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A. Theory of the Heat Pipes

A.1 Heat Pipe Heat Sink Performance

A resistance network, analogous to electrical circuits, is the simplest way to predict the overall performance of the parallel plate/heat pipe heat sink.

The resistances can be used to calculate an associated temperature drop. The following is a brief explanation of the network. The conductive losses that are associated with an evaporator block ($R_{\text{Block}}$) are governed by Fourier’s Law. Therefore:

$$\Delta T_{\text{Block}} = \frac{Q \cdot t_{\text{Block}}}{k_{\text{Block}} \cdot A_{\text{Block}}} \quad (\text{Eq. A.1})$$

The loss associated with the interface between the evaporator block and the heat pipe ($R_{\text{Inter}}$) can be calculated using the thermal resistance of the interface material, which is typically solder ($R_{\text{Inter}} \approx 0.5 \text{ C/W/cm}^2$) or thermal epoxy ($R_{\text{Inter}} \approx 1.0 \text{ C/W/cm}^2$), and the interface area.

$$\Delta T_{\text{Inter}} = \frac{Q \cdot R_{\text{Inter}}}{\Pi \cdot D_{\text{HP}} \cdot L_{\text{Evap}}} \quad (\text{Eq. A.2})$$

The detailed analysis of the heat pipe is rather complex. The total thermal resistance of a heat pipe is the sum of the resistances due to conduction through the evaporator section wall and wick, evaporation or boiling, axial vapour flow, condensation, and conduction losses back through the condenser section wick and wall. A rough estimate for a copper/water heat pipe with a powder metal wick structure is to use $0.2 \text{ C/W/cm}^2$ for the axial resistance.

$$\Delta T_{\text{HP}} = \frac{Q \cdot R_{\text{Evap}}}{\Pi \cdot D_{\text{HP}} \cdot L_{\text{Evap}}} + \frac{Q \cdot R_{\text{Axial}}}{0.025 \cdot \Pi \cdot D_{\text{VS}}^2} + \frac{Q \cdot R_{\text{cond}}}{\Pi \cdot D_{\text{HP}} \cdot L_{\text{cond}}} \quad (\text{Eq. A.3})$$

The resistance in transferring the heat from the fin to the air ($R_{\text{Conv}}$) is calculated using the convection coefficient as follows:

$$\Delta T_{\text{Conv}} = \frac{Q}{h \cdot A_{\text{Fin}}} \quad (\text{Eq. A.4})$$
The conductive losses that are associated with the fin \( R_{\text{Eff}} \) are governed by the fin efficiency defined as:

\[
\eta_{\text{Fin}} = \tanh\left( \frac{m_{\text{Fin}} \cdot L_{\text{Eff}}}{m_{\text{Fin}} \cdot L_{\text{Eff}}} \right) \tag{Eq. A.5}
\]

where:

\[
m_{\text{Fin}} = \sqrt{\frac{2 \cdot h}{k_{\text{Fin}} \cdot t_{\text{Fin}}}} \tag{Eq. A.6}
\]

then:

\[
\Delta T_{\text{Fin}} = \Delta T_{\text{Conv}} \cdot \left(1 - \eta_{\text{Fin}} \right) \tag{Eq. A.7}
\]

The effective air rise can be calculated by using the bulk fluid properties:

\[
\Delta T_{\text{Air}} = \frac{1}{2} \left( \frac{Q}{\dot{m} \cdot C_p} \right) \tag{Eq. A.8}
\]

The overall performance of the sink is the sum of the individual temperature drops:

\[
\Delta T_{\text{Total}} = \Delta T_{\text{Block}} + \Delta T_{\text{Inter}} + \Delta T_{\text{HP}} + \Delta T_{\text{Conv}} + \Delta T_{\text{Fin}} + \Delta T_{\text{Air}} \tag{Eq. A.9}
\]

The thermal resistance of the sink to ambient is:

\[
R_{s-a} = \frac{\Delta T_{\text{Total}}}{Q} \tag{Eq.A.10}
\]

The above calculation should provide a reasonable estimate on the feasibility of a heat pipe heat sink.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
<th>Name of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$ (K)</td>
<td>Thermic variability</td>
<td>$D_h$ (m)</td>
<td>Diameter</td>
</tr>
<tr>
<td>$Q$ (W)</td>
<td>power</td>
<td>$R$ (K/W)</td>
<td>Thermic resistance</td>
</tr>
<tr>
<td>$k$ (W/m·K)</td>
<td>Thermic conductivity</td>
<td>$\eta_{fin}$</td>
<td>Efficiency of the fin</td>
</tr>
<tr>
<td>$A$ (m$^2$)</td>
<td>Working area</td>
<td>$m_{fin}$ (m$^3$)</td>
<td></td>
</tr>
<tr>
<td>$C_p$ (J/kg·K)</td>
<td>Specific heat (constant pressure)</td>
<td>$t$</td>
<td>thermic</td>
</tr>
<tr>
<td>$\dot{m}$ (kg/s)</td>
<td>Mass flow</td>
<td>$h$ (W/m$^2$·K)</td>
<td>Convection coefficient</td>
</tr>
</tbody>
</table>

Fig A.0 Graphic: $Q=f(T)$
A.2 Performance limits

The most important heat pipe design consideration is the amount of power the heat pipe is capable of transferring. Heat pipes can be designed to carry a few watts or several kilowatts, depending on the application. Heat pipes can transfer much higher powers for a given temperature gradient than even the best metallic conductors. If driven beyond its capacity, however, the effective thermal conductivity of the heat pipe will be significantly reduced. Therefore, it is important to assure that the heat pipe is designed to safely transport the required heat load.

