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COBRA-TF ANALYSIS OF RBHT STEAM COOLING EXPERIMENTS

A Thesis in
Nuclear Engineering
by
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ABSTRACT

The Rod Bundle Heat Transfer facility has performed a series of steady-state steam cooling experiments to calculate local convective heat transfer coefficients. Experimental temperature measurements taken during these tests reflect combined convective and thermal radiative heat transfer, therefore to calculate a “true” convective heat transfer coefficient the radiative heat flux for each rod surface must be calculated and subtracted from the total measured rod heat flux. Improvements were made to the existing cavity thermal radiation model used in earlier versions of COBRA-TF. The Rod Bundle Heat Transfer facility steam cooling experiments were analyzed using the improved radiation model. COBRA-TF results show good agreement with the experimental data and show that rod surface radiation increases as one moves from rods located in the bundle center to rods located closer to the bundle wall. For most of the steam cooling experiments, the radiative heat transfer from rods at least two rows from the flow housing wall (inner 3x3 rods) represents less than 10% of the total measured rod heat flux at the peak temperature location. For rods one row from the flow housing wall (5x5 peripheral rods) the radiative heat flux represents less than 20% of the total heat flux.
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Nomenclature

Acronyms

BWR – Boiling Water Reactor

COBRA-TF – Coolant Boiling Rod Array - Two Fluid

LBLOCA – Large Break Loss of Coolant Accident

PWR – Pressurized Water Reactor

RBHT – Rod Bundle Heat Transfer

SC – Steam Cooling

a  absorptance

A  area

B  radiosity (radiant heat flux leaving a surface)

C  view factor including effects of participating medium

D  radiant energy arriving at a surface

D_e  subchannel hydraulic diameter

E  emissive power

F  laminar enhancement factor; view factor

g  gravity

h  enthalpy; convective heat transfer coefficient

L  length

Nu  Nusselt number

P  subchannel pitch; Pressure
Pr  Prandtl number
q  interfacial heat transfer
Q  wall heat flux; radiant heat flux
Re  Reynolds number
t  time
T  temperature
U  velocity
x  distance

Greek letters
\( \alpha \)  void fraction
\( \Gamma' \)  mass gain by interfacial transfer
\( \varepsilon \)  spacer grid blockage, emissivity
\( \Gamma \)  entrainment term
\( \rho \)  density
\( \sigma \)  Stefan-Boltzmann constant; scattering coefficient
\( \tau \)  shear stress; total transmittance
\( \phi \)  mixing vane angle
\( \Omega \)  total fluid product of emissive power and absorptance

Subscripts
\( 1\varphi \)  single phase
g  noncondensible gas mixture
i  surface
j  surface
l  liquid phase
M  Markoczy correlation
v  vapor phase
w  wall

Superscripts
T  turbulence
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Chapter 1

INTRODUCTION

Through the joint efforts of the Pennsylvania State University and the United States Nuclear Regulatory Commission, an experimental Rod Bundle Heat Transfer (RBHT) facility was designed and built. A series of steady-state steam cooling experiments were conducted at the facility for the purpose of collecting experimental data such that local convective heat transfer coefficients could be calculated. Experimental wall heat flux measurements taken during these tests reflect a combined convective and thermal radiative heat transfer. Since the rod temperatures achieved during these experiments are relatively high, one would expect the rod surface-to-surface thermal radiative heat transfer to account for a substantial portion of the total rod heat transfer. Thus, to accurately correlate the convective heat transfer, the thermal radiation must be accounted for in the calculations.

This paper will provide a background on the RBHT facility with emphasis placed on the steam cooling experimental series. It will then discuss the method of modeling thermal radiation in rod bundle geometries and present an improved model that was added to COBRA-TF [1, 2] a thermal hydraulic subchannel analysis program used by the nuclear industry.
With the improved thermal radiation model in place, COBRA-TF was used to analyze the steam cooling experiments to determine the amount of surface thermal radiation in the bundle on a rod-by-rod basis. It will be shown that the COBRA-TF predictions are in good agreement with measurements taken during the experiments and that the percentage of total rod heat flux transferred by thermal radiation increases as one moves from rods at the center of the bundle to rods closer to the bundle walls.
Chapter 2

RBHT EXPERIMENTAL PROGRAM

2.1 Facility Layout

The RBHT Facility was developed by The Pennsylvania State University and the United States Nuclear Regulatory Commission [3]. The facility was designed to conduct systematic separate effects tests under well-controlled laboratory conditions in order to generate fundamental rod bundle heat transfer data including: two-phase level swell tests, steam flow tests with and without droplet injection, inverted annular film boiling tests, and dispersed flow film boiling reflood heat transfer tests. The facility is capable of operating in steady-state forced and variable reflood modes covering a wide range of flows and heat transfer conditions at pressures from 1.0 (14.5 psia) to 4.2 bars (61 psia).

The test facility, as shown in Figure 2-1 is a once-through flow facility in which either water or steam can enter the lower plenum and flow upward through the rod bundle. The lower plenum is attached to the bottom of the flow housing and is used as a reservoir for the coolant prior to injection into the rod bundle during reflood. The upper plenum serves as the first stage for phase separation and liquid collection of the two-phase effluent exiting the rod bundle. The liquid phase separates from the flow due to the sudden expansion from the bundle to the larger plenum flow area.
The facility has a large and small liquid carryover tank provided to collect the liquid carryover in the fluid flow in order to measure the amount of entrainment in the flow. The de-entrained liquid from the upper plenum drains into the top of a 25.6 mm tube, which extends inside a small carryover tank to detect and measure the carryover liquid. This tank collects and measures the amount of liquid overflow from the smaller carryover tank. A centrifugal two-phase separator is located downstream of the upper plenum also acts to separate out the remaining liquid flow from the vapor flow such that the vortex meter at the exit of the steam pipe will measure single phase vapor flow. There is a third liquid collection tank on the phase separator, which measures the separated liquid.
A pressure-damping tank located before the vortex flow meter and pressure control valve acts to damp out any pressure oscillations to maintain tight pressure control on the facility. Separating the exit flows from the bundle provides a means of calculating a transient mass balance as well as an energy balance on the facility.

The RBHT facility consists of a 7 x 7 bundle with 45 heated full-length electrical heater rods, which simulates a portion of a 17 x 17 PWR fuel assembly, as shown in Figure 2-2. The letters in the figure represent whether a heater rod is instrumented (I), not instrumented (U), or a support rod (S). The electrically powered heater rods have a diameter of 9.5 mm (0.374 in) and a square pitch of 12.6 mm (0.496 in). There are four unheated Inconel support rods, one in each corner, which provide structural support for the bundle.
The heater rods have a 3.657 m (144 in) heated length with a skewed axial power profile with the peak power located at the 2.74 m (108 in) elevation, as seen in Figure 2-3.

![Power Profile for RBHT Rod Bundle](image)

The spacer grids used in the bundle have mixing vanes, as seen in Figure 2-4, which improve heat transfer downstream of their position. The grids have high blockage, the rod bundle flow area is reduced by 39% such that the flow is accelerated through the grids and entrained droplets can be shattered.
In the RBHT facility, subchannel instrumentation is used to measure the local vapor temperature at the center of the subchannel. Measurements of the subchannel vapor temperature were made using two types of miniature thermocouple probes. The first type of miniature thermocouple used is suspended from the mixing vane grids and faces into the flow. The thermocouples have a 0.38 mm diameter and are supported by 2.44 mm long Inconel tubes which are tack welded to the mixing vane grids. The thermocouple leads are routed along the grid straps to the corner support tubes and out of the bundle.

The same type of thermocouples are spot welded to the mixing vane grid walls which measure the grid temperature to determine if the grid is dry or quenched. These thermocouple leads are also routed to the corner support tubes and out of the bundle.
The second subchannel vapor measurement is made using traversing thermocouple rakes which consist of three 0.38 mm diameter thermocouples attached to a thin piece of Inconel shim that is welded to a small tube that can be moved to different radial positions within the bundle, as shown in Figure 2-5. The thermocouples are located one rod pitch (12.6 mm) apart on the Inconel shim and can measure vapor temperatures at three different subchannel centers within the bundle. There are 13 traversing thermocouple rakes at different axial positions, most of which are powered by a stepping motor that allows the rake to traverse across a subchannel centerline.
A boiler with a capacity of 2613 kg/hr (5760 lbm/hr) at 10.3 bars (150 psia) provides steam for the experiments. The boiler is connected to the lower plenum by means of stainless steel piping equipped with a Vortex flow meter to measure steam flows. The piping also has fluid and wall thermocouples, a V-ball control valve, and a quick acting solenoid valve. Electrical heaters on the outside of the flow housing perform preheating of the facility test components prior to each experiment.

The test facility instrumentation is designed to measure temperatures, power, flows, liquid levels, pressures, void fractions, droplet sizes, droplet distribution, and droplet velocities. There are approximately 500 channels of instrumentation for the facility. Overall and transient mass and energy balances, mass inventories, carryover liquid, and steam flows can be calculated.
2.2 Steam Cooling Experiments

The objective of the Rod Bundle Heat Transfer (RBHT) Facility steam cooling series was to perform steady-state steam cooling heat transfer experiments over a range of conditions typical of a Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) following a postulated Large Break Loss of Coolant Accident (LBLOCA). The steam cooling experiments performed in the RBHT facility are specifically designed for model development and computer code validation. Therefore, the facility was instrumented to measure the quantities necessary for determining local convective heat transfer coefficients that reflect the heat transfer enhancement caused by mixing vane grids. The measured quantities include vapor temperatures at subchannel centerlines, mixing vane grid temperatures, a detailed axial pressure drop along the bundle length, absolute pressure in the upper plenum, rod temperatures upstream and downstream of mixing vane grids, and vapor flow rates in and out of the bundle.

