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HEAT PIPES FOR HIGH TEMPERATURE THERMAL MANAGEMENT

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ABSTRACT

Copper water heat pipes are a well-established solution for many conventional electronics cooling applications; however they have several problems when applied to high temperature electronics. The high vapor pressure of the working fluid combined with the decreasing strength of an already soft material leads to excessive wall thickness, high mass, and an inability to make thermally useful structures such as planar heat pipes (vapor chambers) or heat pipes with flat input surfaces. Titanium/water and Monel/water heat pipes can overcome the disadvantages of copper/water heat pipes and produce a viable thermal management solution for high temperature electronics. Water remains the fluid of choice at temperature up to about 280°C due to its favorable transport properties. Life tests have shown compatibility at high temperature. At temperatures above roughly 300°C, water is no longer a suitable fluid, due to high vapor pressure and low surface tension as the critical point is approached. At higher temperatures, another working fluid/envelope combination is required, either an organic or halide working fluid. Preliminary halide life test results are presented, giving fluids that can operate at temperatures as high as 425°C. At higher temperatures, alkali metal heat pipes are suitable. Water and the higher temperature working fluids can offer solutions for cooling high-temperature electronics, or those working at or above 150°C.

INTRODUCTION

High Temperature Electronics require innovative thermal management devices. Copper water heat pipes are a well-established solution for many conventional electronics cooling applications; however they have several problems when applied to high temperature electronics. The high vapor pressure of the working fluid combined with the decreasing strength of an already soft material leads to excessive wall thickness, high mass, and an inability to make thermally useful structures such as planar heat pipes (vapor chambers) or heat pipes with flat input surfaces.

Historically, water was used with copper at temperatures up to about 150°C. Recent work has shown that titanium/water and Monel/water heat pipes can overcome the disadvantages of copper/water heat pipes, and produce a viable thermal management solution for high temperature electronics. Water remains the fluid of choice for temperatures up to 280°C, due to its favorable transport properties. Monel and titanium offer much higher strength and result in reasonable wall thickness and mass. The paper will present evidence that high temperature water heat pipes are now a mature technology that is ready for widespread application, including life test data (over 2.2 years with no problems), suitable wick structures, and heat pipe fabrication and testing.

At higher temperatures, the water vapor pressure is too high, and alternative working fluids are required. These fluids offer good thermal performance but at much lower vapor pressures and offer the potential of using low-mass wall materials such as aluminum or titanium. Potential working fluids include several organic compounds, as well as halides. The paper will discuss work to qualify working fluids at temperatures up to 425°C (at higher temperatures, alkali metal working fluids can be used). Water and the higher temperature working fluids can offer solutions for cooling high-temperature electronics, or those working at or above 150°C.

NOMENCLATURE

$E_{P\_M_xX_y}(T)$	decomposition potential of the metallic halide M_xX_y at the reaction temperature T (V)
ΔE	electromotive force difference (V)
ΔE^0	standard electromotive force difference (V)
M	Merit number, W/m^2
M_bX_c	halide of metal M_b (working fluid)
M_aX_{cp}	halide of metal M_a (reaction product)
ρ_L	Liquid density, kg/m^3
σ	Surface tension, n/m
λ	Latent heat, J/kg
μ_L	Liquid viscosity, Pa

HIGH STRENGTH ENVELOPE MATERIALS

Titanium, titanium alloys, Monel 400, and Monel K500 have higher yield strength and lower density than copper. As discussed below, they have been shown to be compatible with water, hence be used for thinner and lighter weight heat pipes than copper at a given operating temperature and working fluid vapor pressure. Titanium has been used in heat pipes with the following fluids:

- Sodium (Anderson et al., 2006)
- Potassium (Lundberg, 1984, Sena and Merrigan, 1989)
- Cesium (Dussinger, Anderson, and Sunada, 2005)
- Dowtherm A (Heine, Groll, and Brost, 1984, Groll, 1989)
- Toluene (Heine, Groll, and Brost, 1984, Groll, 1989)
- Water (Heine, Groll, and Brost, 1984, Groll, 1989), Antoniak et al., 1991, Anderson et al., 2006)
- Ammonia (Ishizuka, Sasaki, and Miyazaki 1985)
- Nitrogen (Swanson et al., 1995)

Titanium has also been used in loop heat pipes with water and cesium (Anderson et al., 2006).

