M-40

RETURN TO 396-SS

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September 11, 1987
THL/87/17/ETS

Mr. John Roberts
Fuel Cycle Safety Branch
Division of Fuel Cycle, Medical, Academic
and Commercial Use Safety
U. S. Nuclear Regulatory Commission
7915 Eastern Avenue
Silver Spring, Maryland 20910

**RE: Project No. M-40: Safety Analysis Report (Revision 2) For The NAC Storage/Transport Cask For Use At An Independent Spent Fuel Storage Installation**

Dear Mr. Roberts:

The Nuclear Assurance Corporation (NAC) TSAR, Revision 2 (Project M-40) currently under review was the subject of several questions by Mr. Ramsey Chun of Lawrence Livermore National Laboratories during a phone call to NAC on September 9, 1987 regarding the thermal analysis of the NAC S/T cask:

1. Do the spacers in the basket actually contact the aluminum fuel channel walls?

2. The spacing between spacer grids is not the same in the thermal model as in the actual basket drawing. Why?

3. In the basket model, an aluminum region (196) exists at the bottom of one of the fuel regions (195). Why?

4. The conductivity used in the cask analysis is for aluminum at 300°F. The aluminum in the basket is calculated to be as high as 584°F. Will a lower aluminum conductivity result in higher temperatures than those reported in the TSAR for the hottest fuel channel wall?

5. How was the conductivity of the fuel region calculated?

6. Why were values used in insolance calculations a factor of 2.0 lower than the values recommended in NRC Regulatory Guide 7.8? Why was the emissivity of the cask taken into account in the calculations?

7. What are the values for the specific heat of the materials analyzed in the SCOPE analysis? What are the values for the emissivities used in the SCOPE Wooten-Epstein correlation?





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Based on our discussion and further consideration by NAC, the following answers are provided:

1. The spacers are considered to be in contact with the aluminum fuel channel walls for heat transfer analysis purposes. The basket is a tight fit (but not an interference fit when heated) in the cask and leaves very little empty space. The spacers are installed during fabrication by spot welding to the aluminum fuel channel wall. Therefore, from a heat transfer standpoint, the spacers are initially touching. Heat-up of the cask following fuel load, and the subsequent thermal expansion of the aluminum fuel channel walls and the spacer grids, will ensure that any gaps between the fuel channel wall and the spacer grids will be insignificant for heat transfer considerations.

2. The spacing of the heat transfer model is equivalent to the actual basket when considering the heat transfer from the fuel regions to the basket outer shell. The discrete modeling of the spacer grid was modeled because the conductivity of the spacer grid was determined to be a function of the direction of heat transfer through the spacer grid. The model is sufficiently detailed to permit the HEATING-5 computer code to determine the actual heat transfer paths through the basket.

3. Region 196 was required due to a limitation of the HEATING-5 computer code which would not allow the modeling of a heat generation region with a zero-flux (insulated to simulate symmetry) boundary. Region 196 is thus a "dummy" region to allow the HEATING-5 computer code to function without substantially altering the results. For ease of modeling, the thickness of region 196 was chosen to match that of region 134.

4. When this analysis was performed, the aluminum alloy to be used had not yet been determined. Once alloy 5052 had been decided upon, the ASME Table I-4.0 showed the conductivity of 5052-aluminum at 70°F to be almost 10% higher than that used in the TSAR analysis. At 400°F, the conductivity was more than 20% higher. Because the ASME tables did not go above 400°F, it was decided to use the results based on the TSAR conductivity at 350°F (though highly conservative). Refer to TSAR Table 4.2-13.