The maximum heat transport capability of the heat pipe is governed by several limiting factors which must be addressed when designing a heat pipe. There are five primary heat pipe heat transport limitations. These heat transport limits, which are a function of the heat pipe operating temperature, include: viscous, sonic, capillary pumping, entrainment or flooding, and boiling. Figures 2 and 3 show graphs of the axial heat transport limits as a function of operating temperature for typical powder metal and screen wicked heat pipes.

![Fig A.1 Graphic: Q=f(T)](image)

A.3 Operating limitation

The operation of the heat pipes is limited by several operating phenomena. Each of these limitations is depends on:
- Wick structure
- Working fluid
- Temperature
- Orientation
- Size of the heat pipe
Description of the limitations:

A.3.1. Capillary Limit:

The wick structure of the heat pipe generates a capillary pressure, which is dependent on the pore radius of the wick and the surface tension of the working fluid. The capillary pressure generated by the wick must be greater than the sum of the gravitational losses, liquid flow losses through the wick, and vapour flow losses. The liquid and vapour pressure drops are a function of the heat pipe and wick structure geometry (wick thickness, effective length, vapour space diameter, etc) and the fluid properties (latent heat, density, viscosity, etc). A critical heat flux exists that balances the capillary pressure with the pressure drop associated with the fluid and vapour circulation. For horizontal or against gravity (evaporator at a higher elevation than the condenser), the capillary limit is the heat pipe limit. For gravity aided orientations, the capillary limitation may be neglected, and the flooding limit may be used if the heat pipe can have an excess fluid charge.

\[
Q_{c,\text{max}} = \frac{2\sigma}{r_c} \left( \rho_l g d_v \cos \varphi \pm \rho_v g l \sin \varphi \right) \left( F_l + F_v \right)_{\text{eff}}
\]  
(Eq. A.11)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
<th>Name of the parameters</th>
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</thead>
<tbody>
<tr>
<td>(Q_{c,\text{max}}) (W)</td>
<td>Heat power amount</td>
<td>(l) (m)</td>
<td>Liquid length</td>
</tr>
<tr>
<td>(\sigma) (N/m)</td>
<td>Surface tension</td>
<td>(F_l) (N/m²)/(W.m)</td>
<td>Liquid friction</td>
</tr>
<tr>
<td>(r_c) (m)</td>
<td>Pore radius</td>
<td>(F_v) (N/m²)/(W.m)</td>
<td>Vapour friction</td>
</tr>
<tr>
<td>(g)</td>
<td>Gravity constant</td>
<td>(l_{\text{eff}}) (m)</td>
<td>Total HP length</td>
</tr>
<tr>
<td>(d_v) (m)</td>
<td>Vapour diameter</td>
<td>(\rho_l) (kg/m³)</td>
<td>Liquid density</td>
</tr>
</tbody>
</table>

Table A.1 Table of the parameters
A.3.2 Boiling Limit

As more heat is applied to the heat pipe at the evaporator, bubbles may be formed in the evaporator wick. The formation of vapour bubbles in the wick is undesirable because they can cause hot spots and obstruct the bubble formation completely blocks the liquid flow.

This limitation is associated to a radial heat flux. The boiling limitation is typically a high phenomena temperature. Heat flux limitation for various wick structures should be used for design criteria. Sintered powder metal wick structures have more surface area, and can therefore handle higher heat fluxes. Conservative values are 50 W/cm² for powder metal wick, 10 W/cm² for screen wicks, 5 W/cm² for the bare wall thermosyphons.

\[
Q_{b,\text{max}} = \frac{2\pi l_v \lambda_{\text{eff}} T_v}{h_f \rho_v \ln\left(\frac{r_i}{r_v}\right)} \left(\frac{2\sigma}{r_b} - \Delta p_c\right) \quad \text{(Eq. A.12)}
\]

<table>
<thead>
<tr>
<th>Parameters</th>
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<th>Name of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_{b,\text{max}}) (W)</td>
<td>Heat power amount</td>
<td>(\sigma) (N/m)</td>
<td>Surface tension</td>
</tr>
<tr>
<td>(h_f) (J/kg)</td>
<td>Internal energy</td>
<td>(T_v) (K)</td>
<td>Vapour temperature</td>
</tr>
<tr>
<td>(\rho_v) (kg/m³)</td>
<td>Vapour density</td>
<td>(\Delta p_c) (Pa)</td>
<td>Maximum capillary pressure</td>
</tr>
<tr>
<td>(r_i/r_v)</td>
<td>Radius</td>
<td>(\lambda_{\text{eff}}) (W/m·K)</td>
<td></td>
</tr>
<tr>
<td>(l_v) (m)</td>
<td>Length</td>
<td>(r_b) (m)</td>
<td>Radius</td>
</tr>
</tbody>
</table>

