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Checked by

Albert M. Weston

Albert M. Weston
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ABSTRACT

A diagnostic beam dump, able to withstand 72,000 pulses (10 kA, 50 MeV/pulse) per shift was designed and analyzed. The analysis shows that the conceptual beam dump design consisting of 80 vitreous carbon plate-foam elements is able to withstand the thermal and mechanical stresses generated. X-rays produced by bremsstrahlung are absorbed by a three element copper plate-foam X-ray absorber. Cooling between bursts of electron pulses is provided by pressurized helium.
1. INTRODUCTION

In order to measure beam performance at various points of the ATA accelerator structure, a retractable and relocateable beam dump is needed.

The proposed beam dump consists of four main elements:
1. Eighty element carbon foam-plate section which absorbs more than eighty percent of the beam energy. The thermal and mechanical properties of carbon allow small beam diameters.
2. Four element copper foam-plate section which absorbs most of the X-rays produced by the slowing down of the electrons in the carbon section.
3. A stainless steel jacket with cooling gas inlets and outlets connected through bellows to the high pressure, high speed helium pumping system.
4. Heat exchanger system with associated plumbing. In this report, the thermal and mechanical behavior of the carbon, the copper section and the cooling gas are analyzed. The pumping, heat exchanger system, and other associated hardware required to activate and operate the beam dump have not been studied in any detail and are not part of this report.
2. DESIGN CONCEPT

The design concept presented in Section 2.2 was developed as an answer to the system requirements listed in Section 2.1.

2.1 SYSTEM REQUIREMENTS

The system requirements are excerpted from the SR No. 23.1a dated 4/3/81. The full document is contained in Appendix A.

REQUIREMENTS

1. The diagnostic beam dump should allow for variable location in the experiment tank within the tunnel.

2. Beam Conditions:

<table>
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<th>Requirement</th>
<th>Specification</th>
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<tr>
<td>Beam Current</td>
<td>10000 Amp</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Beam Diameter</td>
<td>&lt;2 cm</td>
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3. Pulse count is 70000 pulses per shift. Fifty percent of the pulses will be in the burst mode of operation with 10 pulses every two seconds and 1 millisecond between the pulses.

4. Beam dump dimensions shall be no more than 1 foot diameter and 6 feet in length. They include a beam scattering region and the possibility of a segmented approach using more than one carbon foil in front of the beam dump. They exclude any heat exchanger system and associated plumbing. Provisions must be made for activation of the cooling system.

5. Provisions shall be made to safely exhaust gaseous products from this unit.
6. All carbon foils/materials used shall be easily replaceable. Provisions must be made to easily inspect the deterioration of these foils.

2.2 DESCRIPTION OF THE DESIGN CONCEPT

A cross-section of the diagnostic beam dump is shown in Figure 1. During operation the E-beam hits the concave first surface of the beam dump which separates the vacuum from the pressurized (five to ten atmospheres) cooling medium (helium) which is pumped through the vitreous carbon foam backing. The concavity of the first surface plus the bonding to the rigid carbon foam backing supplies the needed structural strength and assures good thermal contact for rapid cooling. The first surface can be cooled convectively from one side only and the maximum thickness of the first plate is dictated by the needed cooling response. As designed the first surface should cool from \( \sim 2000^\circ\text{C} \) to ambient in less than two seconds.

The beam dump consists of 80 elements 79 of which are of the same design plus the first element with the convex surface. The 80 elements are contained in a stainless steel shell which provides radial and axial rigidity and flanging for the cooling gas inlet and outlets.

During absorption, beam energy is deposited along the axial beam dump direction. About 18 percent\(^{1}\) of the beam energy is released as X-rays (bremsstrahlung effect) and since carbon is quite transparent to X-rays, a short copper X-ray absorbing section consisting of four copper foam elements has been added.

A tight vacuum seal is achieved by pressing the first surface against a C-seal seated against the stainless steel jacket.
TABLE 1. Key Beam Dump Dimensions

Key dimensions of the beam dump structure are:

<table>
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<tr>
<th>Dimension</th>
<th>Value</th>
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<tr>
<td>Length overall</td>
<td>100 cm</td>
</tr>
<tr>
<td>Vitreous carbon</td>
<td>84 cm</td>
</tr>
<tr>
<td>X-ray absorber</td>
<td>16 cm</td>
</tr>
<tr>
<td>Cross-section</td>
<td>10 x 10 cm</td>
</tr>
<tr>
<td>Thickness of front plate</td>
<td>0.152 cm</td>
</tr>
<tr>
<td>Thickness of one plate-foam element</td>
<td>1 cm</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>0.1017 cm</td>
</tr>
<tr>
<td>Foam thickness</td>
<td>0.8983 cm</td>
</tr>
<tr>
<td>Number of elements</td>
<td>80</td>
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</table>

A drawing of the beam dump showing the attached plumbing for the cooling system is attached in Appendix E.

3. DESIGN DEVELOPMENT

In operation the beam dump has to absorb significant amounts of energy in very short time periods. The problem is to select the material best suited to:

- withstand the thermal stresses
- minimize the temperature rise
- maximizes surface area for convective cooling

The above problem areas plus the problem of X-ray production and absorption are dealt with in Section 3.1 through 3.5.
3.1 MATERIAL SELECTION

The prime criterion for any beam dump material is to have a temperature rise less than the melting point. The temperature rise is calculated as follows:

Energy per pulse

\[ Q_r = V \cdot I \cdot t \]

\[ V = 50 \cdot 10^6 \text{ V} \quad \text{Total Accelerator Voltage} \]
\[ I = 10 \cdot 10^3 \text{ Amp} \quad \text{Beam Current} \]
\[ t = 70 \cdot 10^{-9} \text{ Sec} \quad \text{Half Magnitude Full Wave Pulse Duration} \]

\[ Q_r = 50 \cdot 10^6 \cdot 10^3 \cdot 70 \cdot 10^{-9} \]
\[ = 35000 \text{ Joules/Pulse (8365 cal/Pulse)} \]
\[ = 33.18 \text{ BTU/Pulse} \]

Assume a beam diameter of 1 cm and a 1 mm thick copper plate as absorber. The heat rise (ignoring second order effects) is:

\[ \Delta T = \frac{Q}{m \cdot C_p} \]

where \( Q \) equals the energy absorbed by the 1 mm thick copper plate.

The stopping range for copper is listed as 2 cm. A one millimeter thick copper plate will absorb approximately five percent of the total energy.

The copper volume for the 1 cm beam diameter is:

\[ V = \frac{\pi}{4} \cdot D \cdot \ell = \frac{\pi}{4} \cdot 1 \times 0.1 = 0.0785 \text{ cm} \]

Weight:

\[ m = V \cdot \rho = 0.0785 \cdot 8.96 = 0.7037 \text{ gr} \]

Specific heat of copper

\[ C_p = 0.092 \text{ cal/gr} \text{ } ^0\text{C} \]
Heat input into 1mm thick copper plate

\[ Q_i = \frac{Q_t \times t}{R} \]
\[ \text{R is stopping range} \]
\[ Q_t \text{ is total pulse energy} \]
\[ t \text{ is plate thickness} \]

\[ Q_i = \frac{8365 \times .1}{2} \]
\[ = 418 \text{ cal} \]

The temperature rise is then:

\[ \Delta T = \frac{Q_i}{m \cdot C_p} \]
\[ = \frac{418}{.7037 \times .092} \]
\[ = 6456 \text{ °C} \]

Since the melting point of copper is 1084 °C, copper is clearly not a good choice as an electron stopping material.

The temperature rise calculations have been done for all elements and a representative sample is listed in Table 1, Page 6. From Table 1 it can be seen that only elements with a low atomic number have a melting point higher than the temperature rise. The three candidates are:

Beryllium
Boron
Carbon

Considering toxicity, availability and manufacturability carbon is the clear choice for an electron absorber material.
Calculated Temperature Rise (For 1 cm Dia Beam -35 x 10^6 Joules Beam Energy Per Pulse) for Various Elements.

Specific Heats from Table 2-173 Perry's Chem. Eng. Handbook
Melting Points from D-190 CRC Handbook of Chem. Physics 61st Edition
Range Data from UCRL-2426 Vol. II (1966 Rev.)

<table>
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<tr>
<th>Atomic Number</th>
<th>Symbol</th>
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<th>Specific Heat @ 20°C (cal/g°C)</th>
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TABLE 2. Temperature Rise of Low Z-Elements

WILLIAM M. BROBECK & ASSOCIATES
3.2 FIRST WALL

The first wall has to provide a seal between the hard vacuum of the accelerator and the pressurized cooling medium. It has to withstand the gas pressure and allow for sufficient cooling between the burst of electron pulses. A view of the first wall including the vitreous carbon foam backing is shown in Figure 2.

FIGURE 2. Front Plate

The hemispherical part of the first element can be ground or turned from a solid block of vitreous carbon. The matching hemispherical contour in the foam backing can be ground or turned in the same manner.

3.3 VITREOUS CARBON FOAM CORE

In order to withstand the burst mode of operation (10 pulses every two seconds) the cooling system has to be able to cool the vitreous carbon plate-foam elements from over 2000°C to ambient in less than two seconds.
Liquid cooling methods cannot be used because liquids would undergo a phase change (liquid to gaseous) during the heating. The associated pressure pulse would destroy the beam dump. Use of foam greatly increases the convective heat transfer coefficient if there is good thermal contact between the plate and the foam.

Good thermal contact between the plate and the foam can be assured by using a high temperature carbon cement which essentially fuses the parts together when heated above 1000°C. A description of bonding methods is part of Appendix C.

The dimensions of the foam are:
8.89 x 8.89 x .8983 cm

The dimensions of the plate are:
8.89 x 3.89 x .152 cm

One plate and foam make up one element. The beam dump consists of 79 square foam-plate elements plus the front element and the copper X-ray absorber.

3.4 COOLING GAS

As mentioned in 3.3, liquid cooling cannot be used because of pressure wave associated with the liquid to gas phase change.

Air also cannot be used because vitreous carbon oxidizes when heated above 500°C. Considering cost and safety, nitrogen would be a good choice, but calculation of the temperature rise and the associated pressure increase (Section 4.2.3) indicates that nitrogen would cause a first wall buckling problem.
Of all other commercially available gases helium has the best thermal properties, is chemically inert and has a low temperature rise. Thus, it was chosen as the cooling medium despite the relatively high cost.

During operation approximately 2000 ft$^3$/min of pressurized (5-10 ATM) helium is pumped through the beam dump.

3.5 X-RAY ABSORBER

During the slowing down of the electrons a fraction of the initial kinetic energy is released in the form of X-rays (bremsstrahlung effect). According to (1) electrons with an initial energy of 50 MeV radiate 18.23 percent of their energy in the form of bremsstrahlung. The X-rays produced are tightly focussed and easily penetrate the carbon foam-plate elements because carbon is quite transparent to X-rays. Elements with a high atomic number like lead are very good X-ray absorbers. Calculations in Section 4.1.4 show that the front surface of a lead absorber would experience a temperature rise above the melting point. An X-ray absorber built up of copper foam-plate elements seems attractive considering temperature rise, overall length required and ease of cooling. A cross-section of the X-ray absorber chosen for this design is shown in Figure 1 on page 5.

