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January 26, 2005

PG&E Letter HIL-05-002

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Docket No. 72-27
Humboldt Bay Independent Spent Fuel Storage Installation
Submittal of Nonproprietary Holtec Report HI-2033005

Dear Commissioners and Staff:

On December 15, 2003, Pacific Gas and Electric Company (PG&E) submitted an application to the U.S. Nuclear Regulatory Commission (NRC), in PG&E Letter HIL-03-001, requesting a site-specific license to build and operate an independent spent fuel storage installation (ISFSI) at the Humboldt Bay Power Plant.

By letter dated July 22, 2004, the NRC staff requested additional information needed to continue their review of the Humboldt Bay ISFSI License Application. PG&E responded to this request in PG&E Letter HIL-04-007, dated October 1, 2004. The response contained reference to proprietary Holtec Report HI-2033005, which was submitted to the NRC staff for use in their review of the application in PG&E Letter HIL-04-009, dated October 1, 2004.

In accordance with 10 CFR 72.4 and as committed to in PG&E Letter HIL-04-009, PG&E is submitting the nonproprietary version of Holtec Report HI-2033005 with this letter.

If you have any questions regarding this submittal, please contact Mr. Terence Grebel at (805) 545-4160.

Sincerely,

Donna Jacobs
Vice President - Nuclear Services

emb/3522
Enclosure
cc: James R. Hall
PG Fossil Gen HBPP Humboldt Distribution

NMSS01

Enclosure
PG&E Letter HIL-05-002

ATTACHED NONPROPRIETARY HOLTEC REPORT

1. Effective Thermal Property Evaluations for HBPP Fuel Assemblies and MPC-HB
   Holtec Report No. HI-2033005, Revision 0

HOLTEC INTERNATIONAL

DOCUMENT ISSUANCE AND REVISION STATUS[1]

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DOCUMENT CATEGORIZATION

In accordance with the Holtec Quality Assurance Manual and associated Holtec Quality Procedures (HQPs), this document is categorized as a:

☒ Calculation Package[3] (Per HQP 3.2)

☐ Technical Report (Per HQP 3.2) (Such as a Licensing Report)

☐ Design Criterion Document (Per HQP 3.4)

☐ Design Specification (Per HQP 3.4)

☐ Other (Specify):

DOCUMENT FORMATTING

The formatting of the contents of this document is in accordance with the instructions of HQP 3.2 or 3.4 except as noted below:

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SUMMARY OF REVISIONS

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PREFACE

This work product has been labeled a *safety-significant* document in Holtec's QA System. In order to gain acceptance as a *safety significant* document in the company's quality assurance system, this document is required to undergo a prescribed review and concurrence process that requires the preparer and reviewer(s) of the document to answer a long list of questions crafted to ensure that the document has been purged of all errors of any material significance. A record of the review and verification activities is maintained in electronic form within the company's network to enable future retrieval and recapitulation of the programmatic acceptance process leading to the acceptance and release of this document under the company's QA system. Among the numerous requirements that a document of this genre must fulfill to muster approval within the company's QA program are:

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- All significant assumptions, as applicable, are stated.
- The analysis methodology, if utilized, is consistent with the physics of the problem.
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- The material content of this document is understandable to a reader with the requisite academic training and experience in the underlying technical disciplines.

Once a safety significant document produced under the company's QA System completes its review and certification cycle, it should be free of any materially significant error and should not require a revision unless its scope of treatment needs to be altered. Except for regulatory interface documents (i.e., those that are submitted to the NRC in support of a license amendment and request), revisions to Holtec *safety-significant* documents to amend grammar, to improve diction, or to add trivial calculations are made only if such editorial changes are warranted to prevent erroneous conclusions from being inferred by the reader. In other words, the focus in the preparation of this document is to ensure accuracy of the technical content rather than the cosmetics of presentation.

In accordance with the foregoing, this Calculation Package has been prepared pursuant to the provisions of Holtec Quality Procedures HQP 3.0 and 3.2, which require that all analyses utilized in support of the design of a safety-related or important-to-safety structure, component, or system be fully documented such that the analyses can be reproduced at *any time in the future* by a specialist trained in the discipline(s) involved. HQP 3.2 sets down a rigid format structure for the content and organization of Calculation Packages that are intended to create a document that is complete in terms of the exhaustiveness of content. The Calculation Packages, however, lack the narrational smoothness of a Technical Report, and are not intended to serve as a Technical Report.

Because of its function as a repository of all analyses performed on the subject of its scope, this document will require a revision only if an error is discovered in the computations or the equipment design is modified. Additional analyses in the future may be added as numbered supplements to this Package. Each time a supplement is added or the existing material is revised, the revision status of this Package is advanced to the next number and the Table of Contents is amended. Calculation Packages are Holtec proprietary documents. They are shared with a client only under strict controls on their use and dissemination.

This Calculation Package will be saved as a Permanent Record under the company's QA System.

1.0 INTRODUCTION

The HI-STAR HB System allows for the storage and/or transport of the Humboldt Bay Power Plant (HBPP) spent fuel assemblies. Each system consists of an MPC-HB multipurpose canister equipped with a fuel basket that holds 80 HBPP fuel assemblies. Within the fuel basket, a gridwork of stainless steel plates forms an array of square cross-section compartments, each holding a single fuel assembly. Neutron absorber panels are affixed to the stainless steel plates by stainless steel sheathing that is welded to the panels. The fuel basket is positioned within the shell by a basket support structure of various different designs. To allow for unrestrained thermal expansion of the fuel basket, there are small gaps between the MPC-HB shell and the basket support structure.

The contained fuel assemblies generate heat as a result of continuing radioactive decay. All heat generated within an MPC-HB must eventually be rejected from its outer surfaces. Thus, heat must be transported from the fuel assemblies to the outer MPC-HB surfaces. Heat is transported from the fuel rods to he fuel basket structure by the parallel action of conduction and thermal radiation heat transfer. Heat is transported from the interior to the periphery of the fuel basket primarily by conduction through the stainless steel plates.

The MPC-HB and contained fuel assemblies possess considerable mass, and therefore have a substantial thermal capacity. The MPC-HB thermal capacity affects the response of a dry cask system to transient thermal loadings such as external fires and vacuum drying operations. In addition, the MPC-HB is backfilled with an inert gas after loading. The available volume within the loaded MPC-HB affects the amount of gas that can be contained without exceeding design pressure limits at elevated temperatures.

The purpose of this report is to determine effective values for the thermal conductivity, density, heat capacity, and free volume of a loaded MPC-HB. The results of these analyses will become inputs to subsequent thermal analyses of the assembled HI-STAR HB dry cask system. The following sections present a discussion of the analysis methods, input data and results of these effective property calculations.

2.0 METHODOLOGY

2.1 Fuel Assembly Planar Effective Thermal Conductivity

The first step in these analyses is to construct and evaluate geometrically accurate planar models of the HBPP fuel assemblies in damaged fuel containers (DFCs) using the ANSYS [1] finite-element code. These models include full details of the fuel rods including the fuel pellets, the rod fill gas and the cladding. The interstitial spaces between the fuel rods and between the fuel rods and the DFC walls are occupied by the MPC-HB backfill gas and therefore have the thermal conductivity of the gas. The DFC itself is outside of the model boundaries. A uniform volumetric heat generation is applied to the fuel pellet regions, and a uniform temperature is applied to the model periphery (the inner periphery of the DFC). Both conduction and thermal radiation heat transfer mechanisms are included and steady-state temperature distributions are obtained for a range of edge temperatures.

