METEOROID PROTECTION METHODS
FOR SPACECRAFT RADIATORS
USING HEAT PIPES

FINAL REPORT
CONTRACT

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ABSTRACT

The work performed under JPL Contract 955437 was for a preliminary survey program to examine the various aspects of achieving a low mass heat pipe radiator for the NEP spacecraft. Specific emphasis was placed on a concept applicable to a closed Brayton cycle power sub-system.

Three aspects of inter-related problems were examined: the armor for meteoroid protection, emissivity of the radiator surface, and the heat pipe itself.

The study revealed several alternatives for the achievement of the stated goal, but a final recommendation for the best design requires further investigation.
NEW TECHNOLOGY

The following item of new technology was generated under the contract:

1. Segmented Heat Pipe Bumper for Protection Against Meteoroid Collisions - Donald M. Ernst
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SUMMARY AND CONCLUSIONS

This study program examined various aspects of achieving a low mass heat pipe radiator for the NEP spacecraft, with emphasis on a version using a Closed Brayton Cycle power sub-system. The mass of the radiator is a complex function of several variables. Thus three separate items were evaluated: the meteoroid armor, the emissivity of the surface and the heat pipe itself.

These three factors are inter-independent. However, they were analyzed separately in this preliminary survey program. A fully integrated analysis of a low mass heat pipe radiator would require considerably more effort than was permissible under the scope of this program.

The following conclusions can be drawn:
1. Small diameter pipes with the same wall thickness as larger diameter pipes will show a decreased penetration depth for a given meteoroid.
2. Interfaces between armor and underlying heat pipes are beneficial.
3. The armor must look homogeneous to the meteoroid. Taken in conjunction with the high total emissivity requirement of the surface, this consideration rules out the use of powder metallurgy armor.
4. Chevron fin armor is at this time impossible to evaluate completely. However, based on the comments of Southwest Research Institute it should be pursued further.
5. Segmented heat pipes used as bumpers on top of the radiator heat pipes look quite attractive and need additional evaluation.
6. A total emissivity in excess of 0.9 can be obtained by the use of geometrically produced effects in fins.
7. The mass of the CBC heat pipe without protection can be substantially reduced by going to small diameter heat pipes.

Finally one concludes that this study has just scratched the surface of the many possibilities for low mass radiators, and that there is ample and urgent reason for additional work on the design and evaluation of the various alternatives.
1. **METEOROID PROTECTION**

The Nuclear Electric Propulsion Spacecraft being considered for use in exploration and intensive study of the outer planets and the surrounds of the solar system will be subjected to the hazards of meteoroids during its journey through space. Accordingly, the spacecraft design must include some type of armor which will protect the vulnerable areas from catastrophic failure upon impact by these meteoroids.

Armor design is crucial to the success of a mission. Without it, missions could not be made. However, in order to achieve a high overall probability of mission success, the armor may be so massive that the system is no longer viable. Thus low mass armor is highly desirable.

In the 400kWe NEP designs currently being looked at, the total specific mass of the power sub-system is targeted at 27 kg/kWe, of which up to 35% (7 kg/kWe) may be necessary to achieve the required degree of protection from meteoroid impact. Accordingly, a reduction in the mass of the armor could be instrumental in the power sub-system achieving its targeted specific mass.

In the power sub-system, the majority of the armor which is required is for the protection of the power conversion heat rejection system which generally employs a matrix of heat pipes. These heat pipes may use a single element radiator for each conversion device; they may be a matrix of interconnecting heat pipes where several main heat pipes accept heat from many conversion devices for distribution to the radiator heat pipes, or the radiator heat pipes may be fed from a gas or liquid metal pumped loop. Whatever the design, the armor
must be an integral part of the radiator elements which means that it must not act as radiation shield.

To arbitrarily design armor is not possible. In addition to its being integral to the radiator elements, armor design (and therefore mass) is a complex function of the overall system design. This is seen when essential criteria are established beginning with the mission which defines the flight time and path from which a meteoroid flux model can be generated. Additionally, an overall mission success probability must be defined from which sub-system and component probabilities are generated. These component probabilities are themselves a function of unrelated probabilities based on mechanical, thermal, electrical or meteoroid inflicted degradation or failure.

Armor is required to protect sensitive components from meteoroid puncture. Protection from meteoroids is a function of mission time, meteoroid flux, vulnerable area of the smallest component to be protected, the required probability of survival of that component which in turn is a function of the total number of components and the probability of survival of the collection of components. Therefore it becomes obvious that armor design is of primary importance to mission success.

Accordingly, in order to evaluate low mass armor, certain assumptions must be made in order to establish a base line design. For this purpose the CBC base line radiator heat pipe will be used. Section 3 establishes this base line as well as exploring other possible heat pipe designs.

This section looks at the basic phenomena of hypervelocity impact and four different types of meteoroid armor: solid metal, powder metallurgy, chevron fins, and heat pipes used as bumpers.
The initial basis for this study lay in concepts generated under JPL Contract 955100 (powder metallurgy and chevron fin armor). The intent was to evaluate the effectiveness of these armor designs. However, as information was received from new sources, it became apparent that additional theoretical and experimental work must be carried out to fully evaluate them.

Specifically, this study showed that powder metallurgy material, with its relatively low emissivity, is not well suited to the dual role of armor and radiating surface. Solid armor, with an interface between armor and heat pipe, may prove to be lower mass than originally though and is considerably less complex. The chevron fin armor showed promise but needs considerable additional investigation.

One new concept which was developed and showed several advantages as low mass armor is the idea of segmented heat pipes acting as bumpers to protect the underlying radiator heat pipe. This concept evolved late in the study and was not fully evaluated.

1.1 Hypervelocity Impact Phenomena

In examining hypervelocity impact, various books and reports were reviewed along with discussion with eminent professionals in the field. These pointed out the marked differences in single plate armor, a thin shield protecting a backup plate, multiple shields, as well as the effects of velocity, mass and density of the meteoroid, and the effects of various materials.

Hickerson, in Kinslow's book, states "The hypervelocity impact of a projectile with a solid target results in an extremely complex phenomenon. A complete description of this behavior would involve
consideration of all phases of continuum mechanics theory. In the initial high pressure phases of the impact, the material behaves essentially as an inviscid, compressible fluid since the pressures are high with respect to the maximum shear stresses that can be developed within the material. A crater forms which expands rapidly for a time, and a shock wave emanates from its surface. A scage of plastic deformation follows which apparently decays rapidly into a spherical elastic wave which continues through the target. A complete theory for the description of the hypervelocity impact phenomena would involve not only the above phases but also other situations such as melting and resolidification, vaporization and condensation, and the kinetics of phase change."

Accordingly, the evaluation of low density armor will be carried out by first looking at the mass of solid armor capable of protecting the CBC radiator followed by a narrative on several low density armors as best evaluated by the information available.

1.2 Solid Armor

The JPL supplied penetration equation for the NEP missions is

\[ t = 0.0010144 \left( \frac{AT}{-1nP} \right)^{0.2902} \]  

Eq. 1.1

t = Required armor thickness in cm to prevent penetration of the armor by the average meteoroid
K = Materials factor - given as 1 for Lockalloy
A = Component vulnerable area - cm²
T = Mission time in hours
P = Individual component survival probability
The equation predicts the required armor thickness to prevent penetration of Lockalloy at room temperature by the expected average meteoroid to be encountered during the NEP mission. In order to evaluate other armor material at elevated temperatures, additional information is required.

Examination of the various equations which have been theoretically and experimentally developed reveals much similarity in the basic equation. Accordingly, Equation 1.1 can be rewritten in terms of the armor properties as:

\[
t = \gamma_0 a(xa)^{-2/3} (v_s)^{-2/3} \left[ \frac{T_a}{T_o} \right]^{1/6} K_1 \left[ - \frac{A_f}{\alpha n P} \right] 0.2902 \]

Eq. 1.2

Where

- \( \gamma_0 \) = room temperature cratering coefficient
- \( a \) = rear surface damage factor
- \( xa \) = density of armor = g/m\(^3\)
- \( v_s \) = velocity of sound in armor = cm/sec
- \( Ta \) = temperature of armor \( ^o\)K
- \( To \) = room temperature \( ^o\)K
- \( K_1 \) = meteoroid flux constant

The cratering coefficient, \( \gamma_f \), and the rear surface damage factor, \( A \), vary for different materials as seen in Table 1.1. The three modes of damage by meteoroid impact are defined as follows:

1. Dimple – The impacted surface is physically dented but the integrity of the rear surface is not disrupted.

2. Spall – The impacted surface may be partially penetrated and spallation may occur from the rear surface; however, the complete thickness of the material is not perforated.

3. Perforation – The complete thickness of the impacted material is physically perforated.

The absence of a rear surface damage factor for Lockalloy makes it difficult to compare to other armor materials. However, since the rear surface factors for the listed materials are similar except for Nb-1% Zr, and the fact that Lockalloy is 38% aluminum, the
aluminum factor will be used for Lockalloy.

From Equation 1.2 and Table 1.1, the materials factor $K$ in
Equation 1.1 can be calculated. Several values are seen in Table 1.2.
The value of 0.67 for 316SS is higher than the 0.53 value as suggested
by JPL. This discrepancy should be resolved in order to be able to
fully evaluate SS as a possible armor.

Depending on the final design of the radiator heat pipes it
is difficult to estimate whether dimpling or spallation will render
the heat pipe inoperable. Thus, it was decided to use the perforation
rear surface factor in order to evaluate the mass of the armor.
Table 1.3 shows the perforation factor for the selected material at
temperatures of interest for the MNP radiator.

Since Lockalloy and aluminum can not be used throughout the entire
temperature range over which the CBC radiator must operate and are
definitely not suitable for use in conjunction with the thermionic
system, only the higher temperature materials will be evaluated and
only at $700^\circ K$, the upper end of the CBC radiator temperature.

In discussing the required armor thickness, the thickness of
the heat pipe wall must also be taken into consideration, as must
the diameter of the heat pipe which defines the vulnerable area,
and whether there are fins which can be utilized as armor. In order
to reduce the number of variables so that the effects of the armor
design could be evaluated, a base line heat pipe was established as
seen in Table 1.4.
Table 1.1
CRATERING COEFFICIENT AND REAR SURFACE DAMAGE FACTOR
FOR SELECTED MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Cratering Coefficient</th>
<th>Rear Surface Damage Factor &quot;a&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Y_r$</td>
<td>Dimple</td>
</tr>
<tr>
<td>2024 Al</td>
<td>1.07</td>
<td>2.5</td>
</tr>
<tr>
<td>Lockalloy</td>
<td>2.06</td>
<td>-</td>
</tr>
<tr>
<td>316 SS</td>
<td>2.19</td>
<td>2.4</td>
</tr>
<tr>
<td>A-286</td>
<td>1.77</td>
<td>2.4</td>
</tr>
<tr>
<td>Nb-1% Pr</td>
<td>1.81</td>
<td>4.5</td>
</tr>
</tbody>
</table>

*Estimated Value

Table 1.2
MATERIALS FACTOR K FOR SELECTED MATERIALS
AT ROOM TEMPERATURE

<table>
<thead>
<tr>
<th>Material</th>
<th>Dimple</th>
<th>Spall</th>
<th>Perforation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024 Al</td>
<td>1.68</td>
<td>1.54</td>
<td>1.14</td>
</tr>
<tr>
<td>Lockalloy</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>316 SS</td>
<td>1.15</td>
<td>0.91</td>
<td>0.67</td>
</tr>
<tr>
<td>A-286</td>
<td>0.93</td>
<td>0.73</td>
<td>0.54</td>
</tr>
<tr>
<td>Nb-1% Pr</td>
<td>2.22</td>
<td>1.98</td>
<td>0.84</td>
</tr>
</tbody>
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Table 1.3
MATERIALS FACTOR K FOR PERFORATION OF SELECTED
MATERIALS AND TEMPERATURES

<table>
<thead>
<tr>
<th>Material</th>
<th>300°C</th>
<th>500°C</th>
<th>700°C</th>
<th>900°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024 Al</td>
<td>1.14</td>
<td>1.24</td>
<td>1.31</td>
<td>1.37</td>
</tr>
<tr>
<td>Lockalloy</td>
<td>1.00</td>
<td>1.09</td>
<td>1.15</td>
<td>1.20</td>
</tr>
<tr>
<td>316 SS</td>
<td>0.67</td>
<td>0.73</td>
<td>0.77</td>
<td>0.80</td>
</tr>
<tr>
<td>A-286</td>
<td>0.54</td>
<td>0.59</td>
<td>0.62</td>
<td>0.65</td>
</tr>
<tr>
<td>Nb-1% Zr</td>
<td>0.84</td>
<td>0.91</td>
<td>0.87</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 1.4
BASE LINE HEAT PIPE

O.D. - 2.54 (1"
Wall - 0.0254 cm (0.01"
Length - 262 cm (103"
Vulnerable area - 665 cm² (103 in²)
Mass of SS heat pipe - 1.75 kg
Based on a mission time of 87,600 hours and a no-puncture probability of 0.9 for each heat pipe, the required armor thickness and mass for the selected materials at 700°K is seen in Table 1.5.

Table 1.5
REQUIRED ARMOR THICKNESS AND MASS @ 700°K

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>316 SS</td>
<td>0.27 cm</td>
<td>2.26 kg</td>
</tr>
<tr>
<td>A-286</td>
<td>0.22 cm</td>
<td>1.83 kg</td>
</tr>
<tr>
<td>Nb-1% Zr</td>
<td>0.34 cm</td>
<td>3.05 kg</td>
</tr>
</tbody>
</table>

The mass of the armor was taken to be:

\[ M_a = \frac{2 \pi D t \rho_a}{2} \]

Eq. 1.3

When solid armor is employed, there can be some advantage to having an interface between the armor and heat pipe. Ballistic tests
of stainless tubes in aluminum armor show marked improvement over single aluminum tubes. That is, in general, the integrity of the inner tube was not lost nor did spalling of the inner tube take place, even when the inner tube was completely closed. The rear surface thickness factor was found to decrease as a function of H/D. H is the inner tube dimple height and D is the tube diameter. Specific values are seen in Table 1.6.

Table 1.6

REAR SURFACE DAMAGE FACTOR A FOR ALUMINUM OVER STAINLESS STEEL FOR VARIOUS RATIO OF DIMPLE HEIGHT TO TUBE DIAMETER

<table>
<thead>
<tr>
<th>A</th>
<th>H/D</th>
</tr>
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<tbody>
<tr>
<td>2.5</td>
<td>0.0 (No Dimple)</td>
</tr>
<tr>
<td>2.0</td>
<td>0.13</td>
</tr>
<tr>
<td>1.7</td>
<td>0.22</td>
</tr>
<tr>
<td>1.5</td>
<td>0.32</td>
</tr>
<tr>
<td>1.4</td>
<td>0.34</td>
</tr>
<tr>
<td>1.0</td>
<td>0.60</td>
</tr>
<tr>
<td>0.9</td>
<td>0.75</td>
</tr>
<tr>
<td>0.8</td>
<td>1.0 (Inner Tube Closed)</td>
</tr>
</tbody>
</table>

By comparing the "A" factor for aluminum in Table 1 and 6, it is interesting to note that for an H/D of 0.22 or greater, the rear surface damage factor is less than that required to prevent
perforation. If this same relationship holds for stainless on stainless, then the armor thickness required could possibly be reduced below that given in Table 1.5. However, the effects of the dimple on heat pipe operation would have to be taken into consideration.

A dimpled heat pipe can be affected in two ways. First, the liquid flow path could be interrupted or blocked. Second, the vapor flow path could be partially or totally blocked. However, since the armor thicknesses of Table 5 were based on the penetration rear surface damage factor, the heat pipes would have suffered some dimpling and spallation damage by those meteoroids which did not cause penetration. Thus the use of armor over a liner will have a definite advantage over a solid tube. However, this does imply that the armor thickness stands alone, i.e. the thickness of the heat pipe can not be used to reduce the armor thickness.

In order to make use of this interface effect, the validity of it with the materials of construction would have to be proven by tests, as well as establishing what effect a dimple in the heat pipe wall has on the heat pipe’s performance. The reduction in heat pipe performance with dimples has to be considered anyway unless the armor is increased in thickness to prevent dimpling.

1.3 Low Mass Armor

Two types of low mass armor were investigated. They are powder metallurgy foam metal and a collection of thin plates. The investigation or evaluation of these armor types raised as many questions as were answered, which leads to the conclusion that additional work needs to be done in this area.
1.3.1 Powder Metallurgy Armor

In order to have a low mass armor either the real density or apparent density of the armor must be reduced. Materials of low density such as aluminum, beryllium, and Nickel are not useful at the higher temperatures of interest and they also present a bonding problem to a stainless heat pipe. Thus one look at low apparent density materials such as powder metallurgy foam metal.

From Equation 1.2, it is seen that the required armor thickness is proportional to the reciprocal of the square root of the density of the armor. Since mass is equal to the thickness times the density, the armor mass is proportional to the square root of the density. Thus 25% dense armor will be twice as thick and have 50% of the mass of solid armor. On the surface, this appears to be a good method by which to reduce the mass of the armor. However, for this method to be viable, the other physical properties of the armor cannot change with the apparent density. Also, the armor must appear to be a "solid" to the impinging meteoroids. That is, the diameter of the meteoroids must be at least 10 times the diameter of the particles making up the armor.

For a 50% dense armor made from $2 \times 10^{-3}$ cm particles, the meteoroid must be at least $2 \times 10^{-2}$ cm in diameter for the armor to behave as though it were solid. A particle of $2 \times 10^{-2}$ cm diameter with a 0.5 gm/cc density will have a mass of $2.09 \times 10^{-6}$ gm. JPL considers only those meteoroids with a mass in excess of $10^{-6}$ gm as being of concern to the radiator heat pipes. Therefore, if 50% dense armor is to be used it must be made with $2 \times 10^{-3}$ cm or less diameter particles.

For densities less than 50%, non-spherical particles must be used to make up the armor, and the meteoroid size which will see the
armor as being solid will increase accordingly.

The reduction in mass of armor by the use of porous material is based on the other physical properties of the armor being invariant of the density, which is not the case. For instance, the velocity of sound is equal to the square root of the modulus of elasticity divided by the density. The actual velocity of sound of the individual particles will remain the same. However, since the effective path length will be a tortuous one, and increases with decreasing density, the effective velocity of sound should be lower. Thus the required armor thickness and mass will increase as the sonic velocity decreases with decreasing density.

One physical property which definitely changes with the apparent density is the thermal conductivity. A high thermal conductivity is necessary for the armor so that the ΔT through it is low, thus keeping the radiating surface temperature as high as possible. At first one might think that the thermal conductivity is inversely proportional to the apparent density. However, for perfectly square packed spheres of the same diameter the theoretical packing density is 52% and the spheres are tangent to each other. Thus the thermal conductivity can not be 52% of the solid material since the particles only have point contact.

