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HEAT TRANSFER CORRELATION FOR FINNED CASKS

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ABSTRACT

Design of finned casks for dissipation of heat from radioactive decay usually requires reliance on generalized correlations in the literature which do not necessarily apply to the specific cask design. A correlation was developed, based on temperature profile measurements, for the design of upright cylindrical casks with vertical fins for convective and radiant heat transfer to ambient air. Temperature data at various heat loads were obtained for two different cask sizes of the same basic design. Each cask is mounted on a steel pallet and contained within a steel mesh cage. The smaller cask, which has 23 fins, has been approved (DOT-SP-6321) for shipment of up to 1400 W(th), and approval is being obtained (AEC AL USA/9503 BLF) for shipment of up to 3500 W heat load in the larger, 60-fin cask. The applicable theoretical equations were fit to the temperature data for both casks by simply adjusting the value used for the number of fins. The resulting correlation provides a reliable method for interpolation and extrapolation and for design of similar finned casks.

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Temperature profiles must be known for radioactive material shipping containers in order to satisfy United States Atomic Energy Commission\(^1\) and Department of Transportation\(^2\) requirements as well as to ensure satisfactory environments for product materials being shipped. Mound Laboratory designs and uses finned cask shipping containers for shipment of high integrity heat sources containing solid \(^{238}\text{PuO}_2\); to date, heat sources producing as much as 2400 W(th) have been shipped. The design of finned casks for dissipation of heat from radioactive decay usually requires reliance on generalized correlations in the literature which do not necessarily apply to the specific cask design. This study was initiated to develop a correlation, based on temperature profile measurements, for design of upright cylindrical casks with vertical fins for convective and radiant heat transfer to ambient air.

Temperature data at various heat loads were obtained for two different cask sizes of the same basic design. Each cask is mounted on a steel pallet and contained within a steel mesh cage. The Universal Source Container (USC) is the smaller cask; it is shown in Figures 1 and 2. The USC has 23 aluminum fins, and is 38 in. high x 38 in. overall with a maximum gross weight of 1500 lb. It has been approved (DOT-SP-6321) for shipment of up to 1400 W(th).

The Multihundred Watt Container (MWC) shown in Figures 3 and 4 has 60 aluminum fins. Approval is being obtained
1. Universal Source Container Assembly.

The container consists of a finned cask within a cage. It has been approved for shipments of up to 1400 W.

2. Universal Source Container Finned Cask.

The cask has 23 aluminum fins extending radially from the cask body.
3. Multihundred Watt Container Assembly.

The container consists of a finned cask within a cage. Approval is being obtained from shipment of up to 3500 W.


The cask has 60 aluminum fins extending radially from the cask body.
(AEC AL USA/9503 BLF) for shipment of up to 3500 W heat load in the MWC; as of June, 1974, interim approval was obtained for shipment of up to 2400 W(th). The MWC is 60 in. high x 48 in. x 48 in. and the maximum gross weight is 3000 lb. Additional details regarding the container designs are presented for the USC by McDonald and for the MWC by Griffin et al.

The experimental steady state temperature data for the USC and MWC are presented in Figures 5 and 6, respectively. The temperature measurements were obtained using thermocouples and a milliwatt potentiometer. The heat loads were determined from the quantity of plutonium oxide fuel when actual heat sources were used and from the product of the voltage and amperage readings when electrical heat source simulators were used. Additional details regarding the experimental work are provided for the USC by McDonald and for the MWC by Griffin. It is clear from Figures 5 and 6 that the containers do not have uniform surface temperatures as assumed for the calculations.

For both containers, the hottest spot on the cask is the center of the cover and, in general, the temperatures are higher at the top than at the bottom. This can easily be seen by comparison of the "Fin Base at TOP" and "Fin Base - Mid" curves in Figure 6. At 2400 W, the fin base is 28°F hotter at the top than at the container mid-height. Although not shown, the hottest spot for the exterior cage, for the purpose of satisfying regulations regarding the exterior surface temperature, was at the center on the underside of the base plate for both containers. It is necessary to select one location on the containers for comparison with
5. Temperature Increase with Heat Load for the Universal Source Container.

the calculations and subsequent correlation. The fin base at the container mid-height is considered to best represent the surface temperature of the cask body and was selected. The temperature gradients and hot spots must be accounted for in actual design, but are not considered further in this report.

