A User Guide to PARET/ANL

Version 7.6

Nuclear Engineering Division

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Version 7.6

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Abstract

PARET was originally created in 1969 at what is now Idaho National Laboratory (INL), to analyze reactivity insertion events in research and test reactor cores cooled by light or heavy water, with fuel composed of either plates or pins. The use of PARET is also appropriate for fuel assemblies with curved fuel plates when their radii of curvatures are large with respect to the fuel plate thickness. The PARET/ANL version of the code has been developed at Argonne National Laboratory (ANL) under the sponsorship of the U.S. Department of Energy/NNSA, and has been used by the Reactor Conversion Program to determine the expected transient behavior of a large number of reactors.

PARET/ANL models the various fueled regions of a reactor core as channels. Each of these channels consists of a single flat fuel plate/pin (including cladding and, optionally, a gap) with water coolant on each side. In slab geometry the coolant channels for a given fuel plate are of identical dimensions (mirror symmetry), but they can be of different thickness in each channel. There can be many channels, but each channel is independent and coupled only through reactivity feedback effects to the whole core.

The time-dependent differential equations that represent the system are replaced by an equivalent set of finite-difference equations in space and time, which are integrated numerically. PARET/ANL uses fundamentally the same numerical scheme as RELAP5 for the time-integration of the point-kinetics equations.

The one-dimensional thermal-hydraulic model includes temperature-dependent thermal properties of the solid materials, such as heat capacity and thermal conductivity, as well as the transient heat production and heat transfer from the fuel meat to the coolant. Temperature- and pressure-dependent thermal properties of the coolant such as enthalpy, density, thermal conductivity, and viscosity are also used in determining parameters such as friction factors and heat transfer coefficients. The code first determines the steady-state solution for the initial state. Then the solution of the transient is obtained by integration in time and space. Multiple heat transfer, DNB and flow instability correlations are available.

The code was originally developed to model reactors cooled by an open loop, which was adequate for rapid transients in pool-type cores. An external loop model appropriate for Miniature Neutron Source Reactors (MNSR's) was also added to PARET/ANL to model natural circulation within the vessel, heat transfer from the vessel to pool and heat loss by evaporation from the pool. PARET/ANL also contains models for decay heat after shutdown, control rod reactivity versus time or position, time-dependent pump flow, and loss-of-flow event with flow reversal as well as logic for trips on period, power, and flow. Feedback reactivity effects from coolant density changes and temperature changes are represented by tables. Feedback reactivity from fuel heat-up (Doppler Effect) is represented by a four-term polynomial in powers of fuel temperature. Photo-neutrons produced in beryllium or in heavy water may be included in the point-kinetics equations by using additional delayed neutron groups.

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1 INTRODUCTION

To quantitatively predict the course and consequences of a reactivity accident, the various physical processes that can occur during the accident and the interrelationships among them must be well understood. The development of information necessary for this understanding was an objective of the Spert Project, which was conducted for the U.S. Atomic Energy Commission by Phillips Petroleum Company at the National Reactor Testing Station. As a result of experimental programs carried out at Spert and elsewhere, knowledge of certain of the processes that occur during a reactivity accident is thought to be sufficient for use in predicting the course of nondestructive accidents in small cores. To provide a comprehensive method for making such predictions, the development of a computer program, called PARET [1], was undertaken. PARET is an acronym for **P**rogram for the **A**nalysis of **RE**actor **T**ransients.

The PARET/ANL code is the result of continuous improvement and modification applied to the original PARET code by the researchers at Argonne National Laboratory (ANL) over the course of four decades. It is intended primarily for the analysis of research and test reactors that use plate-type (flat) fuel elements or round fuel pins.

This version of the code has been subjected to extensive comparisons with the SPERT I and SPERT II experiments [2, 3, 4] as well as other transient codes. These comparisons were quite favorable for a wide range of transients. A description of those comparisons is provided in the user's guidelines provided in Appendix VIII. Favorable comparisons have also been made for TRIGA reactor pulses in pin geometry. The PARET/ANL code has been used by the RERTR Program for the safety evaluation of many candidate reactors for reduced enrichment

The following information is intended to provide all the pertinent details to the user who wishes to use PARET/ANL. Section 2 list the modifications applied to the code since the last version. Section 3 describes the theory of reactor transient and the model implemented in PARET/ANL. Section 4 provides guidelines on time step control and typical running time. Section 5 describes the input file format and entries item by item. Section 6 describes the files used by PARET/ANL. Section 7 describes how to run PARET/ANL

2 WHAT IS NEW IN VERSION 7.6?

2.1 FLOW REVERSAL MODEL

PARET\ANL V5 and later had a simple approximation for establishing the coolant enthalpy to be used following flow reversal. There was no primary loop simulation in PARET. The time of flow reversal is detected and saved for each channel. After flow reversal, the channel exit becomes the inlet. It was assumed that the reactor to be modeled was a pool-type system. The reactor core is immersed in a pool, with a complex flow path through the pool acting as a primary loop. It is assumed that there is no primary loop piping that confines the exit coolant. In this type of reactor, the exit coolant mixes with the pool water (possibly in a plenum), and is cooled. If the flow reverses, the coolant drawn back into the channel will initially be essentially at the same enthalpy as the coolant most recently discharged. After some time, the reversed flow will draw relatively unheated coolant from the pool. The model assumed that the enthalpy of that coolant well after flow reversal was the same as that of the coolant inlet enthalpy at the start of the calculation. It was assumed, quite arbitrarily, that the mixing would occur linearly over 5 seconds from the time of flow reversal. Some generalizations have been added to Version 7.6:

1. The time between flow reversal and the end of mixing is still 5.0 seconds unless a new Table 21 is provided. Then it can be anything.
2. The mixing process is linear if Table 21 is not provided. Variable ENTHHS is the enthalpy (or temperature) of the "heat sink" coolant that is drawn into the core well after flow reversal. If ENTHHS is not provided on Card 1116, or if ENTHHS is provided and it is the same as ENTHIN, then this option recovers the original model.
3. The mixing process is piece-wise linear in Table 21 if it is provided (up to 20 entries).
4. The enthalpy (or temperature) of the pool coolant well after flow reversal, ENTHHS, can be specified on Card 1116. If not given, it is assumed by default to be the same as ENTHIN.

2.2 CHANGES TO COOLANT PROPERTIES TABLE GENERATION

Changes have been made to the pressure range and spacing used for the internally computed properties tables at a given pressure. There is now an internal table at exactly the user's input pressure. The new logic creates more accurate tables than before at high pressure.

2.3 GROENEVELD CHF AND FILM BOILING DATA

PARET uses the Groeneveld 2006 CHF lookup tables [5].

2.4 REVISED POWER AND FLOW EDITS BY CHANNEL

A new edit is provided of "COOLANT FLOW, kg/s, BY CHANNEL." It appears after major and minor edits. Inlet and outlet values are provided. A new edit of apparent power in the

coolant is also provided which takes a snapshot of actual energy content of each coolant channel, assuming that the reactor is in steady-state. This edit can be used to examine "null-event" transients where steady-state is achieved. This edit shows how much power is delivered to the coolant by channel, and for the sum of all channels. New subroutines volpow and gain were added to compute necessary quantities.

2.5 REVISED CIAE NATURAL CONVECTION MODEL FOR MINIATURE NEUTRON SOURCE REACTORS (MNSR)

The logic in using the CIAE correlation is revised to be sure that its use is only in the laminar flow regime.

2.6 CHANGE TO POWER NORMALIZATION AND NEW COOLANT EDITS

In all prior versions of PARET, there was no check by the code that the reactor was fully specified (or even over-specified) by the channel data provided. Now, in Version 7.6 (IGEOM options 0 and 1 only), there is a check of actual power to be delivered by each channel, accounting for all of its diverse properties (different axial power profile, different core fraction (BM) that it represents, different power density, different meat thickness or width, and so on). If the core is not correctly represented, a correction is automatically made to the power density data (IGEOM options 0 and 1 only). The user will see "CHECK OF POWER NORMALIZATION" in the initialization process, showing a correction to the power density if it is needed. During the run, the user will also see an edit that has the title: "COOLANT POWER GAIN FROM INLET TO OUTLET = XXX MW IF IN STEADY STATE. This is followed by an edit of coolant flow in units of kg/s at the inlet and outlet of each channel. These mass flows are for the core fraction that the user specified. If the user wishes to know the energy conservation error of his model, he can set up a null transient for power and flow conditions of interest, and run it for a few seconds of real time. If the energy loss is of concern, then he may be able to investigate the effect of this loss by changing the power delivered to the fuel. If the transient of interest is controlled by an over-power trip, then it would be best to change both the power and the over-power trip set point.

2.7 COMPUTATION OF THE COOLANT ENERGY REMOVAL

Changes have been made to the PARET program enabling it to calculate the coolant energy removal. The total flow area, P_c , formerly read in on card number 1111, is no longer used.. This card follows the 100I cards and precedes the 200I cards in the data deck.

The coolant energy removal is calculated for each time step from the following Eq.

$$CER = \int \sum_{I=1}^{NC} (ENT_{XI} \cdot MFR_{XI} - ENT_{OI} \cdot MFR_{OI}) dt$$

where

NC is the number of channels

ENT_{XI} is the exit enthalpy (J/kg) of channel I

MFR_{XI} is the exit mass flow rate (kg/s) of channel I

ENT_{OI} is the inlet enthalpy (J/kg) of channel I

MFR_{OI} is the inlet mass flow rate (kg/s) of channel I

The resulting coolant energy removal (MWs) is printed just below the value of the energy every time a full time step printout occurs. These values depend on individual channel flow areas, core fractions represented by each channel, and P_c . Note that the mass flow rates depend in part on individual channel areas, K-losses, hydraulic diameters, core fraction represented by each channel, and total flow area.

3 DESCRIPTION OF THE PARET MODEL – THEORY AND EMPIRICAL CORRELATIONS

3.1 INTRODUCTION

The reactor model assumed in PARET consists of a water-cooled core represented by fuel elements and their associated coolant channels. The core can be divided into up to 50 regions over its radial cross section, each having its own power generation, coolant flow rate, hydraulic parameter, etc., and each represented by a single fuel pin or plate, plus its associated coolant channel. Each of these regions can be further subdivided into a maximum of 97 axial sections. The code is designed to represent the average behavior of each of the several regions into which the core is subdivided. A given fuel plate or pin is normally composed of a radial sequence of layers, such as an inert central pin (TRIGA), fuel meat, gap, clad, and oxide surface layer. Each of these layers can be subdivided radially. It is important to subdivide the meat radially if the meat is relatively thick and there is significant variation in power density or thermal conductivity. It is never necessary to subdivide a material layer that does not have a heat source, and has a fixed thermal conductivity, because the power profile and heat flux will be correct even with a single layer per material slab.

A transient problem can be forced through specification of externally inserted reactivity versus time or average core power versus time (*9000 card series*). Specification of inlet mass flow rate as a function of time can also be used to force a problem. Either the pressure drop across a given region of the core (*10000 card series*) or the coolant inlet mass flow rate to that region must be specified with time (*12000 card series*). The program embodies continuous reactivity feedback from the known major feedback mechanisms (fuel rod expansion, moderator temperature and density effects, and fuel temperature (Doppler) effects), detailed heat transfer calculations (including boiling, as well as non-boiling, convective transfer), and hydrodynamic calculations allowing for coolant flow reversal. A block diagram illustrating the model is presented in Figure 1. Further details of the basic theory underlying the neutronics, heat transfer, and hydrodynamics calculations are presented in the following sections of this chapter.

Figure 1 Block diagram of PARET model

3.2 REACTOR KINETICS

The power behavior of the reactor is either specified as a function of time or is determined through a numerical solution of the point reactor kinetics Eqs.:

$$\frac{d\phi(t)}{dt} = \frac{[\rho(t) - \beta]}{\Lambda} \phi(t) + \sum_{i=1}^I \lambda_i C_i(t) \quad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} \phi(t) - \lambda_i C_i(t), i = 1, 2, \dots, I \quad (2)$$

where

t = time

ϕ = reactor power

ρ = reactivity of the system

β = effective delayed neutron fraction

Λ = prompt neutron generation time

λ_i = decay constant for group i

C_i = concentration of delayed neutron precursors of group i

β_i = delayed neutron fraction for group i

I = number of delayed neutron groups

PARET uses the modified Runge-Kutta method of Cohen [8] for solution of these equations. The solution is computed subsequent to an estimation of the reactivity feedback from time zero up to the time node under consideration. In the reactivity-specified problem, the value of the externally inserted reactivity is specified as a function of time. The feedback reactivity is calculated as the sum of that fed back through the mechanisms of fuel rod expansion, moderator density effects, and fuel temperature effects. This feedback is calculated point-wise throughout each of the regions of the reactor. The point-wise contributions are then weighted volumetrically and summed to yield the total reactivity feedback. A detailed description of the reactivity feedback calculations is presented in section 3.2.2.

3.2.1 REACTOR KINETICS DIFFERENCE EQS.

Except in the case of a power level specified problem, the reactor kinetics equations must be solved at each time node to determine the reactor power level. Using the substitutions

$$r(t) = \frac{\rho(t)}{\beta} \quad (3)$$

and

$$W_i(t) = C_i(t) \left(\frac{\Lambda \lambda_i}{\beta f_i} \right) \quad (4)$$

the point kinetics Eqs. (1) and (2) become

$$\frac{d\phi(t)}{dt} = \frac{\beta}{\Lambda} \left([r(t) - 1]\phi(t) + \sum_{i=1}^I f_i W_i(t) \right) \quad (5)$$

$$\frac{dW_i(t)}{dt} = \lambda_i \phi(t) - \lambda_i W_i(t), i = 1, \dots, I \quad (6)$$

The various terms appearing in these Eqs. are defined in conjunction with Eqs. (1) and (2). The energy release, $E(t)$, is determined from the Eq.

$$\frac{dE(t)}{dt} = \phi(t) \quad (7)$$

Eqs. (5), (6) and (7) are transformed for computation purposes through the following substitutions [9]:

$$a_1 = \frac{\beta}{\Lambda} (r(0) - 1) \quad (8)$$

$$a_2 = 0 \quad (9)$$

$$a_j = -\lambda_i, j = i + 2, i = 1, \dots, I \quad (10)$$

$$R_1(\phi, t) = \frac{\beta}{\Lambda} \left([r(t) - r(0)]\phi(t) + \sum_{i=1}^I f_i W_i(t) \right) \quad (11)$$

$$R_2(E, t) = \phi(t) \quad (12)$$

$$R_j(W_i, t) = \lambda_i \phi(t), j = i + 2, i = 1, \dots, I \quad (13)$$

With these substitutions, the reactor kinetics Eqs. take the form

$$\frac{d\phi(t)}{dt} = a_1\phi(t) + R_1(\phi, t) \quad (14)$$

$$\frac{dW_i(t)}{dt} = a_j W_i(t) + R_j(W_i, t), j = i + 2, i = 1, \dots, I \quad (15)$$

The energy Eq. becomes

$$\frac{dE(t)}{dt} = a_2 E(t) + R_2(E, t) \quad (16)$$

By use of the integrating factor, $\exp(-a_j t)$, the solutions to Eqs. (14), (15) and (16) can all be written in the form

$$\xi_j(t) = \xi_j(0) + t \int_0^1 [a_j \xi_j(0) + R_j(\xi_j, u)] \exp(a_j t(1 - u)) du, j = 1, \dots, I + 2 \quad (17)$$

where

$$\xi_1(t) = \phi(t) \text{ and } \xi_1(0) = \phi(0) \quad (18)$$

$$\xi_2(t) = E(t) \text{ and } \xi_2(0) = E(0) \quad (19)$$

$$\xi_j(t) = W_i(t) \text{ and } \xi_j(0) = W_i(0), j = i + 2, i = 1, \dots, I \quad (20)$$

The system of Eqs. in (17) is solved in stages, according to a modified Runge-Kutta method [8], to yield the functions $\phi(t)$, $E(t)$ and $W_i(t)$.

The error analysis included in the reactor kinetics calculations is based on the analysis carried out in the AIREK code [10]. In this scheme, the following quantities are evaluated

$$\omega_1 = \frac{1}{\phi(0)} \frac{d\phi(0)}{dt}, \text{ instantaneous reciprocal period} \quad (21)$$

$$\omega_2 = \frac{1}{\phi(h)} \frac{d\phi(h)}{dt}, \text{ instantaneous reciprocal period} \quad (22)$$

where the quantity h represents the time step across which the calculations are being made. Further definitions include

$$\bar{\omega} = \frac{1}{h} \ln \left[\frac{\phi(h)}{\phi(0)} \right], \text{ average reciprocal period} \quad (23)$$

$$\delta = \max_j \left(\left| \frac{\xi_j\left(\frac{h}{2}\right) - \xi_j(0)}{\xi_j\left(\frac{h}{2}\right)} \right| \right) \quad (24)$$

$$Q = \frac{h C_2(a_1 h)}{1 + C_1(a_1 h)} (|\omega_1 - 2 \bar{\omega} + \omega_2|) \quad (25)$$

where

$$C_1(a_1 h) = \int_0^1 \exp(a_1 h(1 - u)) du \quad (26)$$

$$C_2(a_1 h) = \int_0^1 u \exp(a_1 h(1 - u)) du \quad (27)$$

The error analysis is based on the following considerations:

1. If $\delta \geq$ and
 - a. If $Q > Q_H$, the time step is halved and the calculations repeated until the error is satisfied.
 - b. If $Q \leq Q_H$, the calculations are accepted and the same time-step size is used for the next advancement
2. If $\delta < 2^{-20}$, the calculations are accepted and the same time step size is used for the next advancement
3. The time-step size is also halved and the calculations repeated if
 - a. $a_j h \geq 150.0$ for any j
 - b. A negative or zero power is computed
 - c. A floating point overflow occurs during the calculation of any a_j or $R_j(W_i, t)$, or during advancement of the solutions.

The quantity, Q_H , is specified as input to the code by the program user. The quantity, Q , calculated in Eq. (25) can be printed out at the user's option.

3.2.2 REACTIVITY FEEDBACK

Reactivity feedback is calculated as the sum of that fed back through the mechanisms of fuel rod expansion, moderator temperature and density changes, and fuel temperature changes (including Doppler broadening of resonance cross-sections).

