and defining acceptable cleaning procedures, for example, the reliability of a properly fabricated heat pipe will be increased. Moreover, since each manufacturer is currently using essentially independent procedures, heat pipes supplied to NASA are built to different specifications and quality. There is a good deal of duplication of effort in the field; many individual company's procedures have been established iteratively, which is a costly and time consuming way to develop a technology. This

effort, therefore, is only the forerunner of others which will ultimately develop basic heat pipe manufacturing specifications and details for all manufacturers.

Because there are so many different types and styles of heat pipes covering a wide range of applications and temperatures, it was mutually decided to limit this study to those commonly used today. Thus, single fluid devices operating in the moderate or room temperature range were selected. Construction materials were aluminum and stainless steel envelopes and wicks; working fluids were ammonia, Freon-21, and methanol.

2 - SUMMARY

As shown in Fig. 2-1, a heat pipe is essentially composed of five elements: the envelope, wick, end cap, fill tube, and working fluid. The envelope may be of any cross section desired by the designer - e.g., circular, square, etc., - and may contain mounting flanges to simplify installation, and bent in various shapes. The wick may be grooves extruded into the envelope, or may be assemblies - such as Grumman's spiral artery design, made from fine wire mesh, sintered screen, or felt metal slabs, etc. An end cap and fill tube are used to complete the envelope.

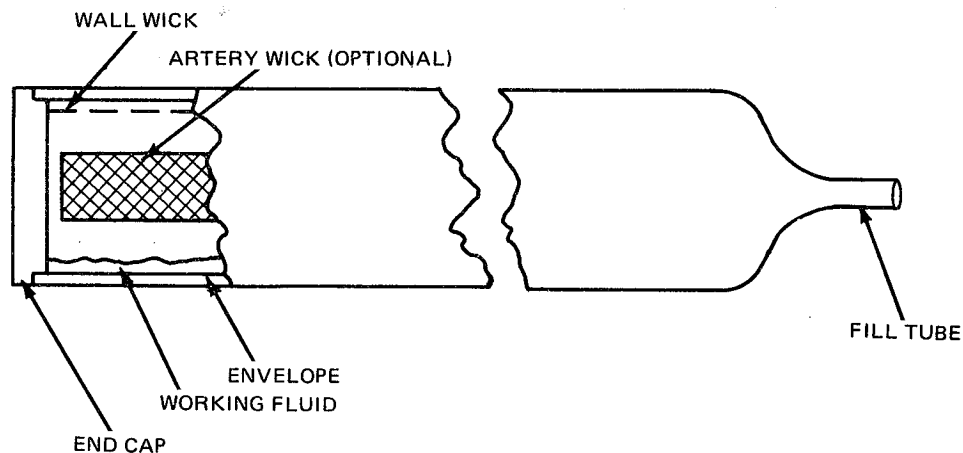


Fig. 2-1 Typical Heat Pipe Components

Working fluid is introduced into the pipe through the fill tube, which is subsequently sealed by a pinch-off. When heat is applied to a section of the heat pipe (evaporator), the working fluid evaporates, causing a local increase of pressure driving the vapor towards the other end of the pipe (condenser). Cooling this end causes the vapor to condense on the walls of the pipe. Finally, by capillary forces the working fluid flows back through the wick to the evaporator section. This cycle is repeated as long as heat is supplied to the evaporator and is removed at the condenser. However, if heat is applied to the pipe at a rate higher than the wick can carry, the pipe will fail to function (dry-out). A serious problem

with heat pipes is the generation of noncondensable gases which will inhibit their performance. Basically, these gases will accumulate at the cold (condenser) end of the pipe, decreasing the effective conductance of the unit, until the condenser is completely "blocked" and the pipe fails to function.

A flow chart of the basic operations involved in manufacturing a heat pipe is presented in Fig. 2-2. A brief summary of the major elements of the manufacturing cycle discussed in this report follows.

2.1 Envelope and Wick Cleaning

Probably the most significant manufacturing problem existing today is the lack of a simple reliable, effective cleaning procedure for heat pipe envelopes and wicks. For example, the incomplete removal of water from aluminum heat pipes has proven to be an expensive oversight for many heat pipe programs. A variety of techniques are currently being used by manufacturers, with varying degrees of success. In Section 3 the experiences encountered with these techniques are presented along with recommended detailed cleaning procedures for both aluminum and stainless steel. These involve solvent, acid, and alkaline cleaning for aluminum, and passivation for stainless steel.

2.2 End Closure and Welding

An improperly designed end cap or poor welding technique can lead to questionable joints which may fail to pass X-ray examination or, worse, fail in service. Weld defects may be present which cannot be detected by X-rays. These minute defects may open up during service causing leaks, cracks, or even catastrophic mechanical failure. Various forces (such as fatigue cycling, the release of internal weld stresses, or a stress riser) may be the triggering action.

A number of joint designs used in the past are evaluated in Section 4. Square butt joint and lipped butt joint end cap designs are recommended for aluminum and stainless steel, respectively. In addition, gas tungsten arc welding is recommended as the most cost-effective welding technique.

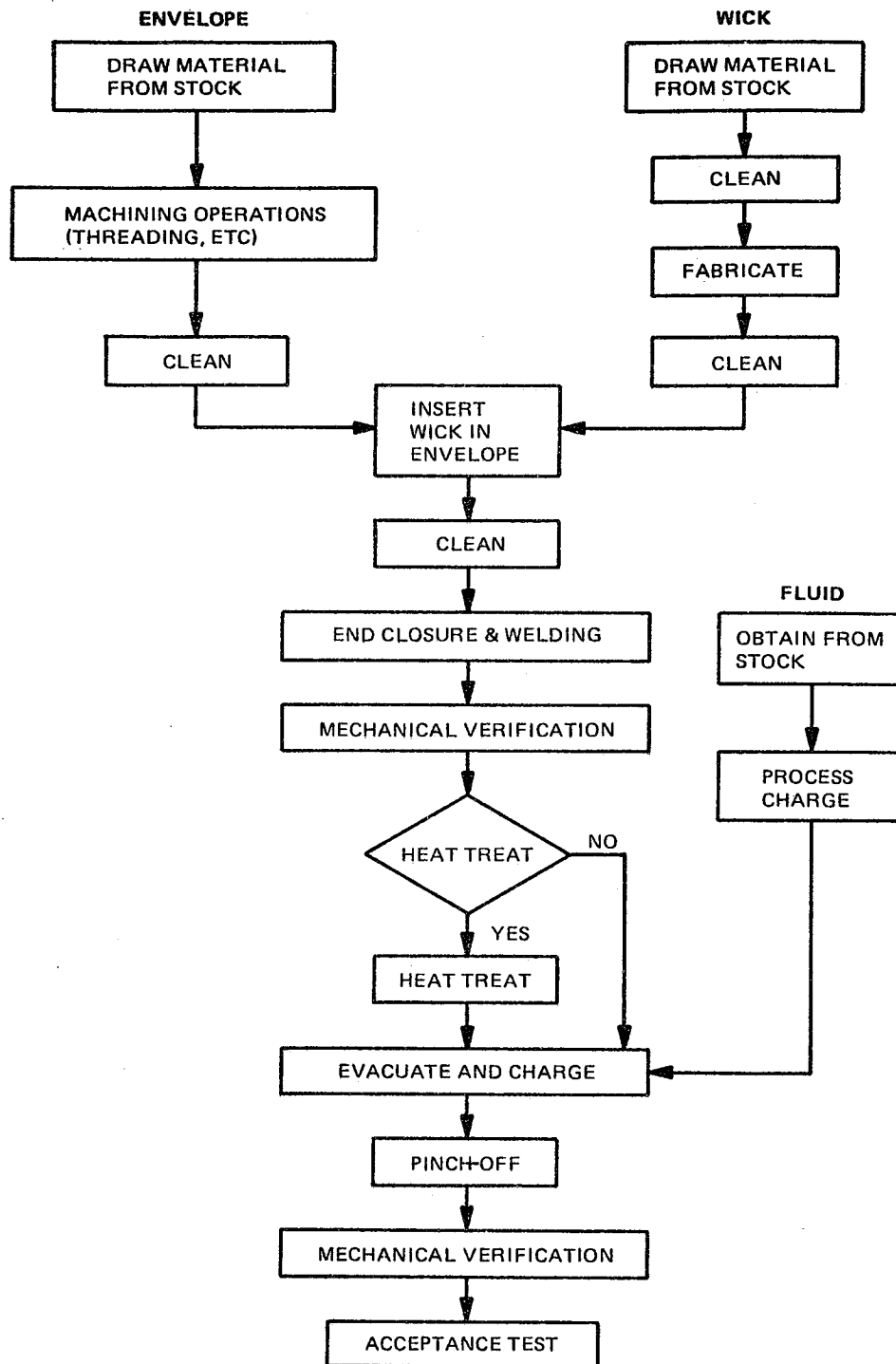


Fig. 2-2 Typical Heat Pipe Manufacturing Flow Chart

2.3 Mechanical Verification

A sound structural design that has been properly verified by non-destructive tests is paramount to reliable, long-term heat-pipe operation. The ASME pressure vessel code is recommended when specifying allowable design stresses, proof pressure, and burst pressure. Simplified methods are also presented in Section 5 for including the stress effects due to internal pressure, end caps, thermal expansion, saddle attachments, pipe bends, and dynamic loading. Cost-effective methods of leak detection for ammonia, Freon, and methanol used during pre-charging and post charging operations include: X-ray examination, pressurization under water, helium detection, and copper sulphate/ethylene glycol (for ammonia).

2.4 Evacuation and Charging

Evacuation of foreign gaseous material from a heat pipe prior to charging must be effective to prevent noncondensable gases from subsequently appearing. The amount of material removed during evacuation is a function of many variables: charge tube geometry, temperature of pipe during evacuation, evacuation time, history of surface from prior cleaning operation, etc. In Section 6 an attempt is made to experimentally correlate some of these variables. This correlation forms the basis for recommending effective evacuation parameters. Charging techniques for high- and low-pressure fluids used by various manufacturers are presented along with methods of charge bottle preparation. Based on test data and manufacturers' experience, techniques are outlined which minimize the introduction of detrimental impurities.

2.5 Fluid Purity

Working fluids available from manufacturers come in different grades, with different purity levels. It is important to know, through a certified analysis, which impurities are present and to what extent to decide if additional purification is required. Considering only the impurities in the pipe prior to charging, it is shown (Section 7) that the material absorbed on the pipe wall can be significant compared to the residual gas remaining after evacuation. Techniques are presented which permit

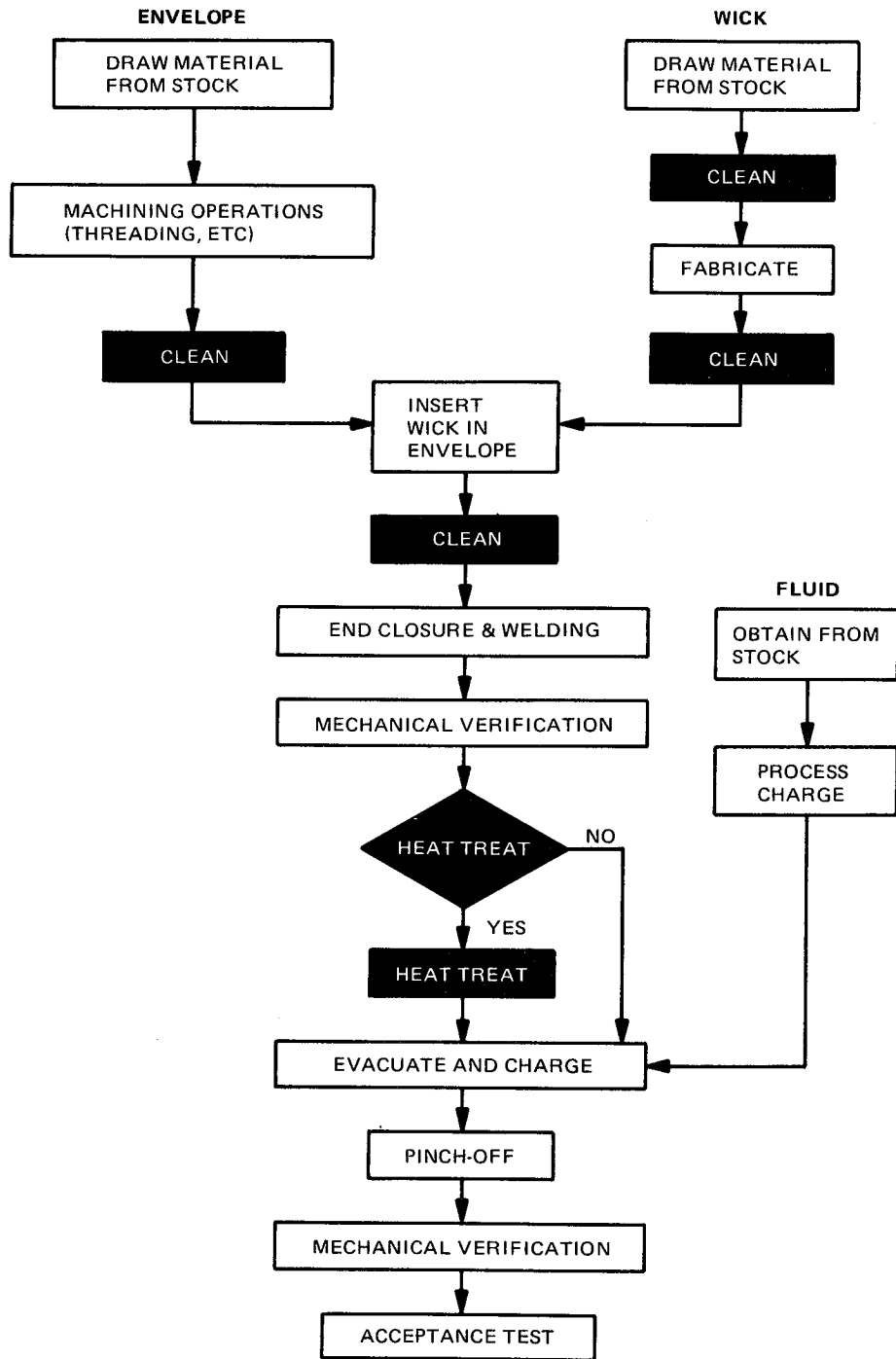
the designer to quickly estimate condenser blockage as a function of impurity level, pipe design, and operating conditions, thereby allowing him to estimate the maximum quantity of impurities for his particular application.

2.6 Charge Tube Pinch-Off

The final mechanical operation performed on the heat pipe is to permanently seal in the working fluid. If not properly done, in-leakage of noncondensable gas can occur during the processes which can result in either scrapping the pipe or placing it through an expensive refurbishment cycle. Except for differences in technique, most manufacturers employ the same procedure involving sequentially: crimping the fill tube to form a temporary leak-tight closure, severing the charge valve from the fill tube, and finally welding shut the cut end (Section 8). Other less common techniques having the potential of making the pinch-off operation less operator-dependent are also presented.

In this report, each of the foregoing areas are discussed in greater depth. Finally, based on these evaluations, a preliminary baseline manufacturing specification is presented (Section 9). It represents an initial attempt at establishing a standardized manufacturing procedure.







3 - ENVELOPE AND WICK CLEANING

3.1 Background

Just as extreme care is required in selecting proper heat pipe materials to avoid compatibility problems, cleaning of the component heat pipe parts is critical to avoid similar consequences. This point was made painfully clear at a recent conference of heat pipe manufacturers held at the Goddard Space Flight Center (refs. 1 and 2). The meeting revealed considerable concern and uncertainty amongst the experts about cleaning. Apparently, this is an area in which no accepted standard exists in the industry at the present time.

Although there are similarities in the procedures, each manufacturer uses a different process, essentially developed independently. The effectiveness of each process can only be evaluated on the basis of past experience.

As seen in the heat pipe manufacturing cycle of Fig. 2-2, there are many areas where contaminants can be introduced into the heat pipe, i. e., through a dirty wick, dirty envelope, impurities in the working fluid, etc. In fact, every operation not properly performed can be a source of contamination. This section discusses envelope and wick cleaning and pretreatment for aluminum and stainless steel envelopes and stainless steel wicks. Originally, it appeared that this area should be treated as two topics, wicks and envelopes. However, during the research effort for this study, it became clear that little wick cleaning information was available. Although most manufacturers were willing to discuss cleaning in general, few were willing to discuss wick cleaning in particular. Each manufacturer considers wick construction and fabrication details as highly proprietary, since it is this element which essentially determines heat pipe performance and separates one company from another. Of the various organizations contacted, therefore, very few were willing to supply information concerning wick cleaning.

Wick cleaning and pretreatment is at least as important as the need for envelope cleaning. Obviously gas generation is just as likely to come from a "dirty" wick as

from other improperly cleaned parts. Oil and greases imbedded in either the fine wire mesh or sintered screening material used to construct wicks must be removed to assure proper heat pipe performance. Foreign substances conducive to gas generation might be introduced in the construction process, requiring that a postwick construction cleaning process be designed to remove this impurity. For example, if a copper electrode is used to assemble a wick with tack-welds, some copper particles may become imbedded in the stainless steel screen. To remove this material, which is incompatible with ammonia, a nitric acid rinse would be required. However, where possible, it is preferable to eliminate this potential problem by using tungsten electrodes.

The heat pipe tube or envelope receives its primary cleaning after dirty operations (such as machining) have been completed. Machining may involve preparing the tube ends for welding, tube bending, and in some cases, cutting fine circular threads on the inside surface to provide a circumferential wicking surface. An assortment of debris such as metal chips, cutting oil, grease, moisture, etc, can be expected after these operations. The overall cleaning operation, therefore, has a number of aims, namely to:

- Mechanically remove particulate matter, such as metal chips which may clog capillary and artery surfaces and/or damage these surfaces during subsequent artery insertion
- Remove water that can cause corrosion, attacking both aluminum and stainless steel, as well as providing a galvanic coupling between the two. Buildup of particulate reaction products, as well as gas generation, are the principal results. Loss of container structural integrity due to crevice corrosion and porosity may also result from the presence of this contaminant
- Remove contaminants, not necessarily corrosive, but which may impair the heat pipe wicking and fluid properties. Examples of these contaminants are the variety of oils and greases used in metal cutting and removal operations, extruding, forming, etc.

These contaminants may coat the internal surfaces and increase the contact angle, or may dissolve in the working fluid, changing its transport properties

- Chemically clean and prepare the surface so as to be nonreactive with subsequent manufacturing environments, the wick, and working fluid
- Treat the wicking surface in a manner that enhances "wettability" with the working fluid.

Failure to achieve these objectives through either improper procedures or operator error has led to heat pipe problems ranging from performance degradation to complete failure. In one reported incident, for example, water inadvertently left on the inside surface of a threaded aluminum tube was judged to be responsible for failure of a heat pipe to achieve its performance goals. Analysis led to the discovery of huge amounts of aluminum hydroxide on the inside surface which were clogging the radial flow passages.

Contaminants can also chemically react with the wall, wick, or fluid to produce noncondensable gaseous products that block the condenser and decrease heat pipe conductance. In the case of arterial wicks, gas bubbles within the wick can, and have, severely limited the heat transport capacity (ref. 3). On the ATS program, groove failure in a single heat pipe was attributed to embrittlement and porosity caused by the presence of water in a closed pipe during heat treatment.

A summary of the foregoing and other problems that can be caused by improper cleaning techniques is as follows:

- Physical clogging of wall and wick capillary surfaces, thereby impairing both heat pipe transport capacity and conductance
- Noncondensable gas generation reducing both heat pipe conductance (loss of condensation area) and transport capacity (bubbles in arterial wicks)

- Decrease in wettability of wick
- Adverse change in fluid properties, such as surface tension, wetting angle, and viscosity
- Loss of structural integrity of container wall due to galvanic corrosion, crevice corrosion, and porosity.

Unfortunately, many of these problems cannot be uncovered until the pipe is charged, sealed and tested. In some cases a long time can occur until some of these effects are noticed; by then, it is usually too late to provide corrective action. Hence, the objective must be to develop cleaning procedures which will prevent these problems from occurring, and produce, therefore, a more reliable product. Moreover, in keeping with the overall aims of this study, the cleaning procedure should also be simple, inexpensive, and as free as possible from human error.

Table 3-1 summarizes the procedures currently employed in the heat pipe industry. A brief general description of various cleaning techniques follows, and each manufacturer's approach will be presented and analyzed. Finally, using this evaluation, recommended cleaning procedures are presented. Note that the procedures used by various manufacturers are typical. If more information is required, it is suggested that the individual company be contacted.

3.2 General Cleaning Procedures

As seen in Table 3-1, a variety of techniques are currently employed to clean tubes used for heat pipe envelopes. These include solvent cleaning, vapor degreasing, alkaline cleaning, acid cleaning, passivation, pickling, ultrasonic cleaning, and vacuum firing. More than one technique may be used in a particular cleaning operation. As a general introduction, a brief description of some of these techniques follows. A more complete description may be found in reference 4.

3.2.1 Vapor degreasing. - Vapor degreasing is a generic term applied to a cleaning process that typically employs the hot vapors of a chlorinated solvent to remove residue - particularly, oils, greases and waxes. Trichloroethylene is a common solvent.

TABLE 3-1. - SUMMARY OF HEAT PIPE CLEANING PROCEDURES CURRENTLY IN USE

Manufacturer	Envelope cleaning		Wick cleaning (stainless steel)
	Aluminum	Stainless steel	
Dynatherm	<ul style="list-style-type: none"> ● Solvent ● Acid 		
NASA/GSFC	<ul style="list-style-type: none"> ● Solvent ● Acid 		
Grumman	<ul style="list-style-type: none"> ● Solvent ● Alkaline/acid 	<ul style="list-style-type: none"> ● Solvent ● Passivation 	<ul style="list-style-type: none"> ● Solvent ● Passivation
TRW	<ul style="list-style-type: none"> ● Solvent ● Alkaline/acid ● Ultrasonic 	<ul style="list-style-type: none"> ● Ultrasonic ● Vacuum fire 	<ul style="list-style-type: none"> ● Ultrasonic ● Vacuum fire
DWDL/MDAC	<ul style="list-style-type: none"> ● Solvent 		
ESRO/MBB	<ul style="list-style-type: none"> ● Ultrasonic 		<ul style="list-style-type: none"> ● Ultrasonic
GE	<ul style="list-style-type: none"> ● Alkaline/acid 	<ul style="list-style-type: none"> ● Alkaline/acid 	
University of Stuttgart		<ul style="list-style-type: none"> ● Ultrasonic ● Passivation 	
NASA/MSFC	<ul style="list-style-type: none"> ● Solvent ● Alkaline/acid 	<ul style="list-style-type: none"> ● Solvent ● Alkaline ● Passivation 	

A vapor degreasing unit consists of an open steel tank with a heated solvent reservoir, or sump, at the bottom and a cooling zone near the top. Sufficient heat is introduced into the sump to boil the solvent and generate hot solvent vapor. Because the hot vapor is heavier than air, it displaces the air and fills the tank up to the cooling zone. The hot vapor is condensed when it reaches the cooling zone, thus maintaining a fixed vapor level and creating a thermal balance. The temperature differential between the hot vapor and the cool workpiece causes the vapor to condense on the workpiece and dissolve the residue.

To supplement vapor cleaning, some degreasing units are equipped with facilities for immersing the work in warm or boiling solvent and for spraying workpiece surfaces with clean solvent. The efficiency of the liquid phase of the cleaning cycle can be augmented by the application of ultrasonic energy.

3.2.2 Solvent cleaning. - Solvent cleaning is a process for removing oil, grease, loose metal chips, and other contaminants from the surfaces of metal parts by the use of common organic solvents, such as aliphatic petroleums, chlorinated hydrocarbons, or blends of these two classes of solvents. Cleaning is usually performed at, or slightly above, room temperature. Parts are cleaned by being immersed and soaked in the solvent, with or without agitation. Parts that are too large to be immersed are sprayed or wiped with the solvent.

Ultrasonic vibration is sometimes used in conjunction with solvent cleaning to loosen and remove residue, such as abrasive compounds, from deep recesses or other difficult-to-reach areas; this reduces the time required for solvent cleaning of complex shapes.

Although some of the solvents used in solvent cleaning are the same as those used in vapor degreasing, solvent cleaning differs from vapor degreasing in that the former process is commonly performed at room temperature. In vapor degreasing, parts may be degreased by exposure to the solvent vapor as well as by immersion in the hot solvent; drying is accomplished by evaporating the solvent from the parts while they are suspended in the hot solvent vapor. In solvent cleaning, parts are dried at

room temperature or by the use of external heat, centrifuging, or an absorptive medium.

3.2.3 Alkaline cleaning. - Alkaline cleaning is employed for the removal of oily, semisolid or solid materials from metals before they are electroplated, conversion coated, or otherwise finished or processed. To a great extent, the solutions used in alkaline cleaning depend on their deterative properties for cleaning action and effectiveness. Agitation of the solution and movement of the workpieces through it, although important, are secondary in their effect.

The principal methods employed in alkaline cleaning are soak, spray, and electrolytic. Other methods are variations incorporating the essential features of these three.

A universal (or all-purpose) cleaner is not available because the requirements for various cleaning jobs are too diverse and are not mutually compatible. Therefore, compromises are made in formulations to fit particular applications.

The cleaning effectiveness of alkaline compounds is attributed mainly to the action of "builders," which are the principal bulk components of the formulation. Most builders are sodium compounds (carbonates, phosphates, silicates, and hydroxide), which provide alkalinity and other desirable properties at low cost.

3.2.4 Acid cleaning. - Acid cleaning is a process in which a solution of a mineral acid, organic acid, or acid salt (possibly in combination with a wetting agent and detergent) is employed to remove oxide, shop soil, oil, grease, and other contaminants from metal surfaces, with or without the application of heat. The distinction between acid cleaning and acid pickling is a matter of degree, and there is often some overlapping in the usage of these terms. In general, however, acid pickling refers to a more severe treatment for the removal of scale from semifinished mill products, forgings, or castings; whereas acid cleaning is the term most frequently used when the acid solution is employed for final or near-final preparation of metal surfaces prior to plating, painting, or storage.

3.2.5 Ultrasonic cleaning. - Ultrasonic energy can be used in conjunction with several types of cleaners, but it is most commonly applied to chlorinated hydrocarbon solvents, water, and water with surfactants. Ultrasonic cleaning, however, is more expensive than other methods because of higher initial cost of equipment and higher maintenance cost. Consequently, the use of this process is largely restricted to applications in which other methods have proved inadequate.

3.2.6 Passivation. - Treatment of stainless steels after fabrication with oxidizing chemicals is known as chemical cleaning, or passivation. If iron particles or other substances have become embedded in the surface during fabrication or polishing operations, they must be removed. Otherwise, these minute foreign particles may promote discoloration, rusting, or even pitting. Besides dissolving such particles, the oxidizing action of the bath also tends to enhance the corrosion resistance of stainless steels by fortifying the natural passive surface film.

Passivation is generally done by immersing the stainless steel part in a nitric acid solution and then rinsing in clear running water, and drying. If immersion of the stainless steel piece is impractical due to size, the acid solution may be applied with suitable swab and removed by rinsing with water.

Nitric acid is recommended because it will dissolve any iron particles and leave the stainless steel unaffected. It is necessary that the surface of the steel be free of scale, heavy grease, and oil if the chemical cleaning treatment is to be effective.

3.3 Discussion of Procedures Currently in Use

3.3.1 Dynatherm Corporation. - Under contract to Fairchild Hiller, Dynatherm is manufacturing heat pipes for the ATS satellite. A typical cross section of the pipe is shown in Fig. 3-1. It is a 6061 aluminum alloy with a square outside surface that is inserted and bonded in honeycomb panels, used for thermal/structural support on the spacecraft.

The pipes are configured in straight, "C" and "Z" shapes, ranging in length from about 2 to 7 ft (0.610 to 2.134 m). Tubing used to make the pipe is purchased from French Tube - Noranda Metal, Inc., Newton, Conn. - in the form of a thick wall tube with axial grooves. It is made in a single draw over a splined mandrel using rotating hammers to swage the tube. Moly-disulfide is used as a lubricant in the process. From this point Dynatherm performs various operations to obtain the final

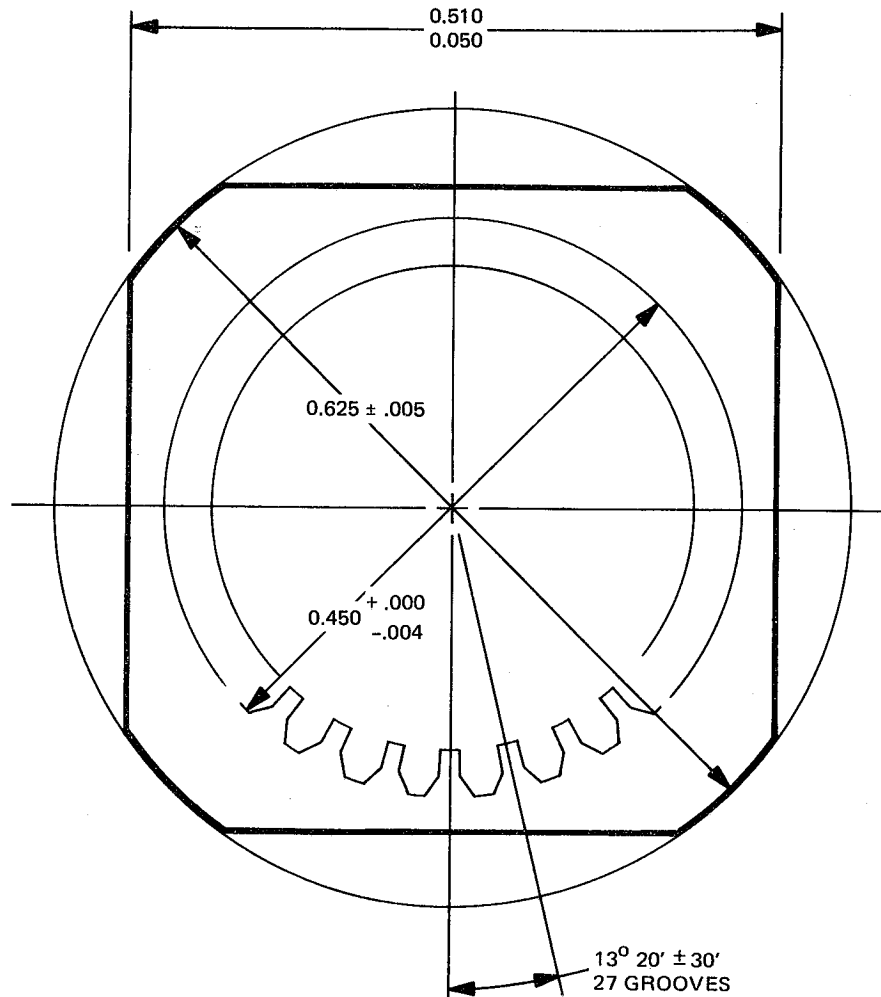


Fig. 3-1 Typical Cross Section of Axial-Groove Heat Pipe

heat pipe configuration. These include cleaning, machining, bending, cutting, charging, etc. Because of high strength requirements, the tubes are heat treated, to the T-6 condition subsequent to welding. A sequential list of these operations is given in Table 3-2 (reference 5).

TABLE 3-2. - DYNATHERM (ATS) CLEANING PROCEDURE - ALUMINUM
6061 AXIALLY GROOVED TUBES

[From Ref. 5]

1. Clean in cold trichloroethylene with nylon brush.
2. Clean in hot (170°F) trichloroethylene.
3. Clean in Illuminate (proprietary cleaner believed to contain phosphoric acid).
4. Rinse in tap water.
5. Clean in 20% nitric acid.
6. Rinse in tap water.
7. Rinse in distilled water.
8. Oven dry at 250°F.
9. Stress relief/anneal at 600°F.
10. Bend C and Z pipes.
11. TIG weld 4043 filler metal to ends of pipes so as to fill in the grooves for a short distance.
12. Machine i.d. of filled-groove area to provide a uniform wall thickness to weld end fittings to.
13. Cut tube to final length.
14. Vapor degrease with TCE.
15. Vapor degrease with methanol.
16. Clean with 20% nitric acid.
17. Rinse in tap water.
18. Rinse in distilled water.
19. Oven dry 1 hr at 250°F.
20. TIG-weld saddles and end fittings to pipes using 4043 filler metal. End fittings incorporate a 4" long x 0.070" i.d. fill tube which is used in evacuating and filling the pipes.
21. Helium leak test: pipe is connected to a Veeco Leak Detector via the fill tube. A plastic bag containing helium surrounds the pipe. Pipe is pumped on for 1 - 3 min during leak check.
22. Fill tube is pinched off while inside of tube is under vacuum and is then welded shut.

TABLE 3-2. - DYNATHERM (ATS) CLEANING PROCEDURE - ALUMINUM
6061 AXIALLY GROOVED TUBES (Cont)

23. Pipes are heat-treated to the T6 condition:
 - (a) Solution anneal at 980°F minimum time at temperature 45 min.
 - (b) Quench in warm (140°F) water. Water is warmed to minimize distortion in pipes. Straighten, if necessary.
 - (c) Age (precipitation harden) at 350°F for 8 hr.
 - (d) Check hardness on saddles and on witness piece wired to center of pipe using Rockwell 15T scale.
24. Machine flats on pipes.
25. Cut open fill tube, attach valve.
26. Leak check as in Step 21.
27. While under vacuum, charge with NH_3 and reflux at 150°F for 8 hr.
28. Bleed out ammonia as gas.
29. Outgas at 300°F for 8 hr under the Veeco vacuum.
30. Charge with ammonia to correct weight.
31. Pinch off and weld fill tube.
32. Proof pressure test: heat to 270°F for 2 hr to develop 1700 psi internal pressure.
33. Recheck for leaks.
34. X-ray welds.

Heat pipes produced from this manufacturing cycle were not of consistent quality. In some cases a fine black residue was found on the inside tube surface. Development of porosity within the groove structure with consequent loss of strength was also noticed. Some pipes showed evidence of the presence of noncondensable gases. One known pipe also had a gray residue on the inner surface characterized by extreme porosity and embrittlement of the longitudinal fins.

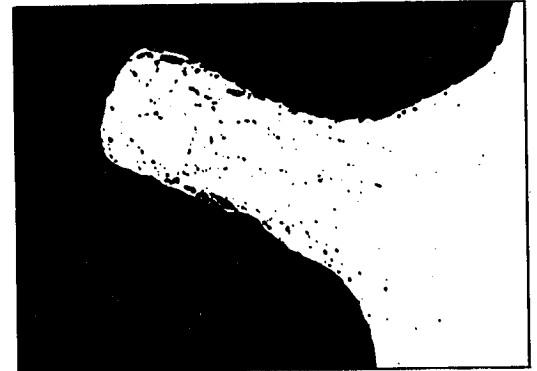
A comprehensive investigation of these problems was conducted primarily by the Materials Engineering Branch of NASA/Goddard. The study concluded that the presence of water within the pipe during the 980°F (526°C) heat treatment (Table 3-2, step 23) was responsible for the discoloration of the internal surfaces and the development of porosity (ref 5 and 6). Tests were conducted which showed that quantities of liquid water as small as 0.005 cc in a 10-in. pipe length (25.400 cm) produced black discoloration, porosity and embrittlement when the tubing was heated to 980°F (526°C), reference 6. To rule out the possibility that greases used in the swaging process were responsible, a heat treat test was conducted on an uncleaned, completely dry tube sample. As expected, the pipe had a sooty black residue from the decomposition of the swaging lubricant but showed no evidence of groove fin porosity or embrittlement. Figure 3-2 shows the porosity obtained in the fin with different quantities of water. The lack of porosity is evident in the dry, but dirty sample. For the 5-ft ATS pipe length, as little as 0.05 gram of water (approximately one drop) or the same amount contained in a hydrated oxide film would be sufficient to produce discoloration, porosity, and embrittlement.

In view of the foregoing it is mandatory that all traces of water, even in hydrated oxide films, be removed prior to heat treatment. Therefore, drying operations in Table 3-2, such as in steps 8, 19 and, particularly, step 21, would require modification to insure more thorough removal of water. In addition, the pinch-off in step 22, if not properly done, could allow a seepage of moisture into the pipe prior to the heat treatment operation in step 23. This is particularly true if there is a long time delay between the two steps.

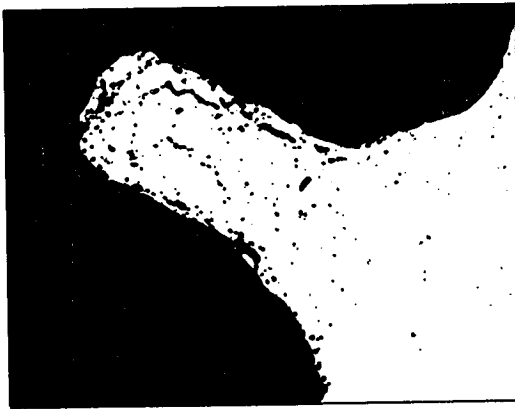
NASA/Goddard's review of this procedure resulted in recommended changes that were felt would eliminate the water problem and simplify, or reduce the number of steps involved. The recommended procedure is given in the next section.



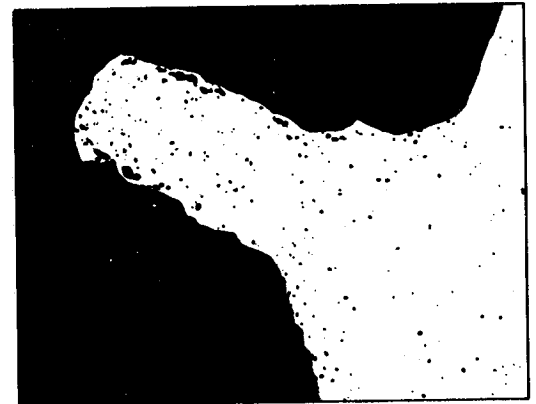
A. 0.005 cc H₂O



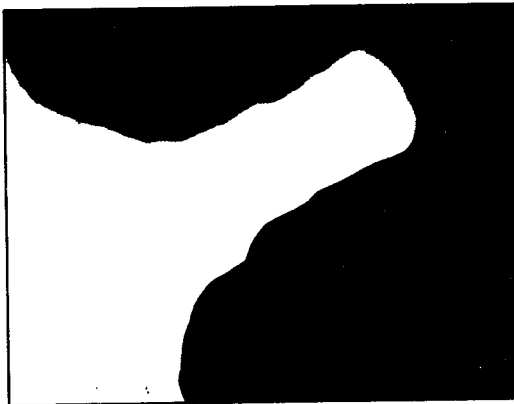
B. 0.010 cc H₂O



C. 0.016 cc H₂O



D. 0.026 cc H₂O



E. HEAT TREATED WITHOUT CLEANING

- BLACK MARKS ARE HYDROGEN PORES AND BLISTERS
- SECTIONS ARE UNETCHED
- ALL PHOTOS 85X

Fig. 3-2 Fin Cross Sections of Sample Heat Pipes — Treated with and without H₂O as Indicated

3.3.2 NASA/GSFC/Procedure for ATS. - As a result of the experiences of the ATS heat pipes two cleaning procedures were recommended by the Materials Engineering Branch of NASA/GSFC (ref. 7). The first was a "quick fix" modification of the original procedure designed to minimize the impact on the heat pipe production schedule. As a result, modifications were tailored to the equipment and facilities immediately available to Dynatherm. The cleaning procedure that evolved produced clean heat pipes with no dark internal films, or microstructural abnormalities. Heat pipes cleaned with this technique successfully passed thermal testing. The modified procedure is outlined in Table 3-3, in a side-by-side comparison to the original procedure. Notice that an isopropyl alcohol rinse has been added after the water rinses in steps 8 and 20. Water, which is very soluble in isopropyl alcohol, is removed by the alcohol leaving the surface free of any water films or droplets. Step 24 has been changed to allow more complete removal of water, particularly the hydrated oxides on the surfaces. The evacuation time was increased to 4 hours and the pipe temperature raised to 600°F (315°C). Reference 8 shows that this temperature is necessary to drive off the water of hydration, which may be in the form $Al_2O_3 \cdot X H_2O$ or as aluminum hydroxide, $Al(OH)_3$. The hydroxide decomposes at 572°F. The steps following heat treatment remain unchanged from Table 3-2.

The second procedure recommended by NASA/GSFC attempted to simplify the original procedure by eliminating steps considered unnecessary. Table 3-3 also describes this simplified procedure. Although ATS heat pipes have not been manufactured using this technique, tests were conducted on 10-in. (25.400 cm) lengths of as-received, lubricant-contaminated ATS swaged-grooved tubing. Results indicate that the simplified cleaning process produced tubes whose inside surfaces were clean and shiny and free from any discoloration. One sample was purposely evacuated and sealed at room temperature instead of 600°F (315°C), as called for in step 24. It showed evidence of discoloration, proving the importance of removal of hydrated films prior to heat treatment. The steps eliminated in the simplified process were:

- Cleaning in hot trichloroethylene (step 2)
- Two cleanings in nitric acid (steps 5 with subsequent water rinse in steps 5, 6, 17, 18 and 19)

**TABLE 3-3. - COMPARISON OF CLEANING PROCEDURES PRIOR TO
HEAT TREAT FOR ATS ALUMINUM HEAT PIPES**

Step	Original	Modified	Simplified
1	Room temp TCE, nylon brush (brush while immersed)	Room temp TCE, nylon brush (brush while immersed)	Room temp TCE, nylon brush (10 min, brush while immersed)
2	170°F TCE, nylon brush (brush while immersed)	170°F TCE, nylon brush (brush while immersed)	
3	Illuminate ^a , nylon brush (brush while immersed)	Illuminate ^a , nylon brush (brush while immersed)	Illuminate ^a , nylon brush (brush while immersed. 15 mins)
4	Rinse in running tap water	Rinse in running demineralized water	Rinse in running tap water, 10 min.
5	Clean in 20% aqueous nitric acid	Clean in 20% aqueous nitric acid	
6	Rinse in running tap water	Rinse in running tap water	
7	Rinse in distilled water	Rinse in distilled water	Rinse in running deionized water (2 min)
8		Rinse in Isopropyl alcohol	Rinse in Isopropyl alcohol 15 min
9	Oven dry, 250°F, 1 hr	Oven dry, 300°F, 1 hr	
10	Stress relief anneal, 600°F, 1 hr	Stress relief anneal, 600°F, 1 hr	Dry & Stress relief anneal,
11	Bend C & Z pipes	Bend C & Z pipes	Bend C & Z pipes
12	TIG weld 4043 filler to fill in grooves at ends of pipes	TIG weld 4043 filler to fill in grooves at ends of pipes	TIG welds 4043 filler to fill in grooves at ends of pipes
13	Machine ID at ends smooth using lubricant	Machine ID at ends smooth - use no lubricant	Machine ID smooth at ends - use no lubricant
14	Trim to final length	Trim to final length	Trim to final length
15	Vapor degrease TCE	Vapor degrease TCE	
16	Vapor degrease with methanol	Vapor degrease with methanol	
17	Clean in 20% nitric acid	Clean in 20% nitric acid	
18	Rinse in running tap water	Rinse in running demineralized water	
19	Rinse in distilled water	Rinse in distilled water	
20		Rinse in Isopropyl Alcohol	Rinse in Isopropyl alcohol, 15 min
21	Oven dry, 250°F, 1 hr	Oven dry, 300°F, 1 hr	Oven dry, 300°F, 1 hr
22		Store in clean room	Store in clean room
23	Weld on end caps, fill tubes and saddles	Weld on end caps and fill tubes in clean room ^b , weld saddles	Weld on end caps and fill tubes in clean room ^b , weld saddles
24	Evacuate and leak check, 1-3 minutes, room temp.	Evacuate and leak check, 4 hr at 600°F	Evacuate and leak check, 4 hr at 600°F
25	Pinch off and weld fill tube	Pinch off and weld fill tube	Pinch off and weld fill tube
	Heat treat	Heat treat	Heat treat
<p>a. Illuminate is a proprietary cleaner developed specifically for cleaning aluminum alloys. The manufacturer's label states it is an aluminum restorer and cleaner, that it rejuvenates oxidized surfaces and removes oil and grease. Although there are many other acceptable cleaning solutions listed in handbooks, such as the Metals Handbook, they all require the measuring and mixing of several chemicals. It was felt that it would be better to stay with the cleaner of experience that is effective, easy to mix and use, and, thereby, lessen the chances for mixing mistakes.</p> <p>b. Fill tubes and end caps are cleaned in a similar manner.</p>			

- A vapor degreasing with TCE (step 2)
- A vapor degreasing with methanol (step 16).

Step number 9 was also eliminated by combining the drying and stress relief operations.

3.3.3 Grumman/Procedure. - Cleaning procedures used by Grumman on aluminum tubes have employed solvent, alkaline, and acid cleaning techniques. These steps are outlined in Table 3-4. The tubes used are internally threaded and have a stainless steel artery which, as indicated in step 9, is inserted after the major portion of the cleaning operation has been accomplished. In contrast to the ATS pipes, the units produced have not required heat treatment.

Grumman uses a chemical process to clean its stainless steel mesh wicks. The over-all cleaning procedure is presented in Table 3-5. As shown, at different stages in the process the wick is cleaned using acetone, nitric acid, and Freon. After cutting a suitable size of stock, the screen is rinsed in an acetone bath. The acetone removes oils and greases which have been imbedded in the screen by the manufacturer. Subsequently, the wick is partially assembled and passivated in nitric acid. Passivation essentially coats the screen with a protective oxide coating. In the sixth step an artery integrity test is performed using acetone. This test verifies that the mechanical assembly is capable of the desired capillary pressure. Depending on the mesh size used, the ability of the wick to lift a certain column of fluid is determined. For example, for 100 mesh screening the wick should be capable of lifting approximately 2 in. (5.080 cm) of acetone. If the wick were to lift only 0.5 in. (1.270 cm), it would be an indication that the artery assembly was unacceptable - perhaps due to improper or incomplete welding which created a hole in the artery. Following this, the wick is cleaned using Freon TF as a final rinse.

Although this procedure has produced heat pipes which have successfully met their thermal requirements, there have been some cases where corrosion was evident. This occurred during the cleaning of an aluminum 6061 pipe for a development heat

pipe radiator program (ref. 9). Following the two minute water rinse in step 5 of Table 3-4, the pipe apparently was improperly dried leaving water droplets on the internal surfaces. The pipe was subsequently charged with ammonia and tested. It failed to reach its transport capacity goals. Upon removal of the charge it was noticed that the ammonia was tainted, leaving a residue on a clean glass surface. Further analysis and examination of the pipe revealed corrosion products clogging the radial groove surfaces. The pipe was subsequently recleaned, charged, and successfully tested, achieving all thermal requirements.

Another aluminum/stainless steel/ NH_3 pipe, manufactured in 1971 using this cleaning procedure, has recently been tested for the presence of noncondensable gas. A gas slug of approximately 3 in. (7.620 cm) was found in the pipe whose overall length is 142 in. (360.680 cm). The slug, although not detectable at room temperature, was evident at approximately -40°F (-40°C). At present it is not clear whether the gas was present from the beginning, or whether it was generated over the past two years.

This experience is generally inconsistent with the results obtained from other heat pipes manufactured the same way. For example, at the time the 142-in. (360.680 cm) pipe was fabricated, a 36-in. (91.440 cm) heat pipe was manufactured using identical techniques. This pipe was life tested for over 2,000 hr at elevated temperatures representing an accelerated test time of approximately 3.7 years. No evidence of gas or material incompatibility were found, even at temperatures as low as -40°F (-40°C), reference 10.

Whether or not the cleaning procedures were responsible for the gas in the 142-in. (360.680 cm) pipe, it is evident (from our earlier experience) that modifications are required to insure more effective water removal. This was done along with other changes which will be presented in detail in Subsection 3.4.

Grumman's experience with stainless steel envelopes is limited, having built the majority of our pipes with aluminum. A liquid blockage diode heat pipe was recently built for the ATFE (Advanced Thermal Control Flight Experiment), which

TABLE 3-4. - GRUMMAN CLEANING PROCEDURE - ALUMINUM 6061

1. Machine inside surface of tube with radial threads.
2. Vapor degrease in Trichloroethylene at 182°F to 200°F.
3. Immerse in alkaline cleaner (e.g., Oakite 164) for 5 min, followed by 2 min water rinse.
4. Immerse in nitric acid/sodium sulfate deoxidizer for one to two min.
5. Water rinse for two min.
6. Force air dry with clean filtered air.
7. Clean with nylon brush.
8. Clean with high velocity fluid, e.g., Freon TF.
9. Insert artery (if applicable).
10. Flush with Freon TF.
11. Perform weld operations, such as end caps, etc.
12. Leak test.
13. Evacuate and flush charge.

TABLE 3-5. - GRUMMAN TYPICAL ARTERY CLEANING PROCEDURE - STAINLESS STEEL 304

1. Cut screen to size.
2. Clean in acetone.
3. Partially fabricate artery.
4. Passivate.
 - 4.1 Immerse in passivation solution, such as nitric acid from 1/2 to 2 hr.
 - 4.2 Rinse in tap water for 1 min minimum.
 - 4.3 Force air dry with clean filtered air.
5. Complete artery fabrication using gloves.
6. Perform artery integrity test in acetone.
7. Flush in Freon TF.
8. Force air dry with clean filtered air or nitrogen.
9. Store in glass tube.

employed stainless steel 304 as the envelope and ammonia as the working fluid (ref. 11). The procedure used to clean the envelope is given in Table 3-6. It primarily employs a passivation treatment which consists of immersing the tube in a 35 - 65% nitric acid solution at 70°F (21°C) for 1/2 to 2 hr. The pipe has operated successfully showing no evidence of noncondensable gas.

TABLE 3-6. - GRUMMAN CLEANING PROCEDURE - STAINLESS
STEEL 304 TUBING

1. Thread Tubes.
2. Vapor degrease in trichloroethylene at 182 to 200°F.
3. Passivate.
 - 3.1 Immerse in passivation solution, such as 35-65% nitric acid from 1/2 to 2 hours at ambient temperature.
 - 3.2 Rinse in tap water for 1 minute minimum.
 - 3.3 Force air dry with clean filtered air.
4. Clean with nylon brush.
5. Clean with high velocity fluid, e.g., acetone.
6. Insert artery (if applicable).
7. Flush with Freon TF.
8. Perform weld operations, such as end caps, etc.
9. Leak test.
10. Evacuate and charge.

TABLE 3-7. - TRW - UPDATED CLEANING PROCEDURES FOR ALUMINUM

Preclean	Post clean
<ul style="list-style-type: none"> ● Materials <ul style="list-style-type: none"> Degreaser Trichloroethylene, technical grade Alkaline Alkaline cleaner - 4215 Caustic Aluminum (M. 1 sodium hydroxide) Deoxidizer . . . No. 2487 (Wyandotte Chemical Co.) Chromate base Deionized water ● Procedure (tubes) <ol style="list-style-type: none"> 1. Vapor degrease and flush with wand 15 min 2. Flowing hot mild alkaline (4215) at 150°F. Scrub i. d. with nylon brush. Repeat until clean to the eye 3. Immersion in hot (120°F) caustic etch 30 sec 4. Immersion in deoxidizer 5 min 5. Flush with deionized water 6. Dry with flowing nitrogen 7. Oven dry 20 min at 150°F 8. Groove tubes 70% kerosene, 30% TS110 	<ul style="list-style-type: none"> ● Materials <ul style="list-style-type: none"> Degrease 1, 1, 1 Trichloroethane Acetone Reagent or electric grade (filtered) Hexane Reagent grade (filtered) Freon TF Solvent grade (filtered) ● Procedure (tubes) <ol style="list-style-type: none"> 1. Vapor degrease and flush with wand 15 min 2. Oven dry (air) 20 min at 150°F 3. Freon TF ultrasonic 15 min 4. Nitrogen dry 1 to 2 min 5. Acetone ultrasonic 15 min 6. Nitrogen dry 1 to 2 min 7. Hexane ultrasonic 15 min 8. Nitrogen dry 1 to 2 min 9. TCE vapor degrease and 15 min flush with wand 10. Oven dry (vacuum) 5 min at 100°C

3.3.4 TRW. - A typical procedure used by TRW to clean aluminum tubes is shown in Table 3-7. The process consists of two operations: precleaning and post cleaning. The precleaning operation is performed prior to machining threads or grooves on the inside surface. This is followed by the post cleaning procedure employing ultrasonics.

Pipes produced using this technique have shown evidence of gas at -40°F (-40°C), which apparently stabilizes after approximately 60 days. However, it is not certain that this is due to the cleaning procedure. It has been postulated that mono layers of water on inside surface are causing the problem (ref. 2).

A typical procedure used by TRW to clean both stainless steel tube and wick assemblies also involves ultrasonics (Table 3-8). In addition a final step is included where both the wick and the tube are vacuum fired for one hour at 1,000°C. Apparently this method works, since TRW reports no gas generation problems with their stainless steel envelope and wick pipes (ref. 2). However, they report the evidence of gas with an aluminum envelope and stainless steel wick. This is possibly caused by an inability to vacuum fire the aluminum at such high temperatures (1,000°C).

TABLE 3-8. - TRW CLEANING PROCEDURES FOR STAINLESS STEEL WICK/TUBE ASSEMBLIES

1. Freon TF ultrasonic15 min
2. Oven dry (vacuum)	5 min at 100°C
3. Acetone ultrasonic15 min
4. Oven dry (vacuum)	5 min at 100°C
5. TCE vapor degrease and flush with wand30 min
6. Oven dry (vacuum)	5 min at 100°C
7. Vacuum fire at 1,000°C	1 hr

3.3.5 Donald W. Douglas Laboratories. - This firm cleans grooved aluminum pipes using a solvent cleaning technique (ref. 2) which essentially consists of:

1. Flushing with Freon-113
2. Dry with dry nitrogen

3. Flush with isopropyl alcohol
4. Dry with dry nitrogen
5. Evacuate and flush charge.

Pipes manufactured using this cleaning procedure have developed gas, but it is not known if this is due to the cleaning technique, absorbed surface molecules not removed during evacuation and charging, or some other yet unknown phenomenon.

3.3.6 European Space Research Organization (ESRO). - Reference 12 reports a procedure used by Messerschmitt-Bolkow-Blohm GMBH for ESRO. The pipe consists of an aluminum 6061-T6 envelope 100 cm long by 0.5 cm diameter with a 250-mesh stainless steel 316 artery. The procedure consists of:

1. Boil tube in acetone in ultrasonic bath
2. Insert artery which has been boiled in acetone in ultrasonic bath
3. Boil assembled unit in acetone
4. Fill with ammonia, operate for one day
5. Evacuate and refill.

Little is known regarding the success of this procedure.

3.3.7 General Electric. - Reference 13 reports on a cleaning procedure for aluminum reflux capsules used to test a variety of working fluids including methanol, ammonia and Freon-11 and -113. The capsules were approximately 23.5 in. (59.690 cm) long and 0.5 in. (1.270 cm) o.d. The design is shown in Fig. 3-3.

In constructing the capsules, all parts were first cut to the required size and then thoroughly cleaned. The cleaning procedure involved an initial soak in hot alkaline cleaner, followed by deoxidation in a solution of 112 gm sodium sulfate and 150 ml concentrated nitric acid, in 850 ml water for 20 min at 140°F (60°C). In addition, the aluminum was either machined or abraded in the area of the welds. A single layer wick of aluminum screen (1100-aluminum alloy, 120-mesh twill) was then inserted in the tube and pressed against the inside wall by rolling over a 3/8 in. (0.953 cm) rod inserted down the axis of the tube. The capsules were then

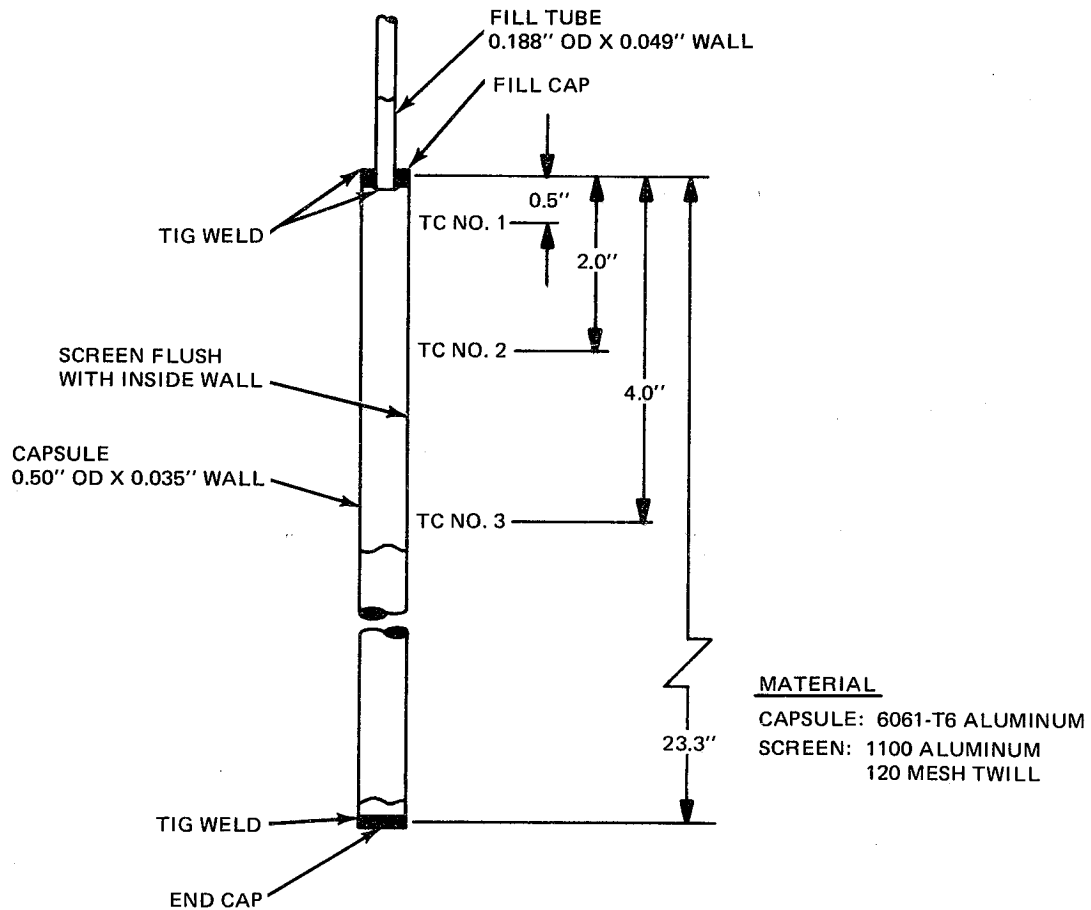


Fig. 3-3 Aluminum Capsule

TIG-welded using helium in a vacuum purged inert gas welding chamber. After welding, the capsules were leak checked with a helium mass spectrometer leak detector and pressure checked with argon at 900 psig (6.205×10^6 newt/m²), after which the leak check was repeated.

Results with ammonia, Freon-11, and Freon-113 showed good stability with no gas generation observable (from temperature measurements) after 500 hr at a test temperature range between 155°F (68°C) and 224°F (107°C). The methanol data is inconclusive due to gas generation during charging. However, it is known that methanol/aluminum heat pipe combinations are incompatible, resulting in gas generation (ref. 14).

In addition to the aluminum capsules, Reference 13 reports on a cleaning procedure for stainless steel 321. Water used for a compatibility test developed gas. The type 321 stainless steel capsule for the water test was similar to the aluminum capsule except that the fill tube was 0.25 in. (0.635 cm) o.d. by 0.035 in. (0.089 cm) wall. The stainless capsule was cleaned before fabrication by soaking in hot alkaline cleaner and pickling for 15 min at 135°F (57°C) in a solution of 15% by volume concentrated nitric acid, 5% by volume concentrated hydrochloric acid, and 80% water. In addition, the stainless steel was passivated by soaking for 15 min at 150°F (66°C) in a 15% volume nitric acid solution. The wick material consisted of a single layer of 150-mesh, type 316 stainless steel screen pressed against the inner wall. The stainless steel capsule was TIG welded in air with argon purging.

3.3.8 University of Stuttgart. - The University of Stuttgart performed a series of life tests using stainless steel envelopes with acetone, methanol, water, hexane, and ethanol (ref. 15). Other structural materials studied included mild steel, copper and nickel. The cleaning procedure employed for the stainless steel pipes involved boiling in acetone in an ultrasonic bath. It is believed that the stainless steel was also passivated. Results are given in Table 3-9. The acetone and methanol pipes showed no evidence of gas at the indicated operating temperatures. Unfortunately, tests at lower temperatures were not conducted. The high delta T obtained with ethanol is due to gas entering the pipe during initial filling. The apparent gas buildup with hexane is believed to be due to decomposition of the hexane, although this has not been proven. Water and stainless produced a high delta T which increased with time and then stabilized - behavior usually attributed to gas generation.

3.3.9 NASA/MSFC. - NASA/MSFC has compiled a list of chemical processing specifications for both aluminum and stainless steel alloys used successfully during the Apollo program (ref. 4). The specifications were prepared by the Product Engineering and Process Technology Laboratory at Marshall Space Flight Center. Although not pertaining to heat pipes per se, they are nevertheless applicable

TABLE 3-9. - STAINLESS STEEL LIFE TESTS

Wall material	Screen material	Working fluid	Operating temp, °K	Overall pipe delta T change after test, °K	Test time, hr
SS 1.4541 ^a	SS 1.4401 ^b	Acetone	370 (206°F)	2	5,000
SS 1.4541	SS 1.4301 ^c	Acetone	370	5	5,000
SS 1.4541	SS 1.4401	Methanol	370	0	5,000
SS 1.4541	SS 1.4301	Methanol	370	3	5,000
SS 1.4541	SS 1.4301	Ethanol	350 (170°F)	10	5,800
SS 1.4541	SS 1.4301	Hexane	350	25	11,850
SS 1.4541	SS 1.4401	Water	370	25	5,000
SS 1.4541	SS 1.4301	Water	370	40	5,000

^aSS 1.4541 is equivalent to stainless steel 321

^bSS 1.4401 is equivalent to stainless steel 316

^cSS 1.4301 is equivalent to stainless steel 304

because of the critical cleanliness requirements imposed on space launch vehicles, particularly for tubing used in propulsion and life support systems.

One specification, M-ME-MPROC-100.8E, is reproduced in Appendix A. It is applicable to aluminum 6061 or stainless steel 304, 304, 304L, 316, 321, and 347 tubing used in liquid oxygen, fuel, and pneumatic systems of space launch vehicles. Note that the cleaning operations employed are similar to those used by heat pipe manufacturers. For example, the internal surfaces of flared stainless steel tubing is cleaned using solvent cleaning, pickling, and passivation. Similarly, aluminum is cleaned using solvent and aqueous (alkaline and acid) cleaning techniques.

Other specifications contained in the document may be useful for other operations such as surface treatment, cleaning prior to welding, etc. A list of these specifications is contained in Table 3-10 for aluminum alloys and Table 3-11 for stainless steel alloys.

TABLE 3-10. - PROCESS SPECIFICATION LIST FOR
ALUMINUM ALLOYS - Continued

[Complete Specifications available in NASA-TM-X-2635]

● Solvent cleaning	
Vapor Degreasing of Metallic Surfaces	MS 150.0
The Cleaning of Spheres for the C-1 Space Vehicle	M-,E-MPROC 150.8
Sulfuric Acid Strip of Space Vehicle Parts	MPD 25008
● Cleaning and deoxidization of aluminum alloys	
Deoxidation of Aluminum Alloys	MS 100.2A
Sand and Vapor Blasting	MS 150.1
Surface Treatment	M-ME-MPROC 150.7B
Cleaning of Aluminum Alloy Weld Joints	MSFC PROC -463
Cleaning and Deoxidation	MPD 25016A
Deoxidation Prior to Welding	MPD 25020A
Cleaning Prior to Welding	MPD 26607
Cleaning ATM Components	MPD 26618
● Cleaning to cryogenic specifications	
Cleaning Liquid Hydrogen Cryogenic Tank for Space Shuttle	MPD 25023
Cryogenic Foam Insulation Application	MPD 38004
Cleaning of Cryogenic Insulation Test Container and Components	M-ME-MPROC 101.6

TABLE 3-10. - PROCESS SPECIFICATION LIST FOR
ALUMINUM ALLOYS - Concluded

●	Cleaning for use in adhesively bonded structures	
	Cleaning Prior to Application of Spray FoamMPD 25017
	Process Control for Application of Urethane Foam.MPD 38001
●	Conversion coating and anodizing	
	Anodizing Aluminum Alloys	MS 150.2A
	Application of Conversion Coating	MS 150.3
●	Chemical milling of aluminum alloys	
	Specifications for Chemical Milling of Aluminum Alloys	MS 550.0
	Chemical Milling of Bulhead GoresM-ME-MPROC 551.0
●	Electrolytic cleaning and plating	
	Electro Cleaning of Space Vehicle PartsMPD 26613
	Cadmium Plating	MS 120.0
	Nickel Plating	MS 120.1
	Chromium Plating	MS 120.2
	Electroless Nickel Plating	MS 120.3
	Copper Plating	MS 120.4
	Use of Marking Inks	MS 150.5
●	Cleaning of tubing and flexible hose	
	Cleaning of Flared and Unflared Flexible Tubing	M-ME-MPROC-100.8E
	Cleaning of Aluminum Tubing EndsMPD 25010
●	Application of dry film lubricants	
	Specifications for Application of Dry Film Lubricants	MS 170.5
	Application of MLF-5 Dry Film LubricantMPD 26621
●	Vacuum drying	
	Drying in a Vacuum	MS 101.0

TABLE 3-11. - PROCESS SPECIFICATION LIST FOR STAINLESS
STEEL ALLOYS - Continued

[Complete Specifications available in NASA-TM-X-2635]

● Cleaning solvents	
Cleaning of Unlined Stainless Steel Bellows	MS 100.5A
Carbon Removal	MS 100.9A
Carbon Removal from Heat Exchangers	MPD 25008
● Cleaning of tubing and flexible hose	
Cleaning of Stainless Steel Tubing Ends	MPD 25009
Cleaning Tubing for Brazing	MPD 26301C
Cleaning Tubing Attached to Instruments	MPD 26302
Cleaning of Unlined Bellows	MS 100.5A
Specifications for Protection of Pipe and Tubing During Welding	MS 200.2A
● Cleaning, pickling, and passivating	
Cleaning and Passivation of Heat Exchangers	MS 100.3C
Cleaning and Passivation of 300 Series Stainless Steel	MS 100.4A
● Electrolytic cleaning and polishing	
Electropolishing of Corrosion Resistant Steel	MS 150.4
● Cleaning miscellaneous material/components	
Cleaning of Control Assemblies	MS 100.7A
Cleaning and Testing of Components in Fuel System	M-ME-MPROC 103.0
Cleaning Electrical Connectors	M-ME-MPROC 104.0
Cleaning and Testing of Hydraulic Systems	M-ME-MPROC 105.0
Cleaning LOX Suction Lines	MPD 25007
Cleaning and Polishing Optical Experiment Chamber	MPD 25018

TABLE 3-11. - PROCESS SPECIFICATION LIST FOR STAINLESS
STEEL ALLOYS - Concluded

Cleaning of Filter Elements	MPD 25019
Cleaning ATM Black Boxes	MPD 26003A
Cleaning Cryogenic Test Tank	MPD 26614
Cleaning Temperature Transducer	MPD 26632
Cleaning ATM Opto-Mechanical Assemblies	MPD 26634

3.4 Conclusions and Recommendations

3.4.1 Aluminum tubes. - Based on an evaluation of past problems experienced by heat pipe manufacturers, particularly with water removal, and an independent study conducted by our Chemical Engineering Department, Grumman recommends the cleaning procedure outlined in Table 3-12. The procedure is relatively simple, employs equipment generally available to industry and, based on previous related experience, should provide a consistently clean surface. It is applicable for aluminum 6061 and 6063 axially grooved, or radially threaded envelopes.