Monel 400 and Monel K500 are two other potential heat pipe materials (Monel 400 Technical Bulletin, 2005, Monel K-500 Technical Bulletin, 2005). Monel 400 is a solid solution alloy with roughly 63% nickel and 30% copper. It is a single phase alloy, since the copper and nickel are mutually soluble in all proportions. It can only be hardened by cold working. Monel K500 is a similar nickel-copper alloy, with the addition of small amounts of aluminum and titanium that give greater strength and hardness. The system is age-hardened by heating so that small particles of Ni3(Ti, Al) are precipitated throughout the matrix, increasing the strength of the material. The material must be annealed before welding, for ductile welds.

TITANIUM/WATER AND TI/MONEL LIFE TESTS

Life tests are required to verify that the heat pipe envelope, wick, and working fluid are compatible for the potentially long operating life of a heat pipe. The two major consequences of incompatibility are corrosion and the generation of non-condensable gas, or both. The resulting corrosion products can block portions of the wick, preventing the heat pipe from operating properly. In more extreme cases, the heat pipe can leak.

A series of simple cylindrical heat pipes were constructed and operated to demonstrate compatibility with the wall materials and working fluid. These life test pipes were electrically heated and had three thermocouples to monitor the temperature gradient along the heat pipe; see Figure 1. Any incompatibility would result in the generation of non-condensable gas, which would then accumulate in the heat pipe condenser and result in a cold end or increased end-to-end temperature gradient. The heat pipes were operated at either 227 or 277°C to accelerate any reaction between the wall and working fluid. Once weekly the input power was reduced so that the heat pipes operated near 60°C. This reduced the vapor pressure of the water from roughly 60 atm (277°C) or 26 atm (227°C) to only 0.2 atm. That allowed any non-condensable gas present to expand and cover more of the condenser so it could be more easily detected.

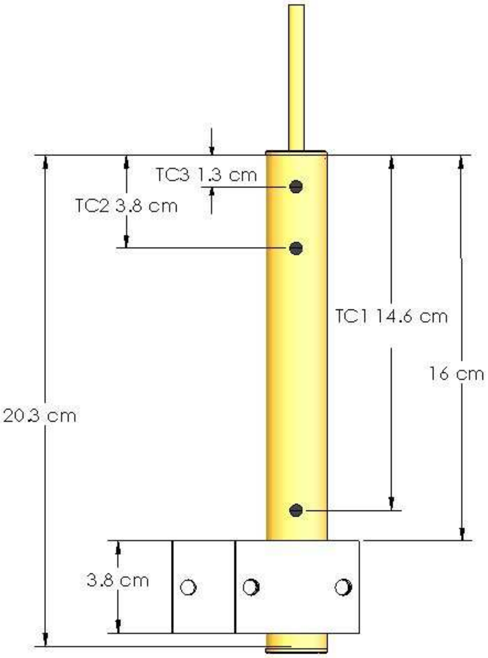


Figure 1. Location of Thermocouples and Heater Block.

Titanium/Water and Monel/Water life tests now have up to 2.3 years of operation, with no incompatibilities detected. The life tests include commercially pure titanium (CP-Ti), titanium alloys, Monel 400, and Monel K500 envelopes. Details of the tests are given in Table 1. The wicks tested include CP-Titanium screen, CP-Titanium sintered powder, Monel 400 screen, and Monel 400 sintered powder.

Table 1. Titanium/Water and Monel/Water Life Tests.