3.2.2.1 REACTIVITY FEEDBACK DUE TO FUEL ROD EXPANSION

The total reactivity feedback from time zero to time t^m due to fuel rod expansion is given, in dollars, by

$$r_{\text{Rod}}^m = \frac{2}{V_{\text{Mod}} \beta_{\text{eff}}} \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} C_{j,k} (V_{\text{Rod}}^0)_{j,k} (y_c)_{j,k}^m - r_{\text{Rod}}^0 \quad (28)$$

where

$$r_{\text{Rod}}^0 = \frac{2}{V_{\text{Mod}} \beta_{\text{eff}}} \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} C_{j,k} (V_{\text{Rod}}^0)_{j,k} (y_c)_{j,k}^0 \quad (29)$$

The term, V_{Mod} , is calculated in PARET according to the Eq.

$$V_{\text{Mod}} = \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} (V_{\text{Mod}}^0)_{j,k} \quad (30)$$

where $(V_{\text{Mod}}^0)_{j,k}$ represents the volume of the moderator in axial increment $\Delta Z_{j,k}$. As mentioned in Chapter IV, 2.61 (5), it is convenient to set X_{k2} equal to the volume fraction of

the core which is represented by channel (region) k . The quantity, $C_{j,k}$, represents the moderator density feedback coefficient appropriate to axial increment $\Delta Z_{j,k}$, in units of δk per percent of the core voided [11]. This coefficient is arbitrarily broken down into the product

$$C_{j,k} = C_k \delta_{j,k} \quad (31)$$

where C_k is constant over a given region, k , of the core, and $\delta_{j,k}$ accounts for the axial dependence of $C_{j,k}$. The quantity $(y_c)_{j,k}^m$, represents the percent linear thermal expansion of the clad and is evaluated at $(\bar{u}_c)_{j,k}$, the volume-weighted, mean clad temperature in axial increment $\Delta Z_{j,k}$.

3.2.2.2 REACTIVITY FEEDBACK DUE TO MODERATOR DENSITY CHANGES

The total reactivity feedback from time zero to time t^m due to moderator density changes is given, in dollars, by

$$r_{MD}^m = \frac{100}{V_{Mod} \beta_{eff} \bar{\rho}_{ref}} \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} C_{j,k} (V_{Mod})_{j,k} (\bar{\rho}_{ref} - \bar{\rho}_{j,k}^m) - r_{MD}^0 \quad (32)$$

where

$$r_{MD}^0 = \frac{100}{V_{Mod} \beta_{eff} \bar{\rho}_{ref}} \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} C_{j,k} (V_{Mod})_{j,k} (\bar{\rho}_{ref} - \bar{\rho}_{j,k}^0) \quad (33)$$

In Eqs. (32) and (33), $\bar{\rho}$ represents a volume-weighted density defined by

$$\bar{\rho} = \rho_v R + \rho_l (1 - R) \quad (34)$$

where R represents vapor volume fraction and ρ_v and ρ_l represent the densities of the vapor and liquid phases, respectively. The quantity, $\bar{\rho}_{ref}$, is the value of $\bar{\rho}$ at some reference condition of temperature and pressure.

3.2.2.3 REACTIVITY FEEDBACK DUE TO FUEL TEMPERATURE CHANGES

The total reactivity feedback from time zero to time t^m due to fuel temperature changes (primarily Doppler broadening) is given, in dollars, by

$$r_{Dop}^m = \frac{1}{V_{MT}} \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} (V_M)_{j,k} D_{j,k} [\gamma_0 + \gamma_1 T_{j,k}^m + \gamma_2 T_{j,k}^{m^2} + \gamma_3 T_{j,k}^{m^3}] - r_{Dop}^0 \quad (35)$$

where

$$r_{Dop}^0 = \frac{1}{V_{MT}} \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} (V_M)_{j,k} D_{j,k} [\gamma_0 + \gamma_1 T_{j,k}^0 + \gamma_2 T_{j,k}^{0^2} + \gamma_3 T_{j,k}^{0^3}] \quad (36)$$

Since the feedback represented in Eqs. (35) and (36) is due primarily to Doppler broadening in most cases of interest, it is referred to throughout the remainder of this document as Doppler feedback. The quantity, $(V_M)_{j,k}$, represents the volume of fuel in axial increment $\Delta Z_{j,k}$ and V_{MT} is given by

$$V_{MT} = \sum_{k=1}^K X_{k2} \sum_{j=1}^{NZ} (V_M)_{j,k} \quad (37)$$

The quantities, $D_{j,k}$ (see chapter IV, 2.63 (5)), are weighting factors for axial increment $\Delta Z_{j,k}$, and the $T_{j,k}^m$ are given by

$$T_{j,k}^m = (\bar{u}_M)_{j,k}^m + \gamma_4 \quad (38)$$

where $(\bar{u}_M)_{j,k}^m$ represents the volumetric mean fuel temperature (in degrees Rankine) in axial increment $\Delta Z_{j,k}$, at time t^m . The quantities γ_0 through γ_4 , are constants which fit the temperature dependence of the Doppler feedback to the Eq. form given. The superscript, n, is an arbitrary power to which one of the $T_{j,k}^m$ is raised and is supplied as input to the code by the user. This allows one to use, for example, a square root temperature dependent Doppler feedback model. Calculation of the various coefficients appearing in Eq. (35) is illustrated in [12].

3.2.2.4 TOTAL COMPENSATED REACTIVITY

The total compensated reactivity, r_c^m , at time t^m , is given by

$$r_c^m = r_{Rod}^m + r_{MD}^m + r_{Dop}^m \quad (39)$$

Therefore the reactivity term, $r(t^m)$, used in solving the reactor kinetics Eqs., is

$$r(t^m) = r_{in}(t^m) - r_c^m \quad (40)$$

where $r_{in}(t^m)$ represents externally inserted reactivity (e.g. control rod induced), the value of which is obtained by linear interpolation from a table of such quantities (Table 9)¹. Compensated reactivity can be calculated directly only at the end of a time step. Therefore, in order to provide reactivity values at advanced times, as is required by the point kinetics equations, an estimate of reactivity is obtained by extrapolation from previous values. The extrapolation procedure is based on a three-point Lagrangian formula. At the end of each time step, the compensated reactivity is calculated and compared with the extrapolated value used in the immediately preceding kinetics calculations. If they do not agree within a specified limit, the calculations for that time step are repeated using the average of these two reactivity values. This process is repeated until two successive reactivity values agree to within the limit specified (0.01 \$). The new total reactivity is then used at the next time node in obtaining an extrapolated reactivity value across the subsequent time step.

3.3 HEAT TRANSFER

Heat transfer in each fuel element is determined on the basis of a one-dimensional conduction solution in each axial section. Additionally, the domain can be further subdivided in radial section for the purpose of this calculation. The moderator in each axial section is not subdivided radially but is assumed to be adequately represented by an average bulk temperature and average fluid properties. A maximum of 10 material types (e.g. fuel, gas gap, clad, an inert central pin section, an oxide layer, etc.) are allowed in each fuel element. Radial subdivision of each axial section of each fuel element is illustrated in Figure 2.

¹ Tables 9, 10, 11, 12 and 14 are data tables supplied as input to the PARET computer code.

Figure 2 Example of radial subdivision for heat transfer calculations

The partial differential Eq. for diffusion of heat within each fuel element is

$$\frac{\partial}{\partial t} [g(u, r)u(r, t)] = \nabla \cdot k(u, r)\nabla u(r, t) + S(r, t) \quad (41)$$

where the symbol $u(r, t)$ represents temperature as a function of radial position, r , and time, t . Volumetric heat capacity and thermal conductivity are denoted by the symbols $g(u, r)$ and $k(u, r)$, respectively, and are treated as functions of both position and temperature. The heat source per unit volume, $S(r, t)$, is assumed to be a separable function of space and time. The magnitude of this local heat source is determined from the calculated or specified average core power level and pre-assigned axial and radial weighting factors. Provision is made for prompt energy generation within the moderator, as well as within each of the various fuel element materials. The particular scheme by which E (41) is solved within PARET is discussed in Section 3.3.1.

PARET employs empirical convective heat transfer correlations in estimating the rate of heat transfer at the clad-moderator interface. These correlations provide the boundary condition at this interface for use in solution of the heat conduction Eq. (Eq. (41)) within the fuel elements. Which boundary condition is appropriate depends, of course, upon which heat transfer regime prevails at the particular node point under consideration. The various boundary conditions included in the code are presented in Section 3.3.2. and described in detail in Appendix II.

The scheme for assessing which of the several heat transfer regimes prevails at a given axial node point at any given time is based on the following primary considerations:

- (1) For clad surface temperatures less than the fluid saturation temperature, it is assumed that the non-boiling regime exists.

- (2) When the clad surface temperature, as calculated on the basis of a non-boiling boundary condition, exceeds the fluid saturation temperature, surface heat fluxes are calculated on the basis of both the non-boiling and nucleate boiling boundary conditions. If the nucleate boiling heat flux is greater than the forced convection heat flux, nucleate boiling is assumed to prevail. Otherwise, forced convection is assumed to prevail.
- (3) If the nucleate boiling heat flux exceeds the DNB heat flux, the possibility of being in either transition boiling or stable film boiling is considered. A clad surface temperature at departure from transition boiling $(u_s)_{DTB}$, is then calculated by equating the film boiling and transition boiling surface heat fluxes and solving for the surface temperature. If the surface temperature calculated on the basis of the film boiling boundary condition is greater than $(u_s)_{DTB}$, film boiling is assumed to prevail. Otherwise, it is assumed that transition boiling exists.
- (4) Saturated boiling can occur only for fluid enthalpies greater than the saturated liquid enthalpy, H_f .
- (5) The vapor regime exists only for fluid enthalpies equal to or greater than the saturated vapor enthalpy, H_g .

At the present time, PARET contains two options with respect to DNB calculations. In the first of these options, the point at which DNB occurs at any axial node is estimated on the basis of a steady-state DNB correlation. In this case, a DNB heat flux is calculated for each axial node at each time node. Since steady-state correlations are not generally valid under transient conditions, a second option provides for specification of a single DNB heat flux which is assumed to apply under transient conditions to each axial node over the duration of the transient. An estimate of a representative transient DNB heat flux can be obtained from Eq. (86). This correlation is based on Bernath's [13] steady-state correlation and Schrock's [14] transient heat transfer data.

3.3.1 THERMAL DIFFUSION EQUATION

Eq. (41) for thermal diffusion within the fuel elements is solved for each axial level of each region into which the core is subdivided. For instance, if the core is divided into four regions with 19 axial increments (20 nodes) per region, then Eq. (41) is solved 80 times at each time node. The particular scheme through which the solution is effected is patterned after that employed in the HEAT-1 heat conduction code [15]. For this purpose, each axial increment is subdivided radially, as exemplified in part (a) of Figure 3, where r_n represents the radial spatial variable.

To obtain the spatial difference approximation for the n^{th} interior mesh point, Eq. (41) is integrated over a volume indicated by the dashed lines in part (b) of Figure 3.

$$\iiint \frac{\partial}{\partial t} [g(u, r)u(r, t)] dv = \iiint \nabla \cdot k(u, r) \nabla u(r, t) dv + \iiint S(r, t) dv \quad (42)$$

Using a forward difference for the time derivative, Eq. (42) can be approximated by the following difference Eq. for the n^{th} interior mesh point at time node $(m+1)$:

$$a_n u_{n-1}^{m+1} + b_n u_n^{m+1} + c_n u_{n+1}^{m+1} = d_n \quad (43)$$

where

$$a_n = \frac{-k_{pn} h_{pn}^s \Delta t}{2} \quad (44)$$

$$b_n = \sigma D_n - a_n - c_n \quad (45)$$

$$c_n = \frac{-k_{sn} h_{sn}^s \Delta t}{2} \quad (46)$$

$$d_n = -\sigma a_n u_{n-1}^m + \sigma(D_n + a_n + c_n) u_n^m - \sigma c_n u_{n+1}^m + \Delta t P_f \frac{\phi^{m+1} + \sigma \phi^m}{2} + (Q_{pn} h_{pn}^v + Q_{sn} h_{sn}^v) \quad (47)$$

$$D_n = g_{pn} h_{pn}^v + g_{sn} h_{sn}^v \quad (48)$$

In the above definitions, the quantity, σ , is set to unity for transient situations and to zero for steady state. Its function is simply to generalize Eq. (43), making it applicable to both situations. The quantities, g and k , represent volumetric heat capacity and thermal conductivity, respectively. The subscript, pn and sn, refer to average conditions existing between mesh points n and n-1, and between n+1 and n, respectively, as illustrated in part (b) of Figure 3. Additional definitions include

$$\left. \begin{aligned} Q_{pn} &= Q_R(r_n) \\ Q_{sn} &= Q_R(r_{n+1}) \end{aligned} \right\} \quad (49)$$

where Q accounts for the radial dependence of the heat source (see Eq. (51)) and

$$\left. \begin{aligned} h_{pn} &= r_n - r_{n-1} \\ h_{sn} &= r_{n+1} - r_n \\ h_{pn}^s &= \frac{1}{h_{pn}} \left[2\pi \left(r_n - \frac{h_{pn}}{2} \right)^\rho \right] \\ h_{pn}^v &= \frac{h_{pn}}{2} \left[2\pi \left(r_n - \frac{h_{pn}}{4} \right)^\rho \right] \end{aligned} \right\} \quad (50)$$

with h_{sn}^s and h_{sn}^v defined analogously. The quantity r_n represents the radial spatial variable, as illustrated in Figure 3. For cylindrical geometry, the parameter, ρ , is set equal to unity and for slab geometry it is set to zero.

The heat source per unit volume, $S(r, t)$, is assumed to be a separable function of space and time and is given, for any axial level, by

$$S(r, t) = P_f \phi(t) Q(r) \quad (51)$$

Power levels at times t^m and t^{m+1} are represented by ϕ^m and ϕ^{m+1} respectively.

(a) RADIAL MESH POINT PATTERN

(b) TWO TYPICAL RADIAL INTERVALS

Figure 3 Radial mesh point pattern for thermal model

Allowable boundary conditions are of the generalized form

$$A(u) \cdot u + B(u) \frac{\partial u}{\partial r} = D(u)C(t) \quad (52)$$

This Eq. is used to represent an adiabatic node at the center of the fuel and each of various convective boundary conditions at the clad-moderator interface. The boundary conditions for the clad-moderator interface are presented in Eqs. (65) through (79). Using a forward difference for the time derivative and substituting Eq. (52) into Eq. (42), the following difference Eq. can be derived for the inner boundary (at $r_n = r_0$)

$$b_0 u_0^{m+1} + c_0 u_1^{m+1} = d_0 \quad (53)$$

where

$$c_0 = -B_0 \frac{k_{s0} h_{s0}^s \Delta t}{2} \quad (54)$$

$$b_0 = B_0 \sigma g_{s0} h_{s0}^v - \frac{k_{s0} A_0 (2\pi r_0)^\rho}{2} - c_0 \quad (55)$$

$$\begin{aligned} d_n = & -\sigma c_0 u_1^m + \sigma (2B_0 g_{s0} h_{s0}^v - b_0) u_0^m - D_0 k_{s0} (2\pi r_0)^\rho \Delta t \frac{C_0^{m+1} + \sigma C_0^m}{2} \\ & + \Delta t P_f B_0 \frac{\phi^{m+1} + \sigma \phi^m}{2} Q_{s0} h_{s0}^v \end{aligned} \quad (56)$$

and A_0 , B_0 , C_0 and D_0 refer to values of $A(u)$, $B(u)$, $C(u)$ and $D(u)$ in Eq. (52) evaluated at the inner boundary ($r_n = r_0$). Similarly, for the boundary at the clad surface ($r_n = r_N$), the following difference Eq. can be derived:

$$a_N u_{N-1}^{m+1} + b_N u_N^{m+1} = d_N \quad (57)$$

where

$$a_N = -B_N \frac{k_{pN} h_{pN}^s \Delta t}{2} \quad (58)$$

$$b_N = B_N \sigma g_{pN} h_{pN}^v - \frac{k_{pN} A_N (2\pi r_N)^\rho}{2} - a_N \quad (59)$$

$$\begin{aligned} d_n = & -\sigma a_N u_{N-1}^m + \sigma (2B_N g_{pN} h_{pN}^v - b_N) u_N^m - D_N k_{pN} (2\pi r_N)^\rho \Delta t \frac{C_N^{m+1} + \sigma C_N^m}{2} \\ & + \Delta t P_f B_N \frac{\phi^{m+1} + \sigma \phi^m}{2} Q_{pN} h_{pN}^v \end{aligned} \quad (60)$$

and A_N , B_N , C_N and D_N refer to values of $A(u)$, $B(u)$, $C(u)$ and $D(u)$ in Eq. (52) evaluated at the outer boundary ($r_n = r_N$). Application of Eq. (43) to N-1 interior mesh points and Eqs. (53) and (57) to the two boundary mesh points leads to a tri-diagonal set of N+1 simultaneous equations. This set of equations is solved by Gaussian elimination for the temperature distribution across a fuel element under both steady-state and transient situations.

Both thermal conductivity and volumetric heat capacity are considered to be temperature dependent and are represented by polynomials. Thermal conductivity is represented by

$$k_{n+\frac{1}{2}} = \alpha_1 T^2 + \alpha_2 T + \alpha_3 + \frac{\alpha_4}{T} \quad (61)$$

where

$$T = \frac{u_n^m + u_{n+1}^m}{2} + \alpha_5 \quad (62)$$

The quantity u represents temperature and the alpha coefficients are constants. Volumetric heat capacity is given similarly by

$$g_{n+\frac{1}{2}} = \beta_1 T^2 + \beta_2 T + \beta_3 + \frac{\beta_4}{T} \quad (63)$$

where

$$T = \frac{u_n^m + u_{n+1}^m}{2} + \beta_5 \quad (64)$$

The variable β_5 is an offset which is used to change from degrees F to R, or from C to K.

3.3.2 BOUNDARY CONDITIONS

The clad-coolant boundary conditions employed in each of the various heat transfer regimes are presented below.

1. Forced convection (FC) boundary condition [16]

$$q''_{FC} = h(u_s - u_b) ; q''_{FC} > q''_{NB} \quad (65)$$

Where, for example,

$$h = 0.023 \frac{k}{De} Re^{0.8} Pr^{0.4} ; Re > 6000 \quad (66)$$

Other correlations are available for h .

2. Nucleate boiling (NC) boundary condition [17]

$$(q''_{NB})^{m+1} = (q''_{NB})^m \left[1 + \frac{4(u_s^{m+1} - u_s^m)}{u_s^m - u_{sat}} \right] \quad (67)$$

$$u_s > u_{sat}$$

$$q''_{DNB} > q''_{NB} > q''_{FC}$$

where the superscript m , refers to the m^{th} time node. This boundary condition is based on the Jens-Lottes correlation [18]

$$u'_s = u_{sat} + 60 \exp\left(-\frac{p}{900}\right) \left(\frac{q''}{10^6}\right)^{\frac{1}{4}} \quad (68)$$

3. Transition boiling (TB) boundary condition [19]

$$q''_{TB} = q''_{DNB} - K_{TB}(u_s - (u_s)_{DNB})$$

$$q''_{TB} < q''_{DNB} \quad (69)$$

$$u_s < (u_s)_{DTB}$$

where K_{TB} is a constant.