The temperature distributions obtained from the finite-element models, however, only include the space enclosed with the DFC. It is desired to replace the entire contents of the fuel basket cell (i.e., fuel assembly, DFC and all interstitial backfill gas) with an equivalent homogeneous medium with an effective planar conductivity. The total temperature gradient from the centerline of the fuel assembly to the inner periphery of the fuel basket cell, including the temperature drop through the DFC walls and across the gaps between the DFC and the inner periphery of the fuel basket cell, is determined as follows:

a. The heat flow, per unit length along the assembly, through each wall of the DFC is determined by dividing the total heat load applied in the finite-element models by four.

b. The temperature drop through the DFC wall is calculated using the Fourier equation for one-dimensional conduction heat transfer. The heat transfer surface area is based on the inner width of the DFC wall.

c. The temperature drops across the gaps from the DFC to the fuel basket are calculated considering conduction and thermal radiation heat transfer acting in parallel. Conduction heat transfer through the backfill gas is modeled using the Fourier equation for one-dimensional conduction heat transfer and thermal radiation heat transfer is modeled using a classic gray-body equation with a DFC to fuel basket view factor of unity.

d. The total temperature gradient from the approximate centerline of the fuel assembly to the fuel basket edge is determined by adding the temperature drops across the DFC inner space (fuel centerline to DFC inner edge), the DFC wall (DFC inner edge to DFC outer edge) and the gaps between the DFC and the fuel basket (DFC outer edge to fuel basket cell inner edge).

Once the total temperature gradient is known, the temperature dependent effective thermal conductivity of the contents of the fuel basket cell is determined as follows. Consider a two-dimensional cross-section of a square shaped block with a size of 2L, a uniform volumetric heat generation Q_g, a constant material thermal conductivity k_s and a constant periphery temperature T_{edge}. The difference between the peak centerline temperature (T_{max}) and the fuel basket cell inner periphery temperature is obtained from an analytic solution [2], as:

$$T_{\max} - T_{edge} = 0.29468 \times \frac{Q_g \times L^2}{k_s}$$

It is recognized that Q_g times $4L^2$ is equal to the total assembly generation per unit of axial length and the effective thermal conductivity k_{eff} can be substituted for k_s, thereby yielding the following equation:

$$k_{eff} = \frac{q}{S \times (T_{\max} - T_{edge})}$$

where:

q is the total assembly heat generation per unit length
S is the conduction shape factor [2] (equal to 4/0.29468 = 13.5740)
T_{max} is the maximum calculated temperature
T_{edge} is the fuel basket inner periphery temperature

The applied volumetric heat generation is kept small enough to ensure that T_{max} and T_{edge} do not differ by more than 20°F under helium backfilled conditions. This minimizes the effects of material property variations within the fuel assembly for a given temperature distribution.

2.2 Composite Fuel Basket Cell Wall Effective Thermal Conductivity

Most of the stainless steel plates in the MPC-HB fuel basket have neutron absorber panels and sheathing attached. The arrangement of metal layers results in a composite wall having different thermal conductivities in the in-plane (along or parallel to panel) and out-of-plane (through thickness or perpendicular to panel) directions. To simplify subsequent fuel basket modeling, non-isotropic thermal conductivities for an equivalent homogeneous material are calculated.

A two-dimensional model of a cross section through the composite wall (including the cell walls, neutron absorber panels, neutron absorber sheathing and any surface-to-surface gaps) is constructed using the ANSYS [1] finite-element code. The following features are included in the model:

1. Nominal 2-mil surface-to-surface gaps (1-mil on each side of the neutron absorber panel) within the sheathing pocket are used. Under helium-backfilled conditions these gaps are, naturally, assigned the thermal conductivity of helium. Under evacuated conditions these gaps are assigned an equivalent thermal conductivity for an appropriate contact resistance in the out-of-plane direction (contact resistances for stainless steel, extrapolated to zero contact pressure) and a nearly zero conductivity in the in-plane direction.

2. A general surface-to-surface thermal radiation model, which includes numeric calculations of radiative view factors, is applied to the inner surfaces of the sheathing pocket and the outer surfaces of the neutron absorber panel.

By applying a relatively small temperature difference (ΔT) across the model, the average heat flux is obtained from a steady-state solution. Both in-plane and out-of-plane solutions are obtained. Evaluations are performed for a range of temperatures (200°F, 450°F and 700°F), to account for the temperature dependence of certain material properties and thermal radiation.

The average heat flux from each evaluation is used to determine the temperature dependent effective thermal conductivity using the following classical equation for conduction heat transfer:

$$k_{eff} = \frac{q \times L}{\Delta T}$$

where:

q is the average heat flux
L is the heat transfer path length
ΔT is the applied temperature difference

The applied temperature difference is kept small to minimize the effects of material property variations within the composite wall.

2.3 Fuel Basket Planar Effective Thermal Conductivity

In order to simplify subsequent thermal modeling, the heterogeneous fuel basket geometry is reduced to a homogeneous solid cylinder. The planar (i.e., radial) effective thermal conductivity of this homogeneous cylinder is determined using a combination of finite-element modeling and analytical post-processing.

These analyses are performed by constructing a planar finite-element model of the MPC-HB fuel basket using the ANSYS [1] finite-element code. The following features are included in the model:

1. The fuel basket cell regions, occupied by fuel assemblies, are modeled as a homogeneous material with a uniform heat generation and a temperature dependent effective thermal conductivity (see Section 2.1).

2. The non-isotropic properties of the composite fuel basket cell walls are modeled by specifying the appropriate effective thermal conductivity values in the two orthogonal directions (see Section 2.2).

In the finite-element model, the fuel basket is modeled as a gridwork of 'equivalent' homogeneous panels that enclose 'equivalent' square fuel spaces. The equivalent homogeneous panels, which have temperature dependent effective material properties, replace the actual composite panels composed of the stainless steel basket wall, neutron absorber panel, and stainless steel sheathing. The equivalent fuel spaces, which also have temperature dependent effective material properties, replace the fuel assembly and interstitial helium gaps inside the fuel basket cells. By applying a relatively small uniform heat generation in each fuel space and setting a uniform temperature (T) at the periphery, the maximum temperature in the basket (T+ΔT) is obtained from a steady-state solution of the finite-element model.

The finite-element model is evaluated with uniform fuel basket periphery temperature boundary conditions and steady-state temperature distributions are obtained. Evaluations are performed for a range of specified periphery temperatures (200°F, 450°F and 700°F), to account for the temperature dependence of certain material properties and thermal radiation.

The maximum calculated temperature gradients from these distributions are used to determine the temperature dependent effective thermal conductivity of the homogeneous fuel basket cylinder. The fuel basket effective thermal conductivity is determined from the temperature distribution with a uniform fuel basket periphery temperature using the following classical equation for conduction heat transfer in a solid cylinder with uniform heat generation:

$$k_{eff} = \frac{q}{4\pi \times \Delta T_{bm}}$$

where:

q is the heat generation per unit length
ΔT_{bm} is the fuel basket maximum temperature gradient

The applied volumetric heat generation is kept small, such that ΔT_{bm} is less than 20°F, to minimize the effects of material property variations for a given temperature distribution.

