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WCAP - 15578

Description of the Westinghouse LOCTA_JR 1-D Heat Conduction Code for LOCA Analysis of Fuel Rods

Westinghouse Electric Company LLC

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1 INTRODUCTION

1.1 PURPOSE AND DESCRIPTION

The LOCTA_JR code is one of a series of computer codes that Westinghouse has developed based on the original LOCTA-IV code [1]. All of the LOCTA codes, as well as several other codes derived from the LOCTA models, have the fundamental capabilities for performing a 1-D, radial heat conduction solution for a nuclear fuel rod geometry, and are capable of predicting the behavior of fuel rods under loss of coolant accident (LOCA) conditions. In order to solve the complete thermal-hydraulic problem for a fuel rod a number of ancillary models are necessary in addition to the heat conduction model. These include models for the thermal-mechanical expansion and contraction of the pellet and clad, rod gas pressure behavior, pellet-to-clad gap conductance, and models for predicting channel fluid conditions. Each particular LOCTA series code has a full complement of these models, which are tailored to the specific problem that the code is used to address.

The LOCTA_JR code was developed for the purpose of solving a simplified problem; one in which channel fluid boundary conditions are known, or can be supplied based upon calculations conducted using another code. It allows the evaluation of fuel rod performance for transients in which the channel hydraulic boundary conditions are not significantly perturbed by the presence of a different or additional fuel rod from those modeled in the base case analysis. It solves the 1-D radial heat conduction problem for a single axial node (with multiple separate nodes per problem) with the assumption that there is no significant interaction between axial nodes on the same rod over the course of a transient. This assumption is generally valid for most LOCA transients of interest. LOCTA_JR has also been designed to allow calculations for fuel assembly control rod thimble tubes or similar geometries.

1.2 GENERAL METHODOLOGY

Figure 1-1 is a depiction of the general problem which is being solved. Figure 1-2 is a depiction of the general 1-D heat conduction problem with the relevant general equations and parameters. Figure 1-3 is a flowchart briefly depicting the salient points of the fuel rod solution for one transient timestep. To solve a problem, first the transient time-dependent channel fluid conditions of pressure [P], fluid temperature [T_{fluid}(N)]and clad surface heat transfer coefficient [HTC(N)]are input for individual axial nodes, along with a normalized rod power curve [$q'(z_N)$]. Since there are no fluid calculations other than timestep interpolations and obtaining steam properties, the bulk of the problem is simply a standard 1-D radial heat conduction problem which consists of setting up the simultaneous equations for the specified radial nodalization and inverting the matrix to obtain the new temperature distribution and clad temperature [T_{clad}(N)]. A number of constitutive models are necessary to provide closure for the problem. These models are all obtained from existing approved Westinghouse codes and are discussed further in Section 3. An exception is the pseudo-full length rod internal pressure (RIP) model which is presented in more detail. Due to the simple nature of the problem and the relative stability of solid heat conduction solutions, a constant timestep is used throughout the transient. Sensitivity studies were conducted to define a suitably converged timestep size.

In general, the problem for two separate axial nodes is solved during each transient; one node which is designated as the "burst" node, and another node which may be any other axial node of interest (e.g. the peak clad temperature elevation). The same axial node elevation may be specified for both in single a problem if desired. One node designated as the reference node is monitored during the course of the transient and used to provide input to the pseudo-full length rod RIP model, and also to determine the time at which clad burst is predicted to occur. For the modeling of RCC thimbles or similar rods that are open to channel fluid pressure this model is neither necessary, nor invoked.

Per the basic equations shown in Figure 2 the following parameters are necessary in order to solve the heat conduction problem for the new timestep temperature distribution (T).

k : Thermal conductivities of the pellet and clad material

ρc_P : Volumetric specific heat of the pellet and clad material

$h|_{Gap}$: Gap conductance

$h|_{Surf}$: Clad surface heat transfer coefficient

$\dot{q}$: Heat transfer rate

$\dot{Q}'''$: Fuel pellet volumetric heat generation rate

$A, \Delta r$: Geometry information for the fuel rod

This information is obtained with the use of various constitutive relationships which will be described in following sections.