4. Film boiling (FB) boundary condition [20]

$$q''_{\text{FB}} = h(u_s - u_{\text{sat}}) ; u_s > (u_s)_{\text{DTB}} \quad (70)$$

where

$$h = 0.023 \frac{k_g}{\text{De}} \text{Re}^{0.8} \text{Pr}_g^{0.4} ; \text{Re} > 2000 \quad (71)$$

5. Superheat (SH) boundary condition [20]

$$q''_{\text{SH}} = h(u_s - u_b) ; H > H_g \quad (72)$$

where the heat transfer coefficient, h , is given by Eq. (71)

6. Departure from nucleate boiling (DNB) correlations

a. Steady-state subcooled correlation [21]

$$q''_{\text{DNB}} = (0.23 \times 10^6 + 0.094G) [3.0 + 0.01(u_{\text{sat}} - u_b)] \left[0.435 + 1.23 \exp\left(-0.0093 \frac{L}{\text{De}}\right) \right] [1.7 - 1.4e^{-a}] \quad (73)$$

where

$$a = 0.532 \left[\frac{H_f - H_l}{H_{fg}} \right]^{\frac{3}{4}} \left(\frac{\rho_f}{\rho_g} \right)^{\frac{1}{3}} \quad (74)$$

b. Steady-state saturated correlation [21]

$$\Delta H_{\text{DNB}} = 0.529(H_f - H_l) + (0.825 + 2.36 \exp(-204\text{De}))H_{fg} \exp\left(\frac{-1.5G}{10^6}\right) - 0.41H_{fg} \exp\left(-0.0048 \frac{L}{\text{De}}\right) - 1.12H_{fg} \frac{\rho_g}{\rho_f} + 0.548H_{fg} \quad (75)$$

c. Transient correlation [22]

$$q''_{\text{DNB}} = \left(12300 + \frac{67V}{\text{De}^{0.6}} \right) \left[102.5 \ln p - 97 \frac{p}{p + 15} + 32 - u_b \right] \exp\left(\frac{4.25}{\tau}\right) \quad (76)$$

where τ represents the initial asymptotic period of the excursion in msec. Eq. (76) is not an integral part of the PARET code, but is merely suggested here as a possible correlation for estimating a transient DNB flux.

7. Natural convection (NC) heat transfer correlation

$$q''_{\text{NC}} = h(u_s - u_b) \quad (77)$$

where

$$h = \frac{k}{\text{De}} \text{Re}^{0.45} \left(\frac{\xi}{k} \right)^{\frac{5}{6}} \mu^{\frac{2}{3}} \left(\frac{\mu}{\mu_s} \right)^{0.14} \delta (u_s - u_b)^n \quad (78)$$

In Eq. (78), the δ and n are constants. μ_s represents coolant viscosity evaluated at the temperature of the heating surface, and ξ is given by

$$\xi = k^{0.6} \left(\frac{C_p}{\mu} \right)^{0.4} \quad (79)$$

3.3.3 TRANSITION MODEL

A transition model to fully develop two-phase heat transfer, as suggested by Bergles and Rohsenow [23], has been implemented in PARET as an option to the original model. The two-phase transition scheme at time step $m+1$ may be expressed as

$$(\mathbf{q}'')^{m+1} = (\mathbf{q}''_{1\phi})^{m+1} \left\{ 1 + \left[\frac{(\mathbf{q}''_{2\phi})^{m+1}}{(\mathbf{q}''_{1\phi})^{m+1}} \left(1 - \frac{(\mathbf{q}''_i)^{m+1}}{(\mathbf{q}''_{2\phi})^{m+1}} \right) \right]^2 \right\}^{1/2}$$

where

$\mathbf{q}''_{1\phi}$ is the single-phase heat flux $\sim \mathbf{h}_{1\phi}$

$\mathbf{q}''_i$ is the two-phase value $\sim (\mathbf{T}_{wi} - \mathbf{T}_{sat})$

$\mathbf{q}''_{2\phi}$ is the two-phase value $\sim (\mathbf{T}_w - \mathbf{T}_{sat})$

with the clad wall temperature at the onset of nucleate boiling (ONB) given by

$$\mathbf{T}_{wi} = (\mathbf{q}''_{ONB} / 15.6 \mathbf{p}^{1.156})^{\frac{\mathbf{p}^{0.0234}}{2.30}} + \mathbf{T}_{sat}, \text{ the Bergles-Rohsenow correlation (B-R).}$$

The two-phase correlation for $\mathbf{q}''_i$ and $\mathbf{q}''_{2\phi}$ may be chosen from the original Jens-Lottes (J-L) or the McAdams correlation on option.

3.4 HYDRODYNAMICS

The hydrodynamics calculations in PARET are based on a modified Momentum Integral Model [24] in which equations representing the laws of conservation of mass, momentum and energy are solved in each coolant channel at each time node.

$$\frac{\partial \bar{\rho}}{\partial t} = - \frac{\partial G}{\partial Z} \quad (80)$$

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial Z} \left(\frac{G^2}{\rho'} \right) = - \frac{\partial p}{\partial Z} - \frac{fv|G|G}{2D_e} - \bar{\rho}g \quad (81)$$

$$\rho'' \frac{\partial H}{\partial t} + G \frac{\partial H}{\partial Z} = \frac{q}{r_h} \quad (82)$$

where

t = time

Z = axial spatial variable

$\bar{\rho}$ = volume weighted two-phase density of coolant

G = mass flow rate of coolant

ρ' = effective density of coolant for momentum considerations

p = pressure

f = friction factor

v = specific volume of coolant

D_e = equivalent diameter of coolant channel

g = gravitational constant

ρ'' = effective slip flow density of coolant

H = enthalpy of coolant

r_h = hydraulic radius of coolant channel

q = thermal energy gained by coolant

The dissipation term $\frac{fv|G|G}{2D_e}$, as well as pressure changes with respect to both space and time, $Gv \frac{\partial p}{\partial Z} + \frac{\partial p}{\partial t}$, have been neglected in Eq. (82). The solutions to Eqs. (80), (81) and (82) yield the pressure drop across the core, as well as point-wise pressures, fluid enthalpies, and mass flow rates along the length of each channel. As in the case of the heat transfer calculations, this also is a one-dimensional treatment; i.e., variations in the fluid velocity and fluid properties are considered only in the direction of flow. The hydrodynamic description allows for coolant flow reversal, and the physical condition of the coolant is allowed to range from sub-cooled liquid through the two-phase region up to and including superheated steam.

A basic assumption of the Momentum Integral Model (MIM), upon which the PARET hydrodynamic model is based, is that all fluid properties, including density, can be evaluated at some single reference pressure. In PARET, however, this model has been modified to consider the dependence of fluid density upon local fluid pressure. The particular scheme through which this pressure dependence is accounted for is as follows. The code calculates local pressures along the length of each channel as a function of time. At any particular time node, however, the pressures calculated are appropriate to the immediately preceding time node. A Lagrangian extrapolation is then used to obtain pressures at the current time node and these extrapolated pressures are used as a basis for evaluating current fluid densities. The scheme includes an iteration on local fluid pressures (until extrapolated values are in agreement with the calculated values) and provision for decreasing the time-step size if the time rate of change of local fluid specific volume exceeds a specified value. All fluid properties are evaluated through a table look up, an extensive fluid properties table being an integral part of the code. Only density is considered to be a function of both temperature and pressure; the other fluid properties (viscosity (μ), heat capacity at constant pressure (C_p) and thermal conductivity (k)) are evaluated as functions of temperature at the specified initial system temperature.

For each channel (region) included in a problem, either the pressure drop across that channel or the coolant inlet mass flow rate must be specified as a function of time. In the latter case, the

so-called flow-forced problem, the pressure drop across the channel is calculated, according to the conservation of momentum, as the sum of the frictional, elevation, spatial acceleration and transient acceleration pressure drops. As a result of integrating the Eq. for the conservation of momentum across the entire channel (Momentum Integral Model), the transient acceleration pressure drop must be determined on the basis of the time rate change of the channel average mass velocity, $\hat{G}$, between successive time nodes, where $\hat{G}$ is given by

$$\hat{G} = \frac{1}{L} \int_0^L G dZ \quad (83)$$

and L represents the length of the channel. The time rate of change of this quantity is given by

$$\frac{\partial \hat{G}}{\partial t} = \frac{1}{L} [\Delta p - F] \quad (84)$$

where Δp , the total channel pressure drop, and F , the sum of the frictional elevation, and spatial acceleration pressure drops, are

$$\Delta p = - \int_0^L \frac{\partial p}{\partial Z} dZ \quad (85)$$

$$F = \int_0^L \frac{f v |G| G}{2D_e} dZ + \int_0^L \bar{\rho} g dZ + \left[\frac{G^2}{\rho'} \right]_{NZ} - \left[\frac{G^2}{\rho'} \right]_1 \quad (86)$$

The difference quantity $[\Delta p - F]$ in Eq. (84) represents the transient acceleration pressure drop. In the pressure-drop forced problem (in which case the total pressure drop across the channel is specified with time), a channel average mass velocity existing at the current time node is calculated on the basis of the average mass velocity at the previous time node and the transient acceleration pressure drop over the present time step (Eq. (84)). This current channel average mass velocity is used as a basis for evaluating the channel entrance mass velocity at the current time node, which effectively reduces the problem to a flow-forced problem. All succeeding mass velocities along the length of the channel are then determined from the Eq. for the conservation of mass. This entire scheme is discussed in detail in Section 3.4.1.

The enthalpy of the inlet coolant is assumed to be the same for each channel (except in the case of flow reversal) and must be specified. Succeeding enthalpies along the length of each channel are determined according to an Eq. for the conservation of energy in the channel, and on the basis of the enthalpy of the inlet coolant.

PARET includes the option of either estimating the vapor volume fraction formed during sub-cooled boiling, or assuming it to be zero for conditions other than saturated boiling. Vapor volume fraction calculations in the sub-cooled region are based on a simplified form of Zuber's [25] Eq.

$$\frac{\partial R}{\partial t} + C_2 V \frac{\partial R}{\partial Z} + \frac{R}{\tau} = \lambda K (q'')^n \quad (87)$$

where the quantity R represents the vapor volume fraction; Z and t are the position and time variables, respectively; V represents the fluid linear velocity; q'' represents the surface heat flux; and C_2 , τ , λ , K and n are constants. The parameter τ represents the bubble collapse time and λ represents the fraction of the clad surface heat flux which is utilized in producing vapor during boiling.

In the case of saturated boiling, the mass flow fraction of vapor is determined directly from the mixing-cup enthalpy. The vapor volume fraction is then obtained from a table lookup, according the revised Martinelli-Nelson [26] development.

PARET uses the Martinelli-Nelson method [27] to estimate two-phase pressure drop (in the case of saturated boiling) and relationships developed at Westinghouse [28] to evaluate sub-cooled two-phase pressure drop. The latter development is based on an Eq. of the form

$$f = \left(\frac{f}{f_{\text{iso}}} \right) f_{\text{iso}} \quad (88)$$

where f represents a two-phase friction factor and f_{iso} a single-phase friction factor. The latter factor, f_{iso} , is correlated with the Reynold's number in the form

$$f_{\text{iso}} = a_0 (Re)^{a_1} \quad (89)$$

where a_0 and a_1 are constants [see Eq. (145) and (146)]. The ratio $\left(\frac{f}{f_{\text{iso}}} \right)$ is determined from empirical correlations based on experimental data obtained at Westinghouse. A detailed description of the friction factor correlations is presented in Chapter 3.4.1.

3.4.1 CONSERVATION OF MASS

Eq. (80) for the conservation of mass can be written in the form

$$\frac{\partial G}{\partial Z} = - \frac{\partial \bar{\rho}}{\partial t} = - \frac{\partial \bar{\rho}}{\partial H} \frac{\partial \bar{H}}{\partial t} \quad (90)$$

Evaluation of $\frac{\partial \bar{H}}{\partial t}$ from Eq. (82) and substitution into Eq. (90) yields

$$\frac{\partial G}{\partial Z} = \frac{G}{\rho''} \frac{\partial \bar{\rho}}{\partial H} \frac{\partial \bar{H}}{\partial z} - \frac{q}{r_h \rho''} \frac{\partial \bar{\rho}}{\partial H} \quad (91)$$

PARET employs the following explicit difference approximation to Eq. (91) for calculating the moderator mass flow rate, G , as a function of position and time (refer to Figure 3):

$$G_j^m = \gamma_{j-\frac{1}{2}}^m G_{j-1}^m - \frac{\beta_{j-\frac{1}{2}}^m}{r_h} q_{j-\frac{1}{2}}^m \quad (92)$$

where

$$\gamma_{j-\frac{1}{2}}^m = \frac{2 + A_{j-\frac{1}{2}}^m}{2 - A_{j-\frac{1}{2}}^m} \quad (93)$$

$$A_{j-\frac{1}{2}}^m = \frac{H_j^m - H_{j-1}^m}{\rho_{j-\frac{1}{2}}^m} \left(\frac{\partial \bar{\rho}}{\partial H} \right)_{j-\frac{1}{2}}^m \quad (94)$$

$$\beta_{j-\frac{1}{2}}^m = \frac{2 \Delta Z_j}{\rho_{j-\frac{1}{2}}^m} \frac{1}{2 - A_{j-\frac{1}{2}}^m} \left(\frac{\partial \bar{\rho}}{\partial H} \right)_{j-\frac{1}{2}}^m \quad (95)$$

and $q_{j-\frac{1}{2}}^m$ represents the sum of the surface heat flux, $q_{j-\frac{1}{2}}^m$, and the prompt energy generation within the coolant, expressed in terms of an equivalent flux.

The quantity ρ'' , which is referred to as the “effective slip-flow density”. is defined by

$$\rho'' = \bar{\rho} \frac{\partial \bar{H}}{\partial H} + (\bar{H} - H) \frac{\partial \bar{\rho}}{\partial H} \quad (96)$$

where $\bar{H}$ represents a volume-weighted enthalpy and H represents a flow-weighted or mixing-cup enthalpy. In the particular situation where both the liquid and vapor phases are saturated, Eq. (96) can be written in the form

$$\rho'' = [\rho_f X + \rho_g (1 - X)] \frac{\partial R}{\partial X} \quad (97)$$

where R represents vapor volume fraction and X represents the mass flow fraction of vapor. Since ρ'' , as defined in Eq. (96) is very difficult to evaluate, it is assumed in PARET that Eq. (97) is applicable to the two-phase system under all conditions, saturated or otherwise. This greatly simplifies the evaluation of ρ'' . The quantity, $\bar{\rho}$, is a volume-weighted density, defined by

$$\bar{\rho} = \rho_v R + \rho_l (1 - R) \quad (98)$$

In the flow-forced problem, the inlet mass flow rate, G_1^m , is specified as a function of time. All succeeding flow rates along the length of the channel are then calculated explicitly, according to Eq. (92). In the pressure-drop-forced problem, however, the inlet mass flow rate of the moderator is not specified and Eq. (92) therefore cannot be used directly. In this case, the computational scheme involves first computing a channel average mass flow rate, $\hat{G}_T^m$, on the basis of the flow rate, $\hat{G}_T^{m-1}$, at the previous time node and the transient acceleration pressure drop, $(\Delta p_{ta})_T^{m-1}$, across the present time step. This $\hat{G}_T^m$ is then used in determining an inlet mass flow rate. Once the inlet mass flow rate has been determined, the pressure-drop-forced problem has been effectively reduced to a flow-forced problem and is handled accordingly.

The Eqs. involved in this scheme include an expression for the evaluation of $\hat{G}_T^m$, derived from Eq. (84)

$$\hat{G}_T^m = \hat{G}_T^{m-1} + \frac{g_c \Delta t^m}{L_T} (\Delta p_{ta})_T^{m-1} \quad (99)$$

where the quantity, $(\Delta p_{ta})_T^{m-1}$, represents the transient acceleration pressure drop over time step Δt^m . After determining $\hat{G}_T^m$ from Eq. (99), the channel inlet mass flow rate, G_1^m , is calculated from the expression

$$G_1^m = \frac{L_T \hat{G}_T^m + L_F \hat{\delta}_T^m - (\alpha_E L_E + P_E) G_{NZ}^{m-1}}{L_F \hat{\sigma}_T^m + (\alpha_I L_I + P_I)} \quad (100)$$

where

$$\hat{\delta}^m = \frac{1}{2L_F} \sum_{j=2}^{NZ} \Delta Z_{j-1} (\delta_j^m + \delta_{j-1}^m) \quad (101)$$

$$\hat{\sigma}^m = \frac{1}{2L_F} \sum_{j=2}^{NZ} \Delta Z_{j-1} (\sigma_j^m + \sigma_{j-1}^m) \quad (102)$$

$$\delta_j^m = \gamma_{j-\frac{1}{2}}^m \delta_{j-1}^m + \beta_{j-\frac{1}{2}}^m \frac{q_{j-\frac{1}{2}}^m}{r_h} \quad (103)$$

$$\sigma_j^m = \gamma_{j-\frac{1}{2}}^m \sigma_{j-1}^m \quad (104)$$

$$\left. \begin{aligned} \sigma_1^m &= 1 \\ \delta_1^m &= 0 \end{aligned} \right\} \quad (105)$$

After determining G_1^m from Eq. (100) for the pressure-drop-forced problem, Eq. (92) is used to calculate the other G_j^m existing along the length of the channel.

In the flow-forced problem, the channel average mass velocity, $\hat{G}_T^m$, is calculated from the Eq.

$$\hat{G}_T^m = \frac{1}{2L_T} \left(2(\alpha_I L_I + P_I) G_1^m + \sum_{j=2}^{NZ} \Delta Z_j (G_j^m + G_{j-1}^m) + 2(\alpha_E L_E + P_E) G_{NZ}^m \right) \quad (106)$$

This average velocity is then used in conjunction with Eq. (99) to determine the transient acceleration pressure drop, Δp_{ta} .

3.4.2 CONSERVATION OF ENERGY

Fluid enthalpies at interior axial node points are calculated in the transient situation from a so-called “four points explicit” difference representation [29] of Eq. (82) for the conservation of energy in the coolant channel. This difference Eq. is given by

$$\begin{aligned} H_j^m = H_j^{m-1} &+ \left[\frac{H_{j-1}^{m-1} - H_{j+1}^{m-1}}{\eta_j^{m-1}} \right] + \frac{DZ_j}{\eta_j^{m-1}} \left(\frac{2}{\eta_{j+\frac{1}{2}}^{m-1}} \frac{H_{j+1}^{m-1} - H_j^{m-1}}{\Delta Z_{j+1}} - \frac{2}{\eta_{j-\frac{1}{2}}^{m-1}} \frac{H_j^{m-1} - H_{j-1}^{m-1}}{\Delta Z_j} \right) \\ &+ \frac{\Delta t^m}{r_h} \left(\frac{1}{2\eta_j^{m-1}} \left[\frac{q_j^{m-1} + q_{j-1}^{m-1}}{(\rho'')_{j-\frac{1}{2}}^{m-1}} - \frac{q_{j+1}^{m-1} + q_j^{m-1}}{(\rho'')_{j+\frac{1}{2}}^{m-1}} \right] \right. \\ &\left. + \frac{q_j^{m-1}}{(\rho'')_j^{m-1}} \left[\frac{\phi^m}{\phi^{m-1}} - 1 \right] \right) \frac{W_F}{2W_p} \end{aligned} \quad (107)$$

where

$$\eta_j^{m-1} = \frac{2DZ_j(\rho'')_j^{m-1}}{\Delta t^m G_j^{m-1}} \quad (108)$$

$$\eta_{j-\frac{1}{2}}^{m-1} = \frac{2DZ_j(\rho'')_{j-\frac{1}{2}}^{m-1}}{\Delta t^m G_{j-\frac{1}{2}}^{m-1}} \quad (109)$$

$$\eta_{j+\frac{1}{2}}^{m-1} = \frac{2DZ_j(\rho'')_{j+\frac{1}{2}}^{m-1}}{\Delta t^m G_{j+\frac{1}{2}}^{m-1}} \quad (110)$$

$$DZ_j = \frac{1}{2}(\Delta Z_j + \Delta Z_{j+1}) \quad (111)$$

and q_j^m is defined in conjunction with Eq. (92).