5. The fuel conductivity was calculated using a technique for evaluating post-accident debris effective conductivities. The $\Delta t$ across the fuel region was determined using the Wooten-Epstein correlation found in the SCOPE computer code. The cask body model was not used to evaluate temperatures in the fuel region other than to supply the temperature of the aluminum fuel channel wall used for the insert temperature in SCOPE. The fuel region conductivity used in the HEATING-5 analysis was provided for completeness of the computer model. Therefore, the value used in the HEATING-5 cask

body analysis for the conductivity of the fuel region will not affect the temperature of the fuel rod cladding determined using SCOPE. Enclosed for your information is a copy of the paper entitled "Effective Thermal Conductivity of Debris Beds" presented by I. Cook and R. S. Peckover at the Post Accident Heat Removal Information Exchange Meeting in 1982.

6. In order to perform a steady state analysis of the cask during normal operations conditions, the 1475 BTU/12 hr.ft.$^2$°F daily insolance was applied as 737.5 BTU/hr.ft.$^2$°F since the average daytime heating period is 12 hours long. It was also decided that the emissivity should be taken into account for this calculation because the cask reflects some of the incident energy. This is the NAC interpretation of the application of the guidelines given for the analysis of insolance found in NRC Regulatory Guide 7.8 and 10 CFR 71.71. The use of the 12 hour day/night cycle has little effect on such a massive object as a cask, especially considering the presence of its internal 26 kw heat source.

7. SCOPE uses heat capacities for the materials analyzed which are shown on TSAR page 4.8-197. The values used for the emissivities in the Wooten-Epstein correlation are 0.7 for the clad material, and 0.22 input for the emissivity of the aluminum fuel channel wall.

Sincerely,

**NUCLEAR ASSURANCE CORPORATION**

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THL:jeb

Enclosure

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U. Müller/C. Günther (ed.)

# Post Accident Debris Cooling

Proceedings of the Fifth
Post Accident Heat Removal
Information Exchange Meeting, 1982
Nuclear Research Center Karlsruhe



G. Braun Karlsruhe

# POST ACCIDENT DEBRIS COOLING

PROCEEDINGS OF THE FIFTH POST ACCIDENT HEAT REMOVAL INFORMATION EXCHANGE MEETING

JULY 28 - 30, 1982

NUCLEAR RESEARCH CENTER KARLSRUHE
KARLSRUHE

EDITED BY

U. MOLLER AND C. GONTHER

INSTITUTE FOR REACTOR COMPONENTS

# EFFECTIVE THERMAL CONDUCTIVITY OF DEBRIS BEDS

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## SUMMARY

The effective thermal conductivity $k_E$ of an isotropic composite material is ill-defined unless the geometric arrangement of the phases is suffic- iently well specified. Nevertheless, Hashin and Shtrikman have obtained rigorous bounds of practical use provided the component conductivities are sufficiently close. For a two-component system, these bounds are the familiar Maxwell formulae. Effective medium theory gives an estimate of effective conductivity ignoring connectedness; it is the formula of Bruggeman. This appears to provide a further bound for characterising debris beds.

## INTRODUCTION

Some of the more commonly used formulae for the effective thermal con- ductivity of composite materials are referred to in [1] or [2] which provides a comparison with a range of experimental data from many dif- ferent sources. The often implicit assumption of such semi-empirical formulae is that for a random mixture of materials, there exists an effective thermal conductivity, independent of the details of the material arrangement. We believe that this idea is mistaken; the geom- etric arrangement of the materials is almost always important. However limiting upper and lower bounds can be specified which can be quite close together. In some circumstances "effective medium theory" can provide a useful estimate. It seems that this approach is relevant to debris beds with an extended spectrum of particle sizes resulting from fragmentation. Since convection and radiation are ignored here, the components of the composite need not be solid; some can be in a (stag- nant) fluid state.

## UPPER AND LOWER BOUNDS

It is well known that the effective conductivity of composite material must lie between the classical bounds:

$$\langle k \rangle \ge k_E \ge \langle k^{-1} \rangle^{-1} \qquad (1)$$

where $\langle X \rangle$ denotes the average of X. If the only information available about the composite is the volume fraction of the phases, then (1) is

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the best possible result, for each of the two bounds can clearly be attained; they correspond to the familiar "in-parallel" and "in-series" arrangement of the material.