A theoretical treatment of the thermal conductivity of porous material should be carried out in a manner similar to that by which the permeability of porous material has been determined. This model should also take radiation into account, and be followed by experimental determination of the thermal conductivity of various porous materials.
As part of the determination of the effective emissivity of porous material (covered in Section 2) several tests were performed from which an effective thermal conductivity of 50% dense nickel at 1100°K was calculated to be about 15% of that of solid nickel. These tests were not designed to measure thermal conductivity. Therefore, the accuracy is at best 25% but it does indicate that indeed the thermal conductivity of porous metal is considerably less than the apparent density times the thermal conductivity of the base metal. Based on this marked reduction in the thermal conductivity of porous metal, its use as a low mass armor may be limited. The combined effect of reduced thermal conductivity and increased armor thickness for porous armor may increase the ΔT through the armor by an order of magnitude. At 700°K the ΔT through solid SS armor is 2.2°K, thus the ΔT through porous armor may be as high as 22°K, which at 700°K would require an increase in radiating surface area of 13.6% in order to dissipate the same amount of heat as compared to a 1.3% increase for the solid armor. Table 1.7 compares the mass of a 700°K SS heat pipe with solid armor and 50% dense porous armor. The armor mass is assumed to be proportional to the square root of the apparent density (optimistic) and the thermal conductivity is 10% of the base material.

From Table 1.7, it appears that the 50% dense armor will have an overall lower mass than solid armor if the assumption about the porous armor material is correct. Further reduction in mass may be possible by going to 25% dense material. However, the effective thermal conductivity will probably decrease by another order of magnitude and the armor will start to look less like a solid surface to the impinging meteoroids.
Additionally, if the interface effect can be utilized, as discussed in 1.2, than the solid armor may be reduced in thickness such that its mass becomes comparable to that of the 50% dense armor.

Table 1.7

MASS COMPARISON

SOLID ARMOR VS. 50% DENSE ARMOR

<table>
<thead>
<tr>
<th>Solid Armor</th>
<th>50% Dense Armor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Pipe</td>
<td>1.75 kg</td>
</tr>
<tr>
<td>Solid Armor</td>
<td>2.26 kg</td>
</tr>
<tr>
<td>Total</td>
<td>4.01 kg</td>
</tr>
<tr>
<td>1.3% increase in</td>
<td>13.6% increase in</td>
</tr>
<tr>
<td>mass due to 220K</td>
<td>mass due to 220K</td>
</tr>
<tr>
<td>armor ( \Delta T )</td>
<td>armor ( \Delta T )</td>
</tr>
<tr>
<td>Total mass</td>
<td>4.06 kg</td>
</tr>
<tr>
<td></td>
<td>Total mass</td>
</tr>
<tr>
<td></td>
<td>3.81 kg</td>
</tr>
</tbody>
</table>

1.3.2 Thin Plate Armor

The evaluation of armor to this point has only considered stopping the meteoroid from puncturing the heat pipe wall with the use of solid or porous armor. This section will look at the use of single or multiple thin sheets as a possible means of achieving low mass armor.

Most of the thin shield work has been aimed at the concept of bumpers protecting an underlying armor. In this concept, the impinging meteoroids strike the thin shield causing the meteoroid to break up and spread radially over a large area such that the
force per unit area which is observed at the underlying armor is substantially reduced. This type of armor has from 35 to 50% of the mass of solid armor. The shield is approximately 10% as thick as solid armor and placed at least five solid armor thickness away from the underlying armor, which is from 25 to 40% of the thickness of solid armor. Thus the total thickness of a bumper and underlying armor is at least six times that of the solid armor and has 50% of the mass of the solid armor. Bumpers are not attractive for radiator service because they will act as radiation shields. However, in examining thin shields several interesting things were brought to light which were instrumental in arriving at the chevron armor design.

Gehring, in Kinlow's book, states for thin shields "the damage mechanisms to be considered are the breakup and dispersion of the projectile and shield debris at high velocities and the gross deformation, tensile failure, and spallation of the rear sheet."

"Upon striking a thin sheet, a particle or projectile may undergo a variety of processes depending upon impact conditions such as the particle velocity, the particle material and composition, the angle of impact, the material strength, and the thickness of the thin sheet. (A thin sheet as used herein will be defined as a sheet whose thickness is equal to or less than the diameter of the projectile). The particle may be stopped by the sheet, may pass through the sheet essentially undamaged, or may pass through the sheet fractured, molten, or vaporized. The last two cases are the cause of interest for meteoroid impacts as the velocities are sufficiently high to cause melting or vaporization."
"If the thin sheet is penetrated, the debris from the projectile and the shield then travel across the space between the sheets and strike a second sheet. Upon striking the second sheet a shock wave is generated within, and traverses, the second sheet. Depending upon the intensity and the structure of this shock an internal fracture or spall may form, resulting in some cases in complete detachment of some material from the surface of the sheet."

"In addition the second sheet will be given an impulsive load by the impact of the particle-shield debris. This load is applied over a very short period of time (a few microseconds) and results in a second sheet moving with some velocity. The sheet can then fail from this load by tensile failure or shear failure."

"The whole process of fracture of a projectile and a thin shield can be interpreted as a multiple spalling phenomenon that starts at the free surfaces. Hence, the significance of a shield is that it can fragment the projectile, spread the fragments radially and significantly reduce the velocity of many of the fragments below the velocity of the original projectile."

Summarizing, the following can be said about thin shield protecting backup plates.

1. For a shield to be effective, it must break up the particle into small pieces or cause melting to insure that no significant penetration of the second sheet will occur.

2. As the shield thickness is increased, the debris is spread out more.

3. The thickness of the backup shield to prevent failure is proportional to the mass of the projectile for high projectile velocity which assures that the projectile is sufficiently broken up and/or
vaporized.

4. The thickness of the backup shield to prevent failure is proportional to the projectile diameter for low velocity impacts.

5. The lower the melting temperature of the shield material, the lower the velocity of the meteoroid required to cause complete fragmentation of the particle and vaporization of the shield material. (\( \sim 6 \text{ km/sec for aluminum} \))

6. Based on thin shields and backup targets, the thickness of a shield to prevent fracture of the back plate for aluminum particles at 30° km/sec is:

\[
 t_t = \frac{M_p}{0.045} \left( \frac{5.08}{S} \right)^2 \left[ \frac{0.0102 + 0.079}{(t_s/D)^2} \right] \quad \text{Eq. 1.4}
\]

- \( t_t \) = Backup target thickness = cm
- \( M_p \) = Mass of projectile - gram
- \( S \) = Shield to target spacing - cm
- \( t_s \) = Thickness of shield - cm
- \( D \) = Particle diameter - cm

This equation is valid for:

\[ S \geq 8D \text{ and } 0.1 \leq t_s/D \leq 1 \]

To use this equation with projectiles of materials other than aluminum, the \( t_s/D \) ratio must be computed on an equivalent mass of aluminum.
particle, i.e. \( D = D \left( \frac{r_p}{t_{al}} \right)^{1/3} \)

7. The \( t_{al}/D \) ratio should be as large as possible.

8. The inter-sheet spacing should be as large as possible.

9. The shield thickness scales with the projectile diameter.

10. The thickness of a single sheet armor scales with the projectile diameter.

11. All things taken into consideration, two sheets are better than one on an equal mass basis because any high velocity impact upon a shield results in the spread of the projectile-shield debris, the loss of energy and at most a slight increase in momentum per unit area are less.

12. Experiments with aluminum-aluminum and cadmium-cadmium impacts, supported the theoretical conclusion that two sheets provide more protection than a greater number sheets. These tests were at 7.4 km/sec for the aluminum and 6.4 km/sec for the cadmium.

13. Experimental results for an aluminum-aluminum system showed that if the back up shield could survive an impact of 10 km/sec, which causes the shield-projectile debris to be molten and/or vaporized, the same size shields could resist failure for all low velocity impacts. For aluminum below 7 km/sec the debris still contains fragments which inflict severe damage on the second sheet. In fact, the damage at 2.5 km/sec is the same as at 20 km/sec.

However, since the average velocity of meteoroids is 20 km/sec the low velocity impact damage will not be critical.

14. The above statements about thin shields are for impacts which are normal to the shield. This is not the case with meteoroids. They will hit at all angles. The tests which have been carried out with...
aluminum – aluminum impacts and cadmium – aluminum impacts show that as the angle from the normal is increased the particle-debris becomes more fragmentary and less molten or vaporized thus having the tendency to increase the damage inflicted on the rear sheet. However, the conclusion is that if a two-sheet structure can resist a low-velocity normal impact it can resist the fragment damage due to an oblique impact.

The significance of oblique impacts is in the fact that the shield debris comes off normal to the shield, while the particle debris appears to be spread in the angle between the direction of initial flight and the normal of the shield. It is this concentration of the particle debris that inflicts fragment damage to the second sheet. However, the important thing is that the integrated center of the debris emanating from the back side of the shield has experienced a shift in the direction of motion towards the normal to the shield. It is this change in direction which may be the key to low density chevron armor.

15. The optimum shield thickness to projectile diameter ratio is \( t_s/D = 0.15 \) and the total thickness of the shield and back up plate divided by the particle diameter is between 1 and 1.5. i.e.

\[
1 \leq (t_s + t_h)/D \leq 1.5
\]

These are the optimum values to prevent failure for high velocity oblique impact and low velocity normal impact.

16. For aluminum – aluminum impacts at 7.4 km/sec with a 5.08 cm spacing the following equation hold for non-optimum shields.
\[
\frac{t_s + t_b}{D} = 4 \frac{t_s}{D} + 1 \quad 5 \geq \frac{t_s}{D} \geq 0.15
\]

Eq. 1.5

\[
\frac{t_s + t_b}{D} = 5 - 25.7 \frac{t_s}{D} \quad \frac{t_b}{D} \leq 0.15
\]

17. The depth of penetration of glass spheres into aluminum tubes, where the tube wall was held constant at 4.75 times the diameter of the projectile, decreased as the tube diameter decreased. The decrease in penetration as compared to that of an infinite diameter tube (flat plate) was 21.5% for a 2" ID, 32.7% for a 0.5" OD, and 41.7% for a 0.125" ID.

As can be seen from the above summary the amount of information directly applicable to the protection of the NEP radiator is limited, thus any conclusions which are drawn should be further examined by a more comprehensive review of the literature, discussion with current workers in the field and experimental verification of the design.

Having summarized the pertinent work in the field of thin shield protection, what can be said for protection of the NEP radiator? First, as mentioned earlier, the concept of the bumper can not be employed due to the radiation shielding effect. However, the use of multiple thin shields in a configuration shown in Section 2 to have a high intrinsic emissivity, may have some merit. For ease of analysis the shield was assumed to be protecting a flat plate rather than a tube and is seen in Figure 1.1. It is hard to say whether or not protecting a flat surface will be less massive than a curved surface.
Thin Chevron-Shaped Meteoroid Shielding Forming Black Body Radiation Surface

Flat Plate to be Protected from Meteoroid Collisions

Figure 1.1
Chevron Armor Design for Flat Plate
As seen in 17 above, the smaller diameter tubes showed considerably less vulnerability than a flat plate. However, in order to contour the armor to a heat pipe additional mass may be required. It may also be possible to construct a heat pipe with one surface flat, such as a "D" shape, thus allowing for the use of the shield design, as shown in Figure 1.1.

The idea behind the armor design of Figure 1.1 is that in all probability most meteoroids will not be normal to the surface. Thus, the impact will be oblique to the outer portion of the shield and according to item 14 above, the debris should start to align itself into a path which is normal to the shield i.e. it will be parallel to the plate that the shield is protecting. Likewise, the offset in the shield will protect the underlying heat pipe from normal impacts and if the impact is such that debris gets close to the heat pipe wall, the portion of the shield which is perpendicular to the heat pipe should change its direction of flight to be parallel to the heat pipe wall.

An initial analysis of thin type of armor was carried out under JPL Contract 955100. This analysis was similar to that one in Section 1.3.1 where the mass of the armor was assumed to be equal to the apparent density of the armor to the one half power. There the apparent density is equal to the mass of the armor divided by the total of the volume of the fins plus the volume of the space between the fins.

This analysis is not valid since the density of this volume will not be homogeneous to an incoming meteoroid. Accordingly, the following analysis utilizes the thin shield approach summarized above.
From Table 1.5, the solid armor thickness for 316 SS was shown to be 0.27 cm with a mass of 2.26 kg. Therefore, this is obviously the upper limit for any low mass armor design. Accordingly, a 50% mass reduction was chosen as the target. Thus, the mass of the armor should not exceed 1.13 kg.

In order to evaluate the effectiveness of the armor certain assumptions must be made. First of all, if a 3-section shield is used, then the last third must exhibit a black body cavity effect as discussed in Section 2. For an emissivity of 0.9 to be achieved for a surface emissivity of 0.7, the minimum depth to width ratio is 2:1. (See Figure 2.1). However, the physical dimensions of the fins preclude the use of Equation 1.4 as they do not fall within the constraints of the equation. Accordingly, the critical mass can not be calculated for chevron armor.

Thus, the conclusion is that since the shield to shield spacing is small with respect to the shield thickness (See number 8 above) it is impossible without additional theoretical and experimental work to determine the effectiveness of chevron type armor. However, its potential is high as seen by the comments of James Rand of the Southwest Research Institute in his letter of August 2, 1979, following.
Mr. Donald M. Ernst
Thermacore, Inc.
P. O. Box 135
Leola, Pennsylvania 17540

Dear Mr. Ernst:

This is in response to your letter of June 12 to Alex Wenzel and our conversation of July 31 pertaining to your proposed heat rejection system. The meteoroid protection system which you propose is quite unique and has definite promise. However, before a rational trade-off study can be performed on the advantages of the chevron armor over the solid armor, research will be necessary to establish the assumptions inherent in the design.

Although much work has been done on the penetration of thin plates at velocities of interest to the ballistics industry, only limited data exist in the hypervelocity regime which is necessary to simulate the meteoroid environment. The advantage of the chevron armor design is dependent on the assumption that the debris and ejecta will occur perpendicular to the fin. Unfortunately, this is only a qualitative observation since data exist which indicate that the projectile will continue on its original flight path while the spall or debris cloud is ejected perpendicular to the target. An experimental program will be necessary to define the limits of this mode of failure. A subsequent program to observe the synergistic effects of your particular design would then be necessary.

The Southwest Research Institute has a highly competent professional staff with experience in defining certain meteoroid impact effects for NASA. However, an estimate of the cost of a program in this area will naturally be dependent on the nature and scope of the work to be performed. I hope that you will plan to visit us when the time comes to prepare a formal proposal for this work.

Again, I would like to encourage you to pursue this concept. The criticism that you will undoubtedly receive regarding the inefficiency of spaced bumper shields is based on normal impact theory. Should the
projectile be completely arrested by the fin and if the debris cloud is normal to the fin, it does in fact seem possible to divert the cloud to a direction parallel to the pipe. Only a well defined ballistics program will confirm this.

If I can be of any further assistance, please do not hesitate to call.

Sincerely yours,

James L. Rand
Staff Engineer

JLR: jc

cc: A. B. Wenzel
    J. S. Wilbeck
1.4 Heat Pipe - Heat Pipe Armor

One concept which grew out of the evaluation of the different types of armor is that of using a thin walled heat pipe to protect the underlying radiator heat pipe. Several possible design configurations are seen in Figure 2.1. These heat pipe designs could employ configuration pumping rather than conventional wicks.

The radiator heat pipe must be capable of axially transferring all of the required power. However, the bumper heat pipe requirement is a radial one with only enough axial capability to even out non-uniformities. Thus, the bumper heat pipe will not require as much wick structure as the radiator heat pipe and will therefore have less mass. In fact, the bumper heat pipe could have a knurled inside surface (x's) thus providing radial and axial grooves for liquid flow paths.

Figure 2.1
Segmented Bumper Heat Pipe (D-Shaped and Configuration Pumped)
If the liquid inventory is small then a stainless steel circular bumper heat pipe could have a wall thickness of 0.135 cm and have 50% of the mass of the solid armor of Table 5.

Likewise, "D" shaped heat pipes with the bumper heat pipe having a thicker flat section, could make use of the interface effect as discussed in 1.2. In addition, the mass of a "D" shape is less than a complete circle of equal wall thickness and diameter.

One thing which has to be considered is what happens when the bumper heat pipe is punctured and the radiator heat pipe remains intact. The remains of the bumper heat pipe will act as a radiation shield and reduce the radiant heat transfer by up to 50%. However, the radiator heat pipe will remain intact. Thus, there arises a trade-off in the bumper heat pipe wall thickness and the radiation shield factor.

It may be possible to make the bumper heat pipe out of ten individual compartments. Thus, if one of the bumper heat pipes is penetrated, then the other nine can still dissipate the heat at a slightly higher overall temperature. For the CBC radiator, if the small diameter heat pipes evaluated in Section 3 were to be protected by large diameter bumper heat pipes with ten segments, the total mass of the system will be considerably reduced. In fact, the bumper heat pipe mass should be much less than that which would be required if a "T" bar bumper was used.

A complete evaluation of the bumper-heat pipe concept was not possible as its evolution as an idea came at the conclusion of the study. However, it does have enough merit to be considered along with the chevron fins to be studied in more detail.
2. HIGH EMISSIVITY SURFACES

The mass of a space vehicle's radiator is directly proportional
to the effective total hemispherical emittance of the radiating surface.
Additionally, the emitting surface must be thermally stable in the
environ of space; i.e. it must not evaporate into the vacuum of
space nor be affected by the slow but continuous erosion by the
micrometeoroids of $10^{-6}$ grams or less which will not otherwise
damage the spacecraft. For minimum mass, the radiating surface
should have an emissivity of 1. Thus, a minimum goal of 0.9 should
be established for the radiating surfaces of a spacecraft radiator.

There are several ways in which an emissivity of 0.9 can be
achieved. They include:

1. Use a material which has an emissivity of 0.9.
2. Chemically treat the surface to oxidize it or produce a compound
   of the base material which has a high emissivity.
3. Apply a coating which has a high emissivity.
4. Geometrically produced effects.

When one looks at each of these four possibilities, it becomes evident
that most high emissivity materials are non-metals of poor thermal
conductivity such as ceramics, porcelain, glass, marble, water, ice,
and wood, and usually exhibit these properties below $200^\circ$C.

Likewise, if a metal such as 316 SS, A-286 or Nb-1% Zr is to be
used as the heat pipe - armor material, the chemical treatment of
these surfaces to produce a high emissivity compound or oxide is
possible. However, reactive layers usually have sufficient vapor
pressure in the range of interest such that they are not stable for
ten years.
The remaining concepts are coatings and geometrically produced effects. Coatings are seen to be capable of producing emissivities of 0.9. Geometrically produced effects are shown to be a function of the geometry and surface emissivity with effective emissivities greater than 0.9 possible.

2.1 Coatings

Two coatings of interest have been shown to be thermally stable at 1000°C for 10,000 hours in a vacuum by Pratt and Whitney Company. These were calcium titanate and iron titanate on 310 SS tubing, both of which exhibited emissivities of 0.9.

The extrapolation of 10,000 hours to 87,600 hours is not unreasonable. However, it is not known whether these coatings will be able to survive the ten or so thermal cycles which will be required for the multiple fabrication steps and ground level system check out, and then survive the shock and vibration of launch, plus the continuous erosion by the cosmic dust.

The high emissivity of these coatings is a function of at least two things: the normal high emittance of the titanates and the fact that the coatings are granular in composition which produces a high emissivity by geometric effects as is discussed in 2.2 below.