The calculated results were determined using the approach recommended by Shappert. The basic equation that describes convection and radiation from a cask surface is:

\[
Q_T = h_c A_c (T_s - T_a) + 0.173 \bar{F}_{12} A_r \left[ \left( \frac{T_s + 460}{100} \right)^4 - \left( \frac{T_a + 460}{100} \right)^4 \right],
\]

where

- \( Q_T \) = total heat transferred, Btu/hr,
- \( h_c \) = the convective heat transfer coefficient, Btu/hr-ft\(^2\)-°F,
- \( A_c \) = the effective convective surface area, ft\(^2\),
- \( A_r \) = the effective radiative surface area, ft\(^2\),
- \( T_s \) = the cask surface temperature, °F,
- \( T_a \) = the ambient temperature, °F,
- \( \bar{F}_{12} \) = the gray-body shape factor.

The heat transfer coefficient \( (h_c) \) is calculated using a simplified equation as follows:

\[
h_c = 0.19 (T_s - T_a)^{1/2}.
\]

The area for convection does not equal the area for radiation in the case of finned casks. For the cask shown in Figure 7:

\[
A_c = (\pi D_0 - n_f \gamma_0) L + n_f (2\pi L'),
\]
where
\[ D_o = \text{cask outer diameter, ft} \]
\[ n_f = \text{number of fins} \]
\[ y_0 = \text{fin thickness, ft} \]
\[ L = \text{cask length, ft} \]
\[ \eta = \text{fin efficiency} \]
\[ I = \text{fin height, ft} \]
\[ L' = \text{fin length, ft} \]

The useful heat transfer area is dependent on the fin efficiency, which is calculated for longitudinal fins using the following two equations:

\[ \eta = \frac{\tanh(b)}{b} \quad (4) \]

where
\[ b = \text{fin parameter} = \sqrt[2]{\frac{2h_c}{ky'''_0}} \quad (5) \]

\[ k = \text{the thermal conductivity of the fins}. \]

The radiative heat transfer area of the finned cask is assumed to be the "string" area of the cask; this is the area of the total cask envelope, which, irrespective of the type of fin, can be calculated by:

\[ A_r = \pi(D_o + 2\ell) L. \quad (6) \]

Since the surroundings are large as compared with the cask, \( F_{12} \) is approximated by \( \varepsilon \), the emissivity of the cask surface. The sides are considered cavity-type radiators and \( \varepsilon \) is calculated as follows:

\[ \varepsilon = \frac{1}{1 + \frac{a}{\varepsilon_r} \left( \frac{1}{\varepsilon_r} - 1 \right)} \quad (7) \]
where

\( \varepsilon_r \) is the surface emissivity of the cask shell and fins,
\( s \) is the average face-to-face distance between fins,
and
\( S \) is defined as:
\[
S = s + 2\tau.
\]

The dimensions and other parameters required for the USC and MWC calculations are presented in Table 1.

Table 1. USC and MWC dimensions and parameters for heat transfer calculations

<table>
<thead>
<tr>
<th></th>
<th>USC</th>
<th>MWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_a (\degree F) )</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>( D_0 (ft) )</td>
<td>1.417</td>
<td>2.063</td>
</tr>
<tr>
<td>( n_f )</td>
<td>23</td>
<td>57.57*</td>
</tr>
<tr>
<td>( y_0 (ft) )</td>
<td>0.01042</td>
<td>0.01563</td>
</tr>
<tr>
<td>( L (ft) )</td>
<td>1.958</td>
<td>3.396</td>
</tr>
<tr>
<td>( L' (ft) )</td>
<td>0.6667</td>
<td>0.7396</td>
</tr>
<tr>
<td>( L'' (ft) )</td>
<td>1.833</td>
<td>2.958</td>
</tr>
<tr>
<td>( k (Btu/ft \text{ hr \degree F}) )</td>
<td>119</td>
<td>119</td>
</tr>
<tr>
<td>( s (ft) )</td>
<td>3.290</td>
<td>0.1311</td>
</tr>
<tr>
<td>( \varepsilon_r )</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>( \text{conversion} \frac{W}{Btu/hr} )</td>
<td>0.2931</td>
<td>0.2931</td>
</tr>
</tbody>
</table>