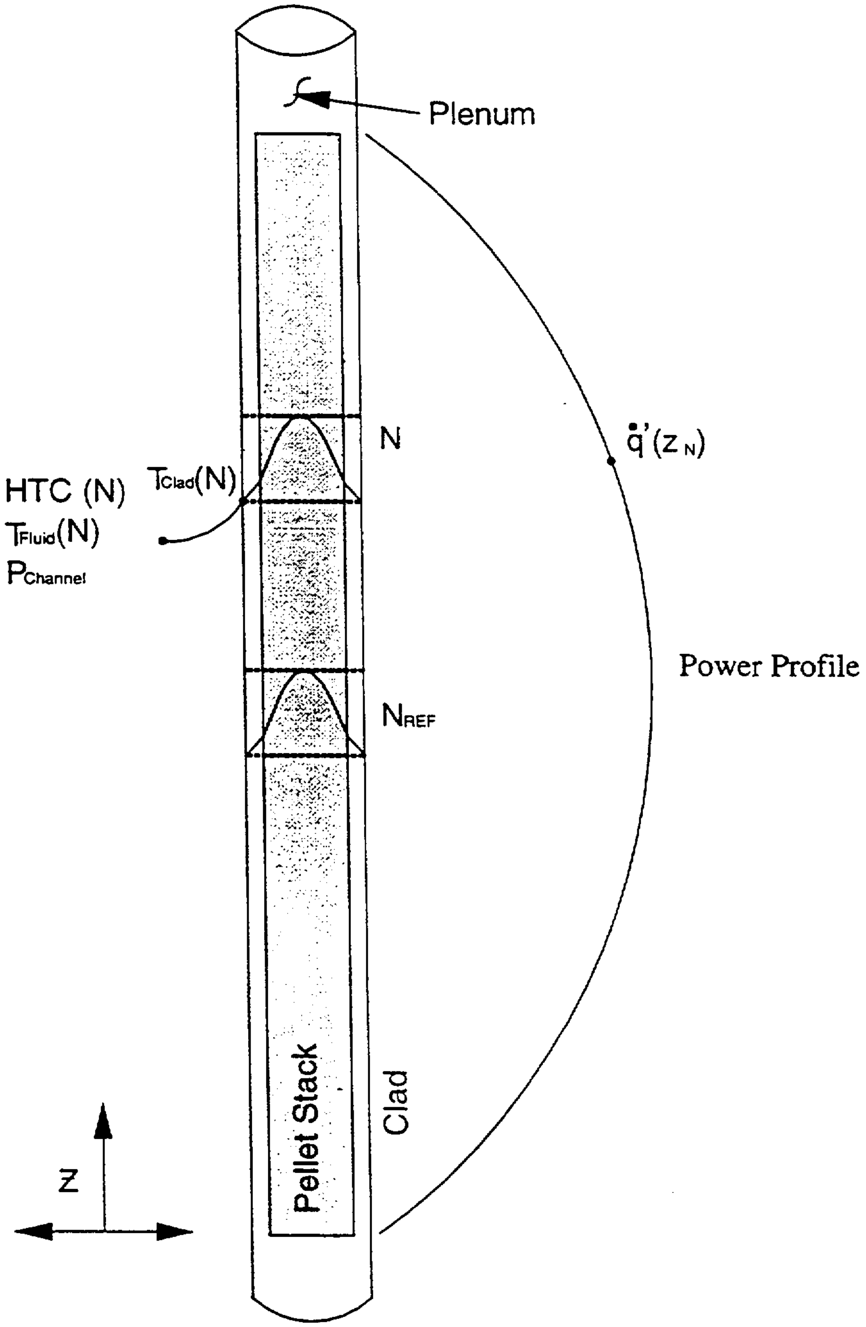
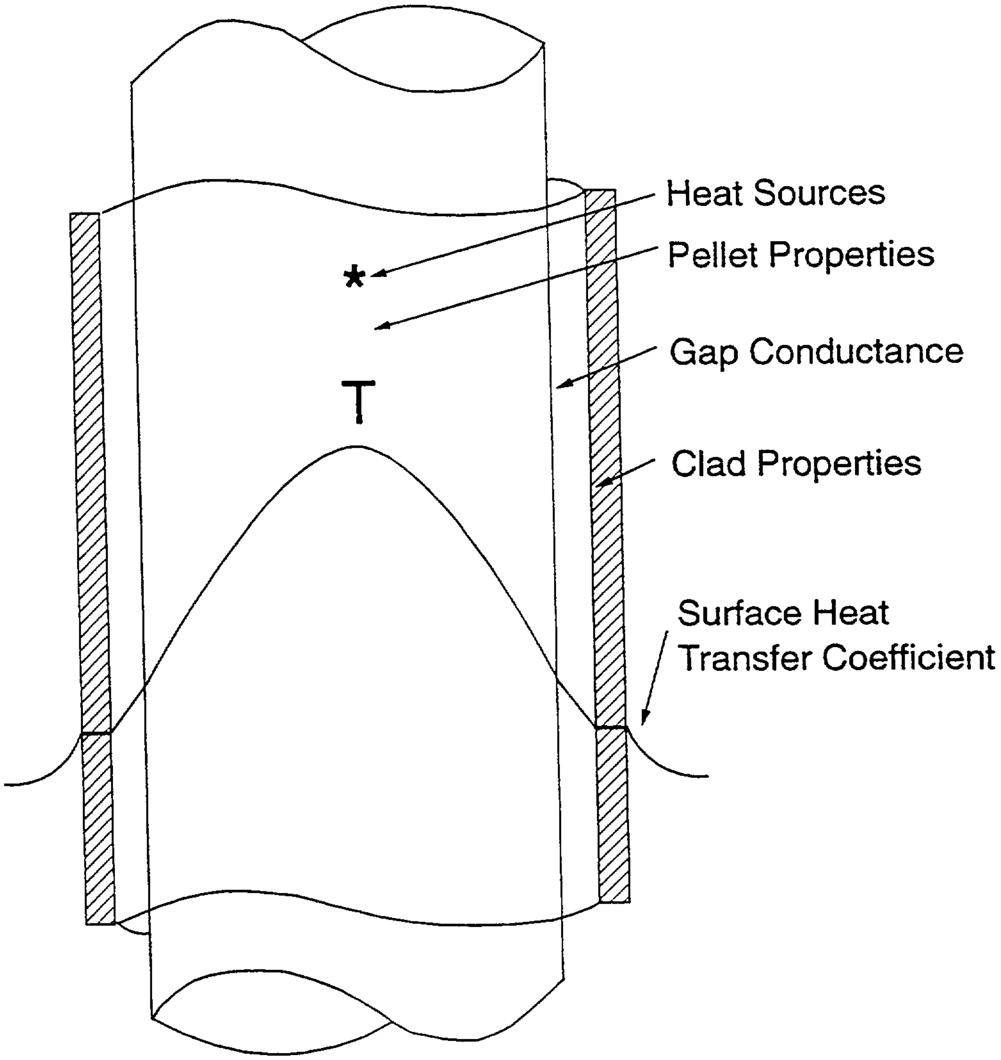


Figure 1-1 Depiction of Fuel Rod Model



Steady-State: $\dot{q} = h\,A\,\Delta T$

$$\dot{q} = \frac{\Delta T}{\left.\frac{\Delta r}{kA_{ln}}\right|_{Fuel} + \left.\frac{1}{hA_{ln}}\right|_{Gap} + \left.\frac{\Delta r}{kA_{ln}}\right|_{Clad} + \left.\frac{1}{hA_{ln}}\right|_{Surf}}$$

Transient: $\frac{\dot{q}}{A} + \dot{Q}''' = \rho\, c_p \frac{\Delta T}{\Delta t}$