In order to cover the range of possible conditions that could occur during a postulated LBLOCA a test matrix containing twenty one separate experiments was developed. Table 2-1 shows the test matrix, which summarizes the as designed boundary conditions for each test. The table shows that the flow was varied such that the inlet Reynolds number ranged from 1400 to 30000 over the entire experimental series. This covers the laminar flow regime through a transition region and into the fully turbulent regime. The power was adjusted for each test such that the power-to-flow ratio was approximately 0.25 kW-hr/kg (0.11 kW-hr/lbm) for each test.
A summary of the test procedure is as follows; steam entered the rod bundle through the lower plenum, passed through the heater rods, and exited via the upper plenum to the exhaust piping. The boiler steam injection rate was computer controlled and was verified for the correct pressure and temperature. The steam injection line was preheated to avoid any condensation. After approximately fifteen minutes of preheating the injection line, the inlet valve to the bundle was opened slightly to preheat the bundle and exit lines. The bypass lines around the rod bundle were closed during this procedure. The lower plenum, carryover tanks, and steam separator tanks were also drained at this time. In order to account for any carryover from the boiler, the tanks had to be drained to accurately measure the liquid.
Once the bundle was preheated to saturated vapor conditions, the bundle power was set at the desired power level. As the fluid flow stabilized for each matrix test condition, steady-state flow conditions were approached. Data was recorded for the entire length of the test duration, which included warm-up through shutdown and the data collected during a steady-state window was used to calculate local heat transfer coefficients.

Fully developed flow data points occurred at axial locations far downstream of each mixing vane grid. The length-to-hydraulic diameter ratio ($L/D_e$) is approximately 44 at these locations. Data from these points were reduced to local heat transfer coefficients and Nusselt numbers by McLaughlin [4]. The results for calculations made in the inner 3x3 and 5x5 peripheral rods are shown in Figure 2-6.

The local heat transfer over the length of the RBHT facility varies axially due the presence of mixing vane grids. The mixing vane grid has two effects on the flow. The primary effect is to disrupt the boundary layer on the heater rods such that the grid creates an entrance effect and the boundary layers must be reestablished. Secondly, the mixing vane grid induces swirl into the flow to create a secondary fluid motion creating more mixing and better heat transfer. Data collected between mixing vane grids was reduced and the results reflect this behavior as seen in Figure 2-7.
Figure 2-6: Steam Cooling Fully Developed Data

Figure 2-7: Heat Transfer Effects Downstream of Spacer Grids
The COolant Boiling Rod Array – Two Fluid (COBRA-TF) computer program was developed to predict the thermal-hydraulic response of the nuclear reactor vessel to anticipated transients. It provides a two-fluid, three-field representation of two-phase flow. Each field is treated in three dimensions and is compressible. Continuous vapor, continuous liquid, and entrained liquid drop are the three fields. The conservation equations for each of the three fields and for heat transfer, from and within the solid structures in contact with the fluid, are solved using a semi-implicit, finite-difference, numerical technique on an Eulerian mesh. The COBRA-TF vessel model features flexible nodding for both the hydrodynamic mesh and the heat transfer solution. This flexibility provides the capability to model a wide variety of geometries encountered in rod bundles including a subchannel analysis.

COBRA-TF also has the ability to model the heat transfer in electrically heated rods used to simulate nuclear fuel. It can also model unheated structures such as housing walls and unheated rods. This makes it an excellent choice for modeling the RBHT facility.
In the case of the steam cooling experiments, the only field used by COBRA-TF is the continuous vapor field since the working fluid is superheated steam. This greatly simplifies the continuous vapor conservation equations used by COBRA-TF because there is no interaction between different phases. The continuous vapor phase uses three conservation equations; mass, momentum, and energy. The vapor phase equations are listed below in their complete form with an explanation of each term. For a complete listing of the COBRA-TF conservation equations refer to Ergun [5].

The time averaged vapor phase conservation of mass equation, in vector form, is:

\[
\frac{\partial}{\partial t} \alpha_v \rho_v + \nabla \cdot (\alpha_v \rho_v \vec{U}_v) = \Gamma_v^" \quad (3-1)
\]

The individual terms in the equation are:

- Rate of change of mass
- Rate of mass gain by convection
- Rate of mass gain by interfacial transfer

In the case of the steam cooling experiments there is no vapor mass change due to interfacial transfer so the mass equation becomes:

\[
\frac{\partial}{\partial t} \alpha_v \rho_v + \nabla \cdot (\alpha_v \rho_v \vec{U}_v) = 0 \quad (3-2)
\]
A requirement of COBRA-TF is that a fraction of the working fluid be a noncondensable gas mixture. In modeling the steam cooling experiments the noncondensable mixture was considered air and the volume fraction was set to 0.01% such that it can be assumed negligible. A separate mass equation similar to the vapor field is used to model the mixture:

\[
\frac{\partial}{\partial t} \alpha_g \rho_g + \nabla \cdot (\alpha_g \rho_g \vec{U}_g) = 0 \quad (3-3)
\]

The vapor velocity is used in the gas mixture mass equation which assumes that the gas is moving at the same velocity as the vapor.

For energy conservation, the vapor-gas mixture is assumed to interact at a rate sufficient to maintain equilibrium such that only one energy equation is required for the vapor-gas mixture:

\[
\frac{\partial}{\partial t} \alpha_v \rho_{vg} h_{vg} + \nabla \cdot (\alpha_v \rho_{vg} h_{vg} \vec{U}_g) = \Gamma^v h_g + q_{iv} + Q_{vg} - \nabla \cdot (\alpha_v q_{vg}^T) \quad (3-4)
\]

The individual terms in the equation are:

Rate of change of energy + Convection = Energy transport + Interfacial + Wall heat - Turbulent heat flux due to phase change of energy + heat flux transfer
Since the only phase in vapor there is no energy transport due to phase change and no interfacial heat transfer, making the energy equation:

\[ \frac{\partial}{\partial t} \alpha_v \rho_{vg} h_{vg} + \nabla \cdot (\alpha_v \rho_{vg} h_{vg} \vec{U}_v) = Q_{vg} - \nabla \cdot (\alpha_v q_{vg}) \]  

(3-5)

The use of one energy equation for the vapor-gas mixture implies that the vapor and gas are at the same temperature in the same node.

A single momentum equation is used to model the vapor-gas mixture as well. Like the mass equations this assumes the vapor and gas are flowing at the same velocity.

The combined vapor-gas momentum equation is:

\[ \frac{\partial}{\partial t} \alpha_v \rho_{vg} \vec{U}_v + \nabla \cdot (\alpha_v \rho_{vg} \vec{U}_v \vec{U}_v) = -\alpha_v \nabla P + \alpha_v \rho_{vg} \ddot{g} - \vec{\tau}_{vw} \quad - \vec{\tau}_{ev} \quad + (\nabla \vec{U}) + \nabla \cdot (\alpha_v T_{vg}) \]  

(3-6)

The individual terms in the equation are:

Rate of change of momentum + Rate of change by convection = Pressure gradient + Gravity force + Wall shear + Interfacial drag between vapor and continuous liquid + Interfacial drag between vapor and drops + Momentum exchange due to entrainment + Momentum exchange due to turbulence
As in the mass and energy equations, all the interfacial terms cancel out in the momentum equation leaving:

\[
\frac{\partial}{\partial t} \alpha_r \rho_{rg} \vec{U}_r + \nabla \cdot (\alpha_r \rho_{rg} \vec{U}_r \hat{U}_r) = -\alpha_r \nabla P + \alpha_r \rho_{rg} \vec{g} - \tau_{ww}^{'''} + \nabla \cdot (\alpha_r T_{rg}) \quad (3-7)
\]

One important feature to the COBRA-TF code is that the governing equations form a complete set. No terms are omitted particularly in the momentum equations where wall shear and momentum exchange due to turbulence are represented.
Chapter 4

COBRA-TF MODEL IMPROVEMENTS

Heat transfer in the RBHT steady-state steam cooling experiments is a combination of single phase convection and radiative heat transfer. Rod surfaces are convectively cooled by the steam flowing past, while the housing wall and other unheated structures are convectively heated by the steam. Radiative heat transfer occurs between rod surfaces, the bundle wall and structures, as well as to the steam. The previous RBHT steam cooling heat transfer analysis neglected the effects of thermal radiation. However, thermal radiation is expected to account for a portion of the total heat transfer due to the relatively high surface temperatures encountered in the RBHT steam cooling experiments.
4.1 Single Phase Vapor Convective Heat Transfer Model

The original COBRA-TF code contains a convective heat transfer correlation for determining the convective heat transfer coefficient for fully developed flow. For a given Reynolds number the Nusselt number can be determined as shown in Figure 4-1. The correlation is broken into 3 sections; laminar, transition, and fully turbulent.

For a Reynolds number less than 1300 the flow is considered fully laminar. For a Reynolds number between 1300 and 25200 the flow is in transition from laminar to turbulent and for Reynolds numbers above 25200 the flow is considered fully turbulent and the Dittus-Boelter correlation [6] is used:

\[
\begin{align*}
Nu &= 10 & \text{Re} & \leq 1300 \\
Nu &= 0.0797 \text{Re}^{0.6774} \text{Pr}^{0.3} & 1300 & > \text{Re} \leq 25200 \\
Nu &= 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} & \text{Re} & > 25200
\end{align*}
\]  

(4-1)

where Nu is the Nusselt number, Re the Reynolds number, and Pr the Prandtl number.