Eq. (107) is stable [30] for

$$\left| \frac{2}{\eta_j^m} \right| \leq 1 \quad (112)$$

which imposes the hydrodynamic time step criterion:

$$\Delta t^m \leq \min_{j=2, NZ} \left(\frac{(\rho'')_j^m DZ_j}{|G_j^m|} \right) \quad (113)$$

This is the maximum time step that can be used if the enthalpy calculations are to remain stable.

Fluid enthalpies at the two end points of a channel are determined from

$$1. \quad j = 1, G_1^{m-1} \geq 0$$

$$H_1^m = \text{specified value} \quad (114)$$

$$2. \quad j = 1, G_1^{m-1} < 0$$

$$\begin{aligned} H_1^m = H_1^{m-1} - \frac{\Delta t^m}{2(\rho'')_{j+\frac{1}{2}}^{m-1}} & \left(\frac{G_1^{m-1} + G_2^{m-1}}{\Delta Z_2} (H_2^{m-1} - H_1^{m-1}) \right. \\ & \left. - \frac{q_2^{m-1} + q_1^{m-1}}{r_h} \left(\frac{\phi^m}{\phi^{m-1}} + 1 \right) \frac{W_F}{2W_p} \right) \end{aligned} \quad (115)$$

$$3. \quad j = NZ, G_{NZ}^{m-1} > 0$$

$$\begin{aligned} H_{NZ}^m = H_{NZ}^{m-1} - \frac{\Delta t^m}{2(\rho'')_{NZ-\frac{1}{2}}^{m-1}} & \left(\frac{G_{NZ}^{m-1} + G_{NZ-1}^{m-1}}{\Delta Z_{NZ}} (H_{NZ}^{m-1} - H_{NZ-1}^{m-1}) \right. \\ & \left. - \frac{q_{NZ}^{m-1} + q_{NZ-1}^{m-1}}{r_h} \left(\frac{\phi^m}{\phi^{m-1}} + 1 \right) \frac{W_F}{2W_p} \right) \end{aligned} \quad (116)$$

$$j = NZ, G_{NZ}^{m-1} \leq 0$$

$$H_{NZ}^m = H_{NZ}^{m-1} \quad (117)$$

In the special case of steady state, the original Eq. for conservation of energy reduces to

$$G \frac{\partial H}{\partial Z} = \frac{q}{r_h} \quad (118)$$

The difference Eq. reduces, accordingly to

$$H_j^0 = H_{j-1}^0 + \frac{\Delta Z_j}{r_h G_j^0} \frac{q_j^0 + q_{j-1}^0}{2} \frac{W_F}{W_p}, j = 2, \dots, NZ \quad (119)$$

3.4.3 CONSERVATION OF MOMENTUM

Local pressures and channel pressure drop are calculated from Eq. (81) for the conservation of momentum. This Eq. is represented in PARET by

$$\Delta p_T^m = F + (\Delta p_{ta})_T^m \quad (120)$$

In Eq. (120), Δp_T^m represents the total pressure drop across a channel at time node m, and $(\Delta p_{ta})_T^m$ represents the corresponding transition acceleration pressure drop. The latter of these two quantities is calculated on the basis of the change in channel average mass flow rate across the time step Δt^m , according to Eq. (99)

$$(\Delta p_{ta})_T^{m-1} = \frac{L_T}{g_c \Delta t^m} [\hat{G}_T^m - \hat{G}_T^{m-1}] \quad (121)$$

Calculation of $\hat{G}_T^m$ is illustrated in Eq. (106). The quantity F represents the sum of the frictional, elevation, and spatial acceleration pressure drops

$$F = (\Delta p_f)_T^m + (\Delta p_{el})_T^m + (\Delta p_{sa})_T^m \quad (122)$$

where

$$\begin{aligned} (\Delta p_f)_T^m = & \frac{1}{g_c} \left[\frac{1}{2} K_c + \frac{\alpha_I^2 f_I L_I}{2(De)_I} + \frac{f_I P_I}{2De} \right] [v_1^m | G_1^m | G_1^m] \\ & + \frac{1}{4De g_c} \sum_{j=2}^{NZ} \Delta Z_j ([fv|G|G]_j^m + [fv|G|G]_{j-1}^m) \\ & + \frac{1}{g_c} \left[\frac{1}{2} K_E + \frac{\alpha_E^2 f_E L_E}{2(De)_E} + \frac{f_E P_E}{2De} \right] [v_{NZ}^m | G_{NZ}^m | G_{NZ}^m] \end{aligned} \quad (123)$$

$$(\Delta p_{el})_T^m = \frac{g}{g_c} \bar{\rho}_1^m (L_I + P_I) + \frac{g}{g_c} \sum_{j=2}^{NZ} \Delta Z_j (\bar{\rho}_j^m + \bar{\rho}_{j-1}^m) + \frac{g}{g_c} \bar{\rho}_{NZ}^m (L_E + P_E) \quad (124)$$

$$\begin{aligned} (\Delta p_{sa})_T^m = & \frac{1}{2g_c} (1 - \alpha_1^2) v_1^m (G_1^m)^2 - \frac{1}{g_c} (v')_1^m (G_1^m)^2 - \frac{1}{2g_c} (1 - \alpha_E^2) v_{NZ}^m (G_{NZ}^m)^2 \\ & + \frac{1}{g_c} (v')_{NZ}^m (G_{NZ}^m)^2 \end{aligned} \quad (125)$$

The quantity, v' , appearing in Eq. (125), is an effective slip-flow specific volume for momentum considerations, and is given by

$$(v')_j^m = \frac{(1 - X_j^m)^2}{(\rho_l)_j^m (1 - R_j^m)} + \frac{X_j^m}{\rho_g R_j^m} \quad (126)$$

Intermediate pressures along the length of each channel are calculated on the basis of the known system pressure and appropriate calculated pressure differences.

3.4.4 ESTIMATION OF VAPOR VOLUME FRACTION

PARET contains the option of either estimating the vapor volume fraction formed during subcooled boiling or assuming it to be zero for conditions other than saturated boiling. The

vapor volume fraction is estimated in the former case according to a simplified form of Zuber's Eq. [25]

$$\frac{\partial R}{\partial t} + C_2 V \frac{\partial R}{\partial Z} + \frac{R}{\tau} = \lambda K (q'')^n \quad (127)$$

where R represents the vapor volume fraction; Z and t are the position and time variables, respectively; V represents the fluid linear velocity; q'' represents the surface heat flux; and C_2, τ, λ, K and n are constants. The parameter τ represents the bubble collapse time, and λ represents the fraction of the clad surface heat flux which is utilized in producing vapor during boiling. Both of these parameters are supplied as input to the code by the user. Recommended values for use in both the highly subcooled and slightly subcooled regions are given in [29].

PARET employs a four point explicit difference representation of Eq. (127) for calculating the vapor volume fraction. This difference Eq. for the j^{th} interior node is given by

$$R_j^m = \frac{1}{1 + \mu} \left(R_j^{m-1} [1 - \mu - \beta_j^m (\gamma_{j+1}^{m-1} + \delta_j^{m-1})] + R_{j-1}^{m-1} \beta_j^{m-1} [1 - \mu + \delta_j^{m-1}] \right. \\ \left. + R_{j+1}^{m-1} \beta_j^{m-1} [\mu - 1 + \gamma_{j+1}^{m-1}] + \frac{\lambda K \Delta t^m}{2} [\theta_j^m + \theta_j^{m-1} - \beta_j^{m-1} (\theta_{j+1}^{m-1} - \theta_{j-1}^{m-1})] \right) ; j = 2, \dots, NZ - 1 \quad (128)$$

where

$$\mu = \frac{\Delta t^m}{2\tau} \quad (129)$$

$$\beta_j^{m-1} = \frac{C_2 V_j^{m-1} \Delta t^m}{2 D Z_j} \quad (130)$$

$$\delta_j^{m-1} = \frac{\Delta t^m C_2 V_{j-\frac{1}{2}}^{m-1}}{\Delta Z_j} \quad (131)$$

$$\gamma_{j+1}^{m-1} = \frac{C_2 V_{j+\frac{1}{2}}^{m-1} \Delta t^m}{\Delta Z_{j+1}} \quad (132)$$

$$\theta_j^{m-1} = [(q'')_j^{m-1}]^n \quad (133)$$

The two extreme nodes at the entrance and exit to a channel ($j=1$ and $j=NZ$) require special consideration under transient conditions

$$1. \quad j = 1, G_1^{m-1} \geq 0$$

$$R_1^m = 0 \quad (134)$$

$$2. \quad j = 1, G_1^{m-1} < 0$$

$$R_1^m = \frac{1}{1 + \mu} \left(R_1^{m-1} [1 - \mu - \eta_1^{m-1}] + \eta_1^{m-1} R_2^{m-1} + \frac{\lambda K \Delta t^m}{2} [\theta_1^m + \theta_1^{m-1}] \right) \quad (135)$$

$$3. \quad j = NZ, G_{NZ}^{m-1} > 0$$

$$R_{NZ}^m = \frac{1}{1+\mu} \left(R_{NZ}^{m-1} [1 - \mu - \eta_{NZ}^{m-1}] + \eta_{NZ}^{m-1} R_{NZ-1}^{m-1} + \frac{\lambda K \Delta t^m}{2} [\theta_{NZ}^m + \theta_{NZ-1}^{m-1}] \right) \quad (136)$$

$$4. \quad j = NZ, G_{NZ}^{m-1} \leq 0$$

$$R_{NZ}^m = 0 \quad (137)$$

where

$$\eta_j^{m-1} = \frac{C_2 V_j^{m-1} \Delta t^m}{\Delta Z_j} \text{ for } j=1 \text{ and } NZ \quad (138)$$

For the special case of steady state, vapor volume fractions are calculated from

$$R_j^0 = \frac{\tau C_2 V_j^0 R_{j-1}^0 + \lambda K \tau \Delta Z_j \theta_j^0}{\tau C_2 V_j^0 + \Delta Z_j} \quad (139)$$

In the steady-state situation, it is assumed that the value of the vapor volume fraction at the channel entrance is zero.

Having calculated the value of R , the mass flow fraction of vapor, X , is obtained by table lookup, on the basis of the Martinelli-Nelson correlation [26].

In the case of saturated boiling, the mass flow fraction of vapor is obtained directly from the mixing-cup enthalpy, according to the Eq. (140):

$$X = \frac{H - H_f}{H_{fg}} \quad (140)$$

In this case, having calculated X , the vapor volume fraction is obtained by table lookup, on the basis of the Martinelli-Nelson correlation [26].

3.4.5 FRICTION FACTOR CORRELATIONS

PARET uses the Martinelli-Nelson method [27] to predict two-phase pressure drop in the case of saturated boiling and relationships developed at Westinghouse [28] to evaluate subcooled two-phase and single-phase pressure drop. The various relationships employed in evaluating the friction factor are given below.

1. Liquid heating and cooling, $Re < 2000$

$$f = \frac{64}{Re} \quad (141)$$

where

$$Re = \frac{De|G|}{\mu} \quad (142)$$

2. Liquid heating and cooling, $Re > 2000$

$$f = \left(\frac{f}{f_{iso}} \right) f_{iso} \quad (143)$$

where

$$f_{iso} = 1 - a_5 \Delta u_f \quad (144)$$

$$\Delta u_f = a_6 \frac{q''}{h} \quad (145)$$

$$f_{iso} = a_0 Re^{a_1}, \text{ for } Re < a_2 \quad (146)$$

$$f_{iso} = a_3 Re^{a_4}, \text{ for } Re \geq a_2 \quad (147)$$

3. Subcooled nucleate boiling

Use Eqs. 's (143), (146), (147) and the minimum of Eqs. (148) and (149)

$$\left(\frac{f}{f_{iso}} \right) = 1 + a_8 \frac{a_9 \Delta u_f - u'_s + u_b}{a_9 \Delta u_f - u'_s + u_{sat}} \quad (148)$$

$$\left(\frac{f}{f_{iso}} \right) = a_{10} \quad (149)$$

4. Subcooled transition and film boiling

Use Eqs. (143), (146), (147) and the minimum of Eqs. (149) and (150)

$$\left(\frac{f}{f_{iso}} \right) = 1 + a_8 \frac{u_s - u'_s}{u_s - u'_s + u_{sat} - u_b} \quad (150)$$

5. Saturated boiling, Low qualities ($X < a_{11}$)

Use the maximum of Eqs. (151) and (152)

$$f = (f_{iso})_{sat} \phi_{L0}^2 \quad (151)$$

$$f = (f_{iso})_{sat} a_{10} \quad (152)$$

In Eqs. (151) and (152), $(f_{iso})_{sat}$ is calculated according to Eqs. (146) and (147) for f_{iso} , except that the Reynold's number is calculated, in this case from

$$Re = \frac{De|G|}{\mu_{sat}} \quad (153)$$

where μ_{sat} is the viscosity of the saturated liquid.

6. Saturated boiling, Intermediated qualities ($a_{11} \leq X \leq a_{12}$)

$$f = (f_{iso})_{sat} \phi_{L0}^2 \quad (154)$$

7. Saturated boiling, High quality ($X > a_{12}$ where a_{12} is the highest quality in the ϕ_{L0}^2 table)

$$f = (f_{iso})_{sat} \left(\phi_{L0}^2 a_{12} - \left[\phi_{L0}^2 a_{12} - \frac{\rho_f}{\rho_g} \left(\frac{\mu_f}{\mu_g} \right)^{a_1} \right] \frac{X - a_{12}}{1.0 - a_{12}} \right), \quad (155)$$

for $Re < a_2$ (Re based on μ_{sat})

$$f = (f_{iso})_{sat} \left(\phi_{L0}^2 a_{12} - \left[\phi_{L0}^2 a_{12} - \frac{\rho_f}{\rho_g} \left(\frac{\mu_f}{\mu_g} \right)^{a_4} \right] \frac{X - a_{12}}{1.0 - a_{12}} \right), \quad (156)$$

for $Re \geq a_2$ (Re based on μ_{sat})

where ϕ_{L0}^2 is evaluated at $X = a_{12}$.

8. Superheated vapor

$$f = f_{iso} \quad (157)$$

where f_{iso} is evaluated from Eqs. (146) and (147) using

$$Re = \frac{De|G|}{\mu_v} \quad (158)$$

and μ_v represents the viscosity of the superheated vapor.

In all the above correlations containing ϕ_{LO}^2 , this quantity (a function of X, G, and p) is obtained by table lookup.

The various constants appearing in the foregoing pressure drop correlations have the following values in PARET:

$a_0 = 0.2108$	$a_6 = 60$
$a_1 = -0.2137$	$a_8 = (\phi_{LO}^2 \text{ at } 4.2\% \text{ quality}) - 1$
$a_2 = 10^5$	$a_9 = 1.0$
$a_3 = 0.1144$	$a_{10} = \phi_{LO}^2 \text{ at } 4.2\% \text{ quality}$
$a_4 = -0.1606$	$a_{12} = 1.0$
$a_5 = 0.766$	

According to Westinghouse [28], the foregoing correlations provide a reasonable estimate of the friction factor, but their development has indicated the following primary areas of uncertainty:

1. Transition boiling and film boiling
2. Condensing of steam and vapor
3. Carryover of vapor and liquid upon entering and leaving the two-phase region
4. Superheating and de-superheating with high film temperature drops

They point out further that the acquisition of sufficient data to resolve the problem areas will probably require extensive steady-state and transient experimental work

4 TIME STEP CONTROL AND CODE RUNNING TIME

Table 14 provides for specification of time increment as a function of time. At each time node, a comparison is made between this input-specified time step and the maximum time step allowed by the hydrodynamics (Eq. (113)). The code will always use the smaller of the two in order to maintain stability of the enthalpy calculations. The neutron kinetics calculations are carried out using whichever of these two time steps is accepted. If a neutronics error criterion is violated using this time step (see Eqs. (21) through (27) and succeeding discussion), it is automatically halved and the neutron kinetics calculations repeated. This procedure is continued until the error criterion is satisfied. If the original time step must be reduced for the neutron kinetics calculations, this reduced time step may be used for the thermal and hydrodynamics calculations as well. Or, at the user's option, the neutron kinetics calculations may be repeated a number of times sufficient for spanning the input-specified or hydrodynamics-specified time step.

5 INPUT DESCRIPTION FOR PARET/ANL

The FORTRAN input processor routine imposes certain restrictions on the input and requires an additional scratch file (FORTRAN Unit 9) to contain each card image as it is processed. The card input following the card type number (a four or five digit number followed by a comma) must be blocked in fields of 12 columns beginning with column 7. Each field may contain either one floating point number (E12.5 format) or up to two integers (2I6 format). All floating point numbers must include a decimal point. For mixtures of floating point numbers and single or odd numbers of integer entries, a blank field of 6 column must be added with the single or last integer so that the next floating point number starts in the next proper field of 12. Each card can contain a maximum of 6 floating point numbers or 12 fixed point numbers through column 78. Embedded blank fields are allowed unless further restrictions are imposed and in some cases required as noted above. The card input format is further structured to some extent by card type (See sample problem input, APPENDIX V). The initial integer entries on the 1000 series cards must be entered on card types 1001 and 1002 (card type 1002 must be omitted if all 12 integers are on card 1001), and the floating entries for the 1000 series start on 1003 and continue on additional cards in the series as needed. The 1112 card type must have 5 integer entries (with the odd number of integers a blank field of 6 must be imbedded) followed by 3 floating point numbers. The 4000 series cards must have pairs of entries consisting of one floating point number with a maximum of three sets per card. The 5N00 card(s) present special problems.

- a) The second entry may be either an integer number or a floating point number depending on the problem specified.
- b) The amount of data in the fixed format scheme requires a second card.

Thus, if the second entry is an integer, the usual packing rules apply and five floating point numbers follow with three floating point numbers entered on an additional 5N00 card. However, if the second entry is floating point, a blank field of 6 must follow the integer entry and again five floating point entries follow but now the second card must contain four floating point entries. Embedded blank fields, unless required, are not allowed on the 5N00 cards. The remaining card types may be entered following only the general rules described above.