2.4 Fuel Basket Axial Effective Thermal Conductivity

As a result of the long, uninterrupted axial heat transfer paths in the MPC-HB fuel basket, the effective axial thermal conductivity of the fuel basket will be greater than the corresponding planar conductivity, which is limited by the numerous gaps in the heat flow path. The effective axial thermal conductivity is determined by calculating the area occupied by each material in the fuel basket cross-section, multiplying by the corresponding material thermal conductivity, summing the products and dividing by the total fuel basket cross-sectional area:

$$k_{eff} = \frac{\sum(A_n \times k_n)}{A_{total}}$$

where:

A_n is the cross-sectional area of the n^{th} material
K_n is the thermal conductivity of the n^{th} material
A_{total} is the total cross-sectional area of the fuel basket

In accordance with NUREG-1536 guidelines, the fuel rod cladding is the only component of the fuel assemblies credited in this calculation. All other fuel assembly components are assumed to be backfill gas.

2.5 Fuel Basket Effective Density and Heat Capacity

When time-varying thermal loads are applied to the HI-STAR HB system, the thermal response will also be time-varying. An enthalpy balance for a cask thermal transient analysis will necessarily include density and heat capacity terms. Since the fuel basket and its contents are to be represented by an equivalent homogeneous material, effective density and thermal capacity values must also be determined.

The effective density and thermal capacity are determined by calculating the area fraction of each material in a fuel basket cross-section, multiplying by the corresponding material properties, and summing the products. The estimated area fraction of each material is calculated as:

$$\phi_n = \frac{A_n}{A_{total}}$$

where:

A_n is the cross-sectional area of the n^{th} material
A_{total} is the total cross-sectional area of the fuel basket

The effective fuel basket density is therefore estimated as:

$$\rho_{eff} = \sum(\phi_n \times \rho_n)$$

where ρ_n is the density of the n^{th} material. A similar equation for effective thermal capacity can be obtained by substituting the material specific heat capacities for densities, as:

$$Cp_{eff} = \sum(\phi_n \times Cp_n)$$

The average density and average heat capacity are calculated separately, because the product of the averages is less than the average of the products (i.e., $\rho_{eff} \times Cp_{eff} < (\rho \times Cp)_{eff}$). This helps ensure that subsequent transient evaluations that use these values are conservative.

2.6 MPC-HB Free Volume

The free volume inside the MPC-HB is necessary to calculate gas pressures at various temperatures and fission product concentrations within the MPC-HB. The free volume calculations must conservatively account for the volume occupied by fuel assemblies, including flow channels and DFCs, as well as the MPC-HB internal structures.

The net free volume is determined by calculating the volume occupied by each of the individual components, and subtracting the sum of these volumes from the total MPC-HB cavity volume.

$$V_{net} = V_{total} - \sum V_n$$

where:

V_{net} is the net free volume
V_{total} is the total cavity volume
V_n is the volume occupied by the nth material

The calculations performed in such a manner to yield a conservatively minimized free volume.

3.0 ACCEPTANCE CRITERIA

All calculations presented in this report are performed to generate input data for subsequent analyses. No conclusions are drawn from the calculated results, and therefore no explicit acceptance criteria are applied.

4.0 ASSUMPTIONS

The following assumptions are applicable to the analyses documented in this report.

4.1 Fuel Assembly Planar Effective Thermal Conductivity

- The nominal dimensions are used for all geometric parameters. While effective thermal conductivities are calculated for individual fuel assemblies, the total thermal performance for a dry cask system is determined for an array of fuel assemblies inside a canister. Thus, small uncertainties in the physical dimensions of a single fuel assembly or fuel basket cell will not materially affect the overall thermal performance.

- Material properties are not adjusted for the possible presence of thin oxide layers. Tables of material properties in a commonly used reference [3] show that, in general, the emissivities of metal oxides are greater than the emissivities of the corresponding base metals. This will conservatively minimize the calculated effective thermal conductivities by minimizing thermal radiation heat transfer.

- The presence of fuel assembly grid supports is neglected. This will conservatively minimize the calculated effective thermal conductivities by minimizing conduction heat transfer between fuel rods.

- All fuel assemblies are assumed to have flow channels and to be inside a damaged fuel container (DFC). Both the fuel channel and the DFC prevent direct thermal radiation from the fuel rods to the fuel basket, reducing the net heat transfer for a given applied heat generation and reducing the effective thermal conductivity.

- The fuel assemblies are assumed to be centered in the DFC, which is itself centered in the fuel basket cell. This assumption eliminates direct contact between the fuel assembly and the DFC and between the DFC and the fuel basket cell wall. This will minimize the calculated effective thermal conductivities by excluding credit for highly efficient conduction near regions of metal-to-metal contact [4].

- Vacuum conditions are modeled by specifying a very low value for the thermal conductivity of the MPC-HB backfill gas (approximately two order of magnitude lower than the thermal conductivity of air). Actual thermal conductivities under ultra-low pressure conditions are higher [5], so this is conservative.

4.2 Composite Fuel Basket Cell Wall Effective Thermal Conductivity

- The finite-element models are constructed using nominal, cold dimensions. The neutron absorber coefficient of thermal expansion is higher than that of the stainless steel sheathing, so differential thermal expansion would act to reduce the size of any gaps. This assumption will therefore conservatively minimize conduction heat transfer through the composite wall.

- A conservative total gap thickness is assumed to exist between layers in the composite wall under helium backfill conditions. The fabrication process is designed to minimize the presence of macroscopic gaps and to provide contact between the components, so this assumption is conservative.

- Under helium backfill conditions, the gaps are conservatively held constant across the entire width of the neutron absorber panel. This conservatively eliminates the beneficial conduction effects of localized contact.

- Under evacuated conditions, the contact resistance for a stainless steel to stainless steel interface is used, instead of the stainless steel to aluminum interface that actually exists. The contact resistance for the all stainless steel interface is larger than for the stainless steel to aluminum interface, thereby increasing the total resistance and conservatively decreasing the resulting effective thermal conductivity.

4.3 Fuel Basket Planar Effective Thermal Conductivity

- The finite-element model is constructed using nominal, cold dimensions. The MPC-HB temperatures are greatest near the centerline, so differential thermal expansion would act to reduce the size of any basket-to-shell gaps. This assumption will therefore conservatively minimize conduction heat transfer from the fuel basket to the MPC-HB shell.

- The diameter of the equivalent solid cylinder used to replace the fuel basket is assumed. Use of the calculated effective thermal conductivities of this equivalent cylinder in subsequent calculations requires use of the correct diameter for the equivalent cylinder.

4.4 Fuel Basket Axial Effective Thermal Conductivity

- The fuel rod cladding is the only portion of the fuel rods credited in these calculations. All other fuel assembly components are assumed to be backfill gas. This conservatively neglects any axial heat transport through the fuel pellets or any fuel channels.

- The calculations are performed assuming that all storage locations are loaded with the fuel assembly design that has the lowest fuel rod cross-sectional area. This conservatively minimizes the amount of metal available for heat transport, replacing it with an increased amount of lower conductivity backfill gas.

- All calculations neglect the presence of any DFCs in the fuel basket. This minimizes the amount of steel available for axial heat transfer and maximizes the amount of lower conductivity backfill gas, yielding a conservative axial conductivity.

- No attempt is made to include the effects of any thermal radiation in the axial direction. Due to the long axial lengths and small interstitial gaps, and radiation effects will be negligible.