If it is also known that the composite is randomly arranged and macro- scopically isotropic, more restrictive bounds can be obtained. In this case, Hashin and Shtrikman [3] have shown that

$$k_L + \{B/(1-B/3k_L)\} \le k_E \le k_u + \{A/(1-A/3k_u)\} \qquad (2)$$

where $k_u$ and $k_L$ are the conductivities of the most and least conductive phase respectively and

$$A \equiv \left\langle \left[1/(k(\underline{r}) - k_u) + 1/3k_u\right]^{-1} \right\rangle \qquad (3)$$

$$B \equiv \left\langle \left[1/(k(\underline{r}) - k_L) + 1/3k_L\right]^{-1} \right\rangle \qquad (4)$$

For the derivation, see the original paper or the clear account by Beran [4], alternatively see [5].

For a two-phase system, a well-known formula ($k_{M1}$) was obtained by Maxwell [6], applicable when the porosity $\epsilon$ is close to unity. This can be written

$$1/(k_{M1}+2k_1) = \epsilon/(k_1 + 2k_1) + (1-\epsilon)/(k_2+2k_1) \qquad (5)$$

The dual Maxwell formula ($k_{M2}$), appropriate when $\epsilon$ is small, is

$$1/(k_{M2} + 2k_2) = \epsilon/(k_1 + 2k_2) + (1-\epsilon)/(k_2 + 2k_2) \qquad (6)$$

The Hashin-Shtrikman (H-S) bounds for a two-phase system are precisely these well-known Maxwell formulae applied to the whole range of porosity $0 < \epsilon < 1$. Specifically,

$$k_{M1} \le k_E \le k_{M2} \text{ if } k_2 > k_1 \qquad (7)$$

$$k_{M2} \le k_E \le k_{M1} \text{ if } k_1 > k_2 \qquad (8)$$

These bounds are closer than the classical bounds and are the best possible bounds for a two-phase system if no geometric information other than randomness and isotropy is available, as was shown by Hashin and Shtrikman using a simple constructive algorithm. This exemplifies the general principle stressed by Beran [4] and Ziman [7] that the macroscopic properties of a composite can be extremely sensitive to the geometry and topology of the boundary surfaces between the phases. A measure of the usefulness of these bounds is their separation. If $\Delta k_c$ and $\Delta k_M$ denote the difference between the classical bounds and between the H-S bounds, evaluated at $\epsilon = \frac{1}{2}$, then for

$k_1 = 2k_2$, $\Delta k_c = 0.166(k_1-k_2)$ $\Delta k_M = 0.026(k_1-k_2)$

$= 9k_2$ $= 0.400(k_1-k_2)$ $= 0.199(k_1-k_2)$

It follows that for $k_1/k_2 < 2$ the classical bounds are adequate for practical purposes, and the H-S bounds similarly for $k_1/k_2 \lesssim 10$ (and correspondingly for $k_1 > k_2$).

EFFECTIVE MEDIUM THEORY

When some of the constituent thermal conductivities differ by more than an order of magnitude, the H-S bounds are sufficiently far apart for a better estimate of $k_E$ to be required. This is only possible if addit-ional geometric information is used.

If $k_c$ is the conductivity of the continuous phase, then in general,

$$k_E = k_c - \sum \epsilon_i (k_c - k_i) \lambda_i, \tag{9}$$

where $\epsilon_i$ and $k_i$ are the volume fraction and conductivity of the ith particulate phase and $\lambda_i$ is the ratio of the mean temperature gradient in the $i^{th}$ phase to the mean overall temperature gradient.