For user convenience, an input file pre-processor was created to permit placing comment lines anywhere in the input file. Simply place an exclamation mark (!) in column 1, and any text following that line will be ignored. One can also place the exclamation mark at any column. Then the card image is copied up to the exclamation mark, and the remainder is treated as blanks. This feature can be used to identify key variables, or to denote changes from other similar runs. It makes an input file much easier to review and verify. The pre-processor creates a temporary copy of the user's input file, without the comment lines or comments

An example of the modified input format and the IAEA benchmark problem with SI units is shown in Appendix III.

The following is an item-by-item description of the input file. It is arranged in 16 sections plus a restart section. The user may choose between SI or English units. Variables with dimensions of length only are to be assumed to be in feet (ft) or meters (m). Units for all other dimensioned input variables are given below in both systems.

5.1 PROBLEM TYPE AND RESTART DATA

Any problem begins with this data card. The restart option is functional since V7.5. Since many arrays are now variably dimensioned, it is now necessary upon restart to supply card type 1001 with NCHN, NZ, and NR on it ahead of 14000 cards (or 14000 plus 16000 cards). The user must supply all cards from 1001 to 1099. Then, if desired, supply the 14000, or 14000 and 16000 cards.

First input card (precedes the “* title” card):

IRSTRT,IFREQ,ICHNG,NFILE, Format (4I6,E12.4,7I6)
 TTIME,IFLUID,INAME,JPROP,NLUP2,IDBL,INORM,IOPT

IRSTRT	0	Initial problem (default)
	1	Restart problem
IFREQ	0 (or blank)	Write restart file every 1000 steps (default)
	n	Write restart file every n steps
ICHNG	0 (or blank)	No table changes (default)
	1	Time step data revision (Table 14 input follows)
	2	Time step and edits data revised (Table 14 and Table 16 input follows)
NFILE	blank	Default (IRSTRT=0)
	12 or 14	Desired file number (IRSTRT=1) Restart data is alternately written to units 12 (RESTR1) and 14 (RESTR2). (default 12)
TTIME		New time limit for transient (optional); reset if >0.
IFLUID	0, H2O	Automatic generation of coolant library tables for light water (default=0)
	1, D2O	Automatic generation of coolant library tables for heavy water
INAME	0	Old input format type
	1	NAMelist format type (not available)
JPROP	0	This parameter is no longer used.
NLUP2	0/1	1 if an external coolant loop is to be modeled; else 0. (see further down for additional cards required by the external coolant loop model)
IDBL	0	This parameter is no longer used
INORM	0	run the problem, renormalizing power if needed
	1	check power normalization and run without normalization if the error < 1.E-4; issue a

		warning if the error is between 1.E-4 and 1.E-2, renormalize, and run; otherwise terminate.
	2	do not renormalize power
IOPT	0	optimize axial mesh if not optimal
	1	do not optimize axial mesh

If NLUP2=1, the following external loop data are needed: Format (6E12.5)

VLUP	Volume of primary loop water, m ³
ALUP	Area of contact between primary and secondary loop or pool, m ²
V2LUP	Volume of secondary loop or pool, m ³
ASURF	Area of secondary pool, m ²
T2LUP	Bulk temperature of secondary pool, C
T2AIR	Air temperature over pool, C

If NLUP2=1, the following external loop data are needed: Format (5E12.5)

VAIR	Velocity of air over pool, ft/s
HUM	Humidity of air over pool, %
WALLH	Heat transfer coefficient for heat flow from primary to secondary loop, W/m ² K
PR2LUP	Pressure (nominal) of primary and secondary external loops, Pa
FBREF	Reactivity, $\beta/\text{degree C}$, from bulk heatup of the radial reflector (assumed to be at the bulk temperature of the primary loop, T1LSI). DKPRIM=FBREF*(T1LSI-TINLET1) Note: TINLET1 is the primary loop initial temperature at t=0.

For the initial problem only a blank card image is required if the default frequency for writing a restart file every 1000 steps is desired. For a restart problem, only IRSTRT=1 must be set. Restart data will be taken either from unit 12 or from unit 14 with no changes imposed, and no other input is required.

If TTIME is non-zero, the transient time is reset to that value at restart. IFREQ may also be changed at restart.

If ICHNG=0, no further input data is required.

If ICHNG is non-zero, card type 1001 must first be provided. Then table 14 data must be provided (even if no change is made in the time step data). If ICHNG is 2, Table 16 data must also be provided. The format for these tables is identical to the original 14000 and 16000 series PARET input data.

At this time no other input data may be changed at restart. For multiple cases, only one Restart card is expected. Succeeding cases begin with a new Title Line.

5.2 TITLE LINE

A title line must precede each problem set of data. The format of the title line is as follows:

- (1) An asterisk (*) in column 1.
- (2) An identifying title in columns 2 through 60.

5.3 GENERAL INFORMATION

The data lines immediately following the title line are of the format (80 columns):

10YY, X₁, X₂, ..., X_n

where YY=01, 02, ..., 99 and X_i, i=1, 2, ..., n are the data (items)

- Notes:
- (a) Each line must contain at least one word (item) in addition to the line number.
 - (b) Data must be listed in required order (1 through 12 must be integers, and 13 through 47 must be floating point.)
 - (c) Data may be followed by a comment. Simply place an asterisk (*) after the last data entry, and use the remainder of the line for any text comment. See Section 7 for all input rules.

ITEM	FORTTRAN VARIABLE	DESCRIPTION
1	NCHN	The number of channels, NCHN, where $1 \leq NCHN \leq 50$. This is the number of regions into which the core is subdivided. If NCHN is positive, the code assumes all input to follow will be in United States Customary units (ft, lb _m , Btu, psi, °F, hr). If negative, SI units are assumed (m, kg, J, Pa, °K, s). Power is always in megawatts. Internal calculations are carried out in United States Customary units but output is printed in the same units as the input data. Thus if United States Customary units are used, input data are converted to SI units after the input data is echoed and output data is converted back to United States Customary units for printing. United States Customary units are assumed to be: time in hours when part of a complex unit such as mass flux and viscosity (e.g. lb/hr ft ² ; lb/ft hr); length in ft; mass in lb; pressure in psia; energy in Btu; temperature in F.
2	NZ	The number of axial node points, NZ, where $1 \leq NZ \leq 97$. Type 5k00 logic as presently coded prevents NZ>97.
3	NR	The number of radial node points, NR, in meat, gap and cladding combined in a fuel pin or half-plate where $2 \leq NR \leq 43$.
4	IGEOM	The geometry code: 0 for slab and 1 for cylindrical geometry; 2 for

		nested tubes in slab geometry (modeled as two rectangular half-channels per tube). IGEOM=2 is developmental option, not fully qualified and therefore not recommended.
5	IPROP	The operation code: 0 for power-level-specified and 1 for reactivity-specified (see Table 9000 definition). If 0, omit Table 6000.
6	IRXSWT	Vapor fraction and quality option. A zero indicates the assumption that subcooled $R = X = 0$ where R and X are the void fraction and quality, respectively. An entry of 1 allows the code to calculate values of R and X in both the sub-cooled and saturation regions.
7	IPOP	Coolant pressure code: 0 for the inlet pressure level being specified (see item 15), and 1 for outlet pressure level being specified. Affects only the pressure values being reported in the output. These values are for information purpose only since they are not used as part of the solution.
8	KINTS	Kinetics time step parameter: 0 for reduce and expand, 1 for reduce only, and -1 for reduce only and force printout. In the zero option, the time step is reduced, when necessary, for the neutron kinetics calculations and then expanded to the input-specified or hydrodynamics-specified time step, whichever controls. An integral number of neutron kinetics time steps are contained in each input-specified or hydrodynamics-specified time step. In the 1 option, the time step is reduced for the neutron kinetics calculations, whenever necessary, and this same time step is used for the other calculations (thermal and hydrodynamic), as well. The -1 option is the same as the 1 option except that the printout is forced whenever time step reduction is affected. Reactivity feedback to the neutronics is computed in conjunction with the thermal-hydraulics calculations, and the first estimate of feedback at any particular time node is necessarily based on an extrapolation (since the value is needed prior to the thermal-hydraulics calculations). Therefore, at any time node at which only neutronics calculations are made (zero option), the value of the reactivity is obtained by extrapolation rather than direct calculation. Therefore, the zero option should be used with caution. A value of 2 may also be used for slow reactivity insertion transients that show some irregularity in the kinetics solution.
9	IDLYGP	The number of delayed neutron groups, where $1 \leq IDLYGP \leq 30$.
10	KINPRT	Kinetics print parameter: 0 for no intermediate printout, 1 for printout after every input-specified or NPOFQ-th (see Section 7.15 describing Table 16 for definition of NPOFQ) hydrodynamics-specified time step, and -1 for printout by subroutine TRANSS includes time, reactor power, reactivity, the maximum outlet flow rate of all channels, and average reactor period.
11	ISUPPR	Average temperature printout option. A zero yields no average temperature printout. For an entry of >0, average temperatures for each of the various regions (e.g. fuel, gap or insulator, and clad) are

printed for each axial node of each channel at every ISUPPR time node. These temperatures represent the volumetric average temperatures averaged radially for each of the axial sections, and their printout precedes the detailed printout for the time node to which they apply. If ISUPPR>0, output file TBAR.out can be very large. Try using 1000.

12	MAXHCC	The maximum number of iterations through the heat transfer calculations at each axial node at any given time node. If MAXHCC ≤ 0 , the problem will terminate when the heat code iterations exceed MAXHCC at any axial node. If MAXHCC > 0 and the heat code iterations exceed MAXHCC at any particular axial node, the problem continues, but the temperature printout at that node is accompanied by an asterisk (*). Furthermore, a printout is forced in such cases. This indicates a possible need for a finer radial mesh.
13	POWER	Initial reactor power, megawatts (>0). See card 1113 (OPT, POW0)
14	PF	Total volume of fuel meat in the core.
15	PRESUR	Operating pressure (inlet or outlet), in pounds per square inch (must be between 14.7 and 50.0) or in Pa (1.0E5 and 3.4E5) for the default binary library. This is absolute pressure. The library is extended to higher pressure as needed, automatically.
16	ENTHIN	Enthalpy of inlet coolant in units of Btu/lb or J/kg (> 0). At the users option, the inlet coolant temperature (C or °F) may be used in lieu of its enthalpy by entering the negative of that temperature. The code converts the temperature into the corresponding enthalpy and proceeds as usual. If the flow is negative or becomes negative (i.e., from top of core to bottom), the code senses this and estimates from the previous time step what the prescribed bottom value must be to obtain the desired value of the enthalpy at the top. This can lead to inaccurate inlet values when rapid changes occur such as the commencement of boiling in the channel.
17	RS	Fuel pin radius or plate half-thickness (including clad).
18	RF	Fuel radius or half-thickness. Items 17 and 18 must be in agreement with the radial description given on the 3000 series lines (section III-1.4).
19	RC	Radial distance to inner surface of the clad or, for slab geometry, the half-distance to the inner surface of the clad. This is the same as item 18, unless another material (e.g. gas gap) lies between fuel and clad.
20	PW	Plate width. Set to zero for cylindrical geometry.
21	FW	Fuel width. Set to zero for cylindrical geometry. Items 20 and 21 must both be greater than zero for slab geometry and item 20 greater than or equal to item 21.
22	AL	Active fuel length must be in agreement with the axial description

		given on the 4000 series lines (section III-1.5).
23	ALDDIN	Inlet non-fueled section length (≥ 0). Note: full hydraulic length = ALPPIN+ALDDIN+AL+ALDDEX+ALPPEX
24	ALDDEX	Outlet non-fueled section length (≥ 0). Items 23 and 24 refer to end sections of the fuel elements which contain no active fuel.
25	BBEFF	Effective delayed neutron fraction, β (>0).
26	EL	Prompt neutron generation time, l_p , in seconds (>0).
27	GRAV	Acceleration due to gravity, in units of ft/sec^2 or m/s^2
28	QW	Heat source description for coolant (dimensionless and ≥ 0). This parameter is the fraction of the heat generated in the coolant multiplied by the ratio of the fuel meat volume to the coolant volume. The heat is assumed to be deposited instantaneously (e.g. gamma heating). It is in addition to the power otherwise specified. To be consistent, one can use $QR < 1$ to place fraction QR of the heat generation in the fuel meat, and adjust QW such that $QR + QW \cdot (\text{coolant volume}) / (\text{meat volume}) = 1.$ Example: Direct Heating to the Coolant Assume that fraction 0.06 of fission heat is delivered directly and instantaneously to the coolant. The following input parameters are defined: IGEOM=0; NCHN=-2; AL=0.5 m RF=0.0004 m RC=0.0004 m RS=0.0009 m RN(channel 1)= 0.0019 m; BM(channel 1)=0.01 RN(channel 2)= 0.0020 m; BM(channel 2)=0.99 PW=FW=3.375 m PF=1.3500E-3 m^3 Then the water volumes are 3.375E-3 m^3 in channel 1, and 3.7125E-3 m^3 in channel 2. When scaled by BM, the water volumes in the reactor core are 3.375E-5 and 3.675376E-3 m^3 . Hence the "TOTAL WATER VOLUME" edited by PARET is 3.70912E-3 m^3 . From these volumes one obtains $QW = 0.06 * (1.3500\text{E-}3 / 3.70912\text{E-}3) = 0.021838.$
29	TRANST	Transient time, in seconds (≥ 0). This is the total reactor time interval (not computation time) over which it is desired to investigate

		the transient. If zero, only a steady-state calculation will be made. IONEP=1, 2, or 4 requires TRANST>0 before wall temperature effects can be computed.
30	RXXCON	A constant, C_2 (dimensionless), in the void volume generation Eq. (87) (recommended value 0.8)
31	RXXEXP	An exponent, n (dimensionless), in Eq. (87). (recommended value 1.0)
32	RHOREF	Coolant reference density, in units of lb/ft^3 or kg/m^3 (>0). This represents the density of the coolant at the initial reactor conditions. If $I_k = 3$ or 4, see section III-1.6 item 2a, then this value is overridden within the code to assure accurate density difference calculations in natural convection. The new value is printed out to make the user aware of this.
33	GAMMA0	<p>This term will have no effect in any problem other than to change the level of temperature feedback at $t=0$. Set it to zero.</p> <p>Coefficients for the fuel temperature feedback equation. See Eq. (35) See also section III-1.6 item 4c of this document.</p> <p>$\rho(\\$) = \gamma_0 + \gamma_1 T + \gamma_2 T^2 + \gamma_3 T^n$; $T(C) = T(K) - 273.15$ if $\gamma_4 = -273.15$</p> <p>$T(F) = T(R) - 459.58$ if $\gamma_4 = -459.58$</p> <p>Note: the code operates in R if NCHN is positive; else in K. Use of γ_4 as shown converts to F or C.</p> <p>Example: suppose that the fuel temperature feedback Eq. is:</p> $[0.001548 + 1.76E-5 T], \text{ } \$/^{\circ}\text{C}$ <p>This is equivalent to:</p> $[1.161E-5 + 1.32E-7 T], \Delta k/k/^{\circ}\text{C}$
34	GAMMA1	
35	GAMMA2	
36	GAMMA3	
37	GAMMA4	
38	DOPPN	The exponent, n , used in the fuel temperature feedback Eq. referred to above, items 33-37.
39	EPS3	Upper limit for kinetics time step test, Q_H (dimensionless). (see Section 3.2.1) Recommend 0.001.
40	DNBQDP	Transient DNB heat flux. If a value of zero is entered here, the code uses steady-state DNB heat flux values calculated internal to the code for each axial node at each time node. If a nonzero value is entered, this value is used as the DNB heat flux for each axial node at each time node.(see Section 3.3)
41	TAUUNB	Nucleate boiling bubble collapse time, τ_{NB} (in seconds). See Eq. (127) Recommend 0.001
42	TAUUTB	Transition boiling bubble collapse time, τ_{NB} (in seconds). See Eq. (127). Recommend 0.001

43	ALAMNB	Fraction of the clad surface heat flux, λ_{NB} , which is utilized in producing vapor in the sub-cooled nucleate boiling region. See Eq. (127) The fraction $(1 - \lambda_{NB})$ would be used in heating the bulk liquid rather than in producing vapor. Recommend 0.05
44	ALAMTB	λ_{TB} ; analogous to item 43, except that it applies to transition boiling. Recommend 0.05
45	ALAMFB	λ_{FB} ; analogous to item 43, except that it applies to film boiling. Recommend 0.05
46	HTTCON	Natural convection heat transfer constant No. 1 (δ), (see Eq. (78)). Only used when the Reynolds number is less than 2300 and IHT=0. Alternatively this is laminar flow Nusselt No. when $IHT \geq 1$ (see 1112 card for loss-of-flow transients). The Sellars correlation is recommended at $Nu=4.36$.
47	HTTEXP	Natural convection heat transfer constant No. 2: exponent (n), (see Eq. (78)). Only used when the Reynolds number is less than 2300.

5.4 ADDITIONAL GENERAL INFORMATION

ITEM	FORTTRAN VARIABLE	DESCRIPTION
		Data required for revisions that have been made to the PARET code are included in the 111X lines: → 1111, PSUBC, FACT2(1), ..., FACT2(NCHN)
1a	PSUBC	Total cross sectional area of all flow channels in core. (no longer used; provide a value as a place holder)
2a	FACT2 (50 as APPENDIX V)	Flux weighting factor; NCHN values entered on the type 1111 line. FACT2(I) is a factor along with the reactivity feedback weighting factor (section 5.8 item 5a) of the coolant energy and coolant energy removed which are outputs on the header page of major edits. FACT2(I) has no effect on code calculations or results. Its physical significance is not clear and has been taken as unity in ANL calculations. If less than NCHN-2 values are supplied, the code defaults to 1.0 for all values. If $NCHN > 4$, supply only 2 values.