As shown, the procedure requires an initial mechanical brush cleaning with 1,1,1 trichloroethane for the as received, or threaded tube. Mechanical cleaning with a brush is essential at the beginning of the cleaning operation to dislodge the larger particles, which subsequent flushing may not accomplish. The solvent, 1,1,1 trichloroethane, is safer to use than trichloroethylene which has already been disallowed in certain states (e.g., California) and is convenient to use, particularly in a through-the-tube flush operation. A non-etch alkaline cleaner (refer to Table 3-13) is next used, followed by a chromated deoxidizer (refer to Table 3-14). In contrast to a nitric acid/sodium sulfate deoxidizer, the chromated deoxidizer is less aggressive and provides a more corrosion-free surface. Per Table 3-12, step 7, drying with forced, filtered air; followed by an anhydrous isopropyl alcohol rinse; followed again by drying with clean, filtered and heated nitrogen, assures complete water removal.

TABLE 3-12. - RECOMMENDED CLEANING PROCEDURE FOR
ALUMINUM TUBES

[Applicability - Aluminum 6061 or 6063 axially grooved
or radially threaded tubes]

Procedure

1. Clean in cold 1, 1, 1 trichloroethane with bristle brush on wire extension. Periodically clean brush between strokes
2. Flush internal surface with cold trichloroethane; dry with filtered air and cap pipe ends
3. Immerse in non-etch alkaline cleaner for 5 min (minimum). Refer to Table 3-13 for materials, and temperature
4. Follow with a two min tap water rinse, raising and lowering tube during rinsing
5. Immerse in chromated deoxidizer. Refer to Table 3-14 for material, time and temperature
6. Follow with a two min tap water rinse, raising and lowering tube during rinsing
7. Thoroughly dry inside surface with forced filtered air
8. Rinse with anhydrous isopropyl alcohol
9. Force dry with clean, filtered, dry nitrogen heated to 160°F
10. Cap pipe ends
11. If applicable, insert artery, rinse with isopropyl alcohol and dry as in step 9
12. If heat treat is required after welding:
 - (a) Evacuate pipe for 4 hr at 600°F and leak check
 - (b) Seal evacuated heat pipe
 - (c) Perform heat treat operations on sealed pipe

TABLE 3-13. - EXAMPLES OF NON-ETCH ALKALINE CLEANERS

Material	Concentration	Temperature, °F
Ridoline No. 53 (Amchem Products Co.)	2-10 oz/gal	140-180
Oakete No. 164 (Oakite Products Co.)	2-10 oz/gal	140-180
Kelite spray white (Kelite Corp)	40-60% by volume	Ambient
A-38 (Pennwatt Corp)	4-8 oz/gal	160-180

TABLE 3-14. - EXAMPLES OF CHROMATED DEOXIDIZER SOLUTIONS
(IMMERSION TYPE)

Material	Concentration	Temperature, °F	Immersion time
Mixture of: Chromated deoxidizer replenisher No. 17 ^a (Amchem Products Co.) Nitric Acid 42° Be	2-6 oz/gal 10-20% by volume	Ambient to 120	5 to 30 min
Mixture of: Chromated deoxidizer replenisher No. 17 ^a Sulfuric acid 66' Be	2-6 oz/gal 4-7% by volume	Ambient	5 to 30 min

^aDeoxidizer make up No. 7 to be used for initial makeup

At this point, if applicable, an artery may be inserted into the pipe. Depending on the nature of the artery and the cleanliness associated with its installation, an alcohol rinse may be appropriate. If the pipe is to be heat treated after welding operations, the procedure suggested by NASA/GSFC is recommended as shown in steps 12a, 12b and 12c.

The foregoing recommended procedure is based, in part, on facilities being available for tube lengths being processed. For example, immersion tanks may not be available for exceptionally long tubes, and their cost for a "one shot deal" would not be justified. Alternate methods can be equally effective, but should be reviewed by qualified cleaning personnel before implementation.

3.4.2 Stainless steel tubes. - From the limited experience available with stainless steel it would appear from a technical point of view that all the processes described are adequate, in that gas generation is insignificant for working fluids other than water.

However, long-term gas generation, particularly at lower temperatures, has not been analyzed as extensively for stainless steel envelopes as it has for aluminum envelopes.

From the procedures presented, however, it does appear that ultrasonic cleaning and vacuum firing may not be as economical as passivation treatments. Admittedly, the economics are a function of the facilities available to the manufacturer and his experience with a particular technique. Nevertheless, Grumman recommends a passivation treatment for stainless steels, principally because of their general use and availability in industry. The procedure, given in Table 3-15, is based on Grumman's technique with modifications and rationale similar to those for aluminum. Table 3-16 lists examples of passivating solutions.

Note that even though the presence of water on stainless steel is not as corrosive as it is on aluminum, extensive drying operations have still been included as assurance against possible contamination downstream in the manufacturing process.

TABLE 3-15. - RECOMMENDED CLEANING PROCEDURE FOR
STAINLESS STEEL TUBES

[Applicability - Stainless Steel 300 series, radially thread tubes]

Procedure:

1. Clean in cold 1,1,1 trichloroethane with bristle brush on wire extension. Periodically clean brush between strokes
2. Flush internal surface with cold trichloroethane, dry with filtered air and cap pipe ends
3. Immerse in passivating solution. Refer to Table 3-16 for materials, temperature, and time
4. Follow with a two min tap water rinse, raising and lowering tube during rinsing
5. Thoroughly dry inside surface with forced filtered air
6. Rinse with anhydrous isopropyl alcohol
7. Force dry with clean, filtered, dry nitrogen heated to 160°F
8. Cap pipe ends
9. If applicable, insert artery, rinse with isopropyl alcohol and dry as in step 7

TABLE 3-16. - EXAMPLES OF PASSIVATING SOLUTIONS

Material	Concentration	Temperature	Immersion time
Nitric acid	35-65% by volume	Ambient	30 min to 2 hr
Mixture of: sodium dichromate or potassium dichromate	1 - 4 oz/gal	Ambient	30 min to 2 hr
Nitric acid	15-30% by volume		

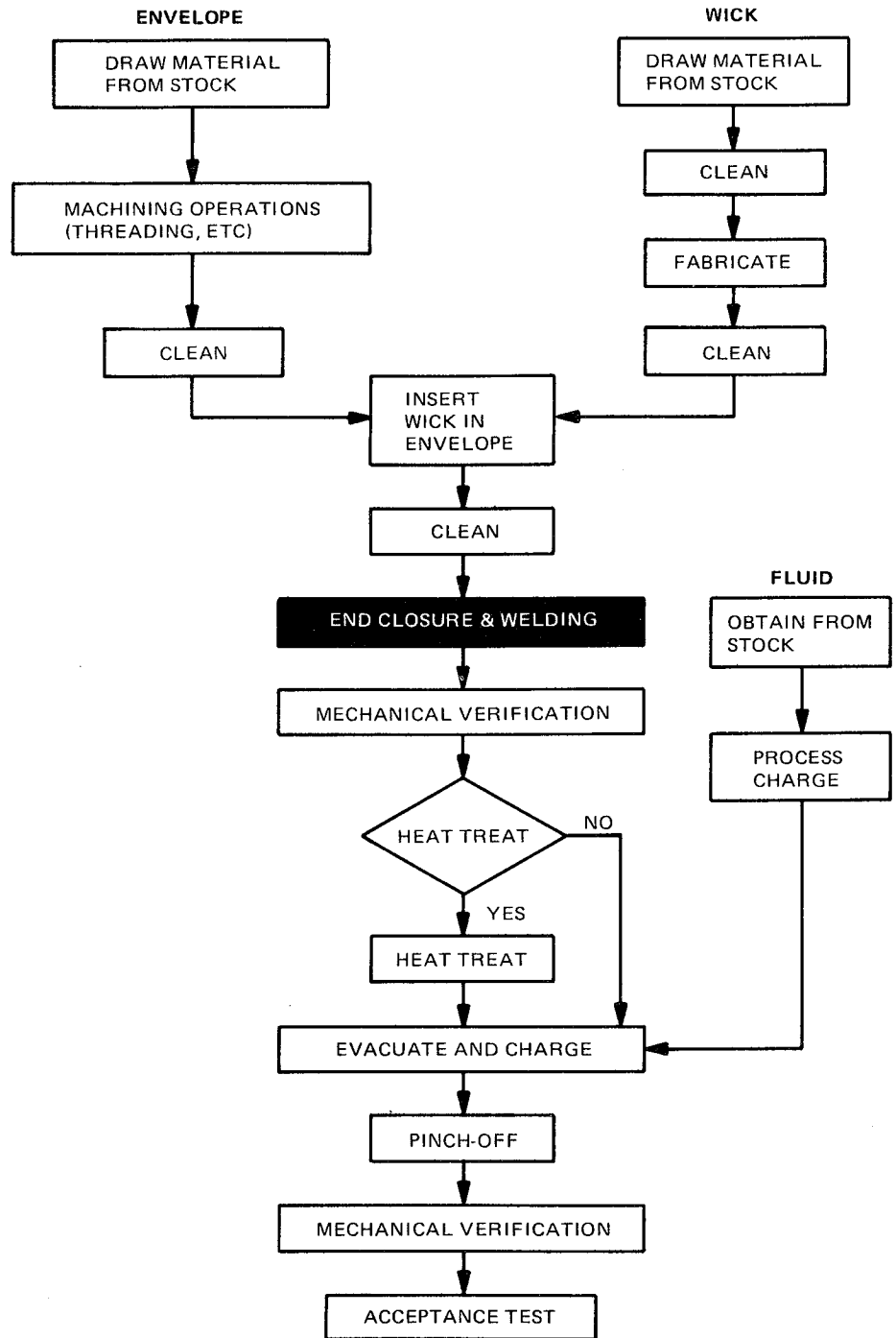
3.4.3 Stainless steel wicks. - Little information was available to evaluate and recommend acceptable cleaning procedures for stainless steel arteries.

Grumman has extensively used its cleaning procedure and believes it to be a good method of performing this task. However, this is an area worthy of further effort in future studies.

3.4.4 Other recommendations. - Verification of the recommended procedures, particularly for stainless steel, should be undertaken, preferably by performing long-term life tests on heat pipe envelopes. In these efforts, low temperature testing to detect the presence of noncondensable gas should be included. The inclusion of wicks in the pipes should be avoided to better isolate potential sources of contamination. Subsequent wick tests could then be performed on proven gas-free envelopes.

The cleaning procedure must be as free from operator error as possible, since improperly executed procedures may also lead to unwanted contamination. Training of personnel to the cleanliness requirements of heat pipes is mandatory, along with adequate safeguards and inspection points during the steps of the procedure consistent with good quality assurance practice.

Cleaning and charging operations should be done in fairly rapid sequence so as to avoid the pipe remaining in storage for long duration, where the likelihood of contamination is increased. Similarly, these operations should be in proximity to one another to lessen the danger of contamination during transportation.



4 - END CLOSURE AND WELDING

4.1 Background

Although a seemingly simple operation, end closure and welding has been a problem for many heat pipe manufacturers. Common concern is porosity or cracks in the weld, which can lead to a loss of the working fluid. To minimize the probability of this failure, inspection should be performed to verify the adequacy of the seal. Experience and research indicates that it is not uncommon for heat pipes to fail this inspection, requiring that the closure be repaired. A reliable process can lead, therefore, to a "hit-or-miss" manufacturing cycle, where the welding operation is repeated several times to repair a fault. Obviously, these added steps will adversely impact both time and cost budgets. In keeping with the overall objectives of this study, the "optimum" sealing process should be easy to perform, repeatable, require moderately priced equipment, and be reliable and easy to inspect.

4.2 Structural Considerations

Structural considerations on end cap design are presented in Section 5, Mechanical Verification.

4.3 Joint Designs for Welded Caps

4.3.1 Design considerations. - Detail design of a heat pipe incorporating welded end caps should consider the following points:

- Fusion welding joining processes result in the best combination of joint strength and leak tightness.
- A fully mechanized fusion welding process should be given preference over a manual process. A mechanized process is significantly more consistent with respect to joint quality, e.g., strength, size of heat affected zone, and weld bead geometry.

- The use of the aluminum alloy 6061 or the stainless steel alloy 304L eliminates the need for post weld heat treatment, such as a stress relief anneal to prevent either corrosion susceptibility or embrittlement.
- Joint efficiency is a prime consideration. The 304L stainless steel alloy is not heat treatable and a relatively high joint efficiency in the "as welded" condition can be obtained. A conservative assumption for this alloy is a weld joint strength that is 85% (automatic process) or 70% (manual process) of the minimum strengths guaranteed for the 304L product form in the annealed condition. In the case of the 6061 aluminum alloy, the condition of the material prior to welding and the use of post weld heat treatment must be taken into consideration in establishing weld joint strength. Tubing fabricated from 6061-T6, with wall thicknesses ranging from 0.018 in. (0.046 cm) to 0.500 in. (1.270 cm) possesses a minimum tensile ultimate strength of 42 ksi (2.896×10^8 newt/m²) and a minimum tensile yield strength of 35 ksi (2.413×10^8 newt/m²). The joint strength levels attainable with 6061 are as follows:

Base material & heat treatment	Weld wire	Minimum strength of weld	
		F _{tu} , ksi	F _{ty} , ksi in 2.0 in. gage
6061, -T4, -T6; "as welded"	4043 or 5356	24 (1.655×10^8 newt/m ²)	14 (9.653×10^7 newt/m ²)
6061-T4; welded and aged to -T6 (320°F for 8 hr)	4043	27 (1.862×10^8 newt/m ²)	18 (1.241×10^8 newt/m ²)
6061, -0, -T4, -T6; welded, solution heat treated and aged to -T6	4043	40 (2.758×10^8 newt/m ²)	33 (2.275×10^8 newt/m ²)

The full solution heat treatment of 6061 requires soaking at 980°F (526°C) from 30 min to 75 min (depending upon material thickness, followed by rapid water quenching (spraying) in 100°F (38°C) or cooler water. The use of full solution heat treatment may not be realistic for heat pipe manufacture because of the danger of distortion during quenching or damage to internal details at the soaking temperature.

- The geometry of the weld bead produced by the welding process selected should be known by the designer beforehand since the weld root bead cannot be machined after welding. An excessively large drop through the root bead can interfere with the operation of the heat pipe. Machining of the crown of the weld bead should be avoided. The removal of the skin material of the weld bead crown may expose interdendritic porosity and result in gas leakage from the heat pipe.
- The use of a square butt joint design is preferable.
- The end cap detail should be designed to be self-aligning during the welding operation. The end cap detail can also provide filler metal to the joint.
- The possible damage to interior details of the heat pipe resulting from welding heat should be considered and, if necessary, determined experimentally.

4.3.2 Weld joint designs. - Based on past Grumman experience and available documented information (refs. 16, 17 and 18), the following weld joint designs were selected for investigation:

- Square butt
- Lipped butt (Grumman design)
- 15° bevel groove butt
- Fillet
- Square butt and fillet
- Lap

4.3.2.1 Square butt joint: For dynamic loads, butt welds are the first choice because of their high fatigue life. The greatest dependability of any single joint type is in resisting any specific kind of stress or combination of stresses. The edge preparation

of a square butt joint is the least expensive of the butt joints (Fig. 4-1). Although some special care is required for alignment, the reliability of this design far outweighs this consideration. This weld joint also permits ease of full weld penetration (minimum heat input and minimum loss of mechanical properties) for thicknesses up to 0.100 in. (0.254 cm) ease of seam tracking during welding, cleanliness of the weld deposit, and ease of inspection after welding.

4.3.2.2 Lipped butt joint: For automatic gas tungsten arc (GTAW-TIG) pulsed arc tube welding, a square butt (Fig. 4-1a and 4-1b) or the Grumman-designed lipped butt joint (Fig. 4-2) can be used for end cap or tube welding with controlled weld penetration bead size. As shown, the lipped butt joint design has one member with a lip which acts as a retainer for the other end. For some metals, the lip may serve as filler material that is consumed during the welding operation. Alignment is easier with the lip design than a standard square butt joint.

Machining costs are slightly higher than the standard square butt, but ease of alignment and resulting quality welds justify these costs. Ease of inspection is the same as a standard square butt joint after welding.

This design has been used successfully on both stainless steel and titanium tubes. In general, aluminum alloy 6061 is crack-sensitive when welded with 6061 filler and, therefore, the use of the lipped butt joint design on this material is cautioned. However, 6061 has been successfully welded without the use of different filler material by using a high pulse frequency in conjunction with a square butt joint design (ref. 19). Also, Bell Aerosystems Co., Niagara Falls, New York uses a flared lip design without filler material which is apparently successful.

An alternate design for welding aluminum 6061 is the use of a 4043 filler insert (Fig. 4-3). This design provides both self-alignment and proper filler material. It is fairly inexpensive and, like the square butt joint designs, is easy to inspect. The design of the insert is a function of the tube thickness, and would have to be worked out for different size pipes.

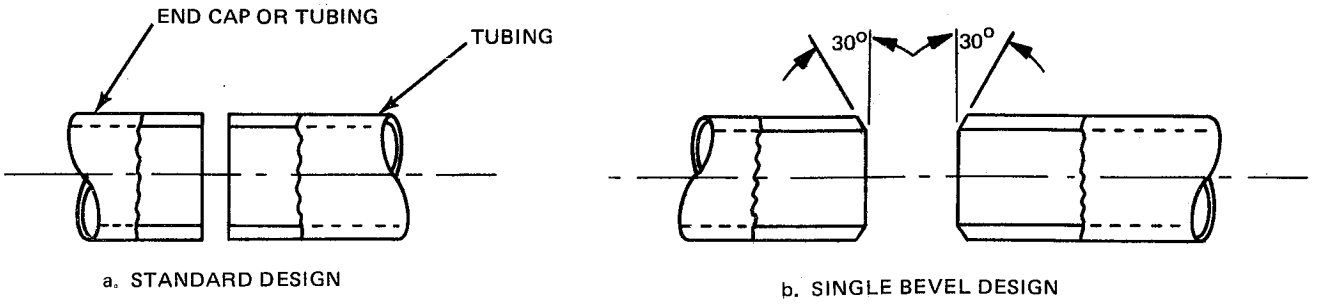
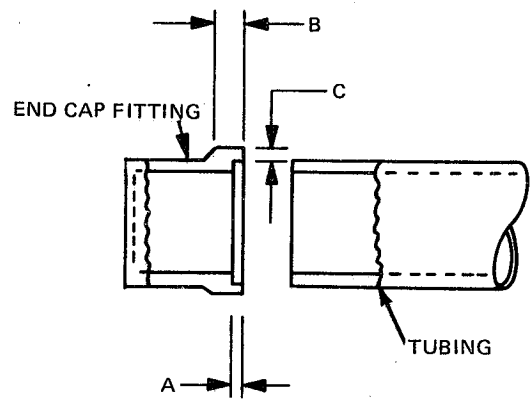


Fig. 4-1 Square Butt Joint Designs



NOTE: DIMENSIONS A, B & C DEPEND ON ON WALL THICKNESS

Fig. 4-2 Lipped Butt Joint Design

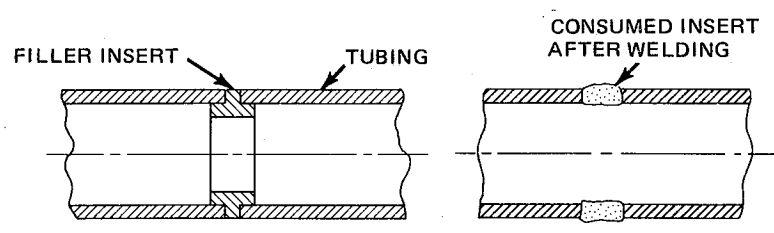


Fig. 4-3 Square Butt Joint with Consumable Filler Insert

4.3.2.3 The 15° bevel groove butt joint: This weld joint design (Fig. 4-4) has been used for ease of alignment. Its disadvantages are: additional machining costs, difficulty in obtaining full penetration, and difficulty of inspection after welding.

4.3.2.4 Fillet: This weld joint design (Fig. 4-5) has been used where a minimum of edge preparation is required or by beveling for thicknesses above 0.100 in. (0.254 cm). With this joint design, full root penetration is not always possible and inspection after welding is difficult.

4.3.2.5 Square butt and fillet: This combination of joint designs (Fig. 4-6) has been used for end cap welding by various heat pipe manufacturers. Although additional costs are necessary to manufacture the detail parts, this may be justified by the ease of alignment for welding. In addition, this design has been used where minimum weld protrusion beyond the pipe envelope is required. However, experience indicates that full weld penetration is difficult to achieve using this design. This incomplete weld penetration is undesirable since it causes a built-in crack which, although leak tight, is suspect to failure under cyclic pressure loads.

4.3.2.6 Lap: This weld joint (Fig. 4-7) is used in applications where fit-up is a problem and/or repair needs to be done for a tube weld joint only. Welding is accomplished by welding through the two tube wall thicknesses, or through one tube wall thickness and partially into the second tube wall. A standard square butt joint should be used for these cases whenever possible, if fit-up and time permit.

4.4 Welding Processes

A number of factors influence the choice of a welding process for a given application. In some instances, two or more processes may prove equally efficient for a given application. Usually, the preferred process is the one which will produce the required quality welds at the most economical level. Selection of the welding process should be made after evaluation of the basic factors involved, which include the following:

- Alloy material to be welded
- Wall thickness of tubing
- Cost of welding equipment and supplemental tooling
- Availability of present equipment
- Economic justification for new equipment

- Specification requirements
- Design requirements:
 - Mechanical properties
 - Type of joints
 - Accessibility
 - Appearance
 - Inspection.

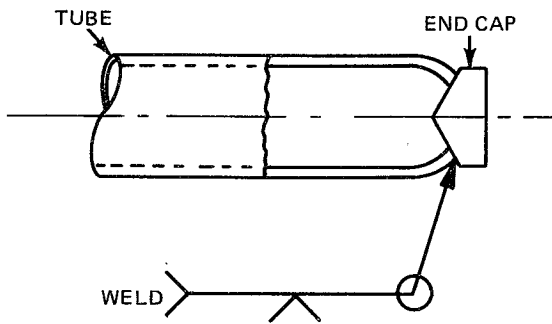


Fig. 4-4 15-Degree Bevel Joint Design

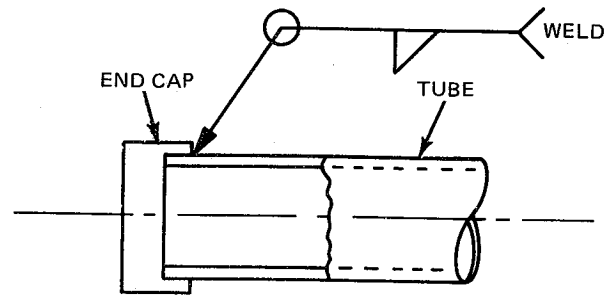


Fig. 4-5 Fillet Joint Design

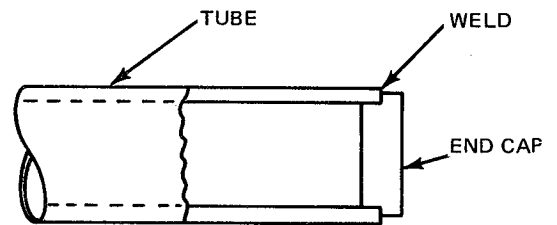
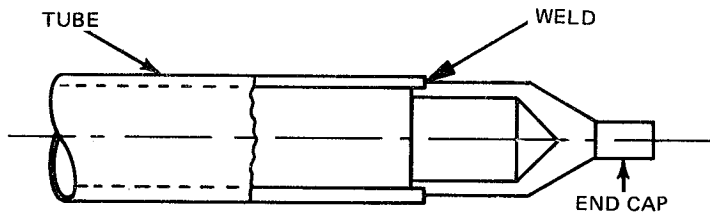


Fig. 4-6 Square Butt and Fillet Joint Designs

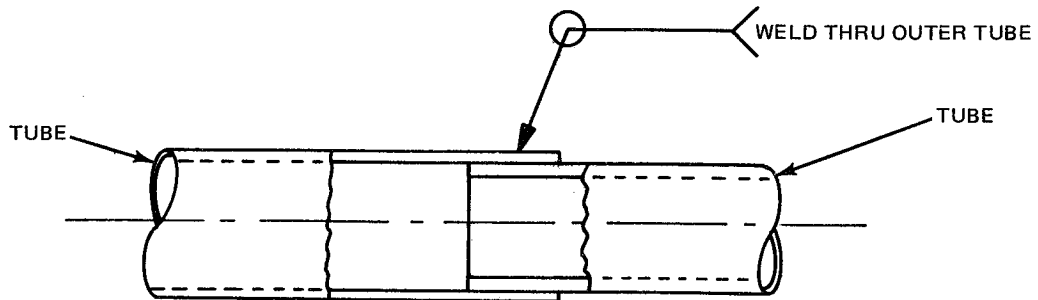


Fig. 4-7 Lap Joint Design

4.4.1 Characteristics of different welding processes. - As stated earlier, the materials under consideration in this effort for heat pipes and caps are 6061-T6 aluminum alloy and type 304 stainless steel. Both alloy and temper influence the choice of the welding process. The metallurgical changes introduced by the heat of welding affect the ultimate mechanical properties of the material. It was decided that the most suitable processes for heat pipe and end cap welding are gas-tungsten-arc manual and automatic (GTAW or TIG), electron beam (EBW), and the plasma-arc processes (PAW) - stainless steel only. Table 4-1 presents a technical comparison of these processes. As shown, all four can be used for end cap or tube welding. However, based on our evaluations we recommended that the orbital automatic GTA pulsed-arc welding process be used whenever possible. From a technical viewpoint, the automatic GTA tube welding machine permits repeatability of production weldments and quality welds with a very low rejection rate (refs. 19, 20, and 21). As will be discussed later, this process is also economical when considering both initial welding cost and the consistency of high quality weldments. Photographs of an orbital automatic GTA welder and its power supply are shown in Fig. 4-8 and 4-9.

4.4.2 Weld-heat affected zone. - Most welding engineers agree that parts to be joined should be designed with the fewest welds possible. The principal reason being that welding heat adversely affects mechanical properties of all metal alloys in the weld zone. The strength in the weld area is usually less than that of the unaffected parent metal. While welds in sections which are in the annealed (softened) condition do not change the strength of the material, the cast-structure of the weld metal may result in lower strength than that of the parent metal. Frequently, joint strength efficiency can be improved by increasing the welding speed to minimize the weld heat input and degradation of the parent metal.

The EB welding process offers minimal heat input with maximum thermal density; i. e., equivalent penetrations can be obtained with the narrowest weld and heat-affected zones. Of particular note are the comparisons in Table 4-1 between joint efficiency, joint quality, and distortion. Joint efficiency relates to both tensile and fatigue efficiencies with weld bead reinforcement removed. To date, EBW is the only known

TABLE 4-1. - COMPARISON OF WELDING PROCESSES FOR ALUMINUM AND STAINLESS STEEL HEAT PIPE WELDMENTS

Characteristic	GTA manual	GTA automatic	EBW	PAW (stainless only)
Thickness joined, in. (cm)	0.030-0.50 (0.076-1.270)	0.015-0.10 (0.038-0.254)	Foil to 2.00 (5.08)	Foil to 0.50 (1.270)
Joint design constraints	Any design	Square butt	Any design	Any design
Welding speed, in./min	4-8	8-20	30-80	5-25
Uniform penetration	Good	Excellent	Good	Excellent (key hole)
Width of heat affected zone in. (cm)*	Medium 0.050-0.100 (0.127-0.254)	Narrow 0.040 max (0.102)	Very narrow 0.015 (0.038)	Medium
Depth-to-width ratio	Less than 1 to 1	2 to 1	15 to 1	1.5 to 1
Tolerance to mismatch, in. (cm)	Excellent ~0.030 max (0.076)	Good ~0.015 max (0.038)	Fair 0.010 max (0.025)	Excellent
Type of shielding	Torch gas & trailing shield	Torch gas & trailing shield	Vacuum chamber	Torch gas & trailing shield
Joint efficiency, %	60-70	85-95	95-100	80-95
Weld quality	Good	Excellent	Excellent	Excellent
Reproducibility	Good	Excellent	Excellent	Excellent
Distortion	Medium	Very low	Very low	Medium-low
Production quantities, No.	Limited (up to approx 15)	Limited & large (>15)	Limited & large (>15)	Limited & large (>15)
Control of weld bead penetration	Fair	Excellent	Good	Excellent
Accessibility to execute weld	Good	Good	Fair	Good
Ease of making circumferential welds	Good	Excellent	Fair	Excellent

*Values shown are typical for aluminum with wall thickness up to approximately 0.063 in. (.160 cm). For stainless steel these values would be less.

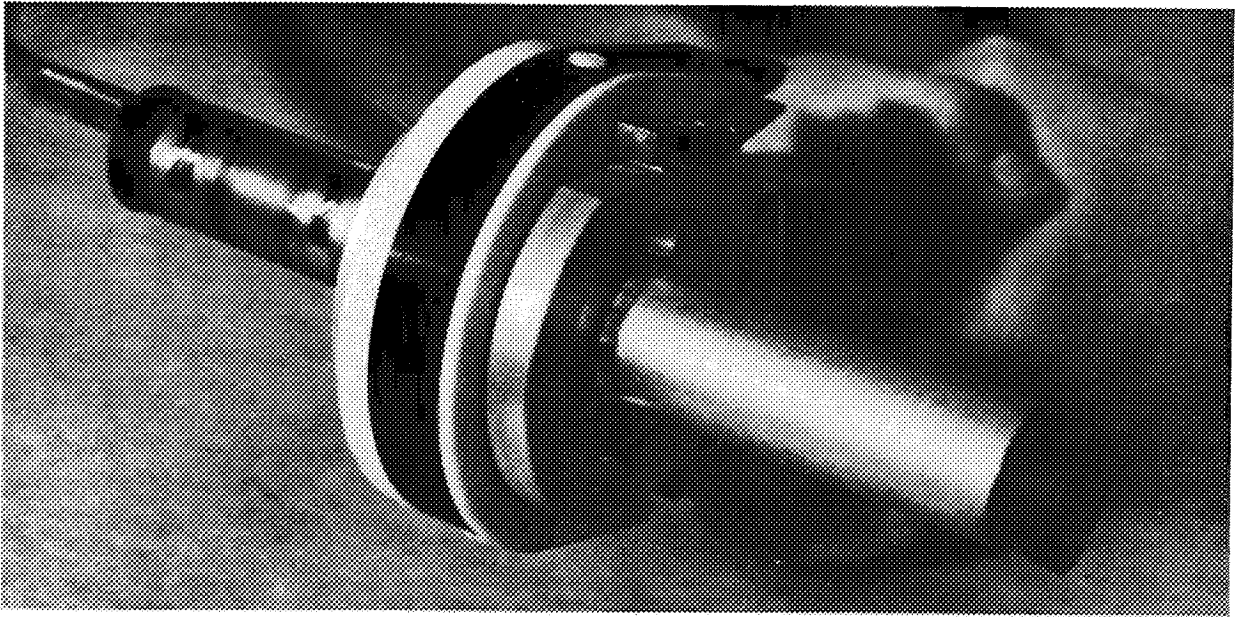


Fig. 4-8 Orbital Welding Head

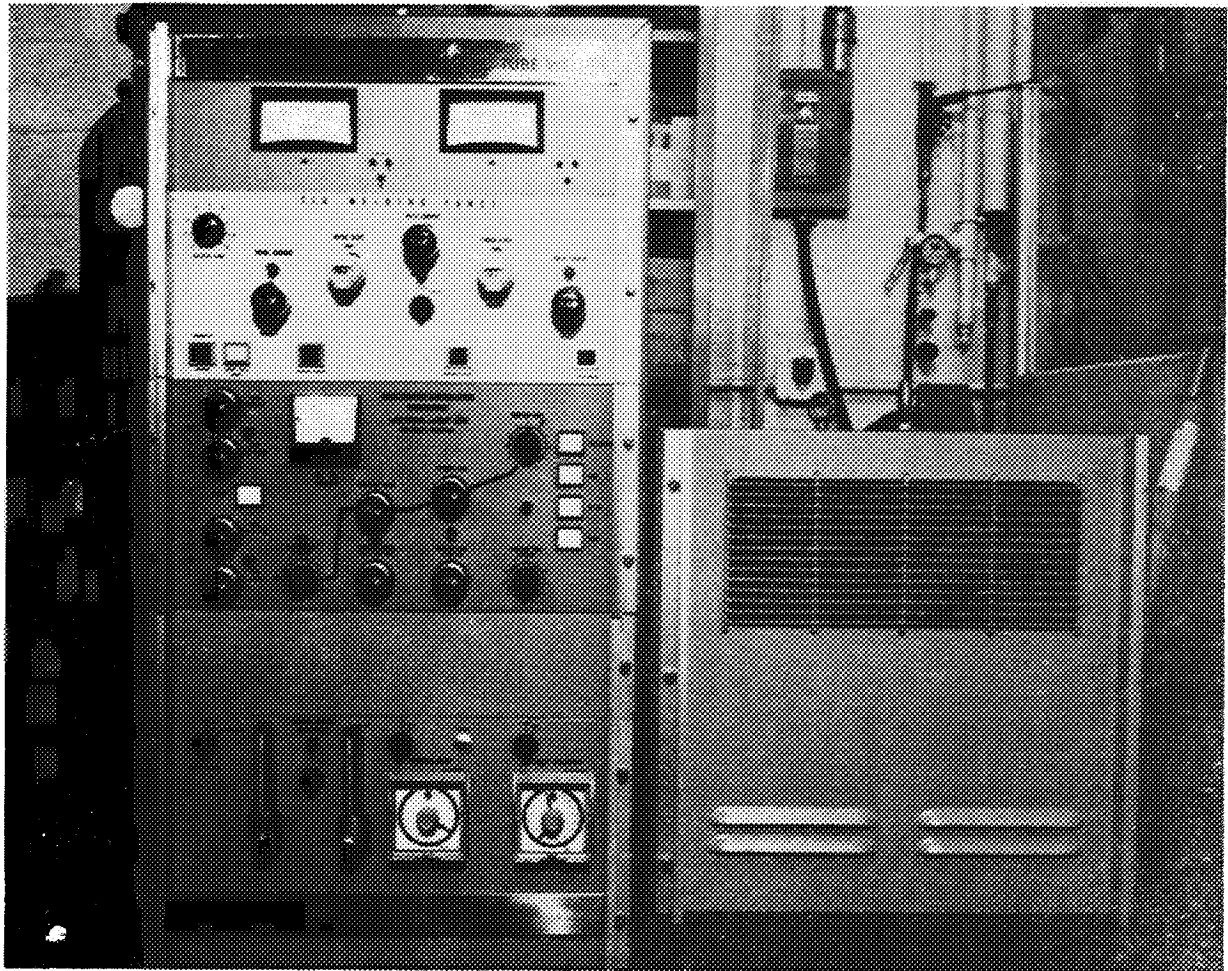


Fig. 4-9 Orbital Welding Power Supply

welding process that has joint efficiencies in fatigue approaching base metal properties. The plasma arc process weldments give joint efficiencies of 80 to 90% of base metal properties. By comparison, the relatively larger amounts of heat used in GTA (TIG) pulsed-arc welding produces a medium width heat-affected zone with some subsequent loss in mechanical properties. The loss of mechanical properties in GTA (TIG) pulsed-arc welded pieces may be as much as 15 to 30% for end cap and tube weldments in material thicknesses under 0.100 in. (0.254 cm) thick. The higher losses would be for the aluminum alloy weldments.

4.4.3 Cost

4.4.3.1 Equipment, manpower and accessories: For some applications, gas-tungsten-arc (GTA-TIG) welding may be the only technically acceptable welding process for the conditions under which the welding can be accomplished. Manual gas tungsten arc (GTA) welding has the versatility and flexibility that, coupled with the low capital equipment outlay, provides a useful tool for small quantity prototype fabrication. Table 4-2 presents a comparison of the cost of several welding processes. From the items in Tables 4-1 and 4-2 it can be seen that the manual gas-tungsten-arc welding (GTA) equipment has the lowest capital investment and is the most versatile and flexible process for welding prototype end cap components. The initial investment for electron beam welding equipment is very high. Since the end cap weldments are made from stainless steel (304) and aluminum alloy (6061-T6), quality welds can be made using the GTA welding process (manual or automatic). The electron beam process can be used if a higher weld quality is desired and justified on the basis of a particular designed application. In general, however, most heat pipe applications do not justify the added expense of the EB welding process.

4.4.3.2 Production vs limited quality runs: Although manual gas tungsten arc welding is least costly for limited production, quantity production dictates that the automated processes be considered. In general, the most acceptable processes for production runs are the automatic, pulsed-arc GTA, or EB welding processes. The additional tooling costs incurred using these operations is justified where a large

TABLE 4-2 - WELDING COSTS

		GTA manual	GTA automatic	EBW	PAW ^a
Typical equipment cost, \$		2,000	20,000	50,000	2,000 (manual)
Welding fixturing ^b		Minimal (2)	Low (16)	Low (16)	Minimal (8)
Labor cost		Low	Low	Low	Low
Welding cost of consumables (power, shielding gases, etc.)		Low	Low	Moderate	Low
Welding time ^c	Set up	5 - 10 min	5 - 10 min	30 min	5 - 10 min
	Welding	2 min	1/2 min	1/2 min	2 min

^aStainless steel only

^bThe values shown are approximate manhours required to design and fabricate fixturing for welding 1/2 in. (1.270 cm) tube

^cApproximate time for welding 1/2 in. (1.27 cm) tube. Setup time includes alignment of welding head, gas purging, pumpdown (for EBW), etc.

number of welds is required. For stainless steel welding, the plasma arc process can be used as a substitute process for either GTA or EB welding. Generally, however, automatic GTA welding is preferred from a quality (refs. 19, 20, and 21) and cost-effective standpoint.

4.4.3.3 Manual vs automatic GTA welding: For small prototype quantities of heat pipe weldments, the most economical and versatile welding process would be the manual gas-tungsten-arc (GTA-TIG) process. For quantities of five or more weldments, however, the automatic GTA process should be used since the cost of holding fixtures and equipment setup time would be justified. The use of automatic pulsed-arc

GTA tube welding equipment of F-14A titanium alloy hydraulic lines that were bench welded has shown a rejection of less than 1% in over 4000 tube-to-tube, and tube-to-fitting weldments (ref. 20). The lipped-butt weld joint was used for these weldments. Tube wall thicknesses were up to 0.10 in. (0.254 cm). The same results (low rejections) could also be obtained with the stainless steel weldments. Rejections for aluminum alloy weldments would probably be higher (5%) because of the tendency of aluminum alloys to form porosity to a larger extent than titanium alloys or stainless steel. However, as aluminum alloy techniques are developed, this value will decrease.

4.4.4 Inspection. - In general, inspection of detail parts should be performed prior to welding, during the welding operation and following the process.

4.4.4.1 Prior to welding: Inspection of detailed parts for dimensional requirements should be per the latest engineering drawing. Requirements for preparation of the detail parts prior to welding should be given in a detailed welding specification, similar, for example, to the Grumman Standard Specification, GSS6206A "Automatic Fusion Welding of Titanium and Stainless Steel Tubing." This specification is included as an illustration in Appendix B. For aluminum tube welding, scraping prior to welding is recommended (ref. 19).

4.4.4.2 Actual welding operation: The requirements for the type of welding equipment, qualification of welding operators and equipment, development and certification of welding parameters and weld schedules, testing of weldments, and requirements to meet engineering drawings should be given in a welding specification.

4.4.4.3 Finished connection: The finished connection should meet the requirements of the engineering drawing. The requirements for testing (tensile, flexure, fatigue, pressure) of the weldment, the quality of the weldment, rejection and repair criteria should be outlined in a specification.

4.5 Conclusions and Recommendations

Table 4-3 presents Grumman's recommendations for end closure design and welding of stainless steel 304L, titanium, and aluminum 6061. As shown, for both stainless steel and titanium the lipped-but joint weld (Fig. 4-2) has been selected. Because a different alloy filler material is required, this design has been judged unsatisfactory for aluminum; a square butt joint with a consumable filler insert (Fig. 4-3) is recommended. This design is also suggested for certain stainless steels (such as 316) and nickel base alloys where a filler material of different composition than the tube material is required. Basically, the above designs have been selected after consideration of the following parameters:

- Ease of alignment
- Ease of inspection
- Convenience of providing filler material
- Provides consistent weld quality.

Special design requirements such as minimum weld protrusion, limited access for welding, etc, may necessitate the use of other designs previously discussed.

The orbital automatic gas tungsten arc welder has been judged the most acceptable process for all heat pipe applications. It is fairly inexpensive - requiring

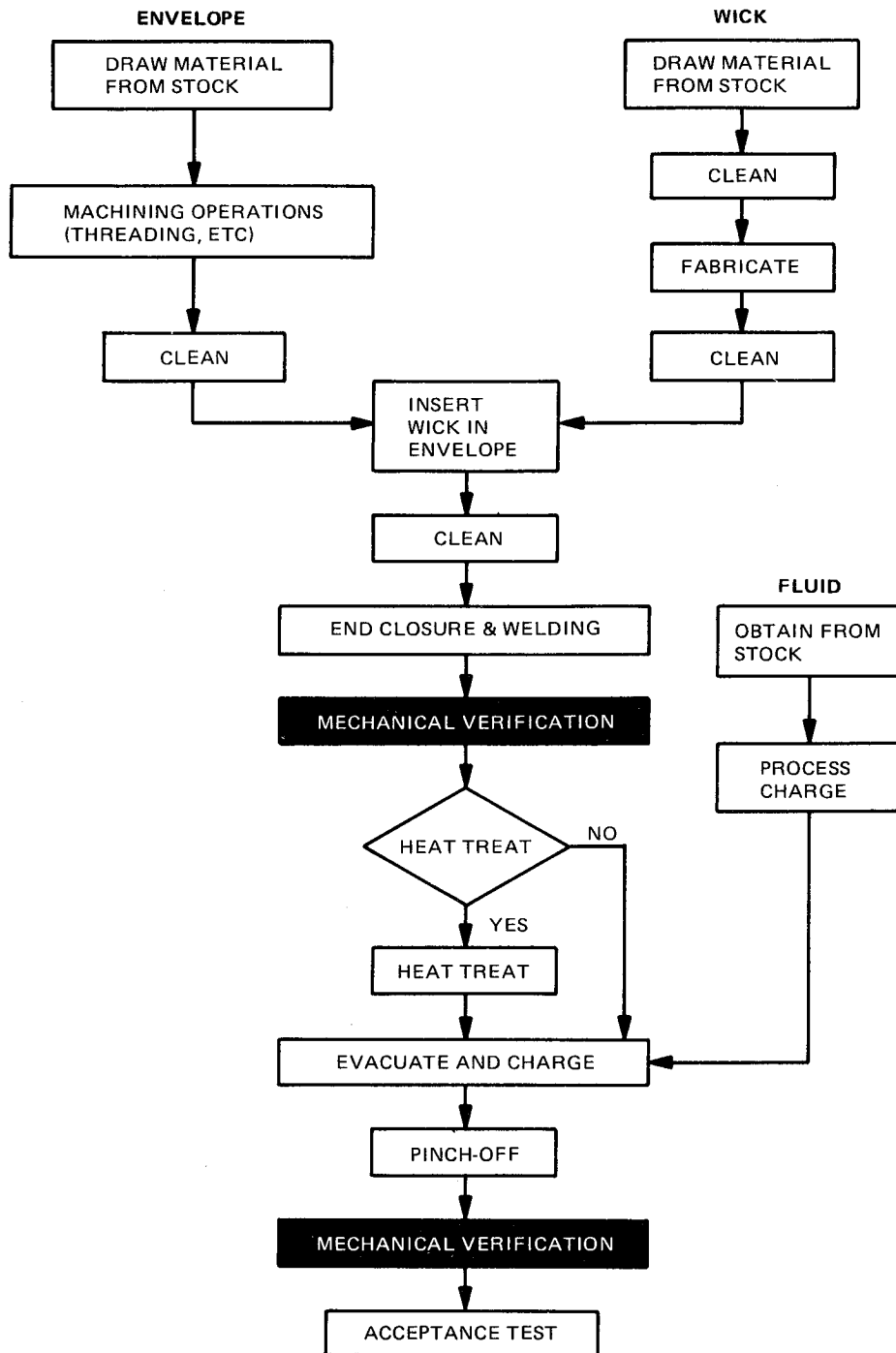
TABLE 4-3. - END CLOSURE AND WELDING RECOMMENDATIONS

Material	Weld joint design	Weld process	
		Prototype (1 - 5 units)	Limited and quantity production (greater than 5 units)
Stainless steel 304L and titanium	Lipped butt joint	Manual or automatic gas-tungsten-arc	Automatic-gas-tungsten-arc
Aluminum 6061	Square butt		

moderately priced equipment; it is easy to use, reliable, and produces high quality welds consistently. For prototype quantities (1 to 5 units), the manual gas-tungsten-arc process may serve as a viable alternate. It is flexible, fast, and uses inexpensive equipment probably available in all manufacturing facilities.

Detailed inspection is mandatory before, after, and during welding operations. The designer must consider this requirement in selecting his choice of joint and welding equipment. To satisfy this objective, a welding specification should be prepared which thoroughly documents inspection requirements.





1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

5 - MECHANICAL VERIFICATION - STRUCTURAL DESIGN AND LEAK DETECTION

5.1 Background

A sound structural design that has been properly verified by nondestructive tests is paramount to reliable, long-term heat pipe operation. The heat pipe envelope must maintain its structural integrity throughout its design life if it is to operate as planned. The cleanest, most thermally efficient heat pipe will fail in its mission if it loses working fluid due to a slight leak, or sudden structural failure. Such a failure in flight would decrease the overall reliability of an experiment package or spacecraft; at worst, it might result in the complete loss of the hardware. If a catastrophic failure occurred on the ground it might present a hazard to personnel.

The ultimate goal of this section is to ensure successful structural designs for heat pipes. This section has been treated as two separate sub-topics: structural design and analysis, and leak detection. In the structural design and analysis discussion, a standardized ASME code is recommended when specifying allowable design stresses, proof pressures, and burst pressures. Curves are presented which allow the user to quickly estimate required thicknesses of the pipe wall and end cap. It also gives the procedures necessary to expand the scope of the preliminary stress analysis beyond just checking the hoop stress. Simplified methods are given for including the stress effects due to end caps, thermal expansion, saddle attachments, pipe bends, and dynamic loading. By knowing these stresses the heat pipe designer can identify potential problem areas early, thereby eliminating several costly iterations in the normal design cycle. The second half of this section concerns leak rates and leak detection techniques. Realistic leak rate specifications that are not overly restrictive are an important consideration when attempting to minimize manufacturing costs. Various leak detection techniques commonly used by HP manufacturers to verify structural integrity are described. They cover wide ranges of simplicity, cost, and sensitivity. Most are acceptable (but not necessarily recommended) for use.

5.2 Structural Design and Analysis

5.2.1 Introduction. - In the following paragraphs, methods of structural analysis directly applicable to strength calculations for heat pipes are outlined for use by heat pipe personnel. Much of the discussion is concerned with pointing out basic strength requirements and problem areas, rather than carrying out a detailed stress analysis procedure. The methods presented, therefore, are useful for a preliminary structural design of a heat pipe. For actual flight hardware, however, a comprehensive structural analysis and design performed by a cognizant stress engineer would be required.

As a ground rule, the design approach for tubes subject to internal pressurization follows that of the ASME Boiler and Pressure Vessel Code, 1965 - Section VIII, "Unfired Pressure Vessels" (ref. 22). The code was selected as the design guide on the basis of its general acceptance in commercial and governmental areas of pressure vessel application.

As per this reference, a factor of safety of 4 on ultimate strength was used. Although some NASA criteria (refs. 23 and 24) do specify lower factors of safety, it is recommended that the higher safety factor be used because of certain heat pipe characteristics which are different from the usual aerospace structures. First, heat pipes are handled and transported in the charged condition, and Federal regulations (refs. 25 and 26) require that pressurized containers shipped by commercial transportation conform to the ASME code. Undoubtedly, this requirement is partly motivated by interest in personnel safety. Secondly, heat pipes are generally not "high technology" items and consequently, extensive structural analysis, design verification testing, and manufacturing quality assurance are not performed, as is the case with the typical aerospace structure. The ASME code also provides a method for experimentally determining the allowable operating pressure when the strength is difficult to calculate (as, for example, pinched-off fill tubes.)

Some of the fracture mechanics aspects of pressure vessels discussed in NASA SP-8040 (ref. 27) are included in the discussion. Additional topics such as local bending stresses at the end caps, the effects of integral saddles, restraint of thermal expansion, and dynamic response are also considered.

5.2.2 Environment. - In general, a heat pipe is subjected to two environments: internal pressure and temperature, and external (induced) loads.

5.2.2.1 Internal pressure and temperature: the primary specification for a heat pipe is the capability of carrying a prescribed thermal load within a specified thermal environment. For a given working fluid, this dictates an internal operating pressure and temperature which may be relatively constant, or have a cyclical variation. These are referred to as the normal operating conditions. Other conditions could occur as a consequence of off-design operation, system malfunction, shipping environment, etc., for which the heat pipe must maintain structural integrity. These latter conditions are usually more severe than the normal operating condition, and the most critical of these is designated the maximum operating condition.

5.2.2.2 Induced loads: in addition to the operating conditions, a heat pipe is also subjected to an induced load environment which could consist of vehicle accelerations, vibrations, and shock. These could occur during shipment, handling, and launch or staging (for aerospace applications), and result in an inertia loading of the heat pipe. Loads due to mounting restraint could also be imposed. These restraints can vary from a complex multipoint support such as in the OAO spacecraft, to a relatively simple support such as the north-south panels of the ATS spacecraft. From the structural analysis viewpoint, these induced loads are equivalent to axial and bending loads being imposed on a heat pipe. The heat pipe structure must be able to sustain these loads without failure or degradation in performance for a prescribed lifetime.

5.2.3 Material properties and allowable stresses. - Since heat pipes are often shipped via commercial carriers, it is recommended that the ASME Boiler and Pressure Vessel Code, 1965 (ref. 22) be the principal source of material properties and

allowable stresses for use in the structural analysis and design of heat pipes. Additional information can be obtained from MIL-HDBK-5B (ref. 28).

The ASME code specifies that the maximum allowable stress at any temperature be one-quarter of the material ultimate tensile strength, F_{tu} , at that temperature. Material properties and allowable stresses for the two most commonly used heat pipe materials (6061-T6 aluminum alloy and 304 stainless steel) are given in Table 5-1. These values were excerpted from the ASME code; similar tables can be constructed for other ductile materials listed in MIL-HDBK-5B for military or aerospace applications.

Allowable stresses for welded tubing are also given in Table 5-1. The ASME code specifies that welds of the type which would be used on heat pipes shall be double-welded (i.e., both sides), fully radiographed butt joints. The allowable stresses in Table 5-1 refer to this type of weld. The code permits the use of single-welded, fully radiographed butt joints if they can be shown to be of the same quality as the double-welded joints. Since the quality of single-welded joints in thinner gage materials can be shown to have the same quality as double-welded (and since double welding is completely impractical on small-diameter tubes), single-welded, fully radiographed butt joints discussed in Section 4 are considered to have a strength equal to that of a double-welded joint.

5.2.4 Design criteria

5.2.4.1 Pressurized tubes - analysis: The ASME pressure vessel code (ref. 22) limits the maximum operating pressure in a vessel to the pressure at which the most critical part reaches one quarter of the material ultimate tensile strength, F_{tu} . The vessel can have different operating pressures at different temperatures. Each vessel must also be tested (proof pressure) to 1.5 times this maximum operating pressure without observable deformation or leaks. In addition, the code lists formulae for use in calculating allowable pressures and stresses. These relations are modifications

TABLE 5-1. - MAXIMUM ALLOWABLE STRESSES

	Ultimate tensile strength, F_{tu} at 100°F	Tensile yield strength, F_{ty} at 100°F	Maximum allowable stress at temperature, ksi				Modulus of elasticity, E	Coefficient of thermal expansion
			100°F	150°F	200°F	400°F		
Aluminum drawn tube (seamless) ^a								
• 6061 -T6	42 ksi	35 ksi	10.5	10.2	9.9	—	10.5x10 ⁶ psi	13.0x10 $\frac{-6 \text{ in.}}{°\text{F}}$
• 6061 -T6 welded ^b	24	(14) ^d	6.0	5.9	5.7	—		
• 6063 -T6	33	28	8.25	7.8	7.5	—		
• 6063 -T6 welded ^b	17	(11) ^d	4.25	4.20	4.0	—		
Aluminum seamless pipe and extruded tube ^a								
• 6061 -T6	38 ksi	35 ksi	9.5	9.2	9.0	—	10.5x10 ⁶ psi	13.0x10 $\frac{-6 \text{ in.}}{°\text{F}}$
• 6061 -T6 welded ^b	24	(14) ^d	6.0	5.9	5.7	—		
• 6063 -T6	30	25	7.5	7.1	6.8	—		
• 6063 -T6 welded ^b	17	(11) ^d	4.25	4.2	4.0	—		
High alloy steel ^c seam- less pipe and tube								
• TP 304 (18-8)	75 ksi	35	18.75	17.85	17.00	15.45	29x10 ⁶ psi	8.5x10 $\frac{-6 \text{ in.}}{°\text{F}}$
• TP 304L (18-8)	70	35	17.50	17.25	17.00	15.00		

^aExcerpted from Table UNF-23 of Section VIII, ASME Unfired Pressure Vessels (ref. 22)

^bThese allowables apply to doubled welded, fully radiographed butt joints as per the ASME code. Refer to discussion in materials section.

^cExcerpted from Table UHA-23 of Section VIII

^dFrom reference 29

of the thick-walled (Lame) solution for cylinders and spheres (ref. 30). The thick-walled solutions are listed in Paragraph 5.2.4.1.1, and then reduced to the simplified thin-walled formulae which are sufficiently accurate for the geometry usually encountered in heat pipes, although they are somewhat different than those listed in the code.

For an acceptable heat pipe design, the maximum operating stress must be less than the maximum allowable stress ($0.25 F_{tu}$). The general procedure for determining the maximum operating stress includes separately calculating individual stresses and then adding together those that act at the same time and place and in the same direction. Methods for calculating the most significant stresses encountered in heat pipe applications are given in the following paragraphs. In addition to the familiar hoop stress and axial stress, these include various localized axial stresses due to bends, end caps, saddles, restrained thermal expansion and dynamic (vibration) loading. Table 5-2 summarizes the various stress combinations that must be checked to determine the maximum operating stress in a heat pipe. The checkmarks in each column indicate the stresses that are additive for a particular situation. Although the major contributors are given, the table is not all inclusive and it is conceivable that other combinations can occur that are not listed.

TABLE 5-2. - STRESS CHECKLIST

Stress	Reference section	Possible stress combinations					Design criteria
Hoop	5.2.4.1	✓					<ul style="list-style-type: none"> • f_{max} = largest of the possible combinations • $f_{max} \leq 1/4 F_{tu}$
Axial	5.2.4.1		✓	✓	✓	✓	
Bends	5.2.4.3		✓				
End caps	5.2.4.4			✓			
Saddles	5.2.4.5				✓		
Thermal expansion	5.2.4.6				✓		
Dynamic loading	5.2.4.7					✓	

5.2.4.1.1 HOOP AND AXIAL STRESSES

The maximum hoop stress in a thick-walled cylinder subject to internal pressure, p , is given by the expression:

$$f_{\text{hoop max}} = p(R_2^2 + R_1^2)/(R_2^2 - R_1^2) \quad \text{Thick-walled cylinder}$$

where R_1 and R_2 are the inner and outer radii, respectively. In a thin-walled cylinder, the average hoop stress is simply:

$$f_{\text{hoop}} = \frac{pR}{t} \quad \text{Thin-walled cylinder}$$

where $R = 1/2 (R_2 + R_1)$ and $t = R_2 - R_1$. For $R_2/R_1 < 1.25$, (i.e., thin-walled) it can be shown that the two expressions given above are substantially equal. The axial stress in a thin-walled cylinder is given by the expression:

$$f_{\text{axial}} = \frac{pR}{2t} \quad \text{Thin-walled cylinder}$$

which is one-half the value of the hoop stress.

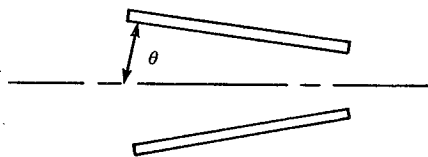
The maximum stress in a thick-walled sphere (e.g., a pipe end closure) is:

$$f = p(R_2^3 + 2R_1^3)/2(R_2^3 - R_1^3) \quad \text{Thick-walled sphere}$$

In a similar manner, this can be approximated by:

$$f \approx \frac{pR}{2t}$$

The hoop and axial stresses due to internal pressure in a thin-walled conical shell (e.g., a reducer) are given by the relations:



$$f_{\text{hoop}} = pR/t \cos \theta$$

$$f_{\text{axial}} = pR/2t \cos \theta$$

Conical shell

In the previous equations, the wall thickness, t , is the minimum net section after all allowances for corrosion, threading or grooving have been made (i.e., subtracted from the nominal internal dimension). The minimum t and maximum R obtainable within manufacturing tolerances should also be used.

Figure 5-1 contains preliminary design curves, for 6061 and 6063 aluminum and 304 stainless steel, which can be used to quickly determine the required tube size when the maximum operating pressure is given. The corresponding radial tube conductance per inch of heat pipe length (BTU/hr-in. $^{\circ}$ F) is given in Fig. 5-2.

As an example, consider the design of a stainless steel heat pipe for a 2200 psi (1.517×10^7 newt/m²) maximum operating pressure at 200 $^{\circ}$ F. From Fig. 5-1, the minimum D_o/D_i for the tube is 1.16. This can be obtained by either a 0.375 in. (0.953 cm) o.d. tube with a 0.028 in. (0.071 cm) wall, or a 0.500 in. (1.270 cm) o.d. tube with a 0.035 in. (0.089 cm) wall. The marks on the wall thickness axis of the figure indicate the most commonly available standard tubing sizes.

Using Fig. 5-2 (Curve A), at $D_o/D_i = 1.16$, the tube wall conductance is determined to be 35 BTU/hr $^{\circ}$ F per in. of tube length (726.60 watts/m $^{\circ}$ K). Assuming an internal film heat transfer coefficient of 2000 BTU/hr ft² $^{\circ}$ F (11348 watts/m² $^{\circ}$ K) for the heat pipe, the internal film conductance is 14 BTU/hr $^{\circ}$ F per in. (290.64 watts/m $^{\circ}$ K) for the 0.375 in. (0.953 cm) o.d. and 19 BTU/hr $^{\circ}$ F per in. (394.44 watts/m $^{\circ}$ K) for the 0.500 in. (1.270 cm) o.d. (Curve C).

Since the conductance values for the wall and the film are the same order of magnitude, the effect of the wall conductance should be included in any subsequent heat transfer calculations. If the wall conductance were an order of magnitude larger than the film conductance, as would be the case with aluminum, it could safely be ignored.

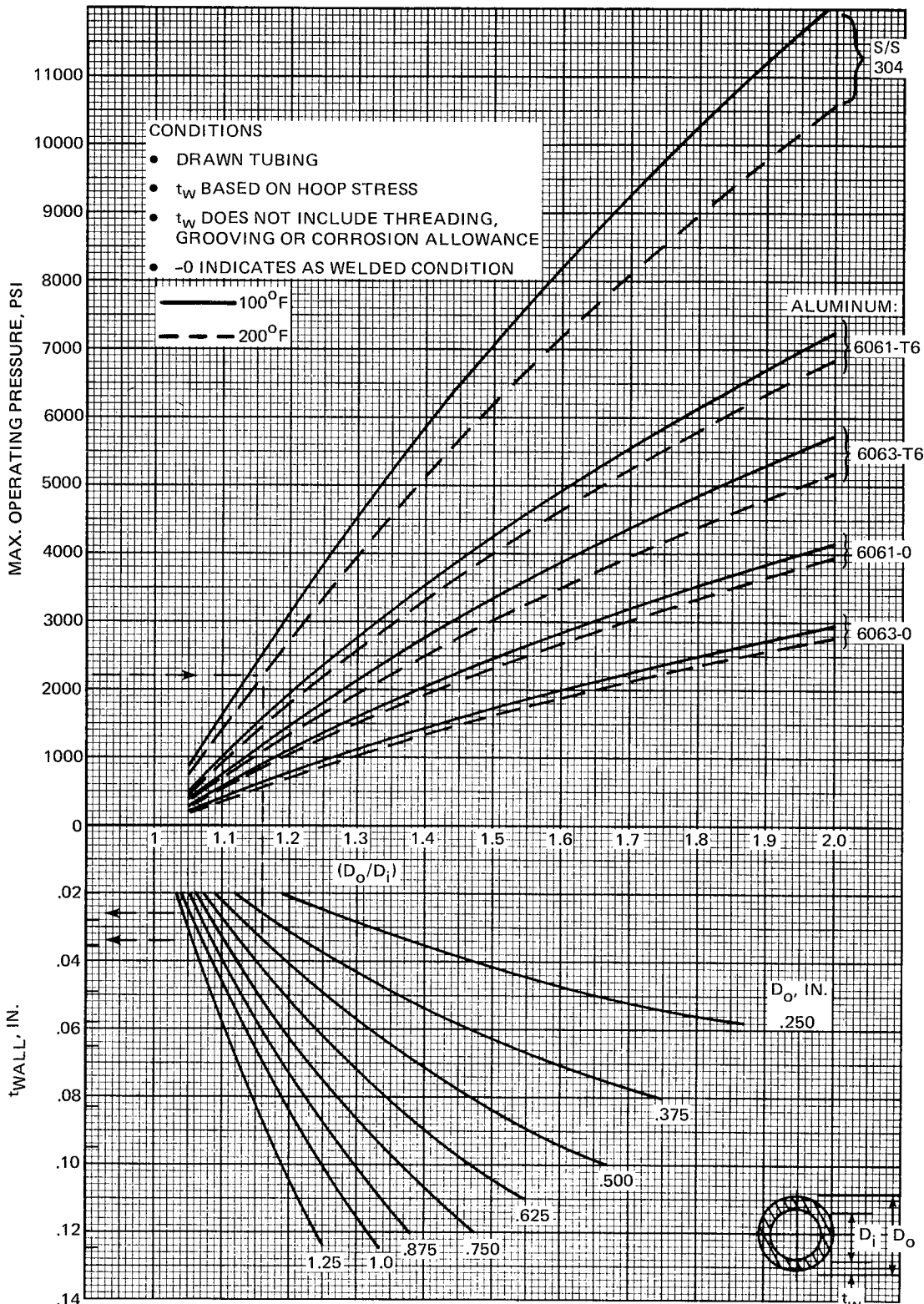


Fig. 5-1 HP Envelope Design Curves

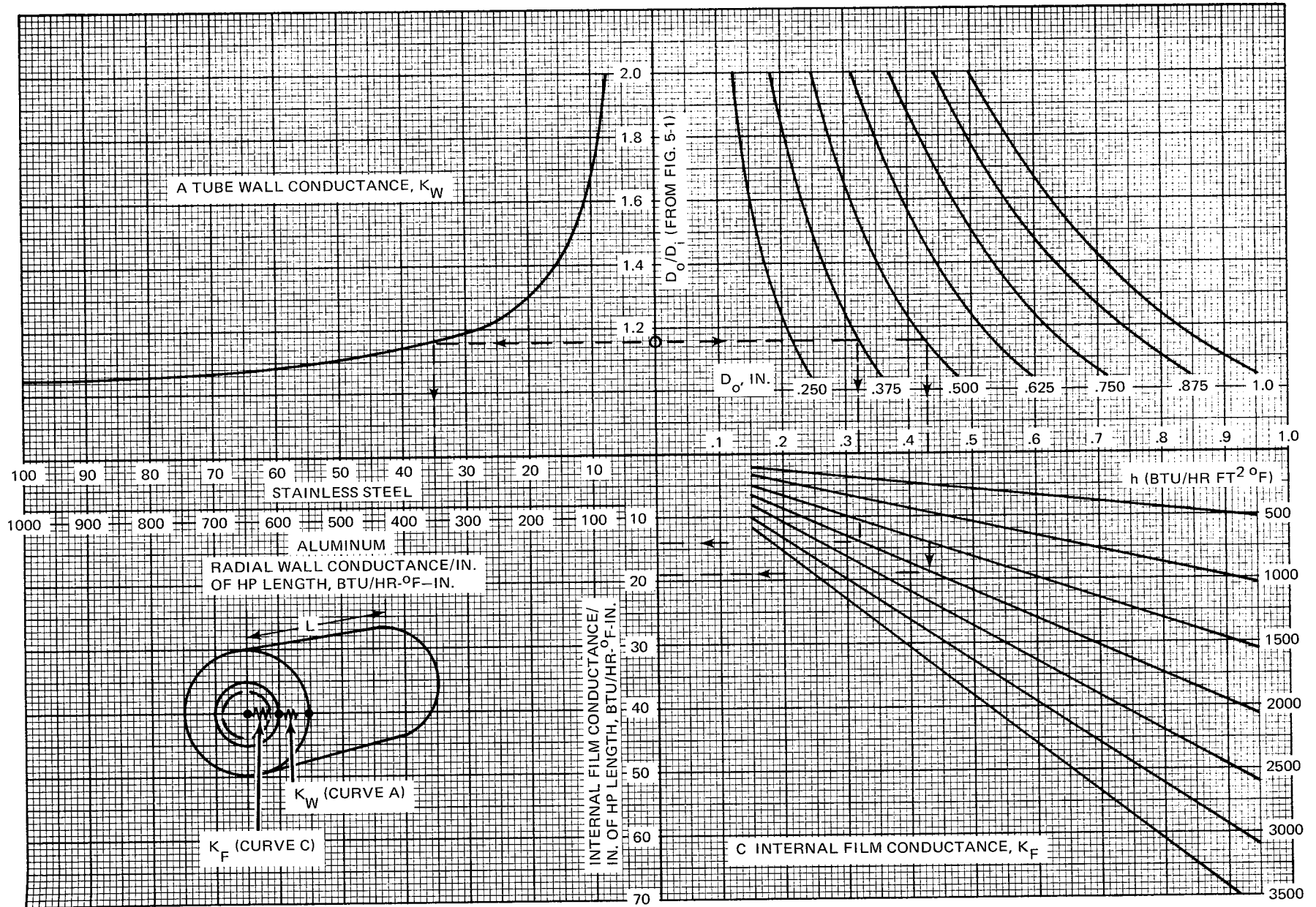
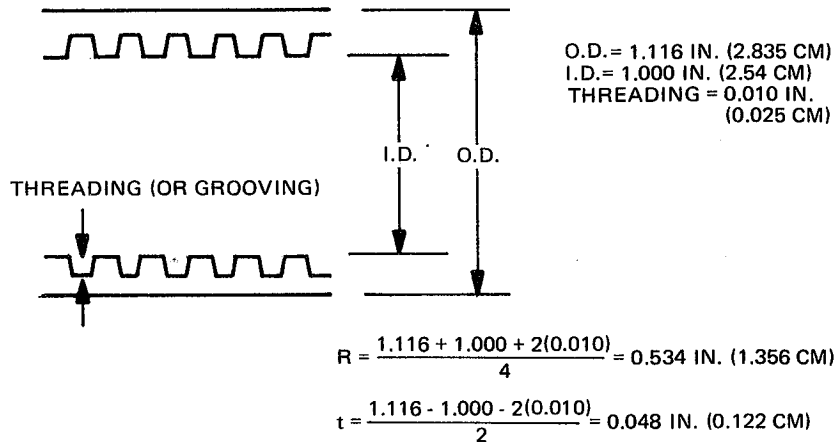


Fig. 5-2 Thermal Conductance Curves

5.2.4.1.2 NUMERICAL EXAMPLES

Example A

It is desired to check the wall thickness of an actual heat pipe. The material is 6061-T6 extruded aluminum alloy welded tube as follows:



The operating conditions are:

- (a) maximum operating pressure, $P_m = 490 \text{ psi (} 3.378 \times 10^6 \text{ newt/m}^2\text{)}$
(ammonia) at $160^\circ\text{F (} 71^\circ\text{C)}$
- (b) normal operating pressure, $p = 230 \text{ psi (} 1.586 \times 10^6 \text{ newt/m}^2\text{)}$ (ammonia)
at $105^\circ\text{F. (} 41^\circ\text{C)}$

The hoop stress is, therefore,

$$f_{\text{hoop}} = pR/t = 490(0.534)/0.048 = 5450 \text{ psi (} 3.758 \times 10^7 \text{ newt/m}^2\text{) at } 160^\circ\text{F}$$

As per the ASME code, the maximum allowable stress for this pipe is:

$$f_{\text{allow}} = 1/4F_{t_u} = 5900 \text{ psi (} 4.068 \times 10^7 \text{ newt/m}^2\text{) at } 150^\circ\text{F (Table 5-1)}$$

and the pipe, therefore satisfies the design criteria. Alternatively, the minimum tube thickness determined from Fig. 5-1 is approximately 0.045 in. (0.114 cm) which is less than the actual thickness of 0.048 in. (0.122 cm).