Coatings such as these are required if solid armor is to be used to protect the radiator heat pipe from meteoroids. However, the use of high emissivity coatings on the surface of low mass armor which also produces a geometric effect may provide emissivity greater than 0.9 which in turn will allow for further radiator mass reduction.
2.2 **Black Body Effect**

The artificial roughening of a surface is a known means of increasing its emissivity. This enhancement of emissivity by surface or geometric effects has been treated quite thoroughly by Sparrow.\(^{11}\) The basis for this enhancement is the multi-reflections between surfaces which "see" each other, and is a function of the angular separation of a Vee-shaped cavity, the depth to width ratio for rectangular groove cavities and depth to radius ratio for cylindrical cavities. Additionally, the absolute value of the emissivity of the enclosing surfaces is important, as is the type of surface involved, which in turn defines the type of reflection, i.e., specular or diffuse.

Sparrow mathematically derived the effective emissivity of parallel plate or rectangular groove cavities for specular and diffuse reflecting surfaces. Figure 2.2 shows Sparrow's results from which one sees that emissivity enhancement is most dramatic for surfaces of low specular emissivity and low depth to width ratio.

This emissivity enhancement assumes that the enclosing surfaces are isothermal, of uniform emissivity and applies only to the projected surface area bound by the cavity and does not include the surfaces of the edges forming the cavity, i.e. fin tips for chevron armor in Figure 1.

Diffuse radiation denotes directional uniformity, i.e. the intensity of the radiation leaving a diffusely emitting and diffusely reflecting surface is uniform in all angular directions. Likewise, radiation arriving with uniform intensity at a surface is diffusely distributed. In other words, regardless of whether the incident radiation arrives as a beam directed along the surface normal, or as
Figure 2.2

Effective Emissivity of Diffuse and Specular Reflecting Rectangular Groove Cavities
a beam grazing the surface, or is uniformly distributed over the hemisphere, the radiation reflected from a diffuse surface is always of uniform intensity.

Specular or mirrorlike reflection maintains directional dependence, and a beam of radiation contained in a solid angle inclined at some angle to the normal of the surface will be reflected in the same solid angle on the opposite side of the normal at the same inclination.

Although a black body is a diffuse emitter of energy it is obvious from Figure 2 that the surfaces of a rectangular cavity can not be diffuse reflectors in order to achieve a high emissivity which is desired.

There is no known material which is a perfectly diffuse reflector. However, it is interesting to note that the nonmetallic materials which have a high emissivity such as Al₂O₃, paper, wood, glass, and ice, also have a uniform emittance for inclination angles between 0 and 60° before falling off to zero.

Conversely the emittance of the metals typically shows a very high degree of directional dependence with a peak around 80°. Thus one concludes that metallic surfaces will behave more like a specular reflector and that nonmetallic surfaces will be more closely described as diffuse reflectors.

2.2.1 Powder Metallurgy Material

In an attempt to understand the properties of powder metallurgy material, Thermacore utilized some of its IR & D funds to construct a potassium heat pipe which had an annulus of sintered nickel powder around a portion of its condenser. This powder had eight holes in
it. Four were 1 mm in diameter, four were 6 mm in diameter. Each
set of holes had depth to diameter ratios of 3:1, 6:1, 7.5:1 and 10:1.

The results of the experiment were quite inconclusive with respect
to measuring the effective emissivity of the material since it was
observed that the thermal conductivity of the 50% nickel powder was
so poor that the matrix could not be kept at a uniform temperature
even with the application of radiation shields.

Qualitatively the following can be said of the experiment:
1. The smaller diameter holes appeared to have a lower effective
emissivity then the larger holes.
2. The larger the depth to diameter ratio the higher the effective
emissivity.

From 1, it can be concluded that there is a relationship between
the diameter of the cavity and the roughness of the cavity walls which
affects the effective emissivity of the cavity. (In the experiment,
the cavity walls were both of identical material, 50% porous nickel).

Quantitatively it was concluded that the effective emissivity of
the 50% nickel fell between 0.4 to 0.7. This is not at all unexpected,
for if one looks at the actual emitting surface of the 50% dense
material one sees that the surface is 80% nickel and 20% voids. Thus
even if the 20% voids have an emissivity of 1, and the 80% nickel has
an emissivity of 0.5 (oxidized nickel), and total effective emissivity
of the surface would then be 0.6.

It can be concluded that for powder metallurgy to be used to
achieve an emissivity of 0.9 or greater, the following is required.
The density will have to be less than 50%, so the projected surface
area of the cavities is increased, and the material which makes up the
powder metallurgy should have a high emissivity to begin with.

2.2.2 Fins

The evaluation of fins such as the chevron design of Figure 1.1 is considerably more straightforward. Based on the results of 2.2.1, a conservative approach is to assume that the surfaces of the fins do not have any roughness factor by which to enhance the surface emissivity. Also, based on the apparent high specular nature of metals, the surfaces will be assumed to be specular reflecting.

From Figure 2.1, it is seen that a depth/width ratio of 10:1 produces an effective emissivity of 0.9 for a material with a specular emissivity as low as 0.3. If the fins have an emissivity of 0.5 a ratio of only 4:1 is required to achieve 0.9.

If one assumes the use of iron titanate on the fin with an emissivity of 0.9, then at a ratio of 2:1 the effective emissivity will be in excess of 0.98. However, this may be risky based on the results of the powder metallurgy tests.

One thing that must be considered is what the total emissivity of the final structure is. If the fins represent 25% of the surface area the cavity represents 75% and the following equation can be written for the effective emissivity:

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_m A_m - \varepsilon_c (A - A_m)}{A}
\]

\[\varepsilon_{\text{eff}} = \text{Total effective emissivity of the radiator surface}\]
\[\varepsilon_m = \text{Emissivity of the edges of the fins}\]
\[\varepsilon_c = \text{Effective emissivity of the cavity}\]
\[A_m = \text{Area of the edges of the fin}\]
\[A = \text{Total area of radiator}\]
Thus if we have 25% fin area and \( \varepsilon_{\text{eff}} = 0.9 \) then

\[
0.6 \leq \varepsilon_m \leq 0.9 \quad \text{while} \quad 1 \geq \varepsilon_c \geq 0.9
\]

Therefore, a high emissivity fin material is required to increase the effective emissivity of the cavity as well as the edges of the fins.

Additionally, if the \( \Delta T \) through the fin is taken into consideration it is seen that short stubby fins will perform thermally the best, but may not provide the required amount of meteoroid protection.

It is concluded that fins can produce a total surface emissivity in excess of 0.9. To achieve these high emissivities the surface area of the fin tips should be as low as possible and the surface emissivity as high as possible.

Additionally, it is seen that there will be a delicate balance in the protection afforded by the fins, a chevron armor, the \( \Delta T \) in the fins and the associated mass increase and the effective emissivity of the radiating surface. Additional work is necessary to fully evaluate the total effectiveness of chevron fins to produce an effective low mass armor with a total effective emissivity in excess of 0.9.
3. HEAT PIPE DESIGN FOR CBC RADIATOR

The 400 kW<sub>e</sub> Closed Brayton Cycle power system for the Nuclear Electric Propulsion Spacecraft has been designed by Garrett AirResearch<sup>12</sup> to use heat pipes to achieve a thermally effective radiator which has a high survival probability. It is also anticipated that the heat pipe design will lead to a low specific mass. The heat pipe design evaluated in this work is for use in a cylindrical array as seen in Figure 3.1. This design has eight dual gas-to-radiator heat pipe heat exchangers fed from a dual central duct. The heat pipes are attached to both gas ducts over a length of 43 cm on each duct. Thus, the heat pipes provide armor protection for the gas ducts.

In normal operation, the total 86 cm length attachment over the heat pipes to the gas ducts will be used as heat pipe evaporators. The condenser is 176 cm long. If either gas duct or engine should fail, then the whole power load will be transferred to the heat pipes through only one of the 43 cm attachments. Accordingly, for design considerations, the heat pipe must be sized as though it had a 43 cm evaporator, 43 cm adiabatic and 176 cm condenser.

Four different sets of heat pipe designs were analyzed with respect to mass and performance. However, no consideration was given to the required heat pipe armor and tradeoffs in the heat pipe diameter versus T-bar fins for total mass. The overall heat pipe cell dimension as designed by Garrett is 3.175 cm (1.25") and includes heat pipe and fins. All heat pipes discussed in the Sections 3.1 and 3.2 have computer printouts of their performance tabulated in Appendix I.
3.1 Baseline Design

The total power to be dissipated is $1.1 \times 10^6$ watts. From the gas side of the radiator heat exchanger, heat pipe temperatures were calculated by Garrett AirResearch to range from 707°K down to 492°K. The power levels are 720 watts per heat pipe at 707°K and 169 watts per heat pipe at 492°K. Thus, $\sigma A \epsilon T^4$ can be computed to be $2882 \times 10^{-12}$ watts/°K$^4$ from:

$$P = \sigma A \epsilon T^4 \quad \text{Eq. 3.1}$$

where

$P =$ Power radiated - watts  
$\sigma =$ Stefan Boltzmann Constant $= 5.67 \times 10^{-12}$ watts cm$^{-2}$ °K$^{-4}$  
$T =$ Heat pipe temperature - °K  
$A =$ Individual heat pipe radiating area - cm$^2$  
$\epsilon =$ Effective thermal emissivity

Table 3.1 shows the required heat pipe power for each of the end temperatures and each temperature divisible by 25°K.

Garrett AirResearch's baseline design is a 2.54 cm (1") O.D. heat pipe with a 0.0762 cm (.03") wall. The initial heat pipe designs under these conditions are seen in Table 3.2. Rubidium is the preferred heat pipe fluid from 707°K down to 650°K. Below 650°K Dowtherm A (DTA) is the preferred fluid. In both cases, a screen covered groove design is found to be the lowest mass system of those investigated. The rubidium heat pipes have a 1.75 kg mass. The DTA heat pipes have a 1.74 kg mass.
**TABLE 3.1**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Req. Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>°K</td>
<td>°C</td>
</tr>
<tr>
<td>707</td>
<td>434</td>
</tr>
<tr>
<td>700</td>
<td>427</td>
</tr>
<tr>
<td>675</td>
<td>402</td>
</tr>
<tr>
<td>650</td>
<td>377</td>
</tr>
<tr>
<td>625</td>
<td>352</td>
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<tr>
<td>600</td>
<td>327</td>
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<tr>
<td>575</td>
<td>302</td>
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<tr>
<td>550</td>
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<td>252</td>
</tr>
<tr>
<td>500</td>
<td>227</td>
</tr>
<tr>
<td>492</td>
<td>219</td>
</tr>
</tbody>
</table>

**REQUIRED POWER PER HEAT PIPE AT ELEVEN DIFFERENT TEMPERATURES**
### Table 3.2

**Heat Pipe Mass & Performance for Baseline Designs**

<table>
<thead>
<tr>
<th>Evaporator - 43 cm</th>
<th>Fluid: Hb</th>
<th>Vessel: 304 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic - 43 cm</td>
<td>0.D.: 2.54 cm</td>
<td>Wall: 0.0762 cm</td>
</tr>
<tr>
<td>Condenser - 176 cm</td>
<td># Grooves: 25</td>
<td>Groove Width: 0.2 cm</td>
</tr>
<tr>
<td>S = Sonic Limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C = Capillary Limit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Required Power (Watts)</th>
<th>( \Delta T ) @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
<th>( \Delta T ) @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>707</td>
<td>720</td>
<td>2.56</td>
<td>1750-S</td>
<td>1.75</td>
<td>0.05</td>
<td>3.89</td>
<td>545-C</td>
<td>1.74</td>
<td>0.065</td>
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<td>700</td>
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<tr>
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<tr>
<td>650</td>
<td>514</td>
<td>6.44</td>
<td>608-S</td>
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<td>0.05</td>
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<tr>
<td>625</td>
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<tr>
<td>600</td>
<td>373</td>
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<td>575</td>
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<td></td>
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<tr>
<td>1.73</td>
<td>710-C</td>
<td>1.74</td>
<td>0.065</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3 shows the same heat pipes, which have been, for the most part, optimized with respect to the number of grooves and their aspect ratio. The rubidium heat pipes have a 1.48 kg mass. The DTA heat pipes have a 1.55 kg mass.

The average mass reduction is 14%. Further groove optimization may result in an additional 1 or 2% mass reduction. However, far greater mass reduction can be realized by O.D. and/or wall thickness reduction.

Table 3.4 shows the 2.54 cm (1") heat pipe with a 0.025 cm (.01") wall. This wall thickness is 0.01 times the diameter and has been shown to be acceptable for use as a heat pipe containment vessel where external buckling is the ultimate constraint, i.e., the internal pressure of the heat pipe was less than 14.7 psi, thus long term creep due to hoop stress was low.

The use of a wall thickness 0.01 times the diameter was developed for niobium, which has a modulus of elasticity of 15 x 10^6 psi. This includes a safety factor of 2. Stainless steels have moduli of about 28 x 10^6 psi which reduces the thickness/diameter ratio of about 0.008 with a safety factor of 2. However, the use of 0.01 as a thickness to diameter ratio will be used to assure success.

Examination of DTA at 625°K shows a fluid pressure of 85 psi which develops a hoop stress of 4250 psi. This stress is acceptable, since 316 SS will only creep 0.1% in 10^5 hours at 1100°F under a stress of 6000 psi.

The rubidium heat pipes have a mass of 0.69 kg and the DTA heat pipes have a mass of 0.78 kg.
# Optimized Heat Pipe Mass & Performance - Baseline Design

<table>
<thead>
<tr>
<th>Component</th>
<th>Fluid</th>
<th>Vessel</th>
<th>Materials</th>
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</thead>
<tbody>
<tr>
<td>Evaporator - 43 cm</td>
<td>Nb</td>
<td>304 SS</td>
<td></td>
</tr>
<tr>
<td>Adiabatic - 43 cm</td>
<td></td>
<td></td>
<td>0.0762 cm</td>
</tr>
<tr>
<td>Condenser - 176 cm</td>
<td></td>
<td></td>
<td>0.275 cm</td>
</tr>
<tr>
<td>S = Sonic Limit</td>
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<td></td>
</tr>
<tr>
<td>C = Capillary Limit</td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (Cm)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (Cm)</th>
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<td>815-C</td>
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<td></td>
</tr>
<tr>
<td>700</td>
<td>427</td>
<td>2.43</td>
<td>815-C</td>
<td>1.48</td>
<td>0.02</td>
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<tr>
<td>550</td>
<td>277</td>
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<td>0.02</td>
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<tr>
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<td>252</td>
<td>5.53</td>
<td>640-S</td>
<td>1.48</td>
<td>0.02</td>
<td></td>
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<tr>
<td>500</td>
<td>227</td>
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<td>640-S</td>
<td>1.48</td>
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<td>555-C</td>
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</table>
## Table 2.4

**Optimized Heat Pipe Mass & Performance for Thin Walled Baseline Design**

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
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</thead>
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<td>707</td>
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<td>650</td>
<td>514</td>
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<td>5.72</td>
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<td>277</td>
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<td>525</td>
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</tr>
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<td>2.49</td>
<td>710</td>
<td>0.78</td>
<td>0.055</td>
</tr>
</tbody>
</table>
Design Optimization

Examination of Tables 3.2, 3.3 and 3.4 reveals that a reduction in diameter of the rubidium heat pipes would soon result in the heat pipe becoming limited by sonic shock wave development in the vapor. However, the DTA pipes are capillary limited, thus a reduction in O.D. is possible. Accordingly, a higher pressure fluid, mercury, was used in small diameter pipes in place of rubidium. These results are seen in Table 3.5.

The mercury heat pipes are 0.635 cm (.250") in diameter with a wall to diameter ratio of 0.01. The mass of the mercury heat pipes are 0.45 kg and have a hoop stress of 625 psi at 707°K.

The DTA heat pipes are 0.9525 cm (.37") in diameter with a wall to diameter ratio of 0:01. They have 12 grooves 0.275 cm wide by a depth that varies from 0.075 cm down to 0.05 cm. Accordingly, their mass varies from 0.31 kg down to 0.27 kg. The DTA heat pipes at 625°K will have a hoop stress of 1600 psi.

The mercury heat pipes of Table 3.5 have eight grooves 0.2 cm wide by 0.02 cm deep. Optimizing the number of 0.275 cm wide by .02 cm deep grooves for different power levels results in a reduction in mass. At 707°K, a five-groove heat pipe has a mass of 0.29 kg. At 675°K, four grooves have a mass of 0.28 kg and at 550°K, three grooves have a mass of 0.27 kg. These results are seen in Table 3.6. Also shown in Table 3.6 is the thermal performance of two of the mercury heat pipes with 86 cm evaporators, which shows an increase in maximum power capability and a reduction in total ΔT.

Both the DTA heat pipes of Table 3.5 and the mercury heat pipes of Table 3.6 have a performance ΔT. Accordingly, it is important to assess the effect of this temperature loss in terms of increased
### Table 3.5

**OPTIMIZED HEAT PIPE MASS & PERFORMANCE - ALTERNATE DESIGN**

<table>
<thead>
<tr>
<th>Evaporator - 43 cm</th>
<th>Fluid: Hg</th>
<th>Vessel: 304 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic - 43 cm</td>
<td>O.D.: 0.9525 cm</td>
<td>Wall: .01 cm</td>
</tr>
<tr>
<td>Condenser - 176 cm</td>
<td># Grooves: 8</td>
<td>Groove Width: 0.200 cm</td>
</tr>
<tr>
<td>S - Sonic Limit</td>
<td>C - Capillary Limit</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>( \Delta T ) @ Req. Power (°C)</th>
<th>Power Limit</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>707</td>
<td>720</td>
<td>2.69</td>
<td>930-S</td>
<td>0.45</td>
<td>0.02</td>
</tr>
<tr>
<td>700</td>
<td>692</td>
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</tr>
<tr>
<td>675</td>
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<tr>
<td>650</td>
<td>514</td>
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<tr>
<td>625</td>
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<td>0.02</td>
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<td>500</td>
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</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>( \Delta T ) @ Req. Power (°C)</th>
<th>Power Limit</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
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</thead>
<tbody>
<tr>
<td>Fluid: DTA</td>
<td>Vessel: 304 SS</td>
<td>O.D.: 1.27 cm</td>
<td>Wall: 0.0127 cm</td>
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</tr>
<tr>
<td># Grooves: 12</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>( \Delta T ) @ Req. Power (°C)</th>
<th>Power Limit</th>
<th>Mass (Kg)</th>
<th>Groove Depth (cm)</th>
</tr>
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<tbody>
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<td>0.075</td>
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<td>10.73</td>
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<td>0.05</td>
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</tr>
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<td>Req. Power</td>
<td>$\Delta T$ @ Req. Power</td>
<td>Power Limit</td>
<td>Mass</td>
<td>Groove Depth</td>
</tr>
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<td>------</td>
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<td>$^\circ K$</td>
<td>$^\circ C$</td>
<td>Watts</td>
<td>$^\circ C$</td>
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<td>Kg</td>
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<td>434</td>
<td>720</td>
<td>4.13</td>
<td>770-C</td>
<td>0.24 (5) .02</td>
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<tr>
<td>700</td>
<td>427</td>
<td>692</td>
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<tr>
<td>675</td>
<td>402</td>
<td>598</td>
<td>3.62</td>
<td>610-C</td>
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<tr>
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<td></td>
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<tr>
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<tr>
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<td>277</td>
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<td>492</td>
<td>219</td>
<td>169</td>
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</table>
mass (length of condenser) to be able to radiate the required power. Appendix 2 develops Equation 3.2 which is the increase in mass of heat pipe due to its $\Delta T$.

$$dm = m \frac{l_c}{l_t} \left[ \left( \frac{T_o}{T} \right)^4 - 1 \right]$$

Eq. 3.2

Where

$dm$ = Increase in mass

$m$ = Initial mass of heat pipe

$l_c$ = Length of heat pipe condenser

$l_t$ = Total length of heat pipes

$T_o$ = Desired operating temperature

$T$ = Actual operating temperature

$T_o - T = \Delta T$ down heat pipe

From Table 3.5 and 3.6, using the lowest mass heat pipes, the increase in mass was calculated using Equation 3.2 and is tabulated in Table 3.7. Therefore, to a first approximation, one can say that the heat pipes for the CBC radiator will have a mass of 0.3 kg each.