The PARET code supports a selection of heat transfer, flow instability, and DNB correlations and includes a tabulation of decay heat power based on the ANS curve for fission product decay heat. The code also provides a simulation of control rod reactivity insertion with rate and delay time settings, trip points for low flow, period, and overpower, and leg lengths for natural convection effects. The required input for the types 1112, 1113, and 1114 lines follow:

→ 1112, IONEP, ITWOP, IMODE, ICHF, IHT, QAVE, ETA,

CP

- 1b IONEP Single-phase correlation flag
0 - original Dittus - Boelter [31]; the Rosenthal & Miller option is selected if it is the largest heat transfer coefficient.
±1 - Sieder - Tate [32]
±2 - Petukhov - Popov (Must have IHT=0, see 5b) [33]
±3 – Colburn [34]
±4 - Russian
±5 - China Inst. of Atomic Energy MNSR correlation [7] to replace the default PARET natural circulation model
±6 – Dittus-Boelter modified by ANL, scaled by a factor of $[\mu_b/\mu_w]^{0.11}$
±7 – original Dittus - Boelter

Note: IONEP can be negative or positive. If positive, the Rosenthal & Miller transient heat transfer coefficient can be selected if it is the large heat transfer coefficient (this typically occurs when the reactor is on a very short period). If negative, it is never selected. It is calculated from:
$$h=[k\rho C_p/T]^{1/2}$$

where k, ρ , and C_p are the coolant thermal conductivity, density, and specific heat, and T is the reactor period in seconds.
- 2b ITWOP Two-phase correlation flag
0 - original Jens - Lottes [18]
1 – McAdams [16]
2 - No longer available (see users' guidelines)
- 3b IMODE Transient two-phase scheme
0 - original model
1 - transition model, single-phase to two-phase (calls htran2)
2 - ATHENA [35] options for heat transfer; selects 'ORNL ANS 102' options (developed for the Advanced Neutron Source Reactor); original PARET film boiling h
3 – Like 2, but uses Groeneveld film boiling table
4 – Like 2, but uses ATHENA 101 options
5 – Like 3, but uses ATHENA 101 options
Options 2-5 yield CHF margin based on 2006 Groeneveld CHF table.
- 4b ICHF DNB and flow instability correlations
0 - original DNB

1 - Bernath DNB [13]

2 - Mirshak DNB [36]

The following options are not appropriate for use with IMODE=2-5:

3 - Forgan FIR (Plate geometry only—code checks)

4 - CEA FIR (Plate geometry only—code checks)

5 - Lund DNB (cylindrical pin geometry only)

6 - Lund DNB (as option 5, but with bowed pin included)

7 - Groeneveld 2006 CHF lookup table

5b	IHT	Single-phase heat transfer subroutine selection 0 - original; entrance effects included when Reynolds No. $Re \leq RET_T$; code uses subroutine htran0 1 - revised, without entrance effects for h; code uses subroutine htran2 (assumes fully-developed flow) 2 - revised, with entrance effects for simultaneously developing velocity and thermal profiles for h when $Re \leq RET_T$; code uses subroutine htran2. See card 1114 for RET_T
6b	QAVE	Average (core) heat flux used with ICHF = 3 & 4 [Btu/hr ft ² or W/m ²]
7b	ETA	Bubble detachment parameter for ICHF = 3 (default 25)
8b	CP	Specific heat used with ICHF = 3 & 4 [Btu/lb - °F or J/kg - °K] (default 1.0)
→ 1113, RDRATE, TDLAY, POWTP, FLOTP, OPT, POW0		
1c	RDRATE	Constant rate for control rod movement (with scram or withdrawal) [ft/sec or m/sec] or if set to -1.0, Table 18 sets the rate of motion (see Table 18) (default 0.0)
2c	TDLAY	Delay time before rod starts in after trip [sec] (default 36000 sec)
3c	POWTP	Overpower trip point [MW] (default 10000 MW)
4c	FLOTP	Low flow trip point [%] (default 0.0%; not <0)
5c	OPT	Previous operation time of reactor - Used in decay heat level after scram [days] (default 24.0 days)
6c	POW0	Previous operating power of the reactor - Used in decay heat power after scram [MW] (default - initial power input for startup of transient). Decay heat power is checked against initial power. If decay heat exceeds initial power, it is added to POWER and a message is written to notify of the change. The decay heat contribution is held constant at the value at time zero, until a trip occurs. Then the decay heat contribution begins to decay at time $T_{trip} + T_{delay}$.

→ 1114, HNCTOP, HNCBOT, REL_T, RET_T, FINF, PHI

1d	HNCTOP	Height above reactor for natural convection effects.
2d	HNCBOT	Height below reactor for natural convection effects.
		If both HNCTOP and HNCBOT in line 1114 are 0.0, no output is printed for them. These lengths would include the non-fueled section length, Section 5.3 items 23 and 24, and any plenum above or below the core.
3d	REL_T	Reynolds number lower limit for entrance effects (not used; set to 2300 by default)
4d	RET_T	Reynolds number below which entrance effects are computed per IHT flag (set to 6000 by default)
5d	FINF	Fin heat transfer enhancement factor from clad to coolant (h with fins divided by h without fins). (Set to 1.0 by default). One correlation that is used to calculate FINF is the one created by Carnavos [48,49]. It is limited to turbulent flow for $10,000 < Re < 100,000$. There are other geometrical limits on it as well. For PARET, a check is made on the local Reynolds Number. If not in the above range, a WARNING is issued, but the calculation is not terminated and the user-supplied value of FINF is used as given.
6d	PHI	Laminar flow friction factor correction factor: $f_{\lambda} Re = 64 / PHI$ Used for $Re < 2200$. Use 2/3 for flat plates.

→ 1115, PERTP, PTDLAY

1e	PERTP	Period trip point, seconds (default = 0.0001 s). This trip applies only to positive periods. It is initiated by the period becoming less than this value.
2e	PTDLAY	Delay time before rod starts in after trip, seconds (default=36000 s) This card can be omitted if defaults are desired.

→ 1116, SUTOL(1), SUTOL(2), SUTOL(3), SUTOL(4), ENTHHS

SUTOL(1)	Shortened channel output file filter tolerance (default=0.5 C) for peak fuel temperature
SUTOL(2)	Shortened channel output file filter tolerance (default=0.5 C) for peak clad temperature
SUTOL(3)	Shortened channel output file filter tolerance (default=0.5 C) for peak coolant temperature
SUTOL(4)	Shortened channel output file filter tolerance (default=0.5 C) for peak coolant exit temperature

ENTHHS Enthalpy of inlet coolant after flow reversal in units of BTU/lb or J/kg (>0). At user option, the inlet temperature (C or F) may be used in lieu of enthalpy by entering the negative of that temperature. Default: ENTHIN is used if zero supplied. See input for Table 21.

→ 1117, IDKOPT,EPFU5

IDKOPT(1) 0, Default value to select ANSI/ANS 2005 decay heat model
1, Select 1973 ANS decay heat model

EPFU5(2) Energy per fission, MeV. Default is 200.0.

5.5 THERMAL PROPERTIES OF FUEL ELEMENT MATERIALS

5.5.1 WHEN USING OPTION IGEOM = 0 OR IGEOM = 1

These data are input on a pair of lines in the form

Items 1 - 5, [ALPHA1 (10), ..., ALPHA5 (10)] → 200X₁, $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$

Items 6 - 10, [BETA1 (10), ..., BETA5 (10)] → 200X₂, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$

Description

Notes:

(a) There is one pair of lines per material, the number of materials being no more than 10. The fuel meat, by convention, must be the first material. The clad must be the last material.

(b) $X_2 = X_1 + 1$

(c) $X_1 = 1$ for the first material, 3 for the second, and 5 for the third, etc., up to 19 ($X_2 = 2, 4, 6, \dots, 20$).

(d) The α_n , ($n = 1, 2, \dots, 5$) are the thermal conductivity coefficients of the material for an Eq. of the form

$$k_{n+1/2}^m = \alpha_1 T^2 + \alpha_2 T + \alpha_3 + \frac{\alpha_4}{T}$$

Temperature is determined as follows:

1. Define $u_{bar} = 0.5 [u_n^m + u_n^{m+1}]$, where:

u_n^m is the temperature of the material at the n_{th} spatial (radial, axial) node at the m_{th} time node. Because internal temperatures in PARET are in Fahrenheit, the u_n are in F and so is ubar.

2. If the user requested SI units (NCHN<0), T' is set to the equivalent temperature to ubar on the Kelvin scale. Then α_5 is added $T=T'+\alpha_5$ to either leave T in K (Kelvin), if α_5 is zero, or in C (Celsius) if α_5 is -273.15.
3. If the user requested United States Customary units (NCHN >0), T' is set to ubar and is in Fahrenheit.

$$T'=ubar$$

$$T=T'+\alpha_5$$

Then α_5 is added to either leave T in F, if α_5 is zero, or in R (Rankine) if α_5 is +459.67.

$k_{n+1/2}^m$ is the thermal conductivity of the material between the n_{th} and $n + 1^{st}$ radial nodes, in units of

$$\frac{\text{Btu}}{\text{hr} - \text{ft} - ^\circ\text{F}} \text{ or } \frac{\text{W}}{\text{m}^\circ\text{K}}$$

Note: the above units for k should be replaced: R for F, or C for K, if those options are used.

- (e) The β_n ($n = 1, 2, \dots, 5$) are the volumetric heat capacity coefficients of the material for an Eq. of the form

$$g_{n+1/2}^m = \beta_1 T^2 + \beta_2 T + \beta_3 + \beta_4 / T$$

$g_{n+1/2}^m$ is the volumetric heat capacity of the material between the n_{th} and $n + 1^{st}$ radial nodes, in units of

$$\frac{\text{Btu}}{\text{ft}^3 - ^\circ\text{F}} \text{ or } \frac{\text{J}}{\text{m}^3 - ^\circ\text{K}}$$

Note: the above units for g should be replaced: R for F, or C for K, if those options are used. See item (d) above for the definition of temperature.

5.5.2 WHEN USING OPTION IGEOM = 2

These data are input on a pair of lines in the form

Items 1 - 5, [ALPHA1 (10), ..., ALPHA5 (10)] → **200X₁**, α_1 , α_2 , α_3 , α_4 , α_5

Items 6 - 10, [BETA1 (10), ..., BETA5 (10)] → **200X₂**, β_1 , β_2 , β_3 , β_4 , β_5

Description

Notes:

(a) There is one pair of lines per material, the number of materials being no more than 10. The fuel meat, by convention, must be the first material. The clad must be the last material.

(b) $X_2 = X_1 + 1$

(c) $X_1 = 1$ for the first material, 3 for the second, and 5 for the third, etc.

(d) The α_n , ($n = 1, 2, \dots, 5$) are the thermal conductivity coefficients of the material for an Eq. of the form

$$k_{n+1/2}^m = \alpha_1 T^2 + \alpha_2 T + \alpha_3 + \frac{\alpha_4}{T}$$

Temperature is determined as follows:

1. Define $ubar = 0.5 [u_n^m + u_n^{m+1}]$, where:

u_n^m is the temperature of the material at the n_{th} spatial (radial, axial) node at the m_{th} time node. Because internal temperatures in PARET are in Fahrenheit, the u_n are in F and so is $ubar$.

2. If the user requested SI units ($NCHN < 0$), T' is set to the equivalent temperature to $ubar$ on the Kelvin scale. Then α_5 is added:

$$T = T' + \alpha_5$$

to either leave T in K (Kelvin), if α_5 is zero, or in C (Celsius) if

α_5 is -273.15.

3. If the user requested United States Customary units ($NCHN > 0$), T' is set to $ubar$ and is in Fahrenheit.

$$T' = ubar$$

$$T = T' + \alpha_5$$

Then α_5 is added to either leave T in F, if α_5 is zero, or in R (Rankine) if α_5 is +459.67.

$k_{n+1/2}^m$ is the thermal conductivity of the material between the n_{th} and $n + 1^{st}$ radial nodes, in units of

$$\frac{\text{Btu}}{\text{hr} - \text{ft} - ^\circ\text{F}} \text{ or } \frac{\text{W}}{\text{m} - ^\circ\text{K}}$$

Note: the above units for k should be replaced: R for F, or C for K, if those options are used.

(e) The β_n ($n = 1, 2, \dots, 5$) are the volumetric heat capacity coefficients of the material for an Eq. of the form

$$g_{n+1/2}^m = \beta_1 T^2 + \beta_2 T + \beta_3 + \frac{\beta_4}{T}$$

$g_{n+1/2}^m$ is the volumetric heat capacity of the material between the n_{th} and $n + 1^{st}$ radial nodes, in units of

$$\frac{Btu}{ft^3 - ^\circ F} \text{ or } \frac{J}{m^3 - ^\circ K}$$

Note: the above units for g should be replaced: R for F, or C for K, if those options are used. See item (d) above for the definition of temperature.

In order to accommodate two or more quite different classes of “channels” containing different materials, the IGEOM=2 option reads the composition data in an alternative manner.

This data (for this beta version) is not read by the standard input processor. Instead, it is read in a new subroutine expecting fixed-format data. Checks are made that card id’s are in sequence, and that NCLASS, NMAT, NLO, and NHI are acceptable (non-zero, and not over its own limit). If not, a fatal error occurs and an error message is issued.

When all assignments of the input to channels are complete, a final check is made that no channel is left without material assignments.

The formats used are the same as those used by the standard input processor, when the input is in most compact form.

CARD 1: NCARD,NCLASS

FORMAT(I4,2X,I6)

NCARD is the card id, which must be 2001 (it is checked).

NCLASS is the number of classes of CHANNELS (1 ... NCHN)

Note: NCLASS is 1 if all channels are alike regarding the number, sequence from plate centerline, and properties of materials in the fuel plate. In that event, the user only supplies one set of data, which is expanded out to all channels. NCLASS is NCHN if all channels are different regarding the sequence and properties of materials in the fuel plate.

FOR EACH CLASS FROM 1...NCLASS, SUPPLY THE FOLLOWING:

CARD TYPE 2: NCARD,NMAT

FORMAT(I4,2X,I6)

NCARD is the card id, expected to be in sequence after CARD 1 value.

NMAT is the number of materials in this class of fuel plate. For each material, two input cards are read: types 3 and 4.

CARD TYPE 3: NCARD, ALPHA1,...ALPHA5 → 200X₁, α_1 , α_2 , α_3 , α_4 , α_5

FORMAT(I4,2X,5E12.5)

CARD TYPE 4: NCARD, BETA1,...BETA5 → 200X₂, β_1 , β_2 , β_3 , β_4 , β_5

FORMAT(I4,2X,5E12.5)

Note 1: The code will number the materials in the order provided, from 1 to MNAT. This numbering begins again from 1...NMAT for each class.

Note 2: All values of NCARD are checked that they are in sequence. If not, a fatal error occurs and an error message is issued.

EXAMPLE: NCHN=6, BUT TWO CLASSES OF FUEL PLATES

Class 1 consists of two materials in the fuel plate.

Class 2 consists of three materials in the fuel plate.

2001,	2					
2002,	2					
2003,		0.0	0.0	151.53	0.0	0.0
2004,		0.0	1014.0	2.01140+6	0.0	0.0
2005,		0.0	0.0	183.11	0.0	0.0
2006,		0.0	1243.4	2.07090+6	0.0	0.0
2007,	3					
2008,		0.0	0.0	151.53	0.0	0.0
2009,		0.0	0.0	3.00000+6	0.0	0.0
2010,		0.0	0.0	200.00	0.0	0.0
2011,		0.0	0.0	2.50000+6	0.0	0.0
2002,		0.0	0.0	100.00	0.0	0.0
2013,		0.0	0.0	1.00000+6	0.0	0.0

5.6 RADIAL OR HALF-PLATE THICKNESS DESCRIPTION

The radial description refers to cylindrical geometry and half-plate thickness (symmetry assumed) to slab geometry. Each line is of the form

5.6.1 WHEN USING OPTION IGEOM = 0 OR IGEOM = 1

ITEM	FORTTRAN VARIABLE	DESCRIPTION
→ 3XXX, Y, I, J, Z, K		
where XXX = 001, 002, ..., 999		
1	AINCR	Y is the Radial increment length, (>0)
2	KK	I is the radial node out to which the increment applies (integer and >0)
Note: the first card, type 3001, must have $I \geq 2$ in order to define the zero radius point		
3	ICOMP	J is the composition code represented by one of the 10 integers 1, 2, ...10. The composition code begins at the center; i.e., the fuel is composition 1, the next material is composition 2, etc. The clad is the last composition (so the code will know which is clad, even if the clad is not the outermost material next to coolant) and the maximum number of materials is 10. If there are more than one meat layers, assign the outermost meat layer to composition 1. This enables satisfying an error check on meat outer radius.
4	QR	Z is the radial source description (≥ 0). The heat source is assumed to be separable into a function of time, a function of radius, and a function of axial position. QR is dimensionless, as it is with reference to the core average power density. If the radially averaged value of

QR=1., one obtains the full output power from the fuel meat retained in the meat for conduction. If the radially averaged value of QR<1., then there should be direct heating to the coolant to compensate (see item 28, QW, in Section 5.3). The function of axial position is specified on card type 5k00 as variable PFQ.

Notes:

- (a) On line 3001 (XXX=001) the first I -1 radial increment will be represented (I > 2) all of length Y, composition J (see 2000 series lines), and radial heat source magnitude Z.
- (b) On each succeeding line the Y, I, J, and Z values apply to radial increments following those covered by the previous line, up to I - 1 from the new line.
- (c) When either the radial increment, the composition code, or the radial source description changes from one node point to the next, a new line must be input for the next node point or node points.
- (d) The 3000 - series lines describe the pin or plate from the centerline to the outer surface of the clad. The node point at the fuel centerline is node point number one (not zero).
- (e) The sum of the increment lengths between successive pairs of node points must be equal to the pin radius or plate half-thickness given in section 5.3 item 17; also, the dimensions given in items 18 and 19 must bear a correct correspondence to the dimensions given on these 3000 - series lines.
- (f) If QR of a node is zero in a fuel meat node, the contribution to Doppler feedback will be zero.

5 ICLAD K is the node point (interface) number to be edited as "CLAD TEMPERATURE" in edits of peak clad temperature. Any node point can be selected: $1 \leq K \leq NR$. The code assumes that node point 1 is the fuel centerline (slab) or axis (cylindrical). **Caution:** the user MUST put ICLAD on the last type-3000 card. By default it is set to NR if not provided.

- Geometry Example 1: (meat + clad + oxide). The rules are (for slab geometry):
#18 RF = fuel plate meat half thickness
#19 RC = RF as fuel meat is in contact with clad
#17 RS = RF + clad thickness + oxide thickness
card 3000 series:
card 3001: choose $AINCR = RF/(KK-1)$
card 3002: choose $AINCR = (\text{clad thickness})/KK$
card 3003: choose $ANICR = (\text{oxide thickness})/KK$
- Geometry Example 2: (meat + gap + clad + oxide layer). The rules are (for slab geometry):
#18 RF = fuel plate meat half thickness
#19 RC = RF + gap thickness as fuel meat is not in contact with clad

#17 RS = RF + gap thickness + clad thickness + oxide layer thickness

Card 3000 series:

card 3001: fuel: choose AINCR = RF/(KK-1)

card 3002: gap: choose AINCR = (gap thickness)/KK

card 3003: oxide layer: choose AINCR = (oxide thickness)/KK

card 3004: clad: choose AINCR = (clad thickness)/KK (clad must be the last material)

5.6.2 WHEN USING OPTION IGEOM = 2

This input is generalized to enable having classes of channels, where each channel in a given class has identical radial mesh and composition descriptions. But within that class, the other channel-dependent characteristics still are available. There can be up to 120 classes of channels (i.e. every channel in the problem can be unique radially). The purpose of this is to enable having different types of fuel such as LEU and HEU, or different burnup, in the same core model. The input data provided by class is expanded to define the radial data for every channel. A check is made to confirm that all channels are defined.

ITEM	FORTTRAN	DESCRIPTION
	VARIABLE	

→NNNN, I

1	NNNN	3001, The first card of this series
2	NCLASS	Number of classes of channels, each class potentially having different numbers of radial nodes and compositions

For each class (1...NCLASS) provide the following sets of data:

→ LLLL, I, J, K, L, M

1	LLLL	The next card of this series
2	NLO	Lowest channel number to which this class applies
3	NHI	Highest channel number to which this class applies
4	NMAT	Number of materials in this class
5	NR	Number of radial nodes in this class
6	ICLAD	Radial node at which peak temperature is desired. M is the node point (interface) number to be edited as "CLAD TEMPERATURE" in edits of peak clad temperature. Any node point can be selected: $1 \leq K \leq NR$. The code assumes that node point 1 is the fuel centerline. Default: ICLAD either zero or blank yields NR. It need not be the same in all classes.