X-ray absorber key dimensions:

<table>
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<td>Total length (copper)</td>
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<tr>
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<tr>
<td>Total Length Overall Including Copper Back Plate</td>
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4. ANALYTICAL TREATMENT

The analytical treatment was used to establish quantitative numbers regarding beam to beam dump interaction and the associated material response.

The following areas were analysed: beam properties, material properties, thermal and mechanical response.

Closed form analytical and numerical methods were used wherever applicable.

4.1 BEAM PROPERTIES

With the exception of the beam diameter and the radial beam distribution all beam properties were supplied by LLNL.

In order to establish reasonable values for the minimum possible beam diameter, the interaction of the beam with the stopping medium was analyzed. Beam diameters, heating, axial/radial energy distribution and X-ray production and absorption were calculated.

4.1.1 BEAM ENERGY AND NUMBER OF PULSES

The energy of one single pulse is:

\[
\begin{align*}
\text{Energy (MeV)} & = 50 \\
\text{Current (Amp)} & = 10000 \\
\text{Pulse Duration (N-sec)} & = 70
\end{align*}
\]

In more convenient units the energy is:

\[
50 \text{ (MeV)} \times 10000 \text{ (Amp)} \times 70 \text{ (N-sec)} = 35000 \text{ joules (8365 cal)}
\]

Number of pulses - ten beam pulses every two seconds
- time between pulses is one millisecond

A graphic description of the beam pulse is shown in Figure 3.
FIGURE 3. ATA Beam Pulse
4.1.2 RADIAL ENERGY DISTRIBUTION

While the electron beam is in vacuum, the radial intensity assumes a normal gaussian distribution (5). After leaving the accelerator vacuum the beam interacts with the gaseous medium and assumes a Bennett distribution. (13)

The intensity variation in the radial direction is assumed to be a two-dimensional normal distribution as shown in Figure 4 below. While penetrating the beam dump in the axial direction the beam spreads due to scattering but still maintains a normal, albeit less peaked distribution.

FIGURE 4. Distribution Surface for a Two-Dimensional Normal Distribution
The beam diameter has been defined at two times the standard deviation, $\delta_1$. Numerical calculations show that a beam with a normal distribution and a beam diameter of 1.41 cm will have the same peak intensity (electrons/cm$^2$) and temperature rise as a beam with a square distribution and a 2 cm diameter. These results have been derived as follows:

The probability for the two dimensional distribution is given by (6) as:

$$p(r, \phi) = \frac{1}{\sigma^2} \cdot 2\pi \cdot \int_0^{2\pi} d\phi \cdot \int_0^\infty \frac{r^2}{2\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \cdot r \cdot dr$$

This expression has been integrated numerically. The program and results are shown on Pages 17 and 18.

The total number of electrons per beam pulse is:

$$N = I_c \times t = \frac{10000 \times 70 \times 10^{-9}}{1.6 \times 10^{-19}}$$

$$= 43.75 \cdot 10^{14}$$

We define the beam intensity as:

$$I = \frac{N}{A} \text{ Electrons/} \text{cm}^2$$

The intensity for a 2 cm diameter beam with a square distribution (all electrons within a 2 cm diameter and no radial intensity variation) is:

$$I = \frac{N}{A} = 43.75 \cdot 10^{14}/2^2 \cdot \frac{\pi}{4}$$

$$= 13.9 \cdot 10^{14} \text{ Electrons/} \text{cm}^2$$

Normalizing the intensity by setting $N = 1$ we get:

$$I_{NOR} = \frac{1}{2^2} \cdot \frac{\pi}{4} = .3183 \ 1/\text{cm}^2$$
The same peak intensity is obtained for a two-dimensional normal distribution with a standard deviation of .707 as shown by the numerical result in Table 3 on Page 17. A graphic description of the numerical result is shown in Figure 5 on Page 18. The program is listed in Appendix D-1.

To simplify the numerical effort all heat rise calculations were performed with a 2 cm beam diameter and a square beam distribution. This gives the same heat rise in the center spot as a normally distributed electron beam with a beam diameter of 1.41 cm.

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TABLE 3. Two Dimensional Normal Distribution
FIGURE 5. Comparison of the two dimensional gaussian with the square electron distribution giving the same center spot intensity.
4.1.3 AXIAL ENERGY DISTRIBUTION

When traversing the vitreous carbon plate-foam elements the electron beam is scattered due to electron-electron and electron-nucleus interactions. Many small angle deflections take place and the angle at which the electrons emerge is the statistical superposition of all the small angle deflections. According to (3) the mean square scattering angle is given as:

\[ \langle \theta^2 \rangle = 4 \cdot \pi \cdot N \cdot Z^2 \cdot t \cdot \frac{e^2}{T} \cdot \ln \left( \frac{210 \cdot Z^{-2/3}}{T} \right) \text{ (radians)}^2 \]

Where \( N \) = Number of atoms/cm\(^3\) for vitreous carbon with

\[ p = 1.47 \text{ gr/cm}^3 \]
\[ = 6.02 \cdot 10^{23} \cdot 1.47/12 \text{ atoms/mole x gr/cm}^3 \times \text{mole/gr} \]
\[ = .7375 \cdot 10^{23} \text{ atoms/cm}^3 \]

\( t \) = Material length along the beam penetration axis in cm

\( Z \) = Atomic number of stopping material (equals 6 for carbon)

\( e \) = Electron charge in ESU units

\[ = 4.8 \times 10^{-10} \text{ esu} \]

\( T \) = Electron kinetic energy in ERGS, 1 ev = 1.602 \times 10^{-12} \text{ erg} 

Along the axis of penetration the electrons continuously lose energy and since the kinetic energy is the only variable the mean square scattering angle can be expressed as:

\[ \langle \theta^2 \rangle = t \cdot \frac{K}{E^2} \]

Where \( K = 4 \cdot \pi \cdot N \cdot Z^2 \cdot e^2 \cdot \ln \left( \frac{210 \times Z^{-1/3}}{T} \right) \)

\[ = 4 \cdot \pi \left( .7375 \cdot 10^{23} \right) \cdot (4.8 \times 10^{-10}) \cdot (6^2) \cdot \ln \left( \frac{210 \times 6^{-1/3}}{1.6 \times 10^{-12} \times 10^6} \right) \]

\[ = 3.2865 \text{ (mev)}^2 / \text{cm} \]
t = Material stopping length per vitreous carbon foam-plate element. From (1) the general stopping length for carbon is 22.52 gr/cm$^2$. For vitreous carbon, $\rho = 1.47$, it is:

$$L = \frac{22.52}{1.47} = 15.32 \text{ cm}$$

For each of 80 elements, the equivalent solid vitreous carbon thickness is $15.32/80 = 0.1915 \text{ cm}$.

$E = \text{Kinetic energy in MeV}$

For a first foil thickness of .152 cm and an electron energy of 50 MeV, the multiple scattering angle $\theta^2$ is then .8 degrees.

Using formulae given in Reference 12, which take into account relativistic correction effects yields a similar result. A basic program and results based on this approach are listed in Appendix D-2 and D-3.

Energy loss as a function of electron energy:

Figure 7 on Page 23 shows the variation of collision and radiation stopping power versus electron energy. The data for Figure 7 was taken from tables in Reference (1).

To stop a 50 MeV electron beam approximately 15.3 cm of vitreous carbon material are needed; i.e., 22.52/1.47. The average energy loss per cm of penetration is:

$$E_{\text{Loss Average}} = \frac{50 \text{ MeV}}{15.3 \text{ cm}} = 3.26 \text{ MeV/cm}$$

The tables in Reference (1) show that the energy loss for the first foam-plate element, while the electrons are still at their full energy of 50 MeV, will be 4.1 MeV/cm or roughly 1.26 times the average.
energy loss. The energy dependency on the electron energy loss is used on the beam spreading procedure below.

Procedure to calculate the increase in beam diameter.

- Incident energy equals 50 MeV
- Incident beam diameter 2 cm
- Calculate mean square scattering angle and use the angle to calculate increase in beam diameter over foam-plate element length.
- Subtract energy deposited in the first element from incident electron energy.
- Repeat mean square scattering angle calculation with new energy for each of the vitreous foam-plate elements.

Above procedure was solved numerically for the 80 vitreous carbon foam-plate elements. The program is listed in Appendix D-2 and the results are shown on Page 22 in Table 4. A graphic plot of the numerical results is shown in Figure 6 on Page 22.

The numerical results show that the beam diameter increases from 2 cm to ~ 9.5 cm and that most of the increase occurs in the last quarter of the beam dump.
FIGURE 6. Beam Spreading

TABLE 4. Axial Beam Spreading
FIGURE 7. Radiation/Collision Stopping Power
4.1.4 X-RAY PRODUCTION AND ABSORPTION

During the course of slowing down some of the electron beam energy is converted into X-rays (Bremsstrahlung). One third of the X-rays produced are absorbed by the 80 element vitreous carbon foam-plate structure. The remaining two thirds must be stopped by a special X-ray absorber.

The radiation yield of a 50 MeV electron being stopped in carbon is 18.23% according to (1).

18.23 percent of the total beam energy is:

\[
\frac{\text{Energy/Pulse} \times \# \text{ of pulses} \times \text{percentage}}{35000 \times 10 \times 0.1823 = 63805 \text{ Joules}} = 15243 \text{ cal}
\]

Some of the 15243 calories will be absorbed by the vitreous carbon section of the beam dump while the rest of the X-ray energy has to be absorbed by a special X-ray absorber. A beam of X-rays has a characteristic exponential drop off in energy when passing through a stopping medium. The beam energy at a distance \( X \) will be:

\[
E_X = E_0 \times e^{-\frac{X}{X_0}}
\]

where \( E_0 \) = Incident X-ray energy

\( X_0 \) = Radiation length of the stopping medium

The radiation length \( X_0 \) is the distance required to reduce the X-ray energy to 1/e of its initial value. The radiation length of carbon is 23.6 cm according to (4). For a first estimate on how much X-ray energy is absorbed by the carbon we may assume that all X-rays produced by the carbon have to pass through two thirds of the vitreous carbon material.
The X-ray energy absorbed by the carbon section is then:

\[ E_x = E_o \left(1 - e^{-\frac{X}{X_o}}\right) \]

\[ E_o = 15243 \text{ cal} \]

\[ X = \frac{2}{3} \times 15.3 \text{ cm} = 10.18 \text{ cm} \]

\[ X_o = 23.6 \text{ cm} \]

\[ E_x = 15243 \left(1 - e^{-10.18/23.6}\right) \]

Energy absorbed in carbon = 5340.8 cal

The difference between 15243 - 5340.8 cal equals 9902.2 calories and this is the energy which has to be absorbed by the X-ray absorber. More detailed numerical calculations which consider radiation yield contribution of all 80 vitreous carbon elements show that the:

Energy absorbed in carbon = 5201 cal

Energy absorbed in copper = 9983 cal

The program is listed in Appendix D-4 under X-rays. Results of the numerical calculations are shown in Table 5 on Page 26. The heat rise in Table 5 is the surface layer heat rise which is determined as follows:

\[ \Delta T = \frac{\Delta Q}{m \cdot C_p} = \frac{\Delta Q}{x \cdot A \cdot \rho \cdot C_p} \]

Where \( \Delta Q \) = is the amount of energy deposited in the volume \((x \cdot A)\) or mass \( M \)

\[ \rho = \text{density of the stopping medium} \]

\[ C_p = \text{heat capacity} \]

The fraction of energy deposited is

\[ \Delta Q = Q_o \cdot \left(1 - e^{-\frac{X}{X_o}}\right) \]

\[ \Delta T = \frac{Q_o}{A \cdot \rho \cdot C_p} \cdot \left[\left(1 - e^{-\frac{X}{X_o}}\right)\right] \]
Differentiating the expression in the square brackets \((x \to 0)\) yields:

\[
\left[ 1 - e^{-x} \right] = \frac{1}{x_0}
\]

\(x \to 0\)

and the heat rise at the surface layer becomes:

\[
\Delta T = \frac{Q_0}{x_0 A \cdot \rho \cdot C_p}
\]

Along the axis of penetration the intensity and the heat rise drop off exponentially.