Table A.2 Table of the parameters
A.3.3 Sonic Limit

In a heat pipe of constant vapour space diameter, the vapour flow accelerates and decelerates because of the vapour addition in the evaporator and the vapour removal in the condenser. The changes in vapour flow also change the pressures along the heat pipe. As more heat is applied to the heat pipe, the vapour velocities generally increase. A chocked flow condition will eventually arise, where the flow becomes sonic. As this point, the vapour velocities can not increase and a maximum heat transport limitation is archived. The heat flux that results in chocked flow is considered the sonic limit. The addition of more heat will result in an unproportional increase in the heat pipe temperature delta by an increase in the evaporation temperature. This phenomenon is self-correcting as the heat pipe warms up. An additional benefit of the high vapour velocities is the very quick response to heat input.

\[ Q_{s,max} = A_v \rho_v h_{fg} \left( \frac{\gamma_v R_v T_0}{2(\gamma_v + 1)} \right)^{1/2} \]  
(Eq.A.13)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
<th>Name of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{s,max} )</td>
<td>Heat power amount</td>
<td>( R_v ) (J/kg·K)</td>
<td>R_v/M</td>
</tr>
<tr>
<td>( h_{fg} )</td>
<td>Internal energy</td>
<td>( T_0 ) (K)</td>
<td>Working temperature</td>
</tr>
<tr>
<td>( \rho_v ) (kg/m³)</td>
<td>Vapour density</td>
<td>( A_v ) (m²)</td>
<td>Vapour cross section surface</td>
</tr>
<tr>
<td>( \gamma_v )</td>
<td>Specific heat ratio</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A.3 table of the parameters
A.3.4 Entrainment Limit:

Since the vapour and the liquid move in opposite directions in a heat pipe, a shear force exists at the liquid-vapour interface. If the vapour velocity is sufficiently high, a limit can be reached at which the liquid be torn from the pores of the wick and entrained in the vapour. When enough fluid is entrained in the vapour that the condensate flow is stopped, abrupt dry-out of the wick at the evaporator results. The corresponding heat flux that results in this phenomenon is called the Entrainment Limit. The Entrainment Limit is typically not the bounding value.

\[
Q_{e,\text{max}} = A_v h_f g \left[ \frac{\rho_v \sigma}{2 r_{hs}} \right]^{1/2} \quad \text{(Eq. A.14)}
\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
<th>Name of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{e,\text{max}} ) (W)</td>
<td>Heat power amount</td>
<td>( \rho_v ) (kg/m(^3))</td>
<td>Vapour density</td>
</tr>
<tr>
<td>( A_v ) (m(^2))</td>
<td>Vapour cross section surface</td>
<td>( \sigma ) (N/m)</td>
<td>Surface tension</td>
</tr>
<tr>
<td>( h_f g ) (J/kg)</td>
<td>Internal energy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A.4 table of the parameters
A.3.5 Flooding Limit

The flooding limit is only applicable to gravity aided orientations with excess fluid. The wick structure is saturated and the excess fluid results in a “puddle” flow on the surface of the wick structure. The flooding limit, similar to the entrainment, occurs when high vapour velocities preclude the fluid that is flowing on the surface of the wick to return to the evaporator. The vapour shear hold-up prevents the condensate from returning to evaporator and leads to a flooding condition in the condenser section. This causes a partial dry-out of the evaporator which results in wall temperature excursions or in limiting the operation of the system. By increasing the heat flux above the flooding limit, it is possible to achieve liquid flow reversal leading to:

1) The accumulation of liquid in the condenser
2) The accumulated liquid falling to the evaporator due to gravity
3) The reestablishment of a flow reversal
4) The repeat cycle of flooding and normal flow.

A.3.6 Viscous Limit

\[ Q_{vi,max} = \frac{d_v^2 h_{fg}}{64 \mu_v l_{eff}} \rho_{v0} P_{v0} A_{v0} \]  

(Eq.A.15)

<table>
<thead>
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<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
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</thead>
<tbody>
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<td>(Q_{vi,max}) (W)</td>
<td>Heat power amount</td>
<td>(l_{eff}) (m)</td>
<td>Total length</td>
</tr>
<tr>
<td>(d_v^2) (m)</td>
<td>Vapour diameter</td>
<td>(\rho_{v0}) (kg/m(^3))</td>
<td>Vapour density</td>
</tr>
<tr>
<td>(h_{fg}) (J/kg)</td>
<td>Internal energy</td>
<td>(P_{v0}) (Pa)</td>
<td>Vapour pressure</td>
</tr>
<tr>
<td>(\mu_v) (kg/m(\cdot)s)</td>
<td>Vapour viscosity</td>
<td>(A_{v0}) (m(^2))</td>
<td>Vapour cross section surface</td>
</tr>
</tbody>
</table>

Table A.5 table of the parameters
A.3.7 Condenser limitation

For high temperature:

\[ Q_{\text{con, max}} = 2\pi R_0 L_c \varepsilon \sigma \left( T^4 - T_{\infty}^4 \right) \] (Eq.A.16)

