HEAT PIPE PRODUCT RELIABILITY

Introduction

Advanced Cooling Technologies, Inc. (ACT) has worked extensively on heat pipes product reliability. This paper covers the following aspects related to heat pipe product reliability.

1. General Quality
2. Suitable Working Fluid/ Material Systems
    a. Documented Compatibility
    b. ACT's Life Test Data
3. Heat Pipe Performance Limits
    a. Orientation
4. Shock and Vibration
5. Acceleration
6. Frozen Start Up
7. Thermal Cycling
8. Summary

General Quality

Heat pipes are proven, reliable, heat transfer devices which have been used in applications from laptop cooling to satellite thermal control. A well controlled manufacturing process is critical to fabricating reliable, long life heat pipes.

Common causes of heat pipe degradation include leaks between inside and outside of the heat pipe and gas generation within the heat pipe envelope. Even very small leaks in the envelope material, at a joint, or at the seal of the fill tube, may cause degradation over time. Internal gas generation is the result of chemical reactions caused by either an incompatible fluid/material system or contaminants from improper cleaning and processing.

Eliminating these manufacturing problems requires heat pipe specific manufacturing knowledge and experience, and the capability of implementing that knowledge in a consistent manufacturing process. ACT excels in meeting both requirements. First, ACT has a relatively large number of engineers with hundreds of years of combined experience in heat pipe design, fabrication and testing, for both high volume and custom applications. Second, ACT's quality system is certified to ISO9001 and AS9100 standards for terrestrial and aerospace product manufacturing, respectively. Our quality system has passed all audits to date with a perfect, 100% score, indicating a strong and consistent performance in implementing the quality system in the manufacturing practice. As a result, ACT's heat pipe products are reliable and have been used in numerous, mission critical, space, military and commercial systems.

Suitable Working Fluid / Material Systems

A heat pipe material system includes the envelope material, the wick material, the working fluid, and any braze, solder or weld filler materials used in sealing the heat pipe. ACT works with a variety of heat pipe material systems ranging from low temperature Aluminum/Ethane heat pipes operating at -100˚C to high temperature Haynes/Sodium heat pipes operating at 1,100˚C.

Documented Compatibility

Two major results of material incompatibility are corrosion and generation of non-condensable gas (NCG). If the wall or wick material is soluble in the working fluid, mass transfer is likely to occur between the condenser and evaporator, with solid material being deposited in the latter. This will result in either local hot spots or blocking of the pores of the wick. NCG generation is the most common indication of a heat pipe failure. As the NCG accumulates in the heat pipe condenser section, it gradually blocks the heat transfer area, consequently degrading the heat pipe performance. Table 1 shows well documented compatibility data for low temperature working fluids.[1]

Table 1 Documented Compatibility Data for Low Temperature Working Fluids

Wick Material	Working Fluids					
	Water	Acetone	Ammonia	Methanol	Dow-A	Dow-E
Copper	C	C	X	C	C	C
Aluminum	GNC	C	C	X	UK	X
Stainless Steel	GNT	C	C	GNT	C	C
Nickel	C	C	C	C	C	C

C: compatible
X: not compatible
GNC: generates gas at all temperatures
GNT: generates gas at elevated temperature when oxides present.
UK: unknown

Two of the most reliable and most proven heat pipe material/fluid systems are copper/water and aluminum/ammonia. Copper/water is the standard for terrestrial electronics cooling, and aluminum/ammonia is the standard for satellite thermal control.

ACT's Life Test Data

ACT has been developing new material systems for emerging applications. ACT maintains a large number of life test heat pipes made of various material/fluid combinations. Some of our intermediate temperature fluid test results are summarized in Table 2. As shown, titanium and super alloys can be used as the envelope material for certain intermediate temperature fluids in the temperature range of 450 to 700K (177 to 427°C). For instance, $AlBr_3$ showed very strong compatibility with C22, C2000, and B3.

ACT has also performed extensive testing of high temperature water heat pipes[4]. While copper/water heat pipes have been extensively used in the temperature range of 20 to 150°C, they are not suitable for applications requiring operation beyond 150°C. With the vapor pressure rising with temperature, copper is not an ideal envelope material because of its low yield strength and high density. ACT has run life tests to prove the compatibility of stronger envelope materials for high temperature water heat pipes. As shown in Table 3, these results are ongoing and last recording date was April 15 2010.