Figure 1-2 Depiction of Heat Conduction Solution

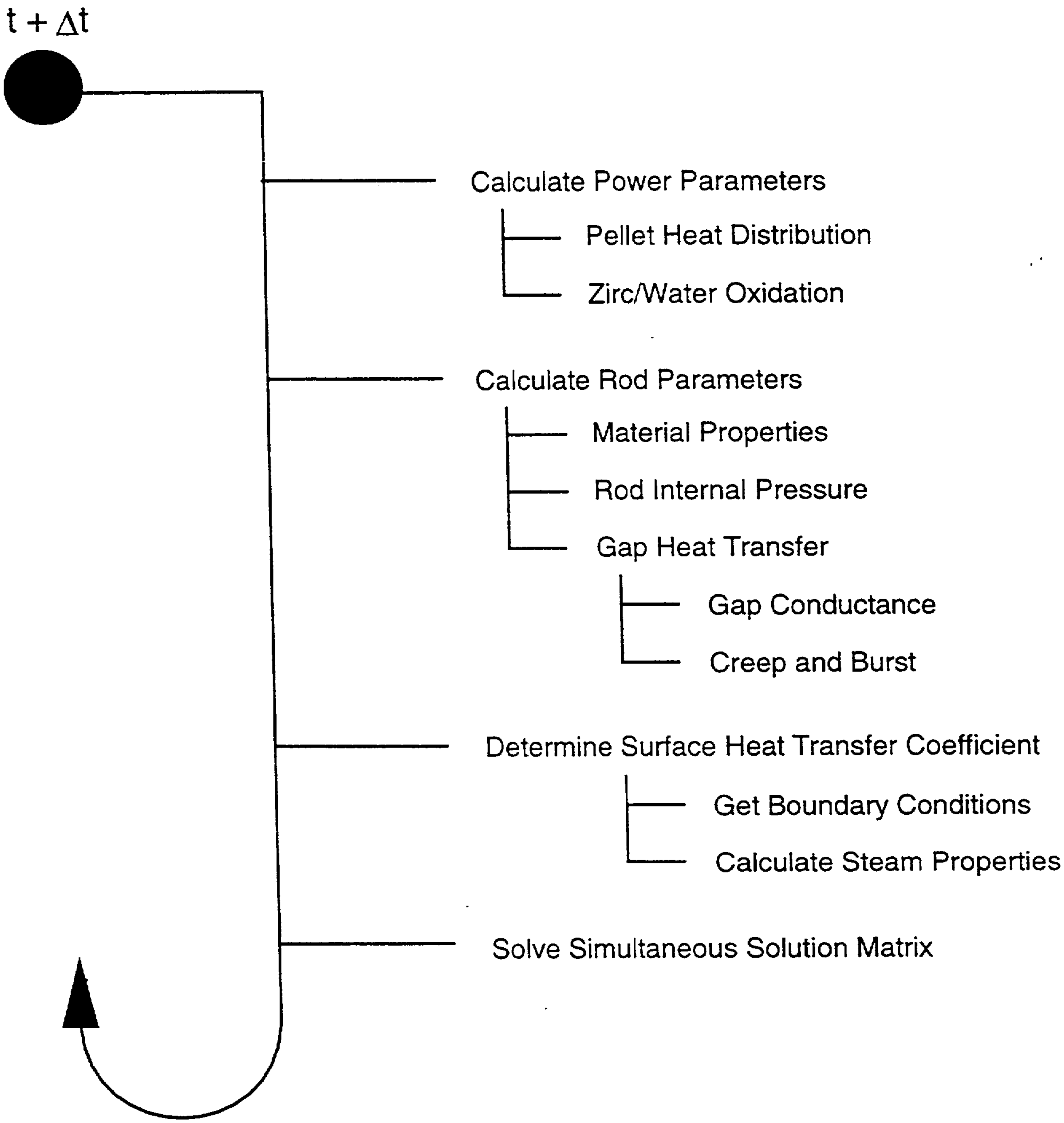


Figure 1-3 LOCTA Timestep Logic Flow

2 GOVERNING EQUATIONS FOR 1-D HEAT CONDUCTION

The general equations describing transient 1-D heat conduction through a solid with cylindrical geometry are presented in the original LOCTA documentation [1] and further developed for an annular pellet geometry in reference 2. The identical solution scheme is used in the LOCTA_JR code and will be briefly presented for completeness and to address minor differences between LOCTA_JR and the other LOCTA codes.

The general heat conduction equation is:

$$\rho c_P \, \partial T/\partial t = 1/r \, \partial/\partial r \, (kr \, \partial T/\partial r) + \dot{q}''' + \partial/\partial z \, (k\partial T/\partial z)$$

Where:

c_P : Heat capacity
k : Thermal conductivity
$\dot{q}'''$: Volumetric heat generation rate
r : Radial distance
t : Time
T : Temperature
z : Axial distance
ρ : Density

Within the pellet stack there is a negligible amount of axial conduction, due to a combination of relatively low thermal conductivity of the UO_2, low temperature gradients, and the fact that there is a high thermal resistance at the dished interfaces of each individual fuel pellet.
[

]^{a,c}

Figure 2-1A depicts a segment of the 1-D radial nodalization specified for a solid pellet, while 4B depicts an annular pellet. The LOCTA codes all use a constant-mesh radius nodalization scheme. [

]^{a,c}

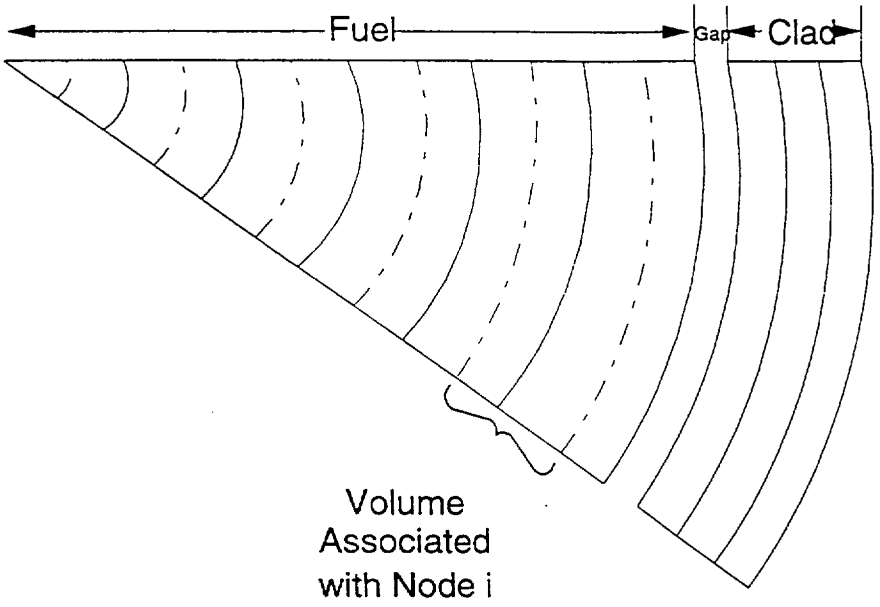


Figure 2-1A Radial Nodalization for Solid Pellet

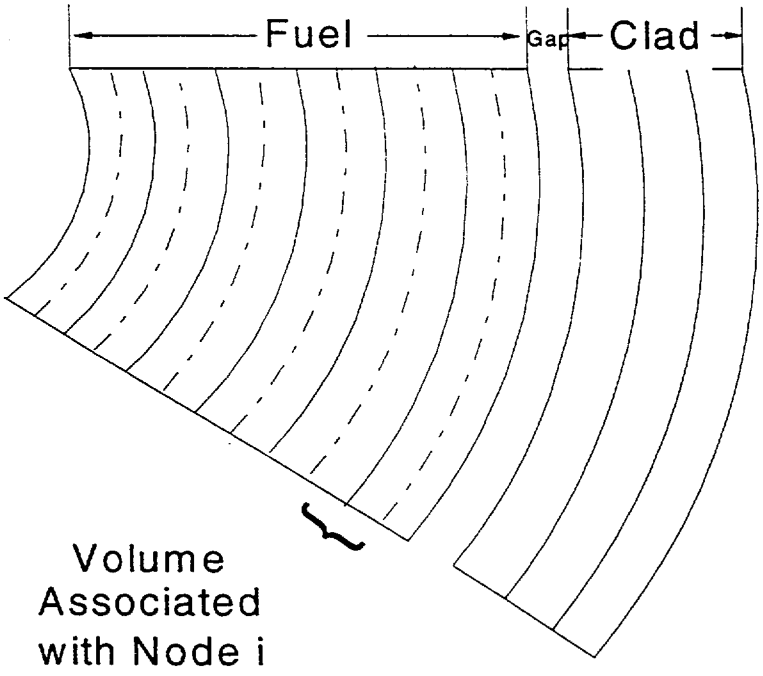


Figure 2-1B Fuel Rod Radial Nodalization for Annular Pellet

The finite element form of equation 1, without axial conduction may be written as:

$$\rho c_P V \Delta T/\Delta t = kA \Delta T/\Delta r + q''' V$$

where V is the node volume.