For low temperature:

\[ Q_{\text{con, max}} = S_c h \left( T_c - T_{\infty} \right) \] (Eq.A.17)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
<th>Name of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_{\text{con, max}}) (W)</td>
<td>Net radiated power</td>
<td>(T_{\infty}^4) (K)</td>
<td>Temperatur of surroundings</td>
</tr>
<tr>
<td>(R_0) (m)</td>
<td>Radius</td>
<td>(Q_{\text{con, max}}) (W)</td>
<td>Heat power amount</td>
</tr>
<tr>
<td>(L_c) (m)</td>
<td>Condenser lentgh</td>
<td>(S_c)</td>
<td>Section of the condenser</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>Emissivity</td>
<td>(h) (W/m(^2))</td>
<td>Plank constant</td>
</tr>
<tr>
<td>(\sigma) (W/m(^2)-K(^4))</td>
<td>Stefan-Boltzmann constant</td>
<td>(T_c) (K)</td>
<td>Temperature of the condenser</td>
</tr>
</tbody>
</table>

Table A.6 table of the parameters

A.3.8 Continuum flow limitation

\[
\ln \left( \frac{T_{tr} \rho_{tr} R_g}{p_{sat}} \right) + h_{fg} \left( \frac{1}{T_{tr}} - \frac{1}{T_{sat}} \right) = 0 \] (Eq.A.18)
A.3.9 Frozen start up limitation:

\[ \frac{\varphi \rho l A_w h_{fg}}{C(T_{mel} - T_{\infty})} \geq 1 \]  

(Eq.A.19)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Name of the parameters</th>
<th>Parameters</th>
<th>Name of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_l ) (kg/m(^3))</td>
<td>Liquid density</td>
<td>( C ) (W/K)</td>
<td>Flux of heat</td>
</tr>
<tr>
<td>( A_w ) (m(^2))</td>
<td>Cross section section of wick</td>
<td>( T_{mel} ) (K)</td>
<td>Melt Temperature</td>
</tr>
<tr>
<td>( h_{fg} ) (J/kg)</td>
<td>Internal energy</td>
<td>( T_{\infty} ) (K)</td>
<td>Temperature</td>
</tr>
</tbody>
</table>

Table A.7 table of the parameters
A.4 Limits to Heat Transport

Typical Horizontal Sintered Wick Limits

As shown in Figures A.2 and A.3, the capillary limit is usually the limiting factor in a heat pipe design. Typical Horizontal Mesh Wick Limits

In order to understand the heat pipe limits, a web page was used:

http://www.electronics-cooling.com/Resources/EC_Articles/SEP96/sep96_02.htm
The capillary limit is set by the pumping capacity of the wick structure. As shown in Figure 4, the capillary limit is a strong function of the operating orientation and the type of wick structure.
Screen and Sintered Wicks Heat Transport vs. Angle

Fig A.4 Capillary limits vs. operating angle
A.5 Heat Pipes operation prediction

In order to know the working position of the heat pipe, an experiment was done with different positions of the heat pipe. The exact positions were: gravity position, horizontal and anti-gravity position.

Gravity Aided:

The evaporator is at lower elevation than the condenser. The Gravity Aided orientation is the most efficient, since the heat pipe acts as a thermosyphon and gravity will return the condenser fluid to the evaporator. Heat pipe operation is typically limited by the flooding limit or the boiling limit. These two limitations are most greatly affected by the diameter of the heat pipe; a larger diameter heat pipe will carry more power.

Horizontal:

The Horizontal orientation relies on the wick structure to provide the capillary pressure to return the condensed fluid to the evaporator. The heat pipe operation is typically limited by the Capillary Limit. This limitation is greatly affected by the diameter of the heat pipe (a large diameter heat pipe will carry more power) and the length of the heat pipe (a longer heat pipe will carry less power).

Against Gravity:

The evaporator is at a higher elevation than the condenser. Heat pipe operation in the Against Gravity orientation relies on the wick structure to return the condenser fluid up to the higher evaporator. Again the heat pipe operation is limited by the Capillary Limit. This orientation is very similar to the Horizontal orientation, except the effects of gravity must be accounted. A larger elevation difference between the evaporator and the condenser results in a lower power capacity.
The experiment consisted to change the position of the Heat Pipe (angles) and at the same time changing the input heat load. The experiment was done with two groove heat pipe but the only different between them it was the dimensions.

Fig A.5 Max Heat Transport=f (Inclination)
Horizontal Orientation

Vertical Orientation

Fig A.6 and A.7 Thermal resistance vs Heat Pipe length
A.6 Radiation Environment

Irradiation Test

- 8 heat pipes and a Peltier have been sent for irradiation
- 2 Methanol, 3 Propane and 3 Xenon, including three kinds of wick structures
- A long straight heat pipe charged with Propane was tested. Grooved wick structure, length=1.1m, outer diameter=12.7mm

A.6.1 Performance test of heat pipes before/after irradiation (1)

<table>
<thead>
<tr>
<th>Items</th>
<th>Average weight (g)</th>
<th>Δw (g)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Before Irradiation</td>
<td>After Irradiation</td>
</tr>
<tr>
<td>T-Methanol-1</td>
<td>36.4545</td>
<td>36.4520</td>
</tr>
<tr>
<td>T-Methanol-2</td>
<td>49.1494</td>
<td>49.1489</td>
</tr>
<tr>
<td>T-S-Pr-1</td>
<td>49.9454</td>
<td>49.9432</td>
</tr>
<tr>
<td>Q-S-Pr-1</td>
<td>28.9314</td>
<td>28.9326</td>
</tr>
<tr>
<td>Q-G-Pr-3</td>
<td>21.8209</td>
<td>21.8190</td>
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<td>Q-M-Xe-1</td>
<td>27.3921</td>
<td>27.3907</td>
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<td>Q-M-Xe-2</td>
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<tr>
<td>Q-M-Xe-3</td>
<td>23.1003</td>
<td>23.0994</td>
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Table A.8 Performance test of heat pipes before/after irradiation
A.6.2 Irradiation tests AT CEA-SACLAY