The performance of the mercury heat pipes is based on perfect wetting, that is, the wetting angle is zero ($0^\circ$). For long term stability, this may not be the case. Wetting angles from 0-60 degrees have been observed, with 30-60 degree angles the most common. Since the capillary force is a function of the cosine of the wetting angle, the mercury heat pipes may have a reduction of capillary force of up to 50% ($\cos 60 = .5$). This reduction in performance will then require a reoptimization of the heat pipes with a small increase in mass.
Development work may be required to establish a reproducible wetting angle for mercury in heat pipe service.

3.3 Advanced Heat Pipe Concept

The grooved heat pipe designs of Sections 3.1 and 3.2 were optimized to an approximate mass of 0.3 kg per heat pipe, exclusive of fins and armor. This mass is quite low and may be acceptable in the overall system. However, there are several heat pipe design concepts which may offer further reduced mass with increased performance. These include but are not limited to arterial wick heat pipes and configuration pumped heat pipes. These wick structures were not available in Thermacore's computer library and were, therefore, not included in the analysis.

3.3.1 Artery/Wick Heat Pipes

There is a natural division in heat pipe fluids which takes place at approximately 600°K. Above 600°K, the liquid metals are useful working fluids. Below 600°K, one generally deals with non-metallic fluids and devises structures which compensate for their inferior physical properties. The low temperature fluids, taken as a class, have relatively low latent heats of vaporization, low surface tension, and low thermal conductivity. The consequences are that for a given heat transfer rate, heat pipes using these fluids must move relatively large quantities of liquid with unusually low pressure losses, yet must maintain very thin liquid films in the heat flow path. The arterial wick structures of Figure 3.2 have been used to offset these property limitations. The artery provides the primary liquid return
## TABLE 3.7

### INCREASE IN MASS DUE TO PERFORMANCE AT

<table>
<thead>
<tr>
<th>TEMPERATURE (°K)</th>
<th>POWER (W)</th>
<th>FLUID</th>
<th>MASS (Kg)</th>
<th>AT (°C)</th>
<th>DM (Kg)</th>
<th>NEW MASS (Kg)</th>
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</thead>
<tbody>
<tr>
<td>707</td>
<td>720</td>
<td>llig</td>
<td>0.291</td>
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<td>4.6 x 10^{-3}</td>
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<td>4.6 x 10^{-3}</td>
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<tr>
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<td>598</td>
<td>llig</td>
<td>0.280</td>
<td>3.63</td>
<td>4.6 x 10^{-3}</td>
<td>0.284</td>
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<tr>
<td>650</td>
<td>514</td>
<td>llig</td>
<td>0.273</td>
<td>3.30</td>
<td>3.9 x 10^{-3}</td>
<td>0.277</td>
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<td>0.273</td>
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<td>3.9 x 10^{-3}</td>
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<td>llig</td>
<td>0.273</td>
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<tr>
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<td>llig</td>
<td>0.273</td>
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<tr>
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<td>169</td>
<td>DTA</td>
<td>0.273</td>
<td>4.05</td>
<td>6.2 x 10^{-3}</td>
<td>0.279</td>
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</table>
Figure 3.2 Representative Wick Geometries
to the evaporator. This passage has a large hydraulic radius and provides a very low drag path. In the evaporator and condenser, a thin film of liquid is distributed circumferentially. The distribution wick is often a thin layer of screen or circumferential grooves.

The artery is removed from the evaporator and condenser heat flow paths. The thin films provided by the circumferential wick prevent the development of excessive temperature gradients. Arterial wicks provide very high performance, sometimes even approaching that obtainable with liquid metals in more conventional wicks. Lengths in excess of ten meters have been reported. The primary limitations of arterial wicks lie in their difficulty of fabrication and their consequent lack of reproducible performance. The wick structures are quite difficult to form and to insert into the heat pipe vessel so as to maintain uniform close fit to the wall. There has been repeated difficulty with the priming of arteries, that is, the ability to fill an artery with fluid and keep it filled.

Two methods of priming are in use. Capillary priming, as the name implies, depends on capillary forces to maintain the fluid within the artery. The basic condition for capillary priming is that the largest single pore at the artery surface in the evaporator must provide sufficient capillary pressure to offset all counter forces including accelerations. Consequently, the evaporator ends of the arteries must be closed and there must be no single inadvertently large pore on the entire periphery of the enclosing surface. Due to the adverse effect of accelerations, capillary primed arteries can be more fractious during ground testing than in subsequent zero g operation. Yet ground testing is essential to establish the operability
of the heat pipe.

If the artery is so located in the heat pipe temperature gradient that it always is the coldest spot, it will operate at a lower vapor pressure than the balance of the heat pipe. If the magnitude of the vapor pressure difference is sufficient, it will cause priming to take place. This is known as vapor pressure or Clapeyron priming. The process is highly temperature dependent. The pressure difference caused by a given temperature difference varies enormously with temperature. Thus, a heat pipe which primes reliably and quickly at high temperature (i.e. high pressure) may fail to prime at all at low temperature. It has also been reported that vibration has caused arteries to lose their prime and that subsequent re-priming can be unreliable.

In spite of their apparent drawbacks, the performance of arterial heat pipes is sufficiently high to justify further work to improve their reliability and reproducibility. In general, arterial wicks require less total mass of wicking material, and may also require less fluid inventory than conventional heat pipes. They are, therefore, serious candidates for use in space radiators.

3.3.2 Wickless (Configuration Pumped) Heat Pipes

A crevice has capillary properties. Therefore, if the wall of a non-round heat pipe is formed so as to produce longitudinal crevices, these may serve the purpose of wicks. That is, the configuration of the wall provides the capillary pumping force. Several potential configuration pumped heat pipe geometries are shown in Figure 3.3. Configuration pumped heat pipes have been built (Figure 3.4) and have
Figure 3.3 Configuration Pumped Geometries
Figure 3.4

Photograph of a Configuration Pumped Heat Pipe
been shown to operate. However, there has been very little work in
the field, and the mathematical prediction of performance is incomplete.

The driving pressure difference which causes liquid flow in a
heat pipe is determined by the surface tension and the difference in
the radius of the liquid meniscus in the condenser and evaporator.
Evaporation in the heat input section tends to depress the liquid
level while condensation at the heat output end tends to increase
the level. Thus, during operation, the liquid level in the evaporator
of a configuration pumped heat pipe recedes into the crevice, increasing
the pumping pressure but decreasing the flow area. The inverse occurs
in the condenser. This makes for a delicate tradeoff of liquid
fill versus power handling capability. The problem is somewhat
alleviated in the configuration/artery geometry of Figure 3.3d and 3.3f.

Configuration pumped heat pipes tend by their nature to have
relatively low capillary pumping forces and low liquid drag. They
therefore lend themselves well to consideration as elements in low
temperature space radiators where large radiating areas require long
heat pipes. The liquid inventory requirement of configuration pumped
heat pipes appears to be comparable to that of the arterial structures
discussed previously. The complete absence of conventional wicks
is a substantial mass reduction. However, the non-round shapes are
relatively poor pressure vessels so that the gain in mass due to
elimination of the wick may be at least partially offset by a thicker
wall requirement unless fluid vapor pressures are kept relatively low.
Thus the operating temperature range for a configuration pumped heat pipe
of low mass may be narrower than that for other geometries.

The ability of configuration pumped heat pipes to hold their
shape is a function of the creep strength of the heat pipe envelope. Thermacore\textsuperscript{12} previously identified the iron alloy, A-286, which exhibits an exceptionally high creep strength, and may well serve as a containment for configuration pumped heat pipes. (A-286 has a 0.1% creep at 1100°F in $10^5$ hours under a 38,000 psi stress load).

3.3.3 Hybrid Wick/Pumped Heat Pipes

Since the dissipating capacity of a space radiator declines as the fourth power of any temperature loss, there is a strong incentive to minimize losses. One of the principal advantages of the heat pipe is the low temperature loss it incurs while moving large amounts of heat. This low ΔT operation is characteristic of vapor heat transfer. There may, therefore, be reason to make use of vapor heat transfer even at power levels which cannot be sustained by capillary pumping alone. Alternative or hybrid pumping means are possible and deserve consideration. This may be true not only for the radiators themselves, but also for the primary loops feeding them. A practical hybrid system may use an alternative pumping means for liquid transport over appreciable distances with capillary pumping for local distribution and collection.

The heat transfer capability of a conventional heat pipe can be limited by entrainment of liquid from the walls by the high velocity, counterflowing vapor. Separation of the liquid and vapor passages will permit greater heat flow under these conditions. Figure 3.5 is a hybrid system where the liquid and vapor flow are in the same direction. Therefore, the vapor shear forces may aid rather than inhibit liquid flow.
Figure 3.5 Mechanically Pumped Hybrid Heat Pipe
Hybrid heat pipes are directly analogous to two-pipe steam heating systems for buildings which use condensate pumps for liquid return. The principle has been extended to liquid metals by Philips Laboratories for use in Stirling engines.

The main disadvantages of the hybrid system are the increased probability of a leak at pump seals and joints and the dependence of operation on an external power source. For maximum redundancy, there should be a pump for each heat pipe, a serious penalty in complexity for a space radiator, making the approach seem more applicable to primary loops.

It may be possible to make use of the "heat of the radiator" to pump the liquid, much the same way that a capillary pump makes use of the "heat of the radiator."

Thermacore has recently begun the exploration of a "liquid piston pump" as part of its internal R & D effort. This pump uses a localized high heat flux, into the fluid, to develop a vapor bubble of sufficient pressure to push the liquid forward. Backward flow is prevented by the use of a check valve. A forward spring loaded valve permits regulation of the pressure at which the pump is activated.

Initial work to date has concentrated on gravity feed liquid systems with encouraging results. The extension of this concept to two phase systems with freedom from gravity will pose challenging work but may be worth a cursory investigation.

3.3.4 Other Concepts

There are numerous concepts which have been suggested as possible fluid pumping mechanisms for heat pipes and includes electro-magnetic,
electrolytic, electrohydrodynamic and electrophoretic pumping. All of these are not suited for individual spacecraft radiator heat pipes. However, osmotic pumped heat pipes and artificial gravity are two possible mechanisms which are suited for spacecraft use.

If a spinning spacecraft can be so arranged that its centrifugal force will aid liquid return in heat pipes, it may be possible to eliminate pumping and depend entirely or predominantly on artificial gravity for this function. The result may be mass reduction (by wick elimination and, possibly, reduced fluid inventory) and an added degree of freedom in fluid selection (fluid need not have high surface tension).

Osmotic pressures can exceed capillary pressures by a factor of 100 to 1,000. An osmotically pumped heat pipe is feasible in principle. Several designs have been proposed, but only one hardware program has been reported. The proposed designs all make use of gravity in one way or another: to keep liquid in place, to redistribute salt by natural convection, etc. It may be possible to devise a geometry which will function in gravity-free space. If so, osmotic heat pipes may avoid entirely the capillary limitations on available pumping pressure.

Flow rates through semi-permeable membranes are low; i.e., large areas are required to permit useful heat flow. There is, however, an interesting factor which may favor further consideration for low temperature space radiators. These radiators also require large areas because of the low radiant power densities. The osmotic process is such that the membrane must be located at the condenser (heat dissipating) end of the system, which is the radiating surface of a radiator. At temperatures below about 900°K, the power density from a black body radiator is less than the power density sustainable
by flow of the best fluids (e.g., water) through membranes. That is, below this temperature the unit liquid flow rate through a membrane is more than sufficient to support the unit radiant heat load from a radiator of equal area, and a basic condition of successful operation has been satisfied.

The geometries considered to date are relatively massive, having two walls and a large liquid inventory. Membranes do not exist for operation above about 400°K. However, since an osmotic heat pipe would need no auxiliary power (comparable to a capillary heat pipe), it deserves further consideration.
REFERENCES


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6. Private Communications, Gehring, John W. Jr., Past Director, Impact Physics Laboratory, General Motors, Corporation.

7. Private Communications, Wenzel, Alex, Director, Department of Ballistics and Explosive Science, Southwest Research Institute, San Antonio, Texas.


9. Hickerson, Norris L., Tennessee Technological University, Cookeville, Tennessee. (Section of Reference 1).


APPENDIX I

This appendix has complete performance printouts of all the heat pipes tabulated in Section 3.1 and 3.2. The heat pipe program used is Thermacore's GROOVE27. Figure A.1 depicts the placement and definitions of many of the symbols in the printout.

![Diagram of heat pipe system]

**Evaporator**

- **TE**
- **(vapor)**
- **PE**

**Adiabatic**

- **TE-A**
- **TA-C**
- **PE-A**
- **PA-C**

**Condenser**

- **TC**
- **PC**

Evaporator Temp. ← (Outside Wall) → Condenser Temp.

**Symbols and Definitions**

- **DPVE** = Pressure drop in vapor in evaporator
- **DPLEG** = Pressure drop in liquid in evaporator grooves
- **DPUA** = Pressure drop in vapor in adiabatic
- **DPLAG** = Pressure drop in liquid in adiabatic grooves
- **DPVC** = Pressure drop in vapor in condenser. (+) means drop, (-) means recovery or increase
- **DPLGG** = Pressure drop in liquid in condenser grooves
FLUID = RUBIDIUM  VALL MATL=304SS
EVAP TEMP = 434'  VAPOR DELTA-T = 50 DEC G
GAP AMG = 0.00  VTO AMG = 0.00 DEC

EVAP LENGTH 16.8891 IN  63.0000 CM
ABR LENGTH 16.8891 IN  63.0000 CM
COND LENGTH 65.2013 IN  165.0000 CM
TOTAL LENGTH 102.0500 IN  259.0000 CM

GAP 0.0
VALL THICK 0.0300 IN  0.7620 CM
GROOVE WIDTH 0.0707 IN  0.1794 CM

MATT VAPOR 0.0546 IN  0.1387 CM
28 GROOFS (CLOSED) COVERED WITH 300 MESH

NO LIMIT ENCOUNTERED AT ------------ 720 WATTS

TOTAL DELTA-T = 2.56 DEC G
TOTAL MASS = 1.769 ED

VAPOR PERFORMANCE DETAILS (T OR H) TT

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SONIC LIMITS: EVAP= 2137 AND= 2487 WATTS

2/A'S= EVAP CORD AXIAL VATTES/CH2
  2     0      142

3 RATES X A RATE= LGIC RATE= C A RATE= C 2 RATE= C 3 RATE=
  21  3344  138  3347  0

HOT FLUID CHAMBER 123.41 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHAMBER 64.6019 CM3

COLD FLUID CHAMBER 121.686 GRAMS
2B.8763 CM3

EVAP PIPE (INCH) & 2 ESCAPE 1506.9 GRAMS

DELTA-T VALUES:

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POWER OF 1770 WATTS CAUSES -------------- AND SONIC LIMIT

LAST NON-LIMITED POWER CALCULATION GAS AT -------------- 1770 WATTS

TOTAL DELTA-T = 7.16 DEC G
TOTAL MASS = 1.769 ED
EM CONDITIONS: 46.44 P.M. 1/22/79

FLUID = DIETHYL ETHER WALL MATT = 304°F
STAB TEM = 57°F VAPOR PREDICT = 50 DBC
STAB AMT = 0.10 VAP AMT = 0.00 DBC

STAB LENGTH: 16.8281 IN 43.0000 CH
AIR LENGTH: 16.8281 IN 43.0000 CH
COLD LENGTH: 68.2923 IN 176.0000 CH
TOTAL LENGTH: 153.1900 IN 203.0000 CH

D.B.: 1.0000 IN 2.0000 CH
WALL WIDTH: 0.0000 IN 0.0000 CH
COLD WIDTH: 0.0000 IN 0.0000 CH
COLD HEIGHT: 0.0000 IN 0.0000 CH
LINED WIDTH: 0.0564 IN 0.0564 CH
25 GROOVES (CLOSED) COVERED WITH 200 HMS

NO LIMIT ENCOUNTERED AT ------------- 914 VETS

---------- TOTAL DELTA-T = 9.44 DBC G
---------- TOTAL HASS = 1.7400 HS

VAPOR PERFORMANCE DETAILS (1T OR H) VS

VAP. FLUID VIAP. DESIGN FLUID DESIGN
35 33 33 33 33 33

VAPOR DESIGN FLUID FLUID FLUID FLUID
35 35 35 35 35 35

VAPOR MEAS. FLUID FLUID FLUID FLUID FLUID
35 35 35 35 35 35

SONIC LIMITS: STAB = 740 AND = 703 VETS

O/A'S: STAB COLD ATUAL VETS/CH2
1 1

2 R BAY: 2 R BAY LAV BAY G4 BAY C2 BAY 3
10 10

HOT FLUID CHARGE 132.019 GHNS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 94.1741 GHNS
COLD FLUID CHARGE 125.526 GHNS
92.9783 GHNS

HOT FLUID (KHES) + 2 HOGGHS 1386.9 GHNS

DELTA-T VALUES:

STAB WALL STAB L.A. STAB MESH EVAPORATION
-0.21606 -712.3163-02 -0.39709-02 -0.00000 DBC G

VAPOR (2): VAPOR (A): VAPOR (C)
8.021123 2.82308 -0.28002

COLD MEAS. COLD L.A. COLD VALL
-1.40653-08 -1.05433-08 -1.70800-08

POWERS? 600 VETS CAUSE ----------- AER JONIC LIMIT?