---

**TABLE 5. X-Ray Heating**

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ENERGY FILED IN (CAL/CM²) = 7544.0
ENERGY RECEIVED IN COPPER (CAL) = 4910.2
TOTAL X-RAY ENERGY (CAL) = 15054.2
PENNY
4.2 MATERIAL PROPERTIES

The temperature rise as a function of beam intensity has been presented in Section 3.1. Table 2 Page 9 lists all the low Z number elements which were examined in more detail. For detailed heat rise and cooling calculations the variations of thermodynamic and mechanical properties with temperature have to be considered.

4.2.1 VITREOUS CARBON

The properties listed below have been taken from Appendix C.

<table>
<thead>
<tr>
<th>Physical and Electrical Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.47 gm/cc</td>
</tr>
<tr>
<td>Permeability (Helium)</td>
<td>less than $2.5 \times 10^{-12}$ cm$^2$ sec$^{-1}$</td>
</tr>
<tr>
<td>Hardness (Knoop) (Moh)</td>
<td>820</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>22,000 PSI</td>
</tr>
<tr>
<td>Modulus</td>
<td>3 to 4 $\times 10^6$ PSI</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>90,000 - 140,000 PSI</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>30 - 80 $\times 10^{-4}$ ohm cm</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.01 to 0.02 cal/cm/sec/C$^0$</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient</td>
<td></td>
</tr>
<tr>
<td>0-100°C</td>
<td>$2.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>100-1000°C</td>
<td>$3.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.3 cal gm$^{-1}$ C$^{-1}$</td>
</tr>
<tr>
<td>Maximum Use Temperature</td>
<td>3000°C (5400°F) plus</td>
</tr>
</tbody>
</table>
Variation of Thermal Conductivity With Temperature

According to (7) the thermal conductivity of vitreous carbons increases from .01 cal/cm sec°K at 25°C to .04 cal/cm sec°K at 1500°C. This is in marked contrast with the behavior of polycrystalline graphites which have a higher conductivity at room than at elevated temperatures.

The exact variations of thermal conductivity with temperature for vitreous carbon still needs to be done. At the present, measurements are being conducted by the Alcoa Company.

In all heat rise and cooling calculations the thermal conductivity is varied between .01 and .04 cal/cm sec°K as a function of temperature.

Variation of Specific Heat With Temperature

Polynomial approximations allow extrapolation of specific heats up to ~1100°C. To find specific heat values at higher temperatures the Debye approximation method was tried.

According to (9) the Debye approximation is given as:

$$C_v = \frac{9 \cdot N \cdot K_B \cdot T^3}{\Theta} \int_0^{X_D} \frac{x^4 e^x}{(e^x - 1)^2} \, dx$$

Where:

- $N = 6.02 \cdot 10^{23}$ number of atoms/mole
- $K_B = 1.38062 \cdot 10^{-23}$ Boltzmann constant
- $T$ = temperature in Kelvins
- $X_D = \frac{\Theta}{T}$ = upper limit of integration
- $\Theta$ = Debye temperature

$= 1860$ for graphite with a density of $2.25$ gr/cm$^3$
To find the Debye temperature of vitreous carbon the value for graphite was adjusted by the ratio of the densities.

$$\theta_{\text{vitreous C}} = \theta_{\text{graphite}} \cdot \frac{\text{vitreous carbon density}}{\text{graphite density}}$$

$$= 1860 \cdot \frac{1.47}{2.25}$$

$$= 1215 \, ^{0}\text{K}$$

The integral in the Debye approximation formula was evaluated numerically. The program is listed in Appendix E and the results of the computation are shown on Page 29. Graphically the results are depicted in Figure 8 on Page 30. For comparison the variation of specific heat with temperature for multicrystalline graphite is shown in Figure 9 on Page 30.

Based on the literature and the calculated data the specific heat in all subsequent calculations was varied between .3 and .5 cal/\(^{\circ}\text{C} \cdot \text{g}\) as tabulated below.

| DEBYE TEMPERATURE = 1215.2 KELVIN |
|-----------------|-----------------|-----------------|
| TEMPERATURE     | SPECIFIC HEAT   | SP. HEAT        |
| (KELVIN)        | (CAL/MOLE K)    | (CAL/GR K)      |
| 293.00          | 2.919E+00       | .24321457       |
| 493.00          | 4.590E+00       | .30251072       |
| 693.00          | 5.275E+00       | .33901054       |
| 893.00          | 5.972E+00       | .46841254       |
| 1093.00         | 5.779E+00       | .48030335       |
| 1293.00         | 5.372E+00       | .4334153        |
| 1493.00         | 5.933E+00       | .43447493       |
| 1693.00         | 5.932E+00       | .43017745       |
| 1893.00         | 5.932E+00       | .50419245       |
| 2093.00         | 5.935E+00       | .50823329       |
| 2293.00         | 5.935E+00       | .50444801       |
| READY           |

**TABLE 6. Specific Heat of Vitreous Carbon**
FIGURE B. Specific Heat of Vitreous Carbon by the Debye Approximation Method

FIGURE 9. Specific Heat of Molded Multicrystalline Graphite
4.2.2 COOLING GAS

The pressure associated with the phase change of liquid coolants precludes their use as a beam dump coolant medium. Water for example would turn into high pressure steam in less than 70 n-sec with a force strong enough to damage the beam dump. Because vitreous carbon oxidizes above 500°C, oxygen and air are eliminated as gaseous cooling mediums. The pressure wave nitrogen would produce during the heat rise of the first pulse is approximately 15 psi. This pressure would require a thick first plate which is difficult to cool. Heavier gases than nitrogen, like neon, argon, etc. have to be excluded for the same reason. Hydrogen would be the ideal cooling medium but has to be excluded for safety reasons. This leaves helium which is inert and safe if not inexpensive.

Properties of Helium

Density (0°C and 1 ATM) .1785 gr/liter
Specific heat (all temperatures) 1.243 cal/°C
Stopping range for 50 MeV electrons 21 gr/cm²

4.3 THERMAL RESPONSE TO THE ELECTRON BEAM

During exposure to the high intensity electron beam the first vitreous carbon plate which separates the accelerator vacuum from the pressurized cooling medium experiences a rapid temperature rise.

One beam pulse is 70 n-sec long and the energy/pulse is 35000 joules (8365 cal). A fraction of the total energy gets deposited in the first wall and causes a temperature rise which is most severe in the center (hot spot).
The time between pulses in the burst mode is 10 milliseconds which is too short for any significant cooling to take place. In the burst mode we have 10 pulses every two seconds. For heat rise calculations the 10 pulses can be lumped together.

4.3.1 TEMPERATURE RISE

The temperature rise is a function of the energy absorbed, the specific heat, the volume and the density of the stopping material.

$$\Delta T = \frac{\Delta Q}{\rho \cdot V \cdot Cp}$$

Where:
- $\Delta Q$ = energy absorbed
- $\rho$ = density of stopping material
- $V$ = volume of stopping material
- $Cp$ = specific heat of stopping material

According to (1) the stopping length of carbon is 12.5 cm @ 50 MeV. Adjusting this for the reduced density of vitreous carbon yields 15.3 cm.

The energy deposited by one pulse in the first element is then:

$$\Delta Q = Q_0 \cdot \frac{t}{R} \quad t = .152 \text{ cm THK's of first plate}$$

$$= 8365 \cdot .152/15.3 \quad Q_0 = 35000 \text{ joules}$$

$$= 83.1 \text{ cal}$$

Because of the higher energy loss per distance traversed (Section 4.1.3) for the more energetic electrons the 83.1 cal have to be increased by a factor 1.2561. For the 10 initial pulses the energy deposited becomes:

$$\Delta Q_{10} = 83.1 \cdot 10 \cdot 1.2561$$

$$= 1043 \text{ cal}$$
Using a specific heat value of 0.5 cal/°C, the heat rise for a 2 cm beam diameter becomes:

$$\Delta T = \frac{A_0 \cdot 10^{43.8}}{\rho \cdot V \cdot Cp} = \frac{1043.8}{(1.47) \times (2^2 \cdot \pi) \times (.152) \times (.5)}$$

$$= 2974 \degree C$$

With rising temperature the specific heat increases from 0.3 to 0.5 cal/°C. Accounting for this variation in specific heat increases the peak temperature rise to 3052 °C.

Not all of the energy deposited in the first plate goes into heat. According to (1) the radiation stopping power is 33.281 percent of the total stopping power for 50 MeV electrons. This means that one third of the electron-energy will be lost to X-ray production (Bremsstrahlung). The approximate amount of X-ray energy reabsorbed by the first plate can be calculated the following way:

$$E_A = E_p (1 - e^{-\frac{x}{x_0}})$$

$$= E_p (1 - e^{-\frac{.152}{23.6}})$$

$$E_A = E_p \times 0.00642$$

Where:

- $x =$ THK's of first plate
  - = 0.152 cm
- $x_0 =$ radiation length of carbon = 23.6 cm
- $E_A =$ energy absorbed
- $E_p =$ first plate X-ray energy.