Quantity	Wall Material	Tube Dimensions	End cap/ Fill Tube	Wick	Operating Temperature	Operating Hours
4	Monel K 500	2.54 cm O.D. by 1.55 mm wall	Monel 400	200x200 Monel 400 Screen 0.064 mm wire	277 & 227°C	20,064 hours
4	CP-2 Ti	1.91 cm O.D. by 1.25 mm wall	CP-Ti	150x150CP-Ti Screen 0.069 mm wire	277 & 227°C	20,064 hours
4	CP-2 Ti	2.54 cm O.D. by 1.3 mm wall	CP-Ti	Sintered Titanium -35+60 Mesh CP-2	277°C	11,621 hours
2	CP-2 Ti	1.000 in. O.D. by .049 in wall	CP-Ti	100 x100 CP-Ti Screen 0.05 mm wire	277°C	1996/8936 hours
2	CP-2 Ti 21 S Foil Inside	2.54 cm O.D. by 1.3 mm wall	CP-Ti	100 x100 CP-Ti Screen 0.05 mm wire	277°C	11,621 hours
2	Grade 5 Ti	2.54 cm O.D. by 1.3 mm wall	CP-Ti	100 x100 CP-Ti Screen 0.05 mm wire	277°C	11,621 hours
2	Grade 7 Ti	2.54 cm O.D. by 1.3 mm wall	CP-Ti	100 x100 CP-Ti Screen 0.05 mm wire	277°C	11,621 hours
2	Grade 9 Ti	2.54 cm O.D. by 1.3 mm wall	CP-Ti	100 x100 CP-Ti Screen 0.05 mm wire	277°C	7,464 hours
2	Monel 400	2.54 cm O.D. by 2.0 mm wall	Monel 400	120x120 Monel 400 Screen 0.05 mm wire	277°C	6,960 hours
2	Monel K 500	2.54 cm O.D. by 2.0 mm wall	Monel 400	120x120 Monel 400 Screen 0.05 mm wire	277°C	6,120 hours
1	Monel 400	2.54 cm O.D. by 2.0 mm wall	Monel 400	-100+170 Mesh Monel 400 Powder	277°C	4,872 hours
2	Monel K 500	2.54 cm O.D. by 2.0 mm wall	Monel 400	-100+170 Mesh Monel 400 Powder	277°C	5,232 hours

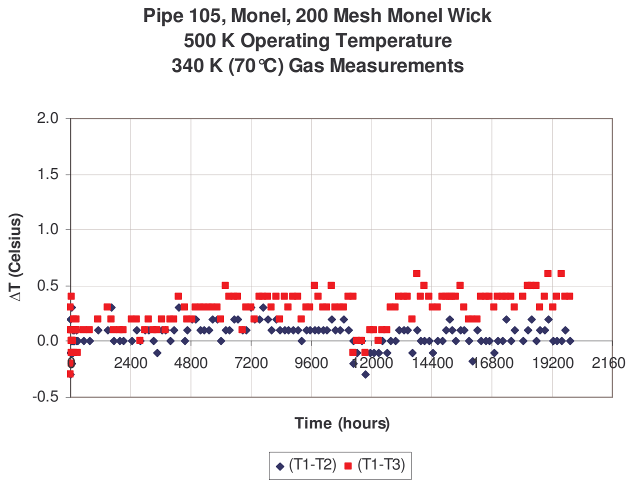


Figure 2. Low Temperature (Non-Condensable Gas) Measurements for Monel /Water Heat Pipe 105, Operating at 500 K.

Typical results are shown in Figures 2 and 3 for Monel and a titanium alloy, respectively. The Monel pipes have shown no signs of gas generation.

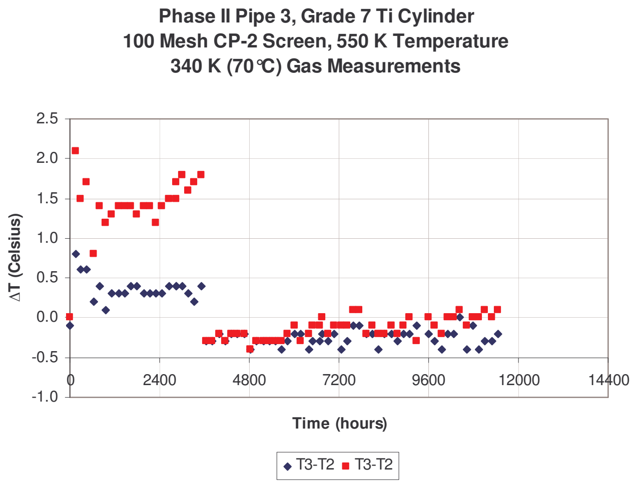


Figure 3. Low Temperature (Non-Condensable Gas) Measurements for Grade 7 Titanium Cylinder/CP-Titanium Screen/Water Heat Pipe 3, Operating at 550 K. Purged after 3509 hours of operation.