*The MWC has 60 fins, but, since some are shortened, the equivalent number of fins is 57.57.

The calculations were performed using a Hewlett-Packard (HP-65) programmable calculator. Selected values for the cask surface temperature \( (T_s) \) were used to calculate the heat load \( (Q_T) \), expressed in watts. The curves developed
in this manner are presented in Figure 8 (solid lines) where they are compared with the experimentally determined values (dashed lines) for both containers. The experimental temperature data for the fin base at mid-height are shown in Figure 5 for the USC and in Figure 6 for the MWC; the lines drawn through the data are reproduced in Figure 8. The points of primary interest (indicated by dashed circles) are 120°F, 800 W for the USC and 123°F, 2400 W for the MWC since these are in the appropriate heat load ranges for the containers. The curve calculated for the USC lies above the experimental data, indicating that the USC dissipates heat better than predicted by the calculations. The curve calculated for the MWC very nearly matches the experimental data at 123°F and 2400 W.

The next objective was to develop a simple adjustment to Shappert's recommended heat transfer equations so that both the USC and MWC performance could be expressed mathematically using the same equations. For substitution into Equation 3, an adjusted value was calculated for the number of fins \( n_f' \) which is based on the actual number of fins \( n_f \). Development of the equation to relate the adjusted to the actual number of fins was based on satisfying the following conditions:

1. The calculations must reproduce the points 80°F, 0 W and 120°F, 800 W for the USC.
2. The calculations must reproduce the points 80°F, 0 W and 123°F, 2400 W for the MWC.

It was determined by trial and error that these conditions were satisfied if a value of 39.45 fins \( n_f' \) were used for
7. Longitudinally Finned Cask Oriented Vertically.

8. Comparison of Unadjusted Calculations with Experimental Results at Fin Base Mid Height for USC and MWC.
the USC and if a value of 58.00 fins (n_f') were used for the MWC. Also, the value of n_f must equal zero when n_f equals zero. Thus, it was necessary to develop an expression which yields the following results:

<table>
<thead>
<tr>
<th>Actual Number of Fins (n_f)</th>
<th>Adjusted Number of Fins (n_f')</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>39.45</td>
</tr>
<tr>
<td>57.57</td>
<td>58.00</td>
</tr>
</tbody>
</table>

An equation of the form \( n_f' = A (n_f)^2 + B n_f \) was assumed and the constants (A and B) were determined to be

\[
A = -0.0205, \text{ and } B = 2.19.
\]

Substitution of these constants into the assumed equation yields the desired results.

Thus, a very simple technique was developed for correlating the experimental data for the Multihundred Watt Container and the Universal Source Container. An adjustment was made to the equations recommended by Shappert for heat transfer from externally finned casks which consists of substituting

\[
n_f' = -0.0205 (n_f)^2 + 2.19 n_f
\]
for the actual number of fins (n_f) in Equation 3. Calculations using the adjusted equation agree satisfactorily with the experimental data up to 800 W for the USC and up to 2400 W for the MWC. The adjusted form of the equation provides an excellent tool for extrapolation and interpolation of the data and for design of new finned casks of similar geometry.
REFERENCES


RADIATION LEVELS FROM PLUTONIUM NITRATE AND THE 1-10-1 SHIPPING PACKAGE

A. Hulsey
M. M. Hendrickson

General Electric Company
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Not available for publication at this time.