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DEVELOPMENT OF A LUMPED PARAMETRIC MODEL
FOR SCOPING INVESTIGATIONS OF UNCERTAINTIES
IN FAST REACTOR PROBABILISTIC SAFETY ANALYSIS

Progress Report

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ABSTRACT

The objective of this research is to explore the possibility of the development of a novel reactor safety analysis methodology suitable for a parametric investigation of uncertainties in the progression of severe fast reactor accidents. The essential feature of this approach is a description of the reactor state by means of volumetric distributions. The description of volume of reactor materials, such as coolant, clad, and fuel, with temperature and in the case of fuel material, also with power, is termed, a volumetric distribution. Stationary volumetric distributions are computed from detailed spatial temperature and power distributions of materials in the steady state reactor. Stationary volumetric distributions and other reactor physics quantities form the input for the reactor transient calculations in which the accident progression is described by the behavior of transient volumetric distributions.

Progress during this period was concerned with two areas; first the further development and refinement of transient volumetric distributions, and second, the formulation of the temperature worth distribution, which is needed in reactivity feedback calculations in conjunction with the transient volumetric distribution.

I. SUMMARY.

A. Purpose and Status.

The purpose of this research, briefly restated, is to develop a lumped parametric model for fast reactor accident analysis, particularly for loss of flow calculations. The accident model is developed for later use in probabilistic safety calculations and as such must meet two objectives: first, a sufficient reduction in computation time compared to detailed mechanistic models to permit a relatively broad uncertainty investigation, and second, the treatment of incoherent accident phenomena. A novel concept, volumetric distributions, describing material temperatures and power production is to be developed and implemented in the model.

The approach requires the use of both stationary volumetric distributions and transient volumetric distributions. The mathematical formulation and practical evaluation of stationary volumetric distributions has been presented in detail in the annual report. The transient volumetric distributions and the related temperature worth distributions, used for reactivity feedback calculations, have been developed during this period and are the subject of this progress report.

B. Transient Volumetric Distributions.

Description of reactor transient phenomena requires a knowledge of the transient temperature field. A detailed mechanistic treatment of within subassembly incoherencies would require a detailed three dimensional representation of the spatial temperature field. Transient calculation of three dimensional temperature fields is complex and time consuming and is therefore not a suitable approach for an economical analysis of accident uncertainties. An alternative approach is a treatment based on the representation of material temperatures by volumetric distributions.

Stationary volumetric distributions are obtained from a detailed calculation using the steady state temperature field. Transient volumetric distributions are approximately determined without the use of a detailed temperature field by means of certain adjustments to the stationary distributions. These adjustments reflect, in a lumped fashion, the changes in the spatial temperature field which occur during the transient. By consideration of only a few principal types of changes the adjustment approach yields approximate transient volumetric distributions for only a small fraction of the cost of a complete treatment.

The basis for the adjustment approach is the assumption that if material volume elements in space are ordered with

respect to temperature at time zero then the ordering will not change during the early phase of the transient. This means that the volume elements may adjust their relative temperatures but will not switch position.

This feature suggests that the transient behavior of volumetric distributions can be represented approximately by several distinct behavior modes:

- (1) Translation, resulting from a change of average value; this mode is produced by a uniform temperature change throughout the material,
- (2) Stretching, resulting from a relative change in maximum and minimum values; this mode is produced by a proportional change in temperature rise at every point in the material,
- (3) Skewing, resulting from a disproportionate temperature change in high and low temperature regions: this mode is produced by nonlinear temperature changes in the material.

Higher order behavior is neglected in this first approximation.

Data necessary for the quantitative description of these behavior modes are the material average, maximum, and minimum transient temperatures. Determination of the

various behavior modes permits the stationary volumetric distribution to be mapped into the transient distribution at any time during the transient.

The behavior modes identified above are represented mathematically by mapping functions relating the temperature variable of the initial stationary volumetric distribution to the temperature variable of the transient distribution. The transient volumetric distribution can thus be expressed as a function of the stationary distribution,

$$(1) \quad V(T,t) = K(t) V_0(T_0) ,$$

where the transient distribution is indicated by V and the stationary distribution by V_0 . The mapping function relating the initial temperature variable, T_0 , to the temperature variable, T , of the transient volumetric distribution is given by,

$$(2) \quad T = A(t) T_0^2 + B(t) T_0 + C(t) ,$$

The time dependent variables $K(t)$, $B(t)$, and $C(t)$ are determined by constraints upon the transient volumetric distribution. These constraints result from known features of the transient temperature field. Specifically, the

average, maximum, and minimum transient temperatures are to be obtained from a few-channel transient treatment. The four unknown functions are determined from the following four equations:

Conservation of volume during the transient based upon the initial volume;

$$(3) \quad \int V(T) dT = \int V_o(T_o) dT_o .$$

Conservation of energy during the transient based upon the result from the transient model;

$$(4) \quad \bar{T}(t) V_{TOTAL} = \int T V(t) dT .$$

Agreement of maximum temperature of the transient volumetric distribution and the transient reactor model;

$$(5) \quad T_{max}(t) = A(t) T_{o,max}^2 + B(t) T_{o,max} + C(t) .$$

Similarly the minimum temperatures must agree;

$$(6) \quad T_{min}(t) = A(t) T_{o,min}^2 + B(t) T_{o,min} + C(t) .$$

Substitution of equations (1) and (2) into equations (3) and (4) along with equations (5) and (6) form a set of four equations in four unknowns. This equation set is solved at discrete times during the transient at which the transient volumetric distribution is desired. Once the variables $K, A, B,$ and C are obtained, the stationary volumetric distribution is then mapped into the transient volumetric distribution by use of equation (1).

C. Reactivity Feedback.

Both Doppler and sodium void reactivity feedback depend on material temperature and spatial location in the reactor. Transient volumetric distributions form a basis for reactivity calculation since they describe the transient variation of material temperatures. However, an additional concept is required since the volumetric distributions themselves do not contain information about the spatial location of particular volume elements with temperature, T . An approach similar to the one used to describe the transient behavior of volumetric distributions can be applied to describe the reactivity feedback. As long as material volume elements have not moved, the reactivity worth of these elements can be related to the indexed temperatures.

The resulting relation of reactivity worth and temperature is called the temperature worth distribution.

This distribution is obtained in the same way as the corresponding volumetric distribution since it is formed by an integration over isothermal regions in space.

Under the assumption of a local $1/T$ variation, the Doppler reactivity can be expressed in terms of the spatial Doppler constant, $A(r)$:

$$(1) \quad \rho_D(t) = \int_{\vec{R}} \int_{T_0(\vec{r})}^{\vec{T}(\vec{r},t)} \frac{A(\vec{r})}{T} dT d\vec{r} ,$$

where T_0 indicates the initial temperature at location r and T the time dependent temperature. The usual form is obtained by integration of the temperature variable,

$$(2) \quad \rho_D(t) = \int_{\vec{R}} A(\vec{r}) \ln \frac{\vec{T}(\vec{r},t)}{T_0(\vec{r})} d\vec{r} .$$

The spatial integration over the reactor volume, R , can be converted into the temperature integral of a surface integral over the isotherm (see section III of the annual report for the derivation). This relation is restated here in operator notation:

$$(3) \quad \int_{\vec{R}} (\cdot) d\vec{r} = \int_T \left[\oint_{S(T)} \frac{(\cdot)}{|\nabla T|} d\sigma \right] dT .$$

Note that if the operand (.) is replaced by unity, the bracketed term forms the expression for the volumetric distribution. (Comp. Section III.2, page 14 of the annual report). The result of the temperature integration then equals the total reactor volume, as required. Application of equation (3) to (2) yields,

$$(4) \quad \rho_D(t) = \int_{T_0} \left[\oint_{S(T_0)} \frac{A(\vec{r}) \ln \frac{T(\vec{r},t)}{T_0(\vec{r})}}{|\vec{\nabla} T_0|} d\sigma \right] dT_0 ,$$

where the surface S is the isothermal surface at initial temperature T_0 .

Since the temperature worth distribution expresses reactivity as a function of temperature, the total reactivity is obtained by integration over temperature. The worth distribution is a function of initial temperature since the distribution was formed by integration over the initial temperature field. Thus, during the transient a relation between transient temperature and initial temperature is required which expresses T as a function of T_0 in the integrand of equation (4). This relation is provided by the mapping function produced in the transient volumetric distribution calculation. The reactivity is thus a function of the time dependent mapping coefficients; ie,

$$\rho_D = \rho_D(K(t), A(t), B(t), C(t)) .$$

The temperature integration in equation (4) can be performed with respect to either the initial temperature variable, T_0 , or the transient temperature variable, T . Since the worth distribution is properly a function of the initial temperature variable, the former convention will be used. The Doppler reactivity, corresponding to the reactivity difference between the initial steady state and the state at time t , is thus given by,

$$\rho_D(t) = \int_{T_0} w(T_0) \ln \frac{T(T_0, t)}{T_0} dT_0 \quad (5)$$

$$w(T_0) = \oint_{S(T_0)} \frac{A(\vec{r})}{|\vec{\nabla} T_0|} d\sigma \quad ,$$

where $w(T_0)$ is the temperature worth distribution.