As shown in Figure 3, the titanium heat pipes all generated gas initially. This was believed to be a result of a passivation process that produced titanium oxide on the surface of the heat pipe. The gas was removed from all of these pipes by heating to about 115°C and venting them. The thermocouples are monitored to verify that the non-condensable gas has been forced out of the condenser by the pressure difference. The heat pipe fill tube is then resealed.

INTERMEDIATE TEMPERATURE WORKING FLUIDS

The heat pipe development work and life tests discussed above show that water working fluid in titanium or Monel heat pipes is an excellent device for cooling electronics at temperatures up to 280°C. As the temperature gets closer to the critical point of water (374°C), the vapor pressure becomes too high, and the surface tension too low, for water to be suitable as a working fluid. For very high temperatures (above roughly 425°C), cesium and other alkali metals can be used as the heat pipe working fluid.

Alternative working fluids are currently under investigation for the temperature range from 150 C to 450 C. In addition to high temperature electronics cooling, other heat pipe applications include spacecraft radiators, fuel cell thermal control, and waste heat recovery systems. Many other working fluids are available which have lower vapor pressure, including mercury, Dowtherm fluids, sulfur/iodine mixtures, Napthalene, Phenol, Toluene, and a variety of halide salts (Anderson et al., 2004, Deverakonda and Anderson, 2005).

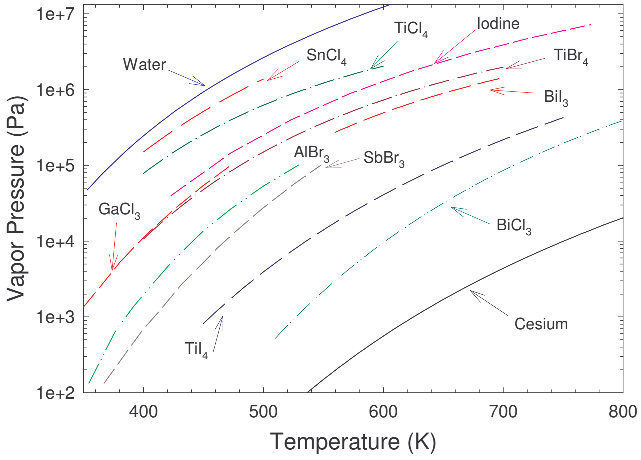


Figure 4. Vapor Pressures for some Halide Intermediate Temperature Fluids. Water and Cesium are shown for Reference.

Typical vapor pressures for several halides are shown in Figure 4. Virtually all of the fluids have a lower vapor pressure than water, and many of them are an order of magnitude lower. An attractive feature of the halides is that the chloride, bromide, and iodide generally cover a wide range of vapor pressure (see $TiCl_4$, $TiBr_4$, and TiI_4 in Figure 4).

For each of these fluids the merit number was also plotted to allow comparison of these materials with each other and with water. The merit number (liquid transport factor) is a means of ranking heat pipe fluids, with higher merit number more desirable:

$$M = \frac{\rho_L \sigma \lambda}{\mu_L} \tag{1}$$

Figure 5 compares the figure of merit of some of the replacement fluids with water. Water has a much higher Merit number than that other fluids, which is why it is used at temperatures up to 300°C. At higher temperature other fluids must be used. Cesium is shown for comparison only. It is suitable only for temperatures above about 450°C, since the sonic limit prevents it from carrying significant power at lower temperatures.