Table 2 ACTs Life Test Data for Intermediate Temperatures

Envelope Material		***Working Fluid***					
		$AlBr_3$	**$GaCl_3$**	**$SnCl_4$**	**$TiCl_4$**	**$TiBr_4$**	**Therminol**
Cp-Ti	ΔT	-	99.5*	-	-	-0.6K	125 K
	hours	-	1272	-	-	1344	1344
C22	ΔT	3.7 K	Failed	132.1 K	7.0 K	-	-
	hours	1272		1464	1464	-	-
C2000	ΔT	0.6 K	Failed	116.2 K	3.3 K	-	-
	hours	1272		1464	1464	-	-
B3	ΔT	1.8 K	Failed	31.5 K	57.2 K	-	-
	hours	312		1464	1464	-	-

Table 3 High Temperature Water Heat Pipes

Wall Material	**Wick Material**	**Operating Temperature**	**Operating Hours**
Monel K 500	200 x 200 Monel 400 Screen	550 & 500 K (277 & 227°C)	45,336
CP-2 Ti	150 x 150 CP-Ti Screen	550 & 500 K (277 & 227°C)	45,336
CP-2 Ti	Sintered Titanium	550 K (277 °C)	36,941
CP-2 Ti	100 x 100 Cp-Ti Screen	550 K (277 °C)	34,256
Cp-2 Ti	100 x 100 Cp-Ti Screen	550 K (277 °C)	36,941
Grade 5 Ti	100 x 100 Cp-Ti Screen	550 K (277 °C)	36,941
Grade 7 Ti	100 x 100 Cp-Ti Screen	550 K (277 °C)	36,941
Grade 9 Ti	100 x 100 CP-Ti Screen	550 K (277 °C)	32,784
Monel 400	120 x 120 Monel 400 Screen	550 K (277 °C)	32,280
Monel K 500	120 x 120 Monel 400 Screen	550 K (277 °C)	31,440
Monel 400	-100+170 Mesh Monel 400	550 K (277 °C)	30,192
Monel K 500	-100+170 Mesh Monel 400	550 K (277 °C)	30,552

Heat Pipe Performance Limits

Understanding and accurately predicting the various heat pipe performance limitations are essential to designing a reliable heat pipe. The design should take into account operating orientation, temperature range and other possible adverse conditions such as shock, vibration and acceleration loading.

Figure 1 shows the various heat pipe limitations for a typical copper/water heat pipe. These limitations are a function of the operating temperature, due to the change in the fluid properties as a function of temperature. It is important to ensure that the appropriate performance limit curve adequately cover the performance requirement for the entire specified temperature range.