IRRADIATION TESTS AT CEA-SACLAY (60Co)
From Monday 7 Nov 2005 at 10:30 until Wednesday 9 Nov 2005 at 16:00

<table>
<thead>
<tr>
<th>Item</th>
<th>Dose rate (Gy/hr)</th>
<th>Start irradiation</th>
<th>Stop irradiation</th>
<th>Duration of irradiation (hr)</th>
<th>TID (Gy)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipes</td>
<td>100</td>
<td>10:30 (7/11/05)</td>
<td>12:00</td>
<td>1.5</td>
<td>150</td>
<td>The irradiation of the pipes was not uniform for the dose rate of 20 kGy/hr. This is because the pipes were longer than the central pot, so only the part of the pipes that was INSIDE the pot (22 cm) received 20 kGy/hr. The rest ~18 cm of the pipes received &lt; 20 kGy/hr (~17 kGy/hr) as they were outside the central pot.</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>18:00 (8/11/05)</td>
<td>08:00</td>
<td>14</td>
<td>280,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>08:30</td>
<td>13:30</td>
<td>5</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>14:15 (9/11/05)</td>
<td>16:00</td>
<td>25h 45min</td>
<td>526,667</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TOTAL for pipes</td>
<td></td>
<td></td>
<td></td>
<td>907,317</td>
<td></td>
</tr>
<tr>
<td>Peltier</td>
<td>500</td>
<td>12:30</td>
<td>17:30</td>
<td>5</td>
<td>2,500</td>
<td>A more precise assessment will be provided by the alanine dosimeters (I had placed one dosimeters on each edge of the pipes). The measurement is expected by the Radiation Protection Group of CERN within this month.</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>18:00 (8/11/05)</td>
<td>08:00</td>
<td>14</td>
<td>280,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>08:30</td>
<td>13:30</td>
<td>5</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>14:15 (9/11/05)</td>
<td>16:00</td>
<td>25h 45min</td>
<td>526,667</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TOTAL for Peltier item</td>
<td></td>
<td></td>
<td></td>
<td>909,167</td>
<td></td>
</tr>
</tbody>
</table>

Evangelia Dimovasili
Radiation Physicist, TS/LEA
for the TOTEM experiment

---

Fig A.9 Irradiation tests AT CEA-SACLAY (60Co)A.6.3
A.6.3 Performance test of heat pipes before/after irradiation (3)

Fig A.10 Temperature distribution = f (Length of the Heat Pipe)
A.11 Temperature distribution = f (Length of the Heat Pipe)
A.6.4 Performance test of heat pipes before/after irradiation (4)

Fig. A.12 Performance test of heat pipes before/after irradiation
A.6.5 Performance test of heat pipes before/after irradiation (5)

Q-M-Xe-2, Direction angle: $0^\circ$

Fig A.13 and A.14 Temperature=f (Length HP); Angle $0^\circ$
A.6.6 Performance test of heat pipes before/after irradiation (6)

Q-M-Xe-2, Direction angle: 70°

Fig A.15 and A.16 Temperature=f(Length HP); Angle 70°
A.6.7 Performance test of heat pipes before/after irradiation (7)

Irradiation has a destructive effect on the heat pipes charged with Methanol or Propane as working fluid, which leads to the heat pipes losing their function completely.

It shows that irradiation has no effect on the heat pipes charged with Xenon as working fluid.

Test of a long straight heat pipe (1)

![Graph showing heat transfer from the evaporator vs. angle of the heat pipe]

Fig A.19 Heat transfer from the evaporator=f (Angle of the Heat Pipe)

The closer to the horizontal position, the better was the performance with more quantity.
Test of a long straight heat pipe (2)

Fig A. 18 $T=f(\text{Length}; \text{Angle } 90^\circ)$

Angle of the heat pipe: $90^\circ$
Charged quantity of Propane: 12g
B. Designing the Model

Characteristics of the materials

316 L (stainless steel)

MECHANICAL CHARACTERISTICS IN THE ANNEALED STATE
- Elastic limit Rp 0.2: min. 200 N/mm²
- Traction resistance Rm: min. 500 N/mm²
- Elongation L = 5D: min. 45%
- Brielle hardness: max. 215 BH
- Inclusions class <=2
- 100% austenitic over hardened structure
- Tolerance: D4 T3 ISO 1127 or *other tolerances permitted with prior approval.