The amount of X-ray energy recaptured by the first plate is less than one percent and can be ignored.
The temperature rise with the X-ray energy taken out and variable specific heat is:

\[ \Delta T = 2063 \, ^\circ C \]

PROGRAM HEATRISE (FILE NAME HEATRS)
THIS PROGRAM CALCULATES THE HEAT RISE IN THE FIRST FOIL FOR A GIVEN BEAM DIAMETER. CONVECTIVE COOLING BETWEEN THE PULSES IS IGNORED AND THE TOTAL HEAT INPUT IS THE EQUIVALENT ENERGY OF 10 PULSES. HIGHER ENERGY LOSS AT BEGINNING OF BEAM DUMP IS ACCOUNTED FOR. TOTAL ENERGY DEPOSITED IN FIRST PLATE IS REDUCED BY THE AMOUNT OF ENERGY WHICH IS CONVERTED INTO X-RAYS (33.281 %)

BEAM DIAMETER (IN) = 2
TOTAL ENERGY INPUT (CAL) = 1043.883
X-RAY ENERGY (CAL) = 347.413

<table>
<thead>
<tr>
<th>TIME (N-SEC)</th>
<th>SPECIFIC HEAT (CAL/G C)</th>
<th>HEAT INPUT (CAL)</th>
<th>TEMP. RISE (DEGREE C)</th>
<th>( \frac{d(T)/dt}{DEG-C/N-SEC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.00</td>
<td>0.30856</td>
<td>6.96</td>
<td>32.15</td>
<td>4.59</td>
</tr>
<tr>
<td>14.00</td>
<td>0.33421</td>
<td>13.93</td>
<td>61.84</td>
<td>4.24</td>
</tr>
<tr>
<td>21.00</td>
<td>0.35365</td>
<td>20.89</td>
<td>89.90</td>
<td>4.01</td>
</tr>
<tr>
<td>28.00</td>
<td>0.36942</td>
<td>27.86</td>
<td>116.76</td>
<td>3.84</td>
</tr>
<tr>
<td>35.00</td>
<td>0.38277</td>
<td>34.82</td>
<td>142.68</td>
<td>3.70</td>
</tr>
<tr>
<td>42.00</td>
<td>0.39441</td>
<td>41.79</td>
<td>167.83</td>
<td>3.59</td>
</tr>
<tr>
<td>49.00</td>
<td>0.40480</td>
<td>48.75</td>
<td>192.94</td>
<td>3.50</td>
</tr>
<tr>
<td>56.00</td>
<td>0.41423</td>
<td>55.72</td>
<td>216.30</td>
<td>3.42</td>
</tr>
<tr>
<td>63.00</td>
<td>0.42290</td>
<td>62.68</td>
<td>239.76</td>
<td>3.35</td>
</tr>
<tr>
<td>70.00</td>
<td>0.43096</td>
<td>69.65</td>
<td>262.78</td>
<td>3.30</td>
</tr>
<tr>
<td>140.00</td>
<td>0.49259</td>
<td>139.29</td>
<td>475.36</td>
<td>2.87</td>
</tr>
<tr>
<td>210.00</td>
<td>0.50000</td>
<td>208.94</td>
<td>673.84</td>
<td>2.83</td>
</tr>
<tr>
<td>280.00</td>
<td>0.50000</td>
<td>278.59</td>
<td>872.28</td>
<td>2.83</td>
</tr>
<tr>
<td>350.00</td>
<td>0.50000</td>
<td>348.22</td>
<td>1070.72</td>
<td>2.83</td>
</tr>
<tr>
<td>420.00</td>
<td>0.50000</td>
<td>417.88</td>
<td>1269.15</td>
<td>2.83</td>
</tr>
<tr>
<td>490.00</td>
<td>0.50000</td>
<td>487.53</td>
<td>1467.59</td>
<td>2.83</td>
</tr>
<tr>
<td>560.00</td>
<td>0.50000</td>
<td>557.17</td>
<td>1666.02</td>
<td>2.83</td>
</tr>
<tr>
<td>630.00</td>
<td>0.50000</td>
<td>626.82</td>
<td>1864.46</td>
<td>2.83</td>
</tr>
<tr>
<td>700.00</td>
<td>0.50000</td>
<td>696.47</td>
<td>2062.90</td>
<td>2.83</td>
</tr>
</tbody>
</table>

MAX. TEMPERATURE WITH X-RAY ENERGY NOT ACCOUNTED FOR = 3051.97

TABLE 7. Heat Rise Vs. Time Over 10 Pulses
The program which calculates the heat rise is listed in Appendix D-6 and the results of the computation are shown in Table 7 on Page 34.

The temperature rise of 2063 °C is the maximum temperature in the center spot of the front plate. In the radial direction the temperature is a function of the beam intensity. Figure 10 below shows graphically the results of the numerical calculation listed in Table 8 on Page 36.

--- Square Distribution, Beam Radius is 1 cm
--- Gaussian Distribution Beam Radius is .707 cm, same center-spot temperature rise
--- Gaussian Distribution with X-ray Energy Subtracted

![Graph of beam radius vs temperature](image)

**FIGURE 10. First Wall Radial Temperature Distribution**
TABLE 8. First Wall Radial Temperature Distribution

In addition to the radial temperature distribution there exists an axial temperature distribution which is a function of the beam diameter. Along the axis of penetration the beam spreads and the temperature decreases. The temperature rise along the beam axis is calculated by the program spread D-2. The results are shown graphically in Figure 11 on Page 37.

In addition to the radial temperature distribution there exists an axial temperature distribution which is a function of the beam diameter. Along the axis of penetration the beam spreads and the temperature decreases. The temperature rise along the beam axis is calculated by the program spread D-2. The results are shown graphically in Figure 11 on Page 37.
4.3.2 COOLING RESPONSE

In the burst mode of operation 10 pulses of 70 n-sec duration occur at a frequency of 1000 Hz followed by a 1.99 second cool down period. The maximum temperature rise in the center spot of the first plate after 10 pulses is 2062.9 °C which has to be reduced to ambient in less than two seconds. The first wall of the beam dump is cooled by convection (helium gas) on one side and by radiation (vacuum side) on the other. In order to determine the necessary convective heat transfer coefficient and the first wall thickness the cooling problem was solved analytically and numerically.

FIGURE 11. Axial Temperature Distribution

Depth of Beam Penetration - cm

Temperature, °C

0 2000 1500 1000 500

0 20 40 60 80
ANALYTICAL SOLUTION

The analytical solution is obtained from a graphical solution of the infinite flat plate transient cooling problem. Several conservative simplifying assumptions are used. The vacuum side is assumed to be insulated, ignoring radiation cooling. The analysis is one dimensional, ignoring heat transfer in the radial direction. It is assumed that no cooling takes place between the ten pulses. Thermal conductivities and specific heats are assumed to be constant.

INFINITE PLATE CONVECTIVE COOLING

Plate Material - Vitreous Carbon

Plate Thickness - .152 cm

Vitreous Carbon:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity</td>
<td>0.01 cal/cm°C sec</td>
</tr>
<tr>
<td>Density</td>
<td>1.47 gr/cm³</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.5 cal/gr°C</td>
</tr>
</tbody>
</table>

Convective Heat Transfer Coefficient (calculated)

\[ h = 0.1 \text{ cal/sec cm}^2 \text{ °C} \]

From graphs and plots in Reference 10.

<table>
<thead>
<tr>
<th>(X/L)</th>
<th>(\Delta T/\Delta T_{MAX})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(t = 0)</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>.2</td>
<td>1</td>
</tr>
<tr>
<td>.4</td>
<td>1</td>
</tr>
<tr>
<td>.6</td>
<td>1</td>
</tr>
<tr>
<td>.8</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
From Section 4.3.1 the maximum temperature rise $\Delta T_{\text{MAX}} = 2063 \, ^\circ\text{C}$. This means that after two seconds the front of the first plate has cooled down to

$$(2062 \cdot 9) \times (.36) = 743 \, ^\circ\text{C}$$

Numerically, using the same values for the specific heat, thermal conductivity and the convective heat transfer coefficient, the result is $799 \, ^\circ\text{C}$ which is in good agreement with the analytical result. The results of the numerical and analytical calculations are shown graphically in Figure 12 on Page 40. The numerical results are listed in Table 9 on Page and the program is listed in Appendix E under the program name CONVEC.
TABLE 9. Convective First Wall Cooling

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>H</th>
<th>H</th>
<th>H</th>
<th>H</th>
<th>H</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>0.001</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>0.002</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>0.003</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**FIGURE 12.** Comparison of Analytical and Numerical Solution to the First Wall Convective Cooling Problem
NUMERICAL SOLUTION

In order to allow for variation in material properties and radiative effects a numerical approach was used. Conductive cooling in the radial direction is assumed to be negligible and the problem can be approximated by a one dimensional transient heat flow problem.

PROBLEM DEFINITION

The first wall of the beam dump is cooled convectively on one side and radiatively on the other as indicated in Figure 13 below:

![Figure 13. First Wall Problem Definition](image)

Density of vitreous carbon = 1.47 gr/cm³
Emissivity = .9
Specific heat of vitreous carbon = .3 - .5 cal/gr °C
Thermal conductivity = .1 - .4 cal/cm sec °C

FIGURE 13. First Wall Problem Definition
The numerical approach is based on an explicit finite difference technique (11). The program is listed in Appendix D-5 and the results are shown below in Table 10. Graphically the results are shown in Figure 14 on Page 43. The single most critical factor is the convective heat transfer coefficient. A value of $0.3623 \text{ cal/sec cm}^2 \text{ °C}$ was used which is based on analytical considerations explained in Section 4.3.3. Using $0.3623 \text{ cal/sec cm}^2 \text{ °C}$ for the heat transfer coefficient reduces the temperature from 2062.9 °C to 81 °C in 1.99 seconds.

**TABLE 10. Convective and Radiative First Wall Cooling With Variable Material Properties**

| TIME (SEC) | 0.0041 |
| 1740, 2063, 2063, 2063, 2063, 2063 |
| TIME (SEC) | 0.0129 |
| 910, 1260, 1440, 1620, 1741, 1967, 2019 |
| TIME (SEC) | 0.0236 |
| 649, 909, 1091, 1252, 1364, 1492, 1526 |
| TIME (SEC) | 0.0375 |
| 472, 669, 826, 973, 1072, 1136, 1149 |
| TIME (SEC) | 0.0491 |
| 349, 510, 645, 761, 845, 923, 984 |
| TIME (SEC) | 0.0622 |
| 263, 353, 456, 559, 667, 769, 824 |
| TIME (SEC) | 0.0746 |
| 201, 267, 329, 474, 558, 564, 571 |
| TIME (SEC) | 0.0870 |
| 157, 246, 317, 390, 423, 451, 469 |
| TIME (SEC) | 0.0934 |
| 125, 194, 254, 303, 341, 363, 376 |
| TIME (SEC) | 0.1117 |
| 102, 152, 205, 245, 275, 297, 307 |
| TIME (SEC) | 0.1234 |
| 84, 109, 167, 199, 223, 242, 263 |
| TIME (SEC) | 1.0857 |
| 71, 106, 130, 164, 183, 195, 199 |
| TIME (SEC) | 1.4401 |
| 61, 89, 115, 135, 151, 161, 164 |
| TIME (SEC) | 1.6168 |
| 55, 76, 96, 113, 126, 134, 136 |
| TIME (SEC) | 1.7266 |
| 47, 66, 82, 95, 106, 112, 114 |
| TIME (SEC) | 1.8604 |
| 43, 57, 70, 81, 89, 95, 98 |
| TIME (SEC) | 1.9941 |
| 29, 51, 61, 70, 72, 81, 82 |
| TIME (SEC) | 2.0199 |
| 29, 59, 61, 69, 78, 86, 81 |

WILLIAM A. BROCK & ASSOCIATES
FIGURE 14. Radiative and Convective First Wall Cooling with Variable Material Properties
4.3.3 FILM COEFFICIENT ANALYSIS

The film coefficient of the cooling gas is calculated with the following assumptions:

1. The cooling gas passes through a rectangular cavity .344 by 3.5 inches.
2. The cavity is filled with vitreous carbon foam.
3. The foam is attached to the first wall and acts as cooling fins.

The configuration is illustrated in Figure 1.

The film coefficient of the cavity is calculated, then the additional effect of the fins is calculated and added to obtain a combined effective cooling coefficient.