LAST JON-LIMITED POWER CALCULATION WAS AT ------------- 000 VETS

---------- TOTAL DELTA-T = 7.34 DBC G
---------- TOTAL HASS = 1.7400 HS

57
RUN CONDITIONS:

4118 P-in.  3/22/79

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VAPOR LENGTH 19.80821 IN  45.00000 CM
COND LENGTH 19.80381 IN  45.00000 CM
TOTAL LENGTH 39.61202 IN  90.00000 CM

0-12
VAPOR 1.00000 IN  2.56000 CM
COND 0.00000 IN  0.07000 CM

NO LIMIT ENCOUNTERED AT 460 VATS

TOTAL DELTA-T = 3.99 DEG C
TOTAL MASS = 1.766 LB

VAPOR PERFORMANCE DETAILS (T OR X) KT

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RECO 3160
COND 0
VAP 3160 DEX/DBR

10
EVAP

986

SONIC LIMITS:

EVAP = 139020 AUS = 160777 VATS

C/A'S

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62

2.25

1.25

345

805

1

HOT FLUID CHARGE 114.967 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE: 107.687 GCS

COLD FLUID CHARGE 153.601 GRAMS

COLD-401 GCS

14.65068 kg 1 2 KGAPS 162.63 GRAMS

DELTA-T VALUES:

| EVAP | EVAP FSS | EVAP MESS | EVAP SFF | EVAP VAP | VAP | VAP FSS | VAP MESS | VAP SFF | VAP VAP | VAP X | VAP Y | VAP Z | VAP C | VAP D |
|------|----------|-----------|----------|----------|-----|---------|----------|---------|----------|------|------|------|------|------|------|
| 358.076 | 1.92421 | 1.94413 | 1.99898 | 1.225 |

POWER OF 650 VATS CAUSES 350 VAYS
CAPILLARY LIMIT: DFL > DFV

LAST NON-LIMITED POWER CALCULATION WAS AT 350 VAYS

TOTAL DELTA-T = 4.79 DEG C
TOTAL MASS = 1.766 LB
### FLUID CONDITIONS:

- **FLUID = LOWEARN**
- **WALL MATT = 304SS**
- **EVAP VOLL = 50**
- **DEG C**
- **EVAP FILM**
- **Sheet Add = 0.00**
- **Sheet Add = 0.00**

<table>
<thead>
<tr>
<th>TRAY LENGTH</th>
<th>15.2501 IN</th>
<th>43.0000 CM</th>
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<tbody>
<tr>
<td>ADD LENGTH</td>
<td>15.2501 IN</td>
<td>43.0000 CM</td>
</tr>
<tr>
<td>COMB LENGTH</td>
<td>65.250 IN</td>
<td>175.000 CM</td>
</tr>
<tr>
<td>TOTAL LENGTH</td>
<td>103.1500 IN</td>
<td>262.000 CM</td>
</tr>
</tbody>
</table>

- **GROOVE WIDTH**
- **0.076 CM**
- **0.025 CM**
- **0.025 CM**
- **27 GROOves (CLOSED) COVERED WITH 200 MESH**

### SO LIMIT ENCOUNTERED AT 160 VAVTS

- **TOTAL DELTA-P = 1.73 DEG C**
- **TOTAL MASH = 1.744 ES**

### AMT PERFORMANCE DETAILS (Y OR X) YT

<table>
<thead>
<tr>
<th>PH</th>
<th>PH-3</th>
<th>PH-4</th>
<th>PH-5</th>
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<th>TH-4</th>
</tr>
</thead>
<tbody>
<tr>
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<td>217.610</td>
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<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>COLD TEMP</th>
<th>DELTA-T</th>
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<tbody>
<tr>
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<td>0.000</td>
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<table>
<thead>
<tr>
<th>DPC = 7201</th>
<th>DPC = 0</th>
<th>DPC=DPC = 7201</th>
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</thead>
</table>

- **DPC = DPC**
- **DPC = 7201**
- **DPC = DPC**

### SORIC LIMITS:

- **EVAP = 15075**
- **ADD = 17120 WATTS**

<table>
<thead>
<tr>
<th>G/A'S = EVAP</th>
<th>COMB</th>
<th>AXIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>33</td>
</tr>
</tbody>
</table>

### HOT FLUID CRANE:

- **112.079 GRAMS**

### COLD FLUID CRANE:

- **135.971 GRAMS**
- **129.001 GRAMS**

### EVAP PIPES (HEX)?

### DELTA-T VALUES:

- **EVAP VOLL**
- **EVAP L65**
- **EVAP NEXK**
- **EVAP VEVATION**

### POWER OF 715 WATTS CAUSES CAPILLARY LIMIT; DPL > DPF

### LAST NON-LIMITED POWER CALCULATION WAS AT 710 WATTS

- **TOTAL DELTA-T = 0.37 DEG C**
- **TOTAL MASH = 1.746 ES**
**RUG CONDITIONS:**

**FLUID = URISIN**
**WALL MAT=30XXS**
**EVAP TEMP = 434**
**VAPOR DELTA-T = 50 DEG C**
**GAS AM = 0.00**
**WV AM = 0.00 DEG**

<table>
<thead>
<tr>
<th>EVAP LENGTH</th>
<th>ADD LENGTH</th>
<th>COMD LENGTH</th>
<th>TOTAL LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.09251 IN</td>
<td>16.09251 IN</td>
<td>62.20531 IN</td>
<td>103.18400 IN</td>
</tr>
</tbody>
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---

**0-D:**
1.00000 IN

**VALL TEMPS:**
- 0.07000 IN
- 0.07652 IN

**GROOVE WIDTH:**
- 0.15000 IN
- 0.27500 IN

**GROOVE HEIGHT:**
- 0.00756 IN
- 0.02000 IN

**LAND WIDTH:**
- 0.00799 IN
- 0.02000 IN

25 GROOVES (CLOSED) COVERED WITH 300 MESH

---

NO LIMIT ENCOUNTERED AT 720 WATTS

---

**TOTAL DELTA-T = 2.43 DEG C**
**TOTAL MASS = 1.494 KG**

---

**VAP PERFORMANCE DETAILS (T OR H) **

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PE-C</th>
<th>PE</th>
<th>PE/CH2</th>
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</thead>
<tbody>
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<td>31206.3</td>
<td>30770.4</td>
<td>30700.4</td>
<td>30715.3</td>
<td>30715.1</td>
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<table>
<thead>
<tr>
<th>TE</th>
<th>TE-A</th>
<th>TE-C</th>
<th>TE</th>
<th>TE/CH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>452.861</td>
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<td>450.762</td>
<td>451.862</td>
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**DPC = 163166**
**DPM = 0**
**DPM+DPM = 163166**
**DPM/CH2 =**

**DPM**
- 025
- 1198
- 259
- 9356
- 416

**DPM+**
- 4900

---

**SONIC LIMITS:**

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<tr>
<th>EVAP</th>
<th>2234</th>
<th>ADD</th>
<th>22031 WATTS</th>
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<tbody>
<tr>
<td>0.155</td>
<td>0.199</td>
<td>1.155</td>
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</tbody>
</table>

---

**HOT FLUID CHARGE:**
- 02.12088 GRAMS

**BOOM TEMP. VOL. OF HOT FLUID CHARGE:**
- 0.01964 CM

**COLD FLUID CHARGE:**
- 107.824 GRAMS
- 70.3814 CM

**HEAT PIPE. (HEAT) & 2 ENDSGAP 1750.82 GRAMS**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LEG</th>
<th>EVAP MESH</th>
<th>EVAP MESH</th>
<th>EVAP MESH</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.055</td>
<td>-0.055</td>
<td>-0.055</td>
<td>-0.055</td>
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</table>

<table>
<thead>
<tr>
<th>VAPOR (2)</th>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.09314</td>
<td>0.05735</td>
<td>-1.0863</td>
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<table>
<thead>
<tr>
<th>COMBINATION MESH LEG</th>
<th>COMB MESH</th>
<th>COMB MESH</th>
<th>COMB MESH</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.73567</td>
<td>-0.73567</td>
<td>-0.73567</td>
<td>-0.73567</td>
</tr>
</tbody>
</table>

**POW OF 620 WATTS CAUSES**
**CAPILLAR LIMIT. DPL = DPV **

---

**LAST HOM-LIMITED POWER CALCULATION WAS AT 415 WATTS**

---

**TOTAL DELTA-T = 2.07 DEG C**
**TOTAL MASS = 1.494 KG**

---

70
FLUID = NITROUS OXIDE
WALL MAT = 3065
SVAP TEMP = 377
VAPOR DELTA-T = 55 D.EG C
GRAV and = 0.00
VEG AND = 0.00

SVAP LENGTH 16.8281 IN 42.0000 CM
ADD LENGTH 16.8281 IN 42.0000 CM
CORD LENGTH 29.2913 IN 75.0000 CM
TOTAL LENGTH 103.1500 IN 262.0000 CM

0.D. 1.0000 IN 2.5400 CM
WALL THICK 0.0350 IN 0.0762 CM
CORD WIDTH 0.1063 IN 0.2700 CM
CORD HEIGHT 0.0079 IN 0.0200 CM
LAND WIDTH 0.0079 IN 0.0200 CM
25 GROOVS (CLOSED) COVERED WITH 200 M.D.

NO LIMIT ENCOUNTERED AT 514 V.VIUS.

TOTAL DELTA-T = 5.83 D.EG C
TOTAL M.ASS = 1.484 G.

VAT HE PERFORMANCE DETAILS (X OR X) IT

<table>
<thead>
<tr>
<th>PH</th>
<th>PE-A</th>
<th>P-A-G</th>
<th>PC</th>
<th>DIRES/CM2</th>
</tr>
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<tbody>
<tr>
<td>0628-9B</td>
<td>0666-98</td>
<td>0081-89</td>
<td>0903-7</td>
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</tr>
<tr>
<td>TH</td>
<td>PE-A</td>
<td>P-A-G</td>
<td>PC</td>
<td>DIRES/CM2</td>
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<td>370.977</td>
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<td>SVAP TEMP</td>
<td>CORD TEMP</td>
<td>DELTA-T</td>
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<tr>
<td>377</td>
<td>371.17</td>
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<td>DPO = 19139</td>
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<td>DPO+DPO = 19139</td>
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<td>DPHA</td>
<td>DPHB</td>
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<td>1420</td>
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<td>DPHD</td>
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<tr>
<td>998</td>
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<tr>
<td>SONIC LIMITS: SVAP = 790 ADD 965 VAUS</td>
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<tr>
<td>Q/A'S =</td>
<td>SVAP</td>
<td>CORD</td>
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<tr>
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<td>R A R EY</td>
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<td>LIG R EY</td>
<td>O A R EY</td>
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<tr>
<td>93</td>
<td>8983</td>
<td>GRAMS</td>
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<tr>
<td>COLD FLUID CHARGE 109.824 GRAMS</td>
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</tr>
<tr>
<td>79.381 CM3</td>
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</tr>
<tr>
<td>HEAT PIPE (MURED) &amp; 2 END CAPS 1375.82 CM3</td>
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<tr>
<td>DELTA-T VALUES:</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SVAP WALL</td>
<td>SVAP LEG</td>
<td>SVAP MESS</td>
<td>SVAP EVAP</td>
<td>EVAPORATION</td>
</tr>
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<td>+01000</td>
<td>+20108E-02</td>
<td>+30406E-02</td>
<td>+50046E-02</td>
<td></td>
</tr>
<tr>
<td>VAPOR (E)</td>
<td>VAPOR (A)</td>
<td>VAPOR (G)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.01495</td>
<td>6.06895</td>
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<td></td>
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<tr>
<td>CONDENSATION</td>
<td>CORD MESS</td>
<td>CORD LEG</td>
<td>CORD WALL</td>
<td></td>
</tr>
<tr>
<td>+12227E-03</td>
<td>+43233E-03</td>
<td>+50066E-03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.EG C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POWER OF 948 VAUS CAUSING ADD SONIC LIMIT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAST NON-LIMITED POWER CALCULATION WAS AT 940 VAUS</td>
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<tr>
<td>TOTAL DELTA-T = 7.13 D.EG C</td>
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</tbody>
</table>
| TOTAL M.ASS = 1.384 G.
**RIM CONDITIONS**

<table>
<thead>
<tr>
<th>FLUID = DOWTHERM A</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVAP TEMP = 352</td>
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<tr>
<td>VAPOR DELTA-T = 50</td>
</tr>
<tr>
<td>GRAV ANG = 0.00</td>
</tr>
<tr>
<td>WTS ANG = 0.00</td>
</tr>
</tbody>
</table>

| EVAP LENGTH 16.0281 IN 45.0000 CM |
| ADD LENGTH 16.0281 IN 45.0000 CM  |
| COLD LENGTH 69.2513 IN 178.0000 CM |
| TOTAL LENGTH 103.500 IN 263.0000 CM |

<table>
<thead>
<tr>
<th>VOLUME ENCOUNTERED AT</th>
<th>440 WATTS</th>
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<tbody>
<tr>
<td>TOTAL DELTA-T = 9.23</td>
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<tr>
<td>TOTAL MASS = 1.9444 KG</td>
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</tr>
</tbody>
</table>

**VAPOR PERFORMANCE DETAILS [X OR X] TT**

<table>
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<tr>
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<th>PB-A</th>
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<th>PC</th>
<th>PB-KS</th>
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<tbody>
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<table>
<thead>
<tr>
<th>TE</th>
<th>TE-A</th>
<th>TE-C</th>
<th>TE</th>
<th>TE-G</th>
</tr>
</thead>
<tbody>
<tr>
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<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>COLD TEMP</th>
<th>DELTA-T</th>
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<tbody>
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<table>
<thead>
<tr>
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<th>DMT-G</th>
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<table>
<thead>
<tr>
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<th>DELAS</th>
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<table>
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**SONIC LIMITS:**

<table>
<thead>
<tr>
<th>EVAP = 150.876</th>
<th>ADD = 193190</th>
<th>WATTS</th>
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<tbody>
<tr>
<td>G/A' = 5</td>
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</tr>
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<td></td>
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<table>
<thead>
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<table>
<thead>
<tr>
<th>X &amp; Y</th>
<th>X &amp; Y</th>
<th>X &amp; Y</th>
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<table>
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<tr>
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<th>281</th>
<th>707</th>
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<table>
<thead>
<tr>
<th>120.200</th>
<th>GRAINS</th>
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</thead>
<tbody>
<tr>
<td>DRY TEMP</td>
<td>VOLUME OF DRY TEMPERATURE</td>
</tr>
<tr>
<td>115.501</td>
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<table>
<thead>
<tr>
<th>141.404</th>
<th>GRAINS</th>
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<tbody>
<tr>
<td>COLD FLOOD</td>
<td></td>
</tr>
<tr>
<td>138.401</td>
<td>CM3</td>
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<table>
<thead>
<tr>
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<th>GRAINS</th>
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<tbody>
<tr>
<td>VAPOR (G)</td>
<td>COLD (G)</td>
</tr>
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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>COLD WALL</td>
<td>COLD LAY</td>
</tr>
<tr>
<td>1.50400</td>
<td>1.50400</td>
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</table>

<table>
<thead>
<tr>
<th>138076</th>
<th>CM3</th>
</tr>
</thead>
</table>

**POWER OF 875 WATTS CAUSES**

| CAPILLARY LIMIT: DFL = DFL-1 |
|-----------------------------|-----------------------------|
| LAST NON-LIMITED POWER CALCULATION WAS AT 870 WATTS |

<table>
<thead>
<tr>
<th>TOTAL DELTA-T = 11.92</th>
<th>DEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS = 1.9444</td>
<td>KG</td>
</tr>
</tbody>
</table>

72
**RHE CONDITIONS:**

**FLUID = DOWTHERM A**  
**VAIL MELT 30-45**

**EVAP TEMP = 219**  
**VAPOR DELTA-T = 50 DEG C**

**315 AM = 0.00**  
**VTR AM = 0.00 DEG**

**EVAP LENGTH 18.9281 IN 43.0000 CM**

**ABD LENGTH 18.9281 IN 43.0000 CM**

**C O R D LENGTH 60.3013 IN 176.0000 CM**

**TOTAL LENGTH 10.1500 IN 252.0000 CM**

**O.D.**

**WALL THICKNESS 0.0500 IN 0.1270 CM**

**GROOVE WIDTH 0.1063 IN 0.2700 CM**

**GROOVE HEIGHT 0.0197 IN 0.0500 CM**

**LAND WIDTH 0.0946 IN 0.2400 CM**

25 GROOVES (CLOSED) COVERED WITH 200 MESH

**NO LIMIT ENCOUNTERED AT --------- 100 VOLTS**

--------- TOTAL DELTA-T = 3.85 DEG C

--------- TOTAL M ASS = 1.055 IN

**WATT PERFORMANCE DETAILS (T OR X) ??**

<table>
<thead>
<tr>
<th>YE</th>
<th>YE-A</th>
<th>YE-C</th>
<th>PC</th>
<th>DYES/GM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>367</td>
<td>367</td>
<td>367</td>
<td>367</td>
<td>367</td>
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<tr>
<td>106</td>
<td>106</td>
<td>106</td>
<td>106</td>
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</table>

**EVAP TEMP**

**COND TEMP**

**DELTA-T**

<table>
<thead>
<tr>
<th>YE</th>
<th>YE-A</th>
<th>YE-C</th>
<th>YE-T</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>219</td>
<td>219</td>
<td>219</td>
<td>219</td>
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<tr>
<td>213</td>
<td>213</td>
<td>213</td>
<td>213</td>
<td>213</td>
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</table>

**DPO = 7307**

**DFM = 1**

**DFO+DPO = 7308**

**DYES/GM2**

<table>
<thead>
<tr>
<th>DF =</th>
<th>DFM</th>
<th>DFT</th>
<th>DFTA</th>
<th>DFLA</th>
<th>DFLB</th>
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</thead>
<tbody>
<tr>
<td>26</td>
<td>179</td>
<td>20</td>
<td>1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
<td></td>
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</table>

**SOMIO LIMITS:**

**EVAP = 146045**

**ADD = 166032 VOLTS**

**G/A'S:**

<table>
<thead>
<tr>
<th>G/A</th>
<th>YE</th>
<th>CORD</th>
<th>AXIAL</th>
<th>WATTS/GM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
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</tbody>
</table>

**HOT FLUID GE A S**

**111.630** GRAMS

**COLD FLUID GE A S**

**121.943** GRAMS

**125.941** GRAMS

**EVAP PIPE (K NEE) & 2 END GAPS 1603.86 GRAMS**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LEA</th>
<th>EVAP AREA</th>
<th>EVAP EVA TION</th>
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</thead>
<tbody>
<tr>
<td>0.05554</td>
<td>2.2882</td>
<td>2.2882</td>
<td>0.05554</td>
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<tr>
<td>VAPOR (1)</td>
<td>VAPOR (1)</td>
<td>VAPOR (2)</td>
<td></td>
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<tr>
<td>0.288035</td>
<td>0.288035</td>
<td>0.288035</td>
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**CORRECTION**

**CORD EVA TION**

**CORD LEA | CORD AREA | CORD WALL |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.055785</td>
<td>0.055785</td>
<td>0.055785</td>
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</tbody>
</table>

**POWER OF 550 VOLTS CAUSES --------------- CAPILLARY LIMIT. DEL = DFM**

**LAST NON-LIMITED POWER CALCULATION WAS AT -------------- 200 VOLTS**

--------- TOTAL DELTA-T = 11.00 DEG C

--------- TOTAL M ASS = 1.535 IN
NO LIMIT ENCOUNTERED AT ----------------- 720 VICTS

TOTAL DELTA-T = 2.43 DEG C
TOTAL MASS = 1.484 KG

VAPOR PERFORMANCE DETAILS (T OR M) TT

<table>
<thead>
<tr>
<th>FLUID</th>
<th>FB</th>
<th>PA</th>
<th>PC</th>
<th>DEG/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>KUB</td>
<td>31230.8</td>
<td>30370.4</td>
<td>30100.8</td>
<td>30715.1</td>
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<table>
<thead>
<tr>
<th>CP</th>
<th>FB</th>
<th>PA</th>
<th>PC</th>
<th>DEG/KG</th>
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<tbody>
<tr>
<td>433.281</td>
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<td>430.782</td>
<td>431.840</td>
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<table>
<thead>
<tr>
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<th>FB</th>
<th>PA</th>
<th>PC</th>
<th>DEG/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>KUB</td>
<td>18214</td>
<td>33587</td>
<td>33458</td>
<td>33386</td>
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<table>
<thead>
<tr>
<th>COP</th>
<th>FB</th>
<th>PA</th>
<th>PC</th>
<th>DEG/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
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<td>0.015</td>
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</table>

<table>
<thead>
<tr>
<th>DEG LIMITS:</th>
<th>FLAP</th>
<th>CR</th>
<th>AXIAL</th>
<th>VICTS/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/1/0/3/0</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