316 LN (stainless steel)

INDICATIVE CHARACTERISTICS WHEN ANNEALED :
- Elastic limit Rp 0.2  300 N/mm² min.
- Traction resistance Rm  600 N/mm²
- Elongation at break A5  35%

---

Fig B.1 Materials composed by the Thermal Model
Brinell hardness  150/190 BH  
Density  7.8  
Magnetic permeability at ambient temperature:  <= 1.005  
Inclusions  standard ASTM E.45-84 method D  
USE : Ultra-high vacuum requiring treatment in vacuum at 950°C (vacuum firing)

**304 L (stainless steel)**

**INDICATIVE CHARACTERISTICS WHEN ANNEALED :**
- Elastic limit  \( \text{Rp} 0.2 \ 300 \text{ N/mm}^2 \) min.  
- Traction resistance  \( \text{Rm} \ 600 \text{ N/mm}^2 \)  
- Elongation at break  \( \text{A}5 \ 35\% \)  
- Brinell hardness 150/190 BH  
- Density 7.8  
- Magnetic permeability at ambient temperature:  <= 1.005  
- Inclusions standard ASTM E.45-84 method D  
- USE : Ultra-high vacuum requiring treatment in vacuum at 950°C (vacuum firing)

**INDICATIVE MECHANICAL CHARACTERISTICS IN THE ANNEALED STATE**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Min. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic limit</td>
<td>180 N/mm²</td>
</tr>
<tr>
<td>Traction resistance Rm</td>
<td>500 N/mm²</td>
</tr>
<tr>
<td>Elongation L = 5D</td>
<td>40%</td>
</tr>
<tr>
<td>Brinell hardness</td>
<td>215 BH</td>
</tr>
</tbody>
</table>

100% austenitic overhardened structure

Tolerance: D4 T3 ISO 1127 or *other tolerances permitted with prior approval.

(1) (2) (COPPER)

**CHEMICAL COMPOSITION :** \( \text{Cu} = 99.99\% \) min.  
\( \text{O}_2 = 5 \text{ ppm max.} \)

**CHARACTERISTICS :**
- Elongation at break  \( \text{A}5 \ 25\% \) min.  
- Density 8.9  
- ELECTRICAL CONDUCTIVITY : 101% IACS min.  
- HEAT CONDUCTIVITY : (4.2 K): 400 W/m²*K

**MANUFACTURE :** Cold-rolled  
>25 mm Hot-rolled

(3) (COPPER)

**CHEMICAL COMPOSITION :** \( \text{Cu} = 99.9\% \) min.  
\( \text{O}_2 = 0.005 \text{ to 0.04\%} \)

**CHARACTERISTICS :**
- Traction resistance  \( \text{Rm} \ 250 \text{ N/mm}^2 \)  
- Elongation at break  \( \text{A}5 \ 15\% \)  
- Density 8.9
ELECTRICAL CONDUCTIVITY : 57 m/Ohm mm2 min.
98% IACS min.
MANUFACTURING LENGTH : 3 – 4 m

(5) Characteristics of the PCB cards

<table>
<thead>
<tr>
<th>PCB FR4</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>4.8 G Pa</td>
</tr>
<tr>
<td>V</td>
<td>0.3 (poisson)</td>
</tr>
<tr>
<td>K</td>
<td>0.3 W/m K</td>
</tr>
<tr>
<td>CTE</td>
<td>14 micro m / m oC</td>
</tr>
</tbody>
</table>
C. Ordering the instrumentation

- Temperature sensor

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Reference (seller)</th>
<th>Quantity</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Heaters</td>
<td>Seller: 230452</td>
<td>40</td>
<td>Roth&amp;Co</td>
</tr>
<tr>
<td></td>
<td>Fabricant: 9.036.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Film Heaters (detectors)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Reference</th>
<th>Quantity</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Heaters</td>
<td>HK5255R8.4L12A</td>
<td>10</td>
<td>Minco</td>
</tr>
</tbody>
</table>

- Film Heaters (Heat Pipes)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Reference</th>
<th>Quantity</th>
<th>Company</th>
<th>Dimensions (mm)</th>
<th>Resistance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Heaters</td>
<td>HK5255R8.4L12A</td>
<td>4</td>
<td>Minco</td>
<td>50.8 x 101.6</td>
<td>21.2</td>
</tr>
</tbody>
</table>

- Heat Pipes

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Reference</th>
<th>Quantity</th>
<th>Company</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Pipes</td>
<td>QB-SHP-D6-300M</td>
<td>4</td>
<td>Quick-Ohm</td>
<td>Ø= 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L=300</td>
</tr>
</tbody>
</table>

- Big Heat Pipe

- Strain Gauges
### Instrument Reference Quantity Company Resistance (ohms)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Reference</th>
<th>Quantity</th>
<th>Company</th>
<th>Resistance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gauges</td>
<td>WK-09-250 BF- 350 LE</td>
<td>10</td>
<td>Vishay</td>
<td>----</td>
</tr>
<tr>
<td>Strain Gauges</td>
<td>1-LC11-6/350</td>
<td>10</td>
<td>HBM</td>
<td>350</td>
</tr>
</tbody>
</table>

- **Conditioner**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Reference</th>
<th>Quantity</th>
<th>Company</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditioner (Strain Gauges)</td>
<td>3310</td>
<td>11</td>
<td>Sensorex</td>
<td>Boîtier DIN conditionneur capteur PDJ 6 fils, alim. 24V, sortie +/- 10V, 0/10VD et 4/20mA, excitation capteur 5 ou 10VDC</td>
</tr>
</tbody>
</table>

- **Scanner HP**
- **Connection wires & solder pads**
- **Precision resistors to complete Wheatstone bridge**
- **Conditioner (1 for each strain gage) to amplify signal**
- **Digital read-out (HP multimeter 34401A & Sensorex display unit)**
- **GPIB card connected to pc**
- **Lab view program**
D. Thermal-Mechanical Results

Concept A

D.1. Finite Element Analysis

In order to fully understand the thermal and mechanical deformations that will occur during normal operation, 3D simulation has been studied using ANSYS software.