- The basket support structure, integral to the fuel basket, is completely neglected in this calculation. This minimizes the amount of steel available for axial heat transfer and yields a conservative axial conductivity.

- The diameter of the equivalent solid cylinder used to replace the fuel basket is assumed. Use of the calculated effective thermal conductivities of this equivalent cylinder in subsequent calculations requires use of the correct diameter for the equivalent cylinder.

4.5 Fuel Basket Effective Density and Heat Capacity

- The average density and average heat capacity are calculated separately, because the product of the averages (i.e., $\rho_{eff} \times Cp_{eff}$) is less than the average of the products (i.e., $(\rho \times Cp)_{eff}$). This helps ensure that subsequent transient evaluations that use these values are conservative.

- The fuel assembly weight is assigned to the entire fuel basket cell area. While the cell will also contain helium, the weight of helium is negligible compared to the fuel assembly weight. The fuel assembly density is therefore based on the fuel weight and the volume of the fuel basket cell along the fuel assembly overall length.

- The specific heat capacity of uranium dioxide is used for the entire fuel assembly. The specific heat for this material is lower than those of either stainless steel or Zircaloy, so this is conservative.

- The basket support structure, integral to the fuel basket, is completely neglected in this calculation. This minimizes the amount of steel, yielding conservative results.

- The diameter of the equivalent solid cylinder used to replace the fuel basket is assumed. Use of the calculated effective density and heat capacity of this equivalent cylinder in subsequent calculations requires use of the correct diameter for the equivalent cylinder.

4.6 MPC-HB Free Volume

- The volume of the upper fuel spacers is conservatively estimated. The actual volume of these items would be less, so this assumption will conservatively reduce the calculated free volume.

- The volumes of the MPC-HB lift lugs, attached to the inside of the shell, and the vent and drain port shield blocks and drain line, attached to the underside of the MPC-HB lid, are conservatively estimated. The actual volumes of these items would be less, so this assumption will conservatively reduce the calculated free volume.

- All fuel assemblies are assumed to have flow channels and to be inside a damaged fuel container (DFC). Both the fuel channel and the DFC displace additional free volume, yielding a conservatively lower result.

- The fuel assemblies are assumed to be composed entirely of Zircaloy. Of all the solid materials that compose the fuel assemblies, Zircaloy has the lowest density. This will yield the maximum fuel assemblies volume, conservatively reducing the calculated free volume.

5.0 INPUT DATA

5.1 Fuel Assembly Planar Effective Thermal Conductivity

The geometric information needed to construct finite-element models of all the HBPP fuel assembly types is presented in the following table.

PARAMETER	VALUE	SOURCE
General Electric Type II Fuel Assemblies		
Array Size	7×7	Reference 6
Fuel Cladding Outer Diameter	0.486 in	Reference 6
Fuel Cladding Inner Diameter	0.420 in	Reference 6
Fuel Pellet Diameter	0.411 in	Reference 6
Fuel Rod Pitch	0.631 in	Reference 6
General Electric Type III and Exxon Type III Fuel Assemblies		
Array Size	6×6	Reference 6
Fuel Cladding Outer Diameter	0.563 in	Reference 6
Fuel Cladding Inner Diameter	0.499 in	Reference 6
Fuel Pellet Diameter	0.488 in	Reference 6
Fuel Rod Pitch	0.740 in	Reference 6
Exxon IV Fuel Assemblies		
Array Size	6×6	Reference 6
Fuel Cladding Outer Diameter	0.5625 in	Reference 6
Maximum Fuel Cladding Inner Diameter	0.4951 in	Reference 6
Minimum Fuel Pellet Diameter	0.461 in	Reference 6
Fuel Rod Pitch	0.740 in	Reference 7
Flow Channel and Damaged Fuel Container		
Flow Channel Outer Width	4.662 in	Reference 8
Flow Channel Inner Width	4.542 in	Reference 8
Damaged Fuel Container Inner Width	4.93 in	Reference 9

In addition the above geometric dimensions, the finite-element models utilize a number of material properties. The following table summarizes the various material thermal conductivity and emissivity values used in the finite-element models.

PARAMETER	VALUE	SOURCE
UO_2 Thermal Conductivity	2.28 Btu/(hr×ft×°F)	Reference 10
Helium Thermal Conductivity @ 200°F	0.0976 Btu/(hr×ft×°F)	Reference 10
Helium Thermal Conductivity @ 450°F	0.1289 Btu/(hr×ft×°F)	Reference 10
Helium Thermal Conductivity @ 700°F	0.1575 Btu/(hr×ft×°F)	Reference 10
Zircaloy Thermal Conductivity	8.28 Btu/(hr×ft×°F)	Reference 10
Emissivity of Zircaloy	0.8	Reference 10
Emissivity of Stainless Steel	0.36	Reference 10

Additional geometric and material properties input data for the analytical calculations that determine the DFC wall and DFC-to-basket gap temperature drops and the overall effective planar thermal conductivity are presented within the calculations themselves (Appendix B), and are not repeated here.

5.2 Composite Fuel Basket Cell Wall Effective Thermal Conductivity

The geometric information needed to construct an accurate two-dimensional finite-element model of the composite fuel basket cell wall is presented in the following table.

PARAMETER	VALUE	SOURCE
Fuel Basket Cell Inner Dimension	5.61 in	Reference 11
Fuel Basket Cell Panel Thickness	3/16 in	Reference 11
Width of Neutron Absorber Panel	4.0 in	Reference 11
Thickness of Neutron Absorber Panel	0.05 in	Reference 11
Width of Neutron Absorber Sheathing	4 3/16 in	Reference 11
Thickness of Neutron Absorber Sheathing	0.035 in	Reference 11

In addition the above geometric dimensions, the finite-element model utilizes a number of material properties. The conductivity of helium and the emissivity of stainless steel presented in Section 5.1 are used in these models, as well the properties summarized in the following table.

PARAMETER	VALUE	SOURCE
Stainless Steel Conductivity @ 200°F	9.3 Btu/(hr×ft×°F)	Reference 12
Stainless Steel Conductivity @ 450°F	10.6 Btu/(hr×ft×°F)	Reference 12
Stainless Steel Conductivity @ 700°F	11.8 Btu/(hr×ft×°F)	Reference 12
Emissivity of Neutron Absorber Panel	0.75	Reference 7

The temperature-dependent thermal conductivity of the neutron absorber panels is presented in a calculation in Appendix C, which determines values at 200°F, 450°F and 700°F from manufacturer's data at other temperatures, and is not repeated here. The manufacturer's data itself is included in Appendix C as well, following the above-mentioned calculation.

5.3 Fuel Basket Planar Effective Thermal Conductivity

Due to the large number of geometric dimensions that are required to construct an accurate two-dimensional cross-section finite-element model of the MPC-HB, it is not feasible to list all dimensions here. All geometric inputs are obtained from the Holtec fuel basket drawing [11].

In addition to geometric dimensions, the fuel basket finite-element model utilizes a number of material properties. The same material properties listed in Sections 5.1 and 5.2 are used in this model as well.

The input data and corresponding references for the calculations of the planar effective thermal conductivities from the finite-element results are presented within the calculations themselves (Appendix D) and are not repeated here.