The film coefficient of the cavity is calculated by using the Dittus-Boelter equation:

\[ \text{Nu} = 0.0243 \left( \frac{\text{Re}^{0.8}}{\text{Pr}^{0.4}} \right) \]

Where:
- \( \text{Nu} \) = Nusselt number
- \( \text{Re} \) = Reynolds number
- \( \text{Pr} \) = Prandtl number

The Nusselt number is \( \frac{\text{hd}}{k} \)

Where:
- \( h \) = film coefficient
- \( d \) = hydraulic diameter
- \( k \) = conductivity of the gas

The film coefficient of the cavity, \( h_1 \), is then:

\[ h_1 = 0.0243 \frac{k}{d} \left( \frac{\text{Re}^{0.8}}{\text{Pr}^{0.4}} \right) \]

The foam structure is assumed to be analytically similar to thin rods. Heat is conducted from the surface of the first wall through the thin rods.
The heat flow into a rod, Q is:

\[ Q = h_{R} \frac{C}{KA} \sqrt{\frac{C}{KA}} \Delta T \tanh (mL) \text{ eq 3-23 Reference 14} \]

Where:

- \( h_{R} \) = film coefficient on the rod
- C = circumference of rod
- K = thermal conductivity of rod
- A = cross sectional area of rod
- L = length of rod
- \( \Delta T \) = temperature difference between bare rod and cooling fluid

The film coefficient on the rod, \( h_{R} \), is determined from equation 9-29, Reference 14. It is assumed that the foam structure is analytically similar to staggered tube bundles.

\[ Nu_{R} = \frac{h_{R}d}{K} = 0.43 + k (Re)^{m} (Pr)^{\frac{31}{3}} \]

Where:

- k, m = functions of rod spacing
- d = rod diameter

Assume that \( N \) is the number of rods in contact with the first wall per unit area, then the equivalent film coefficient of the rods, \( h_{2} \), (with respect to first wall area) is:

\[ h_{2} = NX \]

Where \( X = \frac{h_{R} C}{KA} \tanh (mL) \)

The total film coefficient, \( h \), is the sum of \( h_{1} \) and \( h_{2} \):

\[ h = h_{1} \text{ and } h_{2} \]
The foam has 100 pores per linear inch. Under magnification the "rods" in the foam appear to be .003 inch in diameter. The open cells appear to be .007 inch in diameter. There are 3 struts that would connect to the first wall surface in a .01 x .01 inch square. A magnified view of the foam is in Figure 15 below.

The following conditions are assumed:
1. The cooling gas is helium at a pressure of 13.9 atmospheres.
2. The gas velocity is 50 feet/sec.
3. The foam material is vitreous carbon.

For the above conditions the film coefficient is .3623 cal/sec cm² °C

FIGURE 15. Magnified View of Vitreous Carbon Foam

4.4 MECHANICAL RESPONSE

Mechanical forces are generated during beam absorption. These forces and their effects are analyzed in this section.
4.4.1 MECHANICAL IMPULSE

1. Explanation: The beam particles are stopped by the beam dump from a velocity of 99.995% the speed of light to zero. This change in momentum results in a force upon the beam dump. It will be shown that the total force on the beam dump is 1670 newtons (375.5 lbs). For a 2 cm diameter beam, this results in a 19.3 psi pressure on the first wall and 9.6 psi pressure on the interior foils.

CALCULATIONS

2. Number of Electrons in Beam

\[ \text{Charge} = \text{current} \times \text{period} \]
\[ = 10000 \text{ Amp} \times 70 \times 10^{-8} \text{ sec} \]
\[ = 7 \times 10^{-4} \text{ Amp sec} \]

The charge on one electron is \(1.6 \times 10^{-19} \text{ Amp sec}\)

The total number of electrons, \(n\), is:

\[ n = \frac{7 \times 10^{-4} \text{ Amp sec}}{1.6 \times 10^{-19} \text{ Amp sec/electron}} \]
\[ n = 43.75 \times 10^{14} \text{ electrons per pulse} \]

3. Mass of 50 MeV Electrons

The rest mass, \(M_0\), of an electron is \(0.9109 \times 10^{-30} \text{ kg}\)

The mass \(m\), of an electron at relativistic speed is

\[ m = \gamma M_0 \]

where

\[ \gamma = \left(1 - \beta^2\right)^{-\frac{1}{2}} \]

and

\[ \beta = \frac{V}{C} \]

\(V = \text{particle velocity, } C = \text{velocity of light, } 2.998 \times 10^8 \text{ m/sec} \)
\( \beta \) can be found from the following relationship

Total energy = rest mass energy + kinetic energy

\[
E = M_0 C^2 + M C^2 \left( \frac{1}{1 - \beta^2} \right)^{1/2}
\]

rearranging:

\[
\beta = \left\{ \frac{1 - \left[ 1 - \frac{1}{(E/M_0 C^2 - 1)} \right]^2}{2} \right\}^{1/2}
\]

the total energy, \( E \), is 50 MeV,

\( M_0 C^2 \) is .511 MeV so that:

\[
\beta = .99995
\]

and

\[
\gamma = 97.84
\]

the total mass of the beam, \( M_B \), is

\[
M_B = n M_0 \gamma
\]

\[
M_B = (43.75 \times 10^{14}) (0.9109 \times 10^{-30}) (97.84)
\]

\[
M_B = 3.899 \times 10^{-13} \text{ kg}
\]

4. Beam Momentum

Beam momentum, \( P_B \), is

\[
P_B = M_B V, \quad V = \text{beam velocity}
\]

where

\[
V = \beta C
\]

\[
P_B = (3.899 \times 10^{-13}) (2.997 \times 10^8) (0.99995)
\]

\[
P_B = 11.69 \times 10^{-5} \text{ kg m/sec}
\]
5. Beam Force and Pressure

The momentum of the beam is absorbed by the dump in a period, \( t \), of 70 ns. The force on the dump is \( F \),

\[
F = \frac{P_B}{t}
\]

\[
F = 11.69 \times 10^{-5} \div 70 \times 10^{-9}
\]

\( F = 1670 \) newtons

Assume the beam diameter, \( d \), is 2 cm. The pressure, \( P \), is then:

\[
P = \frac{F}{\pi \frac{d^2}{4}}
\]

\[
P = 1670 \div \left(\frac{0.02}{0.02}\right)^2
\]

\( P = 5.316 \times 10^6 \) Pa or 771 psi

This pressure is divided among 80 elements. The first wall is twice the thickness of the inner elements. The pressure on the first wall is then:

\[
P_w = \frac{5.316 \times 10^6 \times 2}{80}
\]

\( P_w = 132900 \) Pa or 19.27 psi

The pressure on the remaining 79 elements is approximately half the pressure on the first wall (66450 Pa or 9.6 Psi).
4.4.2 THERMAL SHOCK (DYNAMIC)

1. Discussion

A thermal pressure is produced when thermal energy is deposited in a material so fast that volumetric dimensions are unable to expand significantly during the time of energy deposition. We assume that the acoustic velocity of vitreous carbon (\( p = 1.47 \)) is the same as that for pyrolytic graphite (\( p = 2.17 \)), i.e., 3.7 mm/\( \mu \)s. For the first wall half thickness of 0.75 mm, the time for the release wave to reach the centerplane is 203 ns, nearly three times the time for energy deposition. Also for a 0.0 mm spot radius, the time for the radial release wave to converge to the central axis will be 2703 ns. Along the central axis there will be three complete tension/compression plane strain reverberations before the radial release wave converges, for each pulse. In the burst mode each pulse is well separated in time, i.e., by 1,000,000 ns. Each pulse is a separate event.

When the half thickness release wave reaches the centerplane, the plane strain tension produced will equal the thermal pressure. When the radial release wave reaches the central axis the component radial tension produced will be superimposed upon whatever half thickness pressure may exist at that time.

If it is assumed that the thermal energy deposition effectively is instantaneous and radially uniform, the thermal pressure is 7358 psi. The plane strain centerplane tension, therefore, will be 7358 psi.

2. Calculations

It is assumed that the energy is deposited into the material instantly, thus, the material cannot expand.
The magnitude of the pulse is that of a solid body subjected to a temperature change $\Delta T$ throughout while held to the same form and volume. From Reference 15 the resulting stress, $\sigma$, is given below.

$$\sigma = \alpha E \Delta T \left[ \frac{1}{1 - 2v} \right]$$

$\alpha$ = coefficient of thermal expansion, $3.2 \times 10^{-6} \, ^\circ C^{-1}$

$E$ = Young's modulus, $3.5 \times 10^6 \, $ psi

$v$ = Poisson's ratio, assumed to be 0.3

$T$ = the temperature rise from the first pulse, $263 \, ^\circ C$

$$\sigma = \frac{(3.2 \times 10^{-6})(3.5 \times 10^6)(263)}{[1 - (2)(0.3)]}$$

$\sigma = 7358 \, $ psi compression

When this "thermal pressure" is relieved across the thickness of the first wall, the resulting centerplane tension will be 7358 psi.

It should be noted that the above values are limit values. The actual values will be less because the energy is actually deposited over a finite period of time. To obtain more accuracy, a hydrodynamic code should be used.

The Gruneisen number is a dimensionless parameter used to calculate thermal pressure as a multiplier of deposited energy. Here its use is equivalent to the thermal stress calculations above. The Gruneisen number, $G$, for carbon and other materials is listed in Table 11.

$$G = \frac{3 \alpha K}{\rho C_p}$$

where

$\alpha$ = linear coefficient of thermal expansion

$K$ = bulk modulus

$\rho$ = density

$C_p$ = specific heat
The thermal pressure associated with a sudden temperature rise of 263 °C is:

\[ \Delta P = G \cdot \Delta E \]

where \( \Delta E \) is the energy deposited per unit volume.

\[ \Delta E = \rho \cdot C_p \cdot \Delta T \]

Values for energy deposited and the associated thermal pressure are shown in Table 11.

<table>
<thead>
<tr>
<th>Gruneisen Number</th>
<th>Density gr/cm³</th>
<th>Spec. Heat cal/pr °C</th>
<th>Energy Deposited</th>
<th>Thermal Psi Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitreous carbon</td>
<td>.0628</td>
<td>1.47</td>
<td>.5</td>
<td>117,293</td>
</tr>
<tr>
<td>Graphite</td>
<td>.0592</td>
<td>2.25</td>
<td>.3</td>
<td>170,472</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.7</td>
<td>2.77</td>
<td>.213</td>
<td>31,199</td>
</tr>
<tr>
<td>Copper</td>
<td>1.81</td>
<td>8.9</td>
<td>.103</td>
<td>307,405</td>
</tr>
</tbody>
</table>

TABLE 11. Thermal pressure associated with a sudden temperature rise for various materials.

From Table 11 it is clear that the thermal pressure resulting from a sudden temperature rise is approximately 75 times higher in copper than in vitreous carbon.
4.4.3 THERMAL STRESS (STATIC)

1. Discussion

The thermal gradient across the first wall causes differential expansion resulting in a bending thermal stress. Radial expansion of the hot spot causes a similar stress at the spot boundary.

2. Results

The bending stress is 7232. The spot stress is 11550 psi compression in the spot.

3. Calculations

Thermal Gradient Bending Stress

From the results of the cooling response analysis it is determined that the maximum temperature gradient across the first wall, $\Delta T$, is 904 °C.

An acceptable approximation for thermal stress of a spherical plate is a flat plate restrained from bending (Reference 16).