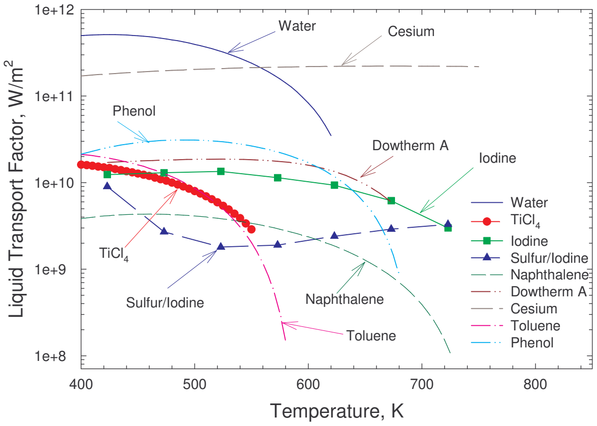


Figure 5. Merit Number as a function of temperature, potential heat pipe and LHP working fluids.

INTERMEDIATE TEMPERATURE LIFE TESTS

As discussed above, water is generally the fluid of choice at temperatures below about 280-300°C, due to its superior fluid properties. At higher temperatures, another fluid must be used. Table 2, based on data in Saaski and Hartl (1980), and Groll et al (1989, Heine et al., 1984) summarizes previous life tests with organic fluids at temperatures above 250°C.

As shown in Table 2, the organic fluids are not compatible at temperatures approaching 400°C, but only at lower temperatures. Because of this, we have concentrated on the halides. The halides are salts of metals such as titanium, aluminum, boron, antimony, tin, and silicon.

HALIDE COMPATIBILITY

Saaski and Owzarsky (1977) proposed an electrochemical method to predict the compatibility of halide working fluids with envelope materials. Tarau et al. (2007) found that this procedure had good agreement with previous life tests, and used it to select new working fluid/envelope combinations to test.

Table 2. Life Tests with Organic Fluids above 250°C, taken from Saaski and Hartl (1980), and Groll et al (1989, Heine et al., 1984).

	Aluminum	Mild Steel	Stainless/SuperAlloys	Titanium
Elements/Water				
Organic Fluids				
Naphthalene	6061 Al/27,750 hrs./215 °C (Saaski et al.)	ST 35 & 13CrMo44/~26,000 hrs./270 °C (Groll et al.)	316L SS/~9,000 hrs/320 °C (Groll et al.)	CP-Ti/~9,000 hrs/320 °C (Groll et al.)
Phenylbenzene		13CrMo44/~9,000 hrs/ Compatible at 250 °C, Not at 400 °C (Groll et al.)	316L SS/~9,000 hrs/ Compatible at 270 °C, Not at 400 °C (Groll et al.)	
Monochloronaphthalene	.	A178/Incomp./287 °C (Saaski et al.)		
O-Terphenyl	6061 Al/Incomp./307 °C (Saaski et al.)	A178/27,750/272 °C/ High NCG (Saaski et al.)		
ortho- and meta-terphenyl		13CrMo44/Incomp./~9,000 hrs/320 & 400 °C (Groll et al.)	316L SS/Incomp./~9,000 hrs/350 & 400 °C (Groll et al.)	
diphenyl, ortho- and meta-terphenyl		13CrMo44/Incomp./~9,000 hrs/350 & 400 °C (Groll et al.)	316L SS/Incomp./~9,000 hrs/350 & 400 °C (Groll et al.)	
Dowtherm A (diphenyl and diphenyl oxide)		ST 35/~40,000 hrs/ compatible at 270 °C, not at 300 °C (Groll et al.)	321 SS/~40,000 hrs/ compatible at 300 °C, not at 350 °C (Groll et al.)	CP-Ti/~9,000 hrs./ 270 °C (Groll et al.)

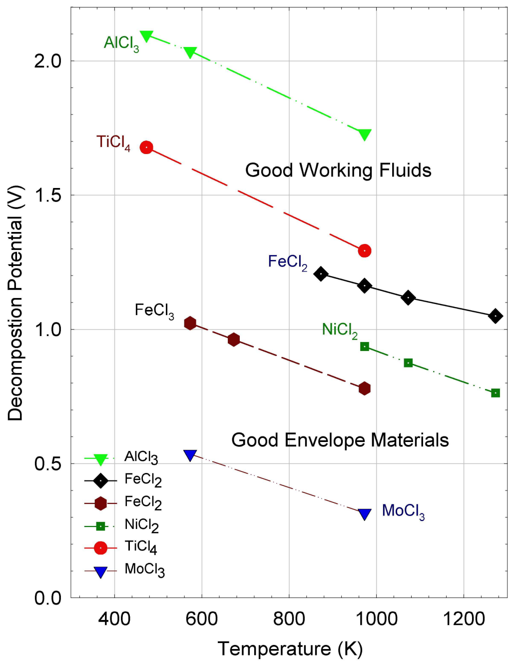


Figure 6. Good Working Fluids (From a Compatibility Standpoint) Have High Decomposition Potentials, While Halides/Salts of Good Envelope Materials Have Low Decomposition Potentials.