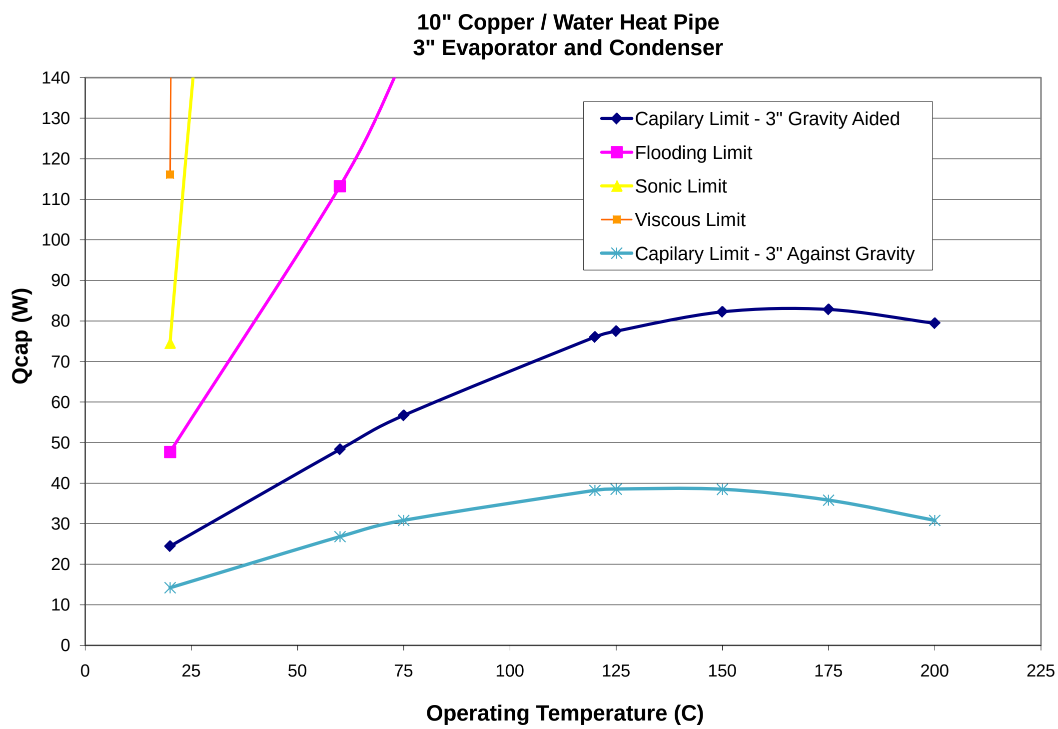


Figure 1 Heat Pipe Performance Limits for 10" Long copper/water heat pipe. Two capillary curves show the effect of orientation.

Orientation

As shown in Figure 1, the heat pipe operating orientation affects the amount of power it can transfer. However, once a heat pipe design has been developed to handle the worst case orientation, changing orientations has little effect on its thermal resistance. The physics behind the gravity orientation effect is described in the following pressure balance equation:

$$\Delta Pc \geq \Delta Pv + \Delta Pl + \Delta Pg \qquad \text{eq. 1.0}$$

where:

ΔPc = Capillary pressure gradient generated by the wick structure $= \frac{2\sigma \cos\theta}{r_c}$ eq. 1.1

ΔPv = Pressure drop of the vapor flow inside the heat pipe
ΔPl = Pressure drop of the liquid flow inside the wick structure
ΔPg = Gravity head upon the liquid can be positive or negative depending on the heat pipe orientation

Equation 1.0 states that for a heat pipe to operate properly, the capillary pressure gradient must be able to overcome the pressure drops in the vapor and liquid flows and the adverse gravity head. Depending on the heat pipe orientation, the gravity head may be beneficial or adverse. In cases where the heat pipe's evaporator is below the condenser, the heat pipe can transfer more power because the gravity head aids in the liquid flow from the condenser to the evaporator. In cases where the evaporator is above the condenser, the gravity head works against the liquid return to the evaporator, consequently lowering the heat transfer capability of a given wick design. It should be pointed out that the thermal resistance of the heat pipe is independent of the orientation as long as the heat pipe operates within the capillary limit.

For most terrestrial applications, the capillary limit is often the controlling limit, because of the potential adverse effect on the liquid return to the evaporator due to gravity. The capillary limit is a function of the wick design, more specifically the wick's pore radius and permeability. Both sintered powder metal and screen wicks are available in a variety of pore sizes. The permeability is inversely proportional to the pore size for both types of wicks. ACT uses in-house heat pipe performance prediction tools to assure our heat pipes exceed the design requirements.

Shock and Vibration

ACT has substantial experience in designing, fabricating and testing heat pipe assemblies to various shock and vibration loadings. ACT has in house mechanical shock and vibration test equipment as shown in Figure 2. ACT's heat pipes and loop heat pipes have been tested to diverse shock and vibration conditions including:

- 4,500 lbf force sustained vibration loads
- Up to 9,000 lbf shock loads
- 0-3,000 Hz Frequency Range
- Over 100g's peak acceleration
- Vibration: Sine, Random, Sine on Random, Random on Random
- Shock: Haversine, Half-Sine, Saw-Tooth, & Trapezoid
- Replication of Measured Field Data
- Gunfire Vibration
- Shock Response Spectrum

ACT's shock test rig can produce a peak acceleration of G_{pk}=123g. The vibration capabilities include a frequency of 267 Hz, G_{rms}=24g, and G_{pk}=45g. Examples of shock and vibration test profiles are shown in Figure 3.