Figure 2-2 depicts the geometry for a general interior node. From this geometry a heat balance on the node using equation 2 is:

$$\text{Heat Storage} = \text{Heat In}\,|_{r1-\Delta r} - \text{Heat Out}\,|_{r1+\Delta r} + \text{Heat Generation}$$

or:

$$\rho c_P V (T_i - T_i')/\Delta t = kA_{i-1} \Delta T_{i-1}/\Delta r - kA_i \Delta T_i/\Delta r + \dot{q}''' V$$

Where:

T_i' : Old timestep temperature

T_i : New timestep temperature

This simplifies to:

$$\rho c_P (T_i - T_i')/\Delta t = (kA_{i-1}/V)(\Delta T_{i-1}/\Delta r) - (kA_i/V)(\Delta T_i/\Delta r) + \dot{q}'''$$

Using the geometry of Figure 2-2 gives:

$$\rho c_P (T_i - T_i')/\Delta t = \frac{k[2\pi(r_i - \Delta r/2)]L}{\pi[(r_i + \Delta r/2)^2 - (r_i - \Delta r/2)^2]L}(T_{i-1} - T_i)/\Delta r$$

$$- \frac{k[2\pi(r_1 + \Delta r/2)]L}{\pi[(r_i + \Delta r/2)^2 - (r_i - \Delta r/2)^2]L}(T_{i+1} - T_i)/\Delta r + \dot{q}'''$$

Expanding, and regrouping terms gives:

$$\left\{\frac{k\Delta t}{\rho c_P}\frac{(r_i - \Delta r/2)}{r_i \Delta r^2}\right\}T_{i-1} - \left\{\frac{k\Delta t}{\rho c_P}\frac{(r_i - \Delta r/2) - (r_1 + \Delta r/2)}{r_i \Delta r^2} - 1\right\}T_i + \left\{\frac{k\Delta t}{\rho c_P}\frac{(r_i + \Delta r/2)}{r_i \Delta r^2}\right\}T_{i+1}$$

$$= - T_i' - \dot{q}''' \frac{\Delta t}{\rho c_P}$$

which has been recast into the form:

$$AT_{i-1} + BT_i + CT_{i+1} = F$$

Where:

$$A = \frac{k\Delta t}{\rho c_p} \frac{(r_i - \Delta r/2)}{r_i \Delta r^2}$$

$$C = \frac{k\Delta t}{\rho c_p} \frac{(r_1 + \Delta r/2)}{r_i \Delta r^2}$$

$$B = -A - C - 1$$

$$F = -T_i' - \dot{q}''' \frac{\Delta t}{\rho c_p}$$

References 1 and 2 contain detailed descriptions of how the above differential equation is cast into finite difference form to be programmed for use in the computer codes. In addition to deriving the equations for heat conduction in a general interior pellet node, the same general equation is used for interior clad nodes. Special solutions are then developed for the nodes at boundaries, which are the pellet center (solid pellets), pellet-to-center void (annular pellets), pellet-to-gap interface, gap-to-clad interface and the clad-to-channel interface. The final equations are all of the same form with different equations for the coefficients A, B, C and F. All of these various solutions are the same in the LOCTA_JR code as in all of the other LOCTA codes.

The stability of the model as a function of timestep size must be considered. However, since the LOCTA_JR code does not perform any fluid calculations, per se, the allowable timestep size for the solid heat conduction problem is generally much larger than would be the case for a code in which concerns for Courant limitations, etc. have to be considered. Also, since computational speed is not of any concern given the small size of the problem the simple technique of using a single, constant timestep size will be used. Verification calculations presented in section 5 provide the basis for the recommended timestep size for a LOCA transient calculation.

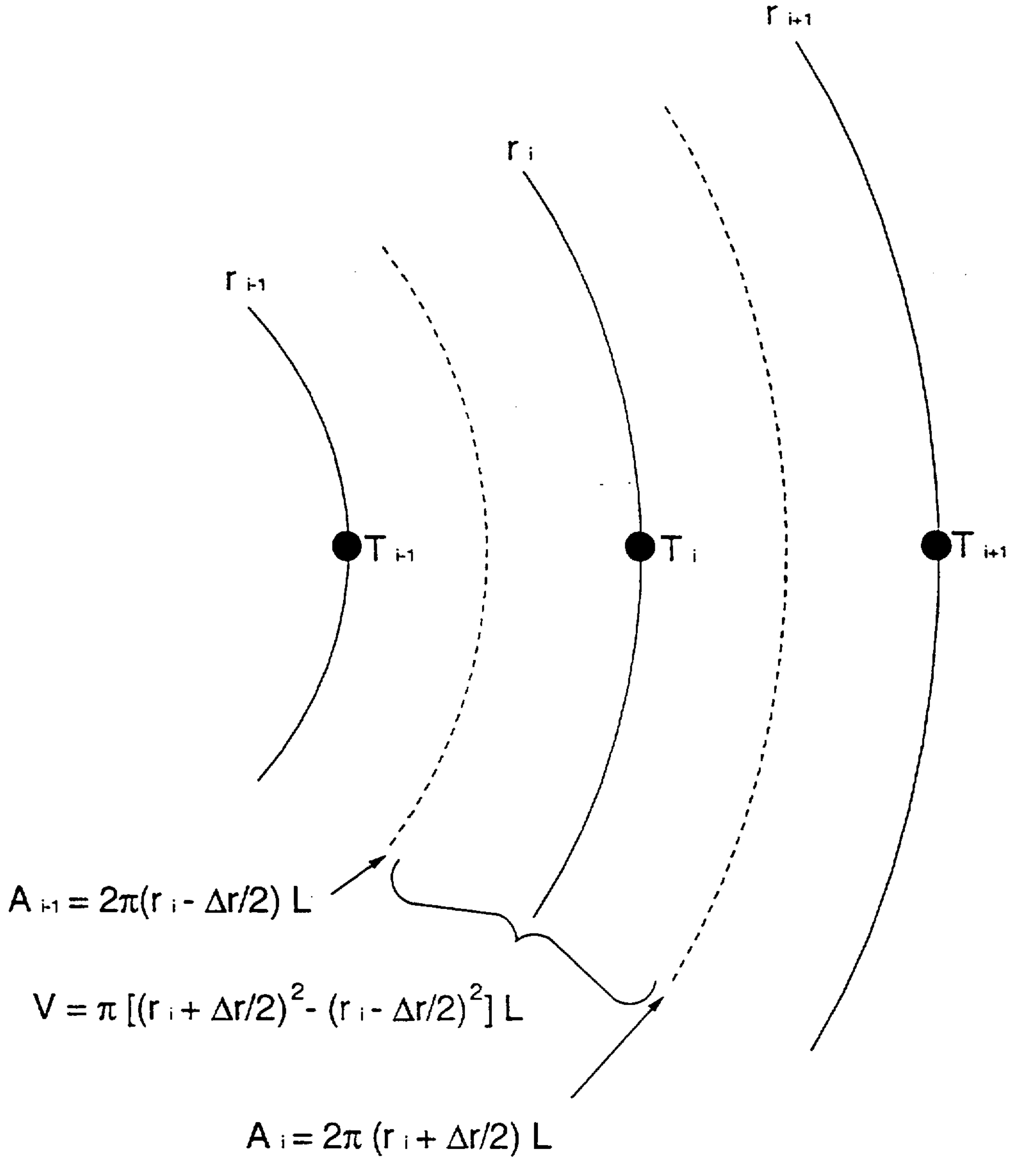


Figure 2-2 Nodalization of A General Interior Node

3 CONSTITUTIVE MODELS AND COMPUTATIONAL SCHEME

3.1 HEAT SOURCES

3.1.1 Power Generation

In order to solve the heat conduction problem it is necessary to define the rod-specific, time-dependent, spatially-dependent, volumetric heat generation rate for each individual axial node and radial ring in the pellet stack. The general form of the complete equation is:

$$\dot{Q}'''(i,j,t) = \dot{Q}'_{AVG} * F(rod) * F(z) * Q(t)/Q_0 * \gamma(t)/\gamma_0 * RADF(j,t) * \Delta\rho * [D_{COLD}/D_{HOT}]^2 * C_V$$