5.4 Fuel Basket Axial Effective Thermal Conductivity

In addition to geometric and material properties input data presented in Sections 5.1 and 5.2, input data corresponding references for these calculations are presented within the calculations themselves (Appendix E) and are not repeated here.

5.5 Fuel Basket Effective Density and Heat Capacity

In addition to geometric input data presented in Section 5.2, the input data and corresponding references for these calculations are presented within the calculations themselves (Appendix F) and are not repeated here.

5.6 MPC-HB Free Volume

In addition to geometric input data presented in Section 5.2, the input data and corresponding references for these calculations are presented within the calculations themselves (Appendix G) and are not repeated here.

6.0 CALCULATIONS

6.1 Fuel Assembly Planar Effective Thermal Conductivity

The planar effective thermal conductivities are calculated for all three distinct HBPP fuel assembly designs under helium backfilled conditions. Due to the temperature dependent material properties used and the presence of thermal radiation, the planar effective thermal conductivities are calculated at three different temperatures: 200°F, 450°F and 700°F. These calculations are performed as described in Section 2.2.

The limiting HBPP fuel assembly design under helium backfilled conditions (i.e., the design with the largest center-to-DFC temperature gradient, particularly at high temperatures) is further evaluated under evacuated conditions. Once again, the planar effective thermal conductivities are calculated at 200°F, 450°F and 700°F and the calculations are performed as described in Section 2.2.

The manual calculations that determine, for the limiting fuel assembly design, the total temperature difference between the inner edge of the fuel basket cell and the hottest location near the centerline of the fuel assemblies and that determine the planar effective thermal conductivities are presented in Appendix B.

The following computer program data files are used or created in performing these calculations:

```
 Directory of G:\PROJECTS\1125\EBR\K_FUEL

05/07/03  02:38p              15,436 GEIIhe.inp
05/07/03  02:40p              15,567 GEIIIhe.inp
05/07/03  02:41p              15,430 ExIVhe.inp
05/07/03  02:44p              15,348 GEIIvac.inp
05/07/03  03:03p               1,954 GEIIhe.err
05/07/03  03:05p               1,092 GEIIhe.RES
05/07/03  03:11p               1,954 GEIIIhe.err
05/07/03  03:12p               1,087 GEIIIhe.RES
05/07/03  03:17p               1,954 ExIVhe.err
05/07/03  03:18p               1,089 ExIVhe.RES
05/07/03  03:30p               1,954 GEIIvac.err
05/07/03  03:32p               1,101 GEIIvac.RES
09/15/03  09:12a              29,033 addDFC.mcd
```

Numeric results of these calculations are presented in Section 7.1.

6.2 Composite Fuel Basket Cell Wall Effective Thermal Conductivity

The neutron absorber manufacturer's thermal conductivity data is used to obtain values at 200°F, 450°F and 700°F. The manual calculations that perform the require interpolation and extrapolation are presented in Appendix C.

The effective thermal conductivities in the two orthogonal directions are calculated for the fuel basket of the MPC-HB. Due to the temperature dependent material properties used and the presence of thermal radiation, the effective thermal conductivities are calculated at three different temperatures: 200°F, 450°F and 700°F. Both helium-backfilled and evacuated conditions are evaluated. These calculations are performed as described in Section 2.2.

The following computer program data files are used or created in performing these calculations:

```
 Directory of G:\PROJECTS\1125\EBR\K_PANELS

05/07/03  03:54p                     8,184 k_mmc.mcd
05/07/03  01:14p                    17,333 m80he.inp
05/07/03  01:14p                    17,378 m80vac.inp
05/07/03  01:20p                     1,501 m80he.err
05/07/03  01:20p                     3,701 M80HE.RES
05/07/03  01:25p                     1,501 m80vac.err
05/07/03  01:25p                     3,693 M80VAC.RES
```

Numeric results of these calculations are presented in Section 7.2.

6.3 Fuel Basket Planar Effective Thermal Conductivity

The planar effective thermal conductivities are calculated for the fuel basket of the MPC-HB. Both helium-backfilled and evacuated conditions are evaluated. Due to the temperature dependent material properties used, the planar effective thermal conductivities are calculated at three different temperatures: 200°F, 450°F and 700°F. These calculations are performed as described in Section 2.3.

The manual calculations that determine the planar effective thermal conductivities from the results of the finite-element models are presented in Appendix D.

The following computer program data files are used or created in performing these calculations:

```
 Directory of G:\PROJECTS\1125\EBR\K_MPC

04/30/03  01:16p                 4,128,768 mpc80.db
09/15/03  09:32a                     4,597 Zrhe80.inp
09/15/03  09:33a                     4,582 Zrva80.inp
09/15/03  09:42a                       444 Zrhe80.err
09/15/03  09:43a                     1,096 ZRHE80.RES
09/15/03  09:44a                       444 Zrva80.err
09/15/03  09:44a                     1,089 ZRVA80.RES
09/15/03  10:37a                     9,914 Zrhe80.mcd
09/15/03  10:38a                     9,906 Zrva80.mcd
```

Numeric results of these calculations are presented in Section 7.3.

6.4 Fuel Basket Axial Effective Thermal Conductivity

The effective axial thermal conductivity of the fuel basket in the MPC-HB is calculated as described in Section 2.4. Both helium backfilled and evaluated conditions are evaluated. These calculations are presented in Appendix E.

The following computer program data files are used or created in performing these calculations:

```
 Directory of G:\PROJECTS\1125\EBR

05/08/03  03:08p                 18,852 Kaxial80.mcd
```

Numeric results of these calculations are presented in Section 7.4.

6.5 Fuel Basket Effective Density and Heat Capacity

The effective density and heat capacity of the MPC-HB fuel basket are calculated as described in Section 2.5. The calculations are presented in Appendix F.

The following computer program data files are used or created in performing these calculations:

```
 Directory of G:\PROJECTS\1125\EBR

05/28/03  04:08p                 17,839 RhoCp80.mcd
```

Numeric results of these calculations are presented in Section 7.4.

6.6 MPC-HB Free Volume

The minimum free volume in the MPC-HB is calculated for a fuel basket filled with the largest fuel assemblies, as described in Section 2.6. These calculations are presented in Appendix G.

The following computer program data files are used or created in performing these calculations:

```
 Directory of G:\PROJECTS\1125\EBR

09/22/03  10:33a                 17,010 Vfree80.mcd
```

Numeric results of these calculations are presented in Section 7.5.

7.0 RESULTS AND CONCLUSIONS

7.1 Fuel Assembly Planar Effective Thermal Conductivity

These evaluations were performed as described in Section 6.1. The temperature results of the finite element models are summarized in the following table.

Fuel Assembly Type, Backfill Condition	T_{max} at 200°F	T_{max} at 450°F	T_{max} at 700°F
General Electric Type II, Helium	206.76°F	454.37°F	702.99°F
GE and Exxon Type III, Helium	206.85°F	454.36°F	702.96°F
Exxon Type IV, Helium	206.25°F	453.99°F	702.71°F
General Electric Type II, Vacuum	236.33°F	464.92°F	707.47°F

It is noted that the General Electric Type II design has the largest center-to-DFC temperature gradient at 450°F and 700°F, so it is identified as the limiting design. The effective thermal conductivity results for this limiting fuel assembly design are summarized in the following table.