Example B

For a 304L stainless steel tube, with the following dimensions:

$$\text{o.d.} = 0.375 \text{ in. (0.953 cm)} \quad R = 0.179 \text{ in. (0.455 cm) (average)}$$

$$\text{i.d.} = 0.319 \text{ in. (0.810 cm)}$$

Threading = 0.010 in. (0.025 cm) depth, giving a wall thickness $t = 0.018$ in. (0.046 cm)

The operating conditions are:

- Maximum operating pressure $P_m = 1500$ psi (ammonia) at 260°F , and
- Normal operating pressure, $P = 230$ psi (ammonia) at 105°F .

The hoop stress is

$$f_{\text{hoop}} = (1500)(0.179)/(0.018) = 14,900 \text{ psi (1.027 x 10}^8 \text{ newt/m}^2\text{) at } 260^\circ\text{F (127}^\circ\text{C)}$$

The maximum allowable stress iterated from Table 5-1 is

$$f_{\text{allow}} = F_{\text{tu}}/4 = 16,400 \text{ psi (1.13 x 10}^8 \text{ newt/m}^2\text{) at } 260^\circ\text{F (124}^\circ\text{C)}$$

which satisfies the design criteria.

5.2.4.2 Pressurized tubes - experimental: The ASME code also provides a means of experimentally determining the maximum operating pressure of vessels for which the strength cannot be calculated with a satisfactory assurance of accuracy. These tests cannot, however, be used to obtain a higher value of maximum operating pressure than would be obtained for a vessel for which the strength can be calculated. There are two types of tests which can be used - a proof test, and a burst test. If the material yield strength, F_{ty} , is less than 0.625 of the material ultimate strength, F_{tu} , a burst test must be performed.

The maximum operating pressure can be obtained from the results of a single destructive burst test by the relation:

$$P_m = P_B F_{tu}/5F_a$$

where:

P_m = maximum operating pressure

P_B = actual burst pressure

F_a = average tensile strength of four test specimens taken from the part after failure or from the same billet as the test specimen; or the maximum tensile strength in the material specification

F_{tu} = material tensile ultimate strength

The maximum operating pressure can be obtained nondestructively from the results of a proof test by the relation:

$$P_m = P_P F_{ty}/2F_{ay}$$

where:

P_P = proof pressure

F_{ay} = average yield strength of four specimens taken from the part after test or from the same billet

F_{ty} = material tensile yield strength

If no material property tests are performed, the maximum operating pressure may be obtained from:

$$P_m = 0.4 P_P$$

where the proof pressure, P_P , is defined as the pressure at which permanent set occurs and is determined using strain, or displacement measurements. In this test, strain gages are affixed to the vessel in the hoop direction and the strain recorded as

the function of internal pressure, or the change in diameter at various locations as a function of internal pressure is recorded, to the point of permanent set.

When a corrosion, "threading" or "grooving" allowance has been included in the wall thickness, the proof or burst test result shall be multiplied by $(t - c)/t$ where t is the total wall thickness and c is the corrosion, "threading", and/or "grooving" allowance.

The test results can be corrected for temperature using the relation

$$P_o = P_t F_o / F_t$$

where the subscripts (t) and (o) refer to test and operating conditions, respectively.

5.2.4.3 Pipe bends: Usual shop practice for thin walled tubes calls for a minimum centerline bend radius of three times the tube diameter, with no heat treatment after bending. Since forming a bend involves plastically deforming the tube, a residual stress will remain in the pipe after elastic springback to the final shape. An analysis to determine the actual residual stress is rather complicated, but the value can be conservatively estimated using the methods contained in reference 31 for plastic bending of beams. Based on this document, for thin-walled tubes, the residual stress remaining after elongating the outer fiber to the yield point and ultimate strength of the material are, respectively, 10% of the yield strength and 22% of the ultimate strength of the material. The actual residual stress lies somewhere between these two values and acts in the axial direction. It must be added to the normal axial stress ($Pr/2t$) that is developed in the pipe.

For a 6061-T6 aluminum tube, these estimated residual stress limits are:

$$\text{residual yield} = 0.10 \times 35000 = 3500 \text{ psi}$$

$$\text{residual ultimate} = 0.22 \times 42000 = 9240 \text{ psi}$$

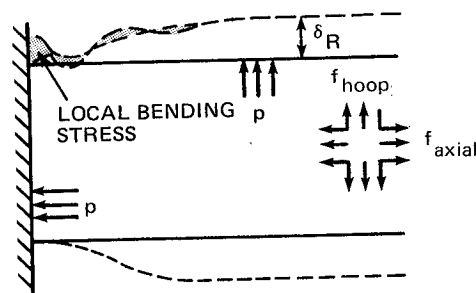
The actual residual stress will be between 3500 psi (2.413×10^7 newt/m²) and 9240 psi (6.371×10^7 newt/m²).

The foregoing criteria for determining the residual stress after bending assumes a smooth-walled tube. If the internal surface of the tube wall is threaded or grooved, a higher than average local strain could be developed in the thinner sections, since these would deform more than the thicker sections.

In actual practice it is recommended that several sample bends be made to determine both minimum bend radius and proper bending speed for the particular tubing in question. If in doubt, a bend radius of five times the tube o.d. has been successfully used as a rule of thumb for threaded aluminum and steel tubing. Table 5-3, extracted from Military standard MS 33611 (ASG), can also be used as a guide for smooth-walled tubing.

5.2.4.4 Local bending stresses at pipe ends: The presence of a cap at the pipe end restrains the radial expansion which occurs in the pipe wall away from the ends. This restraint results in local bending stresses which are maximum at the restraint and die out with increasing distance away from the restraint. The maximum bending stresses for various types of end restraint are determined in reference 32, and are described here.

Consider a pressurized, thin-walled tube attached to a rigid end cap:



FOR INTERNAL PRESSURE

$$f_{\text{hoop}} = pR/t$$

$$f_{\text{axial}} = pR/2t$$

$$\delta_R = (pR^2/Et)(1 - \frac{\nu}{2})$$

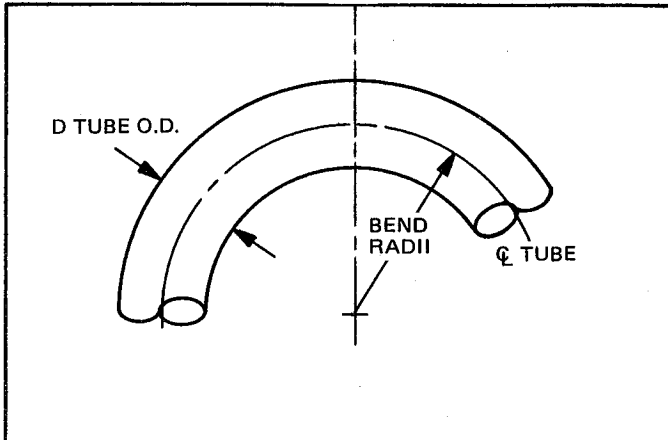
The maximum values of the local bending moment and stress are:

$$M_{\text{max}} = pRt/3.87$$

$$f_{\text{bend}} = 6M/t^2 = 3.10 pR/2t = 3.10 f_{\text{axial}}$$

TABLE 5-3. - TUBE BEND RADII

[Ref: MIL-STD MS 33611 (ASG)]



TUBE O.D.	SPECIAL BEND RADII SEE NOTE ^a		RECOMMENDED BEND RADII SEE NOTE ^b		ADDITIONAL RADII SEE NOTE ^c
	1-1/2D	2D	3D	4D	6D
1/8	0.188	0.250	0.375	0.500	0.750
3/16	0.281	0.375	0.563	0.750	1.125
1/4	0.375	0.500	0.750	1.000	1.500
5/16	0.469	0.625	0.938	1.250	1.875
3/8	0.563	0.750	1.125	1.500	2.250
7/16	0.656	0.875	1.312	1.750	2.625
1/2	0.750	1.000	1.500	2.000	3.000
5/8	0.938	1.250	1.875	2.500	3.750
3/4	1.125	1.500	2.250	3.000	4.500
7/8	1.3125	1.750	2.625	3.500	5.250
1	1.500	2.000	3.000	4.000	6.000
1-1/8	1.688	2.250	3.375	4.500	6.750
1-1/4	1.875	2.500	3.750	5.000	7.500
1-3/8	2.063	2.750	4.125	5.500	8.250
1-1/2	2.250	3.000	4.500	6.000	9.000
1-5/8	2.438	3.250	4.875	6.500	9.750
1-3/4	2.625	3.500	5.250	7.000	10.500
1-7/8	2.813	3.750	5.625	7.500	11.250
2	3.000	4.000	6.000	8.000	12.000
2-1/4	3.375	4.500	6.750	9.000	13.500
2-1/2	3.750	5.000	7.500	10.000	15.000
3	4.500	6.000	9.000	12.000	18.000

NOTES:

- (a) Use of special bends (1-1/2D to 2D) in fluid systems with working pressures of 1500 psi or greater require the approval of the procuring service. Flatness, wrinkle and scratch requirements shall be as specified in Notes (d) and (e).
- (b) Recommended bends (3D and 4D) require no approval and shall be used wherever possible. Flatness, wrinkle and scratch requirements shall be as specified in Notes (d) and (e).
- (c) Additional bends (6D) shall be used only where fabrication or design difficulties preclude the use of recommended bends. Applications do not require specific approval and are limited only by the flatness, wrinkle and scratch requirements provided in Notes (d) and (e).

(d) Flatness limitations

- (1) Flatness in the area of a tube bend shall be defined by the formula:

$$\text{Flatness} = \frac{\text{Max OD} - \text{Min OD}}{\text{Nominal OD}} \times 100 \text{ percent}$$

- (2) Tube flatness for fluid systems with working pressures of 1000 psi or greater shall not exceed 5 percent
- (3) Tube flatness for fluid systems with working pressures less than 1000 psi shall not exceed 10 percent

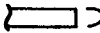
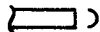

(e) Wrinkles and scratches:

- (1) For fluid systems with working pressures 500 psi or greater, there shall be no wrinkles or kinks deeper than 1 percent of tube OD and no scratches deeper than 5 percent of the nominal wall thickness.
- (2) For fluid systems with working pressures of less than 500 psi there shall be no wrinkles or kinks deeper than 2 percent of tube OD and no scratches deeper than 10 percent the nominal wall thickness.

Bend radii for tube diameters other than those specified may be established by multiplying the tube outside diameter by the appropriate numerical prefix noted in the table for the class bend desired.

Present bending dies may be used until such time as tools must be replaced.

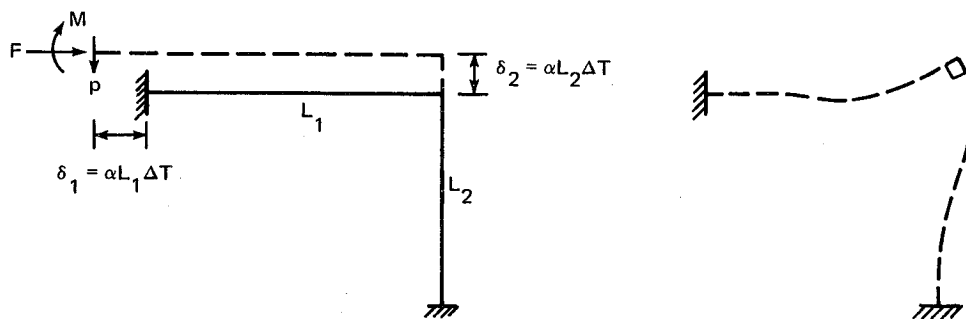
If the tube is attached to a shaped shell of equal thickness, the restraint and hence the bending stresses will be lower. Examples from reference 32 are:

	<u>MAXIMUM BENDING STRESSES</u>	<u>f_{bend}</u>
	CYLINDER ATTACHED TO A HEMISPHERE	0.03 pR/2t
	CYLINDER ATTACHED TO A 2/1 ELLIPSE	1.18 pR/2t
	RIGID END CAP	3.10 pR/2t

These local bending stresses are additive to the basic pressure vessel axial stresses. As shown, an end cap which more closely resembles a hemisphere will produce the lowest bending stresses. The total axial stress in the tube wall is the sum of the axial stresses due to pressure and local bending. This sum should be less than $F_{tu}/4$ for the design criteria to be satisfied. The end cap region is an area of the pipe where "as welded" material properties must be used unless subsequent heat treatment is done after welding.

5.2.4.5 Saddles: Saddles are attached to heat pipe to provide a means of mounting to structure. The sudden change in the cross-sectional area of the heat pipe at the saddle results in a local redistribution of stresses in the pipe wall. Methods of estimating these stresses are given in Appendix C.

5.2.4.6 Restrained thermal expansion: When a heat pipe attached to a rigid structure undergoes a change in temperature from a stress-free state, reaction loads and hence stresses are introduced because free thermal expansion is restrained. An idealized heat pipe installation, depicted here, consists of two straight portions joined at right angles to each other and built in at the opposite end.



If the upper end were free and the pipe underwent a uniform change in temperature, ΔT , the free end would move as shown - where the free thermal expansion is $\alpha L \Delta T$ (α in./in. $^{\circ}$ F = coefficient of thermal expansion). To restore the free end to its original position and slope, forces and a moment are required and the final pipe configuration will be as shown on the right.

Minimization of the strain energy of bending results in the following system of equations:

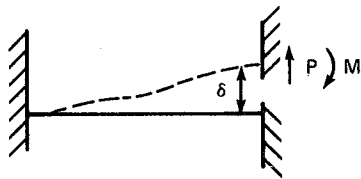
$$\begin{aligned} EI\delta_1 &= FL_2^3/3 - pL_1L_2^2/2 + ML_2^2/2 \\ EI\delta_2 &= -FL_1L_2^2/2 + p(L_1^3/2 + L_1^2L_2) - M(L_1^2/2 + L_1L_2) \\ EI\sigma = 0 &= FL_2^2/2 - p(L_1^2/2 + L_1L_2) + M(L_1 + L_2) \end{aligned}$$

Example C

If $L_1 = L_2 = L$, the forces and moment can be solved for as:

$$\begin{aligned} P = F &= 12 EI\delta / L^3 \\ M = PL/2 &= 6 EI\delta / L^2 \end{aligned}$$

where $\delta_1 = \delta_2 = \delta = \alpha L \Delta T$. This result corresponds to a built in beam with an enforced deflection at one end.



$$f_{\text{bend}} = Mc/I = 6Ec\delta / L^2, \text{ WHERE } \delta = \alpha L \Delta T$$

This stress is also additive to the axial stress due to internal pressure but it generally occurs at a different location than the local bending due to the end cap. If the unlikely situation arises where the heat pipe is restrained at the end cap - then all three stresses are additive; furthermore, it may occur in a region of the pipe which is not welded and for which a higher allowable stress can be used. Again, the criteria requires that the sum of the axial stresses due to internal pressurization and restrained thermal expansion be less than the allowable stress $F_{tu}/4$ at that point.

If the pipe is 6061-T6 with $C = R = 0.534$ in. (1.356 cm) (refer to Example A, Paragraph 5.2.4.1.2), $L = 20$ in., (50.800 cm) and the temperature is raised by $\Delta T = 100^\circ\text{F}$ (56°C)

$$\delta = \alpha L \Delta T = 13 \times 10^{-6} (20)(100) = 0.026 \text{ in. (0.066 cm)}$$

and

$$\begin{aligned} f_{\text{bend}} &= 6(10.5 \times 10^6)(.534)(.026)/(20)^2 \\ f_{\text{max}} &= 2190 \text{ psi } (1.510 \times 10^7 \text{ newt/m}^2) \end{aligned}$$

From Example A cited, the axial stress due to internal pressure is

$$f_{\text{axial}} = pR/2t = 2725 \text{ psi } (1.879 \times 10^7 \text{ newt/m}^2)$$

Note that the sum of the two stresses (2190 + 2725 = 4915 psi) is less than the value of $F_{tu}/4$ (5900 psi) from Example A.

5.2.4.7 Dynamic response: Particularly in spacecraft applications, a heat pipe may have to undergo vibrational loads as a result of a booster launch. Methods of estimating these loads and their relation to other pipe stresses are given in Appendix D.

5.2.4.8 Fracture mechanics approach: Pressure vessels and pressure piping can and often do contain small defects which are present in the material or are introduced during the manufacturing sequence. Depending on the size of the flaw, various situations could occur as follows:

- A flaw could be large enough to be detected by the inspection process and be repaired
- Flaws smaller than the foregoing could be detected by causing leakage or failure during a proof test
- Small flaws could go undetected during the inspection process and proof testing.

The latter small size flaws grow with pressure cycling. If a sufficient number of cycles are applied at a high enough pressure (i.e. high pressure at low cycles or low pressure at high cycles) these flaws will grow to a size large enough to cause failure.

There are certain aspects of the heat pipe structure which make it more critical than typical pressure vessels. The base of the internal "threading" and "grooving" is a region where flaws or sharp edged defects are a strong possibility. Another likely region is at the internal surface of the welds. Furthermore, the material in the weld zone has poor fracture toughness characteristics compared with the base material.

Certain fracture mechanics aspects of heat pipes must be examined in addition to the static strength requirements described previously. Some of the analysis contained in Reference 27 is outlined in Appendix E.

5.2.5 End cap design. - The ASME Code, 1965, describes two configurations, designated here as Type I and Type II, for welded flat circular heads that are recommended for heat pipe use. Design details are given in Fig. 5-3. Wall thickness, t , is the minimum net section after all allowances for corrosion, threading or grooving have been made.

For these designs, the minimum required thickness is specified in the ASME code as:

$$t = D \sqrt{4 C p_m / F_{tu}}$$

where C is a factor obtained from Fig. 5-3, and $D = 2R$ is the average diameter of the pipe. Figures 5-4 and 5-5 show typical variations in required thickness, t , with internal pipe pressure, P_m , for 6061-T6 aluminum and 304 stainless steel, respectively.

The curves for the Type I end cap assume a value of 0.5 for the factor C , which gives conservative results. As an example consider a 0.500 in. (1.270 cm) diameter (average) 6061-T6 aluminum tube with a maximum allowable operating pressure of 2000 psi (1.379×10^7 newt/m²). From Fig. 5-4 at 100°F, the end cap thickness for a Type I design is 0.205 in. (0.521 cm) and for a Type II design, 0.14 in. (0.356 cm).

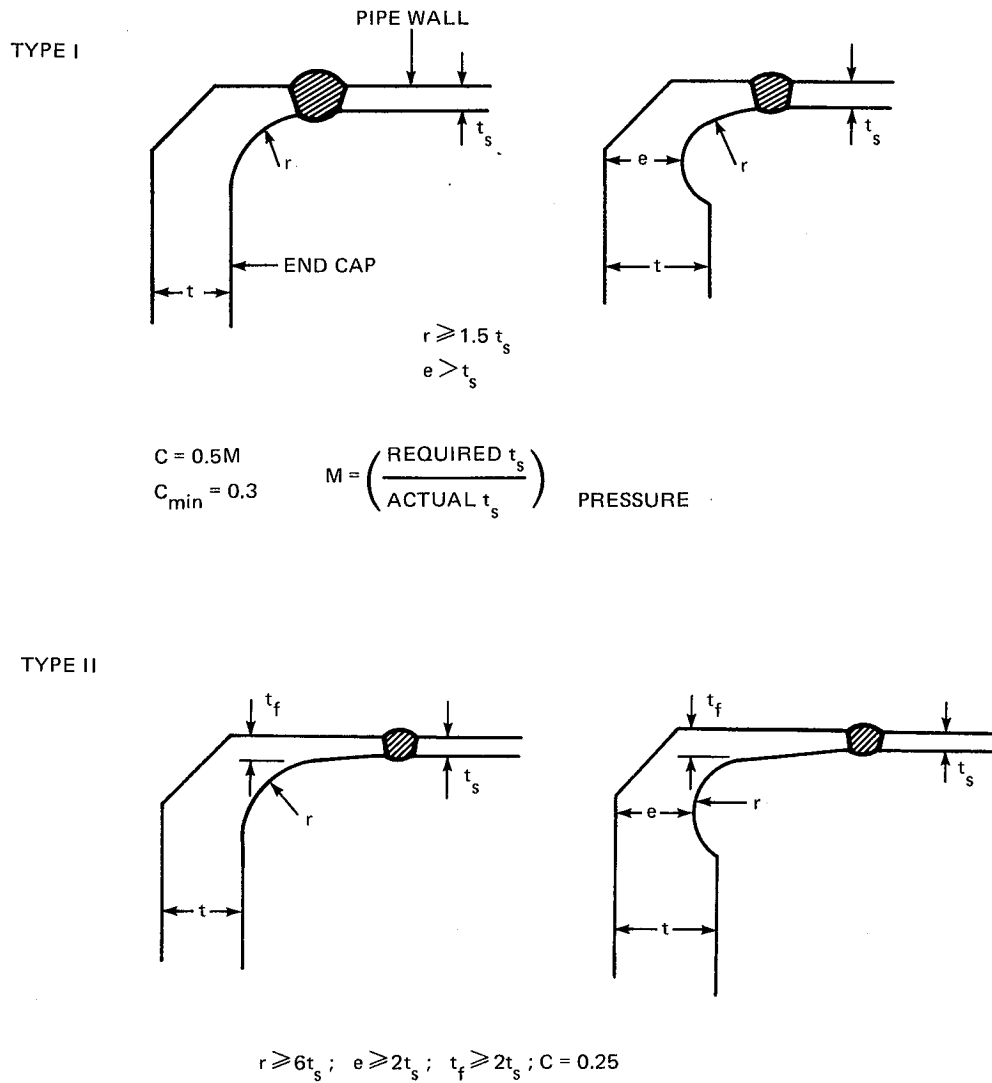


Fig. 5-3 End Cap Design Details

In the designs illustrated below full weld penetration is not always possible, and inspection after welding is difficult. These weld configurations are judged unacceptable for end caps.

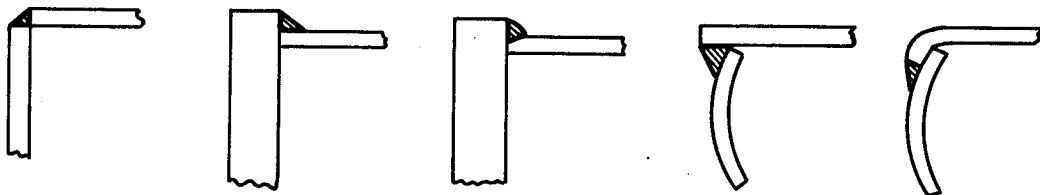


Fig. 5-4 End-Cap Design Curves, 6061-T6 Aluminum (as Welded)

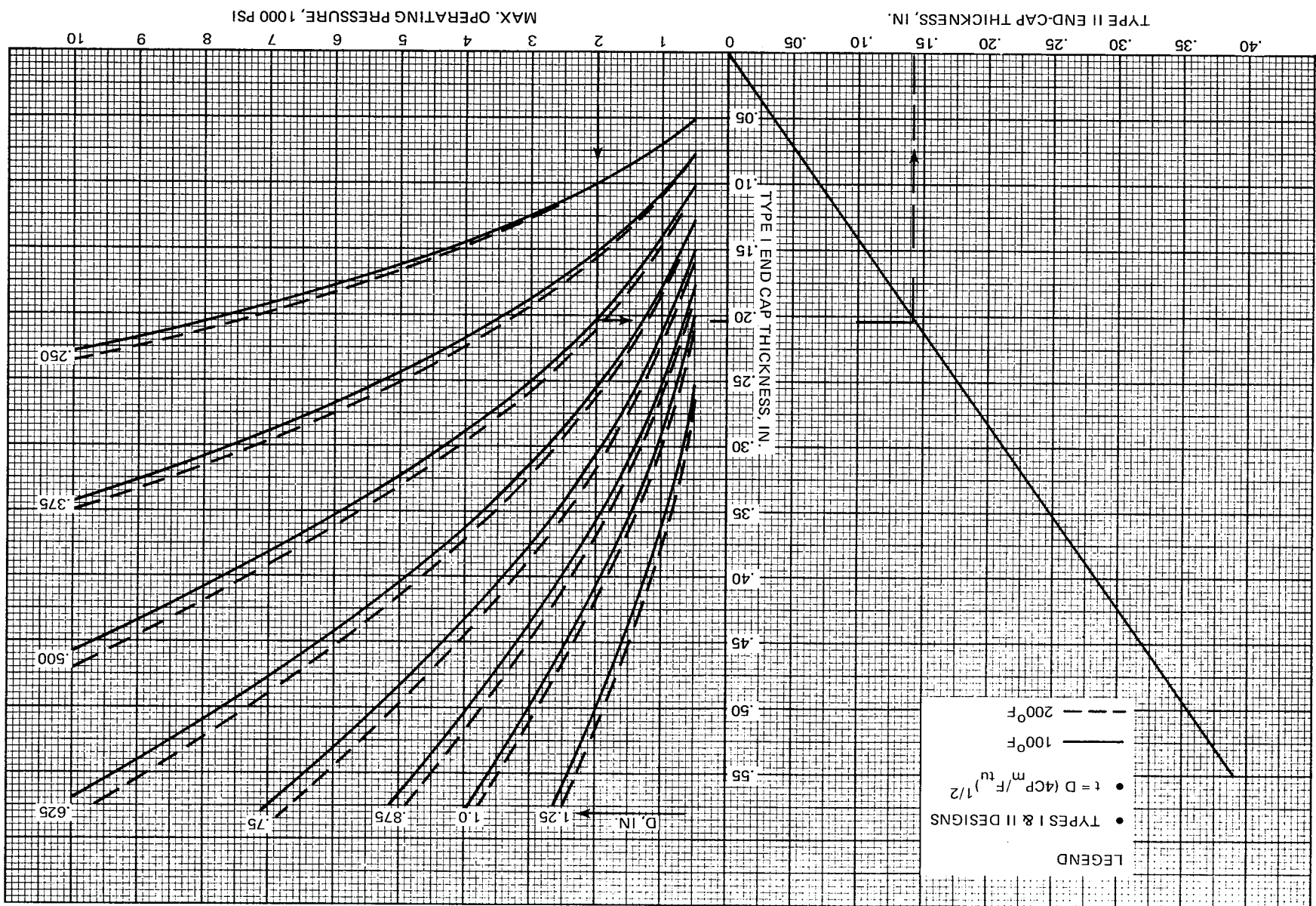
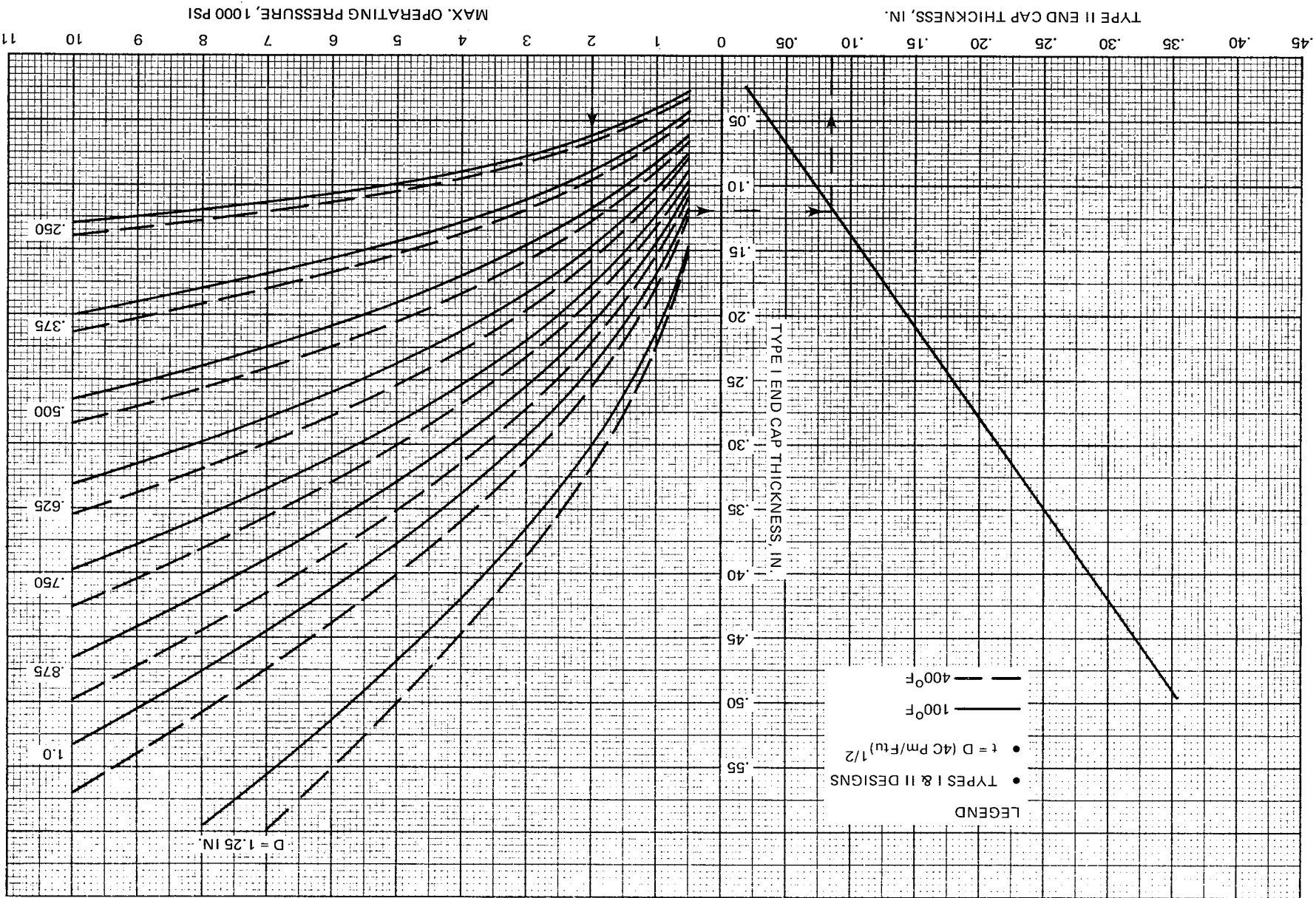
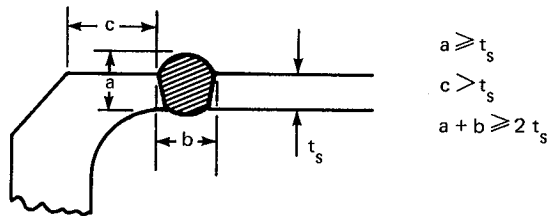


Fig. 5-5 End-Cap Design Curves, 304 Stainless Steel (as Welded)



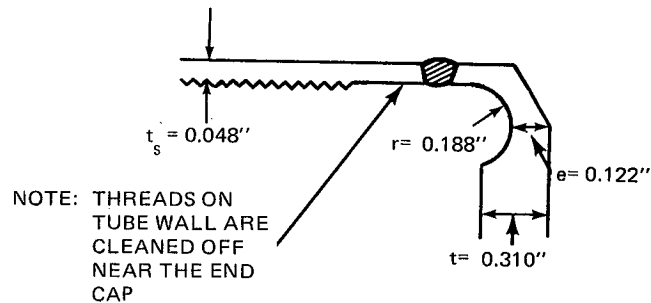
The following sketch illustrates an acceptable post-weld detail.



A more detailed discussion of weld joint designs is presented in Section 4.

Example D

Verify the end cap thickness for the 6061-T6 tube/welded heat pipe given in Example A, Paragraph 5.2.4.1.2.



Noting that:

$$r = 0.188 > 1.5 t_s$$

$$e = 0.122 > t_s$$

then from Example A, maximum operating pressure, p_m , = 490 psi at 160°F and $D = 2R = 1.07$ in., and $t_{s \text{ required}} \approx t_{s \text{ actual}} = 0.048$ thus $C = 0.5$ since

$$t_{s \text{ req}} / t_{s \text{ act}} = 1.$$

$$t_{\text{req}} = D \sqrt{C p_m / F_{\text{allow}}}$$

$$F_{\text{allow}} = F_{tu} / 4 = 5900 \text{ psi } (4.068 \times 10^7 \text{ newt/m}^2) \text{ at } 150^\circ \text{F } (66^\circ \text{C})$$

The required end cap thickness, from Fig. 5-3 or the equation below is:

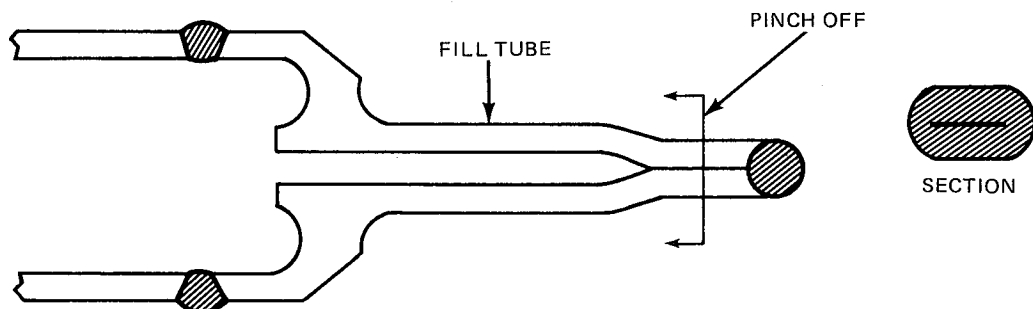
$$t_{\text{req}} = 1.07 \sqrt{(0.5)(490)/5900} = 0.218 \text{ in. (0.554 cm)}$$

But,

$$t_{\text{act}} = 0.310 > 0.218 \text{ in.}$$

The thickness criteria are, therefore, satisfied.

5.2.6 Fill tube design. - The design of fill tubes is similar to that of pipes and end caps with the exception of the fill tube pinch off itself:



Since this is a region of the heat pipe for which strength cannot be calculated with satisfactory accuracy the maximum operating pressure should be determined experimentally (refer to Paragraph 5.2.4.2).

In practice, the fill tube dimensions are determined by how tight a mechanical seal or crimp can be achieved prior to welding. A large inside diameter with a narrow wall will have good pump-down characteristics, but poor crimping properties - cracks are easily developed when the material is deformed. Too narrow an opening with a thick wall will have poor pump-down characteristics.

One fill-tube geometry that has been favored by many experimenters uses a 3/16 to 1/4 in. (0.476 cm to 0.635 cm) o.d. tube with a 1/16 in. (0.159 cm) i.d. hole. It produces reasonable pump-down times ($\approx 1/2$ hr) and repeatable crimp closures, in both stainless steel and aluminum. Burst test samples with aluminum charge tubes have given 3100 psi (2.137×10^7 newt/m²) for a fully annealed condition and 7500 psi (5.171×10^7 newt/m²) for -T6 tubes that were heated to 600°F (316°C) for 1 min and air cooled to room temperature prior to pinch off.

5.3 Leak Detection

One of the most severe, yet easily prevented, failure modes for heat pipes is loss of working fluid through flaws in the pipe envelope. However, the specification and measurement of leakage rates should be closely associated with the life requirements of the particular heat pipe to avoid unnecessary cost and effort. For example, simply specifying an arbitrary leakage rate, say 10^{-9} STD cc/sec, may result in the design of a pipe life well in excess of actual requirements. Although this may be a very conservative value, the equipment and procedures necessary to measure such a leakage can add unwarranted costs. Figure 5-6 relates leakage rates of various heat pipe fluids from standard cubic centimeters/second (cc/sec) to a more realistic unit, grams per year.

Numerous techniques, covering broad ranges of sensitivity and cost, have been used to measure leakage rates. They fall into two general categories: (1) those used before the heat pipe is actually charged with working fluid and (2) those used after charging and pinch off. The before-charging category checks the integrity of the basic pipe envelope, including all weldments, and is used to certify the heat pipe prior to charging. After charging and pinch off, other techniques are used to check the final pinch off closure. The after-pinch off leak detection technique to use depends on what working fluid is in the pipe. Table 5-4 summarizes the basic features of the leak detection techniques that are discussed in the following paragraphs.

5.3.1 Precharging leak detection techniques

5.3.1.1 Penetrant Method:

Penetrant methods can be used to check suspected major flaws (pinholes, porosity) in a heat pipe envelope or weldment. They are generally cheap and easy to use, but are among the least sensitive of the leak detection techniques and will only reveal relatively large surface faults. Although a pipe, or weld, may pass a penetrant test a significant, undetected flaw may still exist.

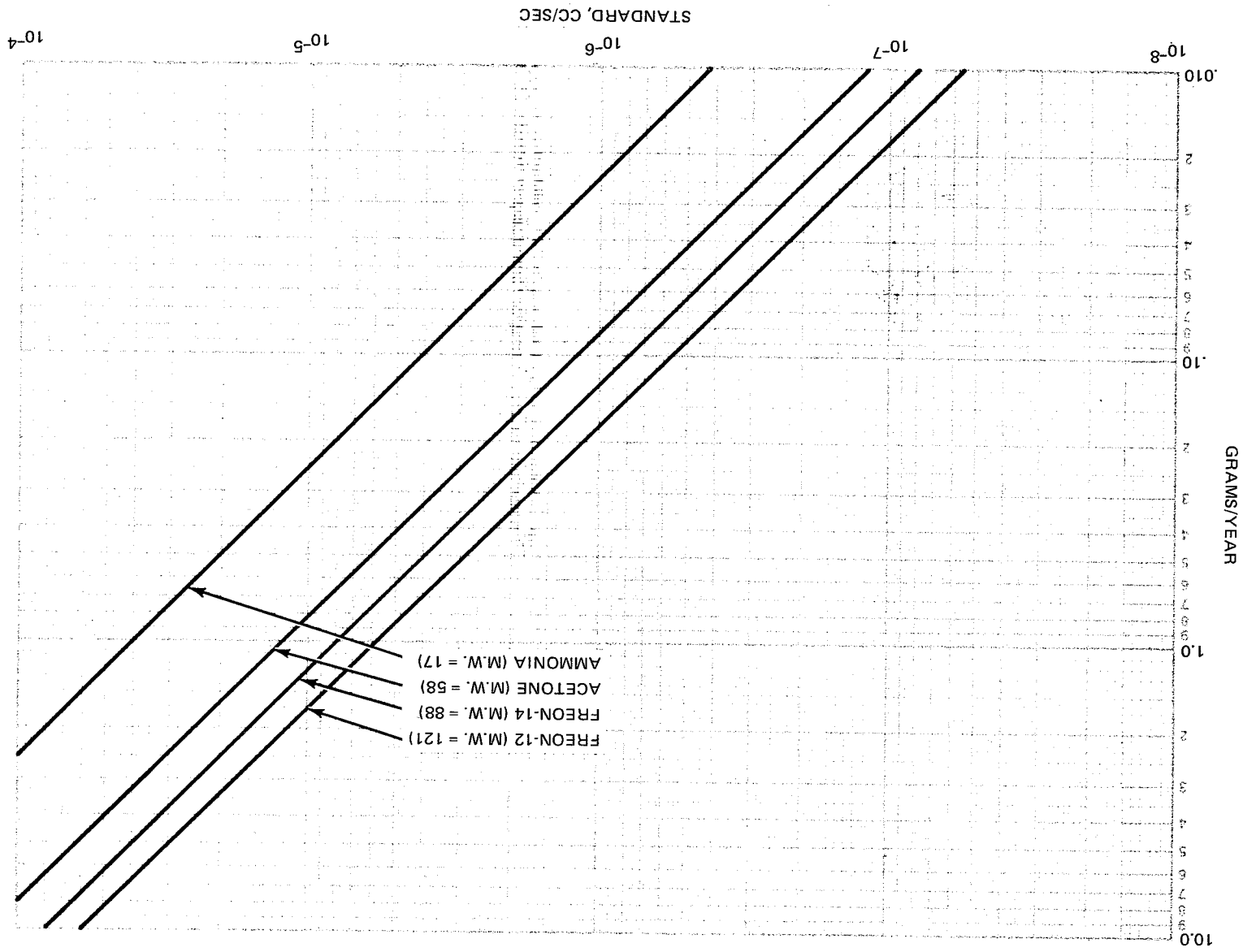


Fig. 5-6 Leakage Rates

TABLE 5-4 - SUMMARY OF LEAK DETECTION TECHNIQUES

Leak detection technique	Sensitivity	Special equipment	Comments
Precharging			
Penetrant method	Poor	None	Requires additional verification
Radiography (X-ray)	Poor	X-ray machine	Not conclusive
Nitrogen pressurization under water	10^{-4} std cc/sec	N2 bottle, water tank	Conclusive, quick and inexpensive
Helium detectors	10^{-11} std cc/sec	He mass spectrometer, vacuum chamber	Much equipment required
Mass spectrometer	10^{-11} std cc/sec	Mass spectrometer, vacuum station	Much equipment required
Halogen leak detector	10^{-7} std cc/sec	Leak detector	Quick and inexpensive
Post-charging			
Phenolphthalein (litmus paper)	Go/no go	None	Ammonia heat pipes, quick and inexpensive
Copper sulfate/ethylene glycol	10^{-7} - 10^{-8} std cc/sec	Chemical solutions	Ammonia heat pipes, 4 hrs
Hot filament ionization gauge	10^{-9} std cc/sec	Ionization gauge	Ammonia heat pipes, quick
Halogen leak detector	10^{-7} std cc/sec	Leak detector	Freon heat pipes, quick
Solution PH	10^{-7} std cc/sec	PH indicator	Ammonia heat pipes, quick
Mass spectrometer	10^{-11} std cc/sec	Mass spectrometer, vacuum station	Much equipment required, applicable to any working fluid

The two basic types of penetrant methods are fluorescent and visible dye, with the latter being the least sensitive but cheapest. With each type there are three possible variations: water washable, post emulsified, and solvent removable. The water washable is the least sensitive, and the solvent removable, the most sensitive of the penetrant methods.

The water washable visible dye penetrants, such as Zyglo, are among the most widely used and are generally recommended if a penetrant method is desired because they are cheap and easy to use. However, additional precharging leak detection methods with greater sensitivity must still be employed. Military specification MIL-I-6866B (ASG) covers the penetrant inspection methods.

5.3.1.2 Radiography (X-ray):

Radiography (X-ray) can be used to inspect weldments with varying degrees of success. The results are not always conclusive because of the many variables involved: skill of the X-ray technician, type of weld joint, and skill of the interpreter. A weld that shows an X-ray flaw may or may not actually leak and could be acceptable over the design life of the pipe. As far as heat pipes are concerned X-ray inspection is necessary but not sufficient. It must still be followed by a more positive leak detection method. It is necessary since X-ray inspection may reveal minor flaws in the weld which could subsequently fail in flight. Minimum radiographic inspection requirements for general application are established in Military standard MIL-STD-00453A (USAF). However, specific acceptance/rejection criteria for X-rays should be specified in a welding specification, as, for example, given in Appendix B.

5.3.1.3 Nitrogen Gas Pressurization Under Water:

This technique involves pressurizing the heat pipe with an inert gas (usually nitrogen) to about 300 psig (2.068×10^6 newt/m²), submerging it in a water tank and observing for bubbles; their appearance, of course, is a positive indication of a leak. Care must be taken to insure that the bubbles observed are actually dynamic gas bubbles coming from inside the pipe and not static bubbles from the exterior.

By observing and counting the number of bubbles over a given time period, a rough indication of the leak rate can be determined. The technique is good up to a sensitivity of about 10^{-4} cc/sec (approximately 1 bubble every 5 sec), but it is actually recommended as a go/no-go test. If any dynamic bubbles at all are observed, the flaw is located and re-welded. If no bubbles are present, the pipe can be slowly brought up to proof pressure (1.5 times maximum operating pressure) and re-inspected for leaks. After this, it is ready for bakeout and charging.

This method is relatively inexpensive, needing only a gaseous nitrogen supply and a water tank, but extremely accurate on a qualitative basis.

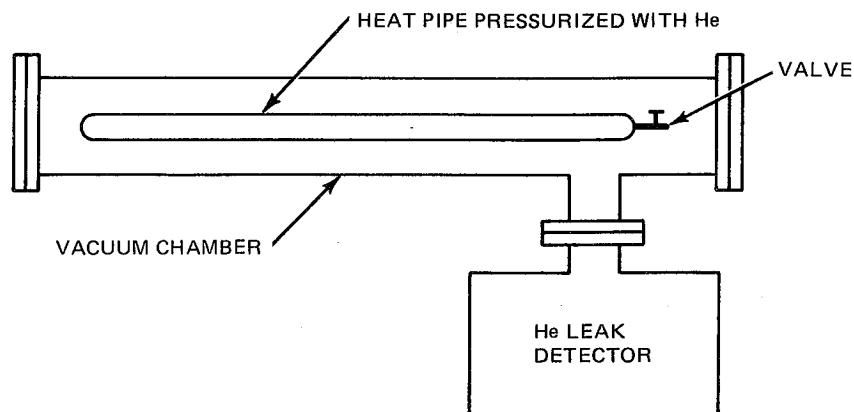
5.3.1.4 Helium Detector Techniques:

Techniques that use helium gas in conjunction with helium mass spectrometers offer much more sensitive, but more expensive, methods of leak detection. One type of procedure involves pressurizing the inside of a pipe with helium and measuring the leakage on the outside, giving an integrated leak rate. Figure 5-7 shows a typical set-up where the pressurized pipe is placed in a vacuum chamber attached to the leak detector/pumping station. Calibration of the system with a known leak is necessary before and after use. This technique allows the pipe to be leak checked at its operating pressure and temperature, and depending on the equipment used, can detect leakage rates in the range of 10^{-11} STD cc/sec.

A somewhat less sensitive, but time saving, alternative is to use a portable helium sniffer in ambient air, thereby avoiding the use of the chamber. The sniffer is directed over specific areas of the pipe and can be used to pinpoint leakage sites. A number of small leaks may be acceptable if the total leakage is less than the specified value. Hence, a detector at least one order of magnitude more sensitive than the specified total leak is required. A technique which also avoids the use of a vacuum chamber is to place the helium pressurized pipe in a sealed air enclosure and periodically sample the air for the presence of helium.

GENERAL METHODS:

1. SNIFF OUTSIDE WITH He SNIFFER IN AMBIENT (METER, AUDIO DETECTOR).
2. PLACE IN EVACUATED CHAMBER AND CALIBRATE SYSTEM WITH STANDARD He LEAK RATE SOURCE



3. PLACE PIPE IN SEALED AIR ENCLOSURE AND PERIODICALLY MEASURE THE He CONTENT OF AIR SAMPLES

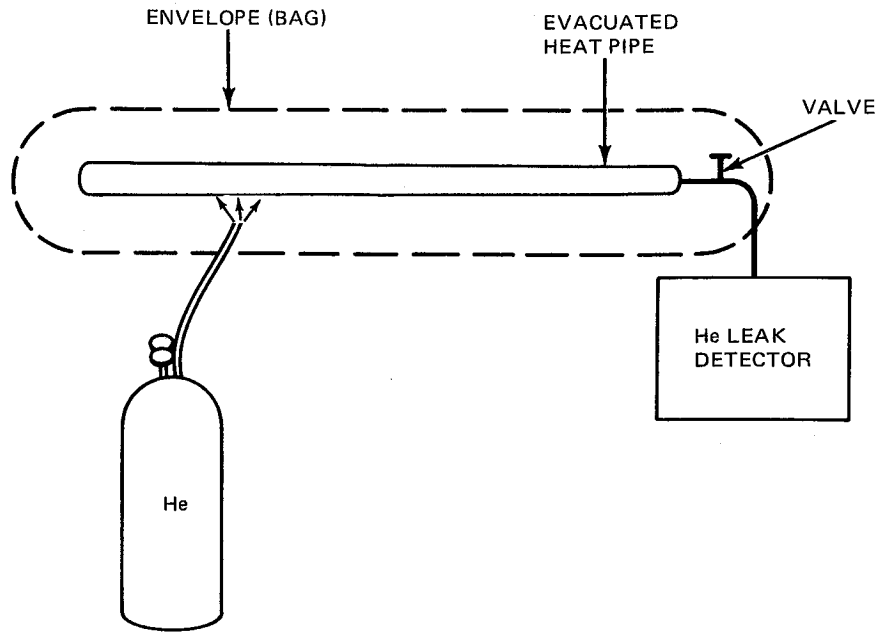
COMMENTS:

- ALLOWS PIPE TO BE PRESSURIZED TO SAME LEVEL AS OPERATING PRESSURE (AND TEMPERATURE)

Fig. 5-7 Helium Leak Detection Techniques: Pressurized Pipe

Figure 5-8 depicts another variation. The pipe is evacuated through a helium leak detector while helium is directed over the outside of the pipe. This can be done through an envelope (or bag) to determine gross leakage, followed by local impingement to identify the faulty area. The disadvantage with this technique is that the helium pressure difference across the pipe (high outside, low inside) is opposite to the normal pipe pressure gradient (high inside, low outside). In addition, the leak is simulated with only a 14.7 psi (1.014×10^5 newt/m²) pressure differential which may be many times smaller than would actually exist in, say, an ammonia pipe at 70°F (129 psia).

A third helium detection technique, employed by Ames Research Center (ref. 33) for use with VCHPs, is described in Fig. 5-9. The technique is similar to that shown in Fig. 5-7, except the pipe is a gas controlled variable conductance heat pipe which has helium as part of the control gas charge. This technique has the benefit of leak testing



PROCEDURE:

- (a) DETERMINE GROSS LEAKAGE BY PRESSURIZING ENVELOPE
- (b) ISOLATE LEAK BY DIRECTING He TO LOCAL AREAS

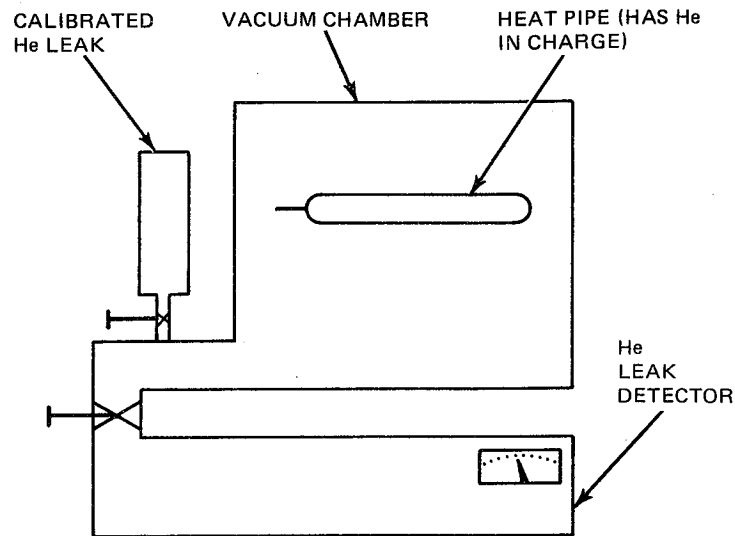
COMMENTS:

- CAN ONLY PRESSURIZE TO A DIFFERENCE OF PRESSURE OF 14.7 PSI, WHICH MAY BE MUCH LESS THAN ACTUAL PIPE OPERATING PRESSURE
- PRESSURE DIFFERENCE IS IN WRONG SENSE (SHOULD BE HIGHER INSIDE THAN OUTSIDE)

Fig. 5-8 Helium Leak Detection Techniques: Evacuated Pipe

a completely charged pipe at its anticipated operating temperature, including the pinch-off tube, a feature not found with the other helium techniques. It is limited to gas controlled VCHP's or heat pipes which can tolerate trace amounts of helium.

Another helium leak detection procedure, described in NASA Technical Brief 67-10178, allows accurate and rapid leak testing of welded pipe joints. This technique, shown in Fig. 5-10, is suited for heat pipe configurations which cannot easily be placed in a vacuum chamber to accurately measure leakage rates. It is useful in examining pipes with multiple welds, to quickly isolate and measure small leaks.



PROCEDURE:

- (a) EVACUATE CHAMBER TO 10^{-4} TORR OR LESS (NOTHING IN CHAMBER)
- (b) CALIBRATE DETECTOR WITH KNOWN SOURCE
- (c) INSTALL PIPE, PUMP DOWN TO 10^{-4} , READ LEAKAGE
- (d) REMOVE PIPE AND RECALIBRATE WITH KNOWN SOURCE
- (e) COMPARE PIPE LEAKAGE WITH PRE- OR POST-TEST CALIBRATED LEAK

COMMENTS:

- TECHNIQUE LIMITED TO GAS-CONTROLLED VCHP'S OR PIPES WITH TOLERABLE He IMPURITY
- CHECKS ENTIRE PIPE INCLUDING PINCHOFF TUBE
- WILL NOT PINPOINT LEAK

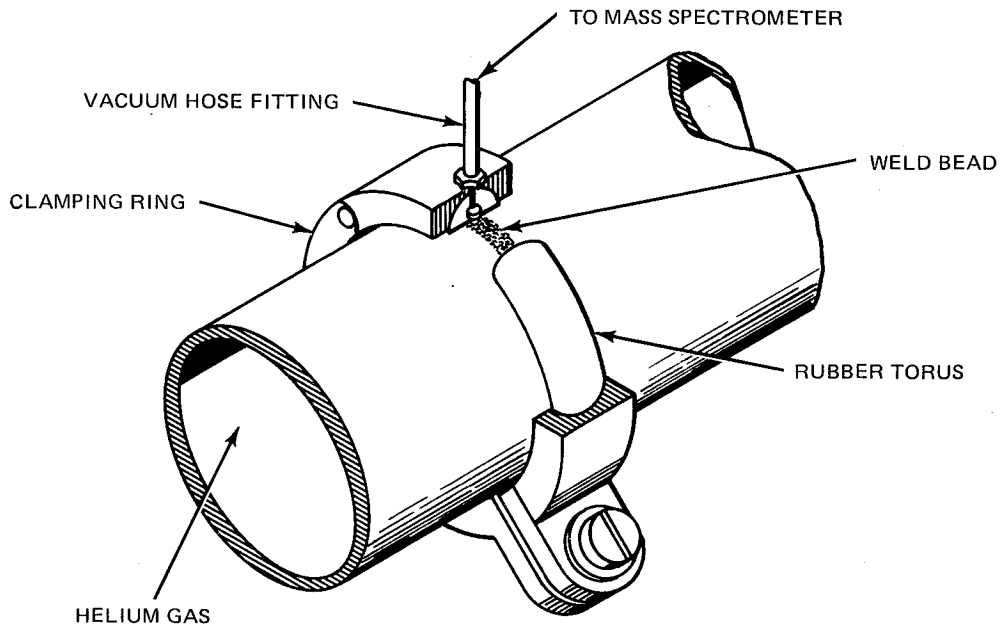
Fig. 5-9 Helium Leak Detection Techniques: Charged Pipe

5.3.1.5 Mass Spectrometer:

A general leak detection technique that can also be used on a completely sealed pipe with any working fluid is shown in Fig. 5-11. It employs a mass spectrometer, e.g., Veeco Residual Gas Analyzer, from which leak rates can be calculated. A problem with this procedure is its relative cost, long pump-down times required and difficulty in distinguishing compounds with similar molecular weights (e.g., water, 18 and ammonia, 17) which depends on experience of operator.

5.3.1.6 Halogen Leak Detector:

Refer to Paragraph 5.3.2.4.



THE PROBLEM:

To devise a fixture that will facilitate inspection testing of circumferential pipe welds for vacuum tightness, using helium gas as a leakage tracer in conjunction with a mass spectrometer. The pipes to be tested were too large for a vacuum chamber, and the use of a plastic bag taped around the welded joint for collection of the tracer gas did not provide sufficient measurement accuracy of the leakage rate.

THE SOLUTION:

A fixture consisting of a split rubber torus and a mating clamping ring with a vacuum hose fitting.

HOW IT'S DONE:

The rubber torus is placed over the weld to be tested and the clamping ring is tightened around the torus to ensure a vacuum tight seal. A vacuum line is then connected between the vacuum hose fitting and the mass spectrometer. Any helium that leaks through the weld accumulates in the annular space within the rubber torus and is conducted to the mass spectrometer. As the pressure of the helium is considerably below atmospheric, helium leakage to the atmosphere is negligible.

Ref. NASA TECH BRIEF 67-10178

NOTES:

1. This fixture enables accurate and rapid helium leak testing of welded pipe joints, since it can be connected (and disconnected) within several seconds and requires only a few more seconds for establishment of the equilibrium gas pressure in the known annular volume of the rubber torus around the weld bead.
2. Inquiries concerning this innovation may be directed to:

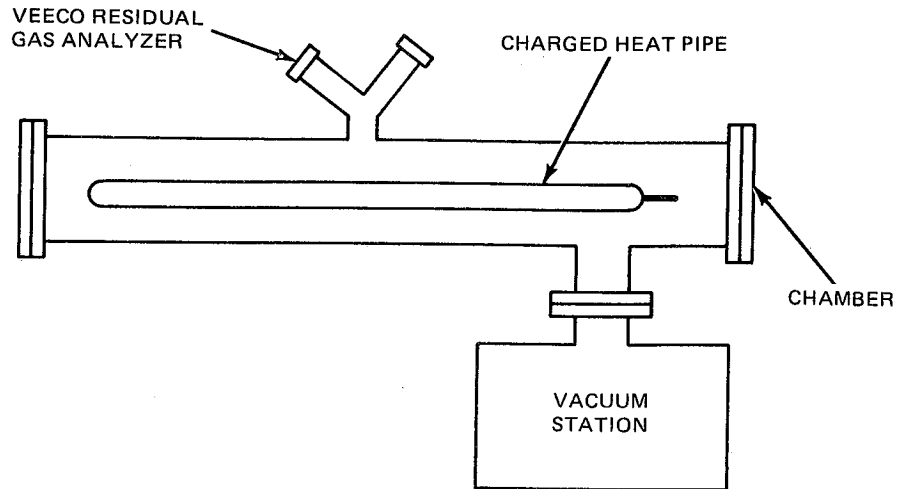
Technology Utilization Officer
 Marshall Space Flight Center
 Huntsville, Alabama 35812
 Reference: B67-10178

PATENT STATUS:

No patent action is contemplated by NASA.

Source: James A. Roney
 of Hayes International Corporation
 under contract to
 Marshall Space Flight Center
 and Robert G. Jones
 (M-FS-2167)

Fig. 5-10 Fixture for Helium Leak Testing of Pipe Welds



GENERAL PROCEDURE:

- (a) DO IMPURITY TRACE OF SYSTEM WITHOUT PIPE
- (b) INSERT PIPE
- (c) DO IMPURITY TRACE AT VARIOUS TIMES

$$\text{LEAK RATE} = \frac{\Delta \text{ MASS}}{\Delta \text{ TIME}}$$

SENSITIVITY: CAN DETECT 10^{-13} TORR OF NITROGEN

COMMENTS:

- CAN LEAK TEST CHARGED PIPE INCLUDING PINCHOFF TUBE
- CERTAIN ELEMENTS MAY BE DIFFICULT TO DISTINGUISH, SUCH AS H_2O (MOLECULAR WT = 18) AND NH_3 (MOLECULAR WT = 17)

Fig. 5-11 General Leak Detection for Any Working Fluid

5.3.2 Post-charging and pinch-off leak detection techniques:

5.3.2.1 Phenolphthalein (Litmus Paper) for NH_3 Heat Pipes:

Red litmus paper is an extremely cheap and effective method for on-the-spot inspection of charge tube closures when the working fluid is ammonia. It involves moistening a strip of red litmus paper, holding it against the closure and then inspecting the paper for tell-tale blue spots. A positive indication means a leak. Qualitatively, the more intense the blue color, the greater the leak rate. Care must be taken to insure that the surface is clean.

The litmus paper test is meant only for convenience to quickly determine if a closure needs to be rewelded. It should be followed by a more sensitive leak detection method.

5.3.2.2 Copper Sulfate/Ethylene Glycol for NH₃ Heat Pipes:

A relatively inexpensive but sensitive (3×10^{-8} std cc/sec) method for leak checking ammonia heat pipes has been developed by NASA/GSFC. It involves soaking filter paper in a copper sulphate/ethylene glycol solution, wrapping it around the weldment and enclosing it in an air-tight bag. After four hours, a simple visual inspection for the absence of dark blue spots will provide a 3.3×10^{-7} cc/sec leak sensitivity measurement. If no dark blue spots are visible, applying a few drops of Nessler's reagent, and looking for dark brown spots, can increase the sensitivity to about 3×10^{-8} cc/sec. Reasonable care must be exercised to avoid false results from contamination of surfaces and reagents. The complete details of this procedure, as contained in OAO Document EX-D0109-C, follow.

Copper Sulfate/Ethylene Glycol Leak Detection Method for NH₃ Heat Pipes

Equipment Required - The equipment required to perform this ammonia leak test includes:

- Filter paper - Wattman No. 120 or equal
- Reagent solution (by weight) - 3% copper sulfate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and 10% ethylene glycol in distilled water
- Small plastic bags to cover ends of pipe after filter paper has been laid down
- Rubber band (or adhesive-backed tape) to hold plastic bags in place
- Nessler's reagent in dropping bottle.

Procedure - The following procedure should be followed when leak checking heat pipes containing ammonia:

- Prepare filter paper as follows:
 - Soak one sheet of filter paper in reagent (copper sulfate) solution
 - Blot wet filter paper between two sheets of dry filter paper
 - Place wet filter paper in air tight container (to prevent evaporation) until ready for use.
- Cut filter paper into sheets approximately 1-1/2 in. (3.810 cm) by 2 in. (5.080 cm).
- Wrap filter paper (prepared previously) around end of pipes.
- Cover ends of pipe and filter paper with small plastic bag and secure with rubber band or adhesive-backed tape.
- Leave ends of pipe covered for at least four hours. This should provide a leak sensitivity of approximately 3.3×10^{-7} std cc/sec.
- After at least four hours, remove plastic bag and filter paper and observe filter paper for dark blue spots. If these spots are visible, a leak rate of $\approx 3.3 \times 10^{-7}$ std cc/sec has been exceeded.
- If no dark blue spots are visible, place a few drops of Nessler's reagent on filter paper. If dark brown spots from the reagent appear, then a leak rate of $\approx 3 \times 10^{-8}$ std cc/sec was exceeded. Note that dark brown spots may have resulted from the aluminum-copper sulfate reaction before the application of the Nessler's reagent and should be disregarded.

5.3.2.3 Hot Filament Ionization Gauge for NH₃ Heat Pipes:

This technique uses a sniffer probe hot filament ionization leak detector with a special shroud that fits around the pinch-off area. The leak detector has a basic sensitivity of 10^{-9} std cc/sec and can be calibrated with a known leak to ensure proper functioning before and after each usage.

5.3.2.4 Halogen Leak Detector for Freon Heat Pipes:

Halogen leak detectors provide a fast, accurate method of checking Freon heat pipes. They are small, portable, relatively inexpensive units that use a pencil probe to pinpoint leaks. They can typically measure absolute leak level on the order of 10^{-7} std cc/sec. Detailed specifications are readily available from any of the manufacturers.

5.3.2.5 Solution PH for NH₃ Heat Pipes:

Another method for leak detection with ammonia heat pipes consists of submerging the pipe, or just the pinch-off weld, in a known PH solution. After a pre-determined time the PH is measured (dyes or meter may be used) and the change in PH can be related to an ammonia leak rate. This would only be sensitive if volumes of solution are kept relatively small.

5.3.2.6 Mass Spectrometer:

This is applicable to any working fluid, and can be used to test pipes at their operating temperature. Refer to Paragraph 5.3.1.5 for additional comments.