Where:

i : Axial node

j : Radial node

t : Time

$\dot{Q}'''(i,j,t)$: Volumetric heat generation rate for axial node i, radial node j and time t

$\dot{Q}'_{AVG}$: Core-wide steady-state linear heat rate (kW/ft)

$F(rod)$: Ratio of rod average power to core average power

$F(z)$: Normalized axial peaking factor

$Q(t)/Q$: Normalized power fraction

$\gamma(t)/\gamma_0$: Gamma energy deposition factor

$RADF(j,t)$: Pellet radial flux depression factor

$\Delta\rho$: Mass defect adjustment from steady-state initialization

$[D_{COLD}/D_{HOT}$]: Transient thermal expansion factor

C_V : Conversion from linear to volumetric heat rate based on cold dimensions

3.1.1.1 Axial Power Distribution

The first portion of the equation, $Q'_{AVG}/V(i,j) * F(rod) * F(z)$, defines the rod-specific steady-state power and axial power distribution at initial conditions. The necessary information to define this is specified via user input for the rod peaking factors. To solve the 1-D heat conduction problem it is only necessary to specify the power factors corresponding to the axial node, or nodes specified in the problem. However, in order to calculate the rod internal pressure behavior, to be discussed further in Section 3.4, it is necessary to provide information on the complete axial power distribution. The code allows the user to input a steady state axial power distribution array, or for convenience a function is available that will generate standard power shapes as used in licensing basis LOCA analyses. These shapes are then scaled to the appropriate rod-specific powers with user input peaking factor information.

3.1.1.2 Fission Power and Decay Heat

The transient power curve, $Q(t)/Q_0$, for a given problem is supplied via a user input table or file in normalized form. This curve represents the aggregate of all individual factors that comprise the total fuel rod heat generation rate, including fission heat, fission product decay and actinide decay. As such, the LOCTA_JR code itself contains no models for these heat sources and they are obtained directly from the approved licensing models used in the main LOCA licensing basis codes, or are defined by the user as dictated by the specific problem to be analyzed.

3.1.1.3 Heat Deposition

Given the total heat generation for the fuel rod node, additional factors must be applied to define the amount and specific location of heat deposition. Two such factors are applied in the LOCTA codes, including LOCTA_JR; a radial flux factor, RADF(j,t) and a gamma heat deposition factor, $\gamma(t)/\gamma_0$. The radial flux factor specifies the heat deposition as a function of radial position in the pellet. It is a function of the capture rate of neutrons and is influenced by the fuel pellet initial enrichment and burnup. The gamma heat deposition factor defines how much total heat is generated in the fuel by the capture of gamma radiation and is mainly a function of whether the core is operating at power, or decay heat is the main heat source. There are no detailed models in the LOCTA codes themselves for calculating these, rather appropriate values for the fuel and core design of interest are obtained from the nuclear design codes, although generic tables of bounding values are provided within the code library. Over the typical range of possible values for both these parameters, neither has a significant influence on the peak clad temperature results. The rate at which these distribution adjustments are factored into the power calculation is a function of the ratio of decay heat to fission heat, and a parameter identified as the "gamma switch time" must be supplied by the user. This time is typically available from the base case analysis from which the remaining boundary conditions are obtained.

3.1.1.3 Volumetric Generation

The two terms in the heat generation equation, $\Delta\rho$ and $[D_{COLD}/D_{HOT}]^2$, are adjustments to the volumetric heat rates. The $\Delta\rho$ term is a small correction to the power generation rate associated with the rod steady-state initialization logic as will be described in Section 3.3.2. The $[D_{COLD}/D_{HOT}]^2$ term merely accounts for thermal expansion and contraction of the pellet over the course of a transient.

3.1.2 Clad Oxidation

Clad oxidation is calculated using the Baker-Just model as prescribed by 10CFR50.46, Appendix K. The correlation is of the form:

$$dr/dt = A/r * e^{-B/T}$$

Where:

r	: Thickness of ZrO_2 layer
t	: Time
T	: Temperature
A,B	: Coefficients as specified by Baker and Just

The application of the model is straightforward and adheres to all of the requirements of Appendix K, including no limitation on reactants. It is performed each timestep for the outside of the clad, and if clad burst is predicted to have occurred, the same model is applied to the inside surface of the clad burst node for the remainder of the transient.

3.2 PELLET AND CLAD MATERIAL PROPERTIES

3.2.1 UO_2 Pellets

Review of the basic equations in Figure 1-2 shows that the following thermal properties are necessary for solving the 1-D heat conduction solution:

k	: Thermal conductivity
ρ	: Density
c_P	: Specific heat

Additionally, a correlation for the thermal expansion characteristics of UO_2 pellets is necessary. Correlations for these properties are all modeled as functions of temperature. The correlations for all of these properties are obtained directly from the nuclear fuel rod design codes used by Westinghouse to perform fuel rod and core design, and as such they have a robust pedigree for validation. Although there is little change over time in these correlations, they are updated as necessary to reflect the current fuel products consistent with the analyses being performed.

[

]^{a,c} Appropriate values for this parameter are obtained from the fuel rod design information specific to the fuel of interest.

3.2.2 Cladding

The same information as for the pellets is necessary for the solution of the cladding portion of the problem. In addition, models for burst and strain are needed. The burst and strain models will be addressed in Section 3.4.2. As for the pellets, the correlations used in the LOCTA codes are obtained directly from the Westinghouse nuclear fuel rod design codes and updated as necessary for consistency. Property libraries are available for both zircaloy-4 and ZIRLO™ cladding material as appropriate to the specific problem. The energy associated with the α phase to β phase transitions for zircaloy are incorporated directly into the specific heat correlations over the temperature ranges associated with the phase transition for the particular clad material.

3.3 GAP CONDUCTANCE

3.3.1 Conductance Model

The pellet-to-clad gap conductance model used in LOCTA_JR is the same as used in the other LOCTA codes and is documented in reference 1. Minor updates to gas properties have been made since reference 1 was published to maintain consistency with the fuel design codes. The

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For instances in which pellet/clad contact occurs the gap conductance is calculated as a function of the contact pressure. This model is also the same as used in the other LOCTA codes and is documented in reference 1; again it is obtained directly from the fuel rod design codes. The correlation for gap conductance with contact is:

$$H_{Gap} = 0.6 * P(contact) + K_{Mixture}/14.4x10^{-6}$$

Where:

H_{Gap} : Gap conductance (BTU/hr-ft^2-F)
P(contact) : Contact pressure (psi)
$K_{Mixture}$: Thermal conductivity of gas mixture (BTU/hr-ft –F)

A maximum limit of 3000 BTU/hr-ft^2 –F is imposed on the H_{Gap} for contact, as per the fuel rod design models.

3.3.2 Steady-State Initialization

The fuel rod models used in the LOCTA codes are the same as, or are directly derived from, those used in the fuel rod design codes. Therefore, given fuel rod parameters of power, dimensions, temperatures, pressures and gas constituents from the design codes, an identical steady-state solution should result. However, small differences arise from differences in nodalization, interpolation, and channel fluid parameters. Additionally, for licensing basis LOCA analyses the steady-state pellet temperatures obtained from the design codes are skewed to include factors which are the aggregate result of statistical uncertainties in numerous variables, including manufacturing tolerances, and are therefore incongruous with the specified dimensional parameters.