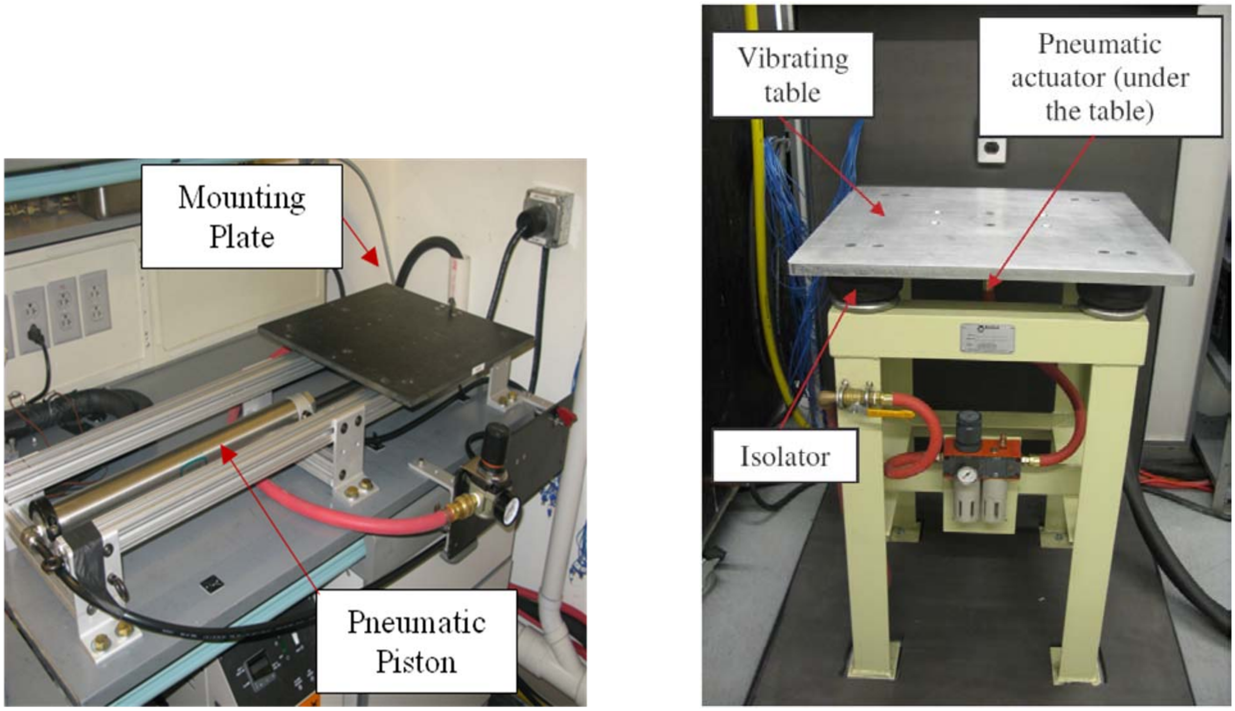


Figure 2. (a) Shock Test Table (Left). (b) Vibration Test Table (Right).

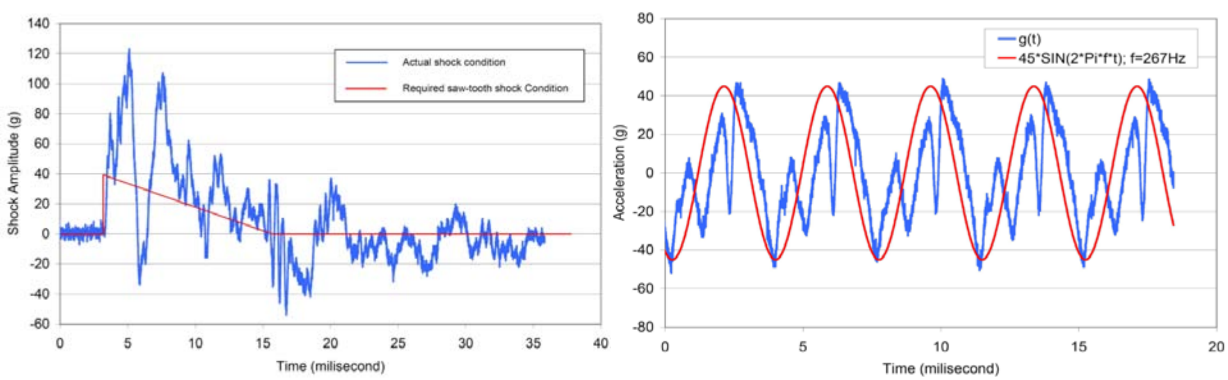
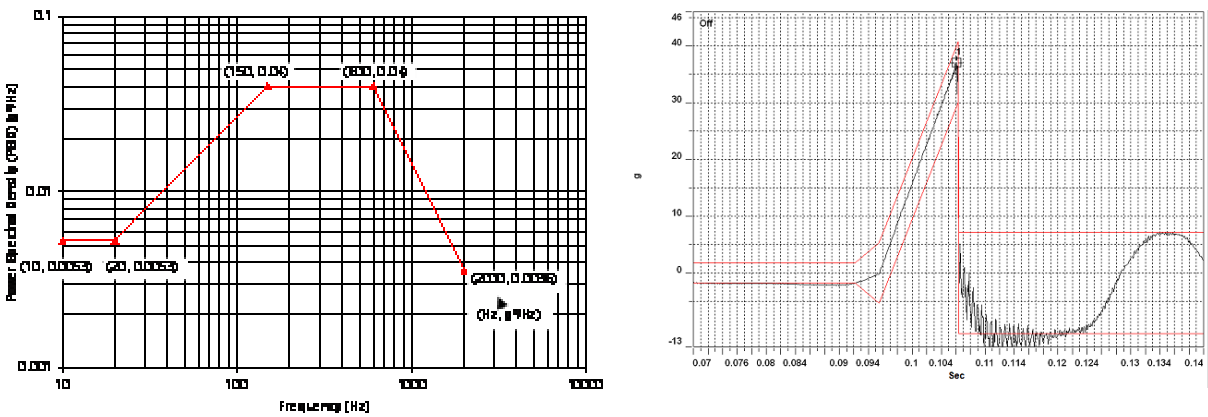