From Reference 15 the stress, $\sigma$, is:

$$\sigma = \frac{E \alpha}{2} \left[ \frac{\Delta T}{(1-\nu)} \right]$$

where

$\alpha = \text{coefficient of thermal expansion, } 3.2 \times 10^{-6} \text{ °C}^{-1}$

$\nu = \text{Poisson's ratio, assumed to be 0.3}$

$E = \text{Young's modulus, } 3.5 \times 10^6 \text{ psi}$

$$\sigma = \frac{(3.5 \times 10^6)(3.2 \times 10^{-6})(904^\circ)}{2(1-0.3)}$$

$$\sigma = 7232 \text{ psi}$$

This is a tensile stress on the cooled side and a compressive stress on the vacuum side.
Spot Stress

For a thin circular disk with a small circular spot raised in temperature by $T$, the radial and tangential stresses in the spot are:

$$S_r = S_t = \frac{T}{2} \alpha E$$

The temperature rise, $T$, is 2063 °C after ten pulses.

$$S_r = S_t = \frac{(2063) \times (3.2 \times 10^{-6}) \times (3.5 \times 10^6)}{2}$$

$$S_r = S_t = 11550 \text{ psi compression}$$

Just outside the spot, the tangential stress changes sign to 11550 psi tension. The stress then decreases with the square of the ratio of the spot radius divided by the distance from the spot center.

These stress levels represent a limit case. The analysis assumes that the energy distribution is rectangular. In reality the distribution is Gaussian. As a result, the maximum stresses will be substantially lower.

4.4.4 COOLING GAS PRESSURE

The pressure of the cooling gas is resisted by the first wall. The first wall, which is a spherical segment, must resist buckling and also must endure membrane stress.

Allowable cooling gas pressure is 13.9 atmospheres. The first wall is .06 inch thick with a buckling safety factor of 2.5. The membrane stress is 5110 psi. Bending stresses at the edge of the spherical segment were not computed.

The buckling pressure of a sphere, $p'$, is:

$$p' = \frac{.365 E t^2}{S r^2}$$

Reference 15, XVI-T
where

\[
S = \text{safety factor, } 2.5
\]
\[
E = \text{Young's modulus, } 3.5 \times 10^6 \text{ psi}
\]
\[
t = \text{thickness, .06 inch}
\]
\[
r = \text{radius of sphere, 3 inches}
\]
\[
p' = \frac{(0.365)(3.5 \times 10^6)(0.06)^2}{(2.5)(3)^2}
\]
\[
p' = 204.4 \text{ psi or 13.9 atmospheres}
\]

The membrane stress in a sphere, \(\sigma\), is:

\[
\sigma = \frac{p' r}{2t}
\]

where

\[
p = \text{pressure = 204.4 psi, external}
\]
\[
\sigma = \frac{(204.4)(3)}{(2)(0.06)}
\]
\[
\sigma = 5110 \text{ psi compression}
\]

4.4.5 GAS EXPANSION IMPULSE

1. Discussion

Both nitrogen and helium were considered for use as a cooling gas. The graph on page shows that the film coefficient for nitrogen is almost as high as for helium. If this were the only consideration, nitrogen would be the logical choice because it is cheaper and easier to contain.

The analysis in this section calculates the pressure pulse on the first wall that results from the column of cooling gas being heated by the electron beam. The resulting stress in the first wall is 15680 psi with nitrogen and 1841 psi with helium. It is this difference that makes helium the better choice.
2. Helium as a Cooling Medium

The temperature rise, $\Delta T$, of the cooling gas is given by:

$$\Delta T = \frac{Q}{\rho V C_p}$$

where

- $Q =$ beam energy per pulse, 35000 joules
- $\rho =$ density of helium at 13.9 atmospheres pressure
- $C_p =$ specific heat, 1.242 cal gm$^{-1}$°C$^{-1}$
- $V =$ volume = $\frac{\pi d^2 R}{4 \rho}$
- $d =$ beam diameter, 2 cm
- $R =$ stopping range, 21 gm/cm$^2$

$$\Delta T = \frac{4Q}{(\rho n d^2 C_p)} = \frac{4Q}{(n d^2 R C_p)}$$

$$\Delta T = \frac{4 \times (35000) \times (0.2389)}{\pi(2)^2 \times (21) \times (1.242)}$$

$$\Delta T = 102.0 \, ^\circ C$$

The pressure increase is calculated.

$$P_1 = \frac{P_2}{T_1 \times T_2}$$

$$P_2 = \frac{P_1 \times T_2}{T_1}$$

Assume initial conditions of $P_1 = 13.9$ atmospheres and $T_1 = 300^\circ K$

$$P_2 = 13.9 \times \frac{(300 + 102)}{300}$$

$$P_2 = 18.63 \text{ atmospheres}$$

The pressure increase is 4.73 atmospheres or 69.5 psi.
Sonic velocity in helium, V, is calculated.

\[ V = \sqrt{\frac{K P g}{\rho}} \]

where

- \( K = \) ratio of specific heats, 1.66
- \( P = \) pressure at 1 atmosphere, 1033 gm/cm²
- \( \rho = \) density at 1 atmosphere, 1.617 \( \times \) 10⁻⁴ gm/cm³
- \( g = \) acceleration of gravity = 980.7 cm/sec²

\[ V = \sqrt{\frac{(1.66)(1033)(980.7)}{(1.617 \times 10^{-4})}} \]

\[ V = 98170 \text{ cm/sec} \]

Assume that the pulse velocity in the porous foam is 30% slower.

\[ V = 0.7 \times 98170 = 68720 \text{ cm/sec} \]

The pulse decays in the time required to relieve the radius of the spot, \( \Delta T \).

\[ \Delta T = \frac{r}{V} = 14.55 \text{ sec} \]

Assume that the pressure pulse is triangular.

Then the impulse, \( I \), is:

\[ I = \frac{1}{3} P \Delta T = \frac{(69.5)}{3} (14.55 \times 10^{-6}) \]

\[ I = 3.371 \times 10^{-4} \text{ psi - sec} \]

The impulse acts on a 2 cm diameter section of the first wall.

\[ I = m \Delta V \]
where: \( m \) is the mass of the first wall section.

\( \Delta V \) is the increase in velocity of the first wall section.

The mass of the first wall section, \( m \), is calculated:

\[
m = \rho V = \frac{\rho t d^2}{g/4}
\]

\( \rho = \) density of first wall, 1.47 gm/cm\(^3\)

\( t = \) thickness of first wall, .06 inch

\( d = \) diameter of segment, 2 cm or .7874 inch

\( g = \) gravity = 386.1 in/sec\(^2\)

\[
m = \left(0.0531\right) \left(0.06\right) \pi \left(0.7874\right)^2 = 4.017 \times 10^{-6} \text{ lb} \cdot \text{sec}^2/\text{in}^4
\]

Solving for the increase in velocity, \( \Delta V \):

\[
\Delta V = \frac{1}{m}
\]

\[
= \frac{3.371 \times 10^{-6}}{4.017 \times 10^{-6}}
\]

\( \Delta V = 83.92 \text{ in/sec} \)

Kinetic energy of the wall segment is equated to elastic energy:

\[
\frac{1}{2} m (\Delta V)^2 = \frac{\sigma^2 V}{2 E}
\]

where:

\( \sigma = \) stress

\( E = \) Young's modulus, 3.5 \( \times \) 10\(^6\) psi

The equation is rearranged to solve for the stress, \( \sigma \):

\[
\sigma = \frac{\Delta V}{V} m E = \frac{\Delta V}{\pi/4 d^2 t} m E
\]

\[
= (83.92) \left(4.017 \times 10^{-6}\right) \left(3.5 \times 10^6\right) \left(0.7874\right) \left(0.06\right)
\]

\( \sigma = 1841 \text{ psi} \)
3. Nitrogen as a Cooling Medium

A similar calculation with nitrogen gives a first wall stress level of 15680 psi.
5. REFERENCES


2. Energy Dissipation by Fast Electrons, by L. V. Spencer, N.B.S. Monograph I, September 10, 1959


4. University of California Radiation Laboratory, UCRL-2426, Volume II, 1966 Revision


APPENDIX A. SYSTEM REQUIREMENTS
A T A
SYSTEM REQUIREMENT (SR)

Title: Beam Dumps

System Requirement:

Three beam dumps shall be provided:

1. Fixed in the Beam Transport Section within the tunnel (36,000 pulses/shift), with integral shielding for forward radiation, amount to be determined.

2. Fixed in the Atmospheric Transport Section within the Atmospheric Transport Bldg. (50,000 pulses/shift).

3. Variable location in the Experiment Tank within the tunnel (72,000 pulses/shift), variable the full length of the Tank.

System Requirements are as follows:

Dumps No. 1 and 2:

1. Beam Conditions: 100 A, 50 MeV, Radius 1.5 to 2.0 cm, Beam Quality 5 mr-cm.

2. Pulse count is 36,000 50,000 pulses per shift.

3. Beam dumps shall have an easily replaceable carbon material front face. The dumps may be slanted if required for full survivability.

4. Dumps shall be rotateable within a 2 minute period starting upon issuance of a command, and shall be retractable within a 1 minute time period.

5. Provisions shall be made for easy inspection of the front face to observe any deterioration caused by the beam.

Dumps No. 3:

1. Beam conditions the same as for Nos. 1 and 2.

2. Pulse count shall be 70,000 pulses per shift and shall accommodate 50% of these pulses in shutter mode operations.

Reference Documents:

Approvals:

Richard J. Highs
Program Leader
Charged Particle Beam Program

I. Hope Pineda
Project Manager
Advanced Test Accelerator Project

A T A
SYSTEM REQUIREMENT (SR)

Title: Beam Dumps

3. Beam dump dimensions shall be no more than 1 foot diameter and 6 feet in length. They include a beam scattering region and the possibility of a segmented approach using more than one carbon foil in front of the beam dump. They exclude any heat exchanger system and associated plumbing. Provisions must be made for activation of the cooling system.

4. The dump shall be moveable within the full length of the Experimental Tank.

5. Provisions shall be made to safely exhaust gaseous products from this unit.

6. All carbon foils/materials used shall be easily replaceable. Provisions must be made to easily inspect the deterioration of these foils.
APPENDIX B. VITREOUS CARBON LITERATURE
Glass-like vitreous carbon resists heat and corrosive chemicals

Made in a variety of complex shapes, this specified form of carbon is beginning to find use in laboratory, optical, electronics and mechanical applications.

A material that seems as plastic and ends up as a glassy form of carbon is attracting considerable interest. It is known as vitreous carbon and has been developed by the Fluorochemical Company (Anaheim, Calif.).

Specifically, vitreous carbon is a material that resists heat and corrosion at high temperatures. It is produced by reacting graphite and novolac, which give a high degree of crosslinking. Shapes are first molded by compression, transfer or injection techniques.

The carbon is processed in the form of a reasonably low-vapor polymer, which, when exposed to air, gives a high-vapor carbon at temperatures as high as 2000°F. The molded shapes, some of complex design, are returned to temperatures of more than 2000°F, reacting them into a high-vapor vitreous carbon at temperatures as high as 3000°F.