To obtain accurate results the model was designed in full scale, and consists of the outer copper frame (where the heat removal is carried out by two heat pipes) and one adjacent detector card.

Some important initial assumptions must be taken into consideration:

---

Fig D.1 Finite Element
The stainless bars will sustain most of the transversal deformation, but there is relevant deformation in ZZ (perpendicular to the detector).

Fig D.2 Deformation of the piece in ZZ
A total deformation of approximately **0.6mm** occurs due to slight “buckling” movement of the detector frame. It can also notice that the detector itself deforms less than 0.35mm.

---

Fig D.3 Deformation _“buckling” movement_
Calculating the Von Misses stress, it can conclude that the detector is subject to almost 50% less stress, in comparison to the initial 4 edge model.

![Deformation with Von Misses stress](image)

---

**Fig D.4 Deformation with Von Misses stress**

This factor must be taken into consideration, whichever model is built. Another simulation may be studied by attaching the detector on 2-3 key points and not one whole edge. And some other small changes can be done to improve the overall stress throughout the copper frame.
E. Introduction to LabVIEW

LabVIEW is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, LabVIEW uses dataflow programming, where the flow of data determines execution.

In LabVIEW, you build a user interface with a set of tools and objects. The user interface is known as the front panel. You then add code using graphical representations of functions to control the front panel objects.

The block diagram contains this code. In some ways, the block diagram resembles a flowchart. You can purchase several add-on software toolsets for developing specialized applications. All the toolsets integrate seamlessly in LabVIEW.

Refer to the National Instruments Web site at ni.com for more information about these toolsets.

E.1 LabVIEW 7.1 National Instruments

Software to read the Thermal Model Data.

The software that it was used to read the result from the Thermal Model has been totally developed in LabVIEW 7.1.

This kind of program had not been created before in our department. Consequently, a new one had to be created in order to readout the temperature for our requirements.

LabVIEW program

LabVIEW programs are called virtual instruments (VI) and they are composed of three main parts: a front panel, a block diagram and an icon-connector.

The front panel allows the user to set the input values of the program and to view the outputs from the VI block diagram. Because the front panel is analogous to a front panel of a real instrument, the inputs are called controls and the outputs are called indicators. There are a variety of controls and indicators hence the programmer can make the front panel easily identifiable and understandable.
Each front panel has an accompanying block, which is the VI program. The language used to build this diagram is graphical and it is called language G. The block diagram replaces the normal source code of the other languages and its components represent program nodes; for example: for loops, case structures, arithmetic functions… The components are wired together to define the flow of data within the block diagram.

The part of the icon-connector is used to turn a VI into an object (subVI) that can be used as a subroutine in the block diagrams of other VIs. The icon graphically represents the VI in the block diagram of other VIs. The connector terminals determine where the inputs and outputs must be wired on the icon. The terminals are analogous to subroutine parameters. They correspond to the controls and indicators on the VI front panel.

LabVIEW sets a special hierarchy at the VI components. After creating a VI it can be used as a subVI in the block diagram of a higher-level VI. There is no limit on the number of layers in the hierarchy.
E.2 Programming structures

Index VI’s Structure

The idea of this LabVIEW program is to translate the data from Volts to Kelvins. It is only measuring the temperatures. The program has to read 40 channels each time and translate this data. In order to realise this objective a subVI’s function called *Scan VI* was created.

Part of the initialization frame in Area VI’s diagram block

![Part of the initialization frame in Area VI’s diagram block](image-url)
This is part of the code inside the initialization frame of the SubVI’s diagram.

When the SubVI called *ScanVI* has taken the measurement, this information is saved in this subVI’s diagram that is above (green rectangle). To activate the loop there must be the boolean function “T” (True). Suddenly the loop starts to save the data received from the *ScanVI*. In every case, this loop is sending all the data into a file to a path (have to be definite), C:/TOTEM. Into each file is saved a table composed for the day, the month, the year, the time (H hour, M minute, S second) and all the temperatures that the user has requested.

---

Fig E.2 The initialization frame of the SubVI’s diagram
This loop shows how many times the program can be run before stopping.

Fig E.3 Loop_time_program stops

Fig E.4 Composition of the graphics
Part A

This SubVI called *ScanVI* is composed for three levels; two of them switch on the instrumentation that reads the data such as the multiplexer and the scanner. The last one translates the Data (volts) that was taken in the multimeter to Kelvin. The function that translates this information is shown in the follow picture.

Fig E.5 SubVI called *ScanVI*
Fig E.5 Initialization program and how to save the program
Part B

In this part of the main VI structure is located the entire loop that in each one selects and determines channels, depending on the temperatures distribution on the Thermal Model. The user can obtain the temperature data in different arrays and different graphs depending on if the user wants to know the temperatures on the PCB cards, on the right frame, etc.

Fig E.6 Temperature distribution on the Thermal Model
This is the interface on the Front Panel that shows first of all the pictures of the temperature sensors and after the respective graphics.