Results from the RBHT steam cooling experiments show that the convective heat transfer is higher than the original COBRA-TF correlation. Therefore, a new fully developed heat transfer convective correlation was implemented into the code. The new model is shown in Figure 4-1 and is compared to the original correlation as well as the fully developed RBHT reduced data.
The new correlation is broken into two sections. For Reynolds numbers below 4500 a constant Nusselt number is used and for flows with Reynolds numbers above 4500 the Weisman correlation [7] is used:

\[
\begin{align*}
Nu &= 25 & \text{Re } \leq 4500 \\
Nu &= \left[0.026\left(\frac{P}{D_c}\right) - 0.006\right]Re^{0.8}Pr^{0.4} & \text{Re } > 4500
\end{align*}
\]  

(4.2)

where \(P\) is the subchannel pitch and \(D_c\) the subchannel hydraulic diameter.
The Weisman correlation has a form similar to that of Dittus-Boelter however it contains subchannel pitch to hydraulic diameter effects which results in a more accurate correlation for rod bundle geometries. The Dittus-Boelter correlation is based on experiments performed with circular tube geometries and was originally used in COBRA-TF due to the lack of empirical correlations for rod bundle geometries. Since then, multiple experiments [8, 9] on convective heat transfer in rod bundles have been conducted. Results from these experiments show that the convective heat transfer is higher in rod bundles than that predicted by the Dittus-Boelter correlation.

A heat transfer enhancement model to account for the effects of mixing vane grids has also been added to COBRA-TF. The RBHT data was compared to the correlation by Yao et al. [10] on heat transfer augmentation in rod bundles near grid spacers. Equation 4-3 accounts for grid vane blockage and the mixing vane angle. The Nusselt number was normalized with respect to the Markoczy fully developed convective heat transfer correlation [11] for rod bundles as seen in Figure 4-2. The enhancement correlation is given as:

$$\left( \frac{\text{Nu}}{\text{Nu}_{M}} \right)_{1 \phi} = \left[ 1 + 5.55 \varepsilon^2 e^{-0.13(x/D_e)} \right] + A^{2} \tan^{2} \phi \varepsilon^{-0.034(x/D_e)} \right]$$

(4-3)

where $\varepsilon$ is the spacer grid blockage, $\phi$ the mixing vane angle, $A$ the fraction of area projected by the mixing vane, $x$ the axial distance from the downstream end of the spacer, and $D_e$ the hydraulic diameter of the flow channel.
Figure 4-2 shows that the Yao correlation agrees well with the high Reynolds number data. However the data shows a greater heat transfer enhancement at lower Reynolds numbers. To capture the additional convective enhancement effects, a laminar enhancement factor was developed by Meholic [12]. The laminar enhancement factor was correlated as a function of Reynolds number. Thus, the resulting convective enhancement model is given as:

\[
\left( \frac{Nu}{Nu_M} \right)_{\phi} F \left[ 1 + 5.55 \phi e^{-0.13(x/D_v)} \left[ 1 + A^2 \tan \phi e^{-0.034(x/D_v)} \right] \right]
\]

(4-4)

where the laminar enhancement factor, \( F \) is given as:
\[ F = 1.75 \quad \text{Re} \leq 736 \]

\[ F = 11.008 \text{Re}^{-0.2788} \quad 736 \leq \text{Re} \leq 5450 \quad (4-5) \]

\[ F = 1.0 \quad \text{Re} > 5450 \]

With the improved single phase convective heat transfer models programmed in COBRA-TF the effects of mixing vane grids in the steam cooling experiments can be more accurately analyzed.
4.2 Thermal Radiation Heat Transfer Model

A complete bundle radiation model requires the computation of the radiosity from every solid surface to every other solid surface in the bundle through a continuously varying medium. COBRA-TF uses a simplified radiation model, on a subchannel basis that provides a reasonable approximation to the complete solution. The following major assumptions have been made in developing this model:

1. All solid surfaces in the enclosure are divided into finite isothermal surfaces.
2. Radiation in the axial direction is neglected.
3. All surfaces are treated as grey, diffuse bodies.
4. All surfaces are assumed to be infinite in length so that Hottel’s cross string method [13] can be used to generate view factors.

The subchannel radiation model consists of a fluid channel and the four ¼ fuel elements of a square pitched rod array. The radiant heat flux between the four rod surfaces and the fluid contained in the channel are calculated in detail, within the assumptions listed above and assuming the fluid within the subchannel is homogeneous with respect to temperature, and density.

The radiant heat flux from the rod surfaces and fluid within the subchannel to surfaces and fluid outside the subchannel are treated in an approximate way. This simplification reduces computer memory requirements and computation time.
Each radiation channel is treated as an enclosure with M surfaces, where M is treated as the number of isothermal solid surfaces plus the number of spaces (gaps) between solid surfaces in the channel. These M surfaces completely bound the radiation channel as shown in Figure 4-3.

![Figure 4-3: Typical Radiation Channel Enclosure](image-url)
The surfaces labeled $T_1$, $T_2$, $T_3$, and $T_4$ represent the four $\frac{1}{4}$ isothermal rod surfaces that are located in the radiation channel. $Q_5$, $Q_6$, $Q_7$, and $Q_8$ represent the radiant heat flux between the radiation channel and surrounding channels. $T_5$, $T_6$, $T_7$, and $T_8$ are “averaged” temperatures of the structures within each of the surrounding channels.

In the original COBRA-TF code these averaged temperatures were determined by taking the area weighted average of only the solid surfaces in the corresponding cavity. This portion of the radiation model was changed to the cavity model developed by Chiou et al. [14] such that the averaged temperatures are obtained by taking the area and view factor weighted average of the solid surface temperatures and the gap temperatures to the 4th power. That is,

$$
\bar{T}_j^4 = \frac{\sum_{i=1}^{7} T_{ji}^4 A_{ji} F_{ji}}{\sum_{i=1}^{7} A_{ji} F_{ji}}, \quad j = 5, 6, 7, 8
$$

(4-6)

where $j$ represents one of the channels which surrounds the radiation channel and the summation, $i$, is over the seven surfaces (4 solid surfaces and 3 gaps) in each surrounding channel. The gap temperature is defined as the weighted average of the solid surface temperatures outside that particular gap. For example, the temperature of gap 56 in Figure 4-3 is expressed by:
The hemispherical emissivity of a RBHT heater rod sample was experimental determined by Thermophysical Properties Research Laboratory Inc. [15]. The result for one of the samples is shown in Figure 4-4. The figure indicates that the emissivity varies from 0.74 to 0.88 over a temperature range of 820 to 1320 K (1000 to 2000 °F). The maximum temperature seen by the RBHT heat rods during the steam cooling experiments is approximately 1000 K (1400 °F) so the value of emissivity used in the COBRA-TF analysis was set to 0.8.
The heat fluxes between the radiation channel and the surrounding channels are calculated using temperatures and emissivities averaged in this way for each subchannel. The radiant heat flux through the gap separating two channels is then calculated by considering the subchannels on either side of the gap as cavities. The heat flux across the gap is given by:

$$\frac{Q_{12}}{A_g} = \left(\frac{1}{\varepsilon_1} - \varepsilon_1\right) \left(\frac{\varepsilon_1}{\Delta T}\right) \left(\frac{1}{\varepsilon_1} - 1\right) \sigma \left(T_1^4 - T_2^4\right)$$  \hspace{1cm} (4-9)
where the subscripts 1 and 2 represent the channels on each side of the gap, \( \varepsilon \) is the average emissivity of the cavity, \( T \) the average cavity temperature, \( \sigma \) the Stefan-Boltzmann constant, and \( \text{DET} \):

\[
\text{DET} = \varepsilon_1 \varepsilon_2 \left[ 1 + \left( \frac{1}{\varepsilon_1} - 1 \right) F_{12} + \left( \frac{1}{\varepsilon_2} - 1 \right) F_{21} \right]
\]  

(4-10)

where \( F_{12} \) is the view factor from cavity 1 to cavity 2 and \( F_{21} \) the view factor from cavity 2 to 1.

The absorption, transmittance, and scattering due to the fluid are not considered in calculating the radiant heat flux between the two cavities. Therefore, this model is limited to applications where the mean penetration distance of the radiation is long when compared to the mean beam length. Generally, the low pressure steam mixture is sufficiently optically thin such that this assumption is acceptable.

The view factors, beam lengths, and surface areas for ten radiation channel geometry types have been coded to simplify the generation of input data for the radiation model. These geometry types are shown in Figures 4-5 through 4-14. Other geometries can be modeled but the user is required to calculate the necessary view factors, beam lengths, and areas for each surface.
The radiation channel in Figures 4-5 through 4-14 is the channel containing the asterisk (*). Surrounding this channel are its immediate neighbors. These channels exchange radiative heat with the radiation channel through each of the gaps. This heat flux is calculated as described above. All rods in the ten location types are assumed to have the same diameter which means this model cannot be used to model control rod guide tubes unless the user specifies the necessary values.

Figure 4-5: Radiation Channel Location Type 1
Figure 4-6: Radiation Channel Location Type 2
Figure 4-7: Radiation Channel Location Type 3
Figure 4-8: Radiation Channel Location Type 4
Figure 4-9: Radiation Channel Location Type 5
Figure 4-10: Radiation Channel Location Type 6
Figure 4-11: Radiation Channel Location Type 7
Figure 4-12: Radiation Channel Location Type 8
To solve for the surface-to-surface and surface-to-fluid radiant heat transfer within the radiation channel a radiosity equation is solved for each solid surface. The equation for each surface, i, for a channel containing M surfaces and N solid surfaces is:
\[ \sum_{j=1}^{M} C(i,j)B(j) = D(i) \quad (4-11) \]

where \( B(j) \) is the radiosity (radian heat flux leaving surface \( j \)), \( D(i) \) is the radiant energy leaving the surfaces in the radiant channel that arrive at surface \( i \), and \( C(i,j) \) is the view factor including the effect of the participating medium:

\[ C(i, j) = F(i, j)\tau(i, j) \quad \text{for } i \neq j \quad (4-12) \]

and

\[ C(i, j) = \frac{\varepsilon_i}{1-\varepsilon_i} + 1 - F(i, j)\tau(i, j) - \sum_{j=1}^{M} F(i, j)\sigma(i, j) \quad \text{for } i = j \quad (4-13) \]

where \( F(i,j) \) is the view factor from surface \( i \) to \( j \), \( \tau(i,j) \) is the total transmittance from surface \( i \) to surface \( j \) (fraction of energy not absorbed or scattered by the fluid), \( \varepsilon_i \) the surface emissivity, and \( \sigma_{ij} \) the scattering coefficient from surface \( i \) to surface \( j \). This term gives the fraction of energy leaving surface \( i \) that is reincident on surface \( i \) and includes the radiant energy transmitted or scattered to other surfaces by the participating medium.