Dr. A. L. Norm, Fluorochemical's manager of high-performance materials, notes that the existence of an essentially unlinked aromatic structure either in the original or in the resulting derivative is stated to possess an environment in a self-supporting structure on subsequent heating. This results in the structure found in vitreous carbon and appears to layer stacking in glassy carbon and the scaling of the pores in graphite. Applications to be found in the field of laboratory, optical, electronics and other industries.

For example, Dr. Norms suggests the following as possible uses for the glassy carbon material:

1. Molding dies for optical lenses and optics
2. Casting netches and flow cells

Vitreous carbon takes abuse at high temperatures

<table>
<thead>
<tr>
<th>Vitreous carbon</th>
<th>Graphite</th>
<th>Porous graphite</th>
<th>Atomic</th>
<th>Heat processed</th>
<th>Stabilized</th>
<th>Microscopic</th>
<th>Polysulfide</th>
<th>Molar</th>
<th>Chemical</th>
<th>Physical</th>
<th>Mechanical</th>
<th>Electrical</th>
<th>Corrosion</th>
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</thead>
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<tr>
<td>Density, g/cm³</td>
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<td>1900-19000</td>
<td>3200-6400</td>
<td></td>
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<td>1.4-2.3</td>
<td>1.8-3.0</td>
<td>1.7-2.1</td>
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<tr>
<td>Molding point, °C</td>
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<td>1200-13000</td>
<td></td>
<td></td>
<td>400</td>
<td>1200-13000</td>
<td>400-600</td>
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<td>1400-15000</td>
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<td>Glass breaking strength, MPa</td>
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<td>2000-40000</td>
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<td>Tensile strength, MPa</td>
<td>25.00-30.00</td>
<td>400-20000</td>
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<td>Yield strength, MPa</td>
<td>20.00-30.00</td>
<td>600-16000</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Young's modulus, MPa</td>
<td>3.4 ± 10²</td>
<td>500-15000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Max. stress, MPa</td>
<td>268 ± 10²</td>
<td>268 ± 10²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Max. temperature, C</td>
<td>3450+500</td>
<td>2450+500</td>
<td></td>
<td></td>
<td>1500</td>
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</tr>
</tbody>
</table>
FLUOROCARBON
CARBON (RVC)

WHAT IS RVC?
RVC is a new open pore "foam" material composed entirely of vitreous carbon (see cover photo). Vitreous carbon, as the name implies, is a new form of glass-like carbon which combines some of the properties of glass with some of those of normal industrial carbons. RVC has an exceptionally high void volume (70%), high surface area combined with a high supporting capability, low reactivity to fluid flow, and resistance to very high temperatures in non-oxidizing environments. It is now available in a wide range of porosity grades weighing about 3 pounds per cubic foot.

WHAT IS DISTINCTIVE ABOUT RVC?
- Exceptional chemical inertness over a very wide temperature range.
- Unique high-temperature strength combined with low bulk thermal conductivity.
- Universal rigid geometry which provides a large surface area combined with low pressure drop to fluid flow, along with high purity semiconducting materials without controlled porosity sites.
- Electrical conductivity.

HOW CAN RVC BE USED?
- High Temperature Insulation—For inert gas and vacuum furnaces where its ease of fabrication, self-supporting nature, low density, low outgassing, low heat capacity, and excellent K value combine to improve efficiency and reduce costs over conventional insulating materials.
- Semi-Conductor Manufacturing—Offers unique advantages in etching and diffusion treatment carriers, reduces manufacturing costs.
- Filters and Membranes—For molecular sieves, microelectronic, high or low temperature gases, and liquids, where maximum chemical inertness, combined with good filtration and self-support is required.
- Storage Batteries—In high energy density batteries such as the sodium/sulfur and lithium-aluminum聘用 discharge systems, where its unique "caging" effect on infused materials benefit performance, reduces cost.
- Biofolds—for biological growth in non-toxic and biologically inert in pollution-control systems, as catalysts or catalyst supports, in lower packings, where low pressure drop combined with large available surface area and chemical inertness is required.

WHAT ARE RVC'S PROPERTIES?

CHEMICAL PROPERTIES
RVC is composed of one of the most chemically inert forms of carbon known, its oxidation resistance is unique for a carbon—i.e., in spite of RVC's large surface area it does not support combustion after heating to bright incandescence in air followed by removal of the heat source. It is also inert to a wide range of very reactive chemicals at high temperatures. It will form carbides, but is inert to non-carbide forming metals and is not wetted by many molten metals. Measuring in air at 2000°F enhances its adsorption properties. Because of RVC's large surface area, heating RVC in air in this area in significant oxidation at rates which increase with increasing temperature.

PHYSICAL PROPERTIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Nominal Values, All Pore Sizes, Standard Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Void Volume, %</td>
<td>87</td>
</tr>
<tr>
<td>Thermal Shock Resistance</td>
<td>Excellent</td>
</tr>
<tr>
<td>Bulk Density lb/ft³</td>
<td>3</td>
</tr>
<tr>
<td>Shrinkage to 2000°F</td>
<td>Nil</td>
</tr>
<tr>
<td>Elongation Density lb/ft³</td>
<td>93</td>
</tr>
<tr>
<td>Volatiles to 2000°F</td>
<td>Nil</td>
</tr>
<tr>
<td>Structural Rigidity, 10 °C cm</td>
<td>50</td>
</tr>
<tr>
<td>Melting Point (Sublimation)</td>
<td>68°C</td>
</tr>
<tr>
<td>Crushing Strength</td>
<td>Nil</td>
</tr>
<tr>
<td>Temperature Limitation: in air</td>
<td>600°F</td>
</tr>
<tr>
<td></td>
<td>In non-oxidizing atmosphere 633°F</td>
</tr>
</tbody>
</table>

APPROXIMATE SURFACE AREA
OF ALL RVC POROSITIES

Special view of the available porosity grades of RVC.

Enlarged view showing the open pore structure of RVC.
Polymeric carbons –
carbon fibre, glass and char

G. M. JENKINS
University College of Swansea
K. KAWAMURA
Rikkyo University, Japan

5 Physical properties

5.0 Generalities

The physical properties of polymeric carbons are directly related to the structure. Thermal vibrations are transferred along the ribbons and the greatest amplitudes are predominantly out-of-plane. The thermal properties must, therefore, be very similar to those of normal poly-crystalline graphite, with small crystallite sizes. The high thermal expansion of free graphite sheets along the c-axis is restricted by the frequent edge-to-edge bonding at ribbon boundaries. Electron movement along perfect ribbons is easy, even though the path is circuitous. The resistivity should, therefore, be very close to that of normal poly-crystalline graphite.

The confirmation of these predictions further justifies our adoption of a ribbon model for polymeric carbons.

5.1 Thermodynamic quantities and thermal conductivity

The heat capacity of glassy carbon has been measured by Takahashi (1970) and Weston (1970). Between 5 and 350 K, it is shown that the heat capacity of glassy carbon is very close to that of normal graphite and therefore is quite independent of temperature. The vibrational properties of the material are, however, quite different from those of graphite.

Thermodynamic quantities for polymeric carbons are given in Table 5.1. The heat capacity at room temperature is given by the following equation:

\[ C_v = \frac{3}{2} N_a \epsilon \frac{R}{\mu} \]

where \( C_v \) is the heat capacity, \( N_a \) is the Avogadro number, \( \epsilon \) is the number of electrons per atom, \( R \) is the gas constant, and \( \mu \) is the effective mass of the electron.

The thermal conductivity \( \kappa \) of polymeric carbons can be calculated using the Wiedemann-Franz law:

\[ \frac{\kappa}{T} = \frac{\pi^2 k_B^2}{3 e^2} \frac{L}{\mu m} \]

where \( L \) is the length of the material, \( m \) is the mass of the electron, and \( e \) is the charge of the electron.

High temperature measurements at 1500°C were made by Davidson and Lowy (1971) using a modulated electron beam. The thermal conductivity at room temperature is 0.064 cal cm\(^{-1}\) K\(^{-1}\) rising very slightly to 0.086 cal cm\(^{-1}\) K\(^{-1}\) at 1500°C. Using published data for the specific heat, the thermal conductivity was calculated to be 0.01 cal cm\(^{-1}\) K\(^{-1}\) at 25°C and 0.04 cal cm\(^{-1}\) K\(^{-1}\) at 1500°C. This fourfold increase, mainly accounted for by an increase in incoherent heat, is in marked contrast with the behaviour of poly-crystalline graphite which has a much higher conductivity of 0.4 units at room temperature but this decreases to 0.04 units at 1500°C. The anisotropy for all types of varying crystallinity in approach a common conductivity at elevated temperatures may be because the predominant phonon scattering process in poly-crystalline graphite is Umklapp scattering. As the test temperature rises the mean free path due to this type of scattering increases exponentially. In glassy carbon, the predominant scattering process may be that due to the boundaries. Thus as the test temperature is increased the thermal conductivity of carbon containing large crystallites approaches that of carbon containing small crystallites. Thermoelectric effects cause the thermal conductivity to increase from 0.01 at 100°C to 0.02 at 1500°C and 0.036 at 3000°C.

Strains (1963) has measured the thermal conductivity of hard interlayer binder carbons at high temperatures and found that such materials show an increase in conductivity as to approach the decreasing values exhibited by soft filter-aid binder graphite as the temperatures increase. For instance, the thermal conductivity \( \kappa \) of a hard binder graphite material of density 1.63 g cm\(^{-3}\) has a value of 0.45 cal cm\(^{-1}\) K\(^{-1}\) at 300 K, rising very slightly to 0.46 cal cm\(^{-1}\) K\(^{-1}\) at 1500 K. Taking into account the effect of porosity, these values are very close and should be compared with those of single crystalline graphite which has a 4 value of 0.46 cal cm\(^{-1}\) K\(^{-1}\) at 300 K in the basal plane and 0.17 cal cm\(^{-1}\) K\(^{-1}\) at 700 K perpendicular to the basal plane. Poly-crystalline graphite has values between 0.25 and 0.40 cal cm\(^{-1}\) K\(^{-1}\).

5.2 Thermal expansion

The thermal expansion coefficient of isotropic polymeric carbon
APPENDIX C. FOAMETAL BROCHURE
**WHAT IS FOAMETAL?**

Foametal starts out as a fine granular powder, but during the sintering process, it expands to form the reticulated cellular structure illustrated here. The potential uses of Foametal are virtually limitless. Currently its applications include exhaust mufflers for air tools, cylinders, shock absorbers, brazed wicking, heat sinks for printed circuit boards, dust and fluid filters, catalysts, and a wide variety of other uses.