Figure 3. (a) Shock Amplitude vs. Time. (b) Acceleration vs. Time

Testing has confirmed that vibration loading has little or no impact on the performance of ACT's heat pipes. Shock and vibration testing showed no evidence of overstress or fatigue on the heat pipes or solder joints. Some examples of vibration tests are listed below:

- Tac-Sat 4 Loop Heat Pipe Assembly. This assembly was tested to both transport and launch acceleration and vibration loads. ACT designed the system to survive customer defined Mass-Acceleration Curve up to 60 G's, and 3 dimensional Random Vibration Spectrum. The design was validated by 3-axis random vibration testing. The predicted and actual responses matched well.

- Hybrid Two Phase Loop System. ACT tested a pumped two phase system with internal wick components to military vehicle shock and vibration requirements. Figure 4 (a) shows the PSD profile of the body and frame in a Future Combat Systems (FCS)-like military vehicle. The PSD curve produces a maximum vibration level of about 5 G_{rms}. Figure 4 (b) shows the shock profile of the same vehicle with a half-sine pulse of 10 G's for 50~75 ms. This thermal performance was identical before and after the tests.
- Heat Pipe Loop Assembly- This assembly was tested to the shock and vibration specifications shown in Figure 4 under full thermal loading with no degradation in performance during testing.



(a) (b)

Figure 4 (a) Vibration and (b) Shock Profiles of FSC-Variant Body/Frame Mounted Components

Acceleration

As long as the wick's capillary force is greater than the pressure drops and the acceleration loading, the heat pipe will perform properly under various acceleration loadings. However, extremely large adverse acceleration loadings may overwhelm the wick's capillary capability, de-priming the wick or eventually causing the wick to dry out.

If the acceleration is for short durations, the wick structure will re-prime and the thermal transient may be within an allowable range. An alternative approach will be required if the transients are for longer durations. If the axis and direction of acceleration are known the heat pipes can be configured such that acceleration helps return the condensed fluid "gravity aided". If the acceleration axis is unknown heat pipes can be arranged in pairs so that regardless of the acceleration vector one heat pipe will always be "gravity aided".

Frozen Start Up

Many military and commercial applications specify temperatures ranging from -45˚C to + 70˚C. Water heat pipes are typically used in these applications because of their proven reliability and capability. The heat pipes must be able to operate with full capacity at the higher end of the temperature range to provide the required cooling. Frozen start up can be an issue if the system thermal mass and heat transfer are such that the fluid in the evaporator is thawed and vaporized by the heat input, travels to the condenser and freezes there. This could result in the depletion of fluid in the evaporator, eventually shutting down the heat pipe.

This is a system design issue and not typically a heat pipe limitation. There are four ways to address this issue. First, design the system so that frozen start up is not an issue. In other words, the input power and vapor transport are sufficient to thaw the entire system. Second, use active controls such as turning off fans to limit heat transfer in freezing conditions. Third, design in a secondary heat transfer mechanism so that the heat pipes are not needed to prevent device from overheating in freezing ambient conditions. Fourth, add a predetermined amount of NCG to the heat pipe to ensure “orderly” freezing and thawing. Options one and three are typical in most assemblies by default, but can be assured through analysis and testing.