[

]^{a,c}

From a first principles basis, the temperature excursion occurring during a LOCA transient is a function of the heat produced and the mass of fuel available to absorb it. To compensate for the "mass defect" which arises from the change to the specified pellet diameter, an adjustment is made to the power calculations as described in Section 3.1.1. [

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3.4 ROD INTERNAL PRESSURE MODEL

The rod internal pressure is derived from the ideal gas law, PV=nRT, and is therefore a function of the free volume and the temperatures throughout the fuel rod. At steady-state conditions the rod internal pressure (RIP) is known, as are the free volumes. The number of moles of gas is treated as a dependent parameter and adjusted such that the pressure in the model exactly matches a user-specified pressure obtained from the fuel rod design codes as a function of the total rod power. The transient pressure is therefore defined by the relationship:

$$P(t) = P_0\,[V_0/V(t)]\,[T(t)/T_0]$$

Where:

P : pressure

V : Volume

T : Temperature

Since, in LOCTA_JR, conditions are only calculated at most for two discrete axial elevations for this problem, it is necessary to develop a means of approximating the conditions for the remainder of the fuel rod in order to provide a reasonable prediction of transient gas pressure. This model is termed the pseudo-full length rod model as described below.

3.4.1 Pseudo-Full Length Rod RIP Model

The void volumes containing gas within the fuel rod consist of:

- the plenum,
- pellet crack and dish volumes,
- the pellet-to-clad gap,
- surface chips on the pellets,
- pellet porosity,
- pellet surface roughness, and
- annular blankets, if installed.

Of these, the chip, roughness and porosity volumes contain less than 10% of the total gas and their volumes do not change appreciably over the course of a transient. They are therefore considered to be of constant volume. The plenum is the largest single volume for rod gas, and in the RIP model used in the large break LOCA versions of the LOCTA codes it is modeled as a constant volume at a constant temperature during the transient. This model is used in the LOCTA_JR code since it reproduces the large break LOCA models exactly, and is generally adequate for small break LOCA transients, at the discretion of the user. Per reference 1, the temperature of the gas in the plenum is:

$$T_{Plenum} = [\qquad\qquad]^{a,c}$$

Where:

T_{Plenum} : Plenum gas temperature (°F)

[ ]^{a,c}

Similarly, the annular blanket volumes do not change appreciably during a LOCA transient due to the low thermal expansion of UO_2, and so they are also modeled as a constant volume for the transient. For fuel that has axial blankets, the annular blanket gas is combined with the plenum gas volume for modeling.

For the remaining volumes, the pellet-to-clad gap and the pellet crack and dish volumes, a relationship was developed which allows extrapolation of the conditions from a selected node where the detailed thermal expansion and temperature calculations are performed to the remainder of the fuel rod elevations. The relationship for the volume change is:

$$V(t) \quad [\qquad\qquad]^{a,c}$$

Where:

V(t) : Total rod volume for volume type of interest

[ ]^{a,c}

[ ]^{a,c}

The remaining variable necessary for calculating the transient pressure behavior is the temperature corresponding to each of the volumes. The transient temperature information used is actually [

]^{a,c}

This pseudo-full length rod modeling approach provides reasonable replication of a true full length rod model because of three main considerations. First, a significant portion of the gas is contained in the plenum region which is static over the course of a LOCA transient (prior to burst). Second, there are only relatively small changes in the void volumes over the course of a transient, which reduces the sensitivity of the resultant pressure to the volume adjustment model described above. And, third, the temperatures in the ideal gas law equation are relative to absolute zero, so that although some detail is lost relative to axial temperature gradients, e.g., quenched elevations, the change in relative temperature from the steady-state condition for a single reference node is adequately representative of the entire rod during a LOCA transient. This is especially true for typical limiting LOCA transient cases in which rod burst is predicted to occur relatively early in a transient, since after clad burst there is no need for RIP calculations for a significant portion of the transient.

3.4.2 Creep, Burst and Blockage Modeling

As discussed previously, the LOCTA_JR code does not perform any channel fluid calculations, per se. As such, the clad surface heat transfer coefficient (HTC) must be supplied by the user. Any factors which may affect the heat transfer coefficient which relate to flow blockage caused by rod burst must therefore be implicitly included in the HTC boundary condition, and no blockage models are needed in the code.

Clad creep, burst and post-burst strain are modeled in the LOCTA_JR code because they do have direct effects on transient results. Clad creep affects the pellet-to-clad gap width, which affects both the gap conductance in the 1-D heat conduction solution and also the RIP calculations via gap volume changes. The prediction of rod burst has similar influences, and for the burst node elevation, post-burst clad strain is important to predict since it dramatically affects the pellet-to-clad gap. The rod creep and burst models are taken directly from the licensing basis large break LOCA versions of the LOCTA code. The basis for the zircaloy-4 model is documented in references 1 and 5, and that for the ZIRLO™ model is in reference 6, Appendix C. Figure 3-1 shows a flow chart of the logic for these calculations. As seen from the flowchart, all aspects of pellet and clad thermal and mechanical expansion, contraction and interaction are considered. Clad burst criteria are included for both zircaloy-4 and ZIRLO™ clad material using previously approved licensing models. Burst temperature versus differential pressure curves are shown in Figure 3-2. For zircaloy-4 clad these curves are from the prescribed model documented in NUREG-0630 [4] and reference 7, while for ZIRLO™ the curves are from reference 6, Appendix D. Similarly, the post-burst strain curves are obtained from previously licensed models, references 4, for zircaloy-4 and reference 6, Appendix D for ZIRLO™. Curves for post-burst strain are shown in Figure 3-3. Per reference 8 there is an additional limit on the maximum allowable post-burst strain which accounts for the constraining effect of the adjacent rods in a bundle. The maximum post-burst strain is calculated as:

$$\varepsilon_{max} = [\qquad\qquad\qquad]^{a,c}$$

and limits the strain obtained from the curve in Figure 3-3. An approximate limit from this model for typical fuel assembly design parameters is shown in Figure 3-3.