---

**TABLE I**

<table>
<thead>
<tr>
<th>DENSITY</th>
<th>GRADE</th>
<th>APPROXIMATE HOLE SIZE - INCHES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% - 3%</td>
<td>10 Pore</td>
<td>.050&quot; - .060&quot;</td>
</tr>
<tr>
<td>3% - 4%</td>
<td>20 Pore</td>
<td>.095&quot; - .105&quot;</td>
</tr>
<tr>
<td>4% - 5%</td>
<td>30 Pore</td>
<td>.125&quot; - .135&quot;</td>
</tr>
<tr>
<td>5% - 6%</td>
<td>40 Pore</td>
<td>.150&quot; - .160&quot;</td>
</tr>
<tr>
<td>6% - 7%</td>
<td>50 Pore</td>
<td>.175&quot; - .185&quot;</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>DENSITY</th>
<th>SPECIFIC SURFACE AREA</th>
<th>(REVISED COPY EFFECTIVE 9-1-75)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Pore Cu or Ni</td>
<td>0.125</td>
<td>0.175</td>
</tr>
<tr>
<td>20 Pore Cu or Ni</td>
<td>0.225</td>
<td>0.325</td>
</tr>
<tr>
<td>30 Pore Cu or Ni</td>
<td>0.250</td>
<td>0.375</td>
</tr>
</tbody>
</table>

**TABLE III**

<table>
<thead>
<tr>
<th>DENSITY</th>
<th>SPECIFIC SURFACE AREA</th>
<th>(REVISED COPY EFFECTIVE 9-1-75)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.03</td>
<td>0.49</td>
</tr>
<tr>
<td>60%</td>
<td>0.06</td>
<td>0.81</td>
</tr>
<tr>
<td>40%</td>
<td>0.10</td>
<td>1.22</td>
</tr>
<tr>
<td>30%</td>
<td>0.15</td>
<td>2.25</td>
</tr>
</tbody>
</table>

---

**FOAMETAL FACTS**

Foametal is a new porous material with a wide range of applications for equipment manufacturing and product design. Foametal is primarily manufactured in nickel and copper, and much of it will be available in these metals. Low density Foametal is in the range of 3 to 15% density, and high density Foametal is available in the range 20% to 50% (expressed in percent of parent metal density).

Foametal has interesting properties, because it has a relatively large specific area per unit of volume. In addition, many of these properties may be varied by compressing low density materials (3 to 10%) to higher densities (15% to 19%) through simple manufacturing operations which include die cutting, stamping, light drawing, and rolling.

Based on the interest shown by the engineering community, Foametal appears to have an excellent future. Unfortunately, many of the specific properties must be estimated by the user. Presently there are few tests evaluating the many properties of the material. Areas where heat transfer, pressure drop, strength in various environments, heat resistance, and other properties must be determined through research and development by individual users.

New production equipment eventually will be available, and this will increase the availability of Foametal and open up new markets.

In low densities, Foametal is characterized as an open pore web structure of metal fiber. In high density, it is more nearly approaching other Foameial materials, except that in this case, the space between joining particles is closely controlled to produce a size openings of various limits.

Foametal media available to the design engineer as a family of products that are distinctly different from woven wire mesh, filter screen, and from conventional powder metal products. Following media has opened up new fields of performance in:

1. High temperature wicking (aluminum, stainless, and other related materials)
2. Filtering media, dust filters, that are not required for conventional dust filters
3. Applications where light weight and low density are essential (nuclear cross-section, shock burdens)
4. Technical literature is limited on Foametal. Recently the heat transfer properties have been developed, and we are publishing a bulletin from time to time entitled Foameial News, which is available by writing to Foametal, Inc.

The manufacture of Foametal is not as expensive as the manufacturing of other Foameial materials, such as: cement, light metals, such as aluminum and brass, etc. For this reason, it is less expensive to produce Foametal. For example, large panels measuring 2 feet x 3 feet are not available.

The Foameial process is an outgrowth of original patents taken out by the General Electric Company. We have modified and improved the process in order to furnish a wide variety of products at a lower unit cost, which permits large scale industrial use of Foametal.
## APPLICATIONS

<table>
<thead>
<tr>
<th>ITEM</th>
<th>METAL</th>
<th>PORE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>APPLICATIONS (ACOUSTICAL ISOUND DEADENING)</strong></td>
<td>COPPER</td>
<td>35% - 64%</td>
<td>45 Pore interweave with nylon pads, external housing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 - 45</td>
<td>-10 Pore 10% density for peripheral mount on exhaust</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 Pore 15% density 10% plus for insertion, internal parts</td>
</tr>
<tr>
<td>2. <strong>Vibration Damping</strong></td>
<td>COPPER/NICKEL</td>
<td>4% - 50%</td>
<td>Pads</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Washers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weights</td>
</tr>
<tr>
<td>3. <strong>WICKING (CAPILLARITY)</strong></td>
<td>COPPER</td>
<td>35% - 64%</td>
<td>Brass of copper parts with AWS BCuP filler metal</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>35% - 64%</td>
<td>Takes up wide gap and misfit of parts, sound joints</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4% - 15%</td>
<td>For high temp, brazing in hydrogen or vacuum, makes a wide gap joint brazable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Filter metal AWS 85% series</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Curved strip, made from lower density. Lines cylinders for service with various liquids</td>
</tr>
<tr>
<td>4. <strong>HEAT TRANSFER</strong></td>
<td>COPPER</td>
<td>4% - 15%</td>
<td>10 - 45</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>4% - 15%</td>
<td>Pads</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sheets</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Discs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contains water, makes a wide gap joint brazeable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Makes a wide gap joint brazeable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contains water, makes a wide gap joint brazeable</td>
</tr>
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<td></td>
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<td></td>
<td>Contains water, makes a wide gap joint brazeable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contains water, makes a wide gap joint brazeable</td>
</tr>
<tr>
<td>5. <strong>FILTERS FLUIDS</strong></td>
<td>COPPER</td>
<td>40% - 60%</td>
<td>Foam packed, better retention of solid particles in filter</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>10% - 15%</td>
<td>10 - 45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sheets</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fabric</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Filters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Media</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Foamed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>6. <strong>CATALYSTS</strong></td>
<td>COPPER</td>
<td>40% - 60%</td>
<td>Silver coated Ni</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>10% - 15%</td>
<td>10 - 45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Various</td>
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<td>Sheets</td>
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<td>Coated Ni</td>
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<td>Foamed</td>
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<td>Same</td>
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<td></td>
<td></td>
<td></td>
<td>Uncoated Ni</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Silver coated Ni</td>
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<td>Foamed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>7. <strong>MAGNETICS</strong></td>
<td>COPPER</td>
<td>40% - 60%</td>
<td>Silver coated Ni</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>10% - 15%</td>
<td>10 - 45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Various</td>
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<td>Sheets</td>
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<td>Foamed</td>
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<td>Coated Ni</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>8. <strong>NUCLEAR</strong></td>
<td>COPPER</td>
<td>40% - 60%</td>
<td>Silver coated Ni</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>10% - 15%</td>
<td>10 - 45</td>
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<td>Various</td>
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<td>Coated Ni</td>
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<td></td>
<td></td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>9. <strong>BOUNDARY LAYER CONTROL</strong></td>
<td>COPPER</td>
<td>40% - 60%</td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>10% - 15%</td>
<td>10 - 45</td>
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<tr>
<td></td>
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<td>Various</td>
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<td></td>
<td></td>
<td>Coated Ni</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Same</td>
</tr>
<tr>
<td>10. <strong>WAVE GUIDES</strong></td>
<td>COPPER</td>
<td>40% - 60%</td>
<td>Various</td>
</tr>
<tr>
<td></td>
<td>NICKEL</td>
<td>10% - 15%</td>
<td>10 - 45</td>
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<td>Various</td>
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<td>Coated Ni</td>
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<td></td>
<td></td>
<td>Same</td>
</tr>
</tbody>
</table>

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### GET ACQUAINTED WITH FOAMETAL AND DISCOVER WHAT IT CAN DO FOR YOU

We have only begun to scratch the surface of potential applications of Foametal. Much of the development and experience "tried on the shoulders" of those involved in the material and its wide range of potential uses. Perhaps the best way to become acquainted with the product is to order one of our Foametal kits. Just select the kit that best suits your needs, and get your research and development program underway.

---

**FOAMETAL SHEET AND ROD FORM**

**KIT NO. 1**
- No. of pieces of FOAMETAL: 15
- Size of pieces: 3" x 3½" x 0.060 (inches)
- Thickness: 0.050 to 0.375
- Application: Automotive Emission Control, Petrochemical Processing, Radiant burners (porous)
- Materials: Nickel and Copper
- Density: 2 to 5%
- Price: $30.00

**KIT NO. 2**
- Identical to above but contains 10 pieces of FOAMETAL
- Price: $30.00

**DELIVERY**: Stock, about 1 week from receipt of purchase order.
APPENDIX D. PROGRAM LISTINGS
Gauss 2 - Multidimensional Normal Distribution

Spread 2 - Axial Beam Spreading
First Plate Beam Spread Program
X-rays - X-ray Production, Absorption and Heating
Specific Heat of Vitreous Carbon

First Plate Center Spot Heat Rise

75
First Plate Convective Cooling -
Fixed Material Parameters

```
110 REM FILENAME: CCONV
120 REM INITIAL CONDITION: THE FOLLOWING CONSTANTS WILL BE USED:
130 REM THE FOLLOWING CONSTANTS WILL BE USED:
140 REM THE FOLLOWING CONSTANTS WILL BE USED:
150 REM THE FOLLOWING CONSTANTS WILL BE USED:
160 REM THE FOLLOWING CONSTANTS WILL BE USED:
170 REM THE FOLLOWING CONSTANTS WILL BE USED:
180 REM THE FOLLOWING CONSTANTS WILL BE USED:
190 REM THE FOLLOWING CONSTANTS WILL BE USED:
200 REM THE FOLLOWING CONSTANTS WILL BE USED:
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230 REM THE FOLLOWING CONSTANTS WILL BE USED:
240 REM THE FOLLOWING CONSTANTS WILL BE USED:
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270 REM THE FOLLOWING CONSTANTS WILL BE USED:
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360 REM THE FOLLOWING CONSTANTS WILL BE USED:
370 REM THE FOLLOWING CONSTANTS WILL BE USED:
380 REM THE FOLLOWING CONSTANTS WILL BE USED:
390 REM THE FOLLOWING CONSTANTS WILL BE USED:
400 REM THE FOLLOWING CONSTANTS WILL BE USED:
410 REM THE FOLLOWING CONSTANTS WILL BE USED:
420 REM THE FOLLOWING CONSTANTS WILL BE USED:
430 REM THE FOLLOWING CONSTANTS WILL BE USED:
440 REM THE FOLLOWING CONSTANTS WILL BE USED:
450 REM THE FOLLOWING CONSTANTS WILL BE USED:
460 REM THE FOLLOWING CONSTANTS WILL BE USED:
470 REM THE FOLLOWING CONSTANTS WILL BE USED:
480 REM THE FOLLOWING CONSTANTS WILL BE USED:
490 REM THE FOLLOWING CONSTANTS WILL BE USED:
500 REM THE FOLLOWING CONSTANTS WILL BE USED:
510 REM THE FOLLOWING CONSTANTS WILL BE USED:
520 REM THE FOLLOWING CONSTANTS WILL BE USED:
530 REM THE FOLLOWING CONSTANTS WILL BE USED:
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700 REM THE FOLLOWING CONSTANTS WILL BE USED:
710 REM THE FOLLOWING CONSTANTS WILL BE USED:
720 REM THE FOLLOWING CONSTANTS WILL BE USED:
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980 REM THE FOLLOWING CONSTANTS WILL BE USED:
990 REM THE FOLLOWING CONSTANTS WILL BE USED:
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First Plate Radiative/Convective Cooling -
Variable Parameters

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LIST
100 REM FILENAME: CCONV
110 PRINT FILENAME: CCONV
120 PRINT FILENAME: CCONV
130 PRINT FILENAME: CCONV
140 PRINT FILENAME: CCONV
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