The temperature worth distribution is evaluated only once by integration over the initial temperature field. Although this is a relatively time consuming process, the resulting temperature worth distribution can be used for many transient calculations.

D. Lumped Parametric Model.

The lumped parametric model solves the heat transfer, hydraulics, and neutronics relationships necessary to determine reactor transient behavior. This model consists of three parts which calculate:

1. Coolant flow rate, ?
2. Nuclear heat generation,
3. Material temperatures.

The transient coolant flow rate is determined by balancing coolant momentum loss rate with the decaying pumphead in the primary system. The equations result from fundamental hydraulics relations. Coupling with other transient variables is small and can be neglected to a good approximation. The time variation of the nuclear heat generation is determined by solving the point kinetics equations for power amplitude. This calculation is coupled to the material temperature calculation through Doppler and sodium void reactivity effects.

Transient material temperatures calculated include fuel, clad, and coolant average values. The equations are formed by spatially integrating the temperature field equations. Since the temperature* field equations are fundamental relations based on conservation of energy, the result is a set of equations expressing the system energy balance. Additional equations for the average coolant outlet temperature and the heat transfer rates from fuel to clad and from clad to coolant are necessary to complete the equation set and permit solution. These equations cannot be formed from fundamental relations, but must be devised in

the form of ad hoc models by using assumptions about the spatial temperature distribution.

II. Current Status.

A. Transient Volumetric Distributions.

2

The mathematical formulation and programming necessary for practical evaluation is complete for transients up to the time of coolant voiding. After coolant voiding is initiated, the treatment described must be modified since coolant volume is not constant but becomes a function of time. An extension to treat voiding is in progress. Several alternative schemes are possible; the appropriate choice can be made as the details of the corresponding reactivity treatment are developed.

A more complicated motion, such as the relocation of clad or fuel materials, violates the ordering assumption upon which the incoherency treatment is based. The methodology developed here will thus need to be extended in order to treat material relocation. The transient volumetric distributions described above can directly be applied to describe the incoherent melting progression; however, the subsequent movement if any of melted material will require a specifically devised formulation. This special formulation can be based on the same ideas; e.g. the ordering of temperatures provides an ordering of the onset point of

material motions.

The accuracy achievable with the mapping formulation of transient volumetric distributions is dependent upon the accuracy of the transient parameters used. Error in the maximum and minimum material temperatures are especially important, since they impact the stretching mode. Results based on transient parameters obtained from conventional uniform channel calculations of the transient temperature field have been satisfactory, while results based on the lumped parameter modeling have been relatively poor.

B. Reactivity Feedback.

The mathematical formulation for reactivity is in progress. A formulation for Doppler feedback has been tentatively adopted. The programming necessary for practical evaluation involves an extension of programs which have already been developed for evaluation of stationary volumetric distributions. Results will be compared with results of conventional uniform channel calculations, as with the transient volumetric distributions.

A formulation for the treatment of sodium void reactivity feedback is also in progress. The characterization of the voiding process requires as a basis a subassembly oriented description, due to the nature of the sodium boiling progression.

III. Recommendation for Change of Work Scope.

As indicated in previous sections, the development of the lumped parametric transient model can be carried out more successfully, if at least a coarse channel structure is retained in the treatment. Then, special spatial-temperature-field dependent parameters can be obtained from an explicit calculation of the variation along channels.

The two incoherency phenomena (inter- and intra-channel) can be logically combined by the use of volumetric distributions: The intra-subassembly incoherence is combined with volumetric distributions for each subassembly in a channel, which results in a intra-channel incoherence treatment.

The parametric safety evaluation code PARSEC which is being developed as a tool for probabilistic safety investigations will be applied for the channel type treatments in the approach developed in this work. Transient calculations are sufficiently inexpensive to permit the use of a larger number of channels (e.g. one channel per subassembly). The incoherency methodology developed here can be implemented in PARSEC without major alterations. It is felt that this combined approach will eventually result in a powerful tool for fast reactor safety analysis.