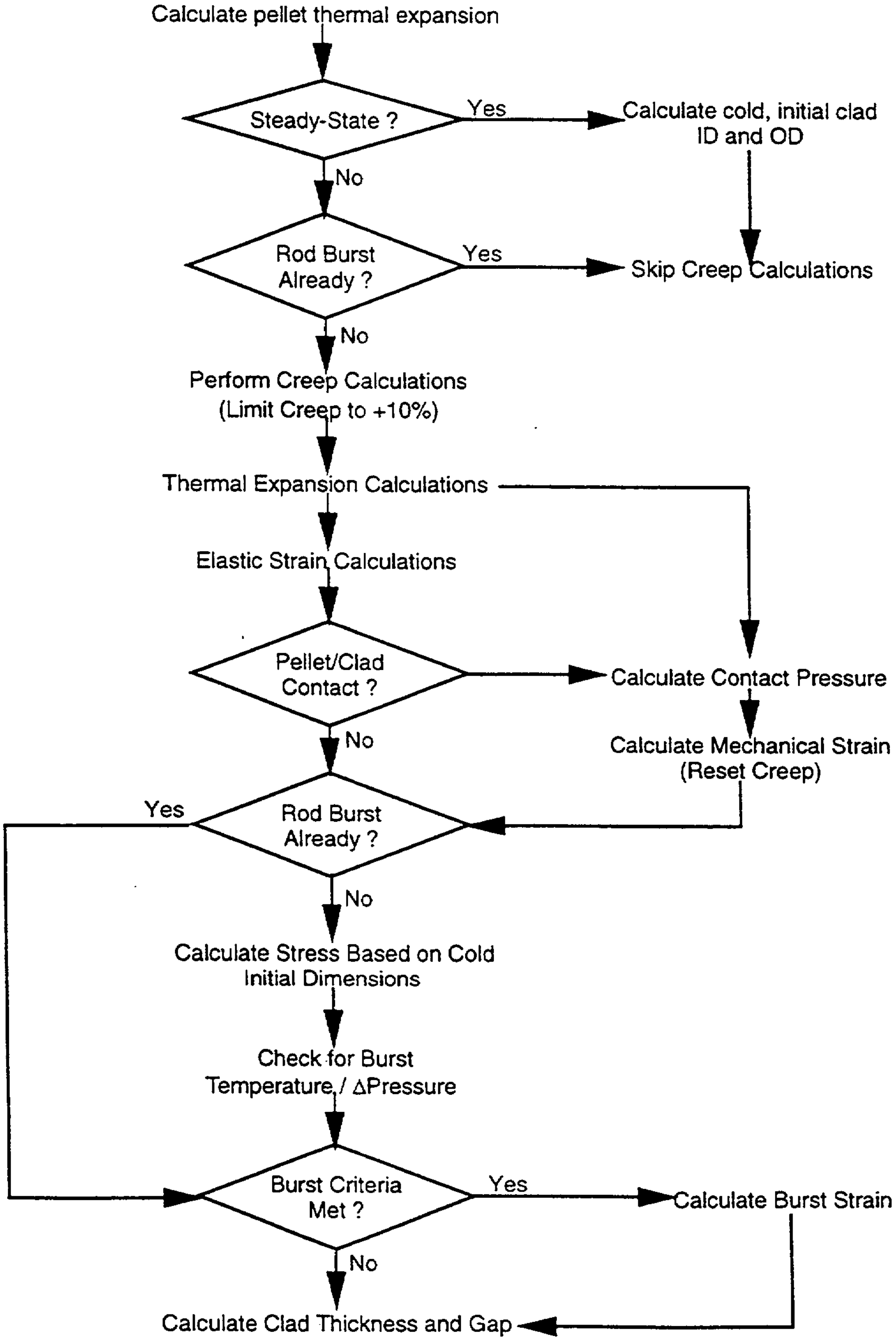

Figure 3-1 Logic for Clad Creep and Burst

a,c

Figure 3-2 Clad Burst Criteria

a,c

Figure 3-3 Clad Post-Burst Strain Correlations

3.5 CHANNEL BOUNDARY CONDITIONS

3.5.1 Fluid Properties

No channel fluid calculations are performed by the LOCTA_JR code. The local fluid properties of pressure and temperature must be supplied as user input for the problem. The only fluid property calculated by the code is the thermal conductivity of any water or steam in the pellet-to-clad gap following clad burst. These are obtained from standard ASME steam table functions [10]. The thermal conductivity is bounded by the temperature limit of the steam tables which is 1600 °F.

3.5.2 Surface Heat Transfer Coefficient

The local clad surface heat transfer coefficient (HTC) for the appropriate axial node(s) must be supplied as user input to the problem. The user must insure that the channel fluid temperature boundary condition that is also supplied properly corresponds to that used in the calculations of the HTC. The code also has the capability to perform rod-to-rod radiation heat transfer, as discussed in section 3.6, and therefore contributions from any such non-convective heat transfer terms must be clearly delineated and accounted for in the input. Also, as discussed in the creep and burst modeling, since there are no fluid channel calculations the input HTC must implicitly include any effects related to post-burst flow blockage.

3.6 ROD-TO-ROD RADIATION HEAT TRANSFER MODEL

The rod-to-rod radiation heat transfer model is the same as used in the other LOCTA codes and documented in reference 1, with an exception to the boundary conditions as discussed below.
[

]^{a,c} Complete details for derivation of the heat transfer equation are provided in reference 1. The final equation is:

$$Q_{rad,1} = \left[\frac{\varepsilon_1 \varepsilon_2 \sigma}{\varepsilon_2 + \varepsilon_1 (1 - \varepsilon_2)\, d / D}\right] \left(T_1^4 - T_2^4\right)$$

Where:

1, 2 : Subscripts for the center rod and annulus, respectively

$Q_{rad,1}$: Radiation heat flux from center rod (BTU/hr-ft^2-°F)

T : Surface temperatures (R)

d : Diameter of center rod (ft)

D : Diameter of annulus (ft)

ε : Emissivity

σ : $= 1.1714 \times 10^{-9}$ BTU/hr-ft^2-R^4

The annulus equivalent diameter, D, is calculated from the set of equations:

$$\left[\qquad \right]^{a,c}$$

Where:

$$\left[\qquad \right]^{a,c}$$

Since no consideration is given to differentiating burst from non-burst rods, the statistical analysis contained in reference 1 for the various permutations of burst and non-burst rods is not relevant to the model in LOCTA_JR.

The user must supply a transient boundary condition for the temperature of the rods surrounding the thimble tube and an appropriate nominal adjacent rod diameter and pitch to implement this model.

Fuel Rod Array

a,c

Annulus Model

a,c

Figure 3-4 Depiction of Radiation Heat Transfer Model

4 OPTIONS FOR MODELING OF THIMBLES AND INSERTS

Since LOCTA_JR has the fundamental capability to solve the 1-D heat conduction problem for a cylindrical geometry it is possible to adapt the code to solve this problem for similar geometries. Figure 4-1 depicts a problem which involves calculating the temperature of a rod inserted into a reactivity control cluster assembly (RCCA) thimble tube. In comparing this figure to Figure 1-2 the overall similarity in geometry can be seen. In particular, all of the fundamental governing equations for the 1-D heat conduction solution are the same. The problem involves solving for the temperature distribution within concentric solid materials separated by a gap, with temperature and heat transfer coefficient boundary conditions imposed on the outside of the thimble tube. The central solid material or "pellet" is assumed to be of one homogeneous material because no detail is available for non-homogeneous modeling. Given this limitation, the validity of the results must be ascertained by the analyst relative to the problem of interest. For situations in which there is little or no heat generation within the insert itself, radial temperature gradients are generally negligible relative to the bulk average material temperatures which are calculated, and the predicted results are representative of those from a more complete model. The following summarizes differences in the models or application of models from the descriptions presented in the previous sections for a nuclear fuel rod.

4.1 HEAT SOURCES

The user may completely control the amount of heat generation and the distribution of generation via input variables. For a passive rod with no power generation all sources of heat may be zeroed out, or any amount of heat generation may be modeled for sensitivity studies. The thimble tube itself is assumed to be made of a zircaloy material, susceptible to oxidation and exothermic heat generation, although a feature to disable this could be easily programmed as a user option, if desired.