HOT FLUID MASS: 95.1794 GRAMS
HEAT TEMPERATURE: VOLUME OF HOT FLUID MASS 20.1664 CMS
COOL FLUID MASS: 107.824 GRAMS
COOL FLUID VOLUME: 70.3816 CMS

HEAT PIPE: (HERE) & 2 ENCAPS 1375-82 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>FLAP WALL</th>
<th>FLAP LAC</th>
<th>FLAP NAC</th>
<th>FLAP EAC</th>
<th>DEG/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6288351</td>
<td>-389813.02</td>
<td>-663753502</td>
<td>-30028302</td>
<td>DEG/KG</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>FLAP (E)</th>
<th>FLAP (A)</th>
<th>FLAP (C)</th>
<th>DEG/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4914</td>
<td>-0.579736</td>
<td>-1.08807</td>
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<table>
<thead>
<tr>
<th>COND FORCE</th>
<th>COND NAC</th>
<th>COND LAC</th>
<th>COND EAC</th>
<th>DEG/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.573047</td>
<td>-14684102</td>
<td>-86475102</td>
<td>-202811</td>
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POWER OF 690 WATTS CAUSES ----------------- CAPILLARY LIMIT; DPL = DPV

LAST NON-LIMITED POWER CALCULATION WAS AT ----------------- 315 WATTS

TOTAL DELTA-T = 2.37 DEG C
TOTAL MASS = 1.484 KG
HEX CONDITIONS:

FLUID = HUMID air
EVAP TEMP = 97
VAPOR DELTA-T = 50 Deg C
GRAY ARR = 0.00
WGO ARR = 0.00 Deg C

EVAP LENGTH 100.000 in 43.0000 cm
AIR LENGTH 100.000 in 43.0000 cm
COND LENGTH 66.250 in 173.0000 cm
TOTAL LENGTH 166.250 in 423.0000 cm

Ox = 1.0000 in 2.5400 cm
WALL TRAXIS 0.0100 in 0.0254 cm
GROOVE WIDTH 0.1083 in 0.2750 cm
GROOVE HEIGHT 0.0079 in 0.0200 cm
LBD WIDTH 0.0120 in 0.0305 cm
25 GROOVES (CLOSED) COVERED WITH 250 mesh

NO LIMIT ENCOUNTERED AT 0.14A WATTS

TOTAL DELTA-T = 4.56 Deg C
TOTAL MASS = 0.0531 lb

WANT PERFORMANCE DETAILS IT OR HT YY

<table>
<thead>
<tr>
<th>PK</th>
<th>PB-A</th>
<th>FA-C</th>
<th>PC</th>
<th>DYES/CM2</th>
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</thead>
<tbody>
<tr>
<td>10019.5</td>
<td>8844.57</td>
<td>9666.41</td>
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<table>
<thead>
<tr>
<th>TE</th>
<th>TH-A</th>
<th>TA-C</th>
<th>TC</th>
<th>DEL C</th>
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<tbody>
<tr>
<td>376.253</td>
<td>376.066</td>
<td>358.045</td>
<td>372.611</td>
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</tbody>
</table>

EVAP TEMP = 377

DELTA-T = 4.56 Deg C

| DPC= 19133 | DPD= 0 | EPC+DPC= 19133 | DYES/CM2 |

<table>
<thead>
<tr>
<th>DPVR</th>
<th>DPLD</th>
<th>DPVA</th>
<th>EPLD</th>
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</thead>
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<tr>
<td>876</td>
<td>395</td>
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<table>
<thead>
<tr>
<th>DFTG</th>
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<tbody>
<tr>
<td>395</td>
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SONIC LIMITS:

<table>
<thead>
<tr>
<th>EVAP</th>
<th>967</th>
<th>ADR</th>
<th>976 WATTS</th>
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</table>

<table>
<thead>
<tr>
<th>Q/A'S</th>
<th>EVAP</th>
<th>COND</th>
<th>AXIAL</th>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
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<td>102</td>
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<table>
<thead>
<tr>
<th>E R EPS</th>
<th>3 A EPS</th>
<th>LGC EPS</th>
<th>G A EPS</th>
<th>G R EPS</th>
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</thead>
<tbody>
<tr>
<td>16</td>
<td>2381</td>
<td>98</td>
<td>2393</td>
<td>3</td>
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</table>

HOT FLUID GRAMS 96.95 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID GRAMS 92.0653 CM3

COLD FLUID GRAMS 110.102 GRAMS
71.8683 CM3

HEAT PIPES (MECH) 4 & 2 MIDCAPS 560-657 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LAD</th>
<th>EVAP MES</th>
<th>EVAPRATION</th>
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<tbody>
<tr>
<td>0.00125</td>
<td>0.007415</td>
<td>0.053623</td>
<td>0.505438</td>
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</table>

VAPOR (S) VAPOR (A) VAPOR (C)
3.65266 1.82544 3.75704

CONDENSATION COND MES COND LAD COND WALL
+12279 810253 5011493 -6929893 01 Deg C

POWER OF 710 WATTS CAUSES ADI SONIC LIMIT

LAST NON-LIMITED POWER CALCULATION WAS AT 760 WATTS

TOTAL DELTA-T = 6.12 Deg C
TOTAL MASS = 0.691 lb
FLUID = DEUTERIUM, WALL MATL = 304 SS
EVAP TEMP = 352°C, VAPOR DELTA-T = 50° DEG C
GRAV ANG = 0.00, WGT ANG = 2.00° DEG

EVAP LENGTH 15.9391 IN 45.0000 CM
ADD LENGTH 15.9391 IN 45.0000 CM
COND LENGTH 69.2815 IN 176.0000 CM
TOTAL LENGTH 103.1500 IN 262.0000 CM

O.D. 1.0000 IN 25.4000 CM
WALL THICK 0.0100 IN 0.0254 CM
GROOVE WIDTH 0.1063 IN 0.2700 CM
GROOVE HEIGHT 0.0217 IN 0.0550 CM
LAND WIDTH 0.0034 IN 0.0086 CM
25 GROOVES (0.0002 IN) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------- 440 WATTS
--------- TOTAL DELTA-T = 5.72 DEG C
--------- TOTAL MASS = 0.777 LS

WATK PERFORMANCE DETAILS (T OR M) ??

PH PH-A PH-A-C PH-C PC ETHANE/CM²
.559376+07 .559376+07 .559376+07 .559376+07

TE TE-A TE-A-C TE-C DEG C
367.402 367.402 367.402 367.402

EVAP TEMP CORD TEMP DELTA-T
352°C 346.278 5.74608

DPC 3206 DPF 0 DPF+DPE 3206 ETHANE/CM²

DPT 216 0 1422
DPTC 216

SONIC LIMITS: EVAP = 170527 AND = 206579 WATTS

Q/A = EVAP CORD AXIAL WATTS/CM²
1 0 0 0

HOT FLUID CHARGE 123.66 GRAMS
HOT VOLUME OF HOT FLUID CHARGE 115.767 CM³

COLD FLUID CHARGE 142.982 GRAMS
103.888 CM³

HEAT PIPE: (MESH) 4 2 MESHCAPS 654.002 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP LEG EVAP Mesh EVAPATION
175328 370928 0.01878 100098 DEG C

VAPOR (S) VAPOR (A) VAPOR (C)
0.695281 ±03 0.246413 ±03 0

COND DENSITY COND MESH COND LEG COND WALL
26.8597 ±01 14.8562 90.9527 43.1516 ±01 DEG C

POWER OF 550 WATTS CAUSES ------- CAPILLARY LIMIT: DPL > DPF
LAST NOX-LIMITED POWER CALCULATION WAS AT ------- 550 WATTS
--------- TOTAL DELTA-T = 7.19 DEG C
--------- TOTAL MASS = 0.777 LS
RUN CONDITIONS:

FLUID = DOWTERM A  WALL MAT=30435
EVAP TEMP = 219  VAPOR DELTA-T = 00 DEG C
GRAY LEN = 0.00  WTG LEN = 0.00 DEG

EVAP LENGTH 18.9261 IN  43.0000 CM
ADD LENGTH 18.9261 IN  43.0000 CM
COND LENGTH 69.2933 IN  176.0000 CM
TOTAL LENGTH 106.1500 IN  262.0000 CM

0.0
WALL THICK 0.0100 IN  0.0254 CM
GROOVE WIDTH 0.1063 IN  0.2700 CM
GROOVE HEIGHT 0.0217 IN  0.0550 CM
LAND WIDTH 0.0094 IN  0.0240 CM
25 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT 160 WATTS

TOTAL DELTA-T = 2.49 DEG C
TOTAL MASS = 0.777 LB

WATT PERFORMANCE DETAILS (Y OR N) YY

PE PA= PA-1 PA=G PA-1 G 396170
396240 396219 396170

TC TA=G TC-1 217-001
217-006 217-005 217-001

EVAP TEMP COND TEMP DELTA-T
219 216.515 2.49747

DP= 7280 DP= 0 DP+DP= 7280 DYNES/CM2

DPMB DPMB DP= 17 926

Sonic Limits:

ETAP 16000 ADD= 12735 VATTS

G/AT= ETAP COND AXIAL VATTS/CM2
0 0 33

R E KEY# E A KEY# LIG E KEY# C A KEY# C B KEY#
2 309 36 309 0

HOT FLUID GRS 2 121.123 GRAMS
COLD FLUID GRS 162.992 GRAMS
133.666 CM3

HOT PIPE (WHE) & 2 ENDCAPS 654.002 GRAMS

DELTA-T VALUES:

EVAP VALUES EVAP LAG EVAP XSH EVAPORATION
+24641.8336-01 +24641.8336 +1000008 +1000008 DEG C

VAPOR (I) VAPOR (A) VAPOR (C)
+27777.02 +24641.8336-02 +24641.8336-02

CONDENSATION COND MSH COND LAG COND VALL
+24641.8336-01 +24641.8336-01 +24641.8336-01 +24641.8336-01 DEG C

POWER OF 715 WATTS CAUSES CAPILLARY LIMIT, DPL > DPY
LAST NON-LIMITED POWER CALCULATION WAS AT 710 WATTS

TOTAL DELTA-T = 10.06 DEG C
TOTAL MASS = 0.777 LB
**Room Conditions:**

- **Fluid = Mercury**
- **Wall Matt = 30 deg C**
- **Vapor Temp = 434 deg C**
- **Vapor Delta-T = 30 deg C**
- **Gray Amb = 0.05**
- **VW Amb = 0.00 deg C**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap Length</td>
<td>16.0331 in</td>
</tr>
<tr>
<td>Ass Length</td>
<td>16.0331 in</td>
</tr>
<tr>
<td>Cold Length</td>
<td>29.2813 in</td>
</tr>
<tr>
<td>Total Length</td>
<td>103.1380 in</td>
</tr>
<tr>
<td>G. D.</td>
<td>0.3750 in</td>
</tr>
<tr>
<td>Wall Thkens</td>
<td>0.0399 in</td>
</tr>
<tr>
<td>Groove Width</td>
<td>0.0776 in</td>
</tr>
<tr>
<td>Groove Height</td>
<td>0.0776 in</td>
</tr>
<tr>
<td>Land Width</td>
<td>0.0826 in</td>
</tr>
<tr>
<td>8 Grooves (Closed) Covered with 200 Mesh</td>
<td></td>
</tr>
</tbody>
</table>

No Limit Encountered At --- 720 Watts

<table>
<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>Total Delta-T</td>
<td>2.69 deg C</td>
</tr>
<tr>
<td>Total Watts</td>
<td>0.6665 Lb</td>
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**Watt Performance Details (It or h) it**

<table>
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<tbody>
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<tr>
<td>TA-C</td>
<td>33009.00-07</td>
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<td>PG</td>
<td>33009.00-07</td>
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<td>431.063</td>
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<td>TA-C</td>
<td>421.333</td>
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<tr>
<td>TG</td>
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<tr>
<td>Evap Temp</td>
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<td>Cond Temp</td>
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<tr>
<td>Delta-T</td>
<td>2.00072</td>
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<tr>
<td>C/W</td>
<td>114105</td>
</tr>
<tr>
<td>DFW</td>
<td>28007</td>
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</tbody>
</table>

**Sonic Limits:**

- Evap = 20097
- Ass = 24000 Watts
- G/A = 1
- Evap = Cond = Axial = Watts/Cbm

**Heat Pipe (Mesh) & 2 Ejectors 150.000 Grams**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta-T Values</td>
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</tr>
<tr>
<td>Evap Wall</td>
<td>392229</td>
</tr>
<tr>
<td>Evap Leg</td>
<td>732886</td>
</tr>
<tr>
<td>Evap Mesh</td>
<td>181954</td>
</tr>
<tr>
<td>Evaporation</td>
<td>100096</td>
</tr>
<tr>
<td>Vapor (h)</td>
<td>162579</td>
</tr>
<tr>
<td>Vapor (a)</td>
<td>124579</td>
</tr>
<tr>
<td>Vapor (c)</td>
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<tr>
<td>Cond Leg</td>
<td>178159</td>
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<tr>
<td>Cond Wall</td>
<td>286514</td>
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**Power of 930 Watts Causes --- Capillary Limit: DPL > DFW**

Last Non-Limited Power Calculation Was At --- 930 Watts

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Total Delta-T</td>
<td>3.04 deg C</td>
</tr>
<tr>
<td>Total Watts</td>
<td>0.349 Lb</td>
</tr>
</tbody>
</table>
FLUID = MERCURY
EVAP TEMP = 252
GRAV ABD = 0.00

EVAP LENGTH 14.6201 in 43.0000 cm
ADD LENGTH 14.6201 in 43.0000 cm
COND LENGTH 66.2013 in 178.0000 cm
TOTAL LENGTH 105.4000 in 267.0000 cm

0.05
WALL THICK 0.0000 in 0.0000 cm
GROOVE WIDTH 0.0078 in 0.0200 cm
GROOVE DEPTH 0.0000 in 0.0000 cm
LAND WIDTH 0.0000 in 0.0000 cm
8 GROOVES (CLOSED) COVERED WITH 500 MILES

NO LIMIT ENCOUNTERED AT 440 WATTS

TOTAL DELTA-T = 1.29 DEG C
TOTAL MASS = 0.046 KG

VAPOR PERFORMANCE DETAILS (T OF R)

<table>
<thead>
<tr>
<th>T0</th>
<th>T0-A</th>
<th>T0-C</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

DELTA-T LIMITS:
EVAP = 6000 ABD = 7012 WATTS

WATER:
EVAP 3 0 607
C A 9 369 167 3460 2

COLD FLUID GRAMS 200-5 GRAMS 21.6456 KG
EVAP PIPE (NEED) 1/2 MIDGET 102.621 GRAMS

DELTA-T VALUES:

| EVAP FALL | EVAP L-30 | EVAP L-34 | EVAP MAX | EVAP MAX
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>.1044146</td>
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<td>.055787</td>
<td>.026329</td>
<td>.000000</td>
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<table>
<thead>
<tr>
<th>VAPOR (J)</th>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
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<tbody>
<tr>
<td>.105555</td>
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<table>
<thead>
<tr>
<th>COND MAX</th>
<th>COND MAX</th>
<th>COND L-34</th>
<th>COND L-30</th>
<th>COND FALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>.115000</td>
<td>.115000</td>
<td>.115000</td>
<td>.115000</td>
<td>.115000</td>
</tr>
</tbody>
</table>

POWER UP 908 WATTS CAUSES CAPILLARY LIMIT; DEL = DFV
LAST NON-LIMITED POWER CALCULATION WAS AT 300 WATTS

TOTAL DELTA-T = 3.43 DEG C
TOTAL MASS = 0.046 KG
### DEW CONDITIONS

<table>
<thead>
<tr>
<th>FLUID</th>
<th>DATA</th>
<th>FALL RATES</th>
<th>HOURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 g</td>
<td>0.00</td>
<td>0.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STAB TEMP</th>
<th>377</th>
<th>VAPOR DENSITY</th>
<th>0.00</th>
<th>100.00 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00 %</td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL LENGTH</th>
<th>100.00 %</th>
<th>2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00 %</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### DEW CONDITIONS

<table>
<thead>
<tr>
<th>80 LIMIT REACHED AT</th>
<th>304 VOLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEW</td>
<td>2.00</td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>0.450</td>
</tr>
</tbody>
</table>

### FAST PERFORMANCE DETAILS (T OR H) Yr

<table>
<thead>
<tr>
<th>FE</th>
<th>FE-4</th>
<th>FE-6</th>
<th>FE-8</th>
<th>FE-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>THEA</th>
<th>THEA-4</th>
<th>THEA-6</th>
<th>THEA-8</th>
<th>THEA-10</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.00</td>
<td>0.00</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>STAB TEMP</th>
<th>COND TEMP</th>
<th>DEW</th>
<th>COND</th>
<th>DEW</th>
</tr>
</thead>
<tbody>
<tr>
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<td>277</td>
<td>0.00</td>
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</tbody>
</table>

### SONIC LIMITS

<table>
<thead>
<tr>
<th>0/A/2</th>
<th>0/A/2</th>
<th>0/A/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### BUT FLUID EMBRACE

<table>
<thead>
<tr>
<th>ROOM TEMP.</th>
<th>VOLUME OF BUT FLUID EMBRACE</th>
<th>204.000 GAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>204.000 GAMS</td>
<td>220.000 GAMS</td>
<td></td>
</tr>
</tbody>
</table>

### LEAF PIPE: (MERK) & 2 HESTAPS 150.000 GAMS |

### DELTA-T VALUES:  

<table>
<thead>
<tr>
<th>STAB FALL</th>
<th>STAB LAG</th>
<th>STAB AER</th>
<th>STAB ASC</th>
<th>STAB ASC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VAPOR (E)</th>
<th>VAPE (E)</th>
<th>VAPOR (E)</th>
<th>VAPE (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COND Temper</th>
<th>COND LAG</th>
<th>COND WALL</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.040000</td>
<td>0.040000</td>
<td>0.040000</td>
<td>0.040000</td>
</tr>
</tbody>
</table>

### POWER OF 310 VOLS CAUSES ------------- CAPILLARY LIMIT: DPL = DPV  

<table>
<thead>
<tr>
<th>LAST NON-LIMITED POWER CALCULATION WAS AT</th>
<th>305 VOLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL DELTA-T</td>
<td>0.00</td>
</tr>
<tr>
<td>TOTAL NIPS</td>
<td>0.00</td>
</tr>
</tbody>
</table>

---

**Note:** The text contains a mix of technical and partially legible data, including temperatures, pressures, and other physical properties, likely related to a specific process or system. The legibility and interpretation of the data are hindered by the quality of the image.
### MEX Conditions:

**MEX** = **NOVA**
**MEX** = **NOVA**

**Fluid** = **NOVA**
**Fluid** = **NOVA**

**Fluid Temp** = **355**
**Fluid Temp** = **355**

**Vapor Delt. Temp** = **35**
**Vapor Delt. Temp** = **35**

**JAT AND** = **0.00**
**JAT AND** = **0.00**

<table>
<thead>
<tr>
<th>FLUID LENGTH</th>
<th>14.000 IN</th>
<th>43.0000 CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LETH LENGTH</td>
<td>14.0000 IN</td>
<td>43.0000 CM</td>
</tr>
<tr>
<td>G0E LENGTH</td>
<td>28.0000 IN</td>
<td>71.0000 CM</td>
</tr>
<tr>
<td>TOTAL LENGTH</td>
<td>104.0000 IN</td>
<td>260.0000 CM</td>
</tr>
</tbody>
</table>