5.4 Conclusions and Recommendations

5.4.1 Structural design and analysis. - The following are recommended:

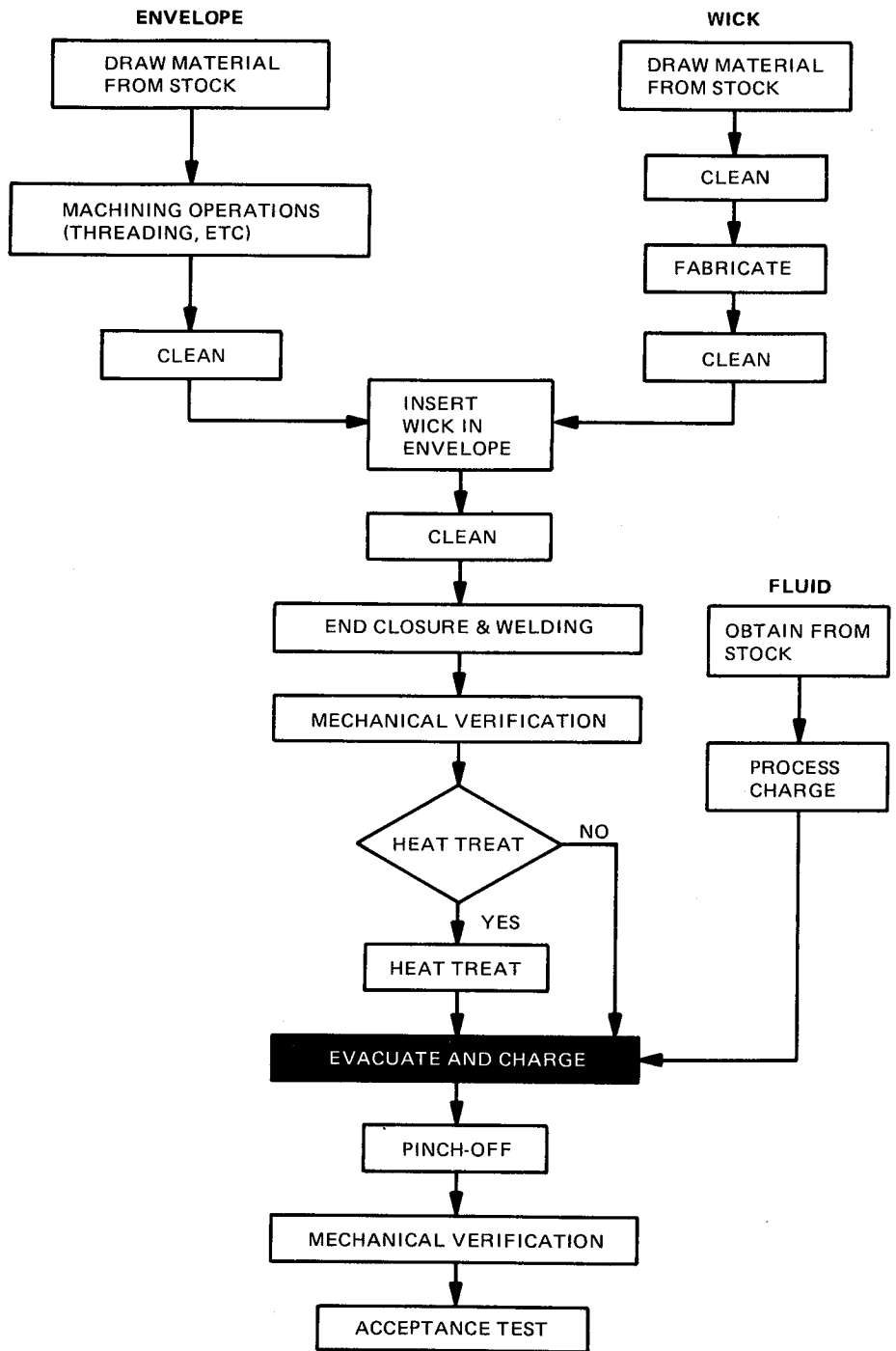
- Use ASME code, 1965, Section VIII, Unfired Pressure Vessels. This is a universally accepted code that presents reasonable design standards that will insure a safely designed heat pipe. Using it will avoid unforeseen design deficiencies such as meeting minimum ICC requirements during shipping; in particular
 - Maximum allowable design stress = 1/4 ultimate tensile stress (at temperature)

- Proof pressure check all heat pipes to 1.5 times maximum operating pressure
- New heat pipe designs (not previously tested) should be burst tested to demonstrate at least 4 times maximum operating pressure.
- Use the stress analysis checklist (refer to Table 5-2) during the preliminary design stages for early identification of critical stress areas. In simple design applications or when a stress specialist is not available it can serve not only as a checklist, but also as the final analysis procedure. At a minimum, it will make the heat pipe designer aware that there are other criteria that must be investigated besides the simple hoop stress, thereby avoiding last minute surprises.
- The stress analysis procedure described may be used as an aid in writing heat pipe specifications. By calling out the applicable potential problem areas, it will standardize the analysis effort at an acceptable level of competence.

5.4.2 Leak detection. - Leak detection criteria recommended are:

- Leak Rate Specification. Realistic leak rates consistent with the actual design life of the heat pipe should be specified. Fig. 5-6 can serve as a guide.
- Leak Detection Technique. The choice of a leak detection technique is governed mainly by its availability and convenience. If inexpensive, high sensitivity methods are available, they should be used to assure high reliability. However, the following basic leak detection methods are recommended as satisfying minimum requirements at the least expense.
- Pre-Charging
 - X-ray all welds
 - Nitrogen gas pressurization under water

- Proof-pressure check with nitrogen
- Helium or halogen leak detection may be necessary where extremely low leakage rates are specified
- Post-Charging and Pinch-Off. Leak detection after charging should be done at maximum operating temperature, if possible
- Ammonia Heat Pipes:
 - Red litmus paper check followed by
 - Copper sulfate/ethylene glycol check (sensitivity to 10^{-8} STD cc/sec); not proven at higher than room temperature
 - Mass Spectrometer techniques may be the only ones now available for use at high temperatures
- Freon Heat Pipes. Halogen leak detector (sensitivity to 10^{-7} STD cc/sec); good for any temperature.



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6 - EVACUATION AND CHARGING

6.1 Background

Prior to charging, a heat pipe must be evacuated to remove materials which may subsequently appear as unwanted noncondensables, or chemically react with the working fluid forming undesirable corrosion products. It is currently felt that noncondensables in heat pipes are due primarily to monolayers of adsorbed molecules, such as water, nitrogen, etc, which are not completely driven off during evacuation even at elevated temperatures.

For the most part, procedures employed by manufacturers to evacuate and charge heat pipes appear to be similar. However, variations do exist in such areas as the length of time and temperature of bake-out, and length of time and temperature of refluxing. In some cases, the manner of fluid introduction into the pipe is different, such as liquid transfer versus vapor distillation. These variations may lead not only to unnecessarily long and expensive procedures, but can result in the introduction of different contaminants, such as oily residues or noncondensables.

This section examines the procedures currently in use, how they differ, and what effects they produce. In addition, a separate pumpdown study is described which attempts to correlate a pumpdown model with test data. Recommendations aimed at standardizing these procedures are given.

6.2 Pumpdown Study

6.2.1 Purpose. - Pumpdown of a pipe prior to charging can be a time consuming operation. Some manufacturers pump for as long as 48 hr. Prediction of required pumpdown time is difficult because it depends not only on temperature and geometry of the charge tube and pipe, but also on the method used to clean the pipe. A series of pumpdown tests were, therefore, conducted to determine the effect of bake-out

temperature and internal geometry on the pumpdown characteristics of a heat pipe. It is intended that the output of these tests will be recommended pumpdown times as a function of pipe temperature during pumpdown and heat pipe configuration.

6.2.2 Test description. - Six separate pumpdown tests were conducted to access the following variables: pumpdown temperature, heat pipe length, internal heat pipe configuration. The following table summarizes the test conditions:

Test number	Pipe length, Ft	Pumpdown temp, °F	Internal configurations
1	4 (1.219 m)	75 (24 °C)	Axial grooves
2	4	200 (93 °C)	Axial grooves
3	4	400 (204 °C)	Axial grooves
4	4	600 (316 °C)	Axial grooves
5	10 (3.048 m)	75	Axial grooves
6	10	75	Axial groove & spiral artery

Five separate samples were used for the first five tests. They consisted of 1/2 in. (1.270 cm) axially grooved aluminum 6061 pipes manufactured by the French Tube Company. For test No. 6, a 100-mesh stainless steel spiral screen 5-1/2 in. (13.970 cm) by 10 ft (3.048 m) was inserted in the same envelope used for test No. 5. A charge tube, measuring 1/16 in. (0.159 cm) i.d. by 3 in. (7.6 cm) long was attached to one end of the pipe. Both ends of each pipe had provisions for installing a thermocouple vacuum gage.

Figure 6-1 shows the test setup. Prior to being installed on the station each pipe was cleaned according to the procedure in Table 3-12. The screen used for test No. 6 was cleaned according to the procedure in Table 3-5, then inserted into the tube.

Typically, each test was conducted as follows:

- Connect test specimen to station
- Close charge tube valve

- Bring station pressure down using roughing pump
- For tests involving bake-out temperatures of 200, 400, and 600^oF, bring pipe pressure down to about 1000 μ by adjusting charge tube valve
- Bring pipe to desired temperature with clam-shell heater extending over entire pipe length
- Open charge tube valve and record out-put of the T/C vacuum gages
- When pipe pressure is approximately 50 μ turn on diffusion pump.

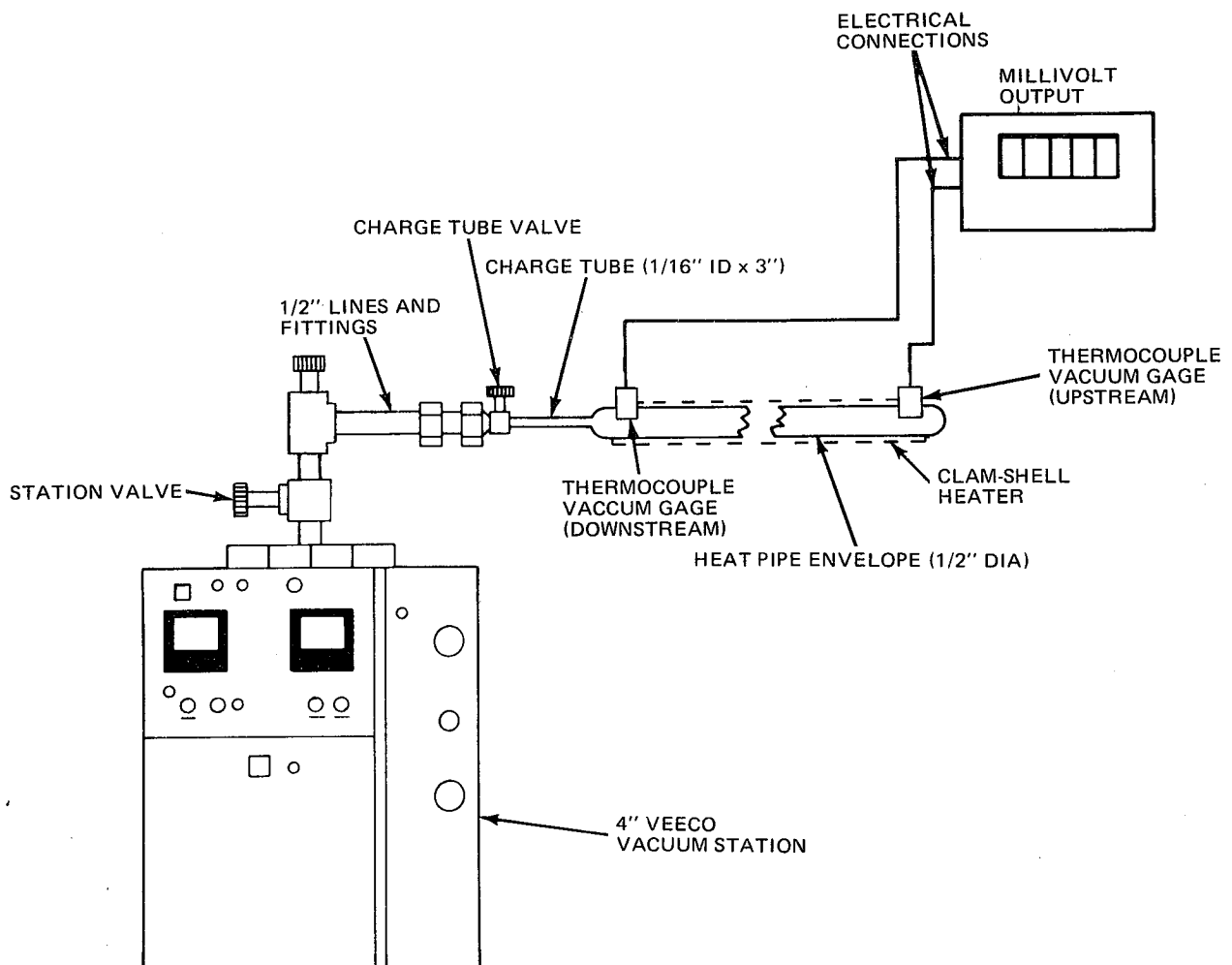


Fig. 6-1 Setup for Pumpdown Tests

6.2.3 Test results. - The results of test No. 1 are shown in Fig. 6-2. After 90 min both T/C gages were reading below their calibration limit (approximately 1 to 2 μ) signaling the end of the test. However, before disconnecting this pipe in preparation for test No. 2, its temperature was raised in discreet steps to nominal values of 200, 400, and 600^oF. The pipe pressure response and temperature for this added sequence is also shown in Fig. 6-2. For comparison, the results of the constant 73^oF portion of test No. 1 are replotted in Fig. 6-3. Data points (x) and (●) reflect downstream and upstream pressure measurements, respectively. Where the data appear circled, i.e., (x) or (●), the lower calibration limit of the gage has been reached and actual pressures could be lower than that shown. Results of tests No. 2, 3, 4, 5, and 6 are shown in Fig. 6-4 through 6-8, respectively; they are plotted on semilog paper. To determine if the pressure was below 1- to 2- μ limit of the T/C gage an ionization gage was placed in the down stream location on the heat pipe side of the charge tube during test No. 6. Its reading, indicated on Fig. 6-8, was at 1.1 μ after 3 hr.

6.2.4 Theoretical considerations

6.2.4.1 Gas adsorption: The longitudinal grooved pipe used in these tests has an internal surface area of approximately 43 in.² (277. cm²) per ft of length. If the surface is assumed to be relatively rough, with approximately 6.5×10^{16} adsorption sites/sq in. (10^{16} sites/cm²), one complete layer of adsorbed gas would contain about 2.8×10^{18} molecules or 10^{-8} lbm-moles/ft of pipe length (1.5×10^{-8} kg-moles/m). If this amount of gas were left in the pipe, it could slowly desorb during pipe operation, blocking a portion of the condenser.

For example, if the working fluid were ammonia at 0^oF and the condenser was operating with a 1^oF temperature drop, a gas partial pressure of approximately 100 psf (4788 newt/m²) would be required to block a portion of the condenser. For the grooved pipe used in these tests, 10^{-8} moles would block slightly over 1 in. (2.54 cm) at these conditions. While this is a conservative calculation, it seems

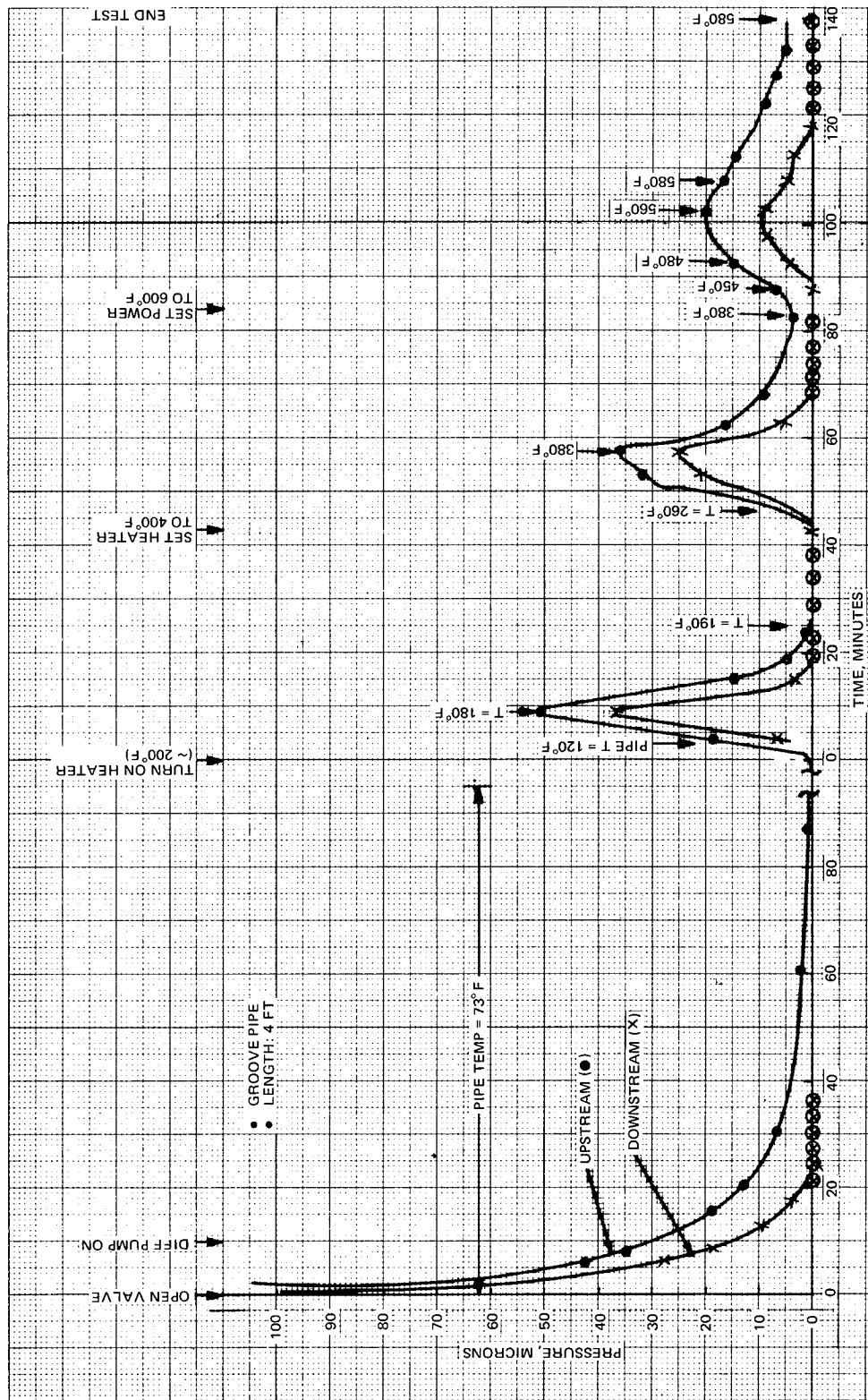


Fig. 6-2 Test Number 1 (With Post-Heating)

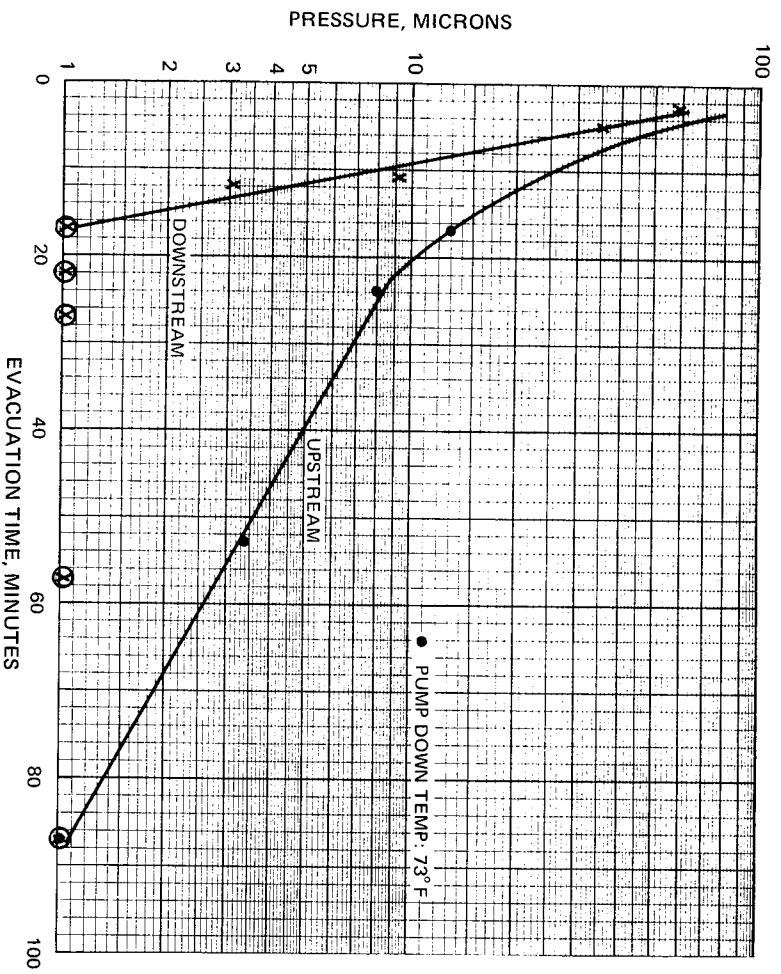


Fig. 6-3 Pumpdown Data - 4-Ft Grooved Pipe, 73° F

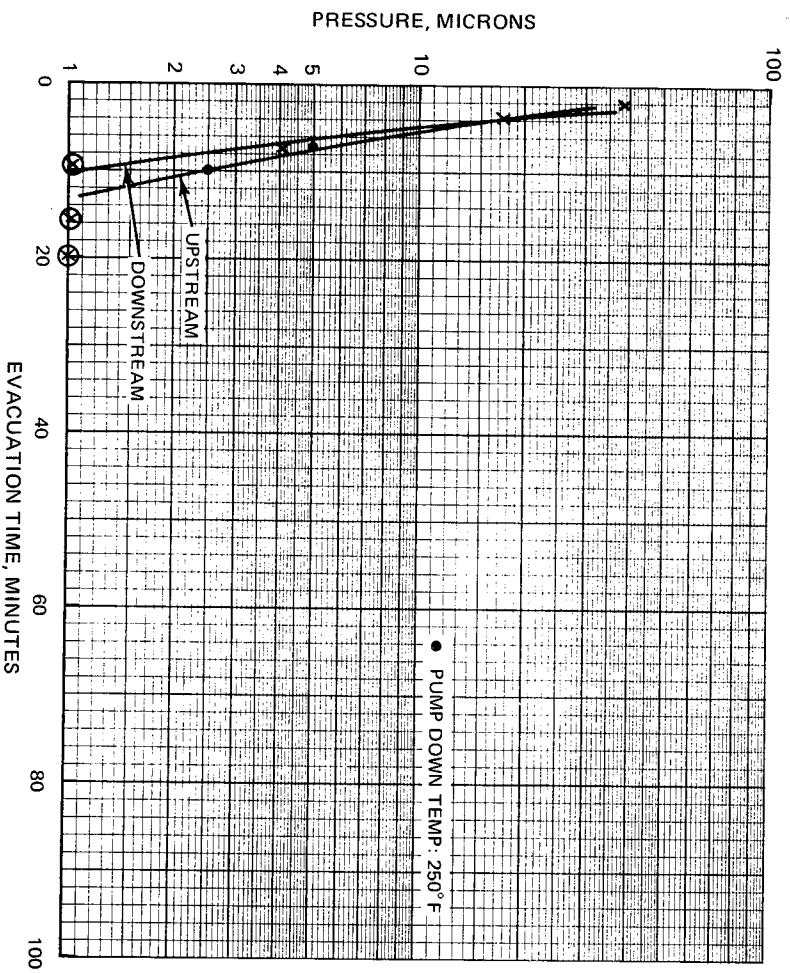


Fig. 6-4 Pumpdown Data - 4-Ft Grooved Pipe, 250° F

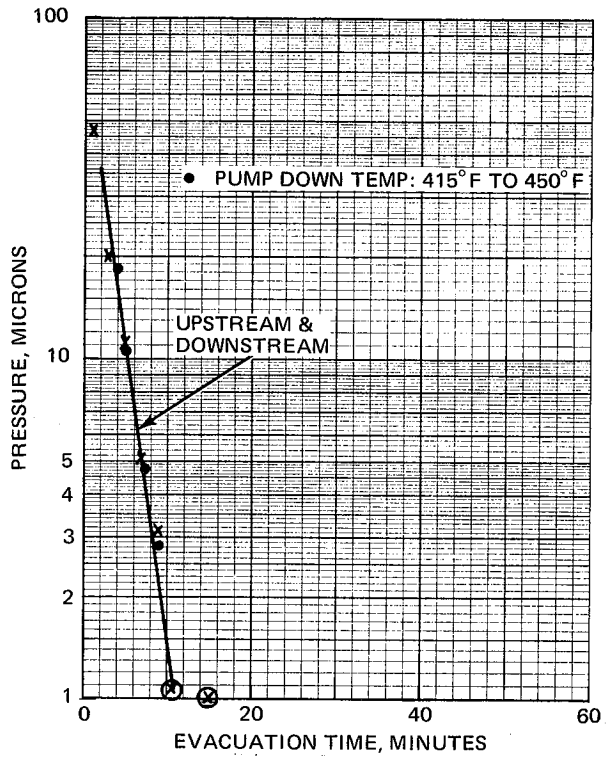


Fig. 6-5 Pumpdown Data - 4-Ft Grooved Pipe, 415 - 450° F

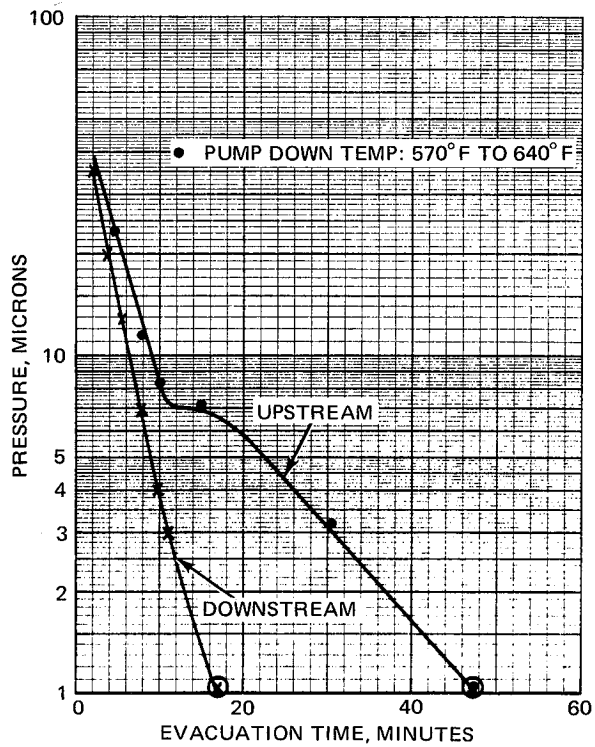


Fig. 6-6 Pumpdown Data - 4-Ft Grooved Pipe, 570-640° F

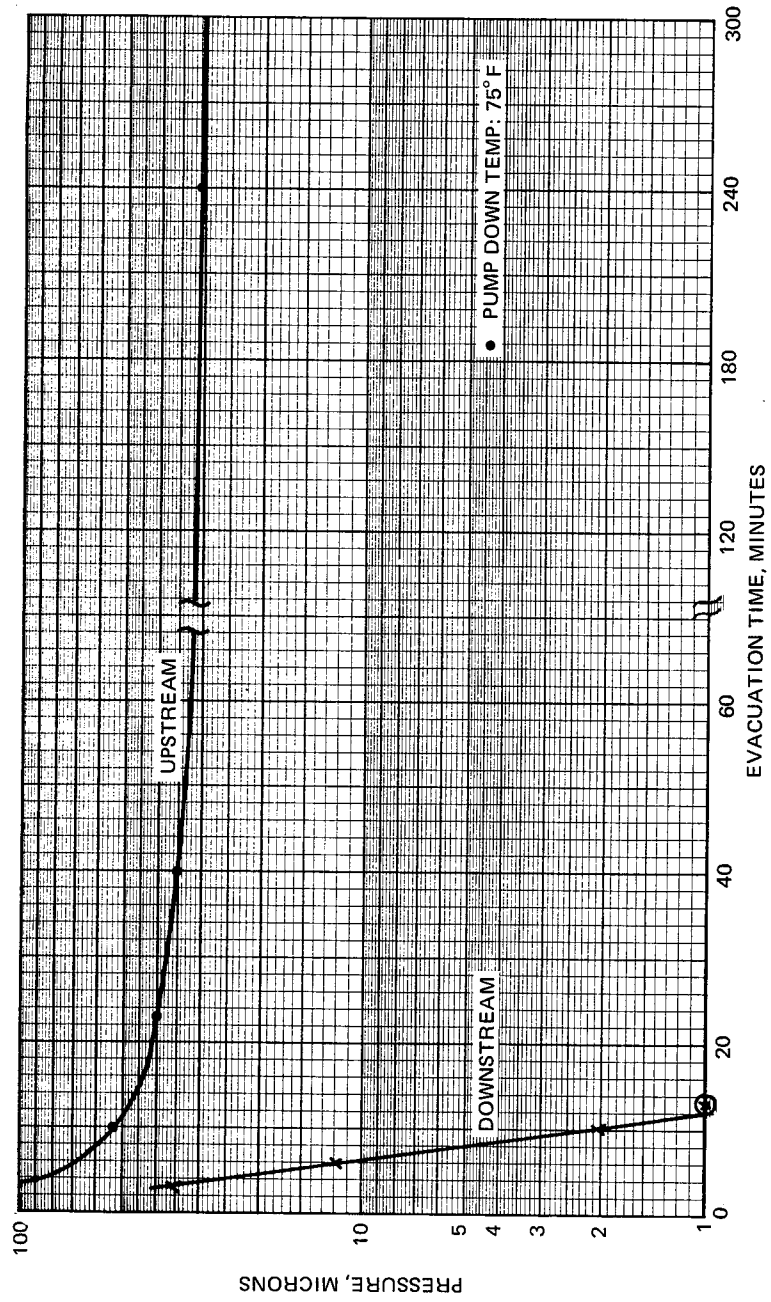


Fig. 6-7 Pumpdown Data - 10-Ft Grooved Pipe, 75°F

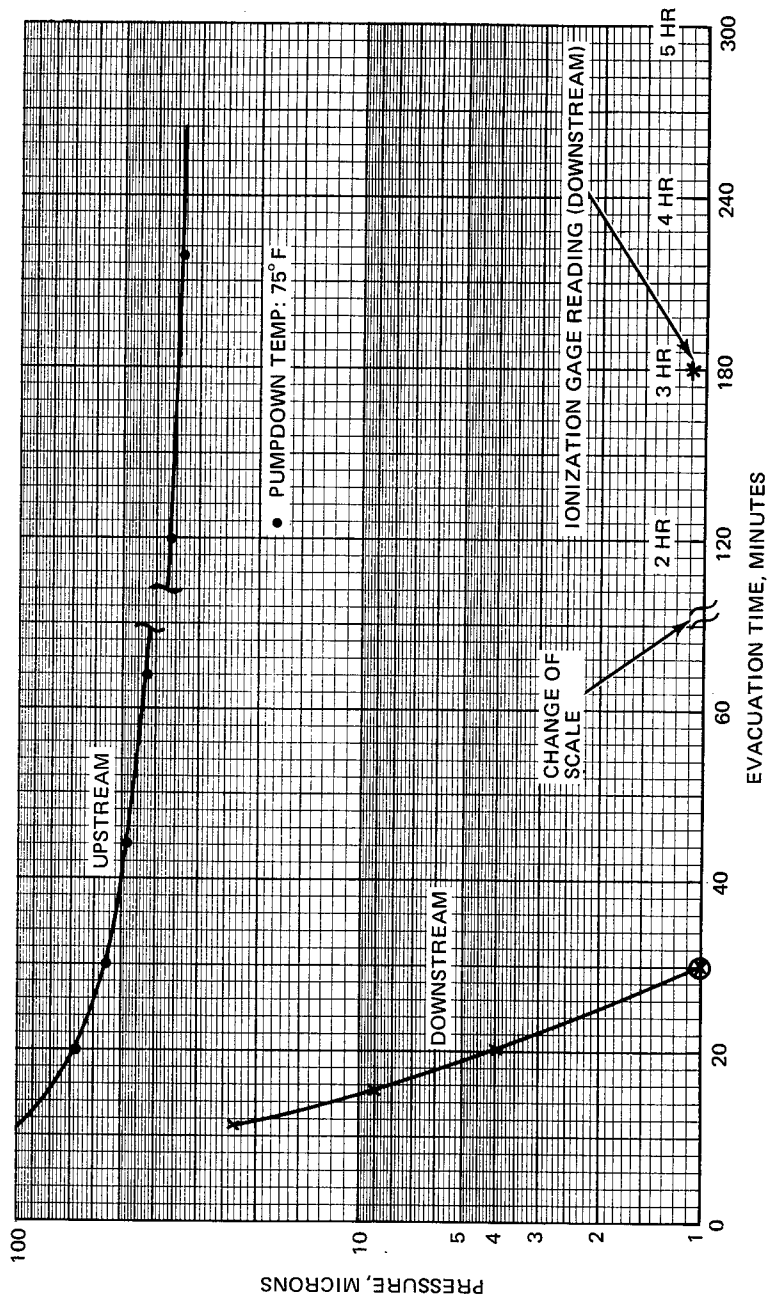


Fig. 6-8 Pumpdown Data - 10-Ft Grooved Pipe with Screen, 75°F

desirable to pumpdown to a condition where the remaining adsorbed gas is less than a monolayer.

The pressure required for desorption is a value low enough to make the mean time between arrivals for gas molecules incident on the adsorption site large compared with the residence time of molecules at the adsorption site.

A characteristic vibration rate for molecules in a crystal lattice is on the order of 10^{13} cycles/sec (ref. 34). The probability of desorption during a single vibration cycle is $e^{-E_o/kT}$. The mean residence time for a molecule on an adsorption site, in seconds, is then given approximately by the relation

$$\tau_{RES} = 10^{-13} e^{E_o/kT}$$

where E_o = binding energy (ev), k = Boltzman's Constant (8.61×10^{-5} , ev/ $^{\circ}$ K), and T = absolute temp, $^{\circ}$ K.

The time interval in seconds, between collisions for molecules from the gas incident on the adsorption site is given approximately by the relation:

$$\tau_{INC} = \frac{N_s \sqrt{MT}}{3.513 \times 10^{19} P_{\mu}}$$

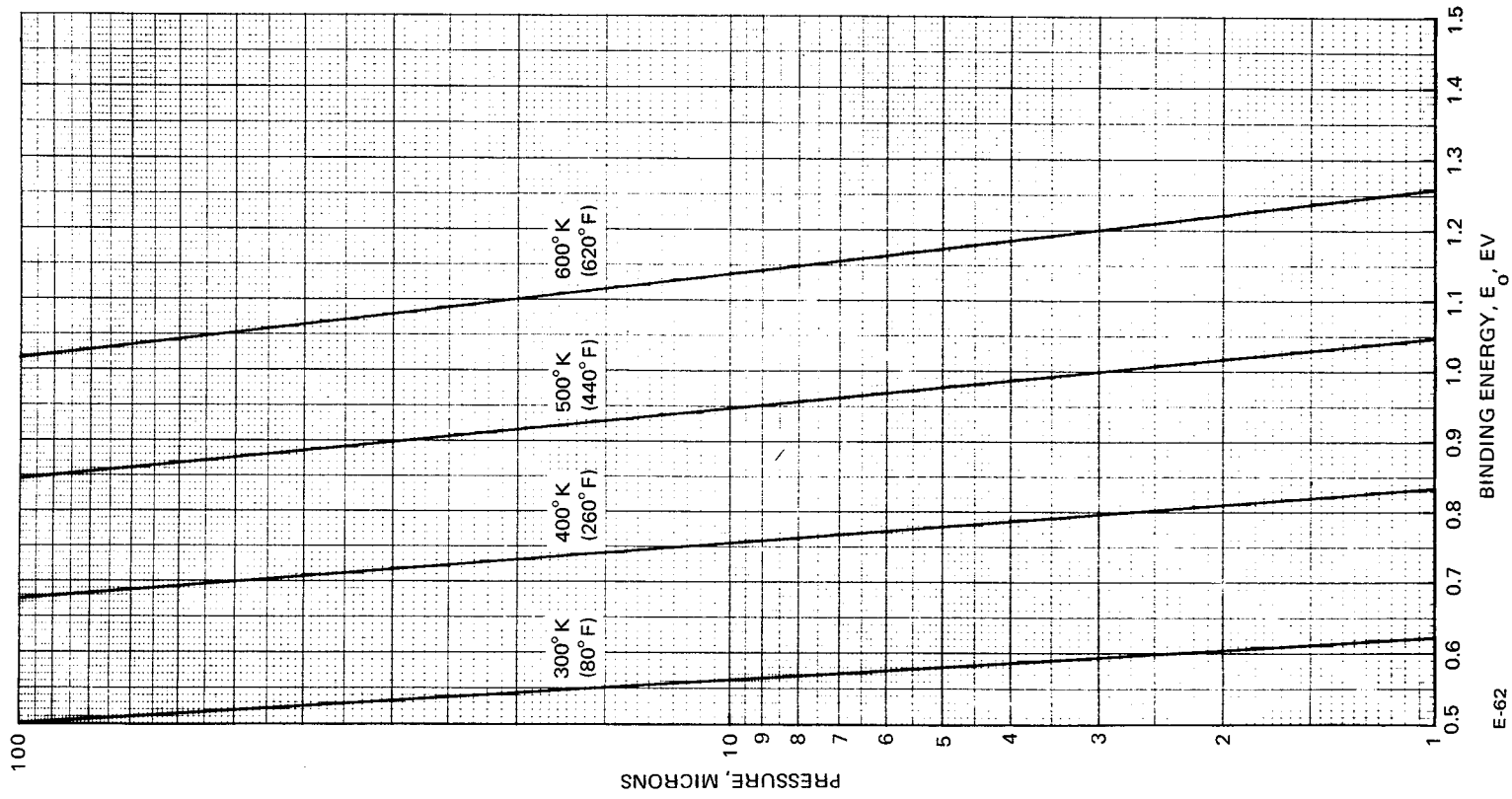
where P_{μ} is the gas pressure in microns. For a molecular weight of 28 (nitrogen) and a rough surface with $N_s = 10^{16}$ sites/cm² this reduces to

$$\tau_{INC} = 1.51 \times 10^{-3} \frac{\sqrt{T}}{P_{\mu}}$$

The pressure for which the incident time is, say, 10 times greater than the residence time, i.e., $\tau_{INC} = 10 \times \tau_{RES}$ is given by:

$$P_{\mu} = 1.51 \times 10^9 \sqrt{T} e^{-E_o/kT}$$

The pressure is seen to depend on binding energy and temperature. For pressures below the value given by this relation, desorption should be substantially complete. The relation is shown plotted for 80, 200, and 400 $^{\circ}$ F in Fig. 6-9. Figure 6-9 may also be interpreted as indicating maximum binding energies for desorption at a given



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Fig. 6-9 Pressure Level for Significant Desorption vs Binding Energy for Several Pipe Temperatures

pressure. Note that the maximum residence time associated with these curves (400° F and 1.1 ev) is 0.037 sec., hence only a short time at pressures below the curve values should result in significant depopulation.

Data presented by Armbruster and Austin (ref. 35) for physical adsorption of oxygen on clean steel surfaces indicates binding energies in the range of 0.15 ev. Similar data by Armbruster (ref. 35) for water vapor indicates binding energies of 0.55 to 0.59 ev.

The curves in Fig. 6-9 indicate that pumping pressures below 100 μ at 260° F or below 1 μ at 80° F should be adequate to remove the physically adsorbed gases.

Note also that at a pressure of 100 μ, the amount of matter in the gaseous state within the pipe, is only 3×10^{-10} moles/ft (10^{-9} moles/m) of grooved pipe. This is more than an order of magnitude less than a single monolayer on the walls. Hence, changes in mass in the gaseous state can be neglected in pumpdown calculations.

6.2.4.2 Pumpdown rate: During pumpdown, the flow through the pipe and pinch-off tube varies from continuum flow initially to free molecular flow at the low pressure near the end of pumpdown. The continuum flow takes place relatively quickly, and free molecular flow applies for most of the time. One criteria for applying free molecular flow relations for flow in a long pipe is that the mean free path be equal to or greater than the pipe hydraulic radius. The mean free path for rigid spherical molecules is:

$$L = \frac{R}{\sqrt{2} (\pi \sigma^2) N_A} \cdot \frac{T}{P}$$

where R = universal gas constant

$\pi \sigma^2$ = molecular collision cross-section

N_A = Avogadro's number.

For water vapor at room temperatures, this reduces to

$$L_{H_2O} = \frac{1.33}{P_{\mu}}, \text{ in.}$$

where $P\mu$ is the pressure in microns.

For the pinch-off tube (1/16 in. i.d.), the mean free path equals tube radius $P\mu = 42 \mu$. For the longitudinal grooved pipe, the effective hydraulic radius, allowing for the extended internal surface area, is approximately 0.065 in. (0.165 cm), which equals the mean free path at about 20μ pressure. Below these pressures, free molecular flow equations apply.

For free molecular flow through long tubes of constant cross-sectional area, the volumetric flow rate (sometimes termed molecular conductance) is:

$$U = \frac{1}{6} \sqrt{\frac{2\pi RT}{M}} \cdot \frac{d^3}{l} \quad \text{ft}^3/\text{sec}$$

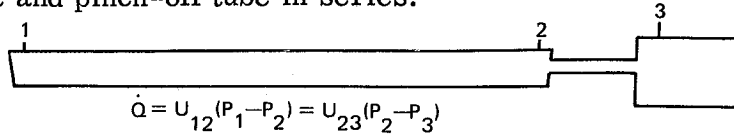
where M = molecular weight, d = tube hydraulic diameter, and l = tube effective length.

Clearly, flow rate depends on d^3/l . Values for the pinch-off tube and the various pipes tested are given in Table 6-1. For the pipes, assuming total outgassing to occur uniformly over the length of the pipe, the effective length is taken as one-half the total length. Note, however, that at any instant of time the outgassing is very nonuniform over the pipe length. Outgassing occurs at the end closest to the pinch-off tube earlier than at the far end of the pipe.

TABLE 6-1. - FREE MOLECULAR GEOMETRY PARAMETER d^3/l

Tube or pipe	d, in.	l_{eff} , in.	d^3/l_{eff} , in. ²
Pinch-off tube	0.0625	3	8.14×10^{-5}
4-ft grooved pipe	0.216	24	42.8×10^{-5}
10-ft grooved pipe	0.216	60	17.1×10^{-5}
10-ft grooved pipe with spiral artery	0.025	60	0.026×10^{-5}

Considering pipe and pinch-off tube in series:



$$\dot{Q} = U_{12}(P_1 - P_2) = U_{23}(P_2 - P_3)$$

For P_3 negligibly small

$$\dot{Q} = P_1 \left(\frac{U_{12} \cdot U_{23}}{U_{12} + U_{23}} \right) = \frac{P_1}{6} \sqrt{\frac{2\pi RT}{M}} \frac{(d^3/l)_{hp}}{1 + (d_{hp}/d_{po})^3 (l_{po}/l_{hp})}$$

For example, assuming the off-gasing is predominantly water vapor, the four-foot grooved pipe gives:

$$\dot{Q} = 2.39 \times 10^{-4} P_1 \text{ micron-ft}^3/\text{sec}$$

For this pipe, one layer is equivalent to 8.6 micron-ft^3 . Therefore,

$$\dot{Q} = 16.7 \times 10^{-4} P_1 \text{ adsorbed layers/min}$$

where P_1 is expressed in microns.

From the pumpdown data the variation in $\ln P_1$ can be approximated by linear reactions with time. For

$$P_1(\tau) = c_1 e^{-C_2 \tau} \text{ and } \dot{Q} = c_3 P_1$$

$$Q = \int_{\tau_1}^{\tau_2} \dot{Q} d\tau = c_1 c_3 \int_{\tau_1}^{\tau_2} e^{-C_2 \tau} d\tau = -\frac{c_1 c_3}{C_2} \left[e^{-C_2 \tau_2} - e^{-C_2 \tau_1} \right]$$

or,

$$Q = \frac{c_3 [P_1(\tau_1) - P_1(\tau_2)]}{C_2}$$

For the 4-ft grooved pipe at room temperature, $C_2 \approx 0.187 \text{ min}^{-1}$ for P_1 values from 30 to 9μ and 0.329 min^{-1} below 9μ (Fig. 6-3). The amount of gas removed from the pipe in going from 30 to 1μ is then

$$Q = 16.7 \times 10^{-4} \left[\frac{(30-9)}{0.187} + \frac{(9-1)}{0.0329} \right] = 0.59 \text{ molecular layers}$$

Assuming the slope below 1μ holds at 0.0329 min^{-1} , the remaining gas in the pipe which might be removed by additional pumping is equivalent to

$$Q = \frac{16.7 \times 10^{-4}}{0.0329} = 0.051 \text{ layers}$$

This is certainly a tolerable level for NH_3 at 0°F .

6.2.5 Discussion of experimental results.

6.2.5.1 Test 1, 4-ft axial grooved pipe: The initial pumpdown curves at room temperature are shown in Fig. 6-2 and 6-3. The ratio of upstream to downstream pressure increases with time. This probably reflects a shift in the region of active off-gasing, with desorption starting at the downstream end and gradually proceeding to the upstream end. The slope of the upstream pressure curve flattens below about 10 microns, probably reflecting the decrease in volumetric flow rate associated with transition to the free molecular flow region. The low pressure may also be raising the net off-gasing rate by reducing the rate of incidence of molecules on each adsorption site.

As stated in the preceding discussion, the net out-flow of gas associated with the upstream pressure drop from 30 to 1μ is estimated to be about 60% of a monolayer. Additional pumping at room temperature would only remove an additional 5% of a monolayer.

From Fig. 6-9, the off-gasing associated with the room temperature pumpdown involves binding energies below 0.6 eV, and is probably mostly water vapor. After reaching upstream pressures of about 1 micron, the pipe was heated in successive steps to 180, 380, and 580°F . As shown in Fig. 6-2, significant off-gasing occurred with each step, corresponding to binding energies of about 0.7, 1.0, and 1.2 eV. The binding energies for aluminum hydrates, i.e., $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, $\text{Al}_2\text{O}_3 \cdot (3\text{H}_2\text{O})$, and $\text{Al}(\text{OH})_3$, straddle this range when the water molecules are released directly to the vapor state.

6.2.5.2 Test 2, 4-ft axial grooved pipe 250^oF: The pumpdown curve is shown in Fig. 6-4 and can be approximated by the relation

$$P_1 = 60e^{-0.315\tau} \mu$$

where τ = time in minutes.

The instantaneous outflow rate is estimated to be

$$\dot{Q} = 2.77 \times 10^{-4} P_1 \quad \mu \text{-ft}^3/\text{sec}$$

giving a total mass evacuated of

$$Q = 2.77 \times 10^{-4} (30-1)/0.315 = 0.0255 \quad \mu \text{-ft}^3$$

between 30- and 1- μ upstream pressure. This is equivalent to 9.4×10^{-11} lb-moles or 2.97×10^{-3} layers.

Clearly very little off-gasing occurred during pumpdown below 30 μ pressure at 250^oF. It may be that the physically adsorbed water has been vaporized before pumpdown, and that little breakdown of hydrates occurs during pumpdown.

6.2.5.3 Test 3, 4-ft axial grooved pipe, 415 to 450^oF: The pumpdown curve for this test is shown in Fig. 6-5. The results are very similar to Test 2 (Fig. 6-4) and also indicate negligible off-gasing during pumpdown. The off-gasing which occurs between 260 and 380^oF (Fig. 6-2) must have been substantially completed before the start of pumpdown.

6.2.5.4 Test 4, 4-ft axial grooved pipe, 570^oF to 640^oF: This test involved a temperature change from 570 to 640^oF during pumpdown and significant off-gasing occurred (Fig. 6-6). The total mass removal amounted to about 1/3 of a monolayer, probably as a result of decomposition of aluminum hydrates. This is consistent with the shape of the fluid pumpdown curve in Fig. 6-2, which shows a relatively slow drop in pressure (indicative of off-gasing) above 560^oF.

6.2.5.5 Test 5, 10-ft axial grooved pipe, 75° F: This test (Fig. 6-7) indicates much more internal flow resistance than might be anticipated based on free molecular flow considerations. The downstream pressure reached a level of 1μ after approximately 12 min, indicating a total mass flow equivalent to off-gasing 0.2 layer, and an instantaneous flow rate of less than 0.05 layer/hr. The upstream pressure stayed above 30μ out to 5 hr. A 30μ pressure difference across the full 10-ft length should produce a flow rate equivalent to off-gasing about one layer/hr. It is also possible that one of the gages is not reading correctly. Note that a leak at the upstream gage would not explain the difference, since this should be reflected in downstream pressure readings of about 5μ .

6.2.5.6 Test 6, 10-ft grooved pipe with spiral artery 75° F: This pipe has a screen surface area approximately seven times the extended internal surface area of the grooved tubing. Consequently, its internal flow conductance (proportional to d_n^3/l_{eff}) is more than two orders of magnitude less than the pipe without screening. Also, the screen surface area provides an additional source of gas which must be removed. A monolayer of gas in this case corresponds to about 6×10^{-7} lb-moles.

The downstream pressure pumpdown curve (Fig. 6-8) below 50μ indicates a net overflow of about 0.2×10^{-7} lb-moles, or 3% of a monolayer. The upstream pressure fell very slowly to a value of about 35μ after 3.5 hr. At this pressure, the net outflow from the pipe, because of the high internal flow resistance, is only 4×10^{-10} lb-moles/hr, or about 0.07% of a monolayer/hour, based on mean effective length. The downstream pressure was off-scale at this condition, but would only have to be about 0.15μ to be consistent with this flow rate. The actual outflow rate was probably higher however, since the outgassing was occurring close to the downstream end. This is confirmed by a subsequent pumpdown with an ionization gauge attached. While a pressure-time history was not obtained, the downstream pressure was about 1.1μ after 3 hr and was dropping very slowly.

It seems clear that extremely long times (more than a month) are required for room temperature pumpdowns for screen artery pipes. A more realistic approach is to raise the temperature to desorb the internal surfaces while pumping. For example, at 640^oF and 35 μ pressure, the internal surfaces should be relatively clean and the amount of material in the gas phase is only 5×10^{-10} lb-moles, equivalent to less than 0.1% of a monolayer.

6.2.6 Conclusions and recommendations.

For the four ft grooved pipe, pumpdown times of 20 min at constant elevated temperature are adequate using the existing pinch-off tube.

Significant desorption seems to occur at temperatures in the 570 to 640^oF range. Presuming this to be hydrate or hydroxide decomposition, it is recommended that pumpdown temperatures be near 640^oF if possible. Experiments should be conducted to determine the species released in this temperature range, to provide a basis for possible long-term effects if pumpdown is conducted at lower temperatures.

The data for the 10-ft (3.048 m) grooved pipe tests are not consistent with theory or with results from any of the other pumpdown tests. Theory indicates pumpdown times of less than two hours at constant elevated temperature should be adequate, but this remains to be confirmed by test data.

Artery wick heat pipes can only be internally cleaned by pumpdown at temperatures high enough to desorb the internal surfaces. The use of pressures below 30 μ to induce desorption will result in a gas load which cannot be removed in reasonable time by pumping.

The 1/16 in. (0.159 cm) diameter x 3 in. (7.620 cm) long charge tube provides an acceptable flow resistance for pumpdown of 1/2 in. (1.270 cm) diameter heat pipes, with resistance comparable to a 20-ft grooved pipe.

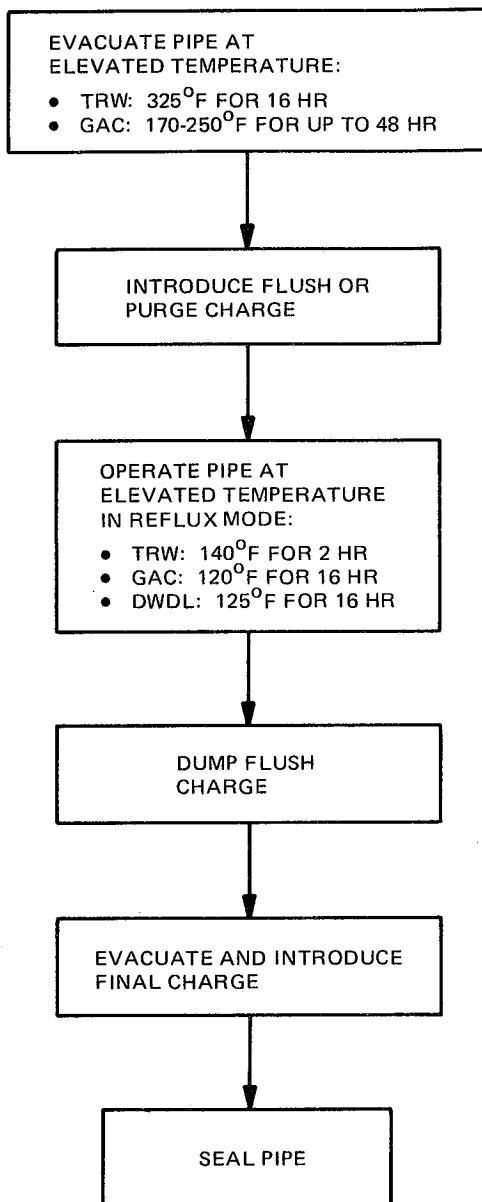
6.3 Discussion of Evacuation and Charging Techniques

6.3.1 High Pressure Fluids. - In general, high pressure fluids such as ammonia, Freon 14, etc, have low boiling points and exist in the vapor phase at room temperature and pressure.

The overall evacuation and charging procedure used by Grumman, TRW, and DWDL/MDAC for these fluids is shown in Fig. 6-10. Initially, the pipe is evacuated, typically on a 4-in. Veeco pumping station at a station pressure of about 10^{-6} mm Hg. Heaters wrapped around the pipe provide the elevated temperatures at which evacuation occurs. A schematic of the setup is shown in Fig. 6-11. The temperatures shown in Fig. 6-10 are representative for aluminum tubes. TRW bakes-out at about 325°F for 16 hr while Grumman bakes out at a lower temperatures of 170 to 250°F , but for a longer time of up to 48 hr. Although higher evacuation temperatures may be beneficial in removing additional adsorbed molecules, loss of mechanical properties of aluminum can occur at temperatures in the 300°F range. Fig. 6-12 and Fig. 6-13 show the effects of elevated temperature exposure on the room-temperature ultimate and yield strength of aluminum 6061-T6 (ref. 36). It is seen that loss of strength begins to occur at a temperature of 380°F for 1/2 hr exposure.

Typically a 1/16 in. (0.159 cm) i.d. tube, about 4 in. (10.160 cm) long, serves as the charge (pinch-off) tube. Based on the results presented in the previous section, this size tube is mildly restrictive during pumpdown for 1/2 in. (1.270 cm) d pipes. A technique which avoids the use of a small diameter charge tube will be presented later.

After evacuation, a flush or purge charge of working fluid is introduced. The pipe is then operated, usually in a reflux mode, at an elevated temperature for the times shown in Fig. 6-10. The flush charge acts as a final cleaning agent, which probably removes some adsorbed molecules. However, little is known about the effectiveness of varying the time, or temperature of the refluxing operation. It is,



Note: Temperatures shown are for aluminum envelopes.

Fig. 6-10 Over-All Evacuation and Procedure Used by TRW, Grumman, and DWDL/McDonnell Douglas

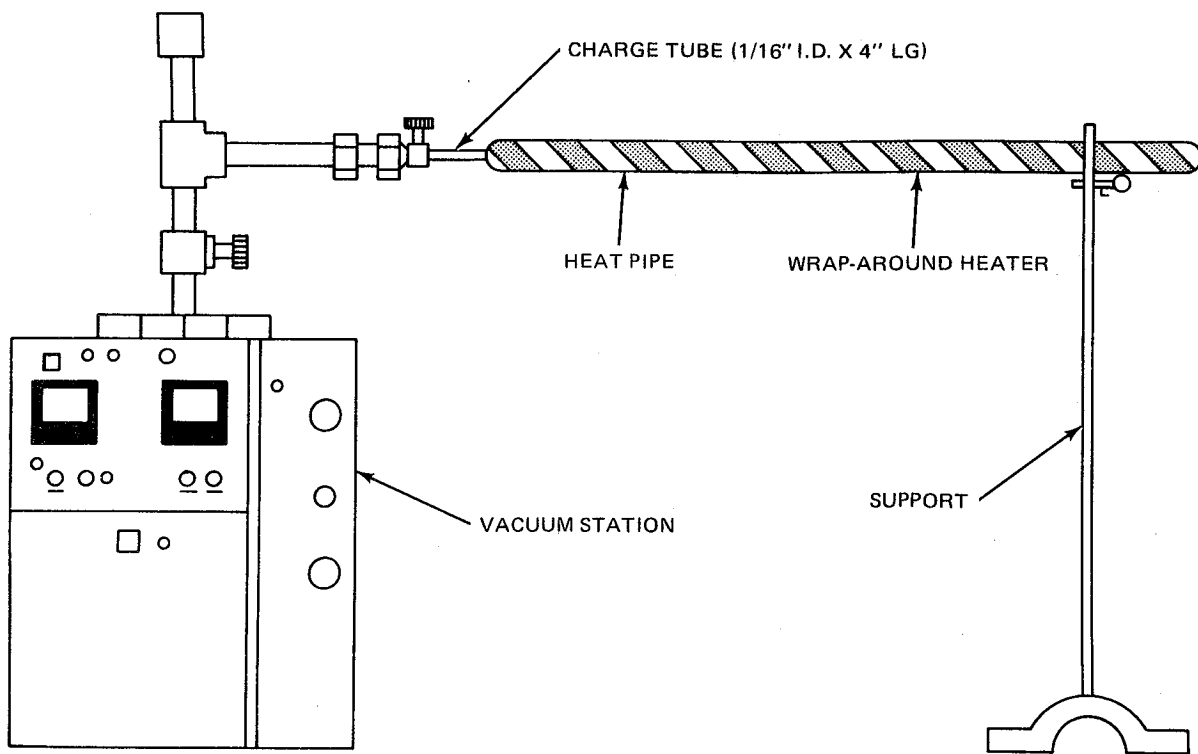


Fig. 6-11 Heat Evacuation Setup

felt however, that increasing the number of flushes to, say, three or four times will result in a cleaner pipe.

After refluxing the flush charge is dumped. This is done in two ways: through the vacuum station, or directly in air. Dumping into the vacuum station is particularly suited for low-pressure fluids, such as methanol or acetone, whose vapor pressure is below atmosphere at room temperature. Ammonia, though, can be dumped directly from the pipe into air preferably in a well vented hooded area. It is important when venting into air that a positive pressure always remain in the pipe, thereby preventing air from being sucked into the pipe and nullifying the benefits of the evacuation and reflux operations. This means that a small amount of ammonia should remain in the pipe, to be removed (through the vacuum station) during the subsequent evacuation and final charge operation.

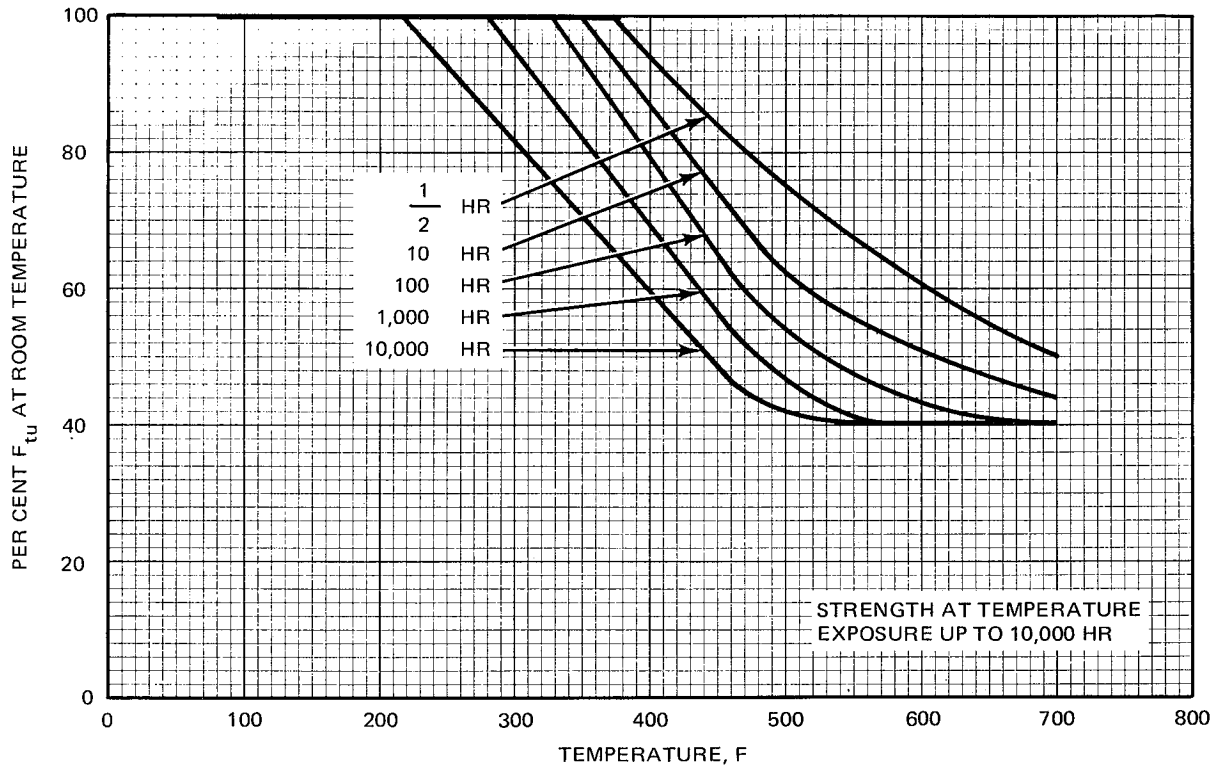


Fig. 6-12 Effect of Exposure at Elevated Temperature on the Room-Temperature Ultimate Tensile Strength (F_{tu}) of 6061-T6 Aluminum Alloy (All Products)

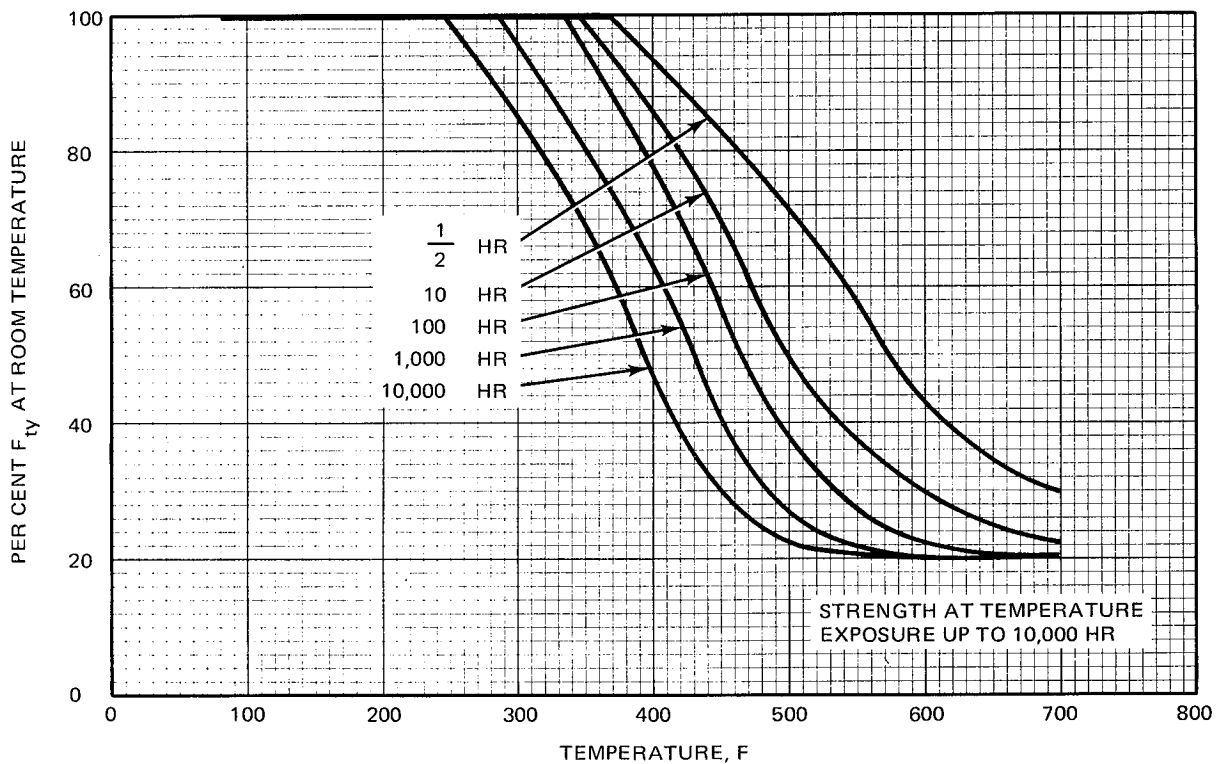


Fig. 6-13 Effect of Exposure at Elevated Temperatures Tensile Yield Strength (F_{ty}) of 6061-T6 Aluminum Alloy (All Products)

The final charge is introduced into the pipe by assembling the heat pipe, and charge bottle containing the required amount of fluid on the vacuum station (Fig. 6-14). Prior to this operation, the fluid charge may be processed. (Preparation of the fluid in the charge bottle is discussed in subsequent paragraphs.)

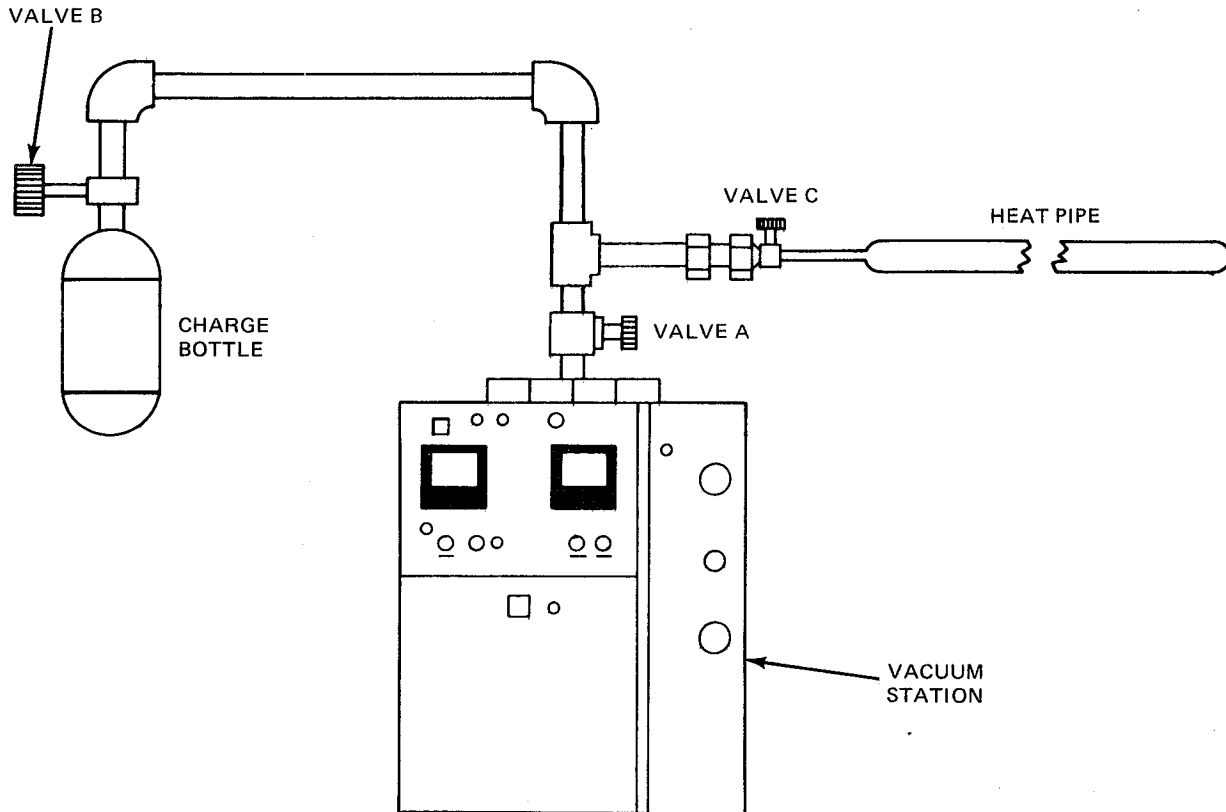


Fig. 6-14 Configuration for Charging High-Pressure Fluids

With valve A open and valves B and C closed (Fig. 6-14), the plumbing lines are pumped-down through the station. Heat is applied to the lines and fittings to aid outgassing. The small amount of flush charge is now dumped from the pipe into the station, by opening valve C. Next, valve A is closed and valve B opened, allowing vapor to distill into the pipe. By applying heat to the charge bottle and lines, and/or chilling the heat pipe, full transfer of the fluid into the pipe is achieved (except for the small amount of vapor in the charge bottle and lines). Valve C is then closed.

This method of fluid transfer is called vapor transfer or distillation. The amount of fluid transferred can be checked by determining the delta weight of the charge bottle and/or heat pipe.