The radiant energy leaving the surfaces in the radiant channel that arrive at surface \( i \) is found from:
\[
D_i = \frac{\varepsilon_i}{1 - \varepsilon_i} \cdot E_i + \left( 1 - \sum_{j=1}^{M} F(i, j) \tau(i, j) - \sum_{j=1}^{M} F(i, j) \sigma(i, j) \right) \frac{\Omega}{a}
\] (4-14)

with

\[
a = a_d + a_g
\] (4-15)

\[
E_i = \sigma T_i^4
\] (4-16)

\[
\Omega = a_d E_d + a_g E_v
\] (4-17)

where \(a_d\) is the droplet absorptance, \(a_g\) the vapor absorptance, and \(a\) the total absorptance. \(E_i\) is the emissive power of surface \(i\) and \(T_i\) the temperature of surface \(i\). \(E_d\) is the emissive power of the drop, and \(E_v\) the emissive power of the vapor which are:

\[
E_d = \sigma T_{sat}^4
\] (4-18)

and

\[
E_v = \sigma T_{vap}^4
\] (4-19)
where $T_{\text{sat}}$ is the liquid saturation temperature, and $T_{\text{vap}}$ the vapor temperature. In the RBHT steam cooling experiments liquid drops do not exist, thus the emissive power of the drop, $E_d$ and the droplet absorptance cancel out of Equation 4-14.

The first term on the right hand side represents the energy radiating from surface $i$ to all other surfaces and the second term represents the energy radiating from surface $i$ to the vapor.

A similar equation can be written for gap $i$ radiating to all other surfaces in the channel:

$$\sum_{j=1}^{M} C(i, j) B(j) = D(i) \quad (4-20)$$

where:

$$C(i, j) = F(i, j) \tau(i, j) \quad \text{for } i \neq j \quad (4-21)$$

and

$$C(i, j) = 1 - F(i, j) \tau(i, j) - \sum_{j=1}^{M} F(i, j) \sigma(i, j) \quad \text{for } i = j \quad (4-22)$$
The radiant energy leaving the surfaces that arrive at gap \( i \) is found from:

\[
D_i = \frac{Q(i)}{A(i)} + \left( 1 - \sum_{j=1}^{M} F(i, j) \tau(i, j) - \sum_{j=1}^{M} F(i, j) \sigma(i, j) \right) \frac{\Omega}{a} \quad (4-23)
\]

where \( Q(i) \) is the heat flux across gap \( i \) and \( A(i) \) is the area of gap \( i \). Again, droplets do not exist in the steam cooling experiments and the droplet terms cancel out of Equation 4-23.

Writing these equations for each of the surfaces within the radiation channel results in a set of \( M \) equations. These equations are solved for the radiosity of the surfaces, given the temperature of the solid surfaces, the fluid properties, and the heat fluxes across the gaps, by using Gaussian elimination to invert the matrix. The old time step surface and gas temperatures are used from the previous time step. The Plank mean absorption coefficient for gas is used for the gas absorptance.

Once the radiosity for each surface has been obtained, then the solid surface heat flux is obtained from:

\[
\frac{Q(i)}{A(i)} = \frac{\varepsilon(i)}{1 - \varepsilon(i)} \left( E(i) - B(i) \right) \quad (4-24)
\]

here \( Q(i) \) is the radiative heat flux on solid surface \( i \).
Heat that is not transmitted or scattered to another surface in the radiation channel is absorbed by the steam. Therefore, the radiant heat flux to the steam is given by:

\[
Q_v(k) = \frac{a_s}{a} \sum_{i=1}^{M} A(i) \left( B(i) - E_{\nu} \right) \left[ 1 - \sum_{j=1}^{M} F(i, j) \tau(i, j) - \sum_{j=1}^{M} F(i, j) \sigma(i, j) \right]
\]

where \(Q_v\) represents the radiant heat transferred to the vapor phase.

These heat fluxes to the solid surfaces and to the fluid are added as explicit source terms to the respective energy equations. Refer to the COBRA-TF input manual [16] for detailed instructions on completing the radiation model input cards.
Chapter 5

ANALYSIS OF RBHT STEAM COOLING EXPERIMENTS

Nine RBHT steam cooling experiments covering the complete range of flows under consideration were chosen for analysis using the version of COBRA-TF with the improvements described above implemented. A summary of the actual conditions achieved during the nine experiments is shown in Table 5-1. All the chosen experiments were run at 271.7 kPa (40 psia) with a measured inlet steam temperature several degrees above saturation. The inlet Reynolds numbers were calculated using the measured inlet bundle flow rate, bundle flow area, and bundle hydraulic diameter. Inlet fluid properties were found at the measured inlet fluid temperature and absolute upper plenum pressure. The value used for atmospheric pressure was 97.1 kPa (14.09 psia) which was added to the measured upper plenum gauge pressure to get absolute upper plenum pressure.

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<th>Data File #</th>
<th>Validated Test Designation</th>
<th>NRC Test Matrix #</th>
<th>Steady State Time (seconds)</th>
<th>Bundle Power (kW)</th>
<th>Upper Plenum Pressure (kPa/psia)</th>
<th>Inlet Steam Temperature (K/F)</th>
<th>Inlet Steam Flow (m³/min)</th>
<th>Inlet Reynolds Number</th>
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<td>4</td>
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<td>498 / 725</td>
<td>1.36 / 48</td>
<td>5413</td>
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<td>498 / 727</td>
<td>1.8 / 64</td>
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<td>498 / 725</td>
<td>0.91 / 32</td>
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<td>406 / 621</td>
<td>0.48 / 17</td>
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<td>0.33 / 12</td>
<td>1320</td>
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<td>271.7 / 40</td>
<td>413 / 284</td>
<td>2.26 / 80</td>
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<td>422 / 300</td>
<td>5.88 / 235</td>
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</tr>
</tbody>
</table>
5.1 COBRA-TF Nodal Scheme

In order to easily compare COBRA-TF predictions to the steam cooling heater rod temperature measurements an axial nodal scheme was chosen such that nodes matched the axial location of as many heater rod thermocouples as possible. This resulted in 22 axial nodes evenly spaced approximately 17 cm (6.5 in) across the bundle heated length as shown in Figure 5-1.

Figure 5-1: COBRA-TF Axial Nodal Scheme for RBHT Steam Cooling Analysis
The heater rods and subchannels are modeled using $1/8^{th}$ symmetry as shown in Figure 5-2. This results in a 10 rod model with 28 unique rod surfaces of a $\frac{1}{4}$ or less of the heater rod and 10 subchannels with 12 gaps connecting the subchannels. The numbers in the center of subchannels indicate the subchannel while the gap identification number is located between the heater rods. The corner rod (rod number 10) is an unheated support rod and is modeled as a tube with no internal heat generation. The flow housing wall is modeled as a slab with no internal heat generation and is divided into 4 nodes. Conduction through the rods and housing wall is modeled in three dimensions including azimuthally from one rod node to its neighboring nodes. The bundle inlet velocity distribution is split uniformly between all subchannels.

Figure 5-2: COBRA-TF Planar Nodal Scheme for RBHT Steam Cooling Analysis
5.2 Steam Cooling Experiment SC-3166-C

Experiment SC-3166-C is the lowest flow experiment in the steam cooling test series. It has a calculated inlet Reynolds number of 1320 and a comparison of the experimental Reynolds number to the COBRA-TF predicted Reynolds number for the inner most subchannel (COBRA-TF subchannel number 1) is shown in Figure 5-3. The figure indicates that the Reynolds number decreases by about half over the length of the bundle and that the experimental Reynolds number calculated assuming a constant subchannel mass flow rate agrees well with the values predicted by COBRA-TF.

![Figure 5-3: Reynolds Number Comparison for RBHT Test SC-3166-C](image-url)
After simulating the experiment using COBRA-TF, the steady-state rod temperature predictions were compared to the rod temperature measurements made during the experiment. All instrumented heater rods were compared to the appropriate rod in the COBRA-TF 1/8th symmetric model. Figures 5-4 through 5-13 show the comparisons for the nine heater rods and the corner support rod. Each data point is at a different elevation along the heater rod and it was assumed that the data was symmetrical. The figures indicate that the COBRA-TF predictions of the heater rod surface temperatures agree fairly well with the experimental temperature measurements. However the general trend is that the temperature predictions made by COBRA-TF are higher than the experimental measurements, in some cases by as much as 140 K (250 °F) as seen in the rod 8 surface temperature comparison shown in Figure 5-11. However predictions for heater rod 8 were expected to be higher than the experimental measurements because the electrical resistance of rod 8 in the RBHT facility was higher than the average resistance of the other rods meaning that the power supply to that heater rod was the lowest resulting in lower temperatures.