The procedure calculates the electromotive force difference of the reaction between the working fluid and envelope. The standard electromotive force difference or the potential difference, ΔE^0, is the difference between the decomposition potentials of the two halides, the metal envelope halide, M_aX_{cp} and the working fluid, M_bX_c:

$$\Delta E^o = E_{P\_M_aX_{cp}}(T) - E_{P\_M_bX_c}(T) \qquad (5)$$

The standard EMF difference, ΔE^0 is the decomposition potential of the envelope minus the decomposition potential of the fluid. *If the standard EMF difference, ΔE^0, is positive, then the reaction can proceed spontaneously and the wall will react chemically. When the standard EMF difference is negative, the probability of spontaneous reaction decreases significantly*. This gives the following working fluid/envelope material selection criterion: The envelope material halide should have a lower decomposition potential than the working fluid halide. This is shown in Figure 6. $AlCl_3$ and $TiCl_4$ have a high decomposition potential, so they are good working fluids. Molybdenum and iron have a low decomposition potential, so should be good envelope materials.

As shown in Table 3, Tarau et al. compared the theoretical predictions with existing halide life test data, and obtained very good agreement in all but two cases. For Titanium/$AlBr_3$, the theory predicts that the system was incompatible.

Table 3. Comparison of Halide Life Tests and Predictions.

Halide	6061 Aluminum	Mild Steel	304 SS Screen (Ni)	Titanium
$AlBr_3$	6061 Incomp./500 K [1] 5052 Failed/4,290 hrs./500 K[3]			No, Ti/Al compounds [1] (different mechanism)
	Partially Agree (attacked grains)			$AlCl_3$ is slightly unstable
$SbCl_3$	Incomp./500 K [2]	Incomp./5,000 hrs./476 K [2]	Incomp./5,000 hrs./476 K [2]	
	Agree	reacted with SS Wick	Agree	
$SbBr_3$				Incomp./5000 hours/500 K[3]
				Agree
$SnCl_4$	Incomp./432 K [2]	27,750 hrs./429 K [2]	27,750 hrs./429 K [2]	
	Agree	Agree	Agree	
$TiCl_4$	Incomp./438 K [2]	28,540 hrs./432 K [2]	28,540 hrs./432 K [2]	4,019 hrs./500 K[3]
	Agree	Agree	Agree	Agree

[1]Locci et al., 2005. [2]Saaski and Hartl, 1980. [3]Tarau et al., 2007

However, TiAl was formed during the tests, which was not predicted by the theory. The theory predicts that $AlBr_3$ should be compatible with pure aluminum. During the life tests, the $AlBr_3$ attacked the grain boundaries in the aluminum alloys; clearly the reactivity of alloying additions in commercial alloys requires closer consideration.

Envelope Material Selection

The electromotive force difference was used to select envelope materials for halide life tests. Potential envelope materials include aluminum, aluminum alloys, titanium, titanium alloys, carbon steel, stainless steels, and the superalloys. The dominant metallic components for these envelopes include Ti, Ni, Fe, Cr, Mo and Al. The following halides were examined: aluminum chloride, aluminum bromide, antimony chloride, antimony bromide, bismuth chloride, gallium chloride, lead chloride, magnesium chloride, tin dichloride, tin tetrachloride, zinc chloride and zirconium chloride.

The electromotive force differences are shown in Figure 7. Values above zero are unstable. The calculations used a temperature of 400°C (673 K), linearly interpolating the available data (The potential difference is only a weak function of temperature).