An alternative method to vapor transfer which has been used to introduce fluid from the charge bottle into the pipe is called liquid transfer. The charge bottle is installed in an inverted position from that shown in Fig. 6-14, allowing liquid to sit directly above the valve. Opening the valve permits the vapor above the liquid to force the liquid into the pipe. This technique minimizes the introduction of contaminants which are more prevalent in the vapor phase of the fluid, such as non-condensable gases since these impurities would tend to remain in the charge bottle. On the other hand, fluid transfer by vapor distillation minimizes the introduction of contaminants which are more likely to be found in the liquid phase. For example, an oily contaminant reported to be found in the liquid phase of ammonia is dioctyl phthalate, (ref. 37). Although denied by the supplier, a concentration of approximately 130 ppm was apparently found in ultra-high purity ammonia whose advertised purity is 10 ppm or less. Vapor distillation would minimize the carry over of this impurity into the pipe. Periodic cleaning of the charge bottle would also be necessary to remove the oil which might otherwise accumulate in the charge bottle.

The overall charging procedure used by Dynatherm for the ATS satellite is given in Fig. 6-15. This procedure differs from that shown in Fig. 6-10 in that the evacuation (at elevated temperature) and flush operations are reversed. In Fig. 6-15 the flush charge is introduced and the pipe operated before the final high temperature evacuation. Both techniques appear to give similar results and, consequently, there is no significant advantage of one over the other.

It was mentioned earlier that the charge tube most commonly used is 1/16 in. (0.159 cm) inside diameter by about 4 in. (10. cm) long. This tube can be the limiting conductance in the pumpdown chain. A technique which avoids this restriction by allowing evacuation on the full pipe diameter has been used by Jet Propulsion

Laboratories and is schematically shown in Fig. 6-16 (ref. 38). Evacuation and charging of both ammonia and water have been successfully performed, by distilling the fluid into the pipe. Sealing is accomplished by screwing in the threaded cap and welding. (Refer to Section 8 for additional details.) The advantage of this technique is that it allows the pipe to be pumped down to a lower pressure, thereby aiding in the removal of adsorbed material. Pump-down times are also faster, an advantage for production situations.

6.3.2 Low pressure fluids. - Low pressure fluids such as methanol, acetone, Freon 21, etc, have higher boiling points and exist in the liquid phase at room temperature and pressure. The procedure used by Grumman and General Electric (ref. 39) is essentially the same; typically it is as follows:

- The pipe is set up on a vacuum station with a graduated charge container as shown in Fig. 6-17.
- With valve B closed, the pipe is evacuated at an elevated temperature of about 200^oF, for approximately 3 hr.
- Charge is introduced into graduated container.
- Valves A and C are now closed, and valve B opened to establish a tare (or zero) liquid level. Lines must be freed of vapor bubbles when establishing this level.
- Open valve C until desired charge is introduced, then close valve C.
- Operate pipe in a reflux mode with valve directed upward. If necessary, vent or "burp" pipe by quickly opening and closing valve C to rid pipe of unwanted noncondensables. Atmosphere into which pipe is vented must be lower than pipe pressure.
- Final charge weight can be obtained by venting excess fluid.

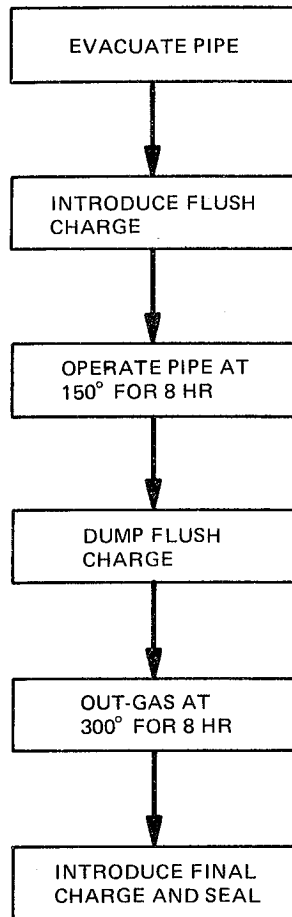


Fig. 6-15 Over-All Evacuation and Charge Procedure Used by Dynatherm for ATS

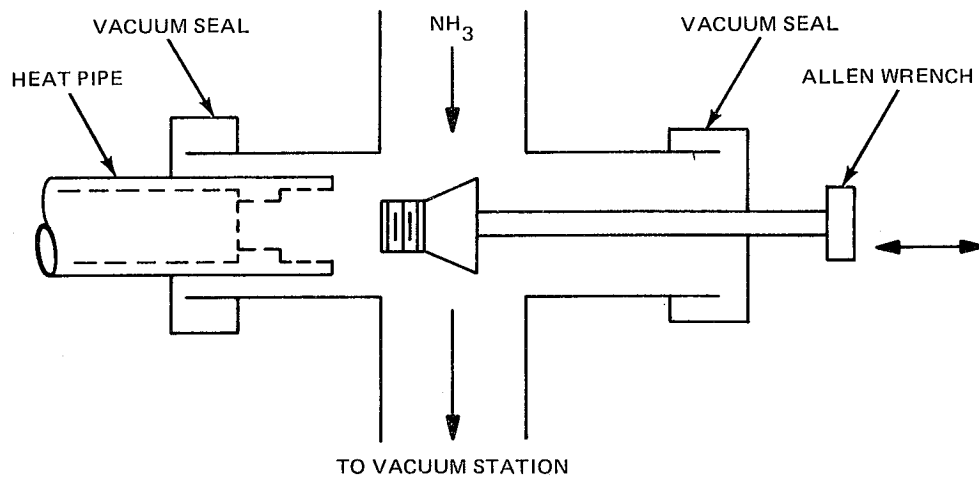


Fig. 6-16 Evacuation/Charging Configuration Used by JPL

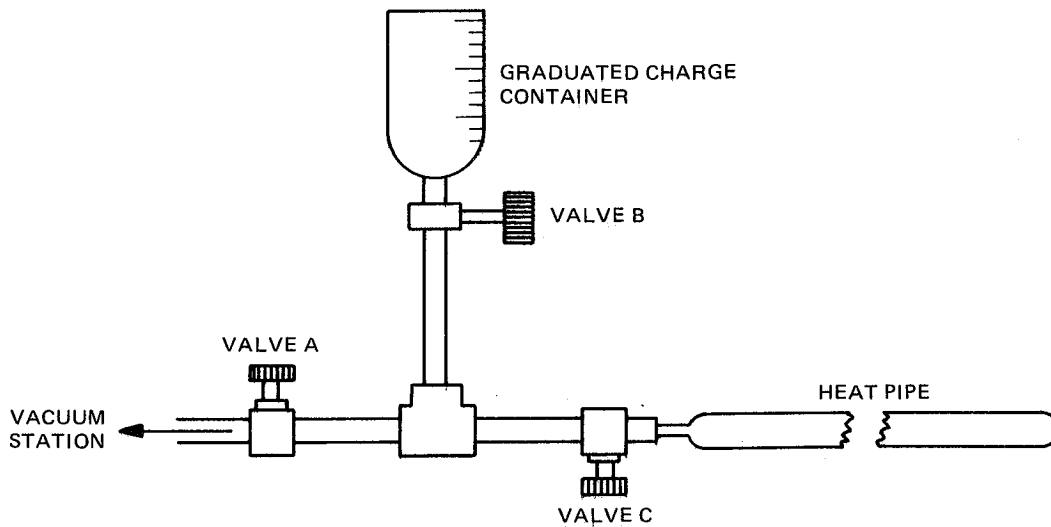


Fig. 6-17 Configuration for Charging Low-Pressure Fluids

This procedure is simple and is employed when it is not possible or practical to obtain ultra-high purity fluid. As seen, purification of the fluid is done within the pipe by refluxing and venting. This may have to be done a number of times until no noncondensables appear.

6.3.3 Charge bottle preparation. - Figure 6-15 shows a charge bottle containing the working fluid, such as ammonia, ready for transfer into the pipe. This section will describe techniques that are commonly employed in preparing or filling the charge bottle.

6.3.3.1 Vapor transfer: The supply cylinder and charge bottle are connected to the vacuum station as shown in Fig. 6-18. The charge bottle, if not new, is one that has only been used for this particular working fluid. During storage it is evacuated except for a small amount of working fluid. The charge bottle and lines are pumped down with heat applied to the lines. Fluid from the supply cylinder is next allowed to distill into the charge bottle which is chilled to accelerate the transfer. When a quantity of fluid larger than required to fill the pipe is transferred to the charge bottle, the valves are closed. The excess fluid in the charge bottle is to allow for

bleed off and residual fluid left in the lines after heat pipe charging. If no further processing is done, vapor is vented from the charge bottle to obtain the desired weight.

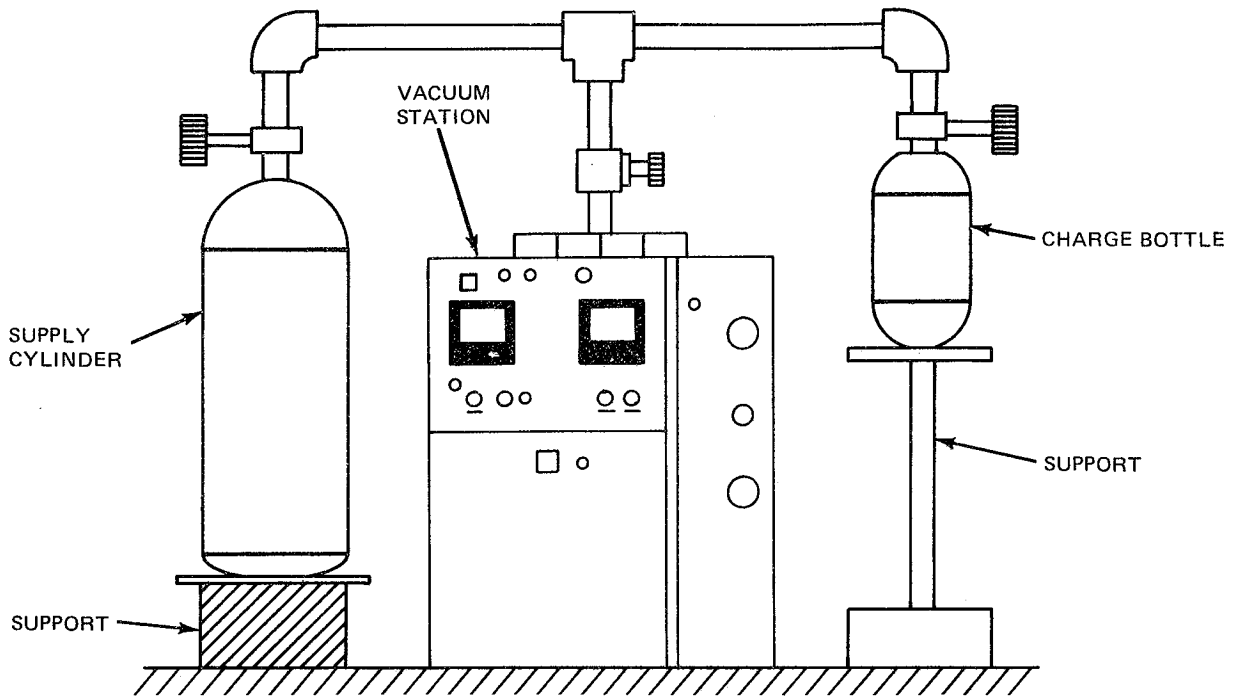


Fig. 6-18 Configuration for Charge Preparation

6.3.3.2 Liquid transfer: Liquid transfer may be accomplished by inverting the supply cylinder and tapping the liquid directly. As mentioned before, this technique may be useful if it is desired to minimize the transfer of noncondensables that are prevalent in the vapor phase, thereby avoiding any further fluid processing. Analysis of the supplier's fluid would be necessary to ensure that the purity level of the liquid is better than the vapor. A danger in using this technique is the possibility of completely filling the charge bottle with liquid, which, after it is sealed, can rupture as the liquid expands.

6.3.3.3 Processing of fluid: Noncondensables which are transferred to the charge bottle during vapor transfer may be removed by subjecting the fluid to repeated freeze/thaw cycles. A schematic of this processing technique is shown in Fig. 6-19. The fluid is frozen in the charge bottle (using, for example, liquid nitrogen). The space above the frozen charge is then open to the vacuum station. The station pressure will first increase and then decrease as it pumps out the mixture of vapor and gas. With the valves closed, the charge is next permitted to thaw, after which it is refrozen and again vented to the station. When the increase in port pressure is minimal, the process can be discontinued, since essentially no additional noncondensables are being removed. In processing ultra-high purity ammonia, typically two to four freeze/thaw cycles are necessary.

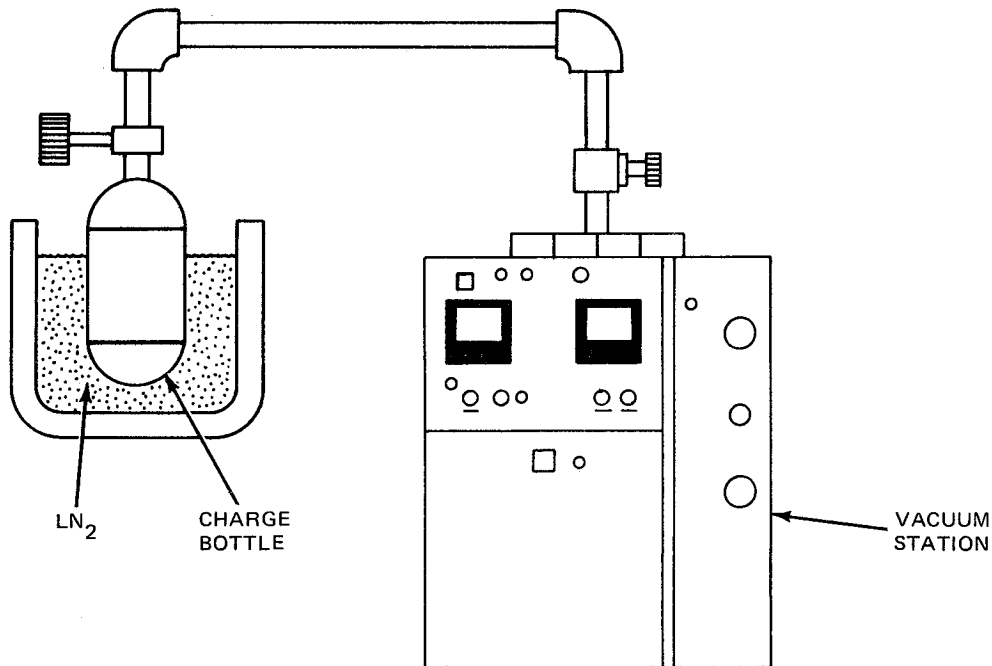


Fig. 6-19 Configuration for Freeze/Thaw Fluid Processing

6.4 Conclusions and Recommendations

Based on past experience, the overall charging procedure shown in Fig. 6-10 should be followed

Evacuate at the highest temperature practical to desorb surface contaminants. For aluminum, this can be up to about 350^oF (177^oC) if loss of strength cannot be tolerated. Otherwise, evacuation at about 640^oF (338^oC) would be beneficial. Experiments should be conducted to determine the species released in this temperature range to provide a basis for possible long-term effects if pumpdown is conducted at lower temperatures. For stainless steel, the optimum evacuation temperature is not known; however, a minimum value of at least 400^oF (204^oC) is suggested.

Evacuation time will depend on the pipe, wick and charge tube configuration, and cleaning procedure used. Tests may be necessary to determine pumpdown characteristics of individual designs (particularly long lengths and artery wicks). However, for a 0.5 in. (1.270 cm) diameter axially grooved 4-foot (1.219 m) long aluminum pipe using a 1/16 in. (0.159 cm) i. d. by 3 in. (7.620 cm) long charge tube, evacuation time of about 1 hr at elevated temperature is sufficient to remove most adsorbed gases. Although the data for a 10-ft (3.048 m) length of groove pipe is inconclusive, a conservative estimate of 4 hr at elevated temperature is suggested.

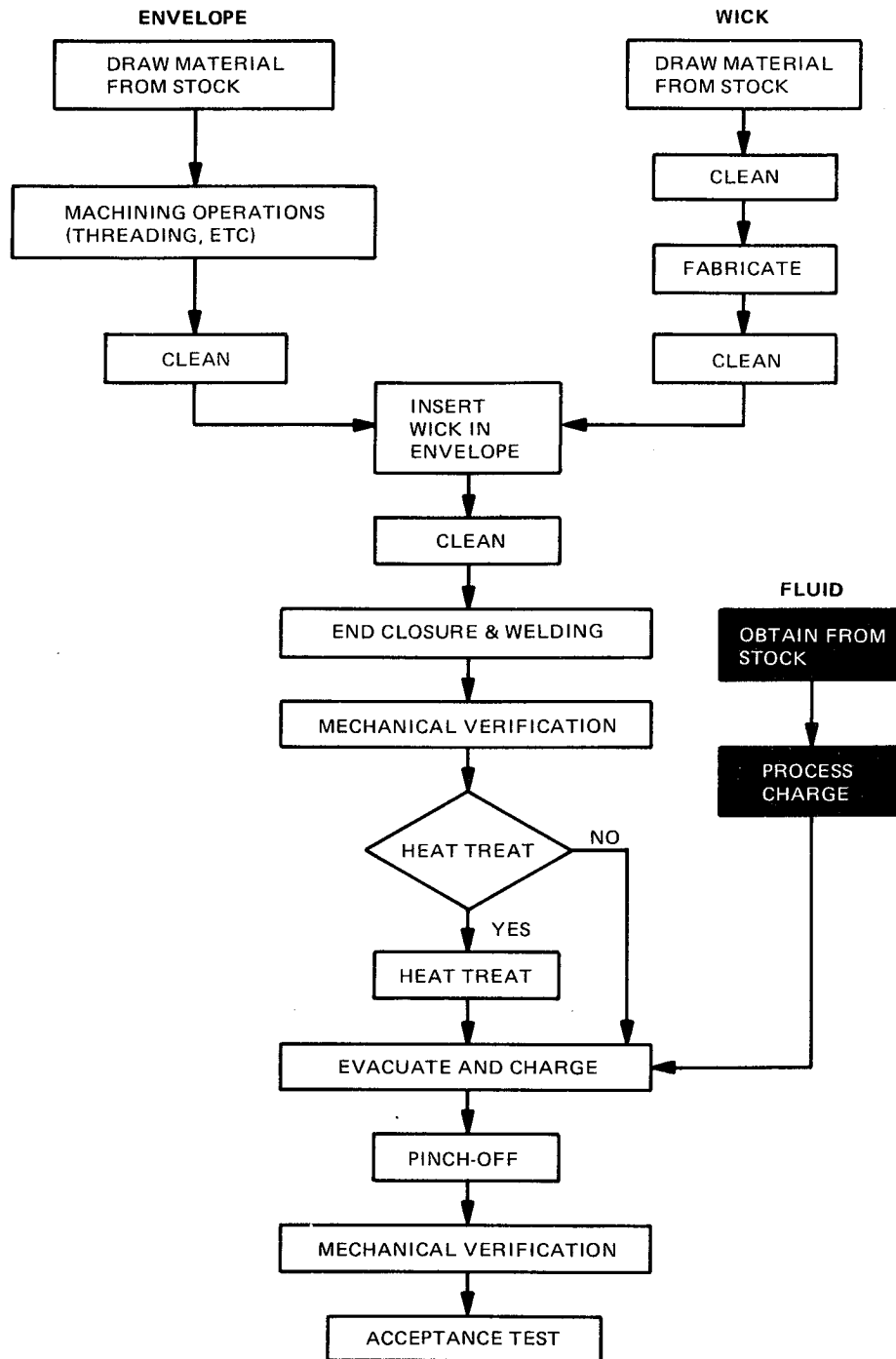
The 1/16 in. (0.159 cm) diameter by 3 in. (7.6 cm) long charge tube provides an acceptable flow resistance for pumpdown of 0.5 in. (1.270 cm) diameter pipes. The charge tube flow path has a relatively small resistance for artery wick pipes, and is mildly restrictive for groove pipes.

Refluxing one or more times for a few hours each is probably beneficial and should be done using purified fluid. However, further tests are recommended to confirm the benefits of multiple refluxing (it can be time consuming).

The same bottles, lines, fittings and valves should be used for charging a particular fluid to minimize the introduction of foreign contaminants.

The same supply cylinder should be used. For ammonia, this would mean returning the (near) empty cylinder to the supplier who would recharge it and return it back to the user. This will prevent the introduction of contamination from a foreign supply cylinder.

In general, vapor transfer of fluids is the safest and best technique with respect to fluid purity. The elimination of noncondensables which may carry over, can, if necessary, be accomplished by various techniques such as freeze/thaw, venting, etc.



7 - FLUID PURITY

7.1 Background

Should a manufacturer use 99.999% pure ammonia costing \$40 per pound, or will 99.99% pure ammonia costing \$2.50 per pound be satisfactory? What impurities are present in the ammonia? How will they affect heat pipe performance? These are some typical questions asked by both manufacturers and users of heat pipes concerning the requirements for the purity of heat pipe working fluids. These considerations can strongly affect both product reliability and cost.

The most prominent manifestation of impurities in a heat pipe is the accumulation of noncondensable gas in the condenser zone, with consequent loss of heat pipe conductance. Depending on the design and operating conditions, the presence of gas may not be serious and may go completely unnoticed. In other cases, significant blockage can occur; for some artery pipes, loss of pumping capacity can result.

Impurities may be in the pipe in the form of adsorbed gas molecules even before the working fluid is introduced. It may be brought in during the fluid transfer operation, or it may be present in the fluid itself. Often, the fluid purchased from the supplier may have significantly higher impurity levels than what was nominally specified.

Certain techniques are available to purify the fluid to a higher state than it is "as received" from the supplier. Additional cleaning may be necessary to satisfy functional requirements, or as a safeguard against uncertain impurity levels in the suppliers fluid.

This section explains how certain impurities affect heat pipe performance, where they come from, and how they can be minimized. It also presents updated materials compatibility data from recent life tests involving a variety of fluids and heat pipe materials.

7.2 Effects of Impurities on Heat Pipe Performance

In general, the impurities found in working fluids, such as ammonia, may consist of:

- Gases, such as nitrogen, oxygen, argon, carbon dioxide, carbon monoxide and methane
- Water
- Miscellaneous materials such as oils, hydrocarbons and non-volatile solids.

Of the miscellaneous materials, the most detrimental affect on heat pipe performance can be loss of wettability of the wick due to oily residues. As previously mentioned, a significant amount (130 ppm) of an oily contaminant was found in the liquid phase of ammonia and identified to be dioctyl phthalate. These materials, some of which may be soluble in the working fluid, may also adversely affect fluid properties, such as surface tension, wetting angle, and viscosity.

The presence of water in an aluminum or stainless steel pipe can cause corrosion, resulting in the loss of structural integrity. However, the quantities of water generally found in working fluids can be minimized by various purification techniques, some of which will be discussed later. The resultant water quantities, in terms of parts per million, are usually small enough so as not to present a serious corrosion loss-of-strength problem, since the corrosive reaction will generally cease when the water is consumed. The reaction products, however, may be far more serious in terms of noncondensable gas generated.

Gases generated from reactions as well as those present in the fluid may cause bubbles within artery wicks, thereby sharply reducing the pipe transport capacity. This is dependent on individual artery design and quantification of this problem is beyond the scope of this study. However, a significant problem common to all single-fluid heat pipes is the loss of conductance due to the accumulation of noncondensable gaseous products.

In the following paragraphs, calculations are presented that relate the amount of condenser blockage to pipe design and operating conditions. The amount of blockage will also be presented as a function of gaseous impurity to give the user a better understanding of what levels of impurity may be intolerable for his particular use.

7.2.1 Analysis of gas blockage. - In Fig. 7-1, the volume occupied by the noncondensables is, from the ideal gas law:

$$V = n_G RT_G / P_G \quad (1)$$

where: n_G = moles of noncondensable gas in pipe

R = gas constant

P_G = partial pressure of inert gas in length, ℓ .

P_G , furthermore, is the difference between the working fluid pressure in the active and inactive portions of the pipe, i.e.,

$$P_G = P(T_P) - P(T_G) \quad (2)$$

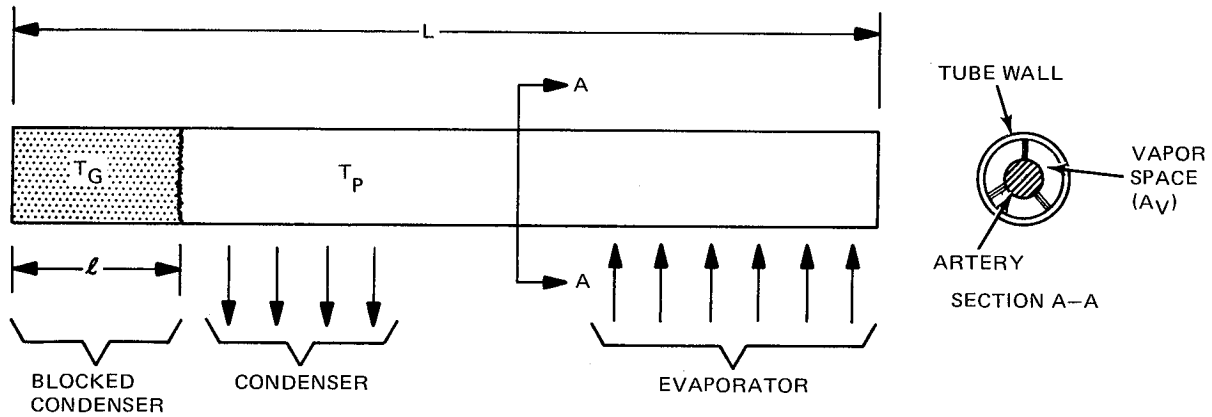
where: $P(T)$ = working fluid pressure at temperature T .

From Fig. 7-1, the gas volume can be related to the blocked length by

$$V = A_V \cdot \ell \quad (3)$$

Substituting (2) and (3) in (1) and solving for ℓ , yields

$$\ell = \frac{n_G RT_G}{A_V [P(T_P) - P(T_G)]} \quad (4)$$



ASSUME

- L = OVERALL PIPE LENGTH
- l = BLOCKED CONDENSER LENGTH
- PIPE CROSS SECTION IS UNIFORM
- A_V = CROSS SECTIONAL AREA OF VAPOR SPACE
- T_G IS THE TEMPERATURE OF THE GAS/VAPOR MIXTURE IN BLOCKED LENGTH. (WHERE THERE IS NO CONDENSATION OR CONDUCTION THIS IS THE ADIABATIC SINK TEMPERATURE.)
- T_P = PIPE VAPOR TEMPERATURE

Fig. 7-1 Schematic for Analysis of Gas Blockage

The moles of noncondensables can now be defined in terms of a working fluid impurity level, f ,

$$f = \frac{n_G}{n_P} \quad (5)$$

where: n_P = moles of working fluid in pipe

f = mole fraction of noncondensables in working fluid.

Substituting (5) into (4) and dividing by the overall pipe length, L , yields the blockage as a fraction of the total pipe length,

$$l/L = \frac{f n_P R T_G}{L A_V [P(T_P) - P(T_G)]} \quad (6)$$

If n'_p is defined as the heat pipe charge per unit length, i. e., $n'_p = n'_p/L$, then (6) becomes.

$$l/L = \frac{fn'_p RT_G}{A_v [P(T_p) - P(T_G)]} \quad (7)$$

This expression now relates the blockage to the operating conditions, T_p and T_G ; to pipe design parameters n'_p , A_v and working fluid; and to an impurity level factor, f .

7.2.2 Effect of heat pipe design and operating conditions on gas blockage. - In Fig. 7-2, the pipe blockage is presented as a function of the temperature difference between the operating and nonoperating sections for 0.5 in. (1.270 cm) axial groove ammonia heat pipe. An impurity content, f , of 0.0001 was assumed which is equivalent to 100 ppm (molar). The gases can be considered as being present in the charge fluid or as gas remaining in the pipe after evacuation.

The curve shows that for a fixed temperature difference ($T_p - T_G$), the blockage decreases at higher temperatures. Also, the blocked length increases for small differences in temperature between the pipe and gas temperature (thermal sink), such as, in the case of isothermalizing heat pipes. As an example, consider a 10-ft (3 m) long axial groove/ammonia heat pipe whose temperature (T_p) is 420°R, attached to a sink (T_G) at 400°R, i. e., $T_p - T_G = 20°R$. The blockage produced by an impurity level of 100 ppm would be 4.2% or 0.42 ft (5.0 in.) (12.7 cm). For an impurity level of 10 ppm (not shown) the blockage, which is proportional to f , would be 0.50 in. (1.27 cm).

The effect of a different pipe configuration is shown in Fig. 7-3, where a 0.5-in. (1.270 cm) spiral artery design is compared to the 0.5-in. groove design. Because of its smaller vapor space, the spiral design produces a greater blockage than the groove under the same conditions.

The effect of different working fluids is shown in Fig. 7-4. Ammonia, acetone and Freon-21 are plotted for the 0.5 in. axial groove design. It is seen that ammonia

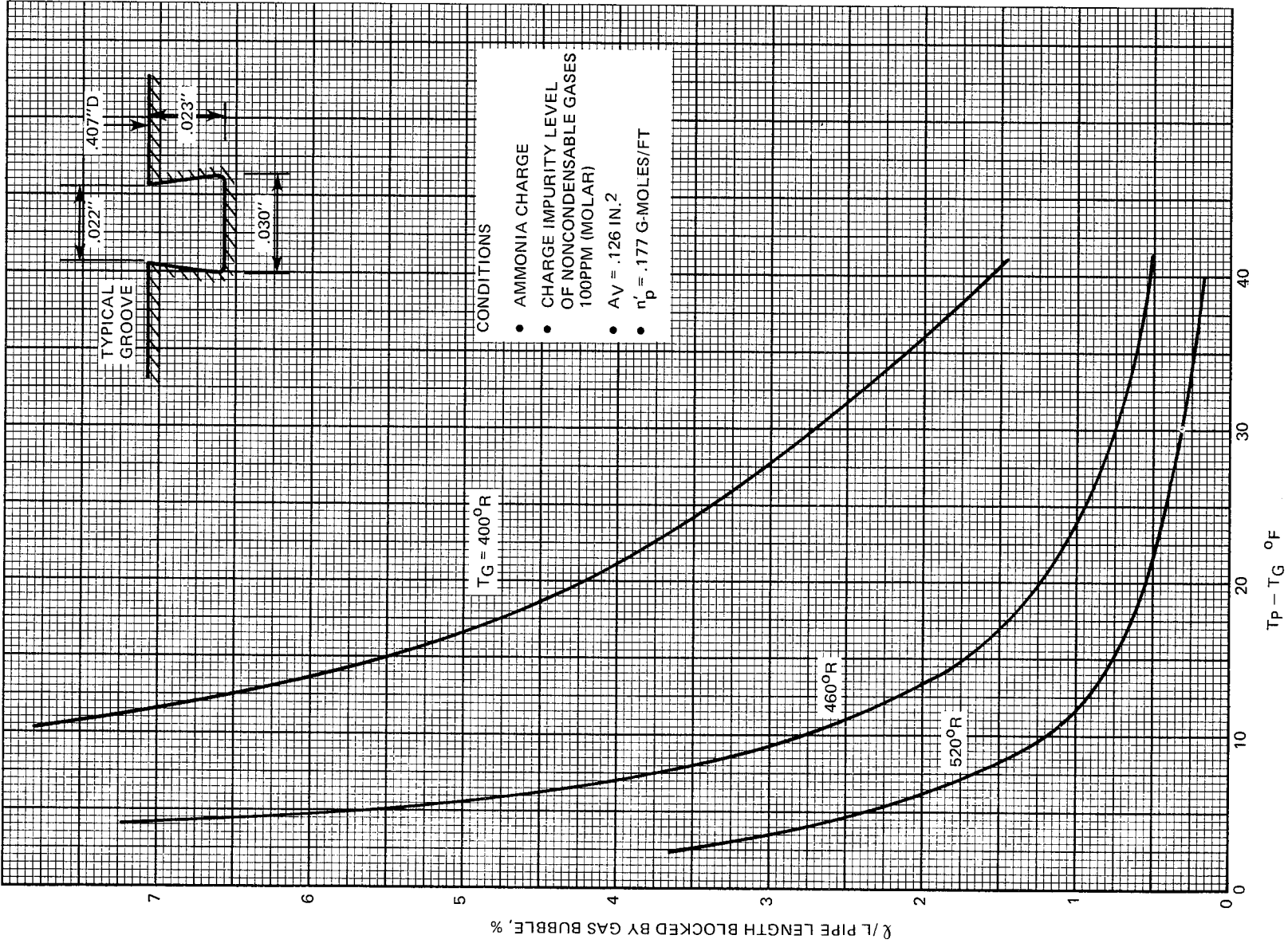


Fig. 7-2 Gas Blockage in a Typical Grooved Heat Pipe

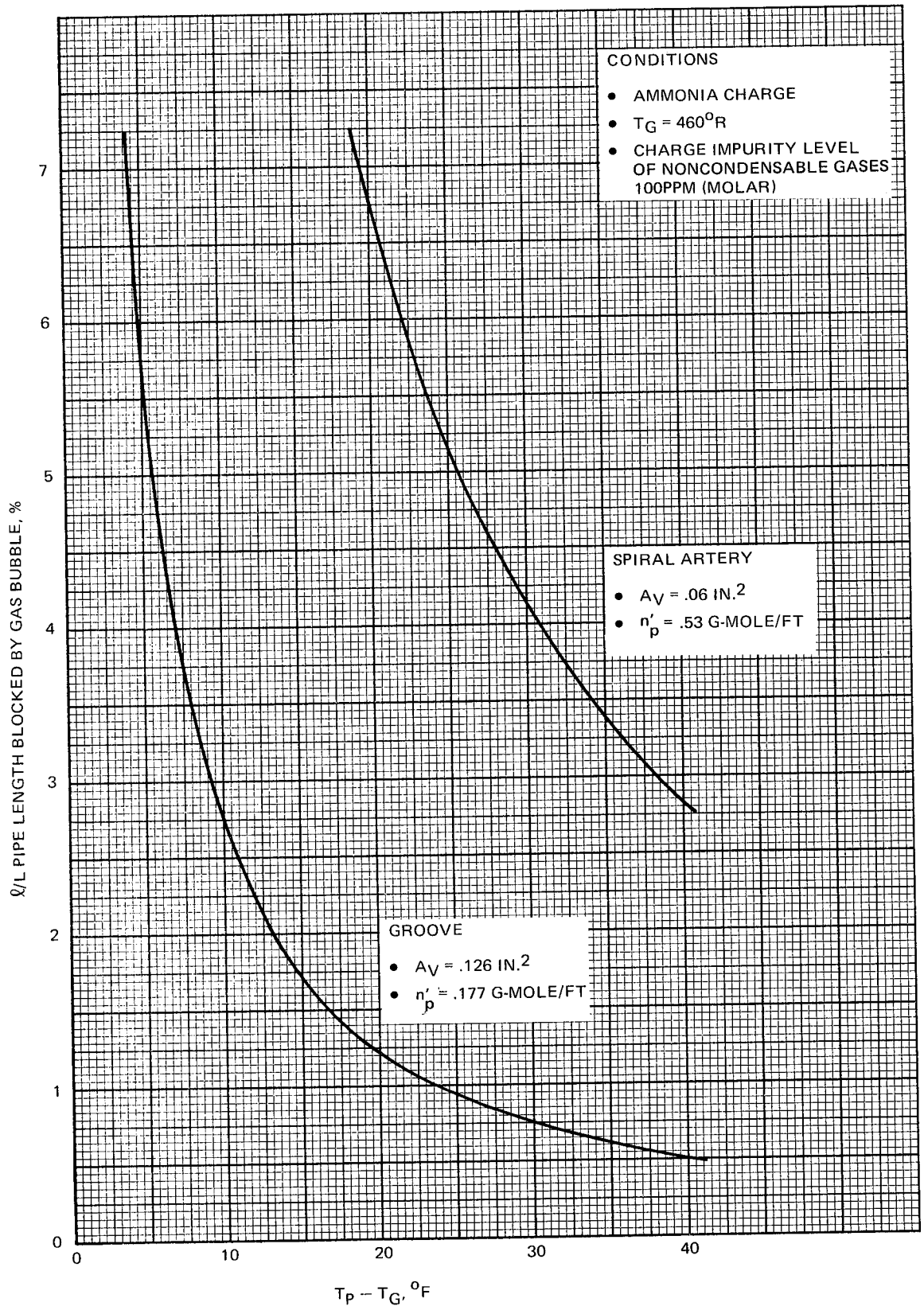


Fig. 7-3 Effect of Heat Pipe Configuration on Gas Blockage

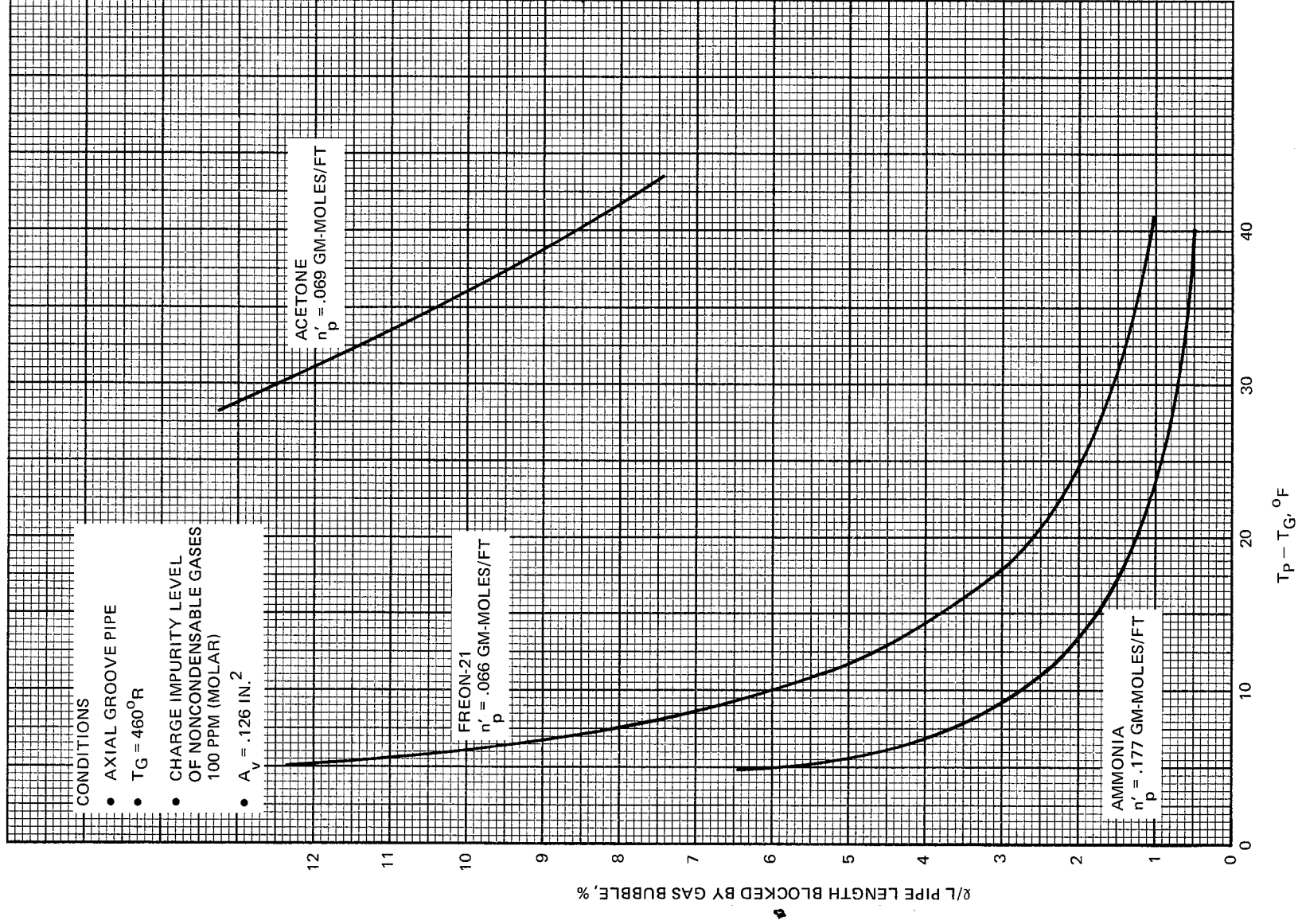


Fig. 7-4 Effect of Working Fluid on Gas Blockage

results in a smaller blocked length than acetone, or Freon-21. This is because the pressure of ammonia changes more rapidly with temperature than the other fluids.

The value of these curves is that it allows the designer, for his particular application, to make a judgment regarding the allowable quantity of gaseous impurities, or conversely, to design the condenser length so as to accommodate some estimated amount of gas that may be present.

7.3 Types and Sources of Impurities

The impurities present in a heat pipe come from three main sources:

- Contamination within heat pipe
- Contamination present in the charge fluid
- Impurities picked-up from the fluid transfer lines.

These three sources are discussed in the paragraphs that follow.

7.3.1 Contamination within heat pipe. - Residuals within the heat pipe come from three sources: improper cleaning, residual gas, and adsorbed gas.

7.3.1.1 Improper cleaning: Improper cleaning of heat pipe envelope and/or wick can result in significant amounts of contamination. These procedures are discussed elsewhere in this report, but a few general comments are repeated here to emphasize the problem. To be effective, a cleaning procedure should be as operator independent as possible. That is, there should be a minimum of steps requiring operator judgment. All components should be cleaned as close as possible to the time of welding and charging. Cleaning processes which leave the surfaces clean, but with low surface activity are preferable to processes which leave the surfaces ultra-clean but with high activity - this latter case can lead to rapid surface reoxidation during storage and/or welding.

7.3.1.2 Residual gases: The lowest pressure reached in a heat pipe, neglecting out-gassing of adsorbed molecules, can only be as good as the vacuum station to

which the pipe is connected. There will always be some free gas molecules left in the pipe; however, they are generally negligible compared to other sources of gas.

The number of free gas molecules left in the pipe can be readily calculated for different heat pipe configurations using the ideal gas law. As was done in the previous section, this gas quantity can be expressed as an impurity level in the charge fluid and related to the length of gas blockage using curves similar to Fig. 7-2, 7-3, and 7-4. For example, if the residual gas pressure is 10^{-1} mm Hg (100μ) in a 0.5-in. dia. 10-ft long axial groove heat pipe, the moles of gas calculated from equation (1) is 1.36×10^{-6} gm-moles. Dividing by the fluid charge of 1.77 gm-moles for the 10 ft ammonia pipe yields the equivalent impurity level, f , which is 0.77 ppm (molar). For a pipe whose temperature is 420° R, attached to a 400° R sink, the blocked length, determined from Fig. 7-2, is

$$\ell = \ell/L \text{ Fig. 7-2 (L) (actual ppm/100)}$$

$$\ell = (0.042) (10) (0.77/100)$$

$$\ell = 0.00324 \text{ ft or } 0.039 \text{ in.}$$

The blocked length is, therefore, negligible. Measurements of the pressure at the end of a 10-ft long, 0.5-in. diameter pipe indicate that levels lower than 10^{-1} mm Hg (100μ) are easily obtainable. (See discussion of pump down study presented in Section 6, "Evacuation and Charging".)

7.3.1.3 Adsorbed gases: All surfaces have a number of adsorbed layers of gas, which are the so-called "mono-layers." The number of adsorbed layers depends on the material and the past history of its surface. For an "average" aluminum surface which has been exposed to the atmosphere for weeks, it is of the order of 100 mono-layers (ref. 40). Chemical cleaning of the surface will reduce the number of layers;

so will out-gassing the surface under vacuum and refluxing with a flush charge. However, the amount of such reductions are not quantitatively known.

It must be assumed that those mono-layers which remain on the surface after final charging will, in time, either react with the working fluid or will be displaced from the surface resulting in pipe blockage. Assuming a single mono-layer of gas occupying 10^{16} sites per cm^2 of surface, the equivalent amount of accumulated gas in an axial groove pipe would be 28.6×10^{-8} gm-moles per in. (11.260×10^{-8} gm-moles/cm) of pipe length. This corresponds to a 19.0 ppm (molar) impurity level for an ammonia charge.

This quantity of gas is not insignificant. It represents a blocked length approximately one fifth of that shown in Fig. 7-2 (the impurity ratio is 19.0/100 or 0.19). However, the number of sites and their population density are not well known for the surface treatments given heat pipes. From the available literature it is thought, though, that the numbers used in this example represent the high range of total adsorbed molecules. The mechanisms involved in depopulation of adsorbed gases have already been presented in Paragraph 6.2.4 along with evacuation conditions (pressure, temperature) necessary to affect their removal.

In summary, a major source of residual contamination within a pipe can be due to an improper cleaning procedure. Even with a proper cleaning procedure, the contamination represented by adsorbed material can be significant. Residual gases, including water vapor, present due to incomplete pipe evacuation, in themselves, do not represent a serious problem.

7.3.2 Contaminants present in charge fluid. - Two grades of ammonia are available: an ultra high purity grade (UHP) and an anhydrous grade. Manufacturers' specifications for both grades of ammonia, are given in Table 7-1, along with approximate cost (refs. 41 and 42). When purchasing this material, the supplier will usually include a batch analysis of the fluid. This represents an average composition of the

entire batch produced by the manufacturers' process. Considerable variations can occur from batch to batch, and also between the batch and the fluid in the purchased cylinder.

The variation between the manufacturers typical analysis and a certified analysis of the material in a purchased cylinder is shown in Table 7-2 for both Matheson UHP and Air Products UHP.

TABLE 7-1. MANUFACTURERS DATA FOR AMMONIA

Grade	Component	Specification ^a	Typical analysis
Matheson Ultra High Purity (\$40/lb)	ammonia oxygen nitrogen water	99.999 % , min 1 ppm, max 5 ppm, max 5 ppm, max	ammonia : balance oxygen:<1 ppm n.d. nitrogen :<2 ppm n.d. water : 2.5 ppm
Matheson Anhydrous Reagent Grade (\$2.50/lb)	ammonia	99.99 % , min	water : 33 ppm residue: : 9.5 ppm non basic gas : 25 ppm oil : 2 ppm
Air Products Ultra High purity	ammonia	99.999 %	water ; 9 ppm oil : 1 ppm Fe, Mg, Si ; 12-120 ppb (each) B, Cu : 6-60 ppb (each) Al, Mn, Ca : 2-24 ppb (each) K, Na, Sr, Ag } 12-12 ppb (each) An, Cr, Pb, Ni, P } Co, Ti, Sn, Cd, Ba, Li : 0.6-6 ppb (each)

^a liquid

ppm - parts per million

ppb - parts per billion

n.d. - nondetectable

TABLE 7-2. - CERTIFIED ANALYSIS OF UHP AMMONIA

Matheson Gas Products: UHP Ammonia						
Certified analysis of samples taken from three 4-lb cylinders performed by Matheson Gas Products.						
	Sample 1		Sample 2		Sample 3	
	G, ^a ppm	L, ^b ppm	G, ppm	L, ppm	G, ppm	L, ppm
Oxygen/Argon	+ nd < 4	nd < 4	nd < 2	nd < 2	nd < 2	nd < 2
Nitrogen	76	2	nd < 2	nd < 2	nd < 2	nd < 2
Methane	nd < 1	nd < 1				
Carbon Monoxide	nd < 2	nd < 2				
Carbon Dioxide	nd < 4	nd < 2				
Water	nd < 3	nd < 3	8	5	2	2
Total	< 90	< 14	< 12	< 9	< 6	< 6

Air Products: UHP Ammonia	
Certified analysis performed by Gollob Analytical Service Corporation	
Component	Liquid Phase, ppm
Oxygen/Argon	< 1
Nitrogen	< 1
Methane	< 1
Carbon Monoxide	< 1
Carbon Dioxide	6
Water	60
Hydrogen	< 15
Non-volatiles (metals)	< 10
Total (gas)	< 85

^aG = gas phase

^bL = liquid phase

nd = nondetected threshold concentration given

ppm = parts per million (molar)

It is noticed that the gas and liquid phases may contain different amounts of impurities, with a greater quantity generally appearing in the gas phase. In one sample, almost seven times as much impurities were found in the gas phase as in the liquid. It is especially important to be aware of this, if fluid is to be tapped from the vapor phase. The analysis of the Air Products sample shows a water content of 60 ppm which significantly exceeds the typical analysis of 9 ppm (Table 7-1). In another instance, noted elsewhere in this report, there was uncertainty as to the presence of an oily substance, dioctyl phthalate, which was apparently found in UHP ammonia.

The experiences gathered in using ammonia strongly suggest that a certified analysis be performed with the purchased sample. Most heat pipe manufacturers do not have the necessary equipment or experience to perform the required chemical analysis and independent laboratories must be used. The cost of this analysis is approximately \$200. This would bring the cost of UHP ammonia to approximately \$360 for a 4-lb cylinder or \$90/lb. For a 10-ft (3.048 m) long groove pipe, the cost of the ammonia would be approximately \$6. Even doubling or tripling this to account for flush charging, etc, the cost is relatively small compared to the total cost of a heat pipe for current specialized spacecraft applications. For the same reason, the use of the less pure grade of anhydrous ammonia is not recommended, since the reduced cost is insignificant compared to the improved reliability offered by the purer grade of ammonia.

The purest form of methanol commercially available (Matheson, Coleman and Bell Corporation) is a chromatographic grade that is 99.9% pure. The water content is 0.02% or 200 ppm. Its cost is approximately \$3/lb.

Some of the more common Freons used in heat pipe are shown in Table 7-3 along with their approximate cost and purity levels. Impurities typically specified by DuPont are water, 10 ppm (max); higher boiling components, 100 ppm (max); soluble residue, 100 ppm. There is also typically 1 to 1.5% (by volume) of noncondensables present in the vapor phase. However, a somewhat more expensive instrument grade is available with 0.3 to 0.5% (by volume) of noncondensables.

TABLE 7-3. - PURIFY LEVEL AND COST OF VARIOUS FREONS

Freon	Approximate cost, \$/lb	PURITY LEVEL, %		
		DuPont	Matheson	Air Products
11	0.40	99.9	99.9	-
12	0.55	99.9	99.0	99.
13	6.00	99.9	99.0	99.
13B1	5.50	99.7	99.0	99.
14	5.50	99.7	99.7	99.7
21	3.00	99.9	99.9	99.9
22	1.10	99.9	99.9	99.9
113	0.75	-	99.0	-

7.3.3 Contamination during transfer of working fluid. - Transfer of working fluid from the suppliers bottle to a heat pipe involves the use of plumbing lines, charge bottle, valves, fittings, etc. All of these can be a source of impurities. A number of techniques for transferring working fluid from a suppliers bottle to a heat pipe have already been discussed in Section 6. They can be classified into three categories shown in Table 7-4, each with their own characteristics.

Tests were performed at Grumman to determine the impurity levels associated with each of these techniques using ammonia as the working fluid.

TABLE 7-4. - FLUID TRANSFER TECHNIQUES

Transfer technique	Comments
1. Direct transfer from suppliers bottle to heat pipe	<ul style="list-style-type: none"> ● Fluid is in minimum contact with transfer lines ● Difficult to control quantity transferred
2. Transfer from suppliers bottle to charge bottle, then to heat pipe	<ul style="list-style-type: none"> ● Good control over quantity transferred ● Introduces additional step
3. Transfer from suppliers bottle to charge bottle, purification of fluid in charge bottle, then transfer to heat pipe	<ul style="list-style-type: none"> ● Same as 2nd transfer technique except purification can be performed ● Additional steps involved in purification

The test procedure used to accomplish the transfer is contained in Appendix F. Briefly, it consists of vapor transfer of ultra-high purity ammonia into three cleaned and evacuated stainless steel sample bottles as follows:

- Sample bottle No. 1 - direct transfer from suppliers bottle to sample bottle No. 1
- Sample bottle No. 2 - transfer from suppliers bottle to charge bottle, then to sample bottle No. 2
- Sample bottle No. 3 - transfer from suppliers bottle to charge bottle, freeze/thaw cycles, then transfer to sample bottle No. 3.

The three sample bottles (which simulate the heat pipe) along with the manufacturers supply bottle were then sent to Gollob Analytical Service Corporation (N. J.) where an analysis of the impurities in both the gas and liquid phases was performed. The results of the gas chromatograph analysis are shown in Table 7-5. Examination of the data reveals certain inconsistencies which casts doubt on the validity of the results. For example,

TABLE 7-5. - AMMONIA ANALYSIS FROM FLUID TRANSFER TESTS^a

Constituents	Matheson supply bottle		Sample bottle					
			No. 1		No. 2		No. 3	
	Liquid phase	Gas phase	Liquid phase	Gas phase	Liquid phase	Gas phase	Liquid phase	Gas phase
Oxygen/argon	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4
Carbon dioxide	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4
Hydrogen	nd 25	nd 25	nd 30	nd 30	nd 30	nd 30	nd 30	nd 30
Carbon monoxide	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4
Methane	na	na	nd 4	nd 4	nd 4	nd 4	nd 4	nd 4
Nitrogen	22	25	nd 4	nd 4	nd 4	170	nd 4	32
Water	nd 5	na	nd 5	na	nd 5	na	nd 5	na

^aConcentration in ppm volume/volume
 nd = none detected, less than
 na = not analyzed

- The supply cylinder from Matheson showed about the same concentration of nitrogen in both the liquid and gas phase. However, the Ostwald coefficient for nitrogen in ammonia (ratio of solute concentration in liquid phase to concentration in gas phase) indicates that there should be about 11 times the concentration of nitrogen in the gas phase than in the liquid phase (ref. 43).
- Sample bottle No. 1 shows that it has less impurities than the Matheson bottle from which it was filled. Since the ammonia was vapor distilled into sample bottle No. 1, it would be expected to have a similar gas phase concentration as the supply bottle, certainly not purer.

In contrast to these inconsistencies, a comparison between sample bottles No. 2 and No. 3 indicates that the nitrogen concentration is appreciably decreased, as expected, when the ammonia is subjected to repeated freeze/thaw cycles. Since some of the data are questionable, all the data must be suspect; therefore, no conclusions regarding the effectiveness of these three transfer techniques can be drawn.

However, a significant fact was uncovered during subsequent investigation of the gas chromatograph technique. This technique, which is commonly used by most laboratories to analyze ammonia, involves passing ammonia vapor through a molecular sieve column to separate certain impurities, such as oxygen, nitrogen, carbon monoxide, etc, and then measuring the thermal conductance of the separated gases to determine their concentration. Prior to making the actual analysis, the apparatus is purged with some of the same vapor that is to be analyzed. Purge volumes of the order of 200 cc are typical, which in the case of the 500 cc samples sent to Gollob, represent a significant amount of material. Thus, when analyzing a sample of gaseous ammonia, the vapor drawn off during the purging operation contains the impurities whose concentrations are being sought. As more vapor is drawn off, the contaminant concentration in the vapor continuously decreases, while relatively purer liquid is evaporated to provide make-up vapor. Apparently, this explains why the concentration of nitrogen in the suppliers bottle was approximately the same in both phases. The experiences encountered here were also typical of those reported by Mindrup, (ref. 44) where impurity concentrations in the vapor phase were found to decrease as the sample was depleted.

In addition, it was determined that the time between the analysis of the vapor and liquid from the same bottle was typically 15 min. This may be insufficient time for gas impurities to come to equilibrium concentrations in both phases resulting in nonrepresentative data.

These studies indicate that the present method of ammonia analysis using gas chromatography is not acceptable and must be revised. One improvement would be to collect either liquid or vapor that is to be analyzed into a clean sample bottle,

convert the fluid into a superheated vapor, which upon subsequent purging and analysis, should remain homogeneous and not vary in contaminant concentration. This technique would eliminate having two phases in the sample bottle, thus avoiding the problem of changes in impurity concentration as the sample is depleted.

This approach has been recently tried at Grumman and appears to be acceptable. A sample of ammonia vapor from a heat pipe was collected and analyzed in the superheated state using a gas chromatograph. After initial purging, a number of analyses were taken from the same sample bottle. Each analysis yielded essentially the same impurity concentration trace.

7.4 Techniques to Minimize Impurities

A number of techniques have been used in the heat pipe industry to purify fluids. Some are discussed in the following paragraphs.

7.4.1 Freeze/thaw. - In this technique the fluid is frozen in a container. The vapor and gas space above the frozen fluid is then evacuated to vacuum. Next, the fluid is allowed to thaw, after which the cycle is repeated. Impurities with lower freezing points than the main fluid can be eliminated. For example, nitrogen, argon, oxygen, etc can be removed from ammonia, methanol, and most Freons. This technique can be performed on fluids contained in a charge bottle, or in a heat pipe (see Fig. 6-19).

7.4.2 Distillation or vapor transfer. - In this process, working fluid is evaporated into a separate container where it is condensed. Impurities in the fluid which are less volatile will tend to concentrate and remain in the liquid. Repeated distillations with the condensed vapor are usually necessary. Removal of dioctyl phthalate from ammonia and removal of water from acetone are examples.

7.4.3 Liquid transfer. - The transfer of only liquid from an equilibrium mixture of liquid and vapor will minimize the amount of volatile impurities in the liquid which tend to concentrate in the vapor phase. Removal of gaseous products, such as nitrogen from ammonia, can be accomplished.

7.4.4 Venting or burping a heat pipe. - The removal of accumulated gas can be accomplished by operating a pipe in the reflux mode with the vent valve higher than the evaporator. Periodic venting of the pipe to a lower pressure environment will remove noncondensable products.

7.4.5 Molecular sieve. - Molecular sieves are synthetic zeolites (sodium or calcium aluminum silicates) which have a uniform network of cavities and a high specific area (700-800 m²/g). Molecules which are small enough to enter the pore structure become adsorbed in the cavities so that these synthetic zeolites "sieve out" molecules which have diameters smaller than the entrances to the cavities. In addition to this sieving effect, true adsorption of the solutes may also occur. Molecular sieves are highly hygroscopic materials and can be used, for example, to remove water from methanol or acetone.

7.5 Updated Materials Compatibility

Reference 14 presented the experimental results of a number of life tests designed to evaluate the compatibility of different heat pipe materials and fluids. Additional information has been reported since then, principally in reference 45. As a means of updating materials compatibility data, this new information is presented in Table 7-6.

7.6 Conclusions and Recommendations

In general, working fluids should be purchased in the highest purity grade available since their cost is usually a small percentage of overall heat pipe costs.

Certified analysis of fluids, particularly ammonia, should be obtained for the container of fluid purchased since suppliers analysis may differ from batch to batch. (Refer to discussion and conclusions regarding ammonia analysis with the gas chromatograph.) It would also be economical to use larger quantity containers instead of many smaller ones.

TABLE 7-6. - HEAT PIPE LIFE TEST DATA

Materials		Heat carrier	Operating temperature, °C	Temperature drop,		Test duration, hr	Remarks
Wall	Wick			Begin °C	End °C		
Cu	Cu-Bronze	Water	130 130	2	8	1,400	No corrosion
Cu	Cu-Bronze	Water	130	2	2	20,000	Continued
Mild Steel	SS 304	Water	130	3	46	4,800	Immediate gas buffer generation
SS 321	SS 316	Water	130	4	25	10,400	Gas buffer generation
Mild Steel	SS 304	Water	130	2.5	44	1,500	Gas buffer generation (H ₂ and CH ₃)
Mild Steel	SS 304	Water	130	10	55	5,000	Gas buffer generation despite NaOH doting
Cu	Cu-Bronze	Water	110	28	40	5,000	2 ppm Cu ⁺⁺
Ni	Ni	Water	90	32	20	4,500	Continued
SS 321	SS 304	Water	130	7.5	30	750	Gas buffer generation despite NaOH doting
SS 321	SS 304	Water	130	0.5	60	1,400	After 20 hr - ΔT+6°C, 7 ppm Ni ⁺⁺
SS 321	SS 304	Acetone	70	2	8	18,600	Continued
Brass	Cu-Bronze	Acetone	50	6	10	2,400	Attack of the wall; Sn and Zn dissolved in acetone
Brass	Cu-Bronze	Acetone	50	5	7	2,400	Attack of the wall; acetone changed colour
SS 321	SS 304	Acetone	50	4	6	15,000	Acetone changed colour
Cu	Cu-Bronze	Acetone	50	2	3	1,300	Grain boundary corrosion
Cu	Cu-Bronze	Acetone	50	3	25	13,000	Continued
Ni	Ni	Acetone	70	0.5	0	8,400	Continued
Cu	Cu-Bronze	Methanol	50	3	3	700	Weld leaked
SS 321	SS 304	Methanol	50	4	4.5	5,500	Slight attack
Brass	Cu-Bronze	Methanol	50	5	15	2,400	Copper deposits, liquid yellowish
Brass	Cu-Bronze	Methanol	50	4	17	1,500	Copper deposits, Sn and Zn dissolved
SS 321	SS 304	Methanol	50	3	45	1,500	200 ppm Fe ⁺⁺ , corrosive attack
Cu	Cu-Bronze	Methanol	50	7	18	1,300	200 ppm Cu ⁺⁺ , grain boundary corrosion
Ni	Ni	Methanol	70	0	30	6,000	29 ppm Ni ⁺⁺
SS 321	SS 304	Ammonia	50	0	1	12,800	Continued
SS 321	Al	Ammonia	50	2	2.5	12,000	Continued
SS 321	SS 304	Ethanol	70	3	7	18,600	Continued
Brass	Cu-Bronze	Ethanol	70	4	9	1,500	Slight attack, copper deposits in evaporator
SS 321	SS 304	Ethanol	50	3	4	1,500	5 ppm Fe ⁺⁺ , slight attack
Cu	Cu-Bronze	Ethanol	50	8	7	1,300	Slight grain boundary corrosion
SS 321	SS 304	Hexane	50	2.5	25	11,900	No attack
Brass	Cu-Bronze	Hexane	70	5	12	1,500	No attack
Cu	Cu-Bronze	Buthanol	50	12	12	5,200	Small gas plug from the beginning
Cu	Cu-Bronze	Propanol	50	12	14	4,500	Small gas plug from the beginning
Cu	Cu-Bronze	Dichlormethane	50	1	1	11,800	No corrosion
Cu	Cu-Bronze	R 113	70	7	13	9,500	Continued
Steel	SS 304	Diphyl	130	68	90	6,200	Slight attack

The allowable quantities of impurities present in the working fluid should be minimized. This is particularly true for those contaminants that are either difficult to remove or can cause permanent heat pipe degradation. Such contaminants would include water, oily residues, and other corrosive products. Noncondensables, which should also be minimized, can, if necessary, be removed by the heat pipe manufacturer.

When re-ordering ammonia, the empty supply cylinder should be returned to the manufacturer for refilling. This avoids the possibility of contaminating the ammonia with a foreign supply cylinder.

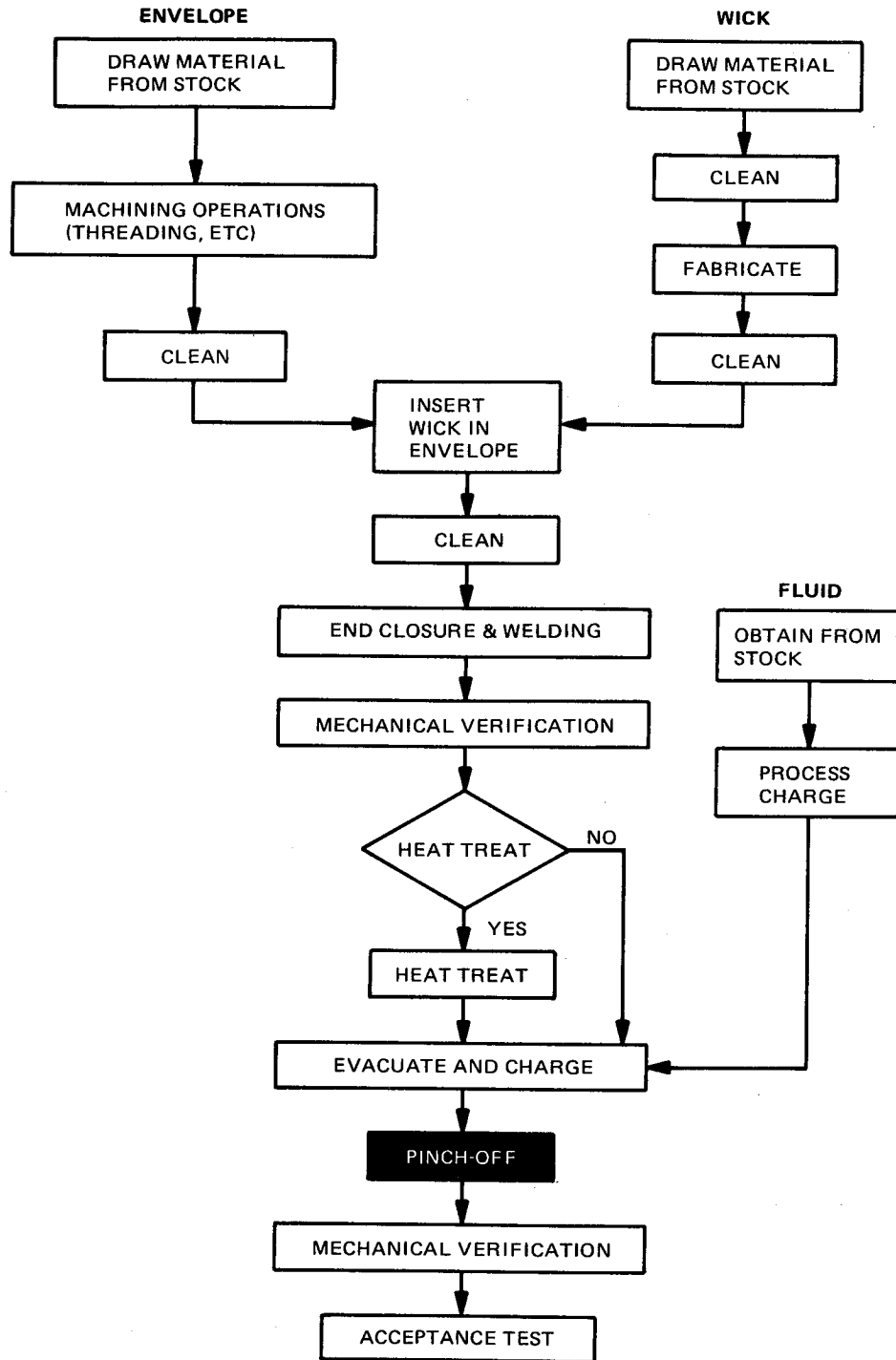
The effect of noncondensables on the conductance or blockage should be determined for the particular pipe design and operating conditions. This can be done as illustrated in Fig. 7-2 through 7-4. Note that as the temperature difference between the pipe and gas ($T_p - T_G$) increases, the amount of blockage decreases. The amount of vapor space in a particular design is very important as seen in Fig. 7-3. Low vapor-space designs amplify the amount of gas, producing longer blocked lengths. Choice of fluid also influences blockage, as seen in Fig. 7-4. For the same relative quantity of working fluid impurity ammonia results in the smallest blocked length.

The information obtained from the blocked length curves allows the designer to determine the sensitivity of his pipe to noncondensables. In addition, he can estimate what amount of gas may be tolerable for his particular application; consequently, he can decide if extensive and costly fluid purification procedures will be required.

Assuming a proper cleaning procedure, the contamination represented by adsorbed material can be significant. High temperature evacuation and possibly flush charging can aid in the removal of this material. Residual gases present due to incomplete pipe evacuation below about 10^{-1} mm Hg (100 μ) is generally not a significant condenser blockage problem for large pipe to sink temperature differences.

The present technique of analyzing ammonia with a gas chromatograph is not acceptable, particularly when both liquid and vapor phases exist in the sample. This is because the purge cycle prior to the analysis may deplete or alter the specimen whose analysis is sought. A technique to avoid this problem is required. One method, which appears to be acceptable for ammonia vapor, is to collect and analyze the sample in a superheated state.