4.2 PELLET AND CLAD MATERIAL PROPERTIES

LOCTA_JR has a user-specified option to redefine the central solid material or "pellet". If the default specification of UO_2 is not appropriate, then it is only necessary to define material properties for thermal conductivity, density, specific heat and thermal expansion in order to solve the problem. [

]^{a,c}

The thimble tube itself is assumed to be made of a zircaloy material, either zircaloy-4 or ZIRLO™, although a feature to allow user-specified options for different materials could easily be programmed as a user option.

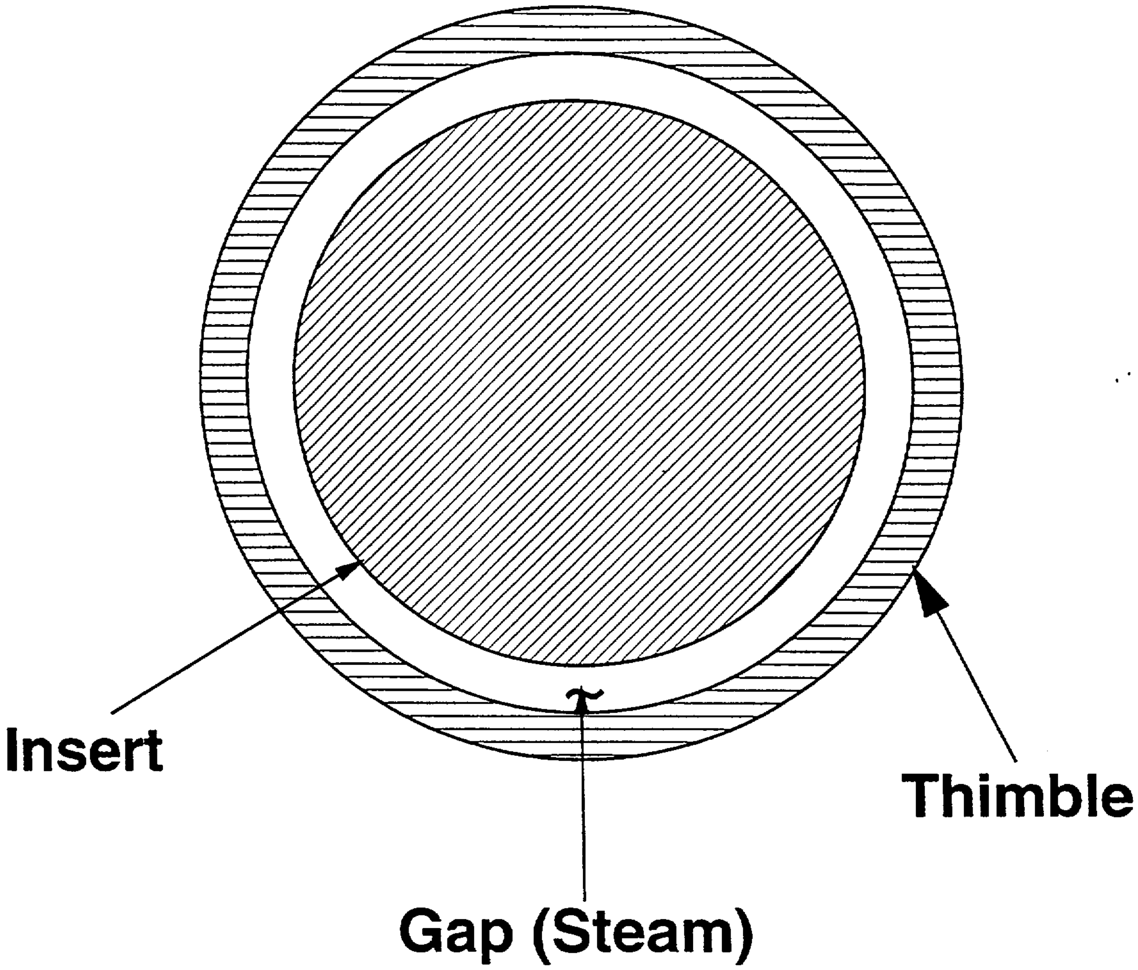

Figure 4-1 Depiction of Model for RCCA Thimble and Insert

4.3 ROD INTERNAL PRESSURE MODEL

For inserts to RCCA thimbles the gap between the thimble tube and the insert is in open communication to the surrounding channel at the bottom and/or top. [

]^{a,c}

Since there is no differential pressure across the thimble tube, there is no creep or burst potential. [

]^{a,c}

4.4 GAP CONDUCTANCE

[

]^{a,c}

4.5 CHANNEL BOUNDARY CONDITIONS

The channel boundary conditions necessary to solve this problem are the same as those for the nuclear fuel rod problem. The user must supply transient information for normalized power, channel pressure, and a HTC/fluid temperature pair for the outer surface of the thimble.

4.6 ROD-TO-ROD RADIATION HEAT TRANSFER MODEL

The rod-to-rod radiation heat transfer model described in section 3.6 is applicable to this problem and is used in the same way as described for nuclear fuel rod modeling, assuming the same fuel assembly geometry on a square pitch. The user must supply a transient boundary condition for the temperature of the rods surrounding the thimble tube and an appropriate nominal adjacent rod diameter and pitch. Material emissivities are assumed to correspond to zircaloy, although an option for different materials could be easily programmed in.

5 VERIFICATION AND VALIDATION

a,c

a,c

Figure 5-1 [ ]^{a,c}

[ ]a,c

Figure 5-2 [ ]a,c

a,c

a,c

Figure 5-3 [ ]^{a,c}

^{a,c}

Figure 5-4 [ ]^{a,c}

a,c

^{a,c}

Figure 5-5 [ ]^{a,c}

]^{a,c}

Figure 5-6 [ ]^{a,c}

a,c

Figure 5-7 [

]a,c

]a,c

Figure 5-8 [ ]a,c

a,c

a,c

Figure 5-9 [

]a,c

^{a,c}

Figure 5-10 [ ]^{a,c}

[ ]^{a,c}

Figure 5-11 [

]^{a,c}

a,c

Figure 5-12 [

]^{a,c}

a,c

a,c

Figure 5-13 [

]a,c

a,c

Figure 5-14 [ ]^{a,c}

a,c

Figure 5-15 [ ]^{a,c}

^{a,c}

Figure 5-16 [

]^{a,c}

a,c

Figure 5-17 [

]^{a,c}

a,c

Figure 5-18 [

]^{a,c}

6 CONCLUSIONS

The LOCTA_JR fuel rod heat conduction code has been constructed from a subset of the models used in the LOCTA series of codes used in the Westinghouse ECCS Evaluation Models. The code is capable of solving a 1-D heat conduction problem for individual axial nodes, given appropriate channel and power boundary conditions.

A special model was developed which allows the transient fuel rod internal pressure to be approximated from reference conditions derived from a single axial node. [

]^{a,c}

Options programmed into the code allow it to model non-nuclear fuel rod configurations, specifically the ability to model an insert contained within a control rod guide thimble.

The code has been validated against reference calculations, and all important features of the models have been exercised to confirm that they function properly.

The code provides a tool by which experienced LOCA analysts can provide estimates of various rod behaviors for transients in which the channel boundary conditions are not significantly perturbed by the presence of different or additional rods.

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