Aluminum is the least suitable envelope material for the halides, with the exception of Mg and Zr. From an EMF standpoint, the best envelope material would be molybdenum, followed by iron. All of the halides have strong negative potential differences with Mo and Fe, hence have a low probability of spontaneous reaction. The results for iron suggest that carbon steel is a relatively stable envelope material for almost all the halides. Nickel, which is a major component in stainless steels and superalloys, shows a moderate lack of stability with bismuth trichloride, antimony trichloride and tin tetrachloride. However, it might be stable with the other halides including tin dichloride. Titanium has a higher tendency for corrosion, especially in the presence of antimony tribromide, bismuth trichloride, antimony trichloride and tin tetrachloride.

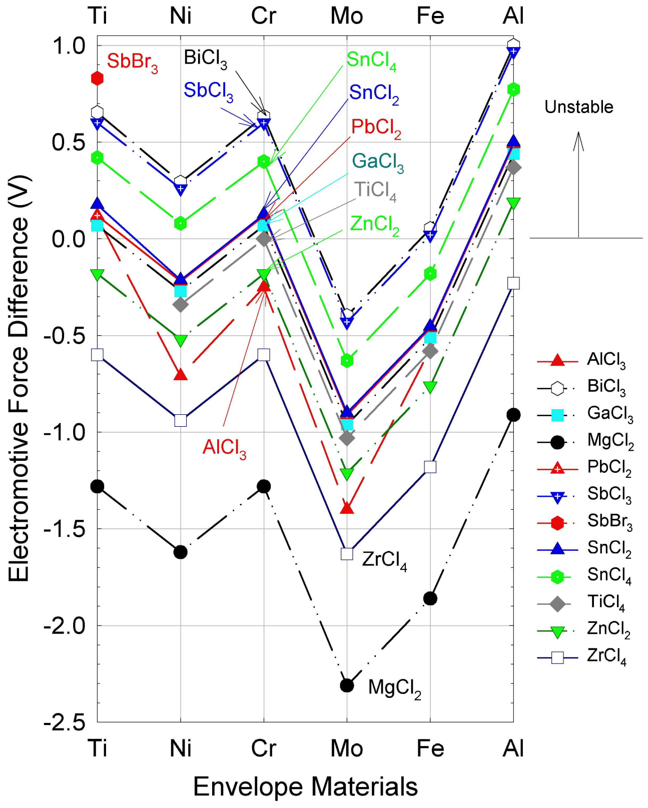
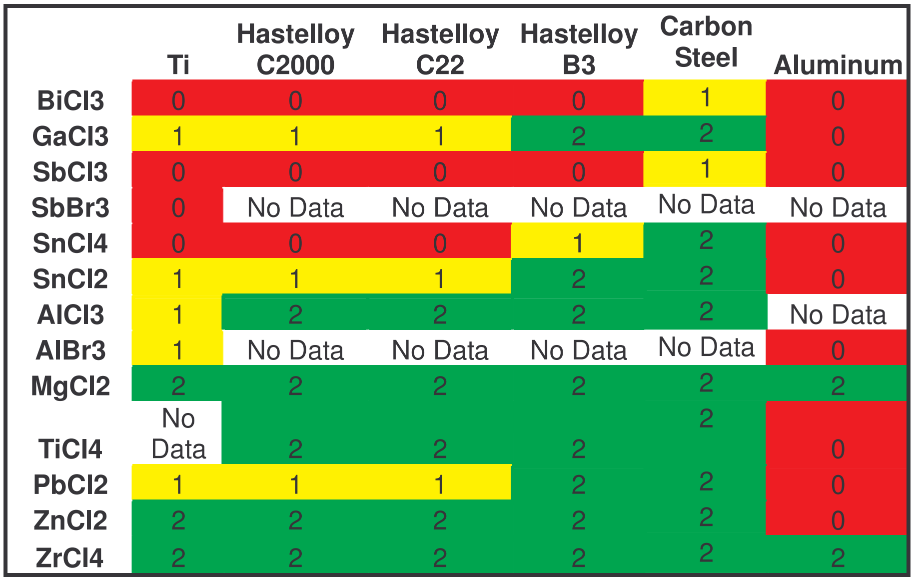


Figure 7. Electromotive Force Difference for Potential Halide/ Envelope Material Reactions.