1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

8 - CHARGE TUBE PINCH-OFF

8.1 Background

After being charged with working fluid, a heat pipe must be temporarily sealed (pinched-off) to permit a final, more permanent closure of the fill port. Any leak past the temporarily pinched section will cause porosity and preclude an effective permanent seal. In the case of a welded closure, only an exceptionally talented welder can weld against even a slight leak. The situation is even more sensitive if an epoxy cement is used as a sealant instead of a weld because of epoxy hardening time.

To date, the only successful pinch-off technique being used on a wide scale involves mechanically deforming a fill tube that connects the heat pipe with a charge valve. The method is both reliable and inexpensive since it calls for only standard shop equipment. Three basic steps to this standard technique are:

- Crimp the fill tube to form a temporary leak-tight closure
- Sever the charge valve from the fill tube
- Effect a permanent end closure (e. g. , welding).

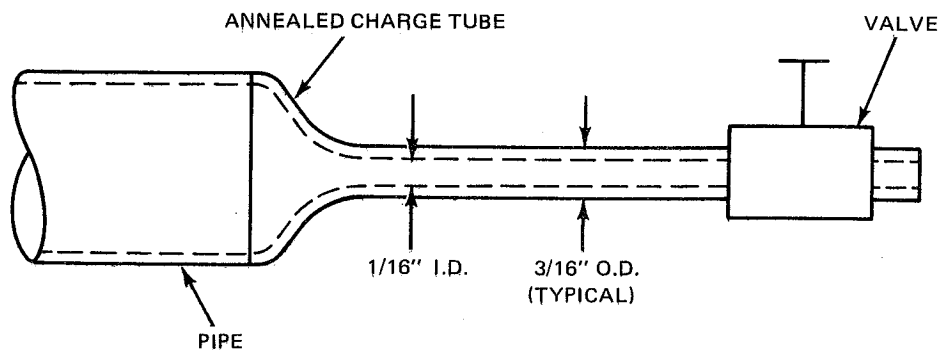
All HP manufacturers go through the same sequence and differ only in their execution of the steps.

8.2 Standard Pinch-Off Techniques

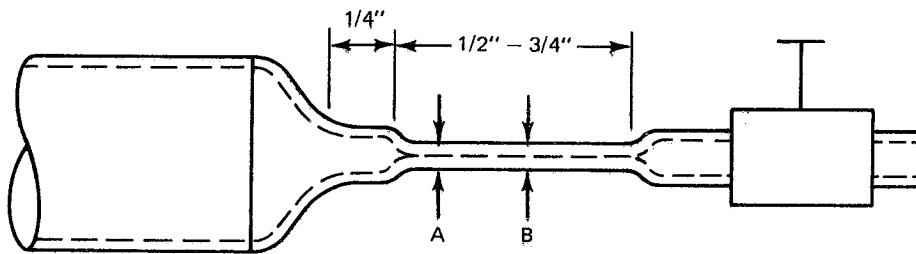
8.2.1 Crimping. - Most techniques specify an annealed condition for the fill tube prior to crimping. This facilitates the flow of material and greatly reduces the tendency of the sidewalls to crack. Various successful crimping techniques are being employed.

One method uses a compression riveter with special flattening jaws that flatten a 0.5-in. (1.270 cm) section of the fill tube, after which a mechanical clamp (winged-nut or 'C' clamp) is used to maintain positive clamping pressure until the final

closure. An illustration of this pinch-off procedure, listing all required steps, is given in Fig. 8-1. Except for the specific crimping technique, all of the steps are generally applicable to any pinch-off method that uses mechanical pincers. Note that step (a) of the procedure calls for adjusting the pipe pressure to just above ambient conditions, thereby decreasing the driving pressure across the pinch-off. For ammonia, this is done by chilling (not freezing) the outer envelope of the pipe to control the vapor pressure inside the heat pipe. By maintaining this pressure just



- (a) ADJUST PIPE PRESSURE JUST ABOVE ATMOSPHERIC
- (b) FLATTEN SECTION OF CHARGE TUBE IN A COMPRESSION RIVETER USING SPECIAL FLATTENING JAWS



- (c) CLAMP AT "A" WITH MECHANICAL DEVICE (C-CLAMP OR WING-NUT CLAMP)
- (d) OPEN VALVE AND CHECK FOR LEAKAGE PAST CLAMP
- (e) CLEAN (SCRAPE) AREA AROUND "B" AND CUT OFF AT "B"
- (f) WELD AT CUT OFF SECTION "B" (INERT GAS TUNGSTEN ARC)
- (g) LOOSEN CLAMP
- (h) LEAK CHECK AT WELD (HALOGEN, AMMONIA, AS APPLICABLE)
- (i) IF NECESSARY, RECLAMP AND REWELD

Fig. 8-1 Typical Pinch-Off Procedure for Aluminum Tube

above atmospheric, any leak past the pinch-off would be from the inside out. If the pipe were below atmospheric pressure there could be an injection of moist air - a condition that could easily compromise the future performance of the heat pipe.

In another method, round, hardened steel bars held in a special fixture are used to squeeze the fill tube, creating cylindrical detents. The fixture is used with a standard bench vise, which applies the clamping pressure. Once pinched, the tooling remains in place during the subsequent steps; it is removed only after final closure. This method has the advantage of never releasing the clamping pressure, but is restricted for use at one location - the welding station.

A third method (ref. 12) uses a portable, vise-like clamp whose jaws contain extended rounded pincers that crimp the tube (Fig. 8-2). As in the previous method, the clamping pressure is never relieved until after final closure. But there is one

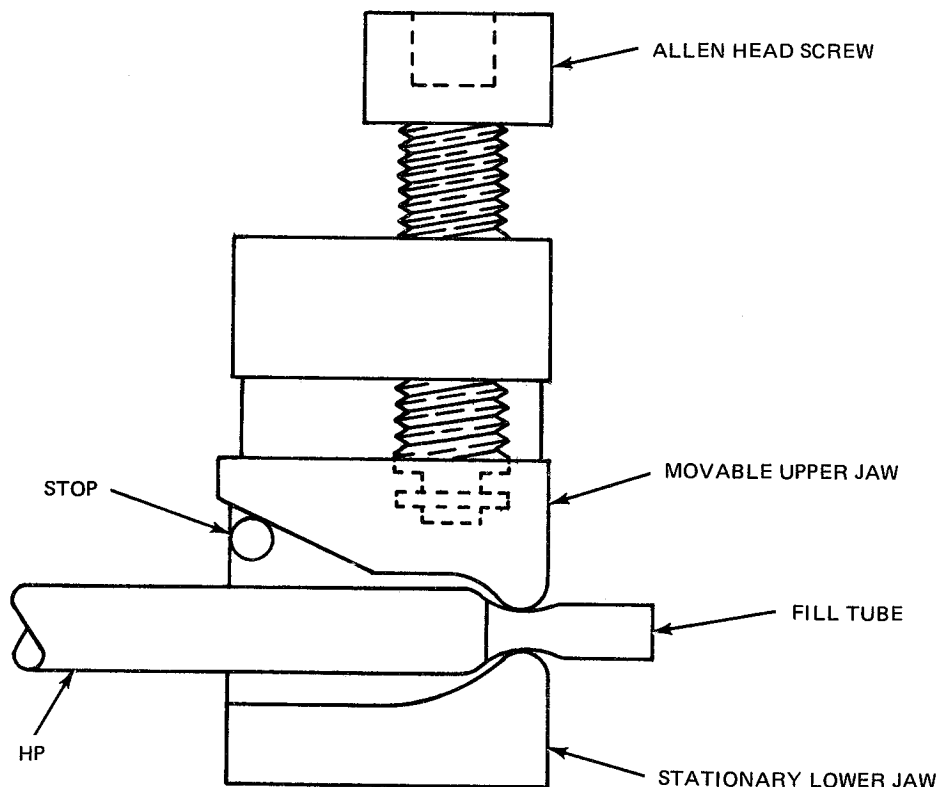


Fig. 8-2 Portable "Round-Bar" Pincer Clamp

important difference - the pipe can be conveniently moved between work stations if desired. Figure 8-3 illustrates the appearance of a typical pinch-off done with roundbar pincers, using either the bench vise or portable pincer clamp method. This technique produces shorter and sturdier pinch off tubes. However, unlike the flattening method, there is an open pocket between the pinch and the final cut that could entrap unwanted gases. The final closure technique should allow these trapped gases to escape.

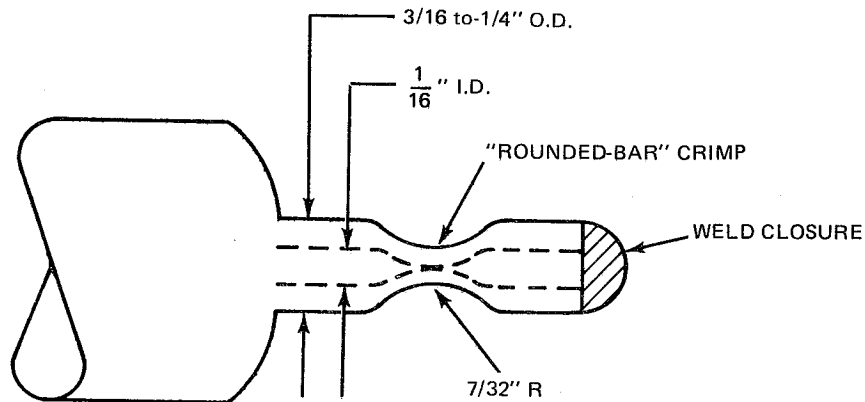


Fig. 8-3 Typical "Round-Bar" Pinch-Off

The foregoing crimping techniques have been proven through extensive use. However, there are a few less tried variations that are noteworthy. Figure 8-4 shows a fill tube that was sealed with a bolt-cutter-type of pinch-off tool that produces a feathered end (ref. 13). Claims are that it produces a leaktight seal that needs no backup clamp. After the pinch-off operation, an aluminum cup, which is

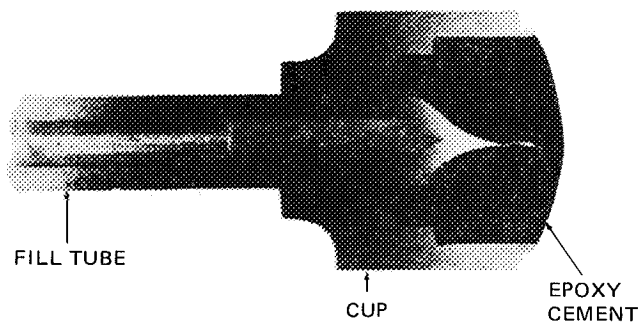


Fig. 8-4 Cross Section of Fill Tube Pinch-Off Potted in Epoxy Cement

placed around the fill tube before the charge valve is attached, is pulled up so that it surrounds the pinch-off; the cup is then filled with epoxy cement. This "potting" of the pinch-off effectively reinforces it against the high internal pipe pressures. The epoxy used reinforces the pinch-off, flows readily, and cures within one hour at 150°F (or overnight at room temperature).

A method developed at Langley Research Center (ref. 46) for crimping small diameter fill tubes uses a modified, hand-operated, electrical-wire crimping tool (Fig. 8-5). The tool has four jaws that act radially to compress or crimp the tube. Different size jaws are required for different size tubing. The tube is crimped once and cut approximately 1 in. from the end, where it may again be crimped. Each crimp is then silver soldered. A reinforcing sleeve can be slipped over the fill tube and soldered in place to protect the crimped area, although sleeving is not needed for a pressure-tight seal. The method has been used for pressures up to 3500 psi (2.413×10^7 newt/m²) with soldering and 100 psi (6.895×10^5 newt/m²) without soldering.

8.2.2 Severing. - Two of the most commonly used techniques for severing the fill tube from the charge valve after it has been crimped are

- Cutting off with a hacksaw blade
- Snipping off with a bolt cutter.

The bolt cutter produces the most material deformation and results in a feathered tip. The hacksaw produces a square shoulder with little deformation, this normally makes venting of the space between the pinch and the cut an easier task. Except for venting, both methods are equally good.

8.2.3 End closure. - Welding is the most commonly used method of permanent fill-tube end closure because it is fast and reliable. It is the recommended procedure. Both tungsten inert gas (TIG) and electron beam (EB) welding have been employed; the choice is a matter of personal convenience. Proper welding procedures are detailed in Section 4.

Epoxy cements (previously cited) have been used on a very limited scale. Their relatively long setting time and limited application do not recommend them for general use. They are not as reliable as a good metallurgical (welded) bond.

8.3 Nonstandard Pinch-Off Techniques

An alternate method that eliminates both the typical fill tube and charge valve is illustrated in Fig. 6-16. The technique, developed by JPL, employs a threaded end cap and has been used for stainless steel pipes in sizes up to 0.5 in. (1.270 cm) dia. with both ammonia and water as working fluids. (Details are given in Fig. 8-6.) Charging is accomplished by placing the open end of the pipe through a vacuum seal into a charging/vacuum manifold. After distilling the preweighed charge into the pipe, the threaded cap is screwed in place. A backup EB weld is then made, although it has been found that the threaded connection is leak tight without the weld.

EB welding is used because it is more expedient than, say, TIG welding. The threaded end cap method is more effectively used with mass-produced heat pipes whose overall requirements (e.g. fluid charge, installation) are well known. The special equipment (vacuum jacket sliding seal, EB welding) preclude economical use of the threaded cap method in a limited production situation.

A diffusion welding technique (Fig. 8-7) has also been successfully tried on both aluminum and stainless steel fill tubes, although there have been some failures with aluminum tubes (ref. 2). The method involves surrounding the fill tubes with a stainless steel collar, and then flattening the collar (and tube) between two opposing electrodes while simultaneously applying voltage. In the case of aluminum, the tube outside diameter must be well oxidized to provide the necessary high electrical resistance. The critical (and proprietary) steps concern the proper electrode design, pressure, and current cycles.

Possible replacements for diffusion welding include ultrasonic welding and explosive welding, however, little information is currently available concerning these methods.

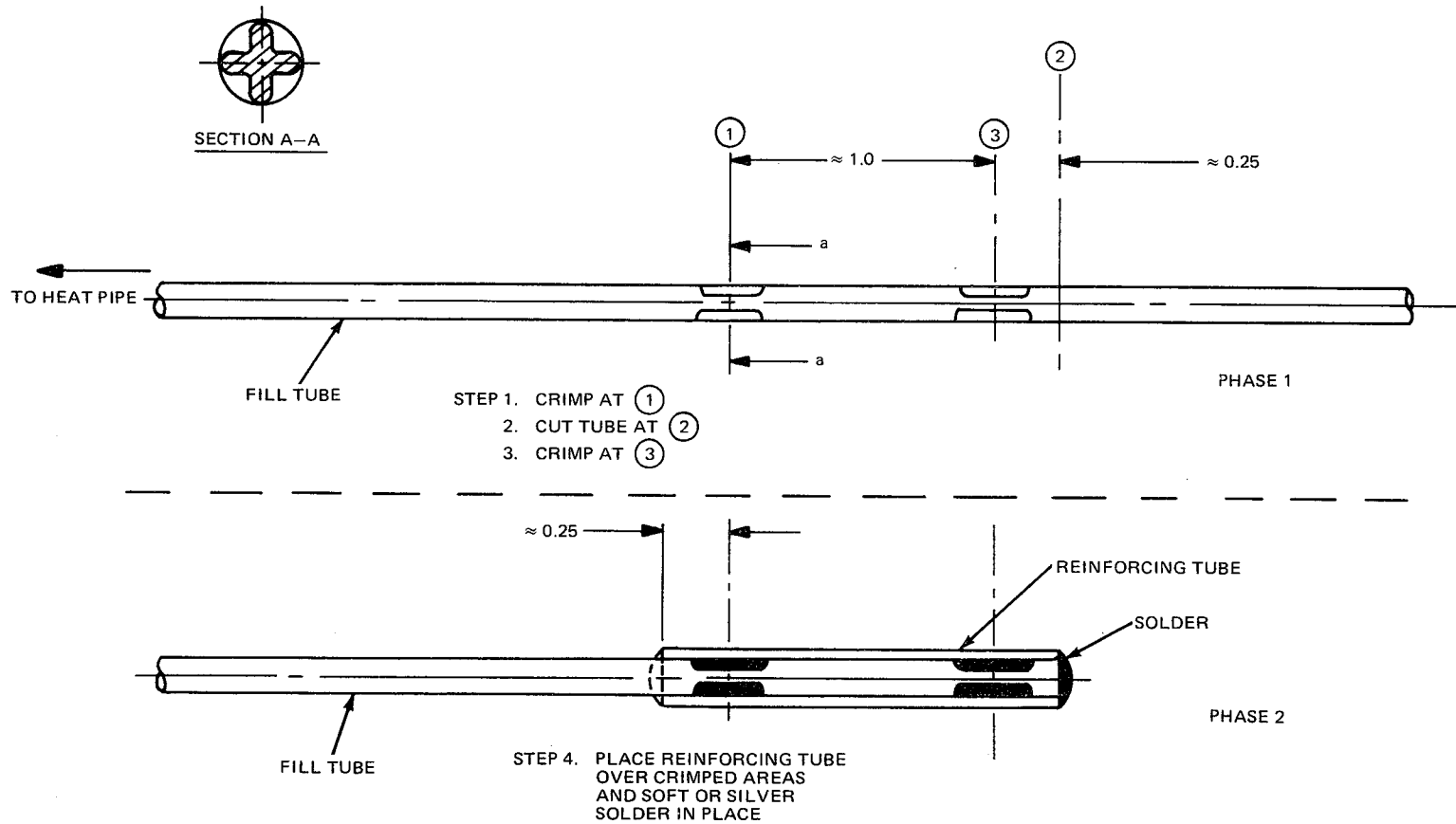


Fig. 8-5 Crimp Technique

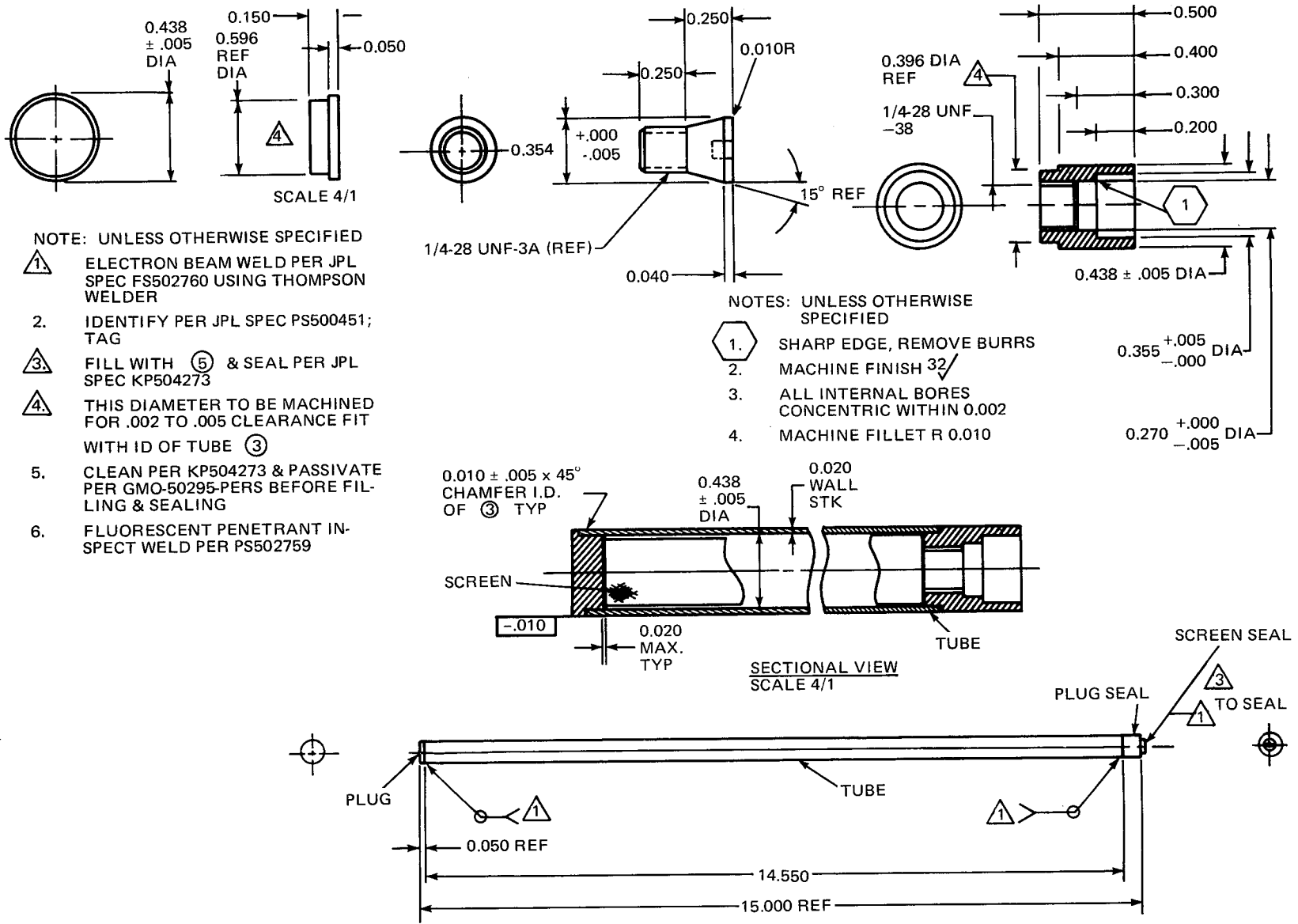


Fig. 8-6 Threaded End Closure (JPL)

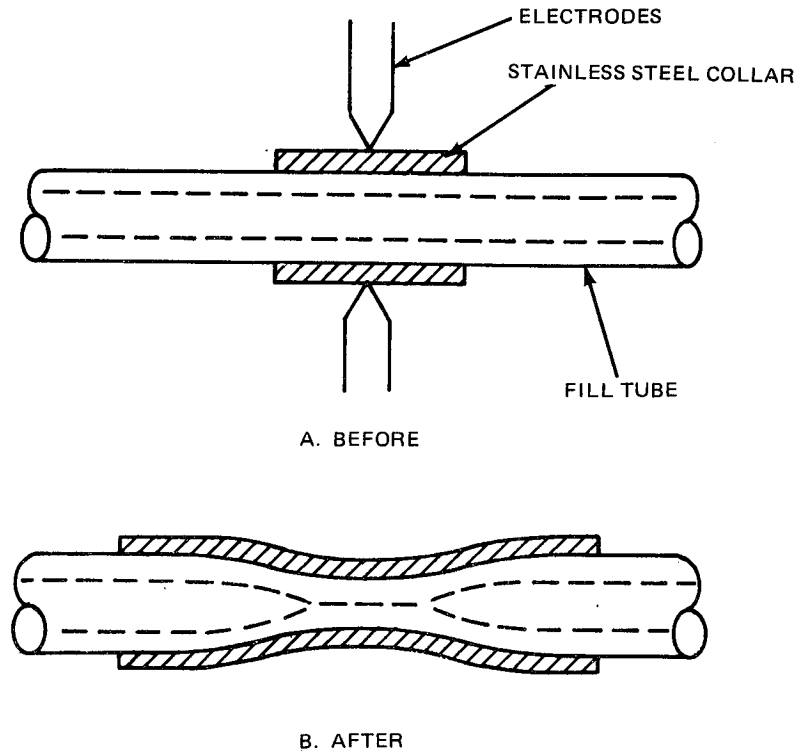


Fig. 8-7 Diffusion Welding Pinch-Off Technique

8.4 Conclusions and Recommendations

The standard procedure (crimp, cut, and weld) is recommended for charge tube pinch-off because it is widely used, fairly reliable and economical, and requires only basic shop equipment. This procedure is detailed below:

1. Crimp
 - a. Start with an annealed, or partially annealed, charge tube to avoid cracking the tube wall. This might necessitate heat treatment after pinch-off if an annealed charge tube cannot meet strength requirements.
 - b. Chill (or warm) the heat pipe to just above ambient pressure being careful not to freeze the working fluid. This will minimize the pressure differential across the pinch-off when the valve is opened.

Figure 8-5 Crimp Technique

- c. Flatten, over a 1/2 - 3/4 in. (1.270-1.905 cm) length, that portion of the tube to be pinched. This will eliminate any gas pocket.
 - d. Follow the flattening operation by applying a clamp on the flattened tube that permits positive clamping pressure to be maintained until final closure.
 - e. Open the charge valve and carefully check for leaks.
2. Cut
- f. Clean the area around the section to be cut.
 - g. Using a hacksaw, or its equivalent, cut the tube at a flattened section between the clamp and the charge valve.
3. Weld
- h. Weld (TIG or EB) the cut section closed.
 - i. Loosen the pinch off clamp.
 - j. Leak check at the weld; reclamp and reweld if necessary.
 - k. Allow the heat pipe to reach room temperature (or preferably maximum operating temperature) and leak check at the weld.
 - l. If necessary, reclamp, chill and reweld.

Although the foregoing procedure is considered adequate, there is room for some improvement. In particular, it would be desirable to combine the crimp, cut and weld operations into a single mechanized operation that would reduce the number of steps. This approach would make the operation less "operator dependent." This could be accomplished with a specially developed tool, or with a diffusion welding technique similar to that previously described.

9 - BASELINE HEAT PIPE MANUFACTURING PROCEDURE

9.1 Scope

This section integrates the detailed data covered in this report into a working document establishing a set of procedures, techniques, and guidelines that can be used to build cost-effective heat pipes. Where possible, a specification format is used (for example, in the procedures for envelope cleaning). In areas where a specification format cannot be written (such as in end cap closure and welding) the data are presented as specific guidelines and design approaches. Wick cleaning and pretreatment have not been included here because they depend to a large extent on the particular design and method of fabrication - items which are generally considered proprietary.

The techniques presented here are those which have been recommended in the foregoing detailed sections, where rationale for their selection is described. In general, these techniques are standard industrial processes; for the most part, they have been proven in actual practice. However, although there are methods which potentially may be more cost-effective, they are not included here if they have a limited "track record", or are in the development stage.

Certain curves and tables are repeated in this section for the convenience of the reader and to permit this section to be separated from the report for use as a self-contained preliminary manufacturing specification. The techniques treated in this section relate to foregoing detailed sections as follows:

<u>Section 9 Subsection</u>	<u>Title</u>	<u>Section in Report</u>
● 9.3	Envelope Cleaning and Pretreatment	3
● 9.4	End Closure and Welding	4
● 9.5	Mechanical Verification	5
● 9.6	Evacuation and Charging	6 & 7
● 9.7	Pinch-off	8

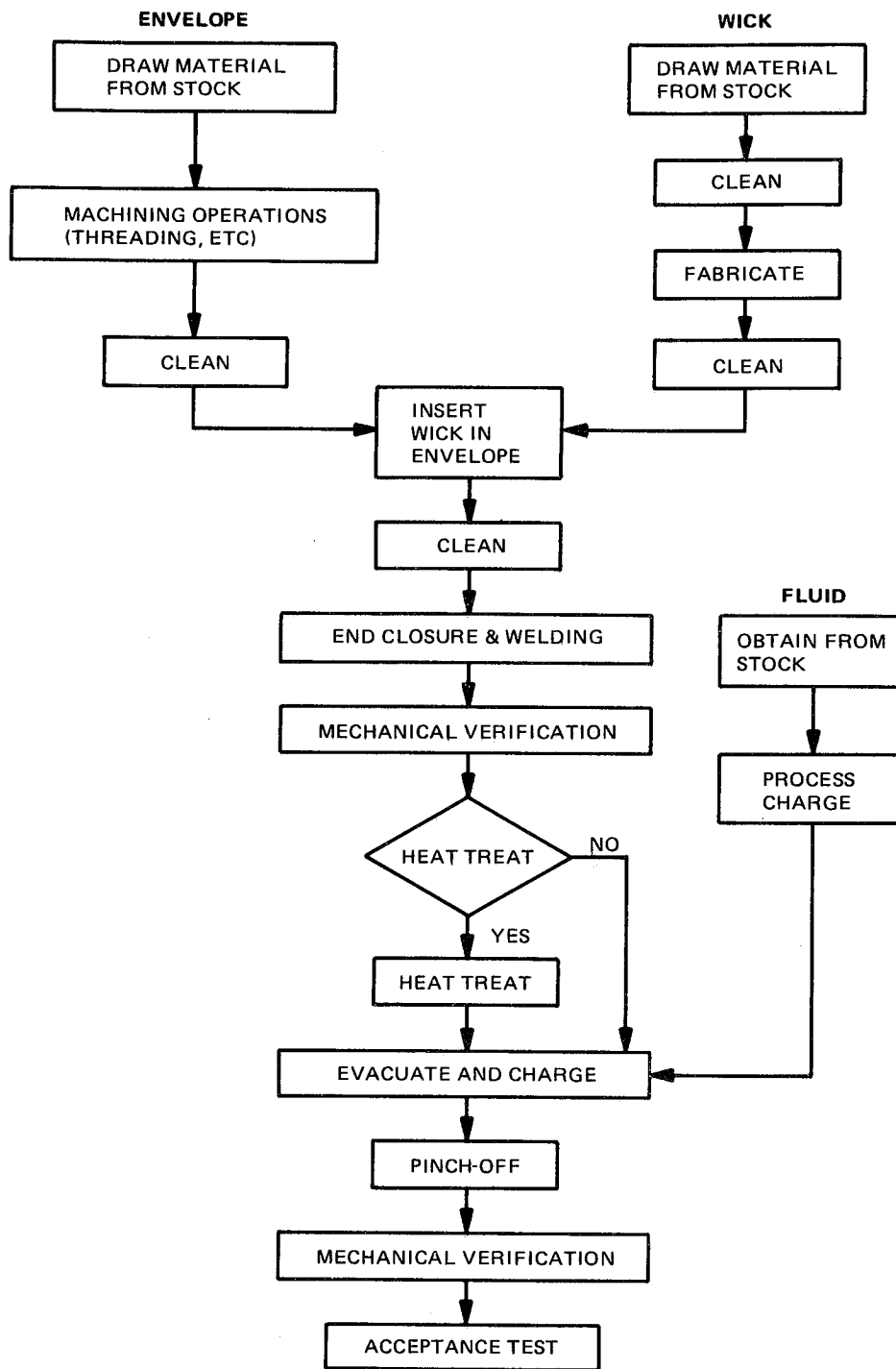


Fig. 9-1 Typical Heat Pipe Manufacturing Flow Chart

9.2 Overall Restrictions and Assumptions

Unless otherwise specified in the individual manufacturing procedures, the following restrictions or assumptions shall apply:

- Envelope materials considered are aluminum and stainless steel tubing
- Working fluids are restricted to ammonia, Freon-21 and methanol
- The pipes are intended for operation in the moderate temperature range, nominally from -100 to 200°F (200 to 366°K)
- Typical pipe sizes are approximately 0.5 in. (0.0127 m) diameter and up to about 12 ft (3.6 m) long
- The procedures described are generally based on small quantity runs up to approximately 10 to 20 units. Large quantity production runs would require more automated operations, the procedures of which might be different from those described here
- The procedures described are based on a heat pipe manufacturing sequence typical of that shown in Fig. 9-1.



9.3 Envelope Cleaning and Pre-treatment

9.3.1 Assumptions:

- Applicable tubing: Aluminum 6061 or 6063; stainless steel 300 series
- Tube condition: Threaded, wicked or otherwise internally machined prior to cleaning
- Tube size: Typically 0.5 in. (0.0127 m) dia. up to 12 ft (3.6 m) long.

9.3.2 Materials:

- 1,1,1 Trichloroethane
- Non-etch alkaline cleaner (Refer to Table 9-1)
- Chromated deoxidizer (Refer to Table 9-2)
- Filtered air
- Anhydrous isopropyl alcohol
- Dry nitrogen
- Passivating solution (Refer to Table 9-3).

9.3.3 Procedure - aluminum tubes:

1. Clean in cold 1,1,1 trichloroethane with bristle brush on wire extension. Periodically clean brush between strokes.
2. Flush internal surface with cold trichloroethane; dry with filtered air and cap pipe ends.
3. Immerse in non-etch alkaline cleaner for 5 minutes minimum. Refer to Table 9-1 for materials and temperatures.
4. Follow with a two (2) minute tap water rinse, raising and lowering tube during rinsing.
5. Immerse in chromated deoxidizer. Refer to Table 9-2 for material, time, and temperature.

TABLE 9-1. - EXAMPLES OF NON-ETCH ALKALINE CLEANERS

Material	Concentration	Temperature
Ridoline No. 53 (Amchem Products Co.)	2-10 oz/gal.	140-180°F
Oakete No. 164 (Oakite Products Co.)	2-10 oz/gal.	140-180°F
Kelite Spray White (Kelite Corp)	40-60% by volume	Ambient
A-38 (Pennwatt Corp)	4-8 oz/gal.	160-180°F

TABLE 9-2. - EXAMPLES OF CHROMATED DEOXIDIZER SOLUTIONS
(IMMERSION TYPE)

Material	Concentration	Temperature	Immersion Time
Mixture of: Chromated deoxidizer replenisher No. 17 ^a (Amchem Products Co.)	2-6 oz/gal	Ambient to 120°F	5 to 30 min
Nitric acid 42° Be	10-20% by volume		
Mixture of: Chromated deoxidizer replenisher No. 17 ^a	2-6 oz/gal	Ambient	5 to 30 min
Sulfuric acid 66' Be	4-7% by volume		

^aDeoxidizer make up No. 7 to be used for initial makeup.

6. Follow with a two (2) minute tap water rinse, raising and lowering tube during rinsing.
7. Thoroughly dry inside surface with forced filtered air.
8. Rinse with anhydrous isopropyl alcohol.
9. Force dry with clean, filtered, dry nitrogen heated to 160°F.
10. Cap pipe ends.
11. If applicable, insert artery, rinse with isopropyl alcohol, and dry as in step 9.
12. If heat treat is required after welding, then
 - Evacuate pipe for 4 hours at 600°F and leak check
 - Seal evacuated heat pipe
 - Perform heat treat operations on sealed pipe.

TABLE 9-3. - EXAMPLES OF PASSIVATING SOLUTIONS

Material	Concentration	Temperature	Immersion time
Nitric acid	35-65% by volume	Ambient	30 min to 2 hr
Mixture of: Sodium dichromate or potassium dichromate	1 - 4 oz/gal.	Ambient	30 min to 2 hr
Nitric acid	15-30% by volume		

9.3.4 Procedure - stainless steel:

1. Clean in cold 1,1,1 trichloroethane with bristle brush on wire extension. Periodically clean brush between strokes.
2. Flush internal surface with cold trichloroethane; dry with filtered air and cap pipe ends.
3. Immerse in passivating solution. Refer to Table 9-3 for materials, temperatures, and time.
4. Follow with a two (2) minute tap water rinse, raising and lowering tube during rinsing.
5. Thoroughly dry inside surface with forced filtered air.
6. Rinse with anhydrous isopropyl alcohol.
7. Force dry with clean, filtered, dry nitrogen heated to 160°F.
8. Cap pipe ends.
9. If applicable, insert artery, rinse with isopropyl alcohol, and dry as in step 7.

9.3.5 General notes

- The cleaning procedure must be as free from operator error as possible, since improperly executed procedures may also lead to unwanted contamination. Training of personnel regarding the cleanliness requirements for heat pipes is mandatory. So are adequate safeguards and inspection points during the steps of the procedure; these must be consistent with good quality assurance practices.
- Do cleaning and charging operations in fairly rapid sequence and in proximity to one another. Avoid storing the pipe for long duration, which increases the likelihood of contamination. Performing these operations near each other lessens the danger of contamination during transportation.

9.4 End Closure and Welding

9.4.1 End closure design guidelines. - Observe the following general guidelines:

- Acceptable end cap designs for flat circular heads may be Type I or II as shown in Fig. 9-2
- End cap thickness can be determined from Fig. 9-3 and 9-4.
- The welded end should have a square butt joint design (see Fig. 9-5).

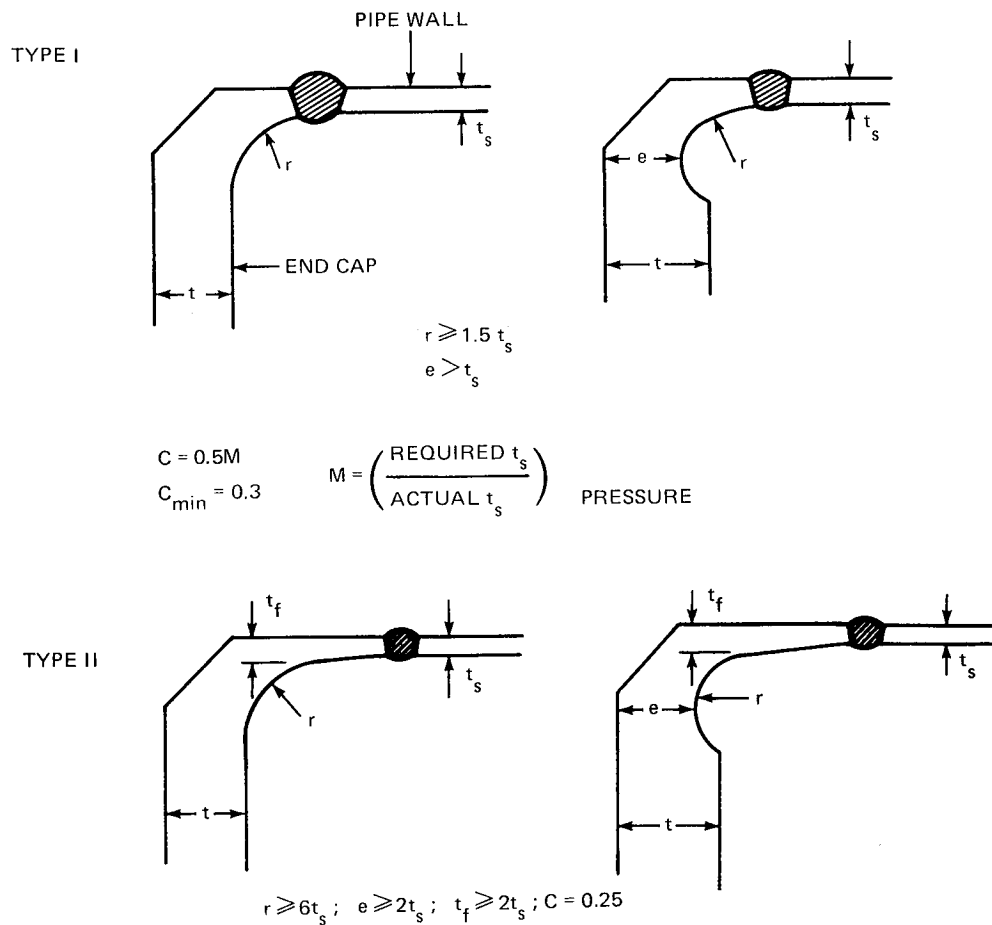
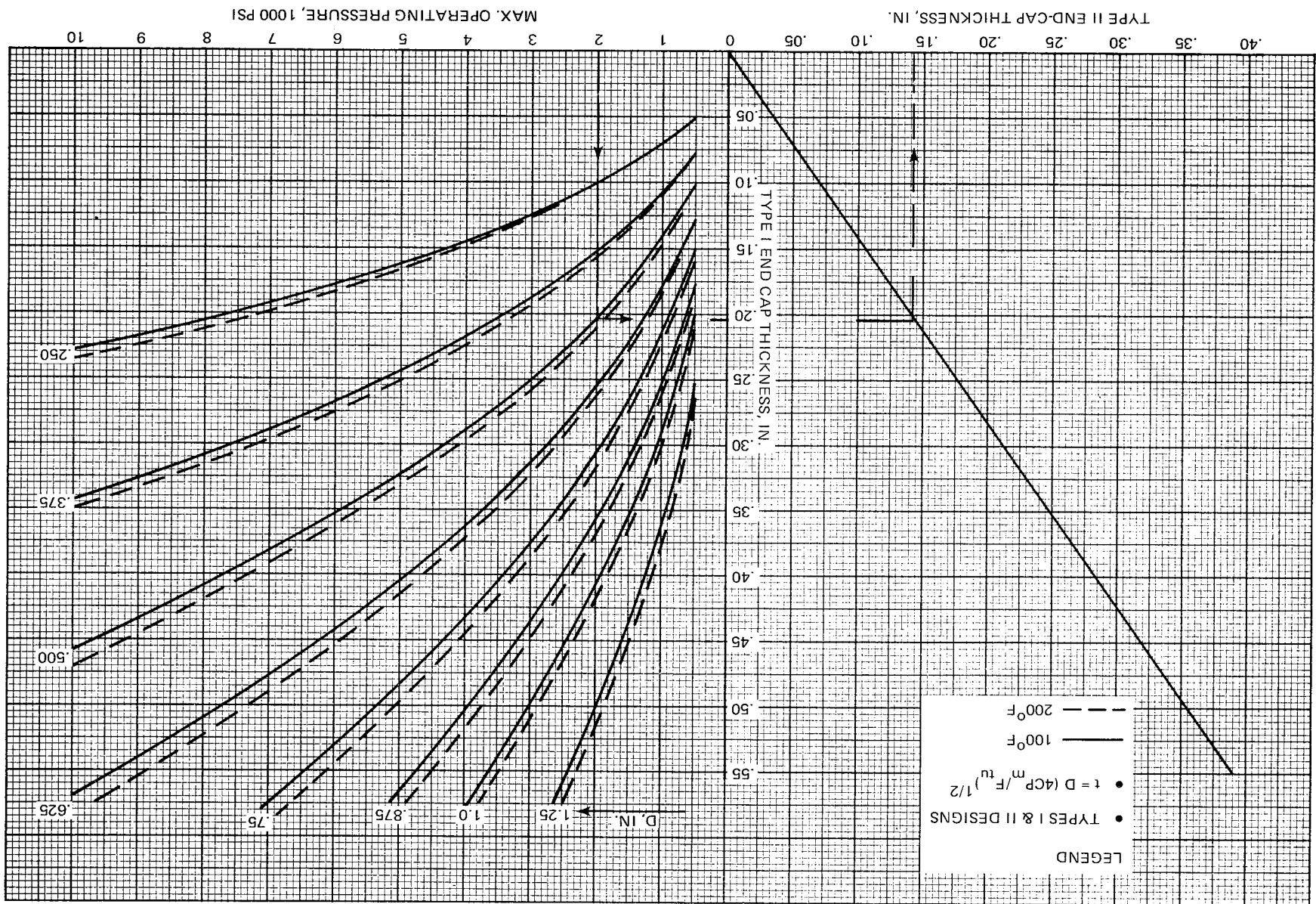


Fig. 9-2 End Cap Design Details

Fig. 9-3 End-Cap Design Curves, 6061-T6 Aluminum (as Welded)



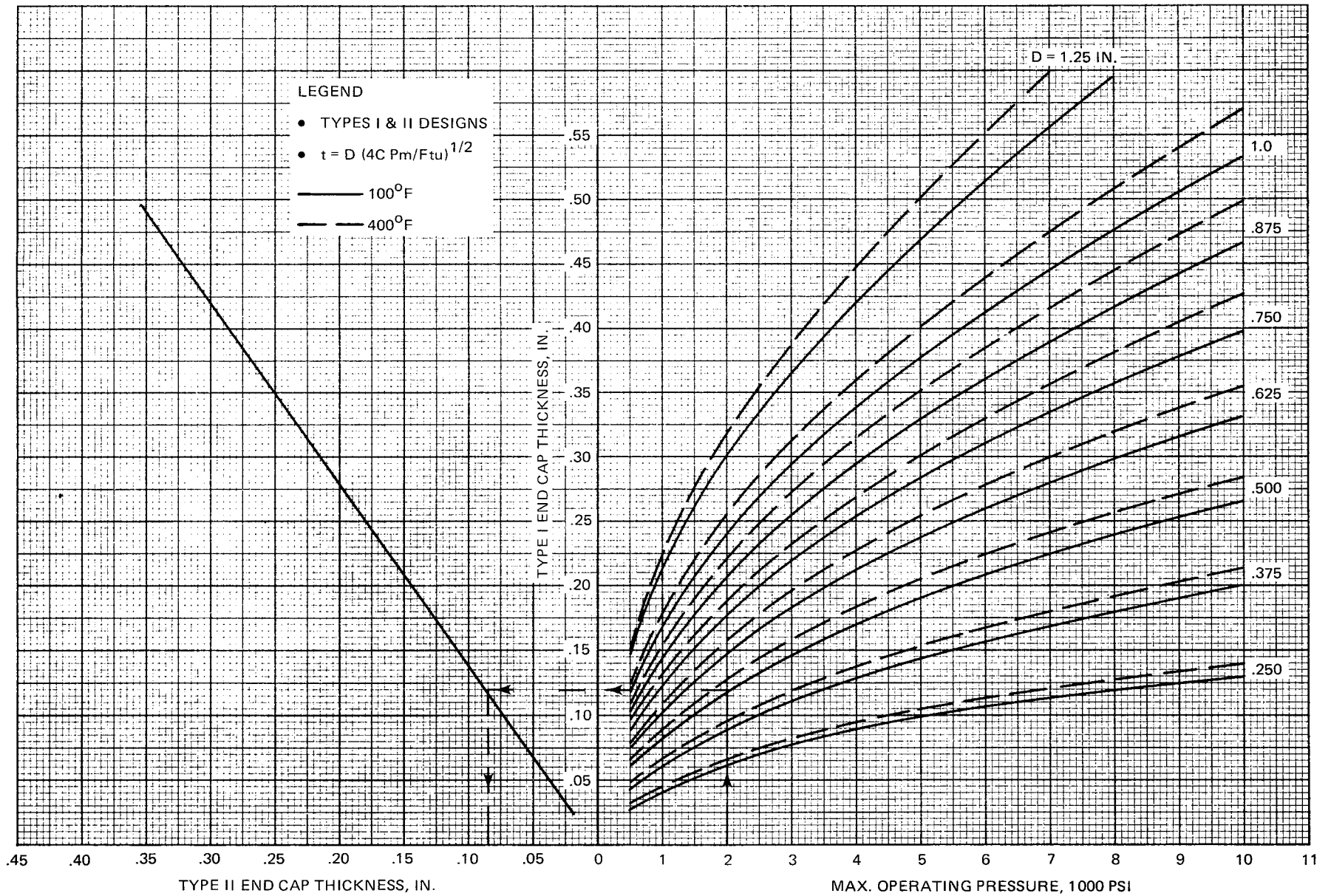


Fig. 9-4 End-Cap Design Curves, 304 Stainless Steel (as Welded)

- Self-alignment during welding should be provided, as per the lipped butt joint for stainless steel (Fig. 9-6), the consumable filler insert for aluminum (Fig. 9-7), or an equivalent design
- Full weld penetration should be achieved
- Machining of the crown of the weld bead should be avoided.

9.4.2 Welding process. - Basic considerations are as follows:

- Depending on the quantities involved, manual or automatic gas tungsten arc welding may be used
- Detailed inspection should be performed before, during, and after welding operations. As a minimum, all welds should receive full radiographic inspection.

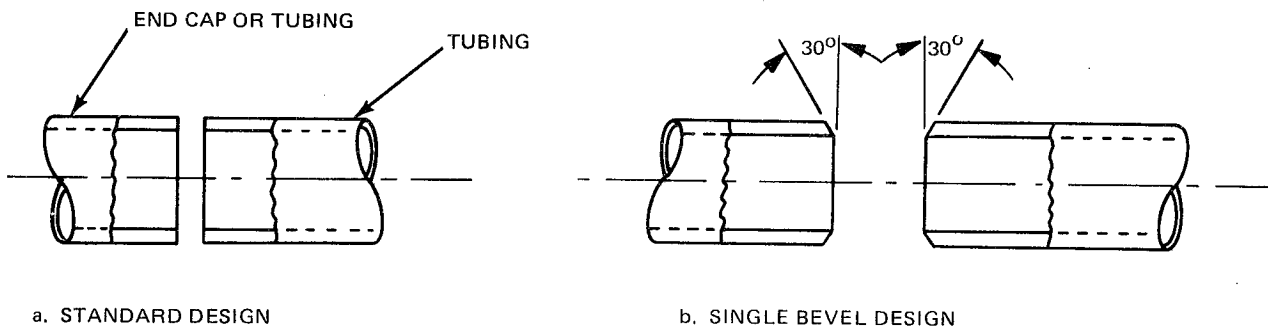


Fig. 9-5 Square Butt Joint Designs

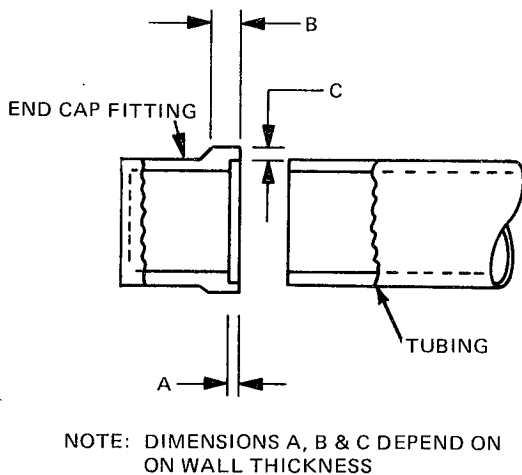


Fig. 9-6 Lipped Butt Joint Design

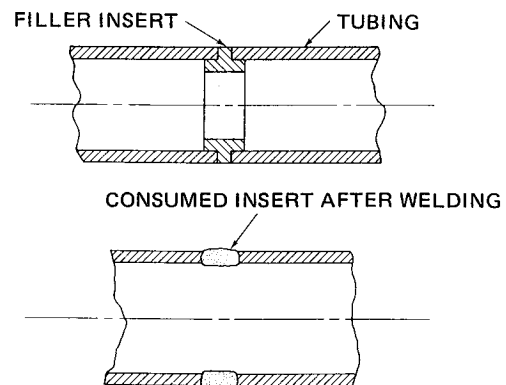


Fig. 9-7 Square Butt Joint with Consumable Filler Insert

9.5 Mechanical Verification

9.5.1 Structural design guidelines. - Observe the following guidelines:

- Use design approach followed by ASME Boiler and Pressure Vessel Code, 1965, Section VIII, "Unfired Pressure Vessels"
- Maximum allowable design stress shall be one-fourth (1/4) of the ultimate tensile stress at temperature
- Proof pressure check all heat pipes to 1.5 times maximum operating pressure
- New heat pipe designs not previously tested should be burst tested to demonstrate at least four (4) times maximum operating pressure
- Use property values shown in Table 9-4 for aluminum and stainless steel tubing and pipe
- Use stress analysis checklist for early identification of problem areas, e.g., hoop and axial stress, pipe bends, end caps, thermal expansion saddles, dynamic loading, etc
- Simple pipe hoop stresses can be estimated from Fig. 9-8.

9.5.2 General notes on leak detection techniques. - The following general considerations apply:

- The choice of leak detection technique is governed by its availability, convenience and leak measurement requirements. The following procedures may be used to check the integrity of the pipe prior to charging:
 - Pressure pipe under water and look for presence of gas bubbles (sensitivity: $\sim 10^{-4}$ std cc/sec)
 - Helium leak detection (sensitivity: 10^{-11} std cc/sec)
 - Halogen leak detection (sensitivity: 10^{-7} std cc/sec)
- After charging, leak detection should be done at maximum operating temperature, if possible.

TABLE 9-4. - MAXIMUM ALLOWABLE STRESSES

	Ultimate tensile strength, F_{tu} at 100°F	Tensile yield strength, F_{ty} at 100°F	Maximum allowable stress at temperature, ksi				Modulus of elasticity, E	Coefficient of thermal expansion
			100°F	150°F	200°F	400°F		
Aluminum drawn tube (seamless) ^a								
• 6061 -T6	42 ksi	35 ksi	10.5	10.2	9.9	—	10.5x10 ⁶ psi	13.0x10 ⁻⁶ $\frac{\text{in.}}{°\text{F}}$
• 6061 -T6 welded ^b	24	(14) ^d	6.0	5.9	5.7	—		
• 6063 -T6	33	28	8.25	7.8	7.5	—		
• 6063 -T6 welded ^b	17	(11) ^d	4.25	4.20	4.0	—		
Aluminum seamless pipe and extruded tube ^a								
• 6061 -T6	38 ksi	35 ksi	9.5	9.2	9.0	—	10.5x10 ⁶ psi	13.0x10 ⁻⁶ $\frac{\text{in.}}{°\text{F}}$
• 6061 -T6 welded ^b	24	(14) ^d	6.0	5.9	5.7	—		
• 6063 -T6	30	25	7.5	7.1	6.8	—		
• 6063 -T6 welded ^b	17	(11) ^d	4.25	4.2	4.0	—		
High alloy steel ^c seam- less pipe and tube								
• TP 304 (18-8)	75 ksi	35	18.75	17.85	17.00	15.45	29x10 ⁶ psi	8.5x10 ⁻⁶ $\frac{\text{in.}}{°\text{F}}$
• TP 304L (18-8)	70	35	17.50	17.25	17.00	15.00		

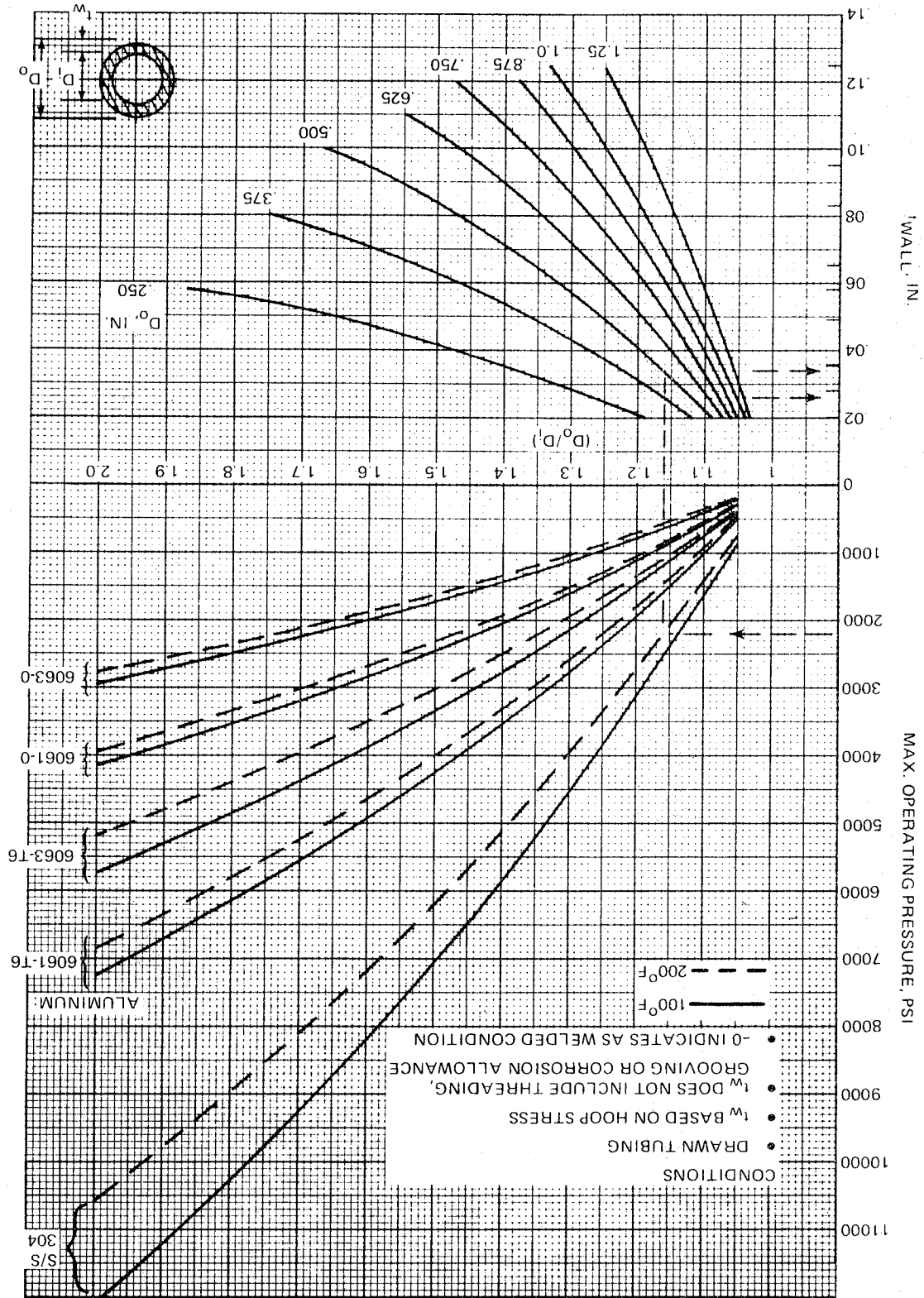
^aExcerpted from Table UNF-23 of Section VIII, ASME Unfired Pressure Vessels (ref. 22)

^bThese allowables apply to doubled welded, fully radiographed butt joints as per the ASME code. Refer to discussion in materials section.

^cExcerpted from Table UHA-23 of Section VIII

^dFrom reference 29

Fig. 9-8 HP Envelope Design Curves



9.5.3 Procedures - ammonia pipes

9.5.3.1 Red litmus paper (sensitivity: Go/No Go)

9.5.3.2 Mass spectrometer (sensitivity: 10^{-11} std cc/sec)

9.5.3.3 Copper sulfate/ethylene glycol (sensitivity: 10^{-8} std cc/sec).

9.5.3.3.1 Restrictions: Use at room temperature.

9.5.3.3.2 Equipment:

- Filter paper - Wattman No. 120 or equal
- Reagent solution (by weight) -3% copper sulfate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and 10% ethylene glycol in distilled water
- Small plastic bags to cover ends of pipe after filter paper has been laid down
- Rubber band (or adhesive-backed tape) to hold plastic bags in place
- Nessler's reagent in dropping bottle.

9.5.3.3.3 Procedure:

1. Prepare filter paper as follows:
 - a. Soak one (1) sheet of filter paper in reagent solution.
 - b. Blot wet filter paper between two sheets of dry filter paper.
 - c. Place wet filter paper in air tight container (to prevent evaporation) until ready for use.
2. Cut filter paper into sheets approximately 1-1/2 in. (3.810 cm) by 2 in (5.080 cm).
3. Wrap filter paper from step 2 around ends of pipes.
4. Cover ends of pipe and filter paper with small plastic bag and secure with rubber band or adhesive-backed tape.

5. Leave ends of pipe covered for at least four (4) hours. (This should provide a leak sensitivity of approximately 3.3×10^{-7} std cc/sec).
6. After at least four (4) hours, remove plastic bag and filter paper and observe filter paper for dark blue spots. If these spots are visible, a leak rate of 3.3×10^{-7} std cc/sec has been exceeded.
7. If no dark blue spots are visible, drop a few drops of Nessler's reagent on filter paper. If dark brown spots from the reagent appear, then a leak rate of 3×10^{-8} std cc/sec was exceeded.

NOTE

Dark brown spots may have resulted from the aluminum-copper sulfate reaction before the application of the Nessler's reagent and should be disregarded.

9.5.4 Procedures - freon pipes. - Halogen leak detection (sensitivity: 10^{-7} std cc/sec).

9.5.5 Procedures - methanol pipes. - Mass Spectrometer (sensitivity: 10^{-11} std cc/sec).



9.6 Evacuation and Charging

9.6.1 Restrictions and assumptions:

- Pipe configuration is nominally 1/2 in. (1.270 cm) dia. axially grooved tube, without artery
- Charge tube is 1/16 in. (0.159 cm) inside diameter by about 3 in. (7.62 cm) long
- Pipe has been cleaned according to procedure given in Subsection 9.3
- Charging procedure is primarily applicable to ammonia. However, other fluids such as Freons and methanol can also be used.

9.6.2 Procedure:

1. Evacuate pipe, using, for example, a 4-in. Veeco vacuum station.
2. Temperature of pipe during evacuation should be as follows:
 - a. For aluminum, 640°F; if loss of strength from a T6 condition cannot be tolerated, pipe temperature should not exceed 350°F.
 - b. For stainless steel, 400°F.
3. Time of evacuation depends on pipe length:
 - a. 4 ft (1.219 m) lengths or smaller; evacuation time should be no less than 1 hr at the evacuation temperature.
 - b. 10 ft (3.048 m) lengths - approximately 4 hr at the evacuation temperature is a conservative estimate.
4. Introduce flush charge of pure working fluid, e.g., ultra high purity ammonia, by vapor transfer.
5. Operate pipe in reflux mode for approximately 8 to 16 hr.
6. Dump flush charge and evacuate pipe on vacuum station. Repeat flush charges may be desirable.

7. Introduce weighed, final charge of ultra high purity ammonia by vapor-transfer.
8. Check amount transferred by delta weight measurements of charge bottle and pipe.

9.6.3 General Notes. - The following general considerations apply:

- The same bottles, lines, fittings and valves should be used for charging a particular working fluid
- The same supply cylinder should be used when re-ordering ammonia from its manufacturer
- Working fluids should be purchased in the highest purity grade available
- A certified analysis should be obtained to verify manufacturers specifications (current industry techniques for gas chromatograph ammonia analysis is questionable)
- Removal of noncondensables can be accomplished, if necessary, by repeated freeze/evacuate/thaw cycles.

9.7 Pinch-Off

9.7.1 Restrictions:

- Charge tube is nominally 1/16 in. (0.159 cm) inside diameter, 1/8 to 3/16 in. (0.318 to 0.476 cm) outside diameter by 3 to 4 in. (7.62 to 10.16 cm) long
- Start with an annealed, or partially annealed, charge tube to avoid cracking the tube wall. This might necessitate heat treatment after pinch-off if an annealed charge tube cannot meet strength requirements.

9.7.2 Procedure:

1. Chill (or warm) the heat pipe to just above ambient pressure being careful not to freeze the working fluid. This will minimize the pressure differential across the pinch-off when the valve is opened.
2. Flatten, over a 1/2 to 3/4 in. length, that portion of the tube to be pinched. This will eliminate any gas pocket.
3. Follow the flattening operation by applying a clamp on the fattened tube to ensure that positive clamping pressure is maintained until final closure.
4. Open the charge valve and carefully check for leaks.
5. Clean the area around the section to be cut.
6. Using a hacksaw, or its equivalent, cut the tube at a flattened section between the clamp and the charge valve.
7. Weld (TIG or EB) the cut section closed.
8. Loosen the pinch-off clamp.
9. Leak check at the weld; reclamp and reweld, if necessary.
10. Allow the heat pipe to reach room temperature (or preferably maximum operating temperature) and leak check at the weld.
11. If necessary, reclamp, chill, and reweld.



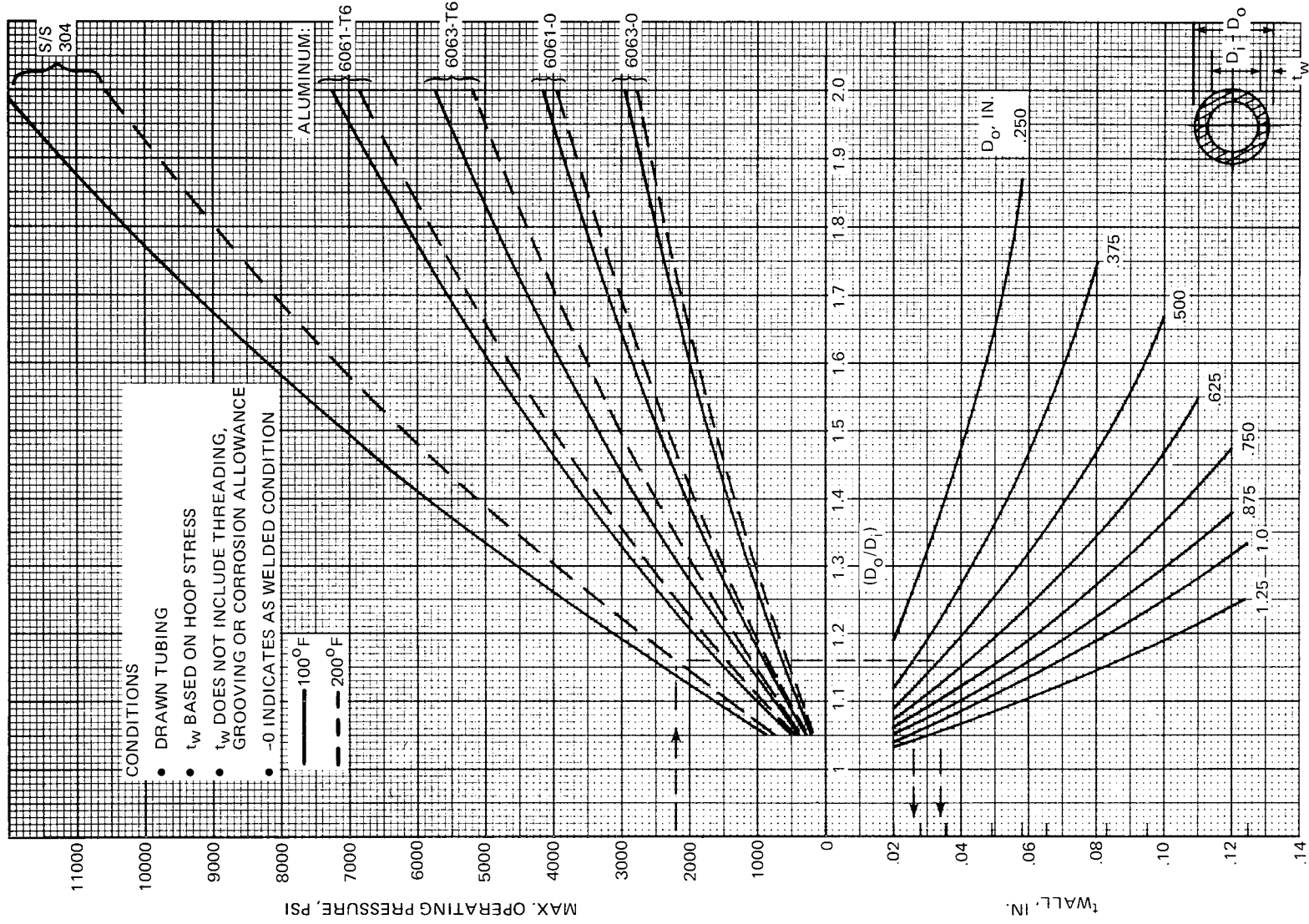


Fig.9-8 HP Envelope Design Curves



10 - REFERENCES

The publications cited throughout this report are listed in this section. In addition to specific text references (1 through 46), a limited bibliography (references 47 and beyond) is included for those readers desiring material beyond the scope of this document. In some instances, the listings include a brief abstract of the referenced document to aid readers who might be seeking specific information. As a further aid (where particularly appropriate), code letters are included in parenthesis at the end of the reference citation to identify specific manufacturing topics covered in that document. These code letters, as assigned by subject, are cross-referenced to the cited document(s) as follows:

Code Letters	Subject	Reference No.
B	Bonding techniques	12, 16 thru 21, 48, 55, 60, 64
CC	Container cleaning	3 thru 7, 11 thru 13, 15, 57, 63
EC	Evacuation and charging	3, 5, 11 thru 13, 39, 40, 50, 63, 65
FP	Fluid purity	41, 42, 43
MC	Materials compatibility	6, 7, 10, 11 thru 15, 45, 51, 52, 54, 58, 66
MD	Mechanical design	22, 23, 24, 27, 28, 30, 31, 32, 36, 56, 61, 62, 64
MV	Mechanical verification	13, 33, 49, 60, 61, 62
PO	Pinch-off	12, 13, 14, 46, 50
TC	Tube closure	3, 13
WC	Wick cleaning	3, 4, 12

Additional heat pipe manufacturing references for the period 1962 to 1972 are contained in Appendix G (NASA Literature Search Number 20604, "Heat Pipe Fabrication"). Two searches are presented - one with 28 limited-distribution citations, and the other with 53 more widely distributed citations. Some of the references cited pertain to the fabrication of liquid metal and cryogenic heat pipes, which, although beyond the scope of this report, may nevertheless be of interest to some readers.