**JAT** = **0.00**
**JAT** = **0.00**

**Vapor Temp** = **0.0000**
**Vapor Temp** = **0.0000**

**LTH Temp** = **0.0000**
**LTH Temp** = **0.0000**

**LTH Temp** = **0.0000**
**LTH Temp** = **0.0000**

<table>
<thead>
<tr>
<th>FLUID TEMP</th>
<th>185.00</th>
<th>470.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAT TEMP</td>
<td>185.00</td>
<td>470.00</td>
</tr>
</tbody>
</table>

**CPS**
**CPS**

**S**
**S**

**S**
**S**

**VAPOR**
**VAPOR**

**COND.**
**COND.**

**COND.**
**COND.**

| POWER OF 515 WATTS CAUSING CAPILLARY LIMIT: DFL = DFL |
|-------------|-------------|
| LAST NON-LIMITED POWER CALCULATION WAS AT 510 WATTS |

<table>
<thead>
<tr>
<th>TOTAL DELTA-T</th>
<th>17.32 DEG C</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL MASS</td>
<td>0.9000 LB</td>
</tr>
</tbody>
</table>
**SUN CONDITIONS:**

|            | 
|------------|-----------------|
| FLAIR      | BLOWN-WIND A    |
| VALVE HURL | 30 DEGREES      |
| EVAP TEMP  | 307             |
| VAPOR ΔT   | 0               |
| FLAIR AM 1 | 0.00            |
| FLAIR AM 2 | 0.00            |

**FLAP LENGTH:** 12.50001 IN 12.50000 CM
**AIL LENGTH:** 12.50001 IN 12.50000 CM
**COLD LENGTH:** .68-2.033 IN 174.00000 CM
**TOTAL LENGTH:** 1.05-1.0000 IN 262.00000 CM

- 0.50
- 0.5000 CM 1.2700 CM

**VALVE TEMPERATURE [12 IN 12]**

<table>
<thead>
<tr>
<th>FE</th>
<th>TP-A</th>
<th>TP-C</th>
<th>PC</th>
<th>1/1E5</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-500-07</td>
<td>12-500-07</td>
<td>12-500-07</td>
<td>12-500-07</td>
<td></td>
</tr>
</tbody>
</table>

**EVAP TEMP**

<table>
<thead>
<tr>
<th>COLD TEMP</th>
<th>32°F 10.73°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEHALS</td>
<td>12</td>
</tr>
</tbody>
</table>

- 316-316
- 316-316
- 316-316

**HPS:**

<table>
<thead>
<tr>
<th>HPS</th>
<th>323</th>
<th>264</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETFB</td>
<td>264</td>
<td>1732</td>
</tr>
<tr>
<td>ETFC</td>
<td>316</td>
<td>1732</td>
</tr>
</tbody>
</table>

**SONIC LIMITS:**

<table>
<thead>
<tr>
<th>O/A' D.</th>
<th>EVAP 0 324</th>
<th>( k ) 0 324</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1372</td>
<td>406</td>
</tr>
<tr>
<td>6</td>
<td>1372</td>
<td>1372</td>
</tr>
</tbody>
</table>

**HOT FLUID CHARGE**

| 177.6632 | 177.6632 |

**COLD FLUID CHARGE**

| 77.6632 | 77.6632 |

**EAST PIPE:** 2 ENDS x 2 ENDS" 216.75 NO. 1"

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>EVAP LSG</th>
<th>EVAP HSER</th>
<th>EVAP EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.50001</td>
<td>12.50000</td>
<td>12.50000</td>
<td></td>
</tr>
</tbody>
</table>

**VAPOR (2):**

<table>
<thead>
<tr>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.50000</td>
<td>12.50000</td>
</tr>
</tbody>
</table>

**CONDENSATION:**

<table>
<thead>
<tr>
<th>COND HSER</th>
<th>COND LSG</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>.284597</td>
<td>.284597</td>
<td></td>
</tr>
</tbody>
</table>

**POWER OF 420 WATTS CAUSES**

CAPILLAR LIMIT: DFE = DPA
\[ \text{Last Non-Limited Power Calculation Was At} \]
\[ \text{420 WATTS} \]

- 420 WATTS

**TOTAL ΔT = 12.08 DBR C**
**TOTAL MASS = 0.2294 KD**
**CONDITIONS**

<table>
<thead>
<tr>
<th>FRA</th>
<th>FRA</th>
<th>FRA</th>
<th>FRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2222</td>
<td>3.222222</td>
<td>3.222222</td>
<td>3.222222</td>
</tr>
</tbody>
</table>

**TOTAL DELTA-T** = 3.22 DEG C

**TOTAL MASS** = 0.266 LB

**FLUID** = SOUTHERN A

**EVAP TEMP** = 302

**VAPOR DELTA-T** = 60 DEG C

**SPAN AND** = 0.00

**VAP AND** = 0.00

**EVAP LENGTH** = 1.6-2.000 IN 43.0000 CM

**ABD LENGTH** = 1.6-2.000 IN 43.0000 CM

**COLD LENGTH** = 0.2-2.000 IN 51.0000 CM

**TOTAL LENGTH** = 1.0-2.000 IN 25.4000 CM

**GAS**:

<table>
<thead>
<tr>
<th>G</th>
<th>G</th>
<th>G</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2000 IN 1.2700 CM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0000 IN 0.0000 CM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0000 IN 0.0000 CM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2000 IN 0.2000 CM</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**JIGS**:

<table>
<thead>
<tr>
<th>JIGS</th>
<th>JIGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0020 IN 0.0005 CM</td>
<td></td>
</tr>
<tr>
<td>0.0000 IN 0.0000 CM</td>
<td></td>
</tr>
</tbody>
</table>

**LARGE Y'VER** = 0.0000 IN 0.0000 CM

**12 GROOVES (CLOSED) COVERED WITH 200 MESH**

**NO LIMIT ENCOUNTERED AT** ~ 316 WATTS

**VAP PERFORMANCE DETAILS (T OR H) TT**

<table>
<thead>
<tr>
<th>T</th>
<th>T</th>
<th>T</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2222</td>
<td>3.222222</td>
<td>3.222222</td>
<td>3.222222</td>
</tr>
</tbody>
</table>

**TE** = 302

**COND TEMP** = 262.2 DEG F

**DELTA-T** =

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>302</td>
<td>262.2</td>
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</tbody>
</table>

**WALL** = 0

**WALL** = 0.266 DEG C

**SONIC LIMITS**:

<table>
<thead>
<tr>
<th>S</th>
<th>S</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>177.10</td>
<td>239.3</td>
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</table>

**G/A'S**:

<table>
<thead>
<tr>
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<th>G/A'S</th>
<th>G/A'S</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVAP</td>
<td>COLD</td>
<td>AXIAL</td>
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<tr>
<td>1</td>
<td>0</td>
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**E R EMT**:

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.0</td>
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</table>

**E R EMT**:

<table>
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<tr>
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<th>E R EMT</th>
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<tbody>
<tr>
<td>3</td>
<td>1151</td>
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**HOT FLUID GRAMS**:

<table>
<thead>
<tr>
<th>HOT FLUID GRAMS</th>
<th>HOT FLUID GRAMS</th>
<th>HOT FLUID GRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>07.0716 GRAMS</td>
<td>07.0716 GRAMS</td>
<td>07.0716 GRAMS</td>
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</table>

**COLD FLUID GRAMS**:

<table>
<thead>
<tr>
<th>COLD FLUID GRAMS</th>
<th>COLD FLUID GRAMS</th>
<th>COLD FLUID GRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.9808 GRAMS</td>
<td>72.9808 GRAMS</td>
<td>72.9808 GRAMS</td>
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</table>

**HEAT PIPES**:

<table>
<thead>
<tr>
<th>HEAT PIPES</th>
<th>HEAT PIPES</th>
<th>HEAT PIPES</th>
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</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
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</table>

**DELTA-T VALUES**:

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>DELTA-T</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVAP WALL</td>
<td>EVAP LAG</td>
<td>EVAP MESH</td>
</tr>
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<td>0.62608</td>
<td>0.62608</td>
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<tr>
<td>0.62608</td>
<td>0.62608</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>DELTA-T</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAPOR (1)</td>
<td>VAPOR (2)</td>
<td>VAPOR (3)</td>
</tr>
<tr>
<td>0.0000000</td>
<td>0.0000000</td>
<td>0.0000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>DELTA-T</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>COND WALL</td>
<td>COND MESH</td>
<td>COND LAG</td>
</tr>
<tr>
<td>1.0000000</td>
<td>1.0000000</td>
<td>1.0000000</td>
</tr>
</tbody>
</table>

**POWER OF 375 WATTS CAUSES** ~ CAPILLARY LIMIT, DPL > DPF

**LAST NON-LIMITED POWER CALCULATION WAS AT** ~ 370 WATTS

**TOTAL DELTA-T** = 0.32 DEG C

**TOTAL MASS** = 0.266 LB
ILLUS = DOWTHERM A        WALL MAT = 50438 E
EVAP TEMP = 277       VAPOR DELTA-T = 90 DEG C
GRAY AM = 0.00        VIB AM = 0.00 DEG

EVAP LENGTH 16.96981 IN  43.0000 CN
AOE LENGTH 16.96981 IN  43.0000 CN
COLD LENGTH 03.93241 IN  0.50000 CN
TOTAL LENGTH 103.1800 IN  203.0000 CN

12 GROOVES (50438E) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT 284 WATTS

TOTAL DELTA-T = 0.46 DEG C
TOTAL MASH = 0.281 CN

WATT PERFORMANCE DETAILS (75 OR H) Y

PA-2  PA-4  PA-6
1000.77 1000.77 1000.77

PA-2  PA-4  PA-6
271.72 271.72 271.72

EVAP TEMP  COLD TEMP  DELTA-T
277  270.811  0.50887

DFC = 0000 DFC = 0000 DFC/CH

DFTC  DFTC  DFTC
320  320  320

3 X EYE 3 X EYE 3 X EYE 3 X EYE
3  3  3  3

Sonic limits:  EVAP = 11912 AOE = 12775 WATTS

WATT/CH

A X 2  B X 2  C X 2
1  0  208

3 X EYE 3 X EYE 3 X EYE 3 X EYE
0  0  0  0

HOT FLUID GRAMS:  50-1456 GRAMS
COLD FLUID GRAMS:  11.995 CN

HEX: PIPE: (HEX) & 2 HEXCAP  213.837 GRAMS

DELTA-T VALUES:

EVAP WALL  EVAP LG  EVAP MESH  EVAP A
-14.233  -1.04333  -0.31347  -100096 DEG C

VAPOR (X)  VAPOR (A)  VAPOR (C)
-1003631-01  -7.32486-02  -7.32486-02

CONDENSATION  COLD MESH  COLD LG  COLD A
-7.42207-01  -1.102163  -7.32486-02 DEG C

POWER OF 310 WATTS CAUSES CAPILLARY LIMIT; DPL = DPV
LAST NON-LIMITED POWER CALCULATION: 718 AT 305 WATTS

TOTAL DELTA-T = 7.46 DEG C
TOTAL MASH = 0.281 CN

84
**RHE CONDITIONS:**

**FLUID = SOUTHERN A**  
**WALL MAT = 304SS**

**EVAP TEMP = 250**  
**VAPOR DELTA-T = 60**  
**DEG C**

**GAS AM = 0.00**  
**VTS AM = 0.00**  
**DEG**

**EVAP LENGTH**  
**10.6200 IN**  
**43.0000 CM**

**ADD LENGTH**  
**10.6200 IN**  
**43.0000 CM**

**COND LENGTH**  
**28.3213 IN**  
**174.3200 CM**

**TOTAL LENGTH**  
**109.4800 IN**  
**280.1000 CM**

**0.0**  
**0.0000 IN**  
**1.2700 CM**

**WALL THICKNESS**  
**0.0000 IN**  
**0.0000 CM**

**GROOVE WIDTH**  
**0.1063 IN**  
**2.7000 CM**

**GROOVE DEPTH**  
**0.0397 IN**  
**0.9100 CM**

**LAND WIDTH**  
**0.0000 IN**  
**0.0000 CM**

12 GROOVES (COVERS) COVERED WITH 500 WATT

**NO LIMIT ENCLOSED AT ~ 219 WATTS**

**TOTAL DELTA-T = 6.98**  
**DEG C**

**TOTAL MASS = 0.6374 lb**

**VAP PERFORMANCE DETAILS (Y OR Z) Y**

<table>
<thead>
<tr>
<th>VET</th>
<th>PA-A</th>
<th>PA-C</th>
<th>PC</th>
<th>OTHERS/UNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>VET</td>
<td>807 E6</td>
<td>807 E6</td>
<td>836043</td>
<td></td>
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<tr>
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<td>248.036</td>
<td>248.037</td>
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<tr>
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<td>247.018</td>
<td>247.018</td>
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<tr>
<td>VET</td>
<td>0.011</td>
<td>0.011</td>
<td>OTHERS/UNR</td>
<td></td>
</tr>
</tbody>
</table>

**SST DPTA | DPTA | DPTA | DPTA |
| SST | 443 | 211 | 2781 |
| SST | 203 | 1083 |

**SST LIMITS:**  
**EVAP = 1017**  
**ADD = 6383 WATTS**

<table>
<thead>
<tr>
<th>O/A = 1</th>
<th>EVAP</th>
<th>COND</th>
<th>AXIAL</th>
<th>WATTS/UNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>O/A = 1</td>
<td>1</td>
<td>0</td>
<td>172</td>
<td></td>
</tr>
</tbody>
</table>

**9.5 PCT:**  
**2 A HINTS**  
**LIG HINT**  
**HINT**  
**HINT**  
**HINT**

| 2 | 606 | 516 | 905 |

**HEAT FLUID CHARGE:**  
**52.3201 GRAMS**

**HEAT FLUID VOLUME:**  
**49.1986 CM**

**COLD FLUID CHARGE:**  
**64.0000 GRAMS**  
**60.3900 CM**

**HEAT PITS (HINT) & 2 PENCAPS 209.031 GRAMS**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LAG</th>
<th>EVAP NECK</th>
<th>EVAP NECK</th>
<th>EVAP NECK</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0000 G</td>
<td>3.0000 G</td>
<td>3.0000 G</td>
<td>3.0000 G</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VAPOR (E)</th>
<th>VAPOR (E)</th>
<th>VAPOR (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>131.6238-01</td>
<td>131.6238-01</td>
<td>131.6238-01</td>
</tr>
<tr>
<td>264.0075-01</td>
<td>264.0075-01</td>
<td>264.0075-01</td>
</tr>
</tbody>
</table>

**POWER OF 245 WATTS CAUSES ~ CAPILLARY LIMIT: DPT > DPT**

**LAST NON-LIMITED POWER CALCULATION WAS AT ~ 260 WATTS**

**TOTAL DELTA-T = 8.48**  
**DEG C**

**TOTAL MASS = 0.5745 lb**

85
### TEST CONDITIONS:

**FLUID** = MERCURY  
**VITAL MATH = 500,000**  
**ETAP TEMP** = 436  
**VAPOR DELTA-T** = 50 DEG C  
**IOV AND** = 0.00  
**VTR AND** = 0.00 DEG  
**ETAP LNGTH** = 16.03211 IN  
**LNG LNGTH** = 16.03211 IN  
**COLD LNGTH** = 63.26313 IN  
**TOLER LENGTH** = 103.14000 IN  
**O.D.** = 0.02000 IN  
**INNER RADIUS** = 0.00000 IN  
**SHUCK RADIUS** = 0.01000 IN  
**LAD WIND** = 0.00000 IN  
**C GROOVES** (CLOSED) COVERED W 200 MESH

NO LIMIT ENCOUNTERED AT --------------- 720 WATTS

--- TOTAL DELTA-T = 4.13 DEG C  
--- TOTAL MATH = 0.280 IN

### THERM PERFORMANCE DETAILS (Y OR X) ??

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>TA-C</th>
<th>FC</th>
<th>DME/CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>23-A</td>
<td>23-C</td>
<td>FC</td>
<td>DME/CM</td>
</tr>
<tr>
<td>420.577</td>
<td>420.577</td>
<td>420.577</td>
<td>420.577</td>
<td>420.577</td>
</tr>
</tbody>
</table>

**ETAP Temp** = 436  
**COLD Temp** = 0  
**DELTA-T** = 436

**EPO** = 114.06  
**DIN** = 0  
**DPC=EPO** = 114.06  
**DME/CM** =

**DFVR** = DFLCS  
**DFVR** = DFLCS  
**DFVR** = DFLCS

### THERM LIMITS: ETAP = 644 IN ADD = 1000 WATTS

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2</td>
<td>3273</td>
<td>7.372</td>
<td>7.786</td>
<td>353</td>
<td>7778</td>
<td>3644</td>
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<td>206.028</td>
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<td>126.602</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**HOT FLUID CHARGE** = 206.028 GRAMS  
**ROOM TEMP.: VOLUME OF HOT FLUID CHARGE** = 126.602 CM

**ETAP PIPE (MEDE) & 2 ENDCAPS** = 76.683 GRAMS

### DELTA-T VALUES:

<table>
<thead>
<tr>
<th>ETAP VALL</th>
<th>ETAP LAG</th>
<th>ETAP KESH</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.19877</td>
<td>1.19877</td>
<td>1.19877</td>
<td>1.19877</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VAPOR (2)</th>
<th>VAPOR (3)</th>
<th>VAPOR (4)</th>
<th>VAPOR (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>CONDENSATION</th>
<th>COND KESH</th>
<th>COND LAG</th>
<th>COND VALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.20000</td>
<td>1.20000</td>
<td>1.20000</td>
<td>1.20000</td>
</tr>
</tbody>
</table>

**POWER OF 770 WATTS CAUSES --------------- CAPILLARY LIMIT, DFL = DPF**

LAST NON-LIMITED POWER CALCULATION WAS AT --------------- 770 WATTS

--- TOTAL DELTA-T = 4.42 DEG C  
--- TOTAL MATH = 0.290 IN

---
**FLUID:** ACETONE  
**WALL MAT: 30453**

**FLAP TEMP:** 648  
**TAPOR DELTA-T:** 50  
**GRAV AM:** 0.00  
**VTD AM:** 0.00

<table>
<thead>
<tr>
<th>Length</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap</td>
<td>16.92911 in</td>
</tr>
<tr>
<td>Air</td>
<td>16.92911 in</td>
</tr>
<tr>
<td>Cond</td>
<td>96.20123 in</td>
</tr>
<tr>
<td>Total</td>
<td>103.12000 in</td>
</tr>
</tbody>
</table>

**WALL THICKNESS:** 0.00820 in  
**GROOVE WIDTH:** 0.1082 in  
**GROOVE DEPTH:** 0.0079 in  
**LAND WIDTH:** 0.0718 in  
**LAND DEPTH:** 0.0620 in

**GROOFS (CLOSED) COVERED WITH 200 Mesh**

**NO LIMIT ENCOUNTERED AT**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Delta-T</td>
<td>3.69</td>
</tr>
<tr>
<td>Total Mass</td>
<td>0.281</td>
</tr>
</tbody>
</table>