We seek a formula appropriate for a debris bed which has a wide spectrum of particle sizes, such as the log-normal distribution predicted by Kolmogorov [8] in 1941 for fragmented debris. For such a size distrib-ution we argue that $\lambda_i$ can be usefully approximated by considering single spheres of particulate in a uniform medium with smeared conduc-tivity $k_E$. This leads to

$$\lambda_i = 3k_E/(2k_E + k_i) \tag{10}$$

One would expect this approximation to be better for a wide spectrum of particle sizes than for roughly equally sized particles: for in the former case a particle of any scale other than the smallest will be in contact with many others and will perceive a much more uniform immediate environment.

Equations (9) and (10) can be combined to give

$$\frac{1}{k_E+2k_E} = \frac{\epsilon_c}{k_c+2k_E} + \sum \frac{\epsilon_i}{k_i+2k_E}, \tag{11}$$

which has the same structure as the 'in-series' classical formula, but with each k augmented by an effective medium contribution (cf.eqs.(5)& (6). This formula is equivalent to the theory of Bruggeman [9] which implies an additional approximation of the form (10) for the continuous phase. Thus all phases are treated equally and the connectedness of the continuous phase ignored. This is plausibly so in a debris bed with a broad spectrum of particle sizes, because the filling of the necks with smaller particles drastically reduces the significance of the connectedness. Below we denote the Bruggeman estimate by $k_B$. It roughly bisects the region between the HS bounds. For real debris beds



the difference in thermal resistance between necks in the continuous phase and particle contacts introduces an asymmetry between the phases. Hence we expect for two components that if $k_p < k_c$, then $k_B \le k_E \le k_{MI}$; whereas if $k_p > k_c$, then $k_B \ge k_E \ge k_{MI}$.

ILLUSTRATIVE CALCULATIONS

We begin with a three-phase example. Consider a bed composed of $UO_2(k=k_c/20)$ and steel $(k=k_c/3)$ particles in a liquid sodium matrix $(k=k_c)$. For simplicity let the volume fractions be equal i.e. $\epsilon_i = 1/3 = \epsilon_c$. Then the classical bounds are $0.46 > k_E/k_c > 0.17$; the H-S bounds are $0.4 > k_E/k_c > 0.22$; the Bruggeman formula gives $k_B/k_c = 0.29$. This formula applies for an unstratified, random isotropic bed with a wide particle spectrum.

Figures 1 to 4 show some illustrative examples for two-phase systems. For fig.1, $k_p/k_c=6$, illustrative of $UO_2$ and water; for fig.2, $k_p/k_c=1/7$, illustrative of a $UO_2$/stainless steel cermet. In cases such as these the HS bounds are so close together that it is unlikely that they could be reliably improved upon. Fig.3 shows the case $k_p/k_c=40$, illustrative of $UO_2$ and sodium vapour; in Fig.4, $k_p/k_c=1/20$, illustrative of $UO_2$ and liquid sodium. Note that the Bruggeman estimate asymptotes at large and small porosity to the Maxwell formulae, appropriate on physical grounds.

DISCUSSION

For isotropic media, equation (9) is valid and the differences in the many formulae in the literature depend on the choice made for $\lambda_i$. However, the H-S bounds do apply and any formula which fails to fall between these bounds must be rejected.

The Kampf and Karsten (KK) formula [10] is widely used in debris bed studies (e.g.[11]), and is based on a semi-empirical rectangular series-parallel model. If the particulate phase is more conductive, then the KK formula falls outside the HS bounds and so is inappropriate (see Fig.3). Secondly, when very little porosity is present the KK formula is erroneous; it tends to the wrong Maxwell bound.(See Fig.4). For a highly conducting coolant, KK falls slightly below the upper H-S bound and is quite close for $0.3 < \epsilon < 0.7$; it should not be used where it falls below $k_B$.

The Schulz estimate [12] for spherical particles approximates to the Bruggeman formula for high porosities; it always satisfies the H-S bounds and lies on the expected side of $k_B$. It is a more robust formula than KK.