	Helium Backfilled	Evacuated
k_{eff} at 200°F	0.158 Btu/(hr×ft×°F)	0.022 Btu/(hr×ft×°F)
k_{eff} at 450°F	0.239 Btu/(hr×ft×°F)	0.057 Btu/(hr×ft×°F)
k_{eff} at 700°F	0.342 Btu/(hr×ft×°F)	0.117 Btu/(hr×ft×°F)

As stated in Section 3.0, no acceptance criteria are applied to these calculations.

7.2 Composite Fuel Basket Cell Wall Effective Thermal Conductivity

These evaluations were performed as described in Section 6.2. The effective thermal conductivity results of these calculations are summarized in the following table.

Orthogonal Direction, Backfill Condition	k_{eff} at 200°F Btu/(hr×ft×°F)	k_{eff} at 450°F Btu/(hr×ft×°F)	k_{eff} at 700°F Btu/(hr×ft×°F)
Through Thickness, Helium	4.808	5.816	6.703
Along Panel, Helium	11.985	13.262	14.404
Through Thickness, Evacuated	0.459	0.508	0.560
Along Panel, Evacuated	9.868	11.000	12.073

As stated in Section 3.0, no acceptance criteria are applied to these calculations.

7.3 Fuel Basket Planar Effective Thermal Conductivity

As described in Section 6.3, finite-element models of each of the MPC-HB designs are evaluated to obtain steady-state temperature distributions. The fuel basket and basket support region effective thermal conductivity values obtained from the maximum and minimum temperatures are summarized in the following tables.

Fuel Basket Effective Thermal Conductivities *			
Backfill Condition	**k_{eff} at 200°F (Btu/hr×ft×°F)**	**k_{eff} at 450°F (Btu/hr×ft×°F)**	**k_{eff} at 700°F (Btu/hr×ft×°F)**
Helium Backfilled	0.730	0.894	1.067
Evacuated	0.325	0.432	0.549

* Note: In subsequent three-dimensional modeling, these planar thermal conductivities are used for the entire fuel basket region. This simplification neglects end effects caused by the lack of neutron absorber at the top and bottom of the cell wall panels (non-heat generating regions). Because the axial burnup distribution of spent fuel concentrates heat near the assembly mid-height and reduces the heat generation near the ends of the active fuel length, this simplification will have a negligible effect on peak cladding temperatures predicted by the three-dimensional models.

As stated in Section 3.0, no acceptance criteria are applied to these calculations.

7.4 Fuel Basket Axial Effective Thermal Conductivity

These evaluations were performed as described in Section 6.4. The axial thermal conductivity results of these calculations for the MPC-HB are summarized in the following table.

Backfill Condition	**k_{eff} at 200°F (Btu/hr×ft×°F)**	**k_{eff} at 450°F (Btu/hr×ft×°F)**	**k_{eff} at 700°F (Btu/hr×ft×°F)**
Helium Backfilled	1.740	1.890	2.043
Evacuated	1.655	1.777	1.905

As stated in Section 3.0, no acceptance criteria are applied to these calculations.

7.5 Fuel Basket Effective Density and Heat Capacity

These evaluations were performed as described in Section 6.5. The effective thermal conductivity results of these calculations for each MPC-HB are summarized in the following table.

Parameter	Calculated Value
Effective Density	143.2 lb/ft^3
Effective Heat Capacity	0.05 Btu/(lb×°F)

As stated in Section 3.0, no acceptance criteria are applied to these calculations.

7.6 MPC-HB Free Volume

These evaluations were performed as described in Section 6.6. The free volume results of these calculations for each MPC-HB are summarized in the following table.

Parameter	Calculated Value
Gross Free Volume (no fuel)	193.57 ft^3
Net Free Volume (loaded with fuel)	123.81 ft^3

As stated in Section 3.0, no acceptance criteria are applied to these calculations.

8.0 REFERENCES[1]

[1] ANSYS Finite-Element Modeling Package, ANSYS Inc., Houston, PA.

[2] "A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements," Sandia Report SAND90-2406, TTC-1019, UC-820.

[3] Avallone and Baumeister, "Marks' Standard Handbook for Mechanical Engineers," McGraw-Hill, Ninth Edition, 1987.

[4] "Effective Thermal Conductivity Evaluations of LWR Fuel Assemblies in Dry Storage Casks," Holtec Report HI-971789, Revision 7.

[5] Reid, Prautsnitz and Poling, "Properties of Liquids and Gases," Fourth Edition.

[6] Pacific Gas and Electric Company Specification No. HBPP-2001-01, Contract No. 3500120394, Appendix B – Spent Fuel Parameters.

[7] Letter from L. Pulley (PG&E) to E. Lewis (Holtec), dated 5 May 2003.

[8] Pacific Gas and Electric Company Record Number 655438 Sheet 8.

[9] Holtec Drawing 4113, Revision 0.

[10] "HI-STAR 100 Final Safety Analysis Report," Holtec Report HI-2012610, Revision 1.

[11] Holtec Drawing 4103, Revision 0.

[12] ASME Boiler and Pressure Vessel Code, Section II, Part D – Properties, 1998.

1 "The revision status of Holtec documents cited in this section is subject to updates as the project progresses. This document will be revised if a revision to any of the above-referenced Holtec work products materially affects the instructions, results, conclusions or analyses contained in this document. Otherwise, a revision to this document will not be made and the latest revision of the referenced Holtec documents shall be assumed to supersede the revision numbers cited above. The Holtec Project Manager bears the undivided responsibility to insure that there is no intra-document conflict with respect to the information contained in all Holtec generated documents on a safety significant project".

APPENDIX A

Holtec QA Approved Computer Programs List

HOLTEC APPROVED COMPUTER PROGRAM LIST				REV. 61 July 25, 2003	
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
ANSYS (A)	5.3, 5.4, 5.6,5.6.2,5.7,7.0	JZ, EBR, PKC, CWB, SPA, AIS, IR, SP, JRT,AK	Windows		7.0
AC-XPERT	1.12		Windows		
AIRCOOL	5.21, 6.1		Windows		
BACKFILL	2.0		DOS/ Windows		
BONAMI (Scale)	4.3, 4.4		Windows		
BULKTEM	3.0		DOS/ Windows		
CASMO-4 (A)	1.13.04 (UNIX), 2.05.03 (WINDOWS)	ELR, SPA, DMM, KC, ST,VJB	UNIX/ Windows	Version 1.13.04 should not be used for new projects and should only be used when necessary for additional calculations on previous projects. The user should refer to the error notice documented in c4ser.04-results.pdf located in \generic\library\ nuclear\error notices\ concerning the use of version 1.13.04. Library N should be used with version 2.05.03 for all new reports issued after June 1st, 2003. Revisions to reports issued prior to June 1st, 2003 may continue to use the old Library L.	
CASMO-3 (A)	4.4, 4.7	ELR, SPA, DMM, KC, ST	UNIX		
CELLDAN	4.4.1		Windows		
CHANBP6 (A)	1.0	SJ, PKC, CWB, AIS, SP,JRT	DOS/Windows		
CHAP08 (CHAPLS10)	1.0		Windows		
CONPRO	1.0		DOS/Windows		
CORRE	1.3		DOS/Windows		
DECAY	1.4, 1.5		DOS/Windows		
DÉCOR	1.0		DOS/Windows		