The flow housing wall temperature predicted by COBRA-TF was also compared to experimental measurements taken at different elevations during the test as shown in Figure 5-14. This figure shows that the wall temperatures predicted by COBRA-TF are larger than the measured wall temperatures recorded during the test. One reason for this over prediction is that the flow housing wall did not reach a steady-state temperature during the experiment as seen in Figure 5-15. The COBRA-TF analysis was run until the flow housing wall reached a steady state.
Figure 5-4: COBRA-TF Rod 1 Temperature Comparison to RBHT Test SC-3166-C

Figure 5-5: COBRA-TF Rod 2 Temperature Comparison to RBHT Test SC-3166-C
Figure 5-6: COBRA-TF Rod 3 Temperature Comparison to RBHT Test SC-3166-C

Figure 5-7: COBRA-TF Rod 4 Temperature Comparison to RBHT Test SC-3166-C
Figure 5-8: COBRA-TF Rod 5 Temperature Comparison to RBHT Test SC-3166-C

Figure 5-9: COBRA-TF Rod 6 Temperature Comparison to RBHT Test SC-3166-C
Figure 5-10: COBRA-TF Rod 7 Temperature Comparison to RBHT Test SC-3166-C

Figure 5-11: COBRA-TF Rod 8 Temperature Comparison to RBHT Test SC-3166-C
Figure 5-12: COBRA-TF Rod 9 Temperature Comparison to RBHT Test SC-3166-C

Figure 5-13: COBRA-TF Rod 10 Temperature Comparison to RBHT Test SC-3166-C
Figure 5-14: COBRA-TF Wall Temperature Comparison to RBHT Test SC-3166-C

Figure 5-15: Measured Flow Housing Wall Temperature during RBHT Test SC-3166-C
In the steam cooling experimental series convective heat transfer coefficients were calculated using a subchannel mean bulk temperature correlation based on the Reynolds analogy which was developed by Cheung [17]. COBRA-TF uses an energy balance method to determine the subchannel vapor temperature at a given elevation. A comparison of the two subchannel vapor temperatures is shown in Figure 5-16. The figure indicates that the COBRA-TF subchannel vapor temperature is higher than the vapor temperature determined for data reduction in the steam cooling experiments. For laminar flows the Reynolds analogy defines a temperature profile with a large gradient across the subchannel. If the temperature profile across the subchannel defined by the Reynolds analogy is integrated and averaged over the subchannel area its value will be lower than the vapor temperature calculated using an energy balance.

This explains, in part, why the rod surface temperatures predicted by COBRA-TF are higher than the temperatures measured in the experiment. For a constant surface heat flux and the same convective heat transfer coefficient the surface temperature must increase if the vapor temperature increases to maintain the same temperature gradient between the rod surface and the passing vapor.

Figure 5-16 also shows that the two vapor temperatures deviate more at the top of the bundle because the bulk temperature calculated using Reynolds analogy drops off while the COBRA-TF vapor temperature remains relatively linear. This is reflected in the rod surface temperatures predicted by COBRA-TF. At elevations near the top of the
bundle the COBRA-TF surface temperatures deviate from the measured values more. This is clearly seen in Figures 5-6 and 5-7.

![Graph showing temperature vs. length for COBRA-TF and RBHT Calculated Tbulk.]

Figure 5-16: COBRA-TF Subchannel 1 Vapor Temperature Comparison to RBHT Test SC-3166-C

When calculating the bulk vapor temperature using Reynolds analogy the subchannel center temperature must be known. In the RBHT steam cooling experiments the subchannel center temperature is measured and used to determine the bulk vapor temperature. Vapor temperature measurements made during the experiments reflect heat loss through the flow housing wall, which is highest at the top due to the higher temperatures of the rods and structures. Axial conduction from the rods to the cooler structures above the bundle also account for the high heat loss.
Although heat loss to the ambient air was modeled in the COBRA-TF analysis, only an average convective heat transfer coefficient over the length of the bundle can be input into the code. This predicts a constant heat loss over the bundle length and a linear heat up of the flow housing outside wall. The measured outside wall temperature recorded during the experiment shows a constant outside wall temperature over the bundle length.

Figures 5-17 through 5-21 show bundle temperature distributions at 5 axial elevations. The figures show that the hottest surface occurs on the center rod. The rod surface temperatures decrease as one moves closer to the bundle wall or the corner support rod which are at approximately the same temperature and are the coolest structures in the bundle.

The figures also show that there is little temperature gradient azimuthally around the rod surfaces which was excepted because azimuthal conduction was turned on in the COBRA-TF model and the heater rods are made from boron nitride which has a high thermal conductivity. This verifies the assumption that the rod surface temperatures are isothermal for a given axial location which was used in the steam cooling data reduction. This assumption had to be made because the exact azimuthal location of the heat rod thermocouples was not known because of the manufacturing technique in which the heater rods were made.
Figure 5-17: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation for Test SC-3166-C
Figure 5-18: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation for Test SC-3166-C
Figure 5-19: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation for Test SC-3166-C
Figure 5-20: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation for Test SC-3166-C
Figure 5-21: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation for Test SC-3166-C
Figures 5-22 through 5-26 show the fraction of total surface heat flux due to thermal radiation for the same five axial elevations in which the surface temperatures were presented above. The figures show that the percentage of heat flux due to radiation increases as one moves from rods at the center of the bundle to rods close to the bundle wall and support rod. This behavior was expected since the temperature gradient in the bundle follows the same trend, as shown in Figures 5-17 through 5-21 above. Since the flow housing wall and support rod are unheated structures they act as a heat sink, taking energy from visible heater rods through surface-to-surface thermal radiative heat transfer.

The figures also show that the percentage of surface-to-surface thermal radiative heat transfer is less than 10% for the inner 3x3 bundle at lower elevations. However at higher elevations, where the surface temperatures are higher, the value can be as much as 15% for rod surfaces facing the flow housing wall.
Figure 5-22: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 0.74 m (29.1 in) Elevation for Test SC-3166-C
Figure 5-23: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 1.44 m (56.5 in) Elevation for Test SC-3166-C
Figure 5-24: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 2.12 m (83.3 in) Elevation for Test SC-3166-C
Figure 5-25: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 2.83 m (111.3 in) Elevation for Test SC-3166-C
Figure 5-26: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 3.52 m (138.6 in) Elevation for Test SC-3166-C
5.3 Steam Cooling Experiment SC-3214-C

Experiment SC-3214-C is the highest flow experiment in the steam cooling test series. It has a calculated inlet Reynolds number of 24776 and a comparison of the experimental Reynolds number to the COBRA-TF predicted Reynolds number for the inner most subchannel (COBRA-TF subchannel number 1) is shown in Figure 5-27. The figure indicates that the Reynolds number decreases by about half over the length of the bundle and that the experimental Reynolds number calculated assuming a constant subchannel mass flow rate agrees well with the values predicted by COBRA-TF.

Figure 5-27: Reynolds Number Comparison for RBHT Test SC-3214-C
After simulating the experiment using COBRA-TF, the rod temperature predictions were compared to the rod temperature measurements made during the experiment. Figures 5-28 through 5-37 show the comparisons for the nine heater rods and the corner support rod. The figures indicate that the COBRA-TF predicted heater rod surface temperatures agree much better with the experimental measurements taken during the test than the low flow analysis presented above. Heater rod number 8 shown in Figure 5-35 has a higher predicted temperature than the measured temperature recorded during the experiment. Like test SC-3166-C, this is because the rod resistance for this heater rod was determined to have a higher value than the other RBHT heater rods.

The flow housing wall temperature predicted by COBRA-TF was also compared to experimental measurements taken during the test as shown in Figure 5-38. This figure shows that the wall temperatures predicted by COBRA-TF are in good agreement with the measured wall temperatures recorded during the test. The comparison to the measured wall temperature is much better for this test than SC-3166-C because the flow housing wall reached a steady-state temperature during the experiment, as shown in Figure 5-39.
Figure 5-28: COBRA-TF Rod 1 Temperature Comparison to RBHT Test SC-3214-C

Figure 5-29: COBRA-TF Rod 2 Temperature Comparison to RBHT Test SC-3214-C
Figure 5-30: COBRA-TF Rod 3 Temperature Comparison to RBHT Test SC-3214-C

Figure 5-31: COBRA-TF Rod 4 Temperature Comparison to RBHT Test SC-3214-C
Figure 5-32: COBRA-TF Rod 5 Temperature Comparison to RBHT Test SC-3214-C

Figure 5-33: COBRA-TF Rod 6 Temperature Comparison to RBHT Test SC-3214-C
Figure 5-34: COBRA-TF Rod 7 Temperature Comparison to RBHT Test SC-3214-C

Figure 5-35: COBRA-TF Rod 8 Temperature Comparison to RBHT Test SC-3214-C
Figure 5-36: COBRA-TF Rod 9 Temperature Comparison to RBHT Test SC-3214-C

Figure 5-37: COBRA-TF Rod 10 Temperature Comparison to RBHT Test SC-3214-C
Figure 5-38: COBRA-TF Housing Wall Temperature Comparison to RBHT Test SC-3214-C

Figure 5-39: Measured Flow Housing Wall Temperature during RBHT Test SC-3214-C
Figure 5-40 shows a comparison of the subchannel vapor bulk temperature calculated for the RBHT data reduction to the COBRA-TF subchannel vapor temperature. The figure shows much better agreement between the two vapor temperatures than for the laminar test described above. This behavior indicates that the bulk temperature calculation based on Reynolds analogy approaches the vapor temperature calculated using an energy balance when the flow becomes turbulent because the subchannel temperature distribution becomes more uniform due to the increased mixing imparted by the turbulence.

Figure 5-40: COBRA-TF Subchannel 1 Vapor Temperature Comparison to RBHT Test SC-3214-C
Figures 5-41 through 5-45 show bundle temperature distributions at 5 axial elevations. The figures show that the hottest surface occurs on the center rod. The rod surface temperatures decrease as one moves closer to the bundle wall or the corner support rod which are at approximately the same temperature and are the coolest structures in the bundle.