This paper has been concerned with isotropic media, but the approaches considered here are capable of generalisation to allow for anisotropy, such as channelled beds.

ACKNOWLEDGEMENTS

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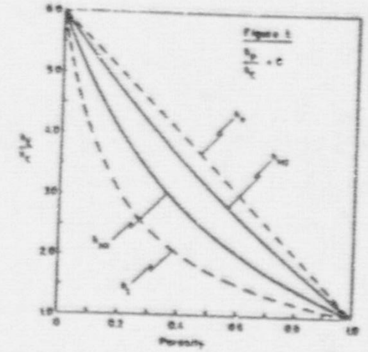


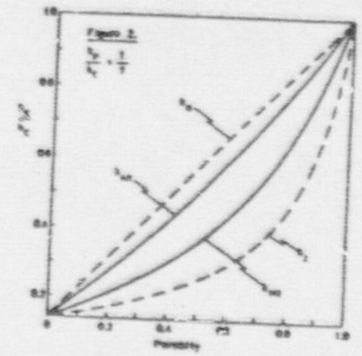


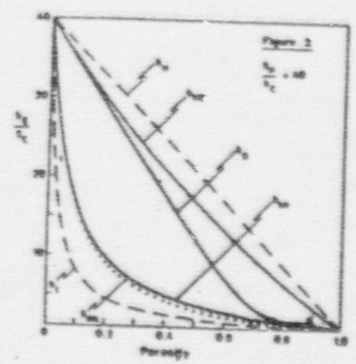


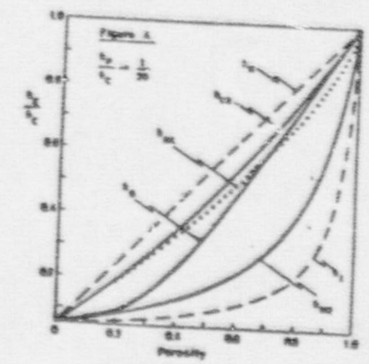


Key to figures.

$k_+$ : Classical upper bound, eq.(1).
$k_-$ : Classical lower bound, eq.(2).
$k_{M1}$ : Maxwell formula, eq.(5). } H-S bounds
$k_{M2}$ : Dual Maxwell formula, eq.(6). } H-S bounds
$k_B$ : Bruggeman formula, Eq.(11).
$k_{KK}$ : Kampf-Karsten formula, ref.[10].
$k_E$ : Effective thermal conductivity.
$k_p$ : Thermal conductivity of particles.
$k_c$ : Thermal conductivity of continuous phase.
Porosity : Volume fraction of continuous phase.

body analysis for the conductivity of the fuel region will not affect the temperature of the fuel rod cladding determined using SCOPE. Enclosed for your information is a copy of the paper entitled "Effective Thermal Conductivity of Debris Beds" presented by I. Cook and R. S. Peckover at the Post Accident Heat Removal Information Exchange Meeting in 1982.

6. In order to perform a steady state analysis of the cask during normal operations conditions, the 1475 BTU/12 hr.ft.$^2$°F daily insolance was applied as 737.5 BTU/hr.ft.$^2$°F since the average daytime heating period is 12 hours long. It was also decided that the emissivity should be taken into account for this calculation because the cask reflects some of the incident energy. This is the NAC interpretation of the application of the guidelines given for the analysis of insolance found in NRC Regulatory Guide 7.8 and 10 CFR 71.71. The use of the 12 hour day/night cycle has little effect on such a massive object as a cask, especially considering the presence of its internal 26 kw heat source.

7. SCOPE uses heat capacities for the materials analyzed which are shown on TSAR page 4.8-197. The values used for the emissivities in the Wooten-Epstein correlation are 0.7 for the clad material, and 0.22 input for the emissivity of the aluminum fuel channel wall.

Sincerely,

**NUCLEAR ASSURANCE CORPORATION**

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Lead Nuclear Engineer
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THL:jeb

Enclosure

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