The graphics are created to show:

- Temperatures distribution upper left (The numbers of the temperature sensors)
- Temperatures distribution down left
- Temperature distribution upper right
- Temperature distribution down right

---

**Fig E.7 Interface on the Front Panel**
Fig E.8 Loop to create the graphics
Fig E.9 Components of the Front panel

- **Graph**
- **Array with all the data that has been selected**
- **Each color represents one channel**
Front Panel

The front panel shows a part of the graphics and the table with the data, an important tool that is needed to run the program.

There are manual buttons from the right to the left. There is the sample rate that the user can use to set the time to run the program. Next to this is the start-recording-button that has to be switched on every time to run the program; the last option is the path function that the user can use in case he/she wants to modified the address of the saved data.

---

Fig E.10 Bar of tools in the Front Panel
F. Planning of the project

All the tasks concerning this project were organised using the Microsoft Office Project program.

The objective of this planning has been to create a time scale in which all of the tasks can be completed.

The distribution of the planning is composed of four columns such as the different tasks, their durations, and the initial and final dates.

This information is also represented in a graph located on the next page.

![Legend of the planning](image-url)
G. Cost of the project

The cost of this project is expressed in terms of the cost of the work done by myself in this period of 14 months. My responsibilities have been devised between the general planning activities and the progress of the Thermal Model development. In this project 2080 h have been worked that could be divided as follows:

<table>
<thead>
<tr>
<th>Worked hours</th>
<th>€/h (Junior engineer)</th>
<th>€</th>
</tr>
</thead>
<tbody>
<tr>
<td>1460 h engineering</td>
<td>15,00</td>
<td>21900</td>
</tr>
<tr>
<td>440 h LabVIEW program</td>
<td>12,00</td>
<td>5280</td>
</tr>
<tr>
<td>180 h Typing</td>
<td>10,00</td>
<td>1800</td>
</tr>
<tr>
<td>TOTAL (14 months)</td>
<td></td>
<td>28980</td>
</tr>
</tbody>
</table>

Fig G.1 Cost of the project during 14 months

The client of this project has been CERN and particularly the TOTEM project.

It should be considered that apart from the costs shown above, most of the machinery needed for the tests of the cooling system had to be purchased except for the Pulse Tube and the compressor which were lent free-of-charge from a nuclear institution in Japan (valour of 22407€).

The Model cost is about 6402 €

For the Model plus the Strain-gauge about 16005 € has been spent.

<table>
<thead>
<tr>
<th>COST</th>
<th>€</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personel costs (14 months)</td>
<td>28980</td>
</tr>
<tr>
<td>The Model (“Thermal Model”)</td>
<td>6402</td>
</tr>
<tr>
<td>Model plus the Strain-Gauge</td>
<td>16005</td>
</tr>
<tr>
<td>TOTAL</td>
<td>51385</td>
</tr>
</tbody>
</table>
H. Environment impacts

H.1. Environment department at CERN

The laboratory's Technical Support Department has developed a waste management system.

There are two broad categories of industrial waste:

- **Special** industrial waste...

Eliminated in specialized companies in Switzerland and France. Management of this waste is under close supervision of experts in CERN's Safety Commission.

- Chemical baths
- Oils and Solvents
- Batteries...

- **Commonplace** industrial waste. *Figure H.1*

---

![Figure H.1 Amounts of waste produced by CERN typically in one year](image)
This project is a technical project that consists of creating a prototype and making experiments on it. In consequence, the study of the environmental impact must include the preparation of the pieces to make the prototype and all the civil engineering that has to be done to locate the TOTEM experiment.

Since its beginning, the only thing that in the project that can affect the environment is the material that was chosen. All the materials were bought from recycling factories in order that after the experiments the materials can be recuperated.

The processes to make the pieces caused no environmental damage because the machine used to cut the pieces works with a special oil that is recycled after use.

Furthermore, the working fluids are Xenon and Helium, which are harmless to the environment.

References to the civil engineering at the point 5 where the TOTEM experiment will be located are explained in the next paragraph.

- **Environment and Safety for the civil engineering:**

  Special care was taken to blend the structures into their environment, including all the measures taken by the "Impact Study" covering both the construction and operating periods.

  French building permits or their equivalents have been issued or are being obtained or prepared in accordance with the schedule for the start of work at each point.

  Finally, the Civil Engineering Group will attach particular importance to the observance of the safety standards in accordance with the European directive dated 24.6.92, which increases the responsibility of employers. A highly comprehensive organisation has thus been set up in accordance with the French laws and decrees in force designed to take all possible steps to prevent the risks inherent in this type of project. Effective support has been obtained through two safety and health protection co-ordination contracts awarded to specialised firms:

  - AIF (France) for the design phase;

  The COSSEC (F) - WATERMAN (GB) consortium for the construction phase.

- **Difficulties:**

  The main difficulties or challenges facing the operative teams in the performance of the work are:

  - The excavation of huge underground halls in the mixed nature of the
molasses of the Leman basin;

- The 55 metre passage through water-bearing moraines during the excavation of the two access shafts to the underground halls for the CMS detector;

- The performance of work closely involved with the existing LEP structures with the absolute requirement not to interfere with LEP's operation until its final shutdown in October 2000, in accordance with the project schedule.