Figures 5-46 through 5-50 show the fraction of total surface heat flux due to thermal radiation for the same five axial elevations in which the surface temperatures were presented above. The figures show that the percentage of heat flux due to radiation increases as one moves from rods at the center of the bundle to rods close to the bundle wall and support rod. The behavior seen in these figures is the same as that witnessed in the laminar flow analysis presented above, however the percentage of total surface heat flux due to thermal radiation is about half. For the inner 3x3 rod bundle the percentage of thermal radiative heat transfer is less than 5% at lower elevations. At higher elevations, where the surface temperatures are higher, the value can be as much as 11% for rod surfaces facing the flow housing wall. The percentage of radiative heat transfer was expected to be lower for this test because the convective heat transfer increases at higher Reynolds numbers and the rod temperatures are about the same for the two tests.
Figure 5-41: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation for Test SC-3214-C
Figure 5-42: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation for Test SC-3214-C
Figure 5-43: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation for Test SC-3214-C
Figure 5-44: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation for Test SC-3214-C
Figure 5-45: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation for Test SC-3214-C
Figure 5-46: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 0.74 m (29.1 in) Elevation for Test SC-3214-C
Figure 5-47: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 1.44 m (56.5 in) Elevation for Test SC-3214-C
Figure 5-48: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 2.12 m (83.3 in) Elevation for Test SC-3214-C
Figure 5-49: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 2.83 m (111.3 in) Elevation for Test SC-3214-C
Figure 5-50: COBRA-TF Predicted Fraction of Heat Flux due to Radiation at 3.52 m (138.6 in) Elevation for Test SC-3214-C
This section has discussed the results for the lowest and highest flow RBHT steam cooling experiments. Seven other steam cooling tests were analyzed using the improved version of COBRA-TF. Results for these experiments can be found below in Appendix A. The results for these tests are very similar to the ones presented above. For low flow, laminar tests, the general trend is that COBRA-TF over predicts the heater rod surface temperatures. For tests with higher flows, COBRA-TF temperature predictions are in much better agreement with the measured values obtained during the experiments. This indicates that the convective heat transfer coefficient in COBRA-TF is too low for laminar flows even with the new convective correlations added to the code.
Chapter 6

CONCLUSIONS

The RBHT steam cooling experiments were analyzed using a version of COBRA-TF with improvements made to the single phase vapor convective and the cavity thermal radiation heat transfer models. The experiments analyzed covered a range of conditions typical of a PWR and BWR following a postulated LBLOCA. With inlet Reynolds numbers varied from 1320 to 24776. Results from the COBRA-TF analyses were in good agreement with measurements made during the steam cooling experiments as shown in Figure 6-1 which shows all heater rod temperature data points. The figure shows that the COBRA-TF predictions agree best at lower rod temperatures which occur at lower bundle elevations. At higher temperatures which occur at the top of the bundle the COBRA-TF predictions deviate from the experimental measurements more.

Figure 6-2 shows the comparison of all wall temperature predictions made by COBRA-TF to the experimental measurements. The figure shows that the majority of wall temperature predictions are higher than the experimental measurements. It is interesting that the predictions that agree best with the experimental data are for the highest flow tests and the predictions that deviate most from the experimental temperatures are from the lowest flow tests.
Figure 6-1: Comparison of All Predicted Rod Surface Temperatures to Experimental Measurements

Figure 6-2: Comparison of All Predicted Housing Wall Temperatures to Experimental Measurements
Results from the thermal radiation calculations showed that the percentage of the rod surface heat flux transferred by surface-to-surface radiation was less than 15% within the inner 3x3 bundle at the peak power location (2.74m/108 in) as shown in Figure 6-3. The figure indicates that the maximum percentage of heat transfer due to thermal radiation occurs at the lowest flow tests and decreases as flow increases. This is because the convective heat transfer increases with increased flow and since the power-to-flow ratio was approximately the same for each test the rod temperatures were similar from test to test and the thermal radiative heat transfer must decrease.

The percentage of heat flux transferred by thermal radiation increased as one moves from rods inside the bundle to rods close to the flow housing wall which is the coldest structure seen by the heat rods. This effect can be seen in Figure 6-3 as well. Notice that the percentage of heat transfer due to thermal radiation is higher at the peak power location for the 5x5 peripheral rods than the inner 3x3 rods.

Figure 6-4 shows the percentage of heat transferred by thermal radiation for the inner 3x3 and 5x5 peripheral rods as a function of local Reynolds number at a bundle elevation of 3.51m (138 in). Comparison of this figure to Figure 6-3 shows that the thermal radiative heat transfer increases with increased bundle elevation because of the increasing rod surface temperatures. At this elevation the percentage of total heat transfer due to thermal radiation is less than 20% for the inner 3x3 bundle and less than 25% for the 5x5 peripheral rods.
Figure 6-3: Percentage of Heat Transferred by Thermal Radiation as a Function of Local Reynolds Number at Peak Power Location.

Figure 6-4: Percentage of Heat Transferred by Thermal Radiation as a Function of Local Reynolds Number at Peak Temperature Location.
The amount of energy transferred from the heater rods to the steam in the form of radiative heat transfer was found to be negligible (< 1%) due to the fact that steam is highly transparent. This indicates that the primary heat transfer mechanisms present in the steam cooling experiments are convective heat transfer from the heater rods to the steam and surface-to-surface thermal radiation. For laminar flows the percentage of heat transfer due to thermal radiation is highest especially at elevations above the peak power location as seen in Figures 6-3 and 6-4. At higher flows the thermal radiation is much less and convection is the primary heat transfer mechanism.
Bibliography


Appendix A

ANALYSIS OF REMAINING RBHT STEAM COOLING EXPERIMENTS

Results from the COBRA-TF analysis for the remaining seven RBHT steam cooling tests are presented here. Table 5-1 above shows the actual conditions achieved during the experiments. The results from these analyses backup the discussion presented in Chapter 5.
RBHT Steam Cooling Test SC-3163-A
Matrix test # 4

Test date – 3/15/2005

Steady state time window: 25920 - 26520 sec
Inlet flow: 1.35 m³/min (47.6 ft³/min)
Inlet steam temperature: 408 K (275 °F)
Upper plenum pressure: 271.7 kPa (39.4 psia)
Bundle power: 29.9 kW
Outlet steam temperature: 790 K (963 °F)
Bundle inlet Reynolds number: 5413

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -16.388x^3 + 100.57x^2 - 49.17x + 436.12 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -8.9366x^3 + 58.937x^2 + 6.0702x + 417.72 \]

where \( x \) is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3163-A-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3163-A-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3163-A-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3163-A-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3163-A-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3163-A-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3163-A-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3163-A-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3163-A-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3163-A-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3163-A-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3163-A-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3163-A-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3163-A-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3163-A-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3163-A-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3163-A-17: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3163-A-18 COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3163-A-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3163-A-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3163-A-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
RBHT Steam Cooling Test SC-3163-B
Matrix test # 5

Test date – 3/15/2005

Steady state time window: 27300 - 27600 sec
Inlet flow: 1.80 m³/min (63.5 ft³/min)
Inlet steam temperature: 409 K (277 °F)
Upper plenum pressure: 272.3 kPa (39.5 psia)
Bundle power: 39.2 kW
Outlet steam temperature: 805 K (990 °F)
Bundle inlet Reynolds number: 7184

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -16.261x^3 + 100.93x^2 - 49.657x + 438.59 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -9.6585x^3 + 64.419x^2 - 2.3145x + 422.76 \]

where \( x \) is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3163-B-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3163-B-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3163-B-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3163-B-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3163-B-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3163-B-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3163-B-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3163-B-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3163-B-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3163-B-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3163-B-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3163-B-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3163-B-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3163-B-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3163-B-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3163-B-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3163-B-17: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3163-B-18: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3163-B-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3163-B-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3163-B-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
RBHT Steam Cooling Test SC-3166-A
Matrix test # 3

Test date – 3/21/2005

Steady state time window: 15000 - 15600 sec
Inlet flow: 0.91 m³/min (32.2 ft³/min)
Inlet steam temperature: 408 K (275 °F)
Upper plenum pressure: 271.7 kPa (39.4 psia)
Bundle power: 21.0 kW
Outlet steam temperature: 780 K (945 °F)
Bundle inlet Reynolds number: 3655

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -15.787x^3 + 96.024x^2 - 41.28x + 433.52 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -10.056x^3 + 62.945x^2 + 2.2908x + 419.79 \]

where x is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3166-A-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3166-A-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3166-A-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3166-A-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3166-A-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3166-A-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3166-A-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3166-A-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3166-A-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3166-A-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3166-A-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3166-A-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3166-A-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3166-A-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3166-A-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3166-A-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3166-A-17 COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3166-A-18: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3166-A-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3166-A-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3166-A-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
RBHT Steam Cooling Test SC-3166-B
Matrix test #2

Test date – 3/21/2005

Steady state time window: 18660 – 19260 sec
Inlet flow: 0.48 m³/min (17.1 ft³/min)
Inlet steam temperature: 406 K (272 °F)
Upper plenum pressure: 271.7 kPa (39.4 psia)
Bundle power: 14.0 kW
Outlet steam temperature: 825 K (1026 °F)
Bundle inlet Reynolds number: 1965

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -18.477x^3 + 106.36x^2 - 31.321x + 429.69 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -10.78x^3 + 62.962x^2 + 26.651x + 409.87 \]

where \( x \) is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3166-B-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3166-B-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3166-B-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3166-B-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3166-B-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3166-B-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3166-B-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3166-B-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3166-B-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3166-B-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3166-B-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3166-B-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3166-B-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3166-B-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3166-B-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3166-B-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3166-B-17: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3166-B-18: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3166-B-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3166-B-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3166-B-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
RBHT Steam Cooling Test SC-3178-C
Matrix test # 6

Test date – 3/31/2005

Steady state time window: 28100 - 28500 sec
Inlet flow: 2.26 m³/min (79.9 ft³/min)
Inlet steam temperature: 413 K (284 °F)
Upper plenum pressure: 271.7 kPa (39.4 psia)
Bundle power: 49.9 kW
Outlet steam temperature: 825 K (1026 °F)
Bundle inlet Reynolds number: 8820

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -14.71x^3 + 93.998x^2 - 37.575x + 438.03 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -10.559x^3 + 70.797x^2 - 9.6599x + 429.36 \]

where \( x \) is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3178-C-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3178-C-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3178-C-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3178-C-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3178-C-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3178-C-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3178-C-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3178-C-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3178-C-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3178-C-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3178-C-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3178-C-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3178-C-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3178-C-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3178-C-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3178-C-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3178-C-17: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3178-C-18: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3178-C-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3178-C-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3178-C-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
RBHT Steam Cooling Test SC-3214-A
Matrix test # 7