For each class, the radial definition data is of the form

ITEM	FORTTRAN	DESCRIPTION
	VARIABLE	

→ LLLL, Y, IJZ

where

1	AINCR	Y is the radial increment length, (>0)
2	KK	I is the radial node out to which the increment applies (integer and >0) Note: the first card, type 3001, must have $I \geq 2$ in order to define the zero radius point
3	ICOMP	J is the composition code represented by one of the 10 integers 1, 2, ...10. The composition code begins at the center; i.e., the fuel is composition 1, the next material is composition 2, etc. The clad is the last composition (so the code will know which is clad, even if the clad is not the outermost material next to coolant) and the maximum number of materials is 10. The meat can be anywhere in the pin, but it must have the lowest composition number. For example, the innermost part of the pin can be a non-fissionable material. The composition data supplied on type-2000 series input are generalized to be by fuel type number. A simple problem with all channels identical will have NCLASS=1. If more than one fuel meat layer is present, then make the outermost (radially) meat composition be number 1 in order to satisfy a radial mesh check comparing with RF.
4	QR	Z is the radial distribution of power density in fuel meat averaged over the radial increment (≥ 0). The heat source is assumed to be separable into a function of time, a function of radius, and a function of axial position. QR is dimensionless, as it is with reference to the core average power density. If the average $QR=1$, one obtains the full output power from the fuel meat retained in the meat for conduction. If the average $QR<1$, then there will be direct heating to the coolant to compensate. The function of axial position is specified on card type 5k00 as variable PFQ.

Notes:

- (a) On line 3001 (XXX=001) the first I -1 radial increment will be represented ($I > 2$) all of length Y, composition J (see 2000 series lines), and radial heat source magnitude Z.
- (b) On each succeeding line the Y, I, J, and Z values apply to radial increments following those covered by the previous line, up to I - 1 from the new line.
- (c) When either the radial increment, the composition code, or the radial source description changes from one node point to the next, a new line must be input for the next node point or node points.
- (d) The 3000 - series lines describe the plate from the centerline to the outer surface of the clad. The node point at the fuel centerline is node point number one (not zero).
- (e) The sum of the increment lengths between successive pairs of node points must be equal to the plate half-thickness given in section

5.3 item 17; also, the dimensions given in items 18 and 19 must bear a correct correspondence to the dimensions given on these 3000 - series lines.

(f) If QR of a node is zero in a fuel meat node, the contribution to Doppler feedback will be zero.

- Geometry Example 1: (meat + clad + oxide). The rules are (for slab geometry):
 #18 RF = fuel plate meat half thickness
 #19 RC = RF as fuel meat is in contact with clad
 #17 RS = RF + clad thickness + oxide thickness
 Card 3000 series:
 card 3001: choose $AINCR = RF/(KK-1)$
 card 3002: choose $AINCR = (clad\ thickness)/KK$
 card 3003: choose $AINCR = (oxide\ thickness)/KK$
- Geometry Example 2: (meat + gap + clad + oxide layer). The rules are (for slab geometry):
 #18 RF = fuel plate meat half thickness
 #19 RC = RF + gap thickness as fuel meat is not in contact with clad
 #17 RS = RF + gap thickness + clad thickness + oxide layer thickness
 Card 3000 series:
 card 3001: fuel: choose $AINCR = RF/(KK-1)$
 card 3002: gap: choose $AINCR = (gap\ thickness)/KK$
 card 3003: oxide layer: choose $AINCR = (oxide\ thickness)/KK$
 card 3004: clad: choose $AINCR = (clad\ thickness)/KK$ (clad must be the last material)

A sample input for 2 classes of channels follows.

It is known from other input that there are 7 channels in the model. Class 1 covers channels 1 and 2, and has three compositions in 7 radial nodes. Class 2 covers channels 3 to 6, and has 2 compositions in 6 radial nodes. Note that the ICOMP=1 specified for class 1 is NOT the same composition as ICOMP=1 for class 2.

```

3001,      2
3002,      1      2      3      7      7
3003,      4.00000E-3      5      1      0.980
3004,      9.00000E-4      6      2      0.000
3005,      5.00000E-5      7      3      0.980
3006,      3      6      2      6      6
3007,      6.00000E-3      5      1      0.960
3008,      7.00000E-4      6      2      0.000

```

5.7 AXIAL DESCRIPTION

ITEM	FORTTRAN	DESCRIPTION
	VARIABLE	

→ 4XXX, Y₁, I₁, Y₂, I₂, ..., Y_i, I_i, ...Y_n, I_n

where XXX = 001, 001, ..., 999

1	DZ (97)	Y_i is the axial region length (>0)
2	KJ	I_i is the region through which the length Y_i , applies, subject to the conditions
$I_1 \geq 1$ and $I_i \geq I_{i-1}$

Notes:

(a) If there are NZ axial regions, there will be NZ axial node points and NZ -1 axial increments, ΔZ_j , as the illustration in Figure 4. Except for the node points 1 and NZ, all axial node points are located at the center of regions I of length Y. Node 1, however, is located at the one end of the fuel and node NZ at the other end of the fuel, rather than at the center of regions 1 and NZ. Thus

$$\Delta Z_1 = R_1 + 1/2 R_2$$

$$\Delta Z_j = 1/2 (R_j + R_{j+1}); \quad 1 < j < \text{NZ}-1$$

$$\Delta Z_{\text{NZ} - 1} = 1/2 R_{\text{NZ} - 1} + R_{\text{NZ}}$$

where ΔZ_j represents the distance between node point J and J + 1, and R_j represents the length of region j. A maximum of 97 axial regions is allowed.

(b) The 4000 - series lines describe the axial spacing in the active fuel only, beginning at the bottom of the active fuel and proceeding to the top.

(c) The sum of the axial increments must be equal to the active fuel length given in section 5.3 item 22.

(d) The information, Y_i and I_i , must be in pairs; a pair may not be split between two lines.

Figure 4 Axial Node Model for NZ=11

The fluid mesh of region 1 is all of power node 1 + half of power node 2.

The fluid mesh of region 2 is half of power node 2 + half of power node 3.

The fluid mesh of region j is half of power node j + half of power node j+1; $j < NZ-2$.

The fluid mesh of region NZ-1 is half of power node NZ-1 + all of power node NZ.

Notes:

1. Temperatures and enthalpies are edited on the Interfaces.
2. An optimal axial mesh has first and last power nodes half the length of all of the other equal-length power nodes. This makes all fluid nodes equal-length.

Figure 5 Axial Geometry Used in PARET for Friction Pressure Loss Calculations

Notes:

1. AL, ALDDIN, ALDDEX are the same for all n channels.
2. Area and hydraulic diameter used in ALDDIN and ALDDEX are those for length AL and do not depend on INLET vs. EXIT location.

3. There is wall friction in all 5 length segments.
4. K-type pressure loss occurs with velocity based on conditions in axial node 1 or NZ of meat.
5. There are other pressure change effects (e.g., gravity) in PARET.
6. This figure is drawn for up-flow (Table 10, AMFRIN>0).
7. "IN" refers to inlet; "EX" refers to exit.
8. HNCTOP is the sum of ALPPEX + ALDDEX.
9. HNCBOT is the sum of ALPPIN + ALDDIN.

5.8 INDIVIDUAL CHANNEL INFORMATION

ITEM	FORTTRAN VARIABLE	DESCRIPTION
------	----------------------	-------------

The data for each channel are input in the form

→ **5k00, I_k, L_k, X_{k1}, X_{k2}, X_{k3}, X_{k4}, X_{k5}, X_{k6}, X_{k7}, X_{k8}**

or, if there are more than 9 channels:

→ **5kk00, I_k, L_k, X_{k1}, X_{k2}, X_{k3}, X_{k4}, X_{k5}, X_{k6}, X_{k7}, X_{k8}**

Note: place the "50000" series in the input file after any data of lesser number; i.e. at the end of the input file.

1a	k	k = 1 for the first channel, 2 for the second, etc. If a problem includes several channels, some of which are flow-forced and some pressure-drop-forced, the flow-forced channels must be numbered lower than the pressure-drop-forced channels unless the pressure drop is obtained from Table 12. This is necessary because the pressure drop across the flow-forced channels must be calculated before it can be imposed across the pressure-drop-forced channels.
2a	IFLOW(50)	I _k is the flow parameter. (a) 1 for flow-forced channel (flow is specified in Table 10). (b) 2 for pressure-drop-forced-channel (pressure drop is specified in Table 12 or in item 3a (b) below). (c) 3 for buoyant forced flow (in all channels) with pump coast down superimposed from Table 17. Initial flow rate is computed from pressure drop given in next entry. (d) 4, same as 3 except initial flow taken from value at zero time in Table 10. If a problem includes some channels which are flow-forced and some which are pressure-drop-forced, then the flow-forced channels must be first. Otherwise, channel ordering is unimportant.
3a	DELP(50)	L _k is (a) Zero if I _k = 1 (b) Either the pressure drop (lb / in. ² or Pa), or a channel number if

$I_k = 2$ (must be positive or nonzero). In the former case, the pressure drop as a function of time is given in Table 12, but the initial pressure drop must be given here. In the latter case, the channel number given is the number of a flow-forced channel across which the pressure drop is calculated as a function of time. This same pressure drop is then automatically imposed across the pressure-drop-forced channel at corresponding times. The initial pressure drop is specified by DELP for $I_k = 3$. If $I_k = 4$ the floating point number provided affects the initial mass flow direction. If the first entry in Table 10 is positive, set DELP positive. If negative, set DELP negative (it is needed as a place holder) but a zero value should not be specified ($DELP \neq 0.0$).

- 4a RN(50)
1. Rod geometry: X_{k1} is the radial distance from the center of the rod to the node in the center of the water channel. RN is the radius enclosing the heated water per rod.
 2. Plate geometry: X_{k1} is the radial distance from the center of the plate to the node in the center of the water channel. RN is the perpendicular distance from the fuel meat centerline to the center of the coolant channel. Note that the channels on either side of the plate are symmetric.
 3. RN must be positive and greater than RS (the pin surface radius or slab half-thickness).
 4. RN must be positive and greater than RS

5a BM(50) X_{k2} is the overall reactivity feedback weighting factor for channel k. It is applied to two effects:

1. fuel meat reactivity change with temperature;
2. coolant reactivity change with clad expansion treated as equivalent void. It is assumed that, during a rapid transient, the clad may expand, whereas the lattice pitch or plate separation remains fixed. If Table 11 data are active, clad expansion will displace coolant just as void does.

For IGEOM=0 or 1 or 2, set BM(k) equal to the volume fraction of the core meat represented by channel k. All channels have the same meat dimensions, but may have different water channel dimensions.

The sum of the X_{k2} summed over the NCHN channels must be unity.

Note that input cards 5k00 provide, for each channel, values DVOID and DTMP. Input cards 5kXX provide for each axial node m in channel k the Doppler feedback Eq. coefficients DOPPLR, the coolant density feedback weighting factor VOIDVC, and the coolant temperature feedback weighting factor TEMPC. Consequently the final feedback values (\$) obtained for axial node m in channel k at time t are the products:

$$\Delta\rho_{\text{dop}}(k,m) = \text{BM}(k) \cdot [\text{DOPPLR}(k,m)] \cdot V_{\text{fuel}}(j) \cdot [\rho_D(t) - \rho_D(t_0)] / \text{PF}.$$

The total volume of fuel in the core is PF.

Index $j=(k-1)*NZ+m$, where $1 \leq m \leq |NCHN|$;

$V_{fuel}(j)$ is fuel volume in node j ;

$\rho_D(t) = \gamma_0 + \gamma_1 T + \gamma_2 T^2 + \gamma_3 T^n$ at time t .

DOPPLR(k,m)] is variable D_{jk} of ref.[1].

6a	ALOSCN(50)	X_{k3} is an unrecoverable pressure loss coefficient for abrupt change in the area at the inlet to the channel k (> 0). This change is the proportionality constant between the pressure change across the abrupt area change and the fluid kinetic energy. See reference document. $\Delta p = \text{Loss coef.} * \rho v^2 / 2g$
7a	ALOSCX(50)	X_{k4} is the outlet unrecoverable pressure loss coefficient analogous to X_{k3} in item 6a (> 0).
8a	SIGIN(50)	X_{k5} is the inlet area ratio (> 0). This is the ratio of the channel area to the area of the associated inlet plenum. See reference document.
9a	SIGEX(50)	X_{k6} is the outlet area ratio (> 0). This is the ratio of the channel area to the area of the associated outlet plenum.
10a	DVOID(50)	X_{k7} is an overall density/void coefficient. The product of X_{k7} and Z_{kXX} given in item 3c below is the value of the local density/void coefficient at the axial node XX of channel k. The product must be in \$/% of core voided. If Table 20000 is present, it provides a scale factor. Note: the code assumes that this feedback is a negative term. Therefore enter DVOID>0 to create a negative feedback, assuming that VOIDVC is positive. If Table 20 is used, values of VCOWTH also should be positive because the final result is the product of DVOID*VOIDVC*[Table 20 interpolated value].
11a	DTMP(50)	X_{k8} is the coolant temperature coefficient. The product of X_{k8} and TEMPC$_{kXX}$ given in item 5c below is the value of the local coolant temperature coefficient at axial node XX of channel k. The product must be \$/°F or \$/C. If Table 19000 is present, it provides a scale factor. Note: the code assumes that this feedback is a negative term. Therefore enter DTMP>0 to create a negative feedback, assuming that TEMPC is positive. If Table 19 is used, values of TCOWTH also should be positive because the final result is the product of DTMP*TE MPC*[Table 19 interpolated value].
12a	DE(50)	X_{k9} is the equivalent hydraulic diameter of the channel, if supplied. Computed from other data if not supplied. The standard Eq. for hydraulic diameter is $D_h = 4(\text{Flow Area})/[\text{Wetted Perimeter}]$.

The 5k01 lines are input in the format

→ **5k01, L_I, L_E, (De)_I, (De)_E, RFW, RPW, RFLOW**

Where

1b	ALPPIN(50)	L _I is the length of the inlet plenum, (≥0).
2b	ALPPEX(50)	L _E is the length of the outlet plenum, (≥0).
3b	DEEIN(50)	(De) _I is the inlet plenum equivalent hydraulic diameter, (≥0).
4b	DEEEX(50)	(De) _E is the outlet plenum equivalent hydraulic diameter, (≥0). Items (1), (2), (3), and (4) refer to the inlet and outlet plena to and from the coolant flow channels.

The following items are needed if IGEOM=2:

5b	RFW(50)	Ratio of fuel meat width to FW (card 10YY #21).
6b	RPW(50)	Ratio of plate width to PW (card 10YY #20); used for calculation of hydraulic diameter.

Begin a new input line here. The 5k02 lines are input in the format:

→ **5k02, RFLOW,ZQW,RS,RF, RC, FACT3**

7b	RFLOW(50)	Scale factor on mass flow rate per unit area; used to match velocity.
The following 5 items are needed if IGEOM=2:		
8b	ZQW	Heat source description for coolant (dimensionless and ≥0). This parameter is the fraction of the heat deposited in the coolant of each channel. The heat is assumed to be deposited instantaneously (e.g. gamma heating). To be consistent, one can use QR<1 to place fraction QR of the heat generation in the fuel meat, and adjust QW such that
QR + QW = 1 for each channel.

9b	RS	Plate half thickness for this channel.
10b	RF	Fuel meat half thickness for this channel.
11b	RC	Half distance to inner surface of the clad.
12b	FACT3	Set to 1.0 in current version of the code.

The following 6 items are needed if IGEOM=2:

13b	GAMA0K	This term will have no effect in any problem other than to change the level of temperature feedback at t=0. Set it to zero.

14b	GAMA1K	Coefficients for the fuel temperature feedback for channel k.
15b	GAMA2K	See Eq. (35) See also section III-1.6 item 4c of this document.
16b	GAMA3K	$\rho(\$) = \gamma_0 + \gamma_1 T + \gamma_2 T^2 + \gamma_3 T^n$; $T(C) = T(K) - 273.15$ if $\gamma_4 = -273.15$
17b	GAMA4K	$T(F) = T(R) - 459.58$ if $\gamma_4 = -459.58$ Note: the code operates in R if NCHN is positive; else in K. Use of γ_4 as shown converts to F or C. Example: suppose that the fuel temperature feedback Eq. is: $[0.001548 + 1.76E-5 T], \text{ } \$/^{\circ} \text{C}$ This is equivalent to: $[1.161E-5 + 1.32E-7 T], \text{ } \Delta k/k/^{\circ} \text{C}$
18b	DOPPNK	The exponent, n, used in the fuel temperature feedback Eq. referred to above, items 13b-17b The following two items are needed (place after item 4b above) if cylindrical pin geometry (IGEOM = 1), IMODE is 0 or 1, and ICHF is 5 or 6:
5b	PDR(50)	Pitch to diameter ratio
6b	BOWPDR(50)	Bowed pitch to diameter ratio (only if ICHF=6) The remaining 5000 - series lines ($XX \geq 02$) are in the format → 5kXX, Y_{kXX}, Z_{kXX}, DOPPLR_{kXX}, TEMPC_{kXX} Where
1c		k is defined in section 5.8 item 1a above. For IGEOM=0 or 1, XX is 02 for the first line, 03 for the second, etc. For IGEOM=2, XX=04, 05, etc.
2c	PFQ(50*97)	Y _{kXX} is the axial source description for axial node (XX-1). This parameter is the value of the ratio of the local fission power density to the core-average fission power density. The PFQ(K,J) array for each channel K must be normalized so that the axial average of PFQ satisfies the following constraint where PTOT(K) is the total power of channel K and POWER is total reactor power (input item 13 of Section 5.3). See Appendix IV for details. $\overline{\text{PFQ}}(K) = \frac{\text{PTOT}(K)}{\text{POWER} \times \text{BM}(K)}$ The axial average of PFQ for a channel is defined as

$$\overline{\text{PFQ}}(\text{K}) = \frac{\sum_{\text{J}=1}^{\text{NZ}} \text{PFQ}(\text{K}, \text{J}) \times \Delta\text{Z}(\text{J})}{\sum_{\text{J}=1}^{\text{NZ}} \Delta\text{Z}(\text{J})}$$

The orientation of the axial power profile is as follows:

Table 10000 value at time zero is >0 (up flow) implies PFQ(1) is at the core bottom (now inlet) for XX -1=1;

Table 10000 value at time zero is <0 (down flow) implies PFQ(1) is at the core top (now inlet) for XX -1=1

Note: Axial node 1 is always at the bottom of the PARET channel, i.e., at the bottom of a coolant channel, fuel assembly or reactor core depending on the basis of the calculation.