Thermal Cycling

Heat pipes utilize a wick structure to transport the liquid working fluid from the condenser to the evaporator. When properly made, the working fluid fully saturates the wick without making a puddle of excess fluid. With the fluid completely contained within the wick, it is not able to bridge the gap across the inside diameter of the heat pipe. This allows multiple freeze thaw cycles to occur without heat pipe deformation. A variety of working fluids may be used which directly affects the freezing temperature of the heat pipe.

ACT routinely subjects heat pipes to thermal cycling to meet customer requirements. Typical freeze thaw tests are conducted from temperatures ranging from -20 to +20°C and -45 to +125°C. ACT has tested heat pipes up to 1,200 cycles, but 50-300 cycles are a more standard practice. Heat pipes may be thermally cycled prior to installation into assemblies. Heat pipe assemblies are also thermally cycled in assembled units to assure system level performance. Below are three examples:

- Heat Pipes. ACT conducted tests to collect data on heat pipe thermal cycling survivability. The data set for these experiments used both fabricated flattened and bent 4mm heat pipes as well as 0.25” diameter copper water heat pipes. Heat pipes were exposed to as many as 1200 freeze thaw cycles without deformation or performance degradation
- AlSiC HiK Plates. This project developed an innovative low-CTE heat spreader by embedding heat pipes into AlSiC plates. These plates showed similar effective thermal conductivity before and after 100 freeze/thaw cycles from -55°C to 125°C.
- Aluminum HiK Plates. In this project, copper water heat pipes are soldered into aluminum plates. Prior to fabrication, the heat pipes are screened by being exposed to 300 cycles from -20°C to +20°C. Once the assemblies were fabricated, the plates were exposed to an additional 50 cycles from -40°C to +75°C in two different orientations

(100 cycles total) to assure freeze/thaw survivability. Figure 5 shows the temperature profile of plates exposed to thermal cycling. This is a 100% test requirement which all assemblies must pass prior to shipping. All plates are checked for any signs of thermal or mechanical degradation.

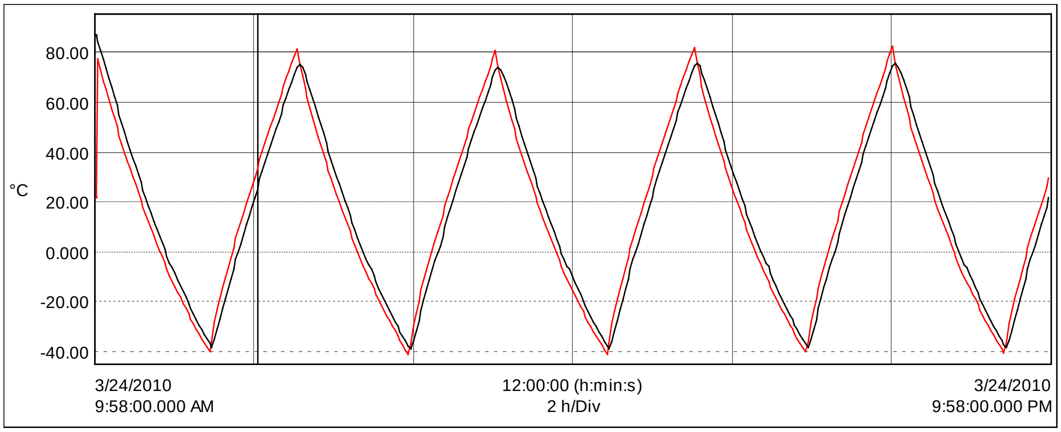


Figure 5: Freeze/Thaw cycle data

Summary

ACT has experienced engineers to design, analyze, and integrate heat pipe based thermal solutions for a wide range of applications. Our expertise includes designing optimal heat pipes based on proven compatible fluids, analyzing heat pipe limitations, and manufacturing heat pipes to the highest quality standards. ACT also has extensive testing capabilities including shock, vibration, acceleration, and freeze/thaw tests. ACT has designed, manufactured and delivered heat pipe products for numerous commercial, military and aerospace systems.

References:

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[2] *Intermediate Temperature Fluids Life Tests - Experiments*, William Anderson, et al., 2007 International Energy Conversion Engineering Conference, St. Louis, MO, June 2007.

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