HOLTEC APPROVED COMPUTER PROGRAM LIST				REV. 61 July 25, 2003	
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
DR.BEAMPRO	1.0.5		Windows		
DR.FRAME	2.0		Windows		
DYNAMO (A)	2.51	AIS, SP, CWB, PKC, SJ, JRT	DOS/Windows	Personnel qualified to use MR216 are automatically qualified to use DYNAMO.	
DYNAPOST	2.0		DOS/Windows		
FIMPACT	1.0		DOS/Windows		
FLUENT (A)	4.32, 4.48, 4.56, 5.1 (see error notice), 4.2.8 (UNS),5.5, 6.1.18	EBR, IR, DMM, SPA	Windows	Do not use porous medium with zero velocity.	
FTLOAD	1.4		DOS		
GENEQ	1.3		DOS		
INSYST	2.01		Windows		
KENO-5A (A)	4.3, 4.4	ELR, SPA, DMM, KC, ST,VJB	Windows		
LONGOR	1.0		DOS/Windows		
LNSMTH2	1.0		DOS/Windows		
LS-DYNA3D (A)	936, 940, 950, 960, 970	JZ, AIS, SPA, SP, JRT	Windows		
MAXDIS16	1.0		DOS/Windows		
MCNP (A)	4A, 4B	ELR, SPA, KC,ST,DMM, VJB, MAP	Windows/ UNIX	CASMO-4 Lumped Fission Products (IDs 401 and 402) and Isotope Pm148M (ID 61248) can be modeled in MCNP 4A using the cross sections documented in HI-2033031. Use of these cross sections is restricted to MCNP 4A, and to material specifications in atom densities.	
MASSINV	1.4, 1.5, 2.1		DOS/Windows		
MR216 (A)	1.0, 2.0, 2.2,2.4	AIS, SP, CWB, PKC, SJ,JRT	DOS/Windows	Versions 2.2 and 2.4 for use in dry storage analyses only. Use DYNAMO for liquefaction problems.	

HOLTEC APPROVED COMPUTER PROGRAM LIST				REV. 61 July 25, 2003	
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
MSREFINE	1.3, 2.1		DOS/Windows		
MULPOOLD	2.1		DOS/Windows		
MULTI1	1.3, 1.4, 1.5, 1.54, 1.55		Windows		
NITAWL (Scale)	4.3, 4.4		Windows		
NASTRAN DESKTOP (WORKING MODEL)	6.2, 2001,6.4,2002, 2003		Windows		
ONEPOOL	1.4.1, 1.5, 1.6		DOS/Windows		
ORIGENS (Scale)	4.3, 4.4		Windows		
PD16	1.1, 1.0, 2.0		Windows		
PREDYNA1	1.5, 1.4		DOS/Windows		
PSD1	1.0		DOS/Windows		
QAD	CGGP		Windows		
SAS2H (Scale)	4.3, 4.4		Windows		
SFMR2A	1.0		DOS/Windows		
SHAPEBUILDER	3.0		DOS/Windows		
SIFATIG	1.0		DOS/Windows		
SOLIDWORKS	2001		DOS/Windows	This program may be used to calculate Weight, Volume, Centroid and Moment of Inertia. As a precaution, user should avoid keeping more than one drawing files open at any given time during a Solidworks session.	

HOLTEC APPROVED COMPUTER PROGRAM LIST				REV. 61 July 25, 2003	
PROGRAM (Category)	**VERSION**	**CERTIFIED USERS**	**OPERATING SYSTEM**	**REMARKS**	**CODE USED**
				If there is a need for multiples drawing files to be open at once, user should ensure that the part names for all open files are uniquely named (i.e. no two parts have the same name.)	
SPG16	1.0, 2.0, 3.0		DOS/Windows		
SHAKE2000	1.1.0		DOS/Windows		
STARDYNE (A)	4.4, 4.5	SP	Windows		
STER	5.04		Windows		
TBOIL	1.7, 1.9		DOS/Windows	See HI-92832 for restriction on v1.7.	
THERPOOL	1.2, 1.2A		DOS/Windows		
TRIEL	2.0		DOS/Windows		
VERSUP	1.0		DOS		
VIB1DOF	1.0		DOS/Windows		
VMCHANGE	1.4, 1.3		Windows		
WEIGHT	1.0		Windows		

NOTES:
1. XXXX = ALPHANUMERIC COMBINATION
2. GENERAL PURPOSES UTILITY CODES (MATHCAD, EXCEL, ETC.) MAY BE USED ANYTIME.

APPENDIX B

Fuel Assembly Planar Effective Thermal Conductivity Calculations

PROPRIETARY CONTENTS OF APPENDIX REMOVED

APPENDIX C

METAMIC™ Thermal Conductivity Calculations

PROPRIETARY CONTENTS OF APPENDIX REMOVED

Metamic

3033 Drane Field Rd., Unit 1
Lakeland, Florida 33811
Tel: (863) 709-9448
Fax: (863) 709-9418
Email Address: metamicllc@msn.com

Manufacturers of METAMIC® High Performance
Aluminum Metal Matrix Composite Materials

June 26, 2002

ATTN: Debu
Holtec International
Fax: (856) 797-0909

Dear Debu,

Attached are the following charts per your request for 6061+25% Boron Carbide metal matrix composites:

1. Elevated temperature tensile/yield graph for 6061+21%B4C from R.T. to 800°F for **as-fabricated** material. This represents annealed or as processed condition for the composition.
2. Elevated temperature elongation of as-fabricated 6061+21%B4C graph from R.T. up to 600°F
3. Chart outlining UTS, Yield, Elongation, Modulus of Elasticity, and CTE for 6061+25%B4C. Note that the room temperature strength represents T-6 heat treat condition (Solution/quench/aged) – not annealed or as-fabricated! The elevated temp. properties are representative for your design parameters.
4. Laser flash thermal conductivity chart for 6061+15%, 21%, and 40%B4C

Sorry that I didn't get you this information yesterday afternoon – but I have many problems to solve.

If you need any other information please call me at anytime!