**WATT PERFORMANCE DETAILS (W OR H) **

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE</td>
<td>2004.08273-07</td>
</tr>
<tr>
<td>PA</td>
<td>226923.07</td>
</tr>
<tr>
<td>PU</td>
<td>2384208/07</td>
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</table>

**PFS**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>FE</td>
<td>3308.670</td>
</tr>
<tr>
<td>PA</td>
<td>3308.670</td>
</tr>
<tr>
<td>PU</td>
<td>3308.670</td>
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</table>

**DPLS**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE</td>
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<tr>
<td>PA</td>
<td>9633.842</td>
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<tr>
<td>PU</td>
<td>9633.842</td>
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</table>

**SONIC LIMITS:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap</td>
<td>9629 ACRE</td>
</tr>
<tr>
<td>ACRE</td>
<td>0.05168 W</td>
</tr>
</tbody>
</table>

**BOF FLUID CHARGE:** 197.01 Grams

**ROOM TEMP: VOLUME OF HOT FLUID CHARGE:** 1.84680 CM

**COLD FLUID CHARGE:** 105.661 Grams

**Evap Pipe: (Mesh) & 2 Endcaps 97.8052 Grams**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap Wall</td>
<td>2252.954</td>
</tr>
<tr>
<td>Evap Lg</td>
<td>990.529</td>
</tr>
<tr>
<td>Evap Mes</td>
<td>1.31773</td>
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<tr>
<td>Evaporation</td>
<td>100008</td>
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**VAPOR (1)**

<table>
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<tr>
<th>Component</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Evap Lg</td>
<td>2252.954</td>
</tr>
<tr>
<td>Evap Mes</td>
<td>1.31773</td>
</tr>
</tbody>
</table>

**COOLD CHARGE:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap Lg</td>
<td>990.529</td>
</tr>
<tr>
<td>EVAP MESC</td>
<td>0.23703</td>
</tr>
<tr>
<td>EVAP MES</td>
<td>0.23703</td>
</tr>
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</table>

**POWER OF 615 WATTS CAUSES**

**CAPILLARY LIMIT:** DELTAP = DPT

**LAST NON-LIMITED POWER CALCULATION WAS AT**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Delta-T</td>
<td>3.69</td>
</tr>
<tr>
<td>Total Mass</td>
<td>0.281</td>
</tr>
</tbody>
</table>

37
### Fluid Conditions:

**FLUID** = MERCURY  
**WALL MATT** = 30°/32°

**EVAP TEMP** = 352  
**VAPOR DELTA-T** = 30° DEG C  
**GRAY ANG** = 0.00  
**VAP ANG** = 0.00° DEG

**EVAP LENGTH** = 13.9991 IN  
**ADA LENGTH** = 16.9991 IN  
**CORD LENGTH** = 40.29915 IN  
**TOTAL LENGTH** = 105.29915 IN

- **3Grooves (Closed): Covers 20° MEAN**

**NO LIMIT ENCOUNTERED AT**  

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>460 WATTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOTAL DELTA-T</strong></td>
<td>3.30 DEG C</td>
</tr>
<tr>
<td><strong>TOTAL MASS</strong></td>
<td>0.272 KG</td>
</tr>
</tbody>
</table>

### Watt Performance Details (Y or X) TT

<table>
<thead>
<tr>
<th>TH</th>
<th>PH-A</th>
<th>PH-B</th>
<th>TC-A</th>
<th>TC-B</th>
<th>TH*</th>
<th>PROBE</th>
<th>MFG/CHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>45K</td>
<td>11462</td>
<td>11462</td>
<td>-14723-07</td>
<td>-14723-07</td>
<td>11462-07</td>
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<td>DTE/CHM</td>
</tr>
<tr>
<td>36K</td>
<td>340-063</td>
<td>340-063</td>
<td>340-173</td>
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<td>340-063</td>
<td>340-173</td>
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<td></td>
</tr>
<tr>
<td>320-118</td>
<td>320-118</td>
<td>DTE/CHM</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DPT</th>
<th>DPT</th>
<th>DPT</th>
<th>DPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>857</td>
<td>7284</td>
<td>10121</td>
<td>59918</td>
</tr>
<tr>
<td>31494</td>
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</table>

### Sonic Limits:

**EVAP** = 2622  
**ADD** = 2321 WATTS

<table>
<thead>
<tr>
<th>Q/A</th>
<th>5</th>
<th>EVAP</th>
<th>CORD</th>
<th>AXIAL</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>1398</td>
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<table>
<thead>
<tr>
<th>B R EFT</th>
<th>B A RFT</th>
<th>LIG RFT</th>
<th>O A RFT</th>
<th>G A RFT</th>
<th>C A RFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>3357</td>
<td>372</td>
<td>3345</td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HOT FLUID CHAMBER VOLUME</th>
<th>162.4822 GRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOM TEMP. VOLUME OF HOT FLUID CHAMBER</td>
<td>12.67408 CM3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COLD FLUID CHAMBER</th>
<th>173.949 GRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.6448 CM3</td>
<td></td>
</tr>
</tbody>
</table>

| EVAP PIPES (INCH) | 2 ENDCAPS | 98.5207 GRAMS |

### Delta-T Values:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LAG</th>
<th>EVAP HEAT</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>-176387</td>
<td>-858505</td>
<td>-0.00319</td>
<td>100000 DEG C</td>
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</table>

<table>
<thead>
<tr>
<th>VAPOR</th>
<th>VAPOR</th>
<th>VAPOR</th>
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</thead>
<tbody>
<tr>
<td>15776</td>
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<table>
<thead>
<tr>
<th>COND HEAT</th>
<th>COND LAG</th>
<th>COND VALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>-188585</td>
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<td>-188585</td>
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</tbody>
</table>

### Power of 460 Watts Causes:

**CAPILLARY LIMIT, DPT > DPT**

**LAST NON-LIMITED POWER CALCULATION WAS AT**  

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>446 WATTS</th>
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</thead>
<tbody>
<tr>
<td><strong>TOTAL DELTA-T</strong></td>
<td>3.54 DEG C</td>
</tr>
<tr>
<td><strong>TOTAL MASS</strong></td>
<td>0.272 KG</td>
</tr>
</tbody>
</table>

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**Reproducibility of the original page is poor.**
**RUN CONDITIONS:**

<table>
<thead>
<tr>
<th>FLUID</th>
<th>MERCURY</th>
<th>WALL HAM-30x80</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVAP TEMP</td>
<td>302</td>
<td>VAPOR DELTA-T = 50</td>
</tr>
<tr>
<td>GRAY AMG</td>
<td>0.00</td>
<td>YTD AMG = 0.00</td>
</tr>
</tbody>
</table>

| EVAP LENGTH | 16.0200 IN | 43.0000 CM |
| ADD LENGTH  | 16.0200 IN | 43.0000 CM  |
| CORD LENGTH | 60.3013 IN | 176.0000 CM |
| TOTAL LENGTH | 103.1000 IN | 262.0000 CM |
| 0-90 | 0.0000 IN | 0.0000 CM |
| VALL THICK | 0.0000 IN | 0.0000 CM |
| GROOVE WIDTH | 0.1250 IN | 0.3175 CM |
| GROOVE HEIGHT | 0.0070 IN | 0.0000 CM |
| LAND WIDTH | 0.1310 IN | 0.3330 CM |
| 3 GROOFS (CLOSED) COVERED WITH 200 MESH |

**NO LIMIT ENCOUNTERED AS**

[Table for total delta-t and total mass]

**WATT PERFORMANCE DETAILS (Y OR X) ?**

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>D13R/CH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>44906</td>
<td>439060</td>
<td>419060</td>
<td>19292</td>
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<table>
<thead>
<tr>
<th>TE</th>
<th>TE-A</th>
<th>21-0</th>
<th>TC</th>
<th>D13R</th>
</tr>
</thead>
<tbody>
<tr>
<td>300.000</td>
<td>209.124</td>
<td>227.797</td>
<td>227.066</td>
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</table>

<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>CORD TEMP</th>
<th>DELTA-T</th>
</tr>
</thead>
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<tr>
<td>302</td>
<td>257.463</td>
<td>4.59070</td>
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</table>

<table>
<thead>
<tr>
<th>124673</th>
<th>DPF= 0</th>
<th>DPF= 124673</th>
<th>D13R/CH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>134767</td>
<td>DPLAG</td>
<td>134767</td>
<td>DPLAG</td>
</tr>
<tr>
<td>13092</td>
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<tr>
<td>1027</td>
<td>22023</td>
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<td>22023</td>
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**SONIC LIMITS:**

<table>
<thead>
<tr>
<th>EVAP</th>
<th>LOGE</th>
<th>ADD</th>
<th>1146 WATTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Gamma 9 = EVAP CORD AXIAL WATTS/CM2**

**3 R EYS = 4306 256 4232**

**FRONTAL charge**

**ROOM TEMP: VOLUME OF HOT FLUID CHARGE 12.9417 CM3**

**COLD FLUID CHARGE 173.995 CM3**

**HEAT PIPE (MESH) & 2 EHCAPS 99.7507 CM3**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP VALL</th>
<th>EVAP LAG</th>
<th>EVAP RESE</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>130209</td>
<td>0.08704</td>
<td>0.740609</td>
<td>10009058</td>
</tr>
<tr>
<td>VAPOUR (E)</td>
<td>VAPOUR (A)</td>
<td>VAPOUR (C)</td>
<td></td>
</tr>
<tr>
<td>1.984643</td>
<td>1.570465</td>
<td>-1.095975</td>
<td></td>
</tr>
</tbody>
</table>

**COND. VANN WALL**

| 0.84657E-01 | 1.66729 | 1.21974 | 0.510635E-01 | D13R C |

**POWER OF 390 WATTS CAUSES**

**CAPILLARY LIMIT: DPL = DPF**

**LAST IOR-LIMITED POWER CALCULATION WAS AT**

**336 WATTS**

| TOTAL DELTA-T | 5.41 D13R C |
| TOTAL MASS | 0.273 KG |

**WATT PERFORMANCE DETAILS (Y OR X) ?**
FLUID = MERCURY   WALL MATE=304SS
TAP TEMP = 277   TAPOR DELTA-T = 60.250 C
G4AY AREA = 0.00   VTS AREA = 0.00 EN

TAP LENGTH 14.8311 IN  43.0000 CN
ADJ LENGTH 16.8921 IN  43.0000 CN
COND LENGTH 65.2913 IN  175.0000 CN
TOTAL LENGTH 104.0454 IN  262.0000 CN

0.25  0.3200 IN  0.5350 CN
VAIL TRESS 0.0028 IN  0.0074 CN
GROOVE WIDTH 0.1035 IN  0.2625 CN
GROOVE HEIGHT 0.0700 IN  0.2700 CN
LAND WIDTH 0.1318 IN  0.3346 CN
3 GROOVS (GROUDED) COVERED VIZ 200 MSK

NO LIMIT ENCOUNTERED AT 264 WATTS

TOTAL DELTA-T = 8.35 EN  
TOTAL MASS = 0.273 KG

VAPOR PERFORMANCE DETAILS (T OR K) TT

<table>
<thead>
<tr>
<th>PR</th>
<th>TP-A</th>
<th>T-J-G</th>
<th>pc</th>
<th>UNITST/CH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>250.6492</td>
<td>240.9693</td>
<td>224.956</td>
<td>224.956</td>
<td></td>
</tr>
</tbody>
</table>

T-J 270-719  270.951  226.961  226.961

VAP TEMP 277  226.961  8.5666

DIF= 127.036  DIF= 0  DFC=DFG= 127.036  UNITST/CH2

BTE 160.649  160.649  159.996  159.996  3733

DFG 160.649  160.649  160.649  160.649

SONIC LIMITS:

VAP= 654  ADD= 640  WATTS

G/A'S

| 3 | 0 | 633 |

R JET# 2 LAG R= 0  O JET# 0  R JET# 1

HOT FLUID GRAM 170.127 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID GRAM 12.5116 CN

COLD FLUID GRAM 173.996 GRAMS

HEAT PIPE: 2 (HEX) & 2 (ENDCAPS) 99.2507 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>VAP VALL</th>
<th>VAP LAG</th>
<th>VAP MSH</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.113333</td>
<td>0.932317</td>
<td>0.23775</td>
<td>0.10998</td>
</tr>
</tbody>
</table>

VAPOR (A1)  VAPOR (A2)  TAPOR  14 C
3.67303  3.68391  0.03128  0.03132  0.03132  0.03132

CONDENSTION  COND MSH  COND LAG  COND WALL
+2465073-01  +1.05789  +1.05789  +2737512-01

POWER OF 360 WATTS CAUSE ---------- CAPILLARY LIMIT: DFL = DFV

LAST NON-LIMITED POWER CALCULATION WAS AT 340 WATTS

TOTAL DELTA-T = 12.83 EN
TOTAL MASS = 0.273 EN
FLUID = MERCURY
VALL DTHL = 30455
STAP TMP = 434
VAPOR DTA-T = 50 DEG C
JULY DTH = 0.00
VAP TMP = 0.00

STAP LENGTH = 22.8083 IN 86.000 CN
AD8 LENGTH = 0.0000 IN 0.0000 CN
GOLD LENGTH = 20.2013 IN 174.000 CN
TOTAL LENGTH = 102.1500 IN 232.000 CN

Q-D 
0.2504 IN 0.0636 CN

VALL LENGTH = 15.085 IN 0.390 CN
1000FT WIDHT = 0.1093 IN 0.0275 CN
1000FT LENGTH = 0.0079 IN 0.0000 CN
LAND WIDTH = 0.0360 IN 0.0915 CN
5 GROVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT RECOGNIZED AT ———— 720 VATTS

TOTAL DTA-T = 2.00 DEG C
TOTAL VATTS = 0.3200 KG

VAPOR PERFORMANCE DETAILS (Y OR N) TT

PS
PC-A PC-G TG UTENS/CM2
.589669+07 .589724+07 .589904+07

TP
TP-A TP-G TG DEG C
.452.39 1.2416 452.216 452.205

STAP TMP GORD TMP DTA-T
474 474 474

DPW 114073 DPW = 0 114073 Cp/CM2

DPW 16538 DPWA DPW

CPC 16538 0 0

DEG C

57743

SONIC LIMITS:

STAP = 9046 AND = 10534 VATTS

G/A = STAP GORD AXIAL VATTS/CM2
4 2 2206

3 R REY R A REY LIQ REY C A REY C R REY
6 7738 294 7738 3

SOT FLUID CHARGE 206-234 GRAMS
BOOK TEMP. VOLUME OF HOT FLUID CHARGE 15.2267 CM3

COLD FLUID CHARGE 212.253 GRAMS
15.7416 CM3

HEAT PIPE (MET) & 2 ENDCAPS 76.7047 GRAMS

DELT-T VALUES:

STAP VALL STAP LAG STAP MESH VAPORATION
-135886 -135829 -773944 -100998 DEG C

VAPOR (C)

VAPOR (A) VAPOR (C)
-172073 -433221-03 -823395-01

CONDENSEN

COND MESH COND LAG COLD VALL
-4291135-01 -379433 -292241 -6612630-01 DEG C

POWER OF 1650 VATTS CAUSES ———— CAPILLARY LIMIT: DPL > DPW

LAST NON-LIMITED POWER CALCULATION WAS AT ———— 1625 VATTS

TOTAL DTA-T = 5.47 DEG C
TOTAL VATTS = 0.3200 KG

91
FLUID = MERCURY WALL MAT=30-45
EVAP TEMP = 277 VAPOR DELTA-T = 50 DEG C
GRAY ERR = 0.00 VTR ERR = 0.00 DEG
EVAP LENGTH 55.40885 IN 86.00000 CM
ADD LENGTH 3.00000 IN 0.00000 CM
COLD LENGTH 09.02913 IN 1.7810000 CM
TOTAL LENGTH 113.16000 IN 282.00000 CM
O=1.2 VON THRES 0.00582 IN 0.00000 CM
COLD VAPOR 0.18588 IN 0.00000 CM
COLD VAPOR 0.10079 IN 0.00000 CM
LAMB VAPOR 0.11248 IN 0.00000 CM
3 CROPS (CLOSED) COVERED WITH 200 MM

NO LIMIT ENCOUNTERED AT ——— 286 WATTS

—— TOTAL DELTA-T = 59.79 DEG C
—— TOTAL MASS = 0.275543

WAT/ PERFORMANCE DETAILS (T OR H) YT

FR PD-AP PA-C PG WATTS/CM2
250531 245531 243017 243017

FR PD-AP PA-C PG WATTS/CM2
275.390 277.362 279.862 272.66

COLD VAPOR 277.21 4.76666

DEG-128.575 DPF-0 DPF=DPF=128.575 DEG/CM2

DPG1 190.20 0 DPF 190.01

SOLVING LIMIT: EVAP= 641 ADD= 542 WATTS

A/A'S= EVAP COLD ACTAL WATTS/CM2

1 0 853

E G REF# E L L# R L# L# G A REF# C R L#1
3 3789 208 3766 1

NOT FLUID CHARGE 170.18 GRAMS
ROOM TEMP. VOLUME OF NOT FLUID CHARGE 12.6531 CM3
COLD FLUID CHARGE 173.938 GRAMS 12.8448 CM3

EVAP PIPES (N/SH) & 2 BEADS 98.2007 GRAMS

DELTA-T VALUES:

EVAP VAPOR EVAP LAM EVAP MRES EVAP WATERS
+0.5063152-01 +0.216132 +0.318761 +0.00732 DEG C

VAPOR H1 VAPOR H2 VAPOR C2
3.7128 +0.7326232-03 +0.4199229-01

CONDENSATION COLD MRES COLD LAM COLD VAPOR
+0.130125-01 +0.126512 +0.103407 +0.272082-01 DEG C

POWER OF 500 WATTS CAUSES ———— ADD SOLVING LIMIT

Last non-limited power calculation was at ———— 485 WATTS

——— TOTAL DELTA-T = 6.34 DEG C
——— TOTAL MASS = 0.275543
This appendix develops Equation 3.2 which shows how the mass of a radiator heat pipe increases with the performance $T$ of the heat pipe.

$T_0$ = desired heat pipe temperature

$\Delta T$ = temperature drop down heat pipe

$T = T_0 - \Delta T$, actual heat pipe radiating temperature

$A_0$ = radiating area of heat pipe at $T_0$

$A = A_0 + da$, actual heat pipe radiator area required at $T$

$Q$ = power to be radiated from heat pipe

$$\frac{da}{dt} = \frac{\text{increase in surface area}}{\text{decrease in temperature}}$$

$$\frac{da}{dt} = \frac{A - A_0}{T_0 - T}$$

Eq. A.1

but

$$A = \frac{Q}{\varepsilon\sigma(T_0 - T)^4}$$

and

$$A_0 = \frac{Q}{\varepsilon\sigma T_0^4}$$

therefore, with substitution into Equation A.1 and proper rearranging,

$$\frac{da}{dt} = \frac{A_0}{\Delta T}[(T_0/T)^4 - 1]$$

Eq. A.2

Now, since area is a function of length, we have

$$dl = l_c[(T_0/T)^4 - 1]$$

Eq. A.3

where $l_c$ = condenser, but $\frac{dl}{l_t} = \frac{dm}{m}$ where $l_t = \text{total heat pipe length}$,

$m = \text{mass}$, we obtain with substitution and rearrangement -

$$dm = \frac{ml_c}{l_t}[(T_0/T)^4 - 1]$$

Eq. A.4

which is Equation 3.2.