Text Ref.

Title

1. NASA Heat Pipe Technology Meeting held at NASA Goddard Space Flight Center. Jan. 16-18, 1973.
2. NASA Cost Effective Heat Pipe Manufacturing Methods. Meeting held at Goddard Space Flight Center, Sep. 17-18, 1973.
3. Large Variable Conductance Heat Pipe. Grumman Aerospace Corp., HPM-6 under Contract NAS 8-27793. (TC/CC/WC/EC)
4. Beyerle F. J.: Chemical Process Manual. MSFC NASA TM X-2635, 1972. (CC/WC)

The manual presents all the documents directly related to chemical processes that were prepared by the Product Engineering and Process Technology Laboratory and are pertinent to the continuing technology of spacecraft development. A general discussion of cleaning techniques is given, followed by specific treatments for aluminum and stainless steel for particular applications. One of the telling points of the manual is the degree of detail gone into making the process less operator-sensitive.

5. Investigation of Embrittled ATS Heat Pipe Containing Grey Residue. Memo from Jellison and Johnson to Thole GSFC, Dec. 4, 1972. (CC/EC)

An analysis is presented of contamination products found in aluminum (6061) grooved heat pipe. Cause is postulated (presence of water) along with a recommended cleaning procedure which emphasizes water removal.

6. Metallurgical Examination of Sample Heat Pipes Heat Treated in the Presence of Water Vapor. Memo from Jellison and Johnson to Thole, GSFC, Feb. 2, 1973. (CC/MC)

Test that were conducted with controlled quantities of water in ATS type tubing demonstrate that small quantities of water (0.005 gm in a 10 in. length) can cause black discoloration, porosity and embrittlement when heat treated to 980°F.

Text Ref.

Title

7. A Simplified Process for Cleaning Aluminum Heat Pipes of the ATS Type. Memo from Johnson and Jellison to Thole, GSFC. May 31, 1973. (CC/MC)

Water present in aluminum groove heat pipes during heat treatment has been shown to be responsible for both internal surface discoloration and porosity with consequent loss of strength. A cleaning procedure has been suggested and tested which stresses residual water removal with alcohol rinses and decomposition of hydrated oxides via a high (600⁰F) temperature evacuation.

8. Vacuum Pumpdown Tests on ATS Straight Heat Pipe. Memo from Johnson and Jellison to Thole, GSFC, Jan. 30, 1973. (EC)

Pumpdown tests are described which show the benefits of properly drying the pipe prior to pumpdown, and pumpdown at elevated temperatures. Pipe pressure vs pumpdown time are shown as a function of water removal and bake-out temperature.

9. Johnson Space Center, National Aeronautics and Space Administration. Contract NAS 9-12848.
10. Results of Life/Compatibility Tests on Spiral Artery Ammonia Heat Pipe for OAO #4, Level 6. Grumman Aerospace Corporation Report. SSYS-252R-186.0, 14 April 1972. (MC)
11. Swerdling, B.; Kosson, R.; Urkowitz, M.; Kirkpatrick J.: Development of Thermal Diode Heat Pipe for the Advanced Thermal Control Flight Experiment (ATFE). AIAA Paper 72-260. (EC/CC)
12. Messerschmitt; Bolkow: Development of a Heat Pipe for Telecommunications Satellite Application. Prepared for ESRO. Blohm GMBH and Institute Fur Kernenergeetik, Stuttgart. Progress Report, June 19; Final Report, August 1972. (PO/CC/WC/EC/B)

Text Ref.

Title

12. (cont) A pinch-off procedure is described for an aluminum (6061T6) pipe with a stainless steel artery and ammonia working fluid. A mechanical clamp is used to temporarily seal the charge tube prior to final sealing with EB welding. A photo of the clamp is shown. Both the pipe and artery are cleaned in boiling acetone in an ultrasonic bath. The pipe is operated for one day with a flush charge of ammonia followed by evacuation and filling, which is done by distilling and freezing the charge in the pipe. Bonding of heat pipes to plates is discussed including: arc welding, friction welding, brazing, sintering, adhesive bonding, galvanic bonding, and plasma spraying.

13. Gerrels, E. E.; and Larson, J. W.: Brayton Cycle Vapor Chamber (Heat Pipe) Radiator Study. General Electric Company. NASA CR-1677, Feb. 1971. (PO/TC/MV/CC/EC/MC)

Aluminum (6061T6) test capsules were charged with 14 different working fluids to study materials compatibility. A brief cleaning procedure is described using an alkaline cleaner and deoxidizer. End caps were TIG-welded under helium in a vacuum-purged inert-gas welding chamber. Leak detection was accomplished with a helium mass spectrometer and pressurization with argon to 900 psig. Cleaning of a stainless steel tube is described. The pipes are filled with excess fluid which is bled off until the proper charge is reached. Pinch-off was accomplished with a mechanical tool followed by an epoxy backup. The following were shown to be compatible with aluminum: benzane, n-heptane, n-pentane, Freon-11, Freon-113, ammonia, n-butane. The following were not compatible: pyridine, CP-34, methyl alcohol, toluene, and water (in st. st. 321).

14. Skrabek, E. A.: Heat Pipe Design Handbook. Dynatherm Corporation NAS 9-11927, 1972. (MC)

Text Ref.

Title

14. (cont) The handbook lists a number of compatibility tests which have been performed by various investigators. All ammonia systems functioned without mishap, i.e., no gas generation; gas generation was noted in some cases with methanol (Al, SS) and water (SS). Gas generation was not a universal problem and may, therefore, be a result of the specific cleaning/charging/fluid preparation process.
15. Groll, M.; Kreeb, H.; Munzel, W. D.; and Zimmermann, P.: Performance and Life Tests of Low Temperature Heat Pipes. Institut Fur Kernenergetik (IKE), 4th International Congress Chisa '72. Praha, Czechoslovakia, September 11-15, 1972. (PO/CC/MC)
- Life tests were conducted for the following combinations in the temperature range 200 to 500⁰K: water-st.st., water-copper, water-nickel, acetone - st.st., acetone-copper, acetone-nickel, ammonia - st.st., ammonia - aluminum. Cleaning of components is done in boiling acetone in an ultrasonic bath. Weldments are done either by argon arc or EB. Pinch-offs are accomplished with EB welding.
16. Welding Kasier Aluminum, Kasier Aluminum and Chemical Sales, Inc. Oakland, California, First Edidtion, 1967. (B)
17. Technical Support Package for Tech Brief 69-10264: Welding, Brazing and Soldering Handbook NASA, Washington, D.C. PB188037, and TSP69-10264. (B)
18. Integration of NASA-Sponsored Studies of Aluminum Welding, Koichi Masubuchi. Washington, D.C. 20546. NASA Report CR-2064, June 1972. (B)
19. Godell, S. E.; et al: In-Place Fusion Welding of Small Diameter Aluminum Tubing. Welding Journal, May 1970. (B)

Text Ref.

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20. Witt, Robert H.; and Sgro, Vincent J.: Automatic Pulsed-Arc Welding of Titanium and Stainless Steel Tubing. Grumman Advanced Development Report No. ADR 08-03-72.2, 1972. (B)
21. Vilkas, Eugene P.: Pulsed Current and It's Applications. Welding Journal, April 1970. (B)
22. ASME Boiler and Pressure Vessel Code, 1965. Section VIII Unfired Pressure Vessels, Section II Material Specifications.
23. Space Vehicle Design Criteria. NASA SP-8057, Jan. 1971. (MD)
24. Solid Rocket Motor Metal Cases. NASA SP-8025, Dec. 1972. (MD)
25. U.S. Civil Aeronautics Act, Title XIII.
26. Code of Federal Regulations. Title 49, Parts 100 to end.
27. Fracture Control of Metallic Pressure Vessels. NASA SP-8040, May 1970. (MD)
28. MIL-HDBK-5B, Metallic Materials and Elements for Aerospace Vehicle Structures, Department of Defense, Sept. 1971. (MD)
29. Cost Effective Methods for the Manufacture of Spacecraft Heat Pipes - Monthly Progress Report CEM-7, Appendix A, May 1973. (Contract NAS 5-23156).
30. Seely, F. B.; and Smith, J. O.; J. Wiley and Sones: Advanced Strength of Materials, second ed., 1963. (MD)
31. Grumman Aerospace Corporation, Structures Manual. (MD)
32. Timoshenko, S.; Woinowsky-Krieger, S.: Theory of Plates and Shells. McGraw-Hill, 1959. (MD)

Text Ref.

Title

33. Environmental Test Procedure for Leak Test - Ames Heat Pipe Experiment, R & QA Document No. PERS-P-1051-A, NASA AMES Research Center, Moffett Field, California. (MV)

Describes procedure for leak checking a VCHP with trace Helium in noncondensable gas.

34. Oman, R.A., Grumman Research Department, private communication.
35. The Adsorption of Oxygen at Low Temperature and Pressure on Smooth Iron. Armbruster and Austin: J. Am. Chem. Soc., vol. 68, pp 1347-1354, July 1946.
36. Military Standardization Handbook, Metallic Materials and Elements for Aerospace Vehicle Structures, MIL-HDBK-5B, 1 Sept. 1971. (MD)
37. Reilly, C.: Marshall Space Flight Center. Alabama Personal Communication, 1973.
38. Petrick, W.: Jet Propulsion Laboratory, Personal Communication, 1973.
39. Long Life High Reliability Thermal Control Systems Study Final Report. General Electric Company, SD Document No. 72SD4243, Aug. 1972. (EC)

A charging procedure is described for methanol using a metered pipette. Evacuation is accomplished through a 1/16 in. i.d. by 1/8 in. o.d. nickel tube using a roughing/diffusion pump for 3 hr with the pipe heated periodically with a heating gun. A procedure for charging a gas controlled VCHP is also presented.

40. Series of Papers presented by B. B. Dayton in the transactions of the American Vacuum Society Symposia of 1959, 1961, 1962, 1963, etc. (EC)

Text Ref.

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41. Physical Properties of Ammonia, Matheson Gas Products. (FP)
42. Letter from Air Products & Chemicals Inc. to Dynatherm Corporation. Oct. 12, 1971. (FP)
43. Saaski, E. W.: Gas Occlusions in Arterial Heat Pipes. AIAA 8th Thermophysics Conference, 1973. Paper No. 73-724.
44. Mindrup, Jr., R. F.; and Taylor, J. H.: Gas Chromatographic Analysis of Trace Contaminants in Liquid Ammonia. Journal of Chromatographic Science, Vol. 8, Dec. 1970, p. 723. (FP)
45. Kreeb, H.; Groll, M.; Zimmermann, P.: Life Test Investigations with Low Temperature Heat Pipes. Institute Fur Kernererget, K. Universitat Stuttgart Federal Republic of Germany. Presented at International Heat Pipe Conference, Oct. 15-17, 1973, Stuttgart. (MC)
46. Letter from F. Greene NASA/LRC to R. McIntosh NASA/GSFC July 9, 1973. (PO)

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47. ASRDI Oxygen Technology Survey Vol. III, Heat Transfer and Fluid Dynamics. NASA SP-3076.

The survey is part of an oxygen safety review by NASA-ASRDI. A number of heat pipe key words appear in the abstracts but for a meaningful evaluation the original publications must be reviewed.

48. Automatic Fusion Welding of Titanium and Stainless Steel Tubing. Grumman Standard Specification, GSS 6206A. (B)

49. Diffusion of Trace Gases for Leak Detection: A Study. NASA TECH BRIEF. Number 69-10067, Mar. 1969. (MV)

Discusses use of Freon and helium as trace gases with recommendation that uniform gas distribution can only be guaranteed if system being leak checked is first evacuated.

50. Eggers, P. E.; Serkiz, A. W.; Burean, R. J.: Development of High Thermal Power Density Ammonia Heat Pipes. ASME Paper 71-WA/HT-20. (PO/EC)

A porous, grooved wick pipe is described with ammonia as the working fluid. The pipe was treated in a hydrogen atmosphere at 1500^oF followed by evacuation to 5×10^{-6} at 120^oC achieved after 16 hr. The pipe was charged by vacuum distillation and sealed with a "conventional" pinch-off tool followed by a final welded closure.

51. Gammel, G.; Heedtmann, V.; and Pawlowski, P. H.: Investigation of Heat and Mass Transfer in Heat Pipes. Brown, Boveri and Cie AG, Mannheim, Central Research Laboratory, Heidelberg, Germany. (MC)

Discusses design and testing of water-nickel and water-copper heat pipes. No significant manufacturing information.

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Ref.

Title

52. Grawmann, D. W.; Richard, C. E., et al: Research Study on Instrument Unit Thermal Conditioning Panel. Airesearch Manuf. Co., NASA CR-8-11291, May 1971. (MC)

A 30 x 30 in. heat pipe panel with water, stainless steel 304 heat pipes, and nickel porous wicks is described. Reports hydrogen generation.

53. International Heat Pipe Conference 1973. Stuttgart, Federal Republic of Germany, Oct. 15-17, 1973.

54. Johnson, G. D.; Saaski, E. W.: Arterial Wick Heat Pipes. ASME Paper #72-WA/HT-36. (MC)

A water/copper heat pipe was built and tested. The copper was oxygen free high conductivity grade treated by etching in a 5% HCl solution; rinsed with water, then treated with Ebanol-C at 210^oF for 12 min then rinsed with hot and cold water. Double distilled water was loaded into the pipe and the pipe burped to remove noncondensable gas. No gas was generated.

55. Joining Processes for Aluminum. Materials Engineering, Mar. 1973. (B)

The article describes an ultrasonic, fluxless soldering process. This involves immersing the cleaned part in an agitated solder bath. This results in a very clean, oxide-free surface which can then be bonded to aluminum, copper or steel. The joint is very clean with no post cleaning or washing operation required. The disadvantage is the 800^oF bath temperature. A fluxless vacuum brazing process is also described. This involves heating the part to 1080/1130^oF for one minute followed by a quench.

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56. Kuhn, P.: Stresses in Aircraft and Shell Structures. McGraw-Hill, 1956. (MD)
57. Mahefky Jr., E. T.: Development of a Planar Heat Pipe for Cooling Large Capacity Batteries. AF APL-TR-71-39. Dec. 1971. (CC)
- A stainless steel 304, 1/2 x 3-1/2 x 12 in. planar pipe with water and 100 mesh stainless steel 304 wick is described. Discusses cleaning of steel container.
58. Marcus, B. D.: Monthly Technical Progress Report No. 38. Contract No. NAS 2-5503, TRW 13111-6042-RO-00. Sept. 1972. (MC)
- Discusses scaling factors that affect gas generation in a nickel-water heat pipe. No significant manufacturing information.
59. Marto, P. J.; Mosteller, W. L.: Effect of Nucleate Boiling on the Operation of Low Temperature Heat Pipes. ASME Paper 69-HT-24.
60. Marshall, R. A.: Radiographic Inspection of Rigid Tubing Joints. North American Rockwell Corp., Space Division, Downey, Calif. NASA Document TSP SP-5952(02). (MV/B)
- Steel tube joints using the brazing and welding processes are discussed, as well as aluminum tube joints using solder and braze bath techniques. Radiograph techniques are presented, including equipment used, interpretation of results, and control. Specifications or acceptance criteria are not presented.
61. Monthly Progress Report No. 9. NAS9-12801, GAC Report No. SHR-9. Mar. 1973. (MD/MV)

The progress report discusses a low-k section of a diode heat pipe. The section was basically a local thinning of the aluminum wall

Bibliography
Ref.

Title

61. (0.007 in.) re-inforced with a fiberglass overwrap. The pipe passed its initial proof test (1600 psi) but subsequently failed its leak test when charged with ammonia. The failure was probably due to inadvertent flexing of the diode during manufacture. The problem was solved by a stainless steel tube pressed into the low-k section again with the fiberglass overwrap.

62. Numerical Analysis of Crack Propagation in Cyclic - Loaded Structures. Forman, R. G.; Kearney, V. E.; and Engle, R. M.: ASME J. of Basic Eng. p. 459, Sept. 1967. (MD)

63. 75° K NASA Vuilleumier Cryogenic Engine. AiResearch Mfg. Co. Tech. Letter #69-5869(17)/(18)/(20). Contract NAS 5-21096, April/June/July 1971. (CC/EC)

A cleaning process is described using Turco #4215 alkaline cleaner followed by SMUTCO #4 which is a mild sulphuric acid/chromic acid solution. This leaves a thin oxide passive layer which is considered "clean". Evacuation is for 44 hours at ambient temperature and 5×10^{-5} Torr followed by 4 hr at 200° F and 5×10^{-5} Torr. Fill is checked by weighing pipe before and after charging. It is not clear whether an intermediate charge bottle is used or if charge is direct from ammonia cylinders.

64. SPACE Materials Handbook. 3rd Edition, NASA SP-3051. (MD/B)

The handbook was reviewed. Two chapters were applicable to heat pipes, meteoroid impact and adhesive bonds.

65. Schwartz, J.: Performance Map of an Ammonia (NH_3) Heat Pipe, ASME, 70-HT/SpT-5, June 1970. (EC)

Bibliography
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Title

65.
(cont)

A charging procedure is described for ammonia in a stainless steel pipe. The fluid is distilled several times prior to introduction into a graduated fill tube, then vacuum distilled into a pipe that was evacuated for 24 hr.

66.

Marcus, B. P.: Theory & Design of Variable Conductance Heat Pipes. NAS CR-2018, TRW, 1972. (MC)

The paper describes compatibility tests run on stainless steel/methanol system. The stainless steel pipes were either vacuum fired at 1100°C or oxidized in air at 500°C for one hour. Spectrographic grade methanol was used either in the as-received condition or dried by passing through a molecular sieve. No noncondensable gas was detected after 5000 hr of test (reflux boiler mode) at 145°F.



**MANUFACTURING PROCESS FOR THE CLEANING
OF FLARED AND UNFLARED TUBING**

L I N E S T A N D A R D S I N S T R U M E N T S C O M P A N Y

MANUFACTURING PROCESS FOR
THE CLEANING OF FLARED AND UNFLARED TUBING

1. SCOPE

1.1 Scope - This process covers the Process Engineering Laboratory requirements for the cleaning of flared or unflared aluminum or stainless steel tubing used in LOX, fuel, and pneumatic systems of space launch vehicles.

1.2 Applicability - Cleaning procedures outlined in this process are applicable to flared or unflared tubing made of the following materials:

- Stainless steel - Grades 304, 304L, 316, 321, and 347.
- Aluminum - Alloys 5052, 5086, 5456, and 6061.

2. APPLICABLE DOCUMENTS

2.1 Governmental - The following documents, of the issue in effect on the date of use of this process, form a part of this process.

SPECIFICATIONS

Federal

0-H-795(2)	Hydrofluoric Acid, Technical
0-N-350	Nitric Acid, Technical
0-0-670	Orthophosphoric (Phosphoric) Acid, Technical
0-P-94a	Paper, Test, pH Indicator
0-S-595a(3)	Sodium Dichromate, Technical-Grade (Sodium Bichromate) Sodium Dichromate Dihydrate
0-S-598	Sodium Hydroxide, Technical

0-S-642B Sodium Phosphate, Tribasic,
Technical, Anhydrous, Dodeca-
hydrate and Monohydrate

0-T-634a Trichloroethylene, Technical

BB-N-411a Nitrogen

UU-T-81f(1) Tags, Shipping and Stock

Military

MIL-A-00148C(2) Aluminum Foil

MIL-A-6091B Alcohol, Ethyl, Specially Denatured,
Aircraft

George C. Marshall Space Flight Center

MSFC-SPEC-164 Cleanliness of Components for Use in
Oxygen, Fuel, and Pneumatic Systems,
Specification for

MS 101.0 Manufacturing Specification for The
Drying of Components in a Vacuum

3. REQUIREMENTS

3.1 General - No deviation from the requirements of this manufacturing process shall be permitted without prior written approval of the Process Engineering Laboratory.

3.2 Materials

3.2.1 Liquid solvent - Trichloroethylene used for liquid or vapor degreasing shall be equivalent to Type II of Specification 0-T-634a.

3.2.2 Test solvent - Trichloroethylene used for testing the cleanliness of sample tubing shall meet the requirements for Type I of Specification 0-T-634a with the exception that the nonvolatile residue shall not be greater than 0.010 gram per 500 cc when the solution is evaporated at 221° to 230°F and that no particle larger than 175 microns in any dimension shall be present.

3.2.3 Demineralized water - Demineralized water shall contain no particle larger than 175 microns in any dimension and shall possess a minimum resistivity of 50,000 ohms.

3.2.4 pH indicator - The pH indicating paper used in this process for checking neutrality shall be of the Medium Range, Class A, of Specification 0-P-94a.

3.2.5 Aluminum foil - Dry annealed aluminum foil shall conform to paragraph 6.3.2 of Specification MIL-A-00148C.

3.2.6 Tags - Tags employed in marking of cleaned components shall conform to Style C of Specification UU-T-81f(1).

3.2.7 Drying and preservation gases - The nitrogen or air employed for drying or preservation shall be filtered to a 100 micron level, shall possess an oil content not greater than 3 parts per million by weight, and shall contain a maximum of 24 parts per million by volume of moisture. Samples of gas shall be taken upon receipt of each bottle of gas for compliance to the applicable specification.

3.2.8 Compressed, heated gases - When drying is performed by blowing or purging a component with heated, compressed gases, the pressure shall be 15 to 25 psi* and the temperature shall be $180^{\circ} \pm 20^{\circ}\text{F}$. The gas shall conform to paragraph 3.2.7 of this process.

3.3 Cleaning Procedures

3.3.1 Flared stainless steel tubing (internal surfaces only)

3.3.1.1 Degrease - Circulate liquid trichloroethylene through the tubing for 3 to 5 minutes at ambient temperature and at a pump pressure of 30 ± 10 psi.** Note safety precautions given in paragraph 6.2 of this process.

3.3.1.2 Dry - Using compressed air (see paragraph 3.2.7) remove all traces of trichloroethylene by drying at $180^{\circ} \pm 20^{\circ}\text{F}$ for 1 to 2 minutes at 15 to 25 psi.*

3.3.1.3 Hot alkaline wash - Circulate a solution of 10 ± 2.0 percent by weight of trisodium phosphate through the tubing at $180^{\circ} \pm 10^{\circ}\text{F}$ for 10 to 15 minutes.

3.3.1.4 Rinse - Circulate tap water at a temperature of 160 to 180°F through the tubing for 5 to 10 minutes.

*(1.034×10^5 to 1.724×10^5 newt/m²)

**($2.068 \times 10^5 \pm 6.845 \times 10^4$ newt/m²)

3.3.1.5 Pickling solution - Pickling solution is to be used at this point, if required, for internally corroded or contaminated tubing only. Do not use pickling solution if the tubing has been previously cleaned by pickling, bright annealing, or other equivalent etchant processes. Protect the flared part of the tubing while circulating through the tubing for 5 to 8 minutes the following aqueous solution at a temperature of 90° to 100°F. (Sodium bifluoride may be used with excess nitric acid to produce the required hydrofluoric acid.)

20 ± 2 percent (by weight) nitric acid
1.5 ± 0.5 percent (by weight) hydrofluoric acid

3.3.1.6 Rinse - Circulate tap water through the tubing at a temperature of 160° to 180°F for 5 to 10 minutes.

3.3.1.7 Passivate - Passivate the tubing by circulating through the tubing for 15 to 20 minutes at 125° ± 5°F the following aqueous solution:

20 ± 2 percent (by weight) nitric acid
2.0 ± 0.5 percent (by weight) sodium dichromate

3.3.1.8 Rinse - Circulate demineralized water through the tubing at ambient temperature until the pH of the effluent is 6 to 8.

3.3.1.9 Pressure-dry - Using nitrogen or air at 180° ± 20°F dry by flushing gas through the interior of the tubing for 15 to 20 minutes at 15 to 25 psi.*

3.3.1.10 Vacuum dry - When applicable, vacuum dry in the manner outlined in Specification MS 101.0.

3.3.2 Unflared stainless steel tubing

3.3.2.1 After lubrication with oil

A. Vapor degrease in the manner outlined in Specification MS 150.0A. Flush the internal surfaces of the tubing with liquid trichloroethylene by using the pump on the vapor degreaser.

B. Using air that meets the requirement of paragraph 3.2.8 remove all traces of trichloroethylene by drying at 180° ± 20°F for 1 to 2 minutes at 15 to 25 psi.*

*(1.034 x 10⁵ to 1.724 x 10⁵ newt/m²)

3.3.2.2 After lubrication with soap

A. Flush with tap water at 160° to 180°F until free of soap.

NOTE: If hot tap water does not remove the soap, use an aqueous solution containing 5 (±2) percent by weight of sodium hydroxide at 160° to 180°F.

B. Rinse by flushing with demineralized water at 160° to 180°F for a minimum of 5 minutes.

C. Dry by flushing nitrogen or air through the inside of the tubing at 180° ± 20°F for 15 to 20 minutes at 15 to 25 psi.*

3.3.3 Aluminum tubing - Prior to cleaning flared aluminum tubing, protect the flared ends of the tubing by connecting sections of tubing together with aluminum AN fittings which fit into the tube flare and protect the flare surfaces from contact with the chemical cleaning solution.

3.3.3.1 Degrease - Circulate liquid trichloroethylene through the tubing for 3 to 5 minutes at ambient temperature and at a pump pressure of 30 ± 10 psi.** Note the safety precautions given in paragraph 6.2.

3.3.3.2 Dry - Using compressed air, remove all traces of trichloroethylene by drying at 180° ± 20°F for 10 to 20 minutes at a pressure of 15 to 25 psi.*

3.3.3.3 Hot alkaline degrease - Circulate for 5 to 10 minutes a solution of 10 ± 2.0 percent by weight trisodium phosphate through the tubing. Maintain a temperature of 170° to 190°F and a pressure of 40 ± 20 psi*** on the circulating solution.

3.3.3.4 Rinse - Circulate tap water at ambient temperature through the tube for 5 to 10 minutes.

3.3.3.5 Nitric acid rinse - Circulate through the tube an aqueous solution at 5.0 ± 1 percent by weight of nitric acid at 85° to 100°F for 5 to 8 minutes.

Alternate phosphoric acid rinse - An aqueous solution of 5.0 ± 0.5 percent by weight phosphoric acid may be used to remove heavy soils that cannot be removed by the nitric acid rinse in paragraph 3.3.3.5 above. In these cases, circulate the solution through the tubing at 160° to 180°F for 5 to 8 minutes.

*(1.034 x 10⁵ to 1.724 x 10⁵ newt/m²)

** (2.068 x 10⁵ ± 6.895 x 10⁴ newt/m²)

*** (2.758 x 10⁵ ± 1.379 x 10⁵ newt/m²)

3.3.3.6 Cold rinse - Circulate and rinse with demineralized water at ambient temperature until the pH of the effluent is between 6 and 8.

3.3.3.7 Dry - Dry per paragraph 3.3.1.9 of this process.

3.3.3.8 Vacuum dry - When applicable, vacuum dry per paragraph 3.3.1.10 of this process.

3.4 Recleaning Procedure - If additional cleaning, or recleaning, of stainless steel tubing (paragraphs 3.3.1 and 3.3.2) or aluminum tubing (paragraph 3.3.3) becomes necessary, the tubing must be cleaned to the original cleanliness level by flushing with trichloroethylene which has been filtered to remove all particles larger than 100 microns (absolute) in any dimension. Make particle count and stop cleaning when the requirements of Specification MSFC-SPEC-164 have been met. Repeat the operation if necessary to meet these requirements.

4. ACCEPTABILITY PROVISIONS

4.1 Cleanliness - Tubing cleaned by the procedures outlined in this process must meet the requirements of paragraphs 3.5.1.1, 3.5.1.2, 3.5.2.1, 3.5.2.2, and the qualification procedures of paragraph 4.2.2.3 of Specification MSFC-SPEC-164.

4.2 Quality Control - Control of the quality of various tank solutions will be assured by adherence to the times, temperatures, and concentrations specified.

5. PREPARATION FOR DELIVERY

5.1 Preservation and Packaging - Tubing shall be sealed with PE Laboratory approved coverings or closures. The sealed tubes shall be placed in clean polyethylene bags purged by nitrogen or air meeting the requirements of paragraph 3.2.7 of this process. The bag openings shall be heat sealed to prevent contamination of the tubes. (Refer to the applicable section of Saturn Packaging Manual.)

5.2 Marking - Tubing cleaned by the procedures outlined in this process shall be marked with tags conforming to Specification UU-T-81f(1), Type C, which shall bear the following information.

- Part or identification number.
- Method of cleaning and micron level.
- Date of cleaning.
- Title and date of this process.
- Any further information required by contract.

NOTES

6.1 Intended Use - This manufacturing process, developed by the PE Laboratory of the George C. Marshall Space Flight Center, is intended for use in the cleaning of aluminum or stainless steel tubing used in LOX, fuel and pneumatic systems.

6.2 Volatile Solvent Safety Precautions - Perform this operation under fume exhaust hood or use room exhaust system. Use gloves and chemical respirator if no exhaust system is available.

Preparing Activity

Process Engineering Laboratory
George C. Marshall Space Flight Center



**AUTOMATIC FUSION WELDING OF TITANIUM
AND STAINLESS STEEL TUBING**



GRUMMAN AEROSPACE CORPORATION

Bethpage, L. I., N. Y.
Code Ident. No. 26512



Page 1 of 12
Specification No. GSS 6206A

Release Date 2-17-72

GRUMMAN STANDARD SPECIFICATION

AUTOMATIC FUSION WELDING OF
TITANIUM AND STAINLESS STEEL TUBING

B. J. Shaver
for F. T. MAIN Jr.
Director, Materials and Processes Department

2-23-72
Date



REVISION DESCRIPTION

Spec No. 6206

Rev.	Date	Description
A	2-17-72	<p>This revision incorporates the following:</p> <ul style="list-style-type: none">(a) Specification Amendment 1 to GSS 6206, dated 5-27-71.(b) Change in Certification procedure.(c) Revised rejection paragraph.(d) Added Para. 5.4 to include, "Marginal indicia".

SPECIFICATION

No. GSS 6206A

1 SCOPE

1.1 Scope. This specification establishes the requirements for automatic fusion welding of titanium and stainless steel tubing to end fittings using an automatic tube welder.

1.2 Superseding data. This specification supersedes GSS 6206, dated 2-17-71, including Amendment 1.

2 APPLICABLE DOCUMENTS

2.1 Government Documents. The following documents (referred to under the basic number in subsequent paragraphs) shall form a part of this specification to the extent specified herein:

MIL-T-5021D	Tests; Aircraft, and Missel Welding Operators Qualification
MIL-T-8808A	Tubing, Steel, Corrosion-Resistant (18-8 Stabilized) Aircraft Hydraulic Quality
MIL-T-8973	Tubing, Steel, Corrosion and Heat Resistant, For Aerospace Vehicle Hydraulic Systems Assembled by Brazing
MIL-A-18455B	Argon, Technical
MIL-STD-453, Change 1	Inspection, Radiographic
MIL-Handbook-H-106	Multi-Level Continuous Sampling Procedures and Tables for Inspection by Attributes

SPECIFICATION

No. GSS 6206A

2.2 Grumman documents. The following documents, of the issue in effect on the date of invitation for bids, shall form a part of this specification to the extent specified herein:

GSS 7015	Cleaning and Descaling of Titanium and Titanium Alloys
GSS 7021	Acid Cleaning of Ferrous Alloys
GM3107	Titanium 3A1-2.5V Tubing, Seamless Cold Worked and Stress Relieved
GM3118	Titanium 3A1-2.5V Tubing, Seamless, Annealed

2.3 Other Documents. The following documents shall form a part of this specification to the extent specified herein:

AWSA3.0-69	Terms and Definitions
------------	-----------------------

3 REQUIREMENTS

3.1 General. When Engineering drawings or specifications required automatic welding of titanium fittings to the ends of titanium tubing or stainless steel fittings to the ends of stainless steel tubing, it shall be accomplished in accordance with the following:

3.2 Qualified personnel. Personnel welding to the requirements of this specification shall be qualified as Welding Operators in accordance with the special applications requirements of MIL-T-5021. The qualification test shall be performed under the cognizance of Quality Control in accordance with parameters established by Materials and Processes. The qualification shall be approved by Quality Control and a list of qualified personnel shall be maintained by the Training Department. Each qualified welding operator shall be assigned an identifying symbol or number.

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3.3 Equipment. The following equipment as approved by Material and Processes shall be used.

3.3.1 Automatic fusion welding equipment. Automatic fusion welding equipment shall be capable of consistently meeting the requirements of Section 4 when parts are processed in accordance with the certified welding schedule per 3.5.4.4.

3.4 Material. Unless otherwise specified on the Engineering drawing, the following materials shall be used.

3.4.1 Fittings. Titanium or stainless steel, weldable fittings as specified on the Engineering drawing.

3.4.2 Tubing

(a) 3A1-2.5V titanium per GM3107 or GM3118

(b) 321 stainless steel per MIL-T-8808

(c) Stainless steel per MIL-T-8973

3.4.3 Gas

(a) Argon per MIL-A-18455

3.5 Procedure.

3.5.1 Joint preparation. Tube ends shall be machined square.

3.5.2 Cleaning. Titanium tubing shall be acid cleaned per GSS 7015. Stainless Steel shall be cleaned per GSS 7021. All cleaned parts shall be bagged. Parts shall be welded within 8 hours after cleaning. Recleaning is premissible.

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3.5.3 Pre-weld fit up. Cleaned parts shall be handled with clean gloves. Tooling shall hold the parts so that no gap is allowed at the weld centerline

3.5.4 Welding.

3.5.4.1 Shielding. Shielding gas per 3.4.3 shall be introduced into the tube system before welding may proceed.

3.5.4.2 Procedure certification. Prior to machine welding of any production part, a Welding Schedule per Table I shall be established by Materials and Processes. Five (5) specimens shall be prepared per Figure 1 by welding production fittings to tubing for testing per 4.2.3.1. These specimens shall be of the same material, heat treat condition, receive the same preparation and be welded under the same conditions as the production part. An established certification may be used to weld other fittings to the same material, diameter and wall thickness tubing provided one (1) Specimen has been prepared, tested and the additional part number, or numbers, has been added to the certification or the original certification number appears on the additional weld certification or certifications.

3.5.4.3 Certification test specimen submittal. The welded specimen(s) and the Welding Schedule shall be submitted to Quality Control and shall meet the requirements of 4.2

3.5.4.4 Welding schedule acceptance. Upon acceptance of the weldments, the Welding Schedule shall be certified and retained by Quality Control and copies shall be forwarded to and retained by Materials and Processes and the Production Welding Foreman.

3.5.4.4.1 Welding schedule program cards. The data recorded in the welding Schedule may be transferred to program cards and the program cards may then be used to program the welding machine automatically by inserting them into the program card reader.

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3.5.4.4.2 Welding parameters. Welding parameters, as specified on the certified welding schedule, may be varied ± 10 percent under the direction of Materials and Processes.

3.5.4.5 Welding schedule recertification. When the certification specimens fail to qualify or when changes greater than 10 percent of the certification values are made in any one of the critical factors (3 thru 25) listed in Table I, a revised welding schedule shall be established by Materials and Processes. The certification tests shall be rerun using the revised welding schedule.

3.6 Marking and identification.

3.6.1 Marking and identification of welds. Each weld shall be suitably tagged with the identifying symbol or number of the welding operator.

4 QUALITY ASSURANCE PROVISIONS

4.1 Responsibility. Quality Control shall be responsible for assuring compliance with the requirements of this specification.

4.2 Inspection.

4.2.1 End product inspection. Production and certification welds shall be inspected by the following methods:

- (a) Visual. All welds shall be visually inspected on the I.D. and O.D. When visual I.D. inspection is not possible, radiographic inspection shall be performed.
- (b) Radiographic. Radiographic inspection in accordance with MIL-STD-453 shall be performed on all certification welds. Production welds shall be radiographically inspected using a sampling plan for each diameter per MIL-Handbook-H-106, AOQL 2.0 and $f = 1/2$. Failure of a weld to conform to the following criteria shall require Production to submit previously welded parts for radiographic inspection back to the last inspected acceptable part.

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4.2.2 Defect criteria. I.D. and O.D. defects disclosed by any method described in 4.2.1 shall be restricted as follows:

4.2.2.1 Color. The titanium weld bead and adjacent base metal shall have a bright silver to light straw appearance. Blue-gray or gray discoloration or the presence of loose scale shall be cause for rejection of titanium welds.

4.2.2.2 Penetration. All butt welds shall show evidence of complete (100 per cent) penetration.

4.2.2.3 Undercut. Undercut in the weld metal shall not be permitted in any weld joint.

4.2.2.4 Craters. Craters shall be acceptable provided there is no evidence of cracks and the base of the crater does not extend below the base metal surface.

4.2.2.5 Weld size. Weld size shall be sufficient to melt the entire fitting alignment lip.

4.2.2.6 Cold laps. Cold laps shall not be permitted in the bead or melt-through area.

4.2.2.7 Arc blow or arc wandering. Arc blow or arc wandering in the bead or melt-through area observed in the finished weld shall be cause for rejection.

4.2.2.8 Underfill. Depressions exceeding 10 percent of the tube wall thickness in the weld metal shall not be permitted in the weld joint.

4.2.2.9 Cracks. The presence of any cracks in the weld or adjacent base metal shall not be permitted.

4.2.2.10 Lack of fusion. Lack of fusion shall not be acceptable.

4.2.2.11 Porosity and inclusions. Weld discontinuities, such as porosity and/or inclusion (metallic or non metallic), occurring within the weld metal shall be restricted as follows:

- (1) Single discontinuity. The maximum dimension of single discontinuity, regardless of type, and the allowable limits for the sum total of the individual dimensions shall be as specified in Table II.

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4.2.2.11 (Continued)

- (2) Aligned porosity. Any group of three (3) or more discontinuities falling on a straight line within one linear inch of weld shall be cause for rejection if the distance between adjacent discontinuities is less than six (6) times the largest dimension of the smaller adjacent discontinuity.
- (3) Surface porosity. Any porosity open to the surface shall be cause for rejection.

4.2.3 Destructive inspection. The following destructive tests shall be made on certification test specimens.

4.2.3.1 Tensile tests. Specimens per 3.5.4.2 shall be assembled per Figure 1 and tensile tested. The ultimate strength of the assembly shall meet or exceed 75 KSI* for stainless steel tube and 90 KSI** for titanium tube.

4.3 Rejection.

4.3.1 Rejected welds. Rejected welds may be rewelded under the direction of the Materials and Processes Department using a suitable repair welding schedule.

5 NOTES

5.1 Definitions. All definitions shall be as per AWS A3.0-69.

5.2 Safety. All safety precautions as specified by the safety Engineer shall be adhered to.

5.3 Suppliers (Sellers). This specification shall be applicable for Suppliers (Sellers) compliance as specified by the Contract, Engineering drawings or specifications. Suppliers (Sellers) are required to submit process documents for approval and deviation requests, via the Purchasing Department, to Engineering Specifications and Standards, Department 640.

5.4 Marginal indicia. The right hand margins of this specification are marked with vertical bars to indicate where changes (additions, modifications, corrections, deletions) from the previous issue were made. This was done as a convenience only and the Contractor assumes no liability whatsoever for any inaccuracies in these notations, or misinterpretations thereof. Suppliers (Sellers) are cautioned to evaluate the requirements of this document based on the entire content irrespective of the marginal notation and relationship to the last previous issue.

*(5.171×10^8 newt/m²) **(6.205×10^8 newt/m²)

SPECIFICATION

No. GSS 6206A

TABLE I

MINIMUM PARAMETERS TO BE RECORDED IN
WELDING SCHEDULE

1. Applicable Detail Fitting Numbers
2. Assembly Name
3. Tubing Diameter
4. Base Metal Alloy
5. Base Metal Thickness
6. Electrode Material
7. Electrode Diameter, Shape and Gap
8. Torch Gas Flow Rate
9. Tube Gas Flow Rate
10. Pre-Purge Time
11. Post Purge Time
12. Rotation Delay Time (Seconds)
13. Up Slope Time (Seconds)
14. Constant Speed Time (Seconds)
15. Constant Speed (RPM)
16. Up Slope Speed (RPM/Sec.)
17. Up Slope Speed Time (Seconds)
18. Final Slope Time (Seconds)
19. Run Out Speed (RPM/Sec.)
20. Initial Current (Amps or Amps/Sec.)
21. Weld Current, First Level or First and Second Level (Amps)

SPECIFICATION

No. GSS 6206A

TABLE I

MINIMUM PARAMETERS TO BE RECORDED IN WELDING SCHEDULE (Cont'd)

22. Final Current (Amps or Amps/Sec.)
23. Pulse Low Current (Amps or percent as applicable)
24. Pulse High Time (Seconds)
25. Pulse Low Time (Seconds)
26. Operator, I.D. Stamp
27. Cognizant Materials and Processes Engineer
28. Quality Control Inspector
29. Power Supply Model and Serial No.
30. Weld Head Model and Serial No.
31. Programmer Control Model No.

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No. GSS 6206A

TABLE II

RADIOGRAPHIC DISCONTINUITY LIMITS

Tube Wall Thickness (T) in inches	Maximum Dimensions Single Discontinuity	Sum at Longest Dimensions Permissible in one Linear Inch of Weld
Up to 0.030	0.010 inch	1.5T or 0.030 inch whichever is less
0.031 and up	T/3 or 0.020 inch whichever is less	T or 0.060 whichever is less

NOTES

1. T = Wall thickness of thinner member being joined
2. See 4.2.2.1(d)(2) for limitations of aligned porosity

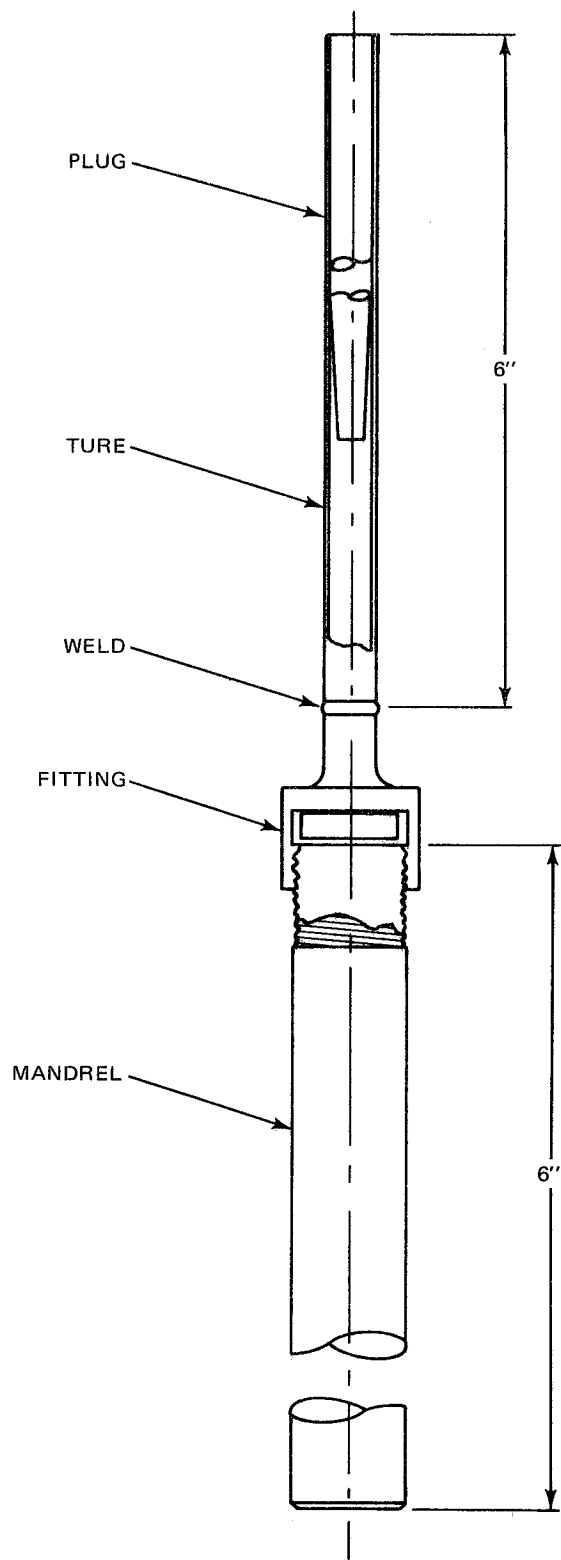


Fig. 1 Tensile Test Set-Up for Destructive Test of Certification Specimen

SADDLE STRESSES

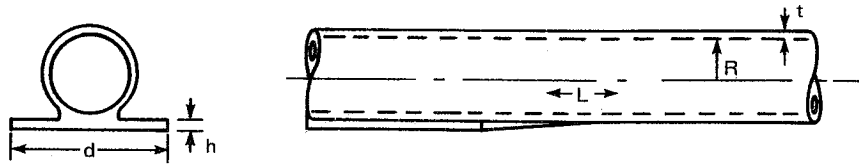


APPENDIX C - SADDLE STRESSES

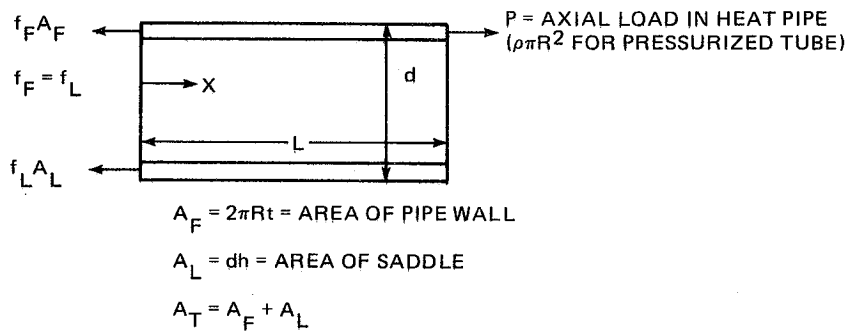
NOTE

Refer to Paragraph 5.2.4.5

The sudden change in the cross-sectional area of the heat pipe at a saddle



results in a local redistribution of stresses in the pipe wall which can be estimated using a shear lag analogy (ref. 56)



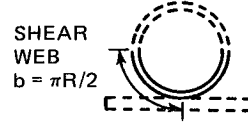
The shear lag solution for the above case is given in reference 56 as,

$$\begin{aligned}
 f_s &= (PK/t) (A_L/A_T) (\text{COSH}KX/\text{SINH}KL), && \text{Shear Stress in Pipe Wall} \\
 f_F &= (P/A_T) [1 + A_L \text{SINH}KX/A_F \text{SINH}KL], && \text{Average Axial Stress in Pipe Wall} \\
 f_L &= (P/A_T) [1 - \text{SINH}KX/\text{SINH}KL], && \text{Average Axial Stress in Saddle}
 \end{aligned}$$

where $K^2 = Gt/b (1/EA_F + 1/EA_L)$

For the heat pipe/saddle configuration

$$\frac{Gt_w}{b} = \frac{E}{2(1+\nu)} \frac{2t}{\pi R/2} = \frac{E}{2(1+\nu)} \frac{4t}{\pi R}$$



Assuming the saddle area to be 3.33 times the pipe area,

$$K^2 = \frac{E}{2(1+0.3)} \frac{4t}{\pi R} (1/E \cdot 2\pi R t + 1/3.33 E \cdot 2\pi R t)$$

$$K^2 = \frac{1}{\pi^2 R^2} \rightarrow K = \frac{1}{\pi R}$$

at $X = L$

$$f_F = P/A_F = p\pi R^2/2\pi R t = pR/2t, f_L = 0$$

$$f_s = (pK/t)(A_L/A_T)(\cosh KL/\sinh KL) = (p\pi R^2/t)(1/\pi R) \left(\frac{3.33}{4.33}\right) \frac{1}{\tanh KL}$$

$$f_s = (pR/t)(0.77/\tanh KL)$$

If the shear lag length is on the order of half the pipe circumference ($L \approx \pi R$),

$$\tanh KL = \tanh L/\pi R \approx \tanh 1 = 0.77$$

and

$$f_s \approx pR/t$$

Therefore, in the vicinity of the change in pipe area at the saddle, a shear stress is developed in the pipe wall. This shear stress acts in conjunction with the axial and hoop stresses. Using the Hencky-Mises yield criterion (ref. 30) for the tube wall, the total stress is:

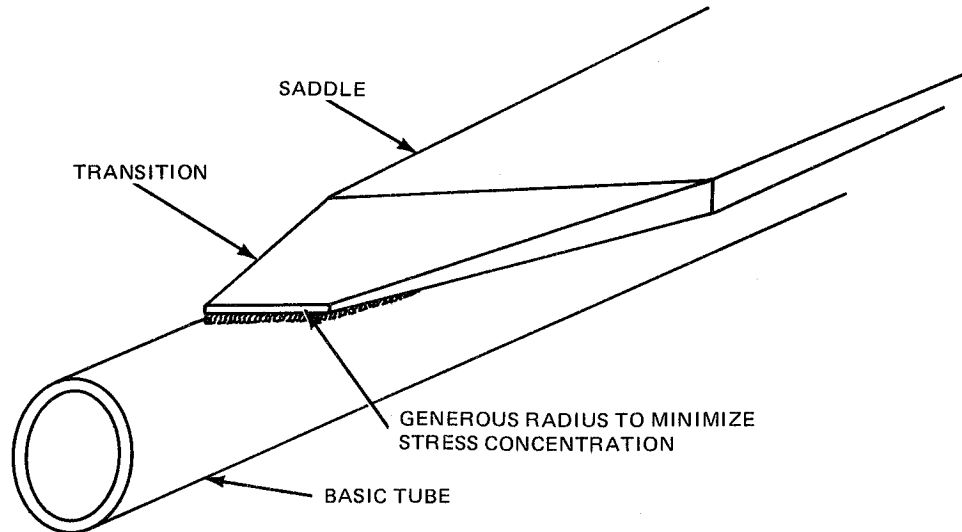
$$F = \sqrt{f_{hoop}^2 + f_{axial}^2 - f_{hoop} f_{axial} + 3f_s^2}$$

$$F = \sqrt{(pR/t)^2 + (pR/2t)^2 - (pR/t)(pR/2t) + 3(pR/t)^2}$$

$$F = pR/t \sqrt{1 + 1/4 + 1/2 + 3} = 1.94pR/t$$

which must be kept less than $F_{tu}/4$.

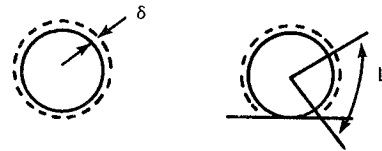
These local stresses due to the pressure of a saddle can be minimized by providing a smooth transition in the pipe cross-sectional area between the basic tube and the full saddle. If the saddle area (dh) starts off as a small area and gradually builds up to the required area, the shear stress will be small. The gradual change in area is illustrated here:



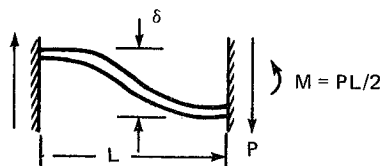
There will also be a bending stress developed in the hoop direction because of the restraint of the saddle, but this can be neglected in most cases. The magnitude of the stress can be estimated as follows:

- The radial expansion of an unrestrained tube under internal pressure is:

$$\delta = PR^2 / Et$$



- The relation between the moment and deflection of a built-in beam is



$$\delta = PL^3 / 12EI = ML^2 / 6EI$$

therefore,

$$M = 6EI\delta/L^2$$

and

$$f_{\text{bend}} = Mc/I = 6Et\delta/2L^2$$

Setting the deflection equal to that of the pressurized tube,

$$f_{\text{bend}} = 6Et\pi R^2/2L^2 Et = 3p(R/L)^2$$

Assuming the effective beam length to be a quarter of the circumference,

$$f_{\text{bend}} = 3p(2R/\pi R)^2 = 3(2/\pi)^2 p \approx 1.2p$$

The hoop stress is usually much larger than this bending stress

$$f_{\text{hoop}} = pR/t \gg 1.2p$$

so that the bending stress can be neglected when

$$\frac{R}{t} \gg 1.2$$

DYNAMIC RESPONSE

APPENDIX D - DYNAMIC RESPONSE

NOTE

Refer to paragraph 5.2.4.7

The response to an acceleration spectral density of a heat pipe supported at discrete points can be determined using the work of reference 31. A typical example of spectral density (S_0) vs natural frequency (f_n) curve for a large booster launch is given in Fig. D-1. It represents the type of information that is provided by the dynamic analysis group of any spacecraft program for particular locations of interest on the vehicle.

FORMULAE FOR SINGLE SPACE BEAMS

End condition	Natural frequency, (f_n)	Displacement, (δ_{max})	Bending moment, (M_{max})
Pinned-pinned	$1.57 \sqrt{EIg/wL^4}$	$5wL^4/384EI$	$wL^2/8$ (midspan)
Pinned-fixed	$2.46 \sqrt{EIg/wL^4}$	$wL^4/185EI$	$wL^2/8$
Fixed-fixed	$3.56 \sqrt{EIg/wL^4}$	$wL^4/384EI$	$wL^2/12$ (ends)

Example

Determine the dynamic response of a 1.07 in. (refer to Paragraph 5.2.4.1.2, Example A) 6061-T6 aluminum alloy, spiral artery heat pipe supported on a 20 in. (50.8 cm) span. Estimate the weight/unit length of the pipe at 1 g as follows:

$$A = \pi Dt$$

$$w = 3\rho A = 3(0.1)(\pi Dt) = 0.3\pi Dt$$

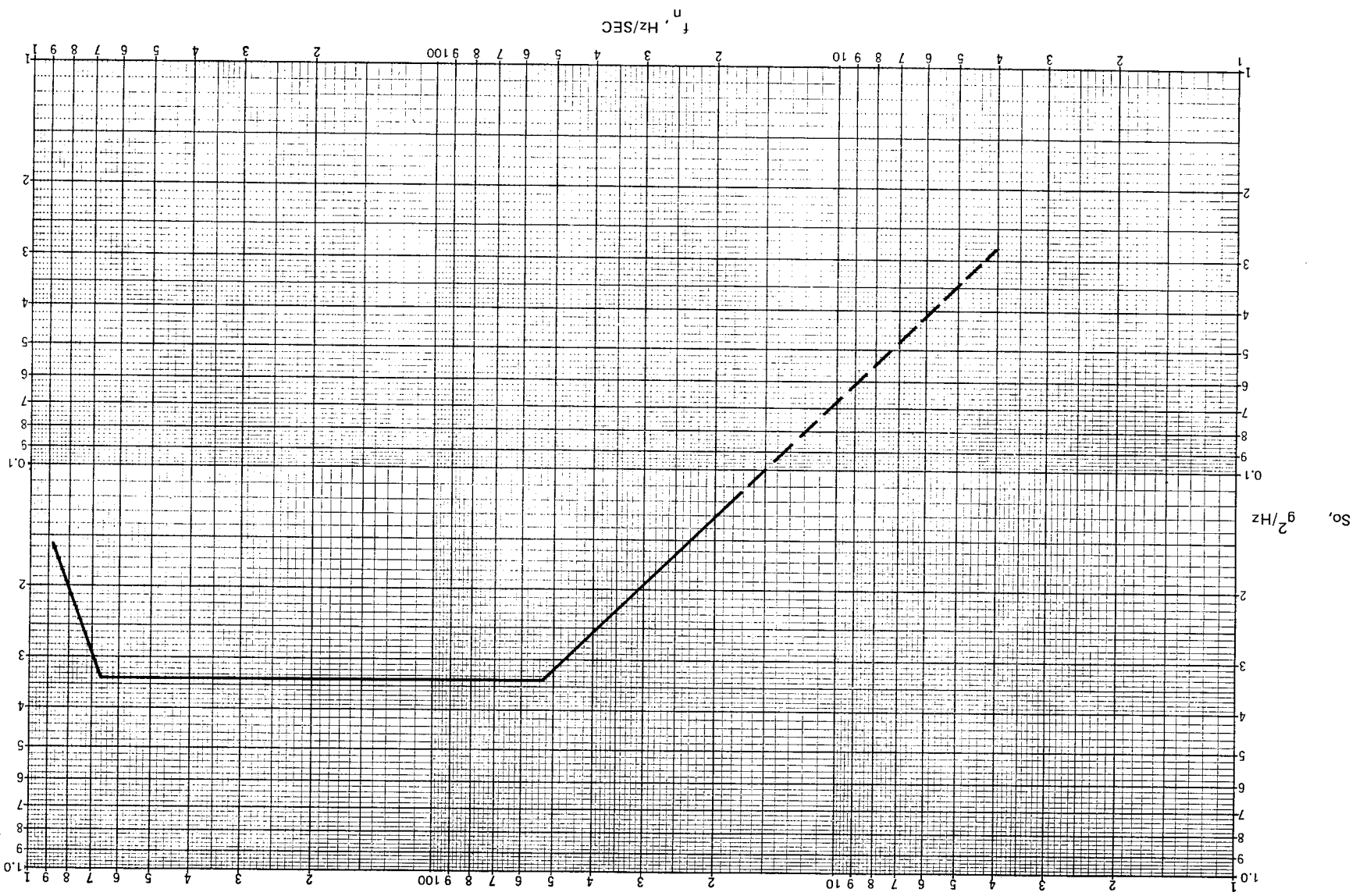


Fig. D-1 Booster-Acceleration Spectral Density (S_o) versus Frequency, (f_n)

The factor 3 is assumed to account for the wire mesh artery inside the pipe and $\rho = 0.1 \text{ lb/in.}^3$ (2768 kg/m³) for aluminum. The pipe moment of inertia is

$$I = \pi R^3 t = \frac{\pi}{8} D^3 t$$

For a pinned-pinned beam, the natural frequency is

$$f_n = 1.57 \sqrt{E(\pi/8)D^3 t g / 0.3\pi D t L^4} = 1.02 \frac{D}{L^2} \sqrt{Eg}$$

For the 1.07 (2.718 cm) in diameter pipe supported on a 20 in. (50.8 cm) span,

$$f_n = 1.02 \left(\frac{1.07}{20^2} \right) \sqrt{10 \times 10^6 (386)} = 170 \text{ cycles/sec}$$

Therefore, the spectral density, S_o , obtained from Fig. D-1 is

$$S_o = 0.34 \text{ g}^2/\text{cycle}$$

The peak response is given by

$$G = 3(Q2\pi f_n S_o/4)^{1/2}$$

where $Q = 30$ for light (structural) damping and G is the peak acceleration in g . Thus,

$$G = 3[30(2\pi)(170)(0.34)/4]^{1/2} = 157g$$

This acceleration multiplies the static, 1-g, loading already on the heat pipe. The stress in the tube wall for this acceleration can now be calculated as follows:

$$f_{\text{bend}} = \frac{Mc}{I} = MR/\pi R^3 t = M/\pi R^2 t$$

$$M_{\text{max}} = GwL^2/8 = G(0.6)\pi R t L^2/8$$

Therefore,

$$f_{\text{bend}} = \frac{1}{\pi R^2 t} \times G(0.6)\pi R t L^2/8 = 0.075 GL^2/R$$

$$f_{\text{bend}} = 0.075(157)(20)^2/0.534 = 8820 \text{ psi } (6.081 \times 10^7 \text{ newt/m}^2)$$

The bending stress obtained above is additive to the basic pressure vessel axial stress. Note that this stress occurs only during the launch phase. At this time, the internal pressure generally corresponds to the normal operating condition rather than the maximum operating condition, for which the axial stress due to pressure is from Paragraph 5.2.4.1.2, Example A,

$$f_{\text{axial}} = 230(0.534)/2(0.048) = 1280 \text{ psi } (8.825 \times 10^6 \text{ newt/m}^2) \text{ at } 105^\circ \text{ F}$$

Again, as in the case of restrained thermal expansion, the stress occurs in a region of the tube which may not be welded. The allowable stress obtained from Table 5-1 is

$$F_{\text{allow}} = Ft_u/4 = 9500 \text{ psi } (6.550 \times 10^7 \text{ newt/m}^2) \text{ at } 100^\circ \text{ F}$$

The total axial stress (sum of dynamic and $p_r/2t$) is

$$f_{\text{axial}} = 8820 + 1280 = 10,100 \text{ psi } (6.964 \times 10^7 \text{ newt/m}^2)$$

which is greater than the allowable stress. The support spacing must, therefore, be reduced below 20 in. (50.8 cm) to reduce the bending stress.

FRACTURE MECHANICS APPROACH

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

APPENDIX E - FRACTURE MECHANICS APPROACH

NOTE

Refer to Paragraph 5.2.4.8

The relation between the gross stress, f , in a sheet and the stress intensity factor, K , at the lip of an embedded elliptical crack or a semi-elliptical surface crack is given (ref. 27) by the expression:

$$f = \frac{K \sqrt{Q}}{\sqrt{\pi a}} \quad (1.1)$$

Values of the parameter, Q , can be determined from Fig. E-1. In this relation, "a" is assumed to be less than half the wall thickness for a surface crack. If "a" is larger than half the wall thickness, this expression can be corrected using the factor M_K from the table included with Fig. E-1.

$$f = \frac{K \sqrt{Q}}{1.1 M_K \sqrt{\pi a}} = \frac{K}{\beta \sqrt{a}}$$

The critical crack size can be determined from the above expression as:

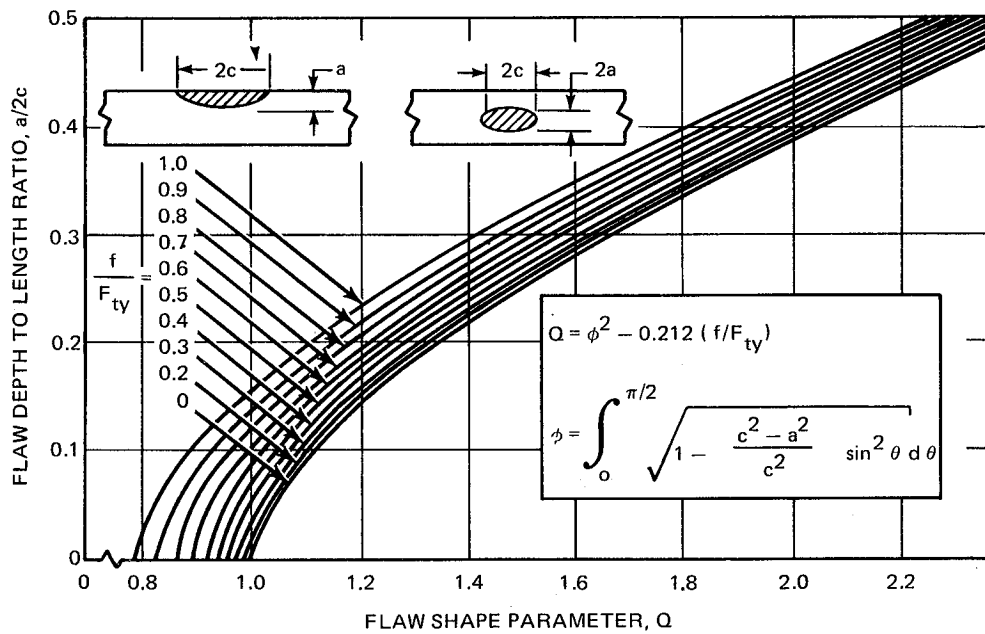
$$a_c = \frac{Q}{1.21 \pi M_K^2} \left(\frac{K_c}{f} \right)^2$$

where K_c is the critical stress intensity factor. As the thickness of a sheet is increased, the value of K_c will decrease to a minimum value, K_{IC} in place of K_c .

The growth rate of a crack can be determined from the expression

$$\frac{dc}{dn} = \frac{C(\Delta K)^m}{K_c(1-R)-\Delta K} \text{ IN./CYCLE}$$

Where $K = K_{\max} - K_{\min}$ and $R = K_{\min}/K_{\max}$, C and m are constants determined from test results.



For "Thick-walled" Tubes ($a < t_{WALL}/2$):

$$\left(\frac{a}{Q}\right)_c = \frac{1}{1.21\pi} \left(\frac{K_c}{f}\right)^2$$

For "Thin-walled" Tubes ($a > t_{WALL}/2$):

$$\left(\frac{a}{Q}\right)_c = \frac{1}{1.21\pi M_K^2} \left(\frac{K_c}{f}\right)^2$$

a/t _{WALL}	0	0.4	0.6	0.8	1.0	FOR a/2c SMALL AND $\sigma/\sigma_{YS} = 0.4$
M _K	1.00	1.08	1.23	1.46	1.62	

Fig. E-1 Flaw-Shape Parameter Curves

If the minimum operating stress is equal to zero and the maximum operating stress results in a K which is much less than K_c , the expression for growth rate reduces to

$$\frac{dc}{dn} = \frac{C}{K_c} (\Delta K)^m = \alpha (\Delta K)^m$$

Since the stress intensity is related to the growth by a relation of the form $K = \beta \Delta f \sqrt{a}$ for a given constant crack shape [$c/a = (c/a)_0 = \text{constant}$], the above expression becomes

$$\frac{dc}{dn} = \alpha (\beta \Delta f)^m a^{m/2}, \text{ WHERE } dc = \text{CONST} \times da$$

This expression can be integrated between the initial and final crack size

$$\Delta N = \int_{a_i}^{a_f} \frac{\text{const} \times da}{\alpha \beta (\Delta f)^m a^{m/2}} = \frac{(c/a)_0}{\alpha (\beta \Delta f)^3} \left(\frac{1}{1-m/2} \right) \left(a_f^{1-m/2} - a_i^{1-m/2} \right)$$

The number of cycles for a given increase in crack size can, therefore, be determined. Constants are given in ref. 60 for two aluminum alloys

ALLOY PLATE	m	C
2024-T3	3	3×10^{-3}
7075-T6	3	5×10^{-3}

If M is assumed to be the same for all heat treated aluminum alloys,

$$\Delta N = \frac{2(c/a)_0 K_c}{c(1.1M_K \sqrt{\pi/Q} f)^3} \left[\frac{1}{\sqrt{a_i}} - \frac{1}{\sqrt{a_f}} \right]$$

Using a higher value of K_c/C , will result in a smaller (conservative) value of ΔN .

The critical crack size in a tube wall can be estimated using the formula. Assume, as an example,

$$\begin{aligned} a/2c &= 0.10 \\ f/F_{ty} &\longrightarrow 1 \\ a/t_{\text{wall}} &= 0.2 \end{aligned}$$

Therefore,

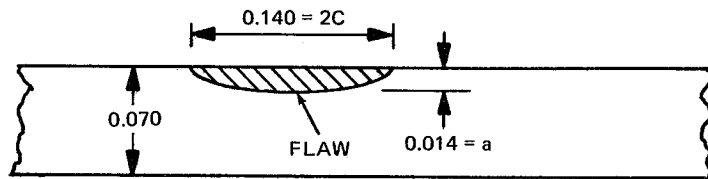
$$\left. \begin{aligned} Q &= 0.90 \\ M_K &= 1.02 \end{aligned} \right\} \text{From Fig. E-1}$$

and

$$a_c = \left[0.90/1.21\pi(1.02) \right] (K_c/F_{ty})^2 = 0.228 (K_c/F_{ty})^2$$

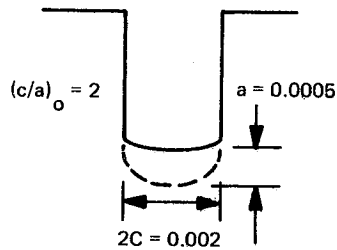
If $K_c \approx F_{ty}/4$ (i.e., a material with poor fracture toughness characteristics)

$$\begin{aligned} a_c &= 0.228/16 = 0.0142 \text{ in.} \\ 2C_c &= 0.0142/0.10 = 0.142 \text{ in.} \\ t_{wall} &= 0.0142/0.2 = 0.071 \end{aligned}$$



If the value of $K_c > F_{ty}/4$, the critical crack size will be larger than shown above. Defects of this size should be easily detectable.