Test date – 4/26/2005

Steady state time window:  11000 - 11500 sec
Inlet flow: 3.54 m³/min (125.0 ft³/min)
Inlet steam temperature: 417 K (291 °F)
Upper plenum pressure:  271.7 kPa (39.4 psia)
Bundle power: 70.0 kW
Outlet steam temperature: 775 K (936 °F)
Bundle inlet Reynolds number: 13508

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -13.233x^3 + 84.376x^2 - 38.8x + 441.58 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -9.9912x^3 + 67.516x^2 - 20.267x + 434.51 \]

where \( x \) is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3214-A-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3214-A-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3214-A-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3214-A-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3214-A-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3214-A-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3214-A-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3214-A-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3214-A-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3214-A-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3214-A-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3214-A-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3214-A-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3214-A-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3214-A-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3214-A-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3214-A-17: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3214-A-18: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3214-A-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3214-A-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3214-A-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
RBHT Steam Cooling Test SC-3214-B
Matrix test # 8

Test date – 4/26/2005

Steady state time window: 12800 - 13800 sec
Inlet flow: 4.81 m³/min (169.8 ft³/min)
Inlet steam temperature: 419 K (294 °F)
Upper plenum pressure: 271.7 kPa (39.4 psia)
Bundle power: 95.0 kW
Outlet steam temperature: 770 K (927 °F)
Bundle inlet Reynolds number: 18198

Subchannel Centerline Temperatures

The equations below were correlated using the axial subchannel centerline temperature distribution.

Subchannels D5 and E5 (use for inner 3x3 rod bundle thermocouple locations)

\[ T_{cl} = -13.119x^3 + 83.696x^2 - 39.122x + 442.54 \]

Subchannel C5 (use for 5x5 peripheral rod bundle thermocouple locations)

\[ T_{cl} = -8.1355x^3 + 57.708x^2 - 7.379x + 431.3 \]

where \( x \) is the elevation (m) and \( T_{cl} \) is in (K)
Figure SC-3214-B-1: COBRA-TF Rod 1 Comparison to RBHT Data

Figure SC-3214-B-2: COBRA-TF Rod 2 Comparison to RBHT Data
Figure SC-3214-B-3: COBRA-TF Rod 3 Comparison to RBHT Data

Figure SC-3214-B-4: COBRA-TF Rod 4 Comparison to RBHT Data
Figure SC-3214-B-5: COBRA-TF Rod 5 Comparison to RBHT Data

Figure SC-3214-B-6: COBRA-TF Rod 6 Comparison to RBHT Data
Figure SC-3214-B-7: COBRA-TF Rod 7 Comparison to RBHT Data

Figure SC-3214-B-8: COBRA-TF Rod 8 Comparison to RBHT Data
Figure SC-3214-B-9: COBRA-TF Rod 9 Comparison to RBHT Data

Figure SC-3214-B-10: COBRA-TF Rod 10 Comparison to RBHT Data
Figure SC-3214-B-11: COBRA-TF Wall Temperature Comparison to RBHT Data
Figure SC-3214-B-12: COBRA-TF Predicted Surface Temperatures (°F) at 0.74 m (29.1 in) Elevation
Figure SC-3214-B-13: COBRA-TF Predicted Surface Temperatures (°F) at 1.44 m (56.5 in) Elevation
Figure SC-3214-B-14: COBRA-TF Predicted Surface Temperatures (°F) at 2.12 m (83.3 in) Elevation
Figure SC-3214-B-15: COBRA-TF Predicted Surface Temperatures (°F) at 2.83 m (111.3 in) Elevation
Figure SC-3214-B-16: COBRA-TF Predicted Surface Temperatures (°F) at 3.52 m (138.6 in) Elevation
Figure SC-3214-B-17: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 0.74 m (29.1 in) Elevation
Figure SC-3214-B-18: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 1.44 m (56.5 in) Elevation
Figure SC-3214-B-19: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.12 m (83.3 in) Elevation
Figure SC-3214-B-20: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 2.83 m (111.3 in) Elevation
Figure SC-3214-B-21: COBRA-TF Predicted Fraction of Heat Flux Due to Radiation at 3.52 m (138.6 in) Elevation
Appendix B

SAMPLE INPUT DECK

******************************************************************************
********
* INPUT DECK
* RBHT - Sub-Channel model
* CREATED BY JAMES SPRING 2008
******************************************************************************
********

* Test Case SC-3214-C
* Steam Cooling with radiation heat transfer
******************************************************************************
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* ICOBRA
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* DTSTEP TIMET
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* EPSO OITMAX IITMAX
  .001 5 40
* INIT
  1 ***1." Sub-Channel Model of RBHT 7x7 Bundle *****
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*GROUP 1 - Calculation Variables and Initial Conditions
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*GTYPE VFRAC
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1.2 8 1 2 3 4 5 6 7 8 9 10
1.2 11 1 2 3 4 5 6 7 8 9 10
1.2 14 1 2 3 4 5 6 7 8 9 10
1.2 17 1 2 3 4 5 6 7 8 9 10
1.2 20 1 2 3 4 5 6 7 8 9 10
1.2 23 1 2 3 4 5 6 7 8 9 10

* ING NGAL NGCL IGMT     GLOSS    GABLOC     GLONG    GPERIM
1 | 8 | 10 | 1 | 1.4 | .2952 | 1.5 | 1.984 |

*NNGL
2 | 5 | 8 | 11 | 14 | 17 | 20 | 23 |

*NCGL   GMLT NGRD NGSF GMLT NGRD NGSF GMLT NGRD NGSF
1 | 0.5 | 1 | 1 | 2 | 1 | 3 | 1 |
2 | 1.0 | 2 | 2 | 3 | 2 | 4 | 1 | 5 | 1 |
3 | 0.5 | 3 | 3 | 5 | 2 | 6 | 1 |
4 | 1.0 | 4 | 2 | 5 | 3 | 7 | 1 | 8 | 1 |
5 | 1.0 | 5 | 4 | 6 | 2 | 8 | 2 | 9 | 1 |
6 | 0.5 | 6 | 3 | 9 | 2 | 10 | 1 |
7 | 0.75 | 7 | 2 | 8 | 3 | 11 | 1 |
8 | 0.75 | 8 | 4 | 9 | 3 | 11 | 2 |
9 | 0.75 | 9 | 4 | 10 | 2 | 11 | 3 |
10 | 0.50 | 10 | 3 | 11 | 4 |

***********************************************************************
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* GROUP 8 - Rod and Unheated Conductor Data *

223
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**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE**

| 1      | .125   |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE**

| 1      | .25    | 2      | .25  |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE**

| 1      | .125   | 2      | .25  | 3      | .125   |

**TAMB**

| 2      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE**

| 1      | .25    | 4      | .25  |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE**

| 1      | .25    | 3      | .25  | 5      | .25    | 4      | .25    |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE NSCH PIE**

| 1      | .125   | 3      | .25  | 5      | .125   | 4      | .125   |

**TAMB**

| 2      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE**

| 1      | .25    | 2      | .25  | 5      | .25    | 8      | .25    |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE NSCH PIE**

| 1      | .25    | 6      | .25  | 9      | .25    | 8      | .25    |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE NSCH PIE**

| 1      | .25    | 9      | .25  | 10     | .125   |

**TAMB**

| 1      | 1      | 1      | 0.05 | 1.0    | 0.0    | 1.0    | 0.0    |

**NSCH PIE NSCH PIE NSCH PIE**

| 1      | .125   | 9      | .25  | 10     | .125   |
* N IFTY IAXP NRND DAXMIN RMULT RADIAL HGAP ISEC HTMB
TAMB
11 3 0 1 0.05 1. 0.0 0. 1 0.65 71.
*NSCH PIE NSCH PIE NSCH PIE NSCH PIE
7 .279 8 .279 9 .279 10 .163
*I NRT1 NST1 NRX1
1 9 0 5
*IRTB IRTB IRTB IRTB IRTB IRTB IRTB IRTB IRTB
1 2 3 4 5 6 7 8 9
*********************************************************************
* Initial heater rod temperature profile *
*********************************************************************
* AXIALT TRINIT AXIALT TRINIT AXIALT TRINIT AXIALT TRINIT AXIALT
TRINIT
0.0 300.0 4.00 320.0 112.00 1000.0 148.00
750.0 155.0 575.0
*I NRT1 NST1 NRX1
2 1 0 5
*IRTB 10
*********************************************************************
* Initial tube temperature profile *
*********************************************************************
* AXIALT TRINIT AXIALT TRINIT AXIALT TRINIT AXIALT TRINIT AXIALT
TRINIT
0.0 200.0 4.00 220.0 112.00 400.0 148.00
200.0 155.0 200.0
*I NRT1 NST1 NRX1
3 1 0 5
*IRTB 11
*********************************************************************
* Initial housing temperature profile *
*********************************************************************
* AXIALT TRINIT TRONIT AXIALT TRINIT AXIALT TRINIT TRONIT AXIALT
TRINIT TRONIT AXIALT TRINIT TRONIT AXIALT TRINIT
* 0.0 180.0 88.0 4.00 200.0 90.0 112.00
670.0 210.0 148.00 610.0 130.0
* 155.0 575.0 100.0
* AXIALT TRINIT TRONIT AXIALT TRINIT TRONIT AXIALT TRINIT TRONIT
TRINIT TRONIT AXIALT TRINIT TRONIT TRONIT
* 0.0 88.0 180.0 4.00 90.0 200.0 112.00
210.0 670.0 148.00 130.0 610.0
* 155.0 100.0 575.0
*IDCR NSDR LCTE NRRD NSYF MLTF1 MLTF2 MLTF3 MLTF4
VDMLT
1 1 -1 52 0 1.0 1.0 1.0 1.0 1.0
1.0
*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
LRAD
2 4 2 1 7 9 5 3 4 2 1 2 1 2 4 2
| 5 9 7 3 16 18 12 8 9 7 3 5 10 13 |
| 10 6 |
| 9 5 3 7 2 1 2 4 3 5 9 7 3 7 |
| 9 5 |
| 12 18 16 8 |