Tom Haynes

REYNOLDS
METALS
COMPANY

METAMIC®
METAL MATRIX COMPOSITES

Laser Flash Thermal Conductivity Data for *METAMIC®* Al / B_4Cp Composites

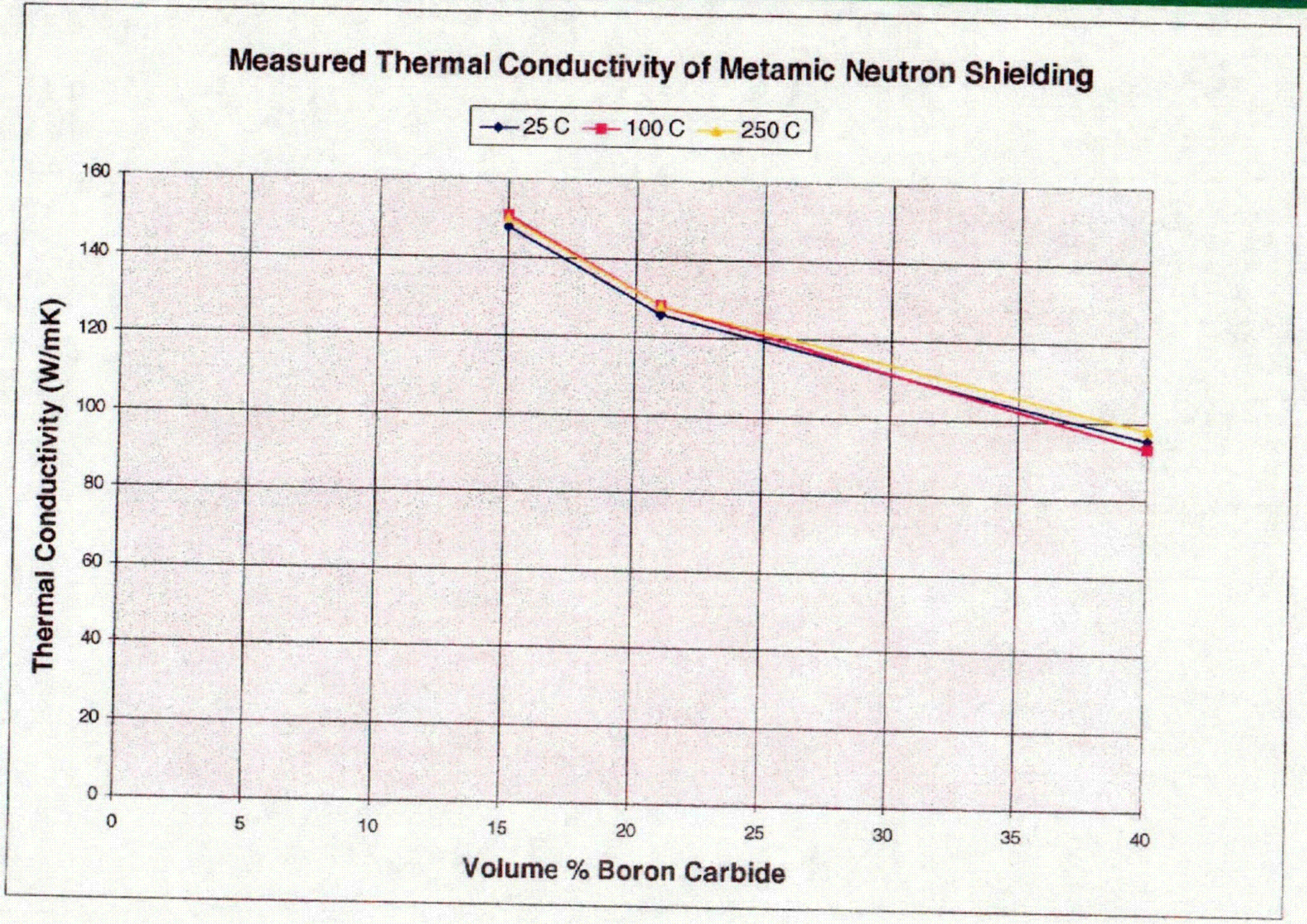
Sample	bulk density ρ @ 25°C (g/cm³)	temp (°C)	temp (°F)	specific heat Cp (J/g-K)	diffusivity α (cm²/s)	conductivity λ (W/m-K)	conductivity λ (Btu/hr-in-°F)
A (tube)	2.67	25	77	0.922	0.600	147	7.06
6061+15% B_4Cp		100	212	0.991	0.569	149	7.20
		250	482	1.084	0.520	150	7.21
B (plate)	2.65	25	77	0.918	0.516	126	6.04
6061+21% B_4Cp		100	212	1.02	0.471	127	6.10
		250	482	1.14	0.421	127	6.12
6061+40% B_4Cp	2.62	25	77	0.924	0.393	94.4	4.54
		100	212	1.01	0.351	91.8	4.42
		250	482	1.23	0.303	96.4	4.64

Reference or Footnote:
*Data generated by Holometrics Micromet in Bedford, MA 01730

METAMIC®

METAL MATRIX COMPOSITE

EPRI - BORAFLEX USERS CONFERENCE NOVEMBER 19-20, 1998

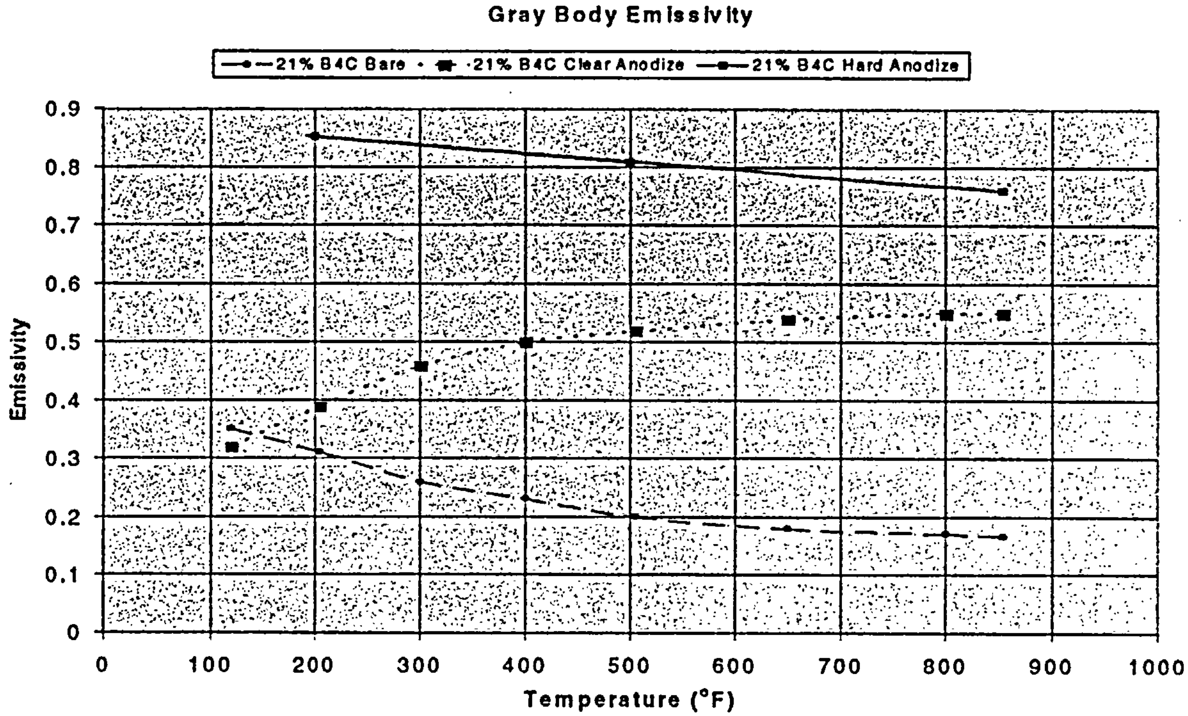


C01

METAMIC®

METAL MATRIX COMPOSITE

EPRI - BORAFLEX USERS CONFERENCE NOVEMBER 19-20, 1998



Note:

1) Since early hard anodizing indicates superior emissivity values - samples are in process to evaluate glass bead and hard anodize coating.
2) Hard anodizing conforms to ASTM-A-8625C/Class I specification.

APPENDIX D

Fuel Basket Planar Effective Thermal Conductivity Calculations

PROPRIETARY CONTENTS OF APPENDIX REMOVED

APPENDIX E

Fuel Basket Axial Effective Thermal Conductivity Calculations

PROPRIETARY CONTENTS OF APPENDIX REMOVED

APPENDIX F

Fuel Basket Effective Density and Heat Capacity Calculations

PROPRIETARY CONTENTS OF APPENDIX REMOVED

APPENDIX G

MPC-HB Free Volume Calculations

PROPRIETARY CONTENTS OF APPENDIX REMOVED