As an example of cyclic crack growth, consider a defect aligned in the hoop direction at the base of the threading as shown.



$$\Delta N = \frac{2(c/a)_o K_c}{C [1.1M_K \sqrt{\pi/Q} \Delta f]^3} \left(1/\sqrt{a_i} - 1/\sqrt{a_f} \right)$$

Assume: $a_f = a_i + 0.015 \approx 0.016$ in.

For 6061-T6 alloy tube, $K_c \approx 2K_{IC} = 64000 \text{ psi} \sqrt{\text{in.}}$, $C \approx 5 \times 10^{-3}$

Also for f/F_{ty} small, $a/2c = 0.25$ and $a/t_{wall} = 0$,

$$Q = 1.45 \text{ (Fig. E-1)}$$

$$M_K = 1$$

$$1.1M_K \sqrt{\pi/Q} = 1.62$$

Therefore,

$$\Delta N = \frac{(2)(2)(64 \times 10^3)}{5 \times 10^{-13} (1.62)^3 (\Delta f)^3} \left[\frac{1}{\sqrt{0.0005}} - \frac{1}{\sqrt{0.016}} \right]$$

$$\Delta N = \frac{4.46 \times 10^{18}}{(\Delta f)^3}$$

For normal operating stress of $\Delta f = F_{ty}/4 \approx 10,000$ psi which is approximately equal to the material allowable stress,

$$\Delta N = \frac{4.46 \times 10^{18}}{(10^4)^3} = 4.46 \times 10^6 \text{ cycles}$$

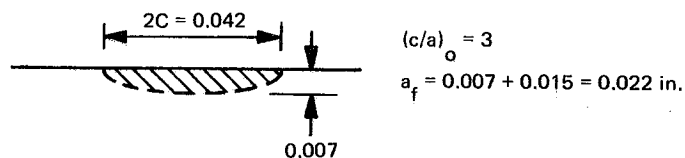
for "a" to increase by 0.015 in. (0.038 cm). Therefore, the defect will not propagate through the tube wall and cause leakage or failure in the above number of cycles. For a long-term orbital application, estimate the total number of cycles as

$$N \approx \frac{1 \text{ cycle}}{1\frac{1}{2} \text{ hr}} \times 24 \frac{\text{hr}}{\text{day}} \times 365 \frac{\text{day}}{\text{yr}} \times 10 \text{ yr} \times 4 \text{ safety factor} = 2.35(10^5) \text{ cycles}$$

Therefore:

$$N = 2.35(10^5) \text{ which is } < 4.46(10^6)$$

As a second example, assume another defect aligned in the axial direction as shown



For this example,

$$1.1M_K \sqrt{\pi/Q} = 1.1(1.02) \sqrt{\pi/1.2} = 1.82$$

$$\Delta N = \frac{(2)(2)(64) \times 10^3}{(5 \times 10^{-13})(1.82)^3 (\Delta f)^3} \left[\frac{1}{\sqrt{0.007}} - \frac{1}{\sqrt{0.022}} \right]$$

$$\Delta N = 44 \times 10^{16} / (\Delta f)^3$$

The operating stress in the axial direction is half the hoop stress, or $\Delta f = 5,000$ psi
(3.447×10^7 newt/m²)

$$\Delta N = 44(10^{16}) / (5 \times 10^3)^3 = 3.52(10^6) \text{ cycles}$$

for "a" to increase by 0.015 in. (0.038 cm) . Again, the defect will not penetrate the wall thickness.

PROCEDURES FOR FLUID TRANSFER TESTS



APPENDIX F - PROCEDURES FOR FLUID TRANSFER TESTS

F-1 Introduction

This procedure covers the transfer of ultra-high purity ammonia from the supplier's bottle to various sample bottles. The object is to determine if any impurities are introduced into a heat pipe as a result of different transfer techniques. Three different transfer techniques will be investigated:

- Direct transfer from supplier bottle to heat pipe
- Transfer from supplier's bottle to a heat pipe using a charge bottle as an intermediate step
- Same as preceding, but with processing the ammonia (freeze and thaw) prior to transfer to the heat pipe.

The three sample bottles (which simulate the heat pipe) along with the manufacturer's supply bottle will be analyzed to determine their impurity level. Based on these results, fluid transfer techniques will be recommended.

F-2 Test Procedure

1. Label four stainless steel charge bottles of at least 500 cc capacity as follows:
 - Sample Bottle No. 1 - Direct Transfer
 - Sample Bottle No. 2 - Indirect Transfer
 - Sample Bottle No. 3 - Indirect Transfer (Processed Ammonia)
 - Charge Bottle

The bottles should be checked to insure they are leak tight, including the valves. They should also have previously been used in ammonia service.

2. Prior to use, each of the three sample bottles and one charge bottle should be prepared as follows:
 - a. Charge bottles with anhydrous ammonia approximately 1/3 full.
 - b. Slosh fluid back and forth in bottle.
 - c. Allow to stand for at least 1/2 hr.
 - d. Dump most, but not all, of charge in clean filter paper lined beaker. Be sure to invert bottle so as to tap ammonia liquid.
 - e. Examine filter paper to insure that no oil or other residue is obtained. Otherwise, supplier's bottle, transfer lines, or charge bottle may be suspect. Take appropriate action.

3. Perform direct transfer (Sample Bottle No. 1) as follows:
 - a. Install Sample Bottle No. 1 and supplier's ultra high purity (UHP) ammonia on vacuum station as shown in Fig. F-1.
 - b. Evaluate remaining anhydrous charge from Sample Bottle through vacuum station.
 - c. Bake out Sample Bottle at 300°F and 10^{-6} mm Hg or better for at least 2 hr. During this time the fluid transfer lines will also be evaluated and heated (with heater tape) in preparation for subsequent ammonia transfer.
 - d. Transfer approximately 200 g of UHP ammonia from supplier's bottle to Sample Bottle. Ammonia in the vapor phase should be tapped from the supplier's bottle.

4. Perform indirect transfer (Sample Bottle No. 2) as follows:
 - a. Install Charge Bottle on station in place of Sample Bottle No. 1. Proceed as in steps 3a through 3d with the exception that the Charge Bottle is used in place of Sample Bottle No. 1.

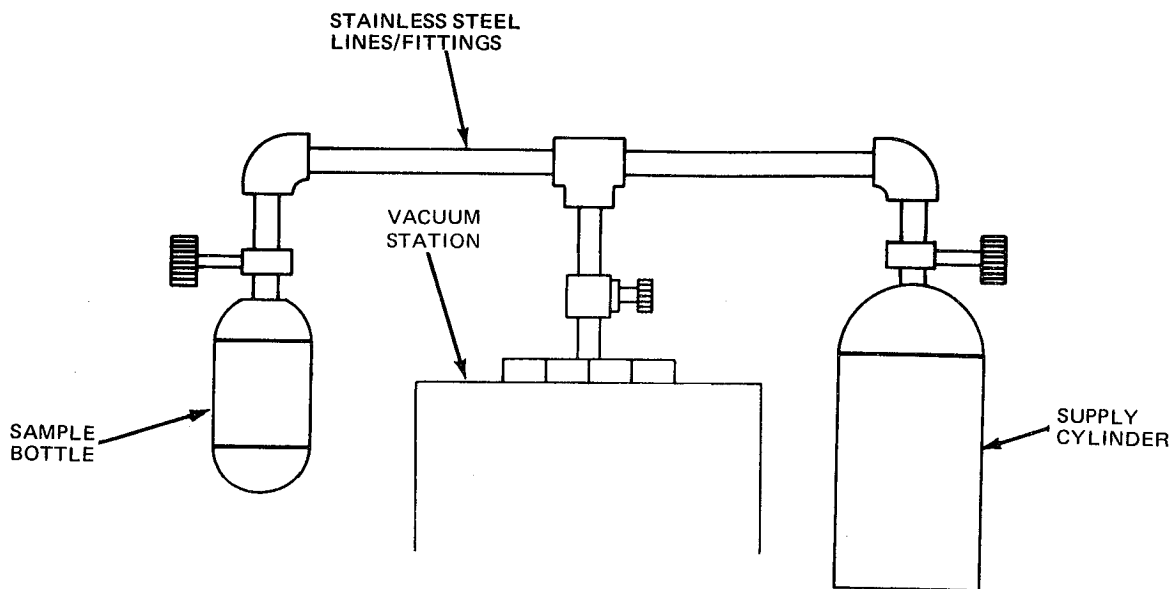


Fig. F-1 Direct Transfer of Ammonia

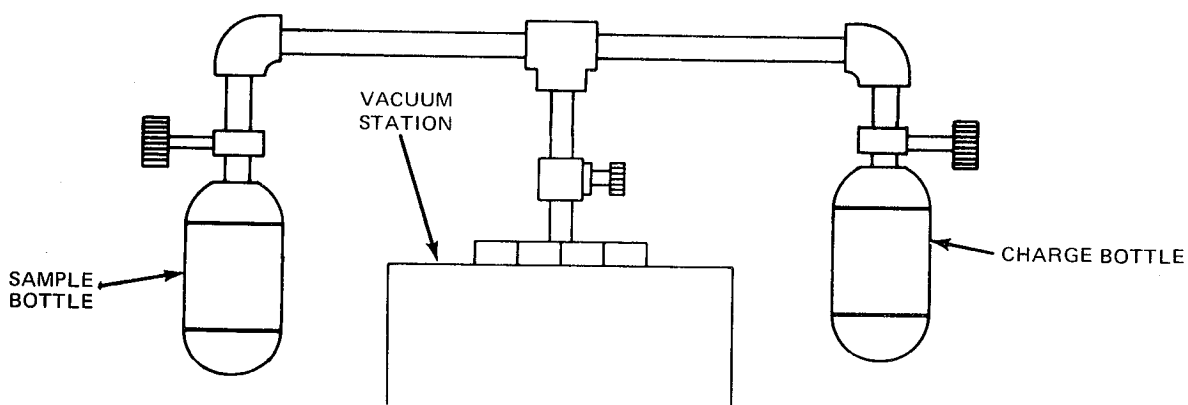


Fig. F-2 Vapor Transfer from Charge to Sample Bottle

- b. Remove supplier's bottle and install the Charge Bottle in its place. Install Sample Bottle No. 2 as shown in Fig. F-2.
- c. Evacuate, bake out, and transfer approximately 200 g to Sample Bottle No. 2 from the Charge Bottle. Follow steps 3b through 3d as applicable. Valve off and store Sample Bottle No. 2.

5. Perform indirect transfer (processed ammonia; Sample Bottle No. 3)
 - a. Transfer approximately 200 g of UHP ammonia from the supplier's bottle to the Charge Bottle. Use setup in Fig. F-1 with the Charge Bottle in place of the Sample Bottle. Prior to the transfer, evacuate Charge Bottle and lines at 10^{-6} mm Hg or better for at least 2 hr. Bake-out of the Charge Bottle is not required.
 - b. Process the ammonia in the Charge Bottle by freezing the ammonia using a surrounding dewar of LN₂. Quickly vent the space above the frozen ammonia to vacuum. Valve off bottle and allow ammonia to thaw. Repeat this freeze-thaw cycle at least two more times for a total of three cycles. Additional cycles will be left to the discretion of the cognizant engineer.
 - c. Install Charge Bottle and Sample Bottle No. 3 as shown in Fig. F-2.
 - d. Evacuate, bake out and transfer approximately 200 g to Sample Bottle No. 3 from the processed ammonia in the Charge Bottle. Follow steps 3b through 3c as applicable. Valve off and store Sample Bottle No. 3.

LITERATURE SEARCH

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

APPENDIX G1 - REPRODUCTION OF NASA LSN 20604
(53 CITATIONS)

NASA Literature Search Number

20604

HEAT PIPE FABRICATION

November 20, 1972

SCOPE: References pertinent to the above subject.

PERIOD: 1962 to date shown above

FORMAT: Citations arranged by Accession Number

NUMBER OF
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FABRICATION AND TESTING OF TUNGSTEN HEAT PIPES F
OR HEAT PIPE COOLED REACTORS.
A/BACIGALUPI, R. J. A/(NASA, LEWIS RESEARCH CE
NTER, CLEVELAND, OHIO)

IN ANNUAL THERMIONIC CONVERSION SPECIALIST CONF
ERENCE, 10TH, SAN DIEGO, CALIF., OCTOBER 4-6, 1971
, CONFERENCE RECORD. (A72-34576 17-03) NEW YORK, I
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RATION/ VAPOR DEPOSITION

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(CHEMICALLY VAPOR DEPOSITED W HEAT PIPE FABRICAT
ION AND EVALUATION FOR APPLICATION TO HIGH TEMPERA
TURE NUCLEAR REACTORS)
A/BACIGALUPI, R. J. A/(NASA, LEWIS RESEARCH CE
NTER, CLEVELAND, OHIO)

AMERICAN NUCLEAR SOCIETY, INTERNATIONAL CONFEREN
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/*TUNGSTEN/*VAPOR DEPOSITION/ CHEMICAL ENERGY/ CON
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ARC-CAST MOLYBDENUM-BASE TZM ALLOY PROPERTIES AND APPLICATIONS.

(ARC CAST VACUUM MELTED MO BASE ALLOY PROPERTIES, PRODUCTION AND APPLICATIONS TO HEAT PIPES, AEROSPACE STRUCTURES AND PRESSURE VESSELS)

A/BRIGGS, J. Z.; B/BARR, R. Q. B/(CLIMAX MOLYBDENUM CO., NEW YORK, N.Y.)

IN PLANSEE SEMINAR, 7TH, REUTTE, AUSTRIA, JUNE 21-25, 1971, PREPRINTS. VOLUME 1. (A72-26826 11-15) REUTTE, AUSTRIA, METALLWERK PLANSEE AG, 1971. 100 P.

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AIAA PAPER 72-260 NAS2-6493 72/04/00 8 PAGES
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DEVELOPMENT OF A THERMAL DIODE HEAT PIPE FOR THE ADVANCED THERMAL CONTROL FLIGHT EXPERIMENT /ATFE/

(THERMAL DIODE HEAT PIPE FOR ADVANCED THERMAL CONTROL FLIGHT EXPERIMENT, DISCUSSING ENGINEERING MODEL ANALYSIS, DESIGN, FABRICATION AND TEST)

A/SWERDLING, B.; B/KOSSON, R.; C/URKOWITZ, M.; D/KIRKPATRICK, J. C/(GRUMMAN AEROSPACE CORP., BETHPAGE, N.Y.); D/(NASA, AMES RESEARCH CENTER, MOFFETT FIELD, CALIF.) MEMBERS, \$1.50; NONMEMBERS, \$2.00

AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS, THERMOPHYSICS CONFERENCE, 7TH, SAN ANTONIO, TEXAS, APR. 10-12, 1972, 8 P.

/*DIODES/*FABRICATION/*FLIGHT TESTS/*HEAT PIPES/*TEMPERATURE CONTROL/*THERMAL RADIATION/ CONFERENCES/ PERFORMANCE TESTS/ STAINLESS STEELS/ TEMPERATURE EFFECTS/ WORKING FLUIDS

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TEST OF 50-KW HEAT-PIPE RADIATOR.

(HEAT PIPE RADIATOR WITH 50 KW HEAT REJECTION CA
PABILITY FOR POTASSIUM WORKING FLUID OF RANKINE CY
CLE SPACE POWER SYSTEM, DISCUSSING DESIGN, FABRICA
TION AND TESTING)

A/KIKIN, G. M.; B/PEELGREN, M. L. B/(CALIFORN
IA INSTITUTE OF TECHNOLOGY, JET PROPULSION LABORAT
ORY, PASADENA, CALIF.) MEMBERS, \$1.00; NONMEMBERS
, \$3.00

AMERICAN SOCIETY OF MECHANICAL ENGINEERS, WINTER
ANNUAL MEETING, WASHINGTON, D. C., NOV. 28-DEC. 2
, 1971, 9 P.

/*HEAT PIPES/*RANKINE CYCLE/*SPACECRAFT POWER S
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FERENCES/ COOLING SYSTEMS/ FABRICATION/ LIQUID MET
ALS/ THERMAL ENERGY

A71-43595*# ISSUE 23 CATEGORY 15 71/10/00 7
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FABRICATION AND TESTING OF TUNGSTEN HEAT PIPES F
OR HEAT PIPE COOLED REACTORS

(LI-FILLED VACUUM-DEPOSITED W HEAT PIPES FOR EFF
ICIENT HEAT EXTRACTION FROM NUCLEAR REACTORS, DISC
USSING DESIGN, FABRICATION AND TESTING)

A/BACIGALUPI, R. J. (AA/NASA, LEWIS RESEARCH C
ENTER, CLEVELAND, OHIO.)

INST. OF ELECTRICAL AND ELECTRONICS ENGINEER
S, THERMIONIC CONVERSION SPECIALISTS CONFERENCE, S
AN DIEGO, CALIF., OCT. 4-6, 1971, PAPER.

/*FABRICATION/*HEAT EXCHANGERS/*HEAT PIPES/*NUC
LEAR REACTORS/*PERFORMANCE TESTS/*TUNGSTEN/ CONFER
ENCES/ HEAT MEASUREMENT/ HEAT TRANSMISSION/ LITHIU
M/ REACTOR DESIGN/ VACUUM DEPOSITION/ WORKING FLUI
DS

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HYBRID THERMOCOUPLE DEVELOPMENT PROGRAM - A STATUS REPORT

(HYBRID THERMOCOUPLE WITH PBTE AND SIGE THERMOELECTRIC MATERIALS, DISCUSSING DEVELOPMENT STATUS AND PERFORMANCE PREDICTION)

A/BIFANO, W. J.; B/GARVEY, L. P.; C/STRAIGHT, R. A. (AA/NASA, LEWIS RESEARCH CENTER, CLEVELAND, OHIO/, AC/RCA, HARRISON, N.J./.)

AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, AMERICAN SOCIETY OF MECHANICAL ENGINEERS, INST. OF ELECTRICAL AND ELECTRONICS ENGINEERS, AND SOCIETY OF AUTOMOTIVE ENGINEERS, INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE, 5TH, LAS VEGAS, NEV., SEP. 21-25, 1970, PAPER.

/*PERFORMANCE PREDICTION/*THERMOCOUPLES/*THERMOELECTRIC MATERIALS/ COMPUTERIZED DESIGN/ CONFERENCES/ GERMANIUM COMPOUNDS/ HEAT PIPES/ HEAT RADIATORS/ LEAD TELLURIDES/ MATHEMATICAL MODELS/ REACTOR DESIGN/ SILICON COMPOUNDS

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DESIGN AND PERFORMANCE OF LOW TEMPERATURE CYLINDRICAL THERMIONIC CONVERTERS

(LOW TEMPERATURE CYLINDRICAL THERMIONIC CONVERTERS WITH CVD RE ELECTRODES, DISCUSSING DESIGN, FABRICATION AND PERFORMANCE)

A/HAMERDINGER, R. W.; B/JACOBSON, D. L. (AB/ELECTRO-OPTICAL SYSTEMS, INC., PASADENA, CALIF./.)

NEW YORK, INST. OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC., NASA- SPONSORED RESEARCH. IN-INST. OF ELECTRICAL AND ELECTRONICS ENGINEERS, ANNUAL THERMIONIC CONVERSION SPECIALIST CONFERENCE, 8TH, CARMEL, CALIF., OCT. 21-23, 1969, CONFERENCE RECORD. P. 122- 129. /A71-12201 02-03/

/*FABRICATION/*PERFORMANCE TESTS/*RHENIUM/*THERMIONIC CONVERTERS/ CONFERENCES/ CYLINDRICAL BODIES / ELECTRODES/ HEAT PIPES

A70-33623** ISSUE 16 PAGE 2950 CATEGORY 22
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APPLICATION OF HEAT PIPES TO A NUCLEAR AIRCRAFT PROPULSION SYSTEM

(HEAT PIPES IN NUCLEAR AIRCRAFT PROPULSION SYSTEM, DESCRIBING CORE, HEAT EXCHANGERS, AND REACTOR TO JET ENGINE HEAT TRANSPORT SYSTEM)

A/PUTHOFF, R. L.; B/SILVERSTEIN, C. C. (AA/NA SA, LEWIS RESEARCH CENTER, CLEVELAND, OHIO/.) MEMBERS, \$1.00, NONMEMBERS, \$1.50.

NEW YORK, AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, PROPULSION JOINT SPECIALIST CONFERENCE, 6TH, SAN DIEGO, CALIF., JUN. 15-19, 1970.

/*ENGINE DESIGN/*HEAT PIPES/*NUCLEAR PROPELLED AIRCRAFT/ ADIABATIC FLW/ CONFERENCES/ HEAT TRANSMISSION/ NUCLEAR PROPULSION/ REACTOR CORES/ TUBE HEAT EXCHANGERS

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APPLICATION OF HEAT-PIPE TECHNOLOGY TO ROCKET-ENGINE COOLING

(HEAT PIPES DESIGN FOR ROCKET ENGINES COOLING, DISCUSSING CONNECTIONS TO SPACE RADIATOR AND TO HEAT REJECTION DEVICE AND HEAT TRANSFER CAPABILITY)

A/HOLMGREN, J. S.; B/STEPHANOU, S. E.; C/WARD, T. E. (AC/MCDONNELL DOUGLAS ASTRONAUTICS CO., SANTA MONICA, CALIF./, AA/DONALD W. DOUGLAS LABS., RICHLAND, WASH./.)

JOURNAL OF SPACECRAFT AND ROCKETS, VOL. 7, P. 748-750. NEW YORK, /AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, PROPULSION JOINT SPECIALIST CONFERENCE, 5TH, U.S. AIR FORCE ACADEMY, COLORADO SPRINGS, COLO., JUN. 9-13, 1969./

/*COOLING SYSTEMS/*ENGINE COOLANTS/*HEAT PIPES/*RADIATIVE HEAT TRANSFER/*ROCKET ENGINE DESIGN/ AEROSPACE ENGINEERING/ COMBUSTION CHAMBERS/ CONFERENCES/ EXPERIMENTAL DESIGN/ HEAT EXCHANGERS/ HEAT RADIATORS/ SPACECRAFT/ SPACECRAFT RADIATORS/ TECHNOLOGY UTILIZATION

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THE HEAT PIPE - A PROGRESS REPORT.

(HEAT PIPE DEVELOPMENT AND FABRICATION IN VARIOUS SIZES AND SHAPES FOR OPERATION OVER RANGE OF TEMPERATURES AND POWER LEVELS, NOTING APPLICATIONS)

A/EASTMAN, G. Y. (AA/RADIO CORP. OF AMERICA, LANCASTER, PA./.)

NEW YORK, AMERICAN INST. OF CHEMICAL ENGINEERS, CONFERENCE CO-SPONSORED BY THE AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, THE AMERICAN NUCLEAR SOCIETY, THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, THE AMERICAN CHEMICAL SOCIETY, THE INST. OF ELECTRICAL AND ELECTRONICS ENGINEERS, AND THE SOCIETY OF AUTOMOTIVE ENGINEERS. IN- AMERICAN INST. OF CHEMICAL ENGINEERS, INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE, 4TH, WASHINGTON, D.C., SEP. 22-26, 1969, PROCEEDINGS. P. 873-878. /A69-42236 23- 03/

/*FABRICATION/*HEAT PIPES/ CONFERENCES/ HEAT SINKS/ POWER EFFICIENCY/ SIZE (DIMENSIONS)/ TEMPERATURE CONTROL

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(ELECTRONIC PACKAGING AND PRODUCTION - CONFERENCE, ANAHEIM, FEBRUARY 1969 AND PHILADELPHIA, JUNE 1969) \$17.50.

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HEAT PIPES FUNCTION ISOTHERMALLY AND ADAPTABLY.

(HEAT PIPES FOR ISOTHERMAL AND ADAPTABLE ENERGY TRANSFER FOR SPACE APPLICATIONS, DISCUSSING TEMPERATURE CONTROL BY FLUID CHOICE)

A/ARCELLA, F. G.; B/DZAKOWIC, G. S. (AB/WESTINGHOUSE ELECTRIC CORP., ASTRONUCLEAR LAB., PITTSBURGH, PA./.)

SPACE/AERONAUTICS, VOL. 52, P. 58-60.

/*HEAT PIPES/*HEAT TRANSFER/*ISOTHERMAL FLOW/*TECHNOLOGY UTILIZATION/ FABRICATION/ FLUID FLOW/ MASS TRANSFER/ PUMPING/ THERMODYNAMICS

PAGE 6 (ITEMS 11- 13 CF 53)

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APPLICATION OF HEAT PIPE TECHNOLOGY TO ROCKET ENGINE COOLING.

(HEAT PIPES DESIGN FOR ROCKET ENGINES COOLING, DISCUSSING CONNECTIONS TO SPACE RADIATOR AND TO HEAT REJECTION DEVICE AND HEAT TRANSFER CAPABILITY)

A/HOLMGREN, J. S.; B/STEPHANOU, S. E.; C/WARD, T. E. (AC/MCDONNELL DOUGLAS CORP., MCDONNELL DOUGLAS AERONAUTICS CO., WESTERN DIV., SANTA MONICA, CALIF./, AA/MCDONNELL DOUGLAS CORP., MCDONNELL DOUGLAS AERONAUTICS CO., DONALD W. DOUGLAS LABS., RICHLAND, WASH./.) MEMBERS, \$1.00, NONMEMBERS, \$1.50.

NEW YORK, AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, PROPULSION JOINT SPECIALIST CONFERENCE, 5TH, U.S. AIR FORCE ACADEMY, COLORADO SPRINGS, COLO., JUN. 9-13, 1969.

/*COOLING SYSTEMS/*ENGINE COOLANTS/*HEAT PIPES/*RADIATIVE HEAT TRANSFER/*ROCKET ENGINE DESIGN/ AEROSPACE ENGINEERING/ COMBUSTION CHAMBERS/ CONFERENCES/ EXPERIMENTAL DESIGN/ HEAT EXCHANGERS/ HEAT RADIATORS/ SPACECRAFT RADIATORS/ TECHNOLOGY UTILIZATION

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A LOOK AT NUCLEAR THERMIONIC SYSTEMS.

(THERMIONIC REACTOR WITH URANIUM DIODES CORE ARRAY, DESCRIBING IN-PILE REACTOR USES, ARCJET, HEAT PIPE AND CONCEPTUAL DESIGN COMPONENTS)

A/SALMI, E. W.; B/SCHREIBER, R. E. (AA/CALIFORNIA, U., LOS ALAMOS SCIENTIFIC LAB., LOS ALAMOS, N. MEX./.) MEMBERS, \$0.75, NONMEMBERS, \$1.50.

AMERICAN INST. OF AERONAUTICS AND ASTRONAUTICS, PROPULSION JOINT SPECIALIST CONFERENCE, 3RD, WASHINGTON, D.C., JUL. 17-21, 1967, PAPER 67-498. 7 P. AEC-SPONSORED RESEARCH.

/*FISSION ELECTRIC CELL/*NUCLEAR-ELECTRIC PROPULSION/*REACTOR DESIGN/*THERMIONIC DIODE/*THERMIONIC REACTOR/ ARC/ CELL/ CHARACTERISTICS/ COMPONENT/ CONFERENCE/ DESIGN/ DIODE/ ELECTRIC/ FISSION/ HEAT / JET/ NUCLEAR/ PERFORMANCE/ PIPE/ PRODUCTION/ PROPULSION/ REACTOR/ THERMIONIC/ URANIUM

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PERFORMANCE STUDIES ON HEAT PIPES.

(HEAT PIPE PERFORMANCE, EMPHASIZING HEAT CARRYING AND WASTE HEAT DISSIPATION FUNCTIONS, CONSTRUCTION AND MATERIALS TESTING)

A/BUSSE, C. A.; B/CARON, R.; C/GEIGER, F.; D/POETZSCHKE, M. (AC/EURATOM AND COMITATO NAZIONALE PER L'ENERGIA NUCLEARE, CENTRO PER LE RICERCHE COMUNI, ISPRA, ITALY/, AD/METALLGESELLSCHAFT AG, FRANKFURT, WEST GERMANY/.)

IN- EUROPEAN NUCLEAR ENERGY AGENCY AND INSTITUTION OF ELECTRICAL ENGINEERS, INTERNATIONAL CONFERENCE ON THERMIONIC ELECTRICAL POWER GENERATION, LONDON, ENGLAND, SEP. 20-25, 1965. <A66-15532 05-03< 1965. 12 P. 9 REFS.

/*EMITTER/*HEAT REJECTION DEVICE/*LIQUID COOLING/*WORKING FLUID/ COLLECTOR/ CONFERENCE/ COOLING/ DEVICE/ EXCHANGER/ FABRICATION/ FLUID/ HEAT/ HEAT TRANSFER/ LIFE/ LIQUID/ MASS/ MATERIAL/ PIPE/ REJECTION/ TEST/ TRANSPORT/ WALL/ WORKING

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TURBULENT HEAT TRANSFER IN A PIPE WITH ARBITRARY HEAT FLUX.

(TURBULENT HEAT TRANSFER IN ROUND PIPE WITH ARBITRARY HEAT FLUX DISTRIBUTION FOR NUCLEAR REACTOR DESIGN APPLICATION)

A/AOKI, S.; B/SHIMAZU, H.; C/TAKAHASHI, T. (AB/TOKYO INST. OF TECH., TOKYO, JAPAN/.)

TOKYO INSTITUTE OF TECHNOLOGY, BULLETIN, NO. 61, 1964, P. 1-11.

/*HEAT FLUX/*REACTOR DESIGN/*TURBULENT HEAT TRANSFER/ ARBITRARY/ COEFFICIENT/ DATA/ DESIGN/ DISTRIBUTION/ FLUX/ HEAT/ HEAT TRANSFER/ NUCLEAR/ NUSSELT NUMBER/ PIPE/ REACTOR/ THERMAL/ TURBULENT

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PAGES UNCLASSIFIED DOCUMENT

SONIC LIMITATIONS AND STARTUP PROBLEMS OF HEAT PIPES

A/DEVERALL, J. E.; B/KEMME, J. E.; C/FLORSCHUETZ, L. W.

LOS ALAMOS SCIENTIFIC LAB., N.MEX.

/*ENGINEERING DRAWINGS/*HEAT PIPES/*PERFORMANCE/*TRANSONIC FLOW/*VAPOR PRESSURE/ DENSITY DISTRIBUTION/ TABLES (DATA)/ TEMPERATURE EFFECTS

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EURO SPECTRA, VOLUME 9, NO. 2 - SCIENTIFIC AND TECHNICAL REVIEW OF THE EUROPEAN COMMUNITIES QUARTERLY PUBLICATION

EUROPEAN ATOMIC ENERGY COMMUNITY, BRUSSELS (BELGIUM).

/*AEROSPACE INDUSTRY/*EUROPE/*HEAT PIPES/*HYDROGEN/*NUCLEAR ENERGY/*RESEARCH AND DEVELOPMENT/*UNITED STATES OF AMERICA/ GREAT BRITAIN/ NUCLEAR ELECTRIC POWER GENERATION/ NUCLEAR HEAT/ PRODUCTION ENGINEERING

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NAVAL RESEARCH REVIEWS, VOLUME 22, NO. 8, AUGUST 1969

A/LESCURE, W. J. (AAED.)

OFFICE OF NAVAL RESEARCH, WASHINGTON, D.C.

/*AMPHIBIOUS VEHICLES/*HEAT PIPES/*HEAT RESISTANT ALLOYS/*HYDROSTATIC PRESSURE/*MOTION SICKNESS/ BOATS/ FORMING TECHNIQUES/ METAL WORKING/ RESEARCH FACILITIES/ SHORT TAKEOFF AIRCRAFT

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HEAT PIPE THERMIONIC CONVERTER DEVELOPMENT QUARTERLY REPORT, 1 MAY - 17 JUL. 1967

JET PROPULSION LAB., CALIF. INST. OF TECH., PASADENA.; THERMO ELECTRON ENGINEERING CORP., WALTHAM, MASS.

17 JUL. 1967 19 P PREPARED FOR JPL

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HEAT PIPE CAPABILITY EXPERIMENTS

A/KEMME, J. E.

LOS ALAMOS SCIENTIFIC LAB., N.MEX.

1965 10 P REFS PRESENTED AT THERMIONIC CONVERSION SPECIALIST CONF., HOUSTON, TEX.

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THE HEAT TRANSFER DURING STEAM CONDENSATION ON PIPE BUNDLES CONSIDERING PRESSURE LOSS
(EFFECTS OF PIPE GEOMETRY, MATERIALS PROPERTIES, AND SERVICE TIMES ON STEAM CONDENSATION AND PRESSURE LOSS IN CONDENSER) PH.D. THESIS
A/DORNIEDEN, M.
TECHNISCHE UNIV., BERLIN (WEST GERMANY). AVAIL
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/*CONDENSERS (LIQUIFIERS)/*PRESSURE DROP/*STEAM FLOW/ CONSTRUCTION MATERIALS/ HEAT EXCHANGERS/ HEAT PIPES/ HEAT TRANSFER/ PIPE FLOW/ SERVICE LIFE/ STRUCTURAL DESIGN

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DEVELOPMENT OF A PLANAR HEAT PIPE FOR COOLING LARGE CAPACITY BATTERIES
(DEVELOPMENT OF PLANAR HEAT FOR COOLING LARGE CAPACITY ELECTRIC BATTERIES USING WATER AS WORKING FLUID)
A/MAHEFKEY, E. T., JR.
AIR FORCE AERC PROPULSION LAB., WRIGHT-PATTERSON AFB, OHIO. AVAIL.NTIS

/*COOLING SYSTEMS/*ELECTRIC BATTERIES/*HEAT PIPES/*HEAT TRANSFER/ EQUIPMENT SPECIFICATIONS/ HEAT EXCHANGERS/ TEMPERATURE CONTROL

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TECHNIQUES ASSOCIATED WITH THERMAL-VACUUM TESTING OF THE OAO C HEAT PIPES
(PERFORMANCE TESTS OF HEAT PIPES INSTALLED IN OAO 3 SPACECRAFT)
A/MARSHBURN, J. P.
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. GODDARD SPACE FLIGHT CENTER, GREENBELT, MD. AVAIL
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AN OUT-OF-CORE VERSION OF A SIX CELL HEAT-PIPE HEATED THERMICNIC CONVERTER ARRAY

(CHARACTERISTICS OF THERMICNIC SYSTEM WITH HEAT-PIPE COOLED FAST SPECTRUM REACTOR AND SIX-CELL THERMICNIC MODULES LOCATED IN SPACE RADIATOR)

A/KRCEGER, E. W.; B/HARD, J. J.; C/BREITWIESER, R.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. LEWIS RESEARCH CENTER, CLEVELAND, OHIO. AVAIL. NTIS HC \$3.00

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/*HEAT PIPES/*HEAT TRANSFER/*THERMICNIC CONVERTERS/*THERMODYNAMIC PROPERTIES/ EQUIPMENT SPECIFICATIONS/ REACTOR DESIGN/ SYSTEMS ENGINEERING

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NASA-CASE-LEW-11390-1 US-PATENT-APPL-SN-247434
72/04/25 9 PAGES UNCLASSIFIED DOCUMENT

PRODUCTION OF I-123

(PRODUCTION OF HIGH PURITY RADIOIODINE BY BOMBARDMENT OF CESIUM HEAT PIPE) PATENT APPLICATION

A/BLUE, J. W. A/INVENTOR (TO NASA)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. LEWIS RESEARCH CENTER, CLEVELAND, OHIO. AVAIL. NTIS HC \$3.00

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ISOTOPE KILOWATT PROGRAM

(DEVELOPMENT OF COMPONENTS AND PROGRESS OF PERFORMANCE TESTS FOR SYSTEMS OF ISOTOPE KILOWATT THERMOELECTRIC GENERATOR) QUARTERLY PROGRESS REPORT, PERIOD ENDING 30 SEP. 1971

A/FRAAS, A. P.; B/SAMPLELS, G.

OAK RIDGE NATIONAL LAB., TENN. AVAIL. NTIS

/*ELECTRIC EQUIPMENT/*PERFORMANCE TESTS/*SYSTEMS ENGINEERING/*THERMOELECTRIC GENERATORS/ EQUIPMENT SPECIFICATIONS/ HEAT PIPES/ PRODUCT DEVELOPMENT/ THERMODYNAMIC PROPERTIES

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HEAT PIPE NEW HIGH-TEMPERATURE HEAT-TRANSFER D
EVICE

(DESCRIPTION, OPERATION, AND APPLICATION OF HEAT
PIPES FOR INDUSTRY AND SCIENTIFIC RESEARCH)

A/YELISEYEV, V. B.; B/SERGEYEV, D. I.

JOINT PUBLICATIONS RESEARCH SERVICE, ARLINGTON,
VA. AVAIL.NTIS

TRANSL. INTO ENGLISH OF THE BOOK "'CHTU TAKO
YE TEPLOVAYA TRUBA'" MOSCOW, ENERGIYA PUBLISHING
HOUSE, 1971 134 P

/*HEAT EXCHANGERS/*HEAT PIPES/*HEATING EQUIPME
NT/*THERMODYNAMIC PROPERTIES/ EQUIPMENT SPECIFICATI
ONS/ HEAT FLUX/ HEAT TRANSFER/ HEAT TRANSMISSION

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DESIGN AND OPTIMIZATION OF A FAST HEAT PIPE THER
MIONIC REACTOR, 2

(OPTIMIZATION OF FAST HEAT PIPE THERMIONIC REACT
OR PARAMETERS BY COMPUTER AND GRAPHICAL METHODS)

A/HANKE, H.

SCIENTIFIC TRANSLATION SERVICE, SANTA BARBARA,
CALIF. AVAIL.NTIS

WASHINGTON NASA TRANSL. INTO ENGLISH FROM A
TGMKERNENERGIE (MUNICH), V. 18, 1971 P 143-150

/*COMPUTERIZED DESIGN/*FAST NUCLEAR REACTORS/*O
PTIMIZATION/*THERMIONIC CONVERTERS/ COOLING SYSTEM
S/ ENGINEERING DRAWINGS/ HEAT PIPES/ PARAMETERIZAT
ION/ STRUCTURAL DESIGN

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POTASSIUM RANKINE CYCLE VAPOR CHAMBER (HEAT PIPE
) RADIATOR STUDY

(DEVELOPMENT AND EVALUATION OF VAPOR CHAMBER FIN
RADIATOR FOR REJECTING WASTE HEAT FROM POTASSIUM
RANKINE CYCLE POWERPLANT)

A/GERRELS, E. E.; B/KILLEN, R. E.

GENERAL ELECTRIC CO., PHILADELPHIA, PA. AVAIL
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WASHINGTON NASA

/*HEAT PIPES/*HEAT RADIATORS/*POWER PLANTS/*RAN
KINE CYCLE/ EQUIPMENT SPECIFICATIONS/ HEAT TRANSFER/
R/ PRODUCT DEVELOPMENT/ THERMODYNAMIC PROPERTIES

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88 PAGES UNCLASSIFIED DOCUMENT
DESIGN AND DEVELOPMENT OF A PROTOTYPE STATIC CRYOGENIC HEAT TRANSFER SYSTEM
(DESIGN AND DEVELOPMENT OF PROTOTYPE STATIC CRYOGENIC HEAT TRANSFER SYSTEM UTILIZING HEAT PIPE WITH WETTING ARTERIAL WICK AND NITROGEN AS WORKING FLUID) FINAL REPORT
DYNATHERM CORP., COCKEYSVILLE, MD. AVAIL. NTIS

/*CRYOGENICS/*HEAT PIPES/*HEAT TRANSFER/*NITROGEN/*PROTOTYPES/*WORKING FLUIDS/ PRODUCT DEVELOPMENT/ SPACECRAFT INSTRUMENTS/ WETTING

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239 PAGES UNCLASSIFIED DOCUMENT
RESEARCH STUDY ON INSTRUMENT UNIT THERMAL CONDITIONING PANEL FINAL REPORT
(DESIGN, FABRICATION, AND PERFORMANCE TEST OF HEAT PIPE PANEL FOR SATURN 5 LAUNCH VEHICLE)
A/ALBRIGHT, C.; B/CCE, C. S.; C/DUNCAN, J. D.; D/GIBSON, J. C.; E/GRAUMANN, D. W.; F/RICHARD, C. E.
AIRESEARCH MFG. CO., LOS ANGELES, CALIF. AVAIL. NTIS

/*HEAT PIPES/*SATURN 5 LAUNCH VEHICLES/*THERMODYNAMIC PROPERTIES/ EQUIPMENT SPECIFICATIONS/ PERFORMANCE TESTS/ PRODUCT DEVELOPMENT

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ISOTOPE KILOWATT PROGRAM QUARTERLY PROGRESS REPORT, PERIOD ENDING 31 DEC. 1970
(DESIGN AND TEST EXPERIMENTS FOR RADIOISOTOPE POWER CONVERSION SYSTEMS)
OAK RIDGE NATIONAL LAB., TENN. (REACTOR DIV.)
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/*ELECTRIC GENERATORS/*PERFORMANCE TESTS/*RADIOACTIVE ISOTOPES/*THERMOELECTRIC POWER GENERATION/ EXPERIMENTAL DESIGN/ FUEL CAPSULES/ HEAT PIPES/ RANKINE CYCLE/ SYSTEMS ANALYSIS/ THERMOELECTRIC MATERIALS

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ACHIEVING UNIFORM SPECIMEN TEMPERATURES IN AN IR
RADIATION CAPSULE USING HEAT PIPES

(LITHIUM FILLED HEAT PIPE FOR OBTAINING NEAR ISO
THERMAL CONDITIONS AXIALLY ALONG CLADDING OF IN-PI
LE FUEL-IRRADIATION CAPSULE)

A/MILLER, N. E.; B/ZIELENBACH, W. J.

BATTELLE MEMORIAL INST., COLUMBUS, OHIO. AVAI
L. NTIS

IN NASA. LEWIS RES. CENTER NATL. SYMP. ON DEV
ELOP. IN IRRADIATION TESTING TECHNOL. 1969 P 157-
164 /SEE N71-24501 13-22/

/*CLADDING/*FUEL CAPSULES/*HEAT PIPES/*ISOTHERM
S/ CONFERENCES/ LITHIUM/ REACTOR TECHNOLOGY

N71-16887*# ISSUE 6 PAGE 961 CATEGORY 33 N
ASA-CR-116175 NGR-09-005-071 70/09/00 123 PAG
ES UNCLASSIFIED DOCUMENT

MATHEMATICAL MODELING OF CRYOGENIC HEAT PIPES
(MATHEMATICAL MODELING OF CRYOGENIC HEAT PIPES)

A/CHI, S. W.

CATHOLIC UNIV. OF AMERICA, WASHINGTON, D.C. (D
EPT. OF SPACE SCIENCE AND APPLIED PHYSICS.) AVA
IL. NTIS

/*CRYOGENIC EQUIPMENT/*HEAT PIPES/*MATHEMATICAL
MODELS/ COMPUTER PROGRAMS/ COMPUTERIZED DESIGN/ F
LUID MECHANICS/ FORTRAN/ PERFORMANCE PREDICTION

N71-14228*# ISSUE 4 PAGE 621 CATEGORY 33 N
ASA-CR-114783 NAS9-10299 70/12/00 177 PAGES
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CIRCUMFERENTIAL HEAT PIPE SYSTEMS FOR LARGE STRU
CTURES FINAL REPORT

(FABRICATION AND TESTING OF CIRCUMFERENTIAL HEAT
PIPE SYSTEMS FOR LARGE STRUCTURES)

A/CLAUSEN, O. W.; B/MARCUS, B. D.; C/PISKE, W.
E.; D/TURNER, R. C.

TRW SYSTEMS GROUP, HOUSTON, TEX. AVAIL. NTIS

/*HEAT PIPES/*PRODUCTION ENGINEERING/*THERMAL V
ACUUM TESTS/ AEROSPACE ENGINEERING/ AMMONIA/ SPACE
ENVIRONMENT SIMULATION/ TEST FACILITIES/ WATER

N71-12251*# ISSUE 3 PAGE 315 CATEGORY 3 NA
SA-TM-X-52934 E-6C66 70/10/29 8 PAGES UNCLASS
IFIED DOCUMENT
FABRICATION AND EVALUATION OF AN CUT-OF-CORE THE
RMIONIC CONVERTER MODULE
(FABRICATION AND EVALUATION OF OUT-CF-CORE THERM
IONIC CONVERTER HEATED AND COOLED BY HEAT PIPES)
A/KROEGER, E. H.
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. L
EMIS RESEARCH CENTER, CLEVELAND, OHIO. AVAIL. NT
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PRESENTED AT THE THERMIONIC CONVERSION SPECI
ALISTS CONF., MIAMI, FLA., 26-29 OCT. 1970, SPONSO
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/*HEAT PIPES/*THERMIONIC CONVERTERS/ COMPONENT
RELIABILITY/ FABRICATION/ HEAT TRANSFER/ STRUCTURA
L DESIGN

N71-10985*# ISSUE 1 PAGE 134 CATEGORY 33 N
ASA-TM-X-52928 E-6059 70/10/29 8 PAGES UNCLAS
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(USE OF HEAT PIPES FOR ELECTRICAL ISOLATION)
A/BREITWIESER, R.
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. L
EMIS RESEARCH CENTER, CLEVELAND, OHIO. AVAIL. NT
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ED BY INST. OF ELEC. AND ELECTRON. ENGR.
/*ELECTRICAL RESISTANCE/*EXPERIMENTAL DESIGN/*H
EAT PIPES/*HEAT TRANSFER/*THERMIONICS/ HEAT SOURCE
S/ PERFORMANCE TESTS/ THERMIONIC CONVERTERS

N71-10702# ISSUE 1 PAGE 134 CATEGORY 33 AD
-709923 70/6/66 61 PAGES UNCLASSIFIED DOCUME
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THE EXPERIMENTAL DESIGN AND OPERATION OF A ROTAT
ING WICKLESS HEAT PIPE
(EXPERIMENTAL DESIGN AND OPERATION OF ROTATING W
ICKLESS HEAT PIPE)
A/DALEY, T. J. (AA/M.S. THESIS/)
NAVAL POSTGRADUATE SCHOOL, MCNTEREY, CALIF. A
VAIL. NT IS

/*EXPERIMENTAL DESIGN/*HEAT PIPES/ HEAT EXCHANG
ERS/ HEAT TRANSFER/ RCTATION

N69-34467# ISSUE 19 PAGE 3555 CATEGORY 9 N
YO-3979-1 AT/30-1/-3979 69/02/28 51 PAGES U
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ADVANCED HEAT PIPE THERMIONIC TECHNOLOGY TASK 1
- DEVELOPMENT OF HIGH VOLTAGE MODULE MIDTERM STAT
US REPORT, 1 MAY 1968 - 28 FEB. 1969

(DESIGN OF HEAT PIPE THERMIONIC MODULE)

A/LONGSDERFF, R. W.

RADIO CORP. OF AMERICA, LANCASTER, PA. AVAIL.
NTIS

/*ELECTRONIC MODULES/*ENGINEERING DRAWINGS/*FAB
RICATION/*HEAT PIPES/*THERMIONICS/ ALUMINUM OXIDES
/ ELECTRIC POTENTIAL/ IONIZATION

N69-24505*# ISSUE 12 PAGE 2029 CATEGORY 3
NASA-CR-100775 WANL-PC/DDD/-005 NAS7-100 JPL-952
196 69/02/28 18 PAGES UNCLASSIFIED DOCUMENT

CASCADED THERMOELECTRIC TEST GENERATOR, PHASE 2
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(FABRICATION AND CHECKOUT TESTING OF CASCADE THE
RMOELECTRIC GENERATOR SYSTEMS)

JET PROPULSION LAB., CALIF. INST. OF TECH., PASA
DENA.; WESTINGHOUSE ELECTRIC CORP., PITTSBURGH, P
A. (ASTRONUCLEAR LAB.) AVAIL. NTIS

PREPARED FOR JPL

/*CHECKOUT/*FABRICATION/*THERMOELECTRIC GENERAT
ORS/ EQUIPMENT SPECIFICATIONS/ FLUID DYNAMICS/ GER
MANIUM COMPOUNDS/ HEAT PIPES/ NONDESTRUCTIVE TESTS
/ SILICON COMPOUNDS

N69-12895# ISSUE 3 PAGE 581 CATEGORY 33 LA
-3986-MS-PT-1 W-7405-ENG-36 68/08/23 6 PAGES
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SPACE ELECTRIC POWER R AND D PROGRAM, PART 1 QUA
RTERLY STATUS REPORT, PERIOD ENDING 31 JUL. 1968

(ANNULAR RETURN HEAT PIPES, PALLADIUM VALVES, AN
D MERCURY HEAT PIPES FOR SPACE ELECTRIC POWER)

LOS ALAMOS SCIENTIFIC LAB., N.MEX. AVAIL. NTIS

/*HEAT PIPES/*SPACECRAFT POWER SUPPLIES/ ELECTR
IC POWER PLANTS/ HEAT TRANSFER/ MERCURY (METAL)/ P
RODUCT DEVELOPMENT/ VALVES

N67-38592# ISSUE 23 PAGE 4363 CATEGORY 33
AFFDL-TR-66-228 AD-657025 67/06/00 59 PAGES U
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(CRYOGENIC HEAT PIPE INVESTIGATIONS)

A/HASKIN, W. L.

AIR FORCE SYSTEMS COMMAND, WRIGHT-PATTERSON AFB,
OHIO. (AIR FORCE FLIGHT DYNAMICS LAB.)

JUN. 1967 59 P REFS PREPARED JOINTLY WITH
OHIO STATE UNIV.

/*CRYOGENICS/*HEAT TRANSFER/*PIPE/ CONDENSATION
/ DESIGN/ EVAPORATION/ FLOW/ GAS/ HEAT/ INSTRUMENT
ATION/ INVESTIGATION/ PRESSURE/ TUBE/ VAPOR

N67-26792# ISSUE 14 PAGE 2631 CATEGORY 33
66/10/00 5 PAGES UNCLASSIFIED DOCUMENT

STATUS OF THE ENGINEERING THEORY OF HEAT PIPES
(APPLICATIONS AND LIMITATIONS OF ENGINEERING THE
ORY OF HEAT PIPES)

A/COTTER, T. R.

LOS ALAMOS SCIENTIFIC LAB., N.MEX.

IN SANDIA CORP. PRCC. OF JOINT AEC/SANDIA LA
B. HEAT PIPE CONF., VOL. I OCT. 1966 P 5-9 /SEE
N67-26791 14-33/

/*ENGINEERING DEVELOPMENT/*PIPE/ APPLICATION/ C
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MANCE/ SPECIFICATION/ SYSTEM/ THEORY/ THERMAL/ TRA
NSPORT/ VAPOR

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SC-M-66-623 CONF-660645 AT/29-1/-789 66/10/00
91 PAGES UNCLASSIFIED DOCUMENT

PROCEEDINGS OF JOINT ATOMIC ENERGY COMMISSION/SA
NDIA LABORATORIES HEAT PIPE CONFERENCE, VOLUME I
(PROCEEDINGS OF HEAT PIPE CONFERENCE)

SANDIA CORP., ALBUQUERQUE, N.MEX. (SPACE ISOTO
PE POWER DEPT.) AVAIL. NTIS

OCT. 1966 91 P REFS CONF. HELD IN ALBUQUER
QUE, N. MEX., 1 JUN. 1966

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ECT/ ELECTRIC/ ENGINEERING/ FLOW/ LIMITATION/ LIQU
ID/ MATERIAL/ OPERATION/ POWER/ RANKINE CYCLE/ SPA
CE/ SPACECRAFT/ SPECIFICATION/ SYSTEM/ TEMPERATURE
/ THEORY/ THERMAL/ TRANSFER/ TUBE/ WICK

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NASA-CR-83920 TE-4067-76-67 QR-2 NAS7-100 JPL-95
1465 67/01/10 22 PAGES UNCLASSIFIED DOCUMENT

HEAT PIPE THERMIONIC CONVERTER DEVELOPMENT QUART
ERLY REPORT, 1 OCT. 1966 - 10 JAN. 1967
(HEAT PIPE THERMIONIC CONVERTER)
THERMO ELECTRON ENGINEERING CORP., WALTHAM, MASS
. AVAIL. NTIS
10 JAN. 1967 22 P PREPARED FOR JPL
/*HEAT EXCHANGER/*THERMIONIC CONVERTER/ COLLECT
OR/ CONVERTER/ DESIGN/ EXCHANGER/ FABRICATION/ HEA
T/ PIPE/ RADIATOR/ THERMIONIC/ TRANSFER

N66-32591# ISSUE 18 PAGE 3571 CATEGORY 17
JPRS-36679 TT-66-33110 66/07/27 38 PAGES UNCL
ASSIFIED DOCUMENT

PIPE PRODUCTION
(ANALYSIS OF CENTRIFUGAL CAST PIPES, MECHANICAL
PROPERTIES OF STEEL ALLOY PIPES, AND EFFECTS OF AL
KALI-ACID TREATMENT OF STEELS)
JOINT PUBLICATIONS RESEARCH SERVICE, WASHINGTON,
D.C. AVAIL. NTIS
26 JUL. 1966 38 P REFS TRANSL. INTO ENGLIS
H FROM PROIZVODSTVO TRUB /MOSCOW/, ISSUE 15, 1965
P 62-66, 80-89, 95-100
/*CENTRIFUGAL CASTING/*PIPE/*STEEL/ ACID/ ALKAL
I/ ALLOY/ CASTING/ CENTRIFUGAL/ DUCTILITY/ GAS/ HE
AT/ INCLUSION/ MECHANICAL/ NONMETALLIC/ PROPERTY/
STRUCTURAL/ TREATMENT/ U.S.S.R.

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LA-DC-7555 CONF-651049-3 W-7405-ENG-36 65/00/0
0 12 PAGES UNCLASSIFIED DOCUMENT

SURVEY OF LOS ALAMOS AND EURATOM HEAT PIPE INVES
TIGATIONS
(THEORY, PROPERTIES, AND DESIGNS OF HEAT PIPES F
OR THERMIONIC DIODE USE)
A/KEMME, J. E.; B/RANKEN, W. A.
LOS ALAMOS SCIENTIFIC LAB., N.MEX. AVAIL. NTIS
<1965> 12 P REFS PRESENTED AT THE IEEE THE
RMIONIC CONVERSION SPECIALIST CONF., SAN DIEGO, CA
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/*PIPE/*THERMIONIC DIODE/ CONDUCTION/ CONFERENC
E/ CONVERSION/ DESIGN/ DIODE/ HEAT/ PROPERTY/ THEO
RY/ THERMIONIC

N66-23113# ISSUE 12 PAGE 2237 CATEGORY 33
TID-22224 AT/30-1/-3496 65/06/30 42 PAGES U
NCLASSIFIED DOCUMENT
TWO-PHASE MOMENTUM FLUX AND DESIGN OF A HEAT PIPE
E PROGRESS REPORT
(MOMENTUM ENERGY FLUCTUATIONS IN TWO-PHASE PIPE
FLOWS)
A/ANDEEN, G. B.; B/GRIFFITH, P.; C/KERN, F. R.
MASSACHUSETTS INST. OF TECH., CAMBRIDGE. AVAIL
L.NTIS

30 JUN. 1965 42 P
/*MOMENTUM ENERGY/*PIPEFLOW/*TWO-PHASE FLOW/ CONDENSATION/ DESIGN/ ENERGY/ FLOW/ FLUCTUATION/ FLUX/ GAS/ HEAT/ HEAT TRANSFER/ MOMENTUM/ OSCILLATION/ PHASE/ PIPE/ TWO/ WATER/ WICK

N65-23377 ISSUE 13 PAGE 2203 CATEGORY 17 6
5/04/19 6 PAGES UNCLASSIFIED DOCUMENT
DESIGN STRENGTH OF HEAT-TREATED TITANIUM ALLOYS
(DESIGN STRENGTH OF SMALL TANKS MADE OF HEAT TREATED TITANIUM ALLOYS)
A/GLAZUNOV, S. G.; B/KHGREV, A. I.; C/MOISEYEV, V. N.
JOINT PUBLICATIONS RESEARCH SERVICE, WASHINGTON, D.C.

IN ITS SOVIET TITANIUM ALLOYS 19 APR. 1965 P
5-10 TRANSL. INTO ENGLISH FROM METALLOVED. I TER
M. OBRABOTKA METAL. /MCSCCW/, NO. 6, JUN. 1964 P
2-5 /SEE N65-23375 13-17/ CFSTI- \$3.00
/HEAT TREATMENT/*TANK/*TITANIUM ALLOY/ ALLOY/ CHEMICAL/ COMPOSITION/ CYLINDER/ DESIGN/ HEATING/ MATERIAL/ MECHANICAL/ PIPE/ PROPERTY/ SMALL/ STRENGTH/ STRUCTURE/ TEMPERATURE/ TITANIUM/ TREATMENT

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LA-3246-MS w-74C5-ENG-36 65/03/26 36 PAGES
UNCLASSIFIED DOCUMENT
THEORY OF HEAT PIPES
(HEAT PIPE - SELF-CONTAINED STRUCTURE USING TWO-PHASE FLOW WITH CAPILLARY CIRCULATION TO ACHIEVE HIGH THERMOCONDUCTIVITY)
A/COITER, T. P.
LOS ALAMOS SCIENTIFIC LAB., N.MEX. AVAIL.NTIS
26 MAR. 1965 36 P REFS
/*CAPILLARY CIRCULATION/*PIPE/*TWO-PHASE FLOW/ CAPILLARY/ CIRCULATION/ CYLINDER/ DESIGN/ ENGINEERING/ FLOW/ FLUID/ FLUX/ HEAT/ PERFORMANCE/ PHASE/ PRESSURE/ STATE/ STATIC/ STEADY/ STRUCTURE/ TWO

PAGE 19 (ITEMS 50- 52 OF 53)

N65-16735 ISSUE 7 PAGE 1092 CATEGORY 17 65
/02/11 17 PAGES UNCLASSIFIED DOCUMENT
CREEP TESTING, STRUCTURE STABILITY, AND PROPERTI
ES OF STEEL
(CREEP TESTING AND MICROSTRUCTURE OF STEEL FOR C
ASTING AND DRAWING APPLICATIONS)
A/SOLONOUTS, M. I.
JOINT PUBLICATICNS RESEARCH SERVICE, WASHINGTON,
D.C.
IN ITS PROPERTIES CF HEAT-RESISTING STEELS FO
R HEAT AND POWER ENG. 11 FEB. 1965 P 34--50 REFS
/SEE N65-16731 C7-17/ CTS- \$3.00
/*MICROSTRUCTURE/*STEEL/ CASTING/ CREEP/ DRAWIN
G/ ENGINEERING/ FAILURE/ HEAT/ PIPE/ POWER/ RUPTUR
E/ STEAM/ STRENGTH/ STRESS/ TESTING/ TREATMENT/ TU
BING

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APPENDIX G2 - REPRODUCTION OF NASA LSN 20604
(PART II - LIMITED DISTRIBUTION REFERENCES; 28 CITATIONS)

NASA Literature Search Number
20604
Part II (Limited Distribution References)

HEAT PIPE FABRICATION

November 20, 1972

SCOPE: References pertinent to the above subject.

PERIOD: 1962 to date shown above

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LONG LIFE HIGH RELIABILITY THERMAL CONTROL SYSTEMS STUDY MONTHLY REPORT, 1-31 JAN. 1972
A/BLCMSTROM, L. E.
GENERAL ELECTRIC CO., PHILADELPHIA, PA. (SPACE DIV.)

/*HEAT PIPES/*HEAT TRANSFER/*TEMPERATURE CONTROL/*THERMODYNAMICS/ EQUIPMENT SPECIFICATIONS/ RELIABILITY ENGINEERING/ SYSTEMS ENGINEERING

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93 71/10/04 5 PAGES UNCLASSIFIED DOCUMENT NASA ONLY

LARGE VARIABLE CONDUCTANCE HEAT PIPE MONTHLY PROGRESS REPORT
A/EDELSTEIN, F.
GRUMMAN AEROSPACE CORP., BETHPAGE, N.Y.

/*HEAT PIPES/*PRODUCT DEVELOPMENT/*RESISTANCE HEATING/ COMPONENT RELIABILITY/ VARIABILITY

X71-73695* NASA-CR-117101 REPT-697-M-24 NAS7-6
97 71/03/12 28 PAGES UNCLASSIFIED DOCUMENT NASA ONLY

HEAT PIPE TECHNOLOGY FOR ADVANCED ROCKET THRUST CHAMBERS INFORMAL MONTHLY STATUS LETTER, 1-28 FEB. 1971

A/ROUSAR, D. C.
AEROJET LIQUID ROCKET CO., SACRAMENTO, CALIF.;
JET PROPULSION LAB., CALIF. INST. OF TECH., PASADENA.

PREPARED FOR JPL

/*EXPERIMENTAL DESIGN/*HEAT PIPES/*LIQUID PROPELLANT ROCKET ENGINES/*THRUST CHAMBERS/ EVAPORATORS / FUEL INJECTION/ PROPULSIVE EFFICIENCY

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70/06/00 117 PAGES UNCLASSIFIED DOCUMENT GCVT ONLY

DEVELOPMENT OF A 250 AMPERE TRANSCALANT RECTIFIER FINAL TECHNICAL REPORT, 28 MAY 1969 - 15 MAY 1970

A/KESSLER, S. W.
RADIO CORP. OF AMERICA, LANCASTER, PA. (ELECTRONIC COMPONENTS.)

/*CRYSTAL RECTIFIERS/*HEAT EXCHANGERS/*HEAT PIPES/ COOLING SYSTEMS/ PRODUCT DEVELOPMENT/ SYSTEMS ENGINEERING

PAGE 1 (ITEMS 1- 3 OF 28)

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HEAT PIPE TECHNOLOGY FOR ADVANCED ROCKET THRUST
CHAMBERS INFORMAL MONTHLY STATUS LETTER
AEROJET LIQUID ROCKET CO., SACRAMENTO, CALIF.

/*COOLING SYSTEMS/*HEAT PIPES/*LIQUID PROPELLANT
ROCKET ENGINES/*REGENERATIVE COOLING/ ENGINE DES
IGN/ FUEL INJECTION/ INJECTORS/ THRUST CHAMBERS

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THE DEVELOPMENT OF THERMIONIC-HEAT PIPE SPACE PO
WER TECHNOLOGY /U/ QUARTERLY TECHNICAL REPORT
A/BUZZARD, R. J.; B/PARKER, A. J., JR.

JET PROPULSION LAB., CALIF. INST. OF TECH., PASA
DENA.; RADIO CORP. OF AMERICA, LANCASTER, PA. (

DIRECT ENERGY CONVERSION DEPT.)

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/*HEAT PIPES/*SPACECRAFT POWER SUPPLIES/*THERMI
ONIC POWER GENERATION/ PRODUCT DEVELOPMENT/ SYSTEM
S ENGINEERING/ THERMODYNAMIC PROPERTIES

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97 70/09/10 22 PAGES UNCLASSIFIED DOCUMENT
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HEAT PIPE TECHNOLOGY FOR ADVANCED ROCKET THRUST
CHAMBERS MONTHLY STATUS REPORT, AUG. 1970
AEROJET LIQUID ROCKET CO., SACRAMENTO, CALIF.

/*COOLING SYSTEMS/*HEAT PIPES/*THRUST CHAMBERS/
EQUIPMENT SPECIFICATIONS/ HEAT TRANSFER/ LIQUID R
OCKET PROPELLANTS/ PROJECT MANAGEMENT/ SYSTEMS ENG
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DEVICES OPERATION.)

/*COOLING SYSTEMS/*HEAT PIPES/*THERMIONIC POWER
GENERATION/ EQUIPMENT SPECIFICATIONS/ PRODUCT DEV
ELOPMENT/ THERMIONIC CONVERTERS

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R TECHNOLOGY /U/ MONTHLY STATUS REPORT, SEP. 1965
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/*ISOTOPES/*SPACECRAFT POWER SUPPLIES/*THERMION
IC POWER GENERATION/ AUXILIARY POWER SOURCES/ EQUI
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ING/ TECHNOLOGY UTILIZATION

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/*ISOTOPES/*SPACECRAFT POWER SUPPLIES/*THERMION
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PMENT SPECIFICATIONS/ HEAT PIPES/ SYSTEMS ENGINEER
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R TECHNOLOGY /U/ MONTHLY STATUS REPORT, MAY 1966
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PLIES/*THERMIONIC POWER GENERATION/ EQUIPMENT SPEC
IFICATIONS/ HEAT PIPES/ ISOTOPES/ SYSTEMS ENGINEER
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FEB. 1967

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/*HEAT PIPES/*THERMIONIC CONVERTERS/*THERMIONIC
POWER GENERATION/ FABRICATION/ FUEL CAPSULES/ PRO
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PAGE 3 (ITEMS 9- 12 OF 28)

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JET PROPULSION LAB., CALIF. INST. OF TECH., PASA
DENA.; RADIO CORP. OF AMERICA, LANCASTER, PA. (
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/*HEAT PIPES/*TEMPERATURE CONTROL/*THERMIONIC C
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/ EVALUATION/ FABRICATION/ PERFORMANCE TESTS

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HEAT PIPE TECHNOLOGY FOR ADVANCED ROCKET THRUST
CHAMBERS MONTHLY STATUS REPORT, FEB. 1970
AEROJET-GENERAL CORP., SACRAMENTO, CALIF.

/*COOLING SYSTEMS/*HEAT PIPES/*THRUST CHAMBERS/
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CHAMBERS MONTHLY STATUS LETTER, 1-31 JAN. 1970
AEROJET-GENERAL CORP., SACRAMENTO, CALIF.

/*HEAT PIPES/*PERFORMANCE TESTS/*THRUST CHAMBER
S/ EQUIPMENT SPECIFICATIONS/ FABRICATION/ GRAPHS (
CHARTS)/ LITHIUM/ PRODUCT DEVELOPMENT/ SODIUM/ SYS
TEMS ENGINEERING/ TECHNOLOGIES

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HEAT PIPE TECHNOLOGY FOR ADVANCED ROCKET THRUST
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AEROJET-GENERAL CORP., SACRAMENTO, CALIF.

/*FABRICATION/*HEAT PIPES/*NICKEL/*PROPELLANT S
TORAGE/*ROCKET THRUST/*THRUST CHAMBERS/ COEFFICIEN
TS/ EVAPORATORS/ HEAT FLUX/ PRODUCTION ENGINEERING

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THE DEVELOPMENT OF A 600 DEG CENTIGRADE HEAT PIPE
ASSEMBLY /U/

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ENERGY CONVERSION DEPT.)

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/ ASSEMBLY/ COOLANT/ DESIGN/ EQUIPMENT/ FAILURE
/ HEAT/ HIGH TEMPERATURE/ LIFE/ PIPE/ POWER/ SUPPL
Y/ TEST

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HEAT PIPE THERMIONIC CONVERTER DEVELOPMENT QUART
ERLY REPORT, 23 JUN. - 30 SEP. 1966

THERMO ELECTRON ENGINEERING CORP., WALTHAM, MASS

30 SEP. 1966 25 P PREPARED FOR JPL

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PE/ SHOCK/ THERMIONIC/ VIBRATION

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