*IDCR NSDR LCTE NRRD NSYF  MLTF1  MLTF2  MLTF3  MLTF4
VDMLT
2 2 -2 51 0 1.0 1.0 1.0 1.0
1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
LRAD LRAD
| 5 9 7 3 10 13 10 6 2 4 2 1 3 7 |
| 9 5 |
| 12 18 16 8 19 22 14 11 7 9 5 3 14 22 |
| 19 11 |
| 4 2 1 2 1 2 4 2 6 10 13 10 8 16 |
| 18 12 |
| 21 29 17 |

*IDCR NSDR LCTE NRRD NSYF  MLTF1  MLTF2  MLTF3  MLTF4
VDMLT
3 3 -3 50 0 1.0 1.0 1.0 1.0
1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
LRAD LRAD
| 10 13 10 6 19 22 14 11 7 9 5 3 5 9 |
| 7 3 |
| 14 22 19 11 30 25 20 16 18 12 8 23 26 23 |
| 15 9 |
| 7 3 5 2 4 2 1 3 7 9 5 12 18 16 |
| 8 25 |
| 30 20 |

*IDCR NSDR LCTE NRRD NSYF  MLTF1  MLTF2  MLTF3  MLTF4
VDMLT
4 4 -4 45 0 1.0 1.0 1.0 1.0
1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
LRAD LRAD
| 12 18 16 8 14 22 19 11 5 9 7 3 8 16 |
| 18 12 |
| 21 29 17 23 26 23 15 10 13 10 6 25 30 20 |
| 2 4 |
| 2 1 3 7 9 5 11 19 22 14 17 29 21 |

*IDCR NSDR LCTE NRRD NSYF  MLTF1  MLTF2  MLTF3  MLTF4
VDMLT
5 5 -5 44 0 1.0 1.0 1.0 1.0
1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
LRAD LRAD
| 14 22 19 11 23 26 23 15 10 13 10 6 12 18 |
| 16 8 |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 25 | 30 | 20 | 31 | 27 | 24 | 19 | 22 | 14 | 11 | 27 | 31 | 24 | 7 9 | 5 |
| 3  | 5  | 9  | 7  | 3  | 8  | 16 | 18 | 12 | 21 | 29 | 17 |

*IDCR NSDR LCTE NRRD NSYF MLTF1 MLTF2 MLTF3 MLTF4 VDMLT
6 6 -6 38 0 1.0 1.0 1.0 1.0 1.0

1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
23 26 23 15 31 27 24 19 22 14 11 14 22 19 11 27 6 12 18 16 18 12 8 10 13 10 6 12 18 16 8 25 30 20

*IDCR NSDR LCTE NRRD NSYF MLTF1 MLTF2 MLTF3 MLTF4 VDMLT
7 7 -7 31 0 1.0 1.0 1.0 1.0 1.0

1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
21 29 17 25 30 20 12 18 16 8 17 29 21 27 31 24 14 22 19 11 5 9 7 3 8 16 18 12 20 30 25

*IDCR NSDR LCTE NRRD NSYF MLTF1 MLTF2 MLTF3 MLTF4 VDMLT
8 8 -8 30 0 1.0 1.0 1.0 1.0 1.0

1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
25 30 20 27 31 24 14 22 19 11 21 29 17 32 28 23 26 23 15 10 13 10 6 12 18 16 8 17 29 21

*IDCR NSDR LCTE NRRD NSYF MLTF1 MLTF2 MLTF3 MLTF4 VDMLT
9 9 -9 26 0 1.0 1.0 1.0 1.0 1.0

1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
27 31 24 32 28 23 26 23 15 25 30 20 31 27 24 19 22 14 11 14 22 19 11 21 29 17

*IDCR NSDR LCTE NRRD NSYF MLTF1 MLTF2 MLTF3 MLTF4 VDMLT
10 10 -10 18 0 1.0 1.0 1.0 1.0 1.0

1.0

*LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD LRAD
32 28 31 27 24 27 31 24 30 25 20 23 26 23 15 25

227
*IDTP
-1
*NOM DIA RODEMISS OVRSZ DIA PITCH .374 .8 .374 .496

*IDTP
-2
*NOM DIA RODEMISS GPWDTH PITCH RAD WALLEMISS .374 .8 .100 .496 0.0 0.0 .8

*IDTP
-3
*NOM DIA RODEMISS GPWDTH PITCH RAD WALLEMISS .374 .8 .100 .496 0.0 0.0 .8

*IDTP
-4
*NOM DIA RODEMISS GPWDTH PITCH RAD WALLEMISS .374 .8 .100 .496 0.0 0.248 .8

*IDTP
-5
*NOM DIA RODEMISS GPWDTH PITCH RAD WALLEMISS .374 .8 .100 .496 0.0 0.248 .8

*IDTP
-6
*NOM DIA RODEMISS GPWDTH PITCH RAD WALLEMISS .374 .8 .100 .496 0.0 0.248 .8

* ** GROUP 9 - Conductor Geometry Description ** *

*NGRP NFLT
  9  3
  * I FTYP DROD DIN NFUL IMTOX
    1 hrod .374 0.0 4 0
  *NODR MATR TREG QREG NODR MATR TREG QREG NODR MATR TREG QREG TREG QREG
    1 2.0675 0.0 2 3 .045 1.0 4 2.0465 0.0 3 1.0280 0.0
  * I FTYP DROD DIN NFUL IMTOX
    2 tube .375 .209 1 0
  *NODR MATR TREG QREG

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**GROUP 10 - Material Properties Tables**

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<th>CPF1</th>
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*GROUP 11 - Axial Power Tables and Forcing Functions
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*NGRP NAXP   NQ
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* I NAXN
1    4
* Y AXIAL    Y AXIAL    Y AXIAL    Y AXIAL    Y AXIAL
AXIAL
0.0 0.500 112.0 1.500 148.0 0.500 148.001
0.0
* power decay
* YQ    FQ    YQ    FQ    YQ    FQ    YQ
FQ
* 0.0 1. 17.5 .921 35.0 .8704 52.5
   .8326
* 70. .803 87.5 .7755 105.0 .7512 122.5
   .7302
* 140. .714 157.5 .6973 175.0 .6837 192.5
   .6710
* 220. .652 255.0 .6332 290.0 .6167 325.0
   .6017
* 360. .588 395.0 .5769 430.0 .5656 465.0
   .5562
* 500. .547 535.0 .5444 570.0 .5304 605.0
   .5243
* 1000. .002
* constant power
0.0 1. 5000.0 1.0
*
***********************************************************************
************
* GROUP 13 - Boundary Condition Data
*
***********************************************************************
************
*NGRP NBND NKBD NFUN NGBD
13    11    0    0    0    0
*NPTS
* 3
*ABSC    ORDINT ABSC    ORDINT ABSC    ORDINT
* 0.0 0.0 0.1 1.41500. 1.4
*IBD1  IBD2  ISPC  NPFN  NHFN  PVALUE  HVALUE  XVALUE
1  1  2  0  03.8090e-03  1170.00  40.0
*HMGA GVAL
124. 1.0.9999.0001
*IBD1  IBD2  ISPC  NPFN  NHFN  PVALUE  HVALUE  XVALUE
2  1  2  0  07.6182e-03  1170.00  40.0
*HMGA GVAL
124. 1.0.9999.0001
*IBD1  IBD2  ISPC  NPFN  NHFN  PVALUE  HVALUE  XVALUE
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### Group 14 - Output Options

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**MXDP IGRF NLLR**

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Appendix C

VIEW FACTOR CALCULATION VERIFICATION

Since the original view factor code written in COBRA-TF calculated all the necessary view factors for the improved cavity thermal radiation model it was not changed. The view factors calculated by COBRA-TF were verified with hand calculations presented here.

The crossed-strings method is used to find view factors in long enclosures, such as the rod bundle used in the RBHT experiments. The formula used in the crossed-strings method is:

\[ F_{4-1} = \frac{[(D_{a-c} + D_{b-d})-(S_{a-d} + S_{b-c})]}{2A_4} \]  

(C-1)

The view factor from Surface 4 to Surface 1, \( F_{4,1} \), is equal to the sum of the diagonal strings, \( D_{a-c} \) and \( D_{b-d} \), differenced with the sum of the side strings, \( S_{a-d} \) and \( S_{b-c} \), divided by twice the arc length of Surface 4.
The length of diagonal $D_{a-c}$ is calculated by adding the length of the straight portion of $D_{a-c}$ to the curved portion of $D_{a-c}$. The straight portion length is found using Pythagorean’s Theorem on the right triangle created by Rod 4’s radius (where it is met by the tangent straight portion of $D_{a-c}$), the straight portion of diagonal $D_{a-c}$ and the hypotenuse, which is comprised of Rod 4’s radius added to the dimension from Point b to Point c (the gap length). The length of the curved portion of $D_{a-c}$ is equal to the arc length of the complement to the angle created by where Rod 4’s radius meets the hypotenuse.

Tables C-1 through C-6 show the hand calculated view factors compared to the COBRA-TF calculated view factors for the three subchannel types. The agreement between the two calculations is good.
Table C-1: View Factor Values for Interior Subchannels (Location Types 1-6)

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<tr>
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<th>0.2512</th>
<th>0.1993</th>
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Table C-3: View Factor Values for Exterior Subchannels (Location Types 7-9)

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Table C-4: COBRA-TF View Factor Values for Exterior Subchannels (Location Types 7-9)

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Table C-5: View Factor Values for Corner Subchannel (Location Type 10)

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Table C-6: COBRA-TF View Factor Values for Corner Subchannel (Location Type 10)

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