Table 4. **Estimated Envelope/Halide Compatibility.**



	Ti	Hastelloy C2000	Hastelloy C22	Hastelloy B3	Carbon Steel	Aluminum
BiCl3	0	0	0	0	1	0
GaCl3	1	1	1	2	2	0
SbCl3	0	0	0	0	1	0
SbBr3	0	No Data	No Data	No Data	No Data	No Data
SnCl4	0	0	0	1	2	0
SnCl2	1	1	1	2	2	0
AlCl3	1	2	2	2	2	No Data
AlBr3	1	No Data	No Data	No Data	No Data	0
MgCl2	2	2	2	2	2	2
TiCl4	No Data	2	2	2	2	0
PbCl2	1	1	1	2	2	0
ZnCl2	2	2	2	2	2	0
ZrCl4	2	2	2	2	2	2

Table 5. Initial Halide Life Test Results**.**

		$AlBr_3$	$SnCl_4$	$TiCl_4$	$TiBr_4$
CP-Ti	ΔT	–	–	–	4.2 K
	Temperature	–	–	–	380 °C (653K)
C22	ΔT	0.9 K	11.2 K	7.4 K	–
	Temperature	400 °C (673K)	280 °C (553K)	300 °C (573K)	–
C2000	ΔT	2.0 K	11.2 K	1.6 K	–
	Temperature	400 °C (673K)	280 °C (553K)	300 °C (573K)	–
B3	ΔT	3.7 K	14.1 K	53.2 K*	–
	Temperature	400 °C (673K)	280 °C (553K)	300 °C (573K)	–

Halide Life Tests

The data in Figure 7 was used to estimate the compatibility of halides with six different potential envelope materials, see Table 4 (0 is least compatible, and 2 is most compatible). Aluminum and titanium were examined because they are lightweight, and steel was considered because iron appears to be very compatible, see Figure 7.

Ivan Locci (2006) identified the following Hastelloy superalloys materials as possible heat pipe wall materials: B-3 (Ni-Mo), C-2000 (Ni-Cr-Mo), and C-22 (Ni-Cr-Mo-W). The selection criteria was (Locci, 2006): “The procurement of the 3 superalloys was initially based on the great general corrosion behavior to acids or excellent stress corrosion cracking and pitting resistance reported on the alloys. [The three alloys can be used to] investigate the influence of ternary additions, e.g. the effect of Mo, Cr, or W to the heat pipe environment. Weldability was another critical factor that was considered, and in general the interest of using superalloys is the much higher specific strength to compete against Ti- or Al-alloys (e.g. reduced wall thickness -> comparable density).”

From Table 4, the four halides that are believed to be most compatible with the superalloys were $AlBr_3$, $SnCl_4$, and $TiCl_4$. Heat pipes were fabricated with the three superalloys and the three halides, see Table 5. $TiBr_4$ is also believed to be compatible, based on its chemical similarity to $TiCl_4$. However, it is significantly more expensive, so it will be examined with superalloys only if $TiCl_4$ is compatible.

Tarau et al. (2007) have already shown that $TiCl_4$ is compatible with titanium, so $TiBr_4$ was put on test in a titanium envelope. Preliminary results for the halide life tests are shown in Table 5. The $AlBr_3$, $TiCl_4$, and $TiBr_4$ appear to be compatible, while the $SnCl_4$ is showing signs of gas generation.

CONCLUSIONS

Two alternatives to copper/water have been presented. The first, using water with high strength wall materials, gives the high performance of water at temperatures up to 300°C. Indications of maturity were presented, including life test data, the existence of suitable wick structure, and the ability to fabricate heat pipes and predict their performance accurately. Titanium/water and Monel/water heat pipes can be considered a mature or mainstream technology that is ready for widespread application. The second alternative presented was replacement working fluids. These offer good thermal performance but at much lower vapor pressures and offer the potential of using low-mass wall materials such as aluminum or thin stainless steel. This alternative is less mature, however, and will require additional work to fully characterize the thermodynamic properties of some of the working fluids and to identify envelopes with long-term compatibility. Either of the two alternatives can offer a solution for cooling high-temperature electronics, or those working at or above 150°C.

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