3c	VOIDVC (50*97)	Z_{kXX} is the coolant density feedback weighting factor for axial node (XX-1).
4c	DOPPLR (50*97)	<p>DOPPLR_{kXX} represents the $D_{\text{j,k}}$ parameter in the feedback fuel temperature Eq. . Refer to Eq. (46) of [1].</p> $\left(R_D\right)_{\text{j,k}} = D_{\text{j,k}} \left[\gamma_0 + \gamma_1 \left(\bar{u}_M + \gamma_4 \right) + \gamma_2 \left(\bar{u}_M + \gamma_4 \right)^2 + \gamma_3 \left(\bar{u}_M + \gamma_4 \right)^n \right]$ <p>The above $(R_D)_{\text{jk}}$ must be scaled by $(VF)_{\text{jk}}/PF$ in order to get its contribution to core reactivity. Here $(VF)_{\text{jk}}$ is the fuel volume in a particular channel k and axial node j.</p> <p>The units of the products $D_{\text{j,k}} \times \gamma_i$ ($i=0, 1, 2, 3$) must be consistent with the units of $(R_D)_{\text{jk}}$, which is dollars. In this Eq. the units of the mean temperature of the fuel, $\bar{u}_M$, may be in units of °F or C and γ_4 may be used to convert to degrees Rankine or K.</p>
5c	TEMPC (50*97)	TEMPC _{kXX} is the dimensionless coolant temperature feedback weighting factor for axial node (XX-1). See ANL revisions.

5.9 DELAYED NEUTRON INFORMATION

[Type 6XXX data must not be provided for a power-level-specified problem. See section 7.3 item 5: IPROP. A fatal error will be identified and the run will terminate.]

ITEM	FORTRAN	DESCRIPTION
	VARIABLE	

This information is input in the following format:

→ 6XXX, Y₁, Z₁, Y₂, Z₂, ..., Y_i, Z_i, ..., Y_n, Z_n

where XXX is 001 for the first line, 002 for the second, etc.

1	FRACT(30)	Y_i is the delayed neutron fraction for group i: $Y_i = \beta_i/\beta$ (>0)
2	DECAY(30)	Z_i is the delayed neutron decay constant λ_i for group i (positive, nonzero, and units of sec ⁻¹).
- (a) Number of pairs, n, is given in section 5.3 item 9 as IDLYGP.
(b) Must be in pairs; a pair may not be split between two lines.
- Notes:
- (c) Sum of all Y_i must be in unity; i.e., $\sum_{i=1}^n Y_i = 1.0$, or $\sum_{i=1}^n \beta_i = \beta$.

5.10 POWER OR REACTIVITY VERSUS TIME (TABLE 9)

ITEM	FORTRAN VARIABLE	DESCRIPTION
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1a	NTBL9	This table is input in the following format: → 9000, N

where N is the number of pairs of entries in the table, $2 \leq N \leq 100$.

The succeeding lines are of the form
→ **9XXX, $Y_1, Z_1, Y_2, Z_2, \dots, Y_i, Z_i, \dots, Y_n, Z_n$**

where XXX is 001 for the first line, 002 for the second, etc.

1b	REACC(100)	<p>Y_i is</p> <p>(a) Power (in megawatts) if section 5.3 item 5 is zero
 (b) Reactivity (in dollars) if section 5.3 item 5 is unity
 This is the reactivity which is externally inserted (i.e., not compensated reactivity). The first reactivity entry in the table, Y_1, must be negative or zero.</p> |
|----|------------|--|

2b	TBL9(100)	Z_i is the time (in seconds) associated with Y_i .

Notes:

- (a) The information must be in pairs; a pair may not be split between two lines.
(b) The data must be in ascending order ($Z_i \leq Z_{i+1}$) with $Z_i = 0$ and the last value of Z greater than the total transient time given in section 5.3 item 29.
(c) There must be at least two pairs of table entries. The first entry at time $t=0$ cannot be precisely 0.

5.11 COOLANT INLET MASS FLUX VERSUS TIME (TABLE 10)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
		This table is input according to the following format:
1a	NTBL10	→ 10000, N
		where N is the number of pairs of entries in the table, $2 \leq N \leq 100$.
		Subsequent lines are in the form → 10XXX, Y₁, Z₁, Y₂, Z₂, ..., Y_n, Z_n
		where XXX is 001 for the first line, 002 for the second, etc.
1b	AMFRIN(100)	Y _i is the inlet mass flux (kg/s/m ² or lb _m /hr/ft ²); positive for up-flow, or negative for down-flow.
2b	TBL10(100)	Z _i is the time (in seconds) associated with Y _i .
	Notes:	(a) The information must be in pairs; a pair may not be split between two lines. (b) The data must be in ascending order ($Z_i \leq Z_{i+1}$) with $Z_1 = 0$ and the last value of Z greater than the total transient time given in section 5.3 item 29. (c) There must be at least two pairs of table entries.

5.12 PERCENT LINEAR THERMAL EXPANSION OF THE CLAD VERSUS TEMPERATURE (TABLE 11)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
		This table is input in the following format:
1a	NTBL11	→ 11000, N
		where N is the number of pairs of entries in the table, $2 \leq N \leq 100$.
		Subsequent lines are of the form → 11XXX, Y₁, Z₁, Y₂, Z₂, ..., Y_n, Z_n
		where XXX is 001 for the first line, 002 for the second, etc.
1b	YYCLAD(100)	Y _i is the percent linear thermal expansion of the clad (%).
2b	YCTEMP(100)	Z _i is the temperature (K or °F) associated with Y _i .
		(a) The information must be in pairs; a pair may not be split

- Notes:
- between two lines.
 - (b) The data must be in ascending order ($Z_i \leq Z_{i+1}$) and must include the maximum and minimum average temperatures of the clad to be encountered throughout the course of the problem.
 - (c) There must be at least two pairs of table entries.

5.13 TOTAL PRESSURE DROP VERSUS TIME (TABLE 12)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
------	-------------------	-------------

This table is input in the following format:

1a NTBL12 $\rightarrow 12000, N$

where N is the number of pairs of entries in the table, $2 \leq N \leq 100$.

Subsequent lines are of the form

$\rightarrow 12XXX, Y_1, Z_1, Y_2, Z_2, \dots, Y_n, Z_n$

where XXX is 001 for the first line, 002 for the second line, etc.

1b PRESSP(100) Y_i is the total pressure drop, Δp_T [N/m^2 (Pascal) or psi], across the channel.

2b TBL12(100) Z_i is the time (in seconds) associated with Y_i .

Notes:

- (a) The information must be in pairs; a pair may not be split between two lines.
- (b) The data must be in ascending order ($Z_i \leq Z_{i+1}$) with $Z_1 = 0$ and the last value of Z greater than the total transient time given in section 5.3 item 29.
- (c) There must be at least two pairs of table entries.

5.14 TABLE OF TIME INCREMENT VERSUS TIME (TABLE 14) - [MAY BE MODIFIED FOR RESTARTS]

ITEM	FORTTRAN VARIABLE	DESCRIPTION
------	-------------------	-------------

This table is input in the following format:

1a NTBL14 $\rightarrow 14000, N$

where N is the number of pairs of entries in the table, $2 \leq N \leq 10$.

Subsequent lines are of the form

→ 14XXX, Y₁, Z₁, Y₂, Z₂, ..., Y_n, Z_n

where XXX is 001 for the first line, 002 for the second, etc.

1b	TINCRR(10)	Y _i is the time increment (in seconds)
2b	TBL14(10)	Z _i is the reactor time at which time-step increment is to go into effect (Z ₁ must be zero).

Notes:

- (a) The information must be in pairs; a pair may not be split between two lines.
- (b) The data must be in ascending order ($Z_i \leq Z_{i+1}$), with $Z_1 = 0$. There must be at least two pairs of table entries.
- (c) If two pairs of zeros are entered into Table 14, the code will calculate its own time step on the basis of the hydrodynamics.

5.15 TABLE OF PRINT FREQUENCY VERSUS TIME (TABLE 16) - [MAY BE MODIFIED FOR RESTARTS]

ITEM	FORTRAN VARIABLE	DESCRIPTION
------	---------------------	-------------

This table is input in the format:

1a	NTBL16	→ 16000, N
----	--------	------------

where N is the number of sets of entries in the table, $1 \leq N \leq 10$.

Subsequent lines are of the form
→ 16XXX, Y₁, M₁, Z₁, Y₂, M₂, Z₂, ..., Y_n, M_n, Z_n

where XXX is 001 for the first line, 002 for the second, etc.

1b	TOPFQ(10)	Y _i is the print time increment (in seconds) for major output edits.
2b	NPOFQ(10)	M _i is the frequency of intermediate printout (i.e., every M _i steps).
3b	TBL16(10)	Z _i is the reactor time at which print time increment is to go into effect (Z ₁ must be zero).

Notes:

- (a) Major output edits will occur at
0, Y₁, 2Y₁, ..., Z₁, Z₁ + Y₂, Z₁ + 2Y₂, ..., Z₂, Z₂ + Y₃, ..., etc.
- (b) Intermediate output edits will occur ever M_i steps when $Z_i < \text{time} < Z_{i+1}$.***

(c) The information must be in triplets; a triplet may not be split between two lines.

(d) The data must be in ascending order ($Z_i \leq Z_{i+1}$), with $Z_1 = 0$.

(e) In addition to the output indicated in section 7.3 item 10, the minimum burnout ratio, the minimum bubble detachment parameter (ETA), the maximum temperature in the coolant, clad, and fuel, and the nucleate (1), transition (2), film (3), and bulk (4) boiling point indicators are printed at each intermediate output time.

*** See the attached tabulation of increment choices by time step size (Table 1).

Table 1 Print-Edit Increment Selection for Table 16

Time Step, seconds	Major Edit Increments	Number of Minor Edits per Increment				
		M_i				
Table 14	Y_i	1	5	10	20	50
0.05	2.0	40	8	4	2	-
	1.0	20	4	2	1	-
	0.5	10	2	1	-	-
0.01	1.0	100	20	10	5	2
	0.5	50	10	5	2	1
	0.1	10	2	1	-	-
0.005	1.0	200	40	20	10	4
	0.5	100	20	10	5	2
	0.1	20	4	2	1	-
0.001 (1 ms)	1.0	1000	200	100	50	20
	0.5	500	100	50	25	10
	0.1	100	20	10	5	2
	0.05	50	10	5	2	-
0.0005	0.5	1000	200	100	50	20
	0.1	200	40	20	10	4
	0.05	100	20	10	5	2
	0.01	20	4	2	1	-
0.0001	0.1	1000	200	100	50	20
	0.05	500	100	50	25	10
	0.01	100	20	10	5	2
	0.005	50	10	5	2	1
0.00005	0.05	1000	200	100	50	20

	0.01 0.005 0.001	200 100 20	40 20 4	20 10 2	10 5 1	4 2 -
0.000001 (1 μ s)	0.001 0.0005 0.0001 0.00005	1000 500 100 50	200 100 20 10	100 20 10 5	50 25 5 2	20 10 2 -
0.0000005	0.0005 0.0001 0.00005 0.00001	1000 200 100 20	200 40 20 4	100 20 10 2	50 10 5 1	20 4 2 -

5.16 TABLE OF PUMP MASS FLUX FRACTION VERSUS TIME (TABLE 17)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
------	----------------------	-------------

		This table is input in the format
1a	NTBL17	$\rightarrow$ 17000, N

where N is the number of pairs of entries in the table, $2 \leq N \leq 20$.

Subsequent lines are of the form
 $\rightarrow$ **17XXX, Y₁, Z₁, Y₂, Z₂, ..., Y_n, Z_n**

where XXX is 001 for the first line, 002 for the second, etc.

1b	FLOWRT(20)	Y _i is the mass flux fraction of the coolant in the channel to its initial value (Y ₁ must be 1.0).
2b	TBL17(20)	Z _i is the reactor time corresponding to Y _i (Z ₁ must be zero).

Notes:

- (a) The information must be in pairs; a pair may not be split between two lines.
- (b) The data must be in ascending order ($Z_i \leq Z_{i+1}$), with $Z_1 = 0$.
- (c) There must be at least two pairs of table entries.
- (d) This table is used in conjunction with I_k = 3 or 4 only, as specified in section 7.8 item 2a (IFLOW).

5.17 TABLE OF ROD WORTH VERSUS ROD LOCATION OR TIME (TABLE 18)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
		This table is input in the format:
1a	NTBL18	→ 18000, N
		where N is the number of pairs of entries in the table, $2 \leq N \leq 20$.
		Subsequent lines are of the form → 18XXX, Y₁, Z₁, Y₂, Z₂, ...Y_n, Z_n
		where XXX is 001 for the first line, 002 for the second, etc.
1b	RODWTH(20)	Y _i is the reactivity (\$) associated with the control rod. Negative values should be entered for a control rod which reduces reactivity.
2b	RODLOC(20)	Z _i is either the rod position (ft or m) corresponding to Y _i where the rate of motion is specified by RDRATE in Card 1113, or the time (sec) corresponding to Y _i where RDRATE is set to -1.0 in Card 1113. If time data is used, the values are relative to the start of rod motion.
	Notes:	Notes: (a) The information must be in pairs; a pair may not be split between two lines. (b) There must be at least two pairs of table entries.

5.18 TABLE OF COOLANT REACTIVITY CHANGE WITH TEMPERATURE (TABLE 19)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
		This table is input in the format:
1a	NTBL19	→ 19000, N
		where N is the number of pairs of entries in the table, $2 \leq N \leq 10$.
		Subsequent lines are of the form → 19XXX, Y₁, Z₁, Y₂, Z₂, ...Y_n, Z_n

where XXX is 001 for the first line, 002 for the second, etc.

1b TCOWTH(10) Y_i is the reactivity (\$/degree K) associated with the paired temperature in TCOLOC.

2b TCOLOC(10) Z_i is the temperature in Kelvin or F corresponding to Y_i .

Note: The information must be in pairs; a pair may not be split between two lines. There must be at least two pairs of table entries, and no more than 10 pairs. The first reactivity entry applies for any temperature up to Z_1 ; the second applies between Z_1 and Z_2 , and so on. The resulting integral reactivity worth is a piece-wise linear, continuous function.

This table may be omitted if Card 5k00 item 11a, DTMP, is sufficient (the coefficient is not temperature-dependent).

If this table is supplied, DTMP may be used to make the resulting reactivity change channel-dependent.

If $T > TCOLOC(NTBL19)$, the last entry TCOWTH(NTBL19) is used to extrapolate the worth table.

5.19 TABLE OF COOLANT DENSITY/VOID REACTIVITY CHANGE (TABLE 20)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
------	-------------------	-------------

This table is input in the format:

1a NTBL20 → 20000, N

where N is the number of pairs of entries in the table, $2 \leq N \leq 10$.

Subsequent lines are of the form

→ 20XXX, Y_1 , Z_1 , Y_2 , Z_2 , ... Y_n , Z_n

where XXX is 001 for the first line, 002 for the second, etc.

1b VCOWTH(10) Y_i is the reactivity (\$ per % void) associated with the paired void % in VCOLOC.

2b VCOLOC(10) Z_i is the void % corresponding to Y_i .

Note: The information must be in pairs; a pair may not be split between two lines. There must be at least two pairs of table entries, and no more than 20 pairs.

The first reactivity entry applies for any void up to Z_i ; the second applies between Z_1 and Z_2 , and so on. The resulting integral reactivity worth is a piece-wise linear, continuous function. This table may be omitted if Card 5k00 item 10a, DVOID, is sufficient. If this table is supplied, DVOID may be used to make the resulting reactivity change channel-dependent.

VCOWTH(M) applies between VCOLOC(M)-VCOLOC(M+1)

If VOID %>VCOLOC(NTBL20), the last entry VCOWTH(NTBL20) is used to extrapolate the worth table.

Example (void worth is always \$0.1/% void):

20000		2
20001	0.1	0.0
20002	0.1	100.

5.20 TABLE OF COOLANT MIXING AFTER FLOW REVERSAL (TABLE 21)

ITEM	FORTTRAN VARIABLE	DESCRIPTION
------	----------------------	-------------

This table is input in the format:

1a	NTBL21
----	--------

→ **21000, N**

where N is the number of pairs of entries in the table, $2 \leq N \leq 20$.

Subsequent lines are of the form

→ **21XXX, Y_1 , Z_1 , Y_2 , Z_2 , ... Y_n , Z_n**

where XXX is 001 for the first line, 002 for the second, etc.

1b	TIME21(20)	Y_i is the time after flow reversal (s) associated with the paired enthalpy mixing fraction of coolant last leaving the channel, in ENTH21. The first time entry should be 0.
----	------------	---

2b	ENTH21(20)	Z_i is the bulk pool enthalpy mixing fraction corresponding to Y_i . At time $Y_1=0$, Z_1 should be 0. The last entry, Z_{NTBL21} , should be 1.0. If
----	------------	--

the last entry is 1.0, then the inlet enthalpy will be ENTHHS for time exceeding TIME21(NTBL21)+t(flow reversal).

The information must be in pairs; a pair may not be split between two lines. There must be at least two pairs of table entries, and no more than 20 pairs. The second applies between Y_1 and Y_2 , and so on. The resulting mixing curve is a piece-wise linear, continuous function. See card type 1116, variable ENTHHS.

If this table is omitted, the original 5-second linear mixing model will be used. Note: if card 1116 variable ENTHHS is supplied, the original 5-second linear mixing model is modified to use ENTHHS instead of ENTHIN.

Example (this is a tabular version of the original 5-second model):

```

!          POWER          PF          PRESUR          ENTHIN
! 07/31/09 - MOD
1003,      1.0400      1.33875e-3      1.35e+5      -35.
!          SUTOL(1)      SUTOL(2)      SUTOL(3)      SUTOL(4)
.
..

          ENTHHS
1116,      0.500      0.500      0.500      0.500
-35.
.
..

!          NTBL21
21000,      12
!          TIME21          ENTH21          TIME21          ENTH21
!          s          fraction          s          fraction
21001,      0.0      0.0      0.5      0.1
21002,      1.0      0.2      1.5      0.3
21003,      2.0      0.4      2.5      0.5
21004,      3.0      0.6      3.5      0.7
21005,      4.0      0.8      4.5      0.9
21006,      5.0      1.0      10000.      1.0

```

NOTE: The “missing” Table 13 is quality vs. vapor fraction, which is supplied in the coolant T-H properties input binary file.

5.21 STEADY-STATE STEP DATA

The radial description refers to cylindrical geometry and half-plate thickness (symmetry assumed) to slab geometry. Each line is of the form

ITEM	FORTTRAN VARIABLE	DESCRIPTION
		→ 22000, Y, Z,
1	TIMSS	Null transient duration. If set to 0., the steady-state iteration is bypassed. Defaults to 100.0 sec for forced flow (IFLOW less than 5) and 300.0 sec for buoyancy driven flow.
2	DTSS	Null transient step size, sec. Defaults to 0.001.

6 FILES USED BY PARET/ANL

UNIT	NAME	DESCRIPTION
1	abc.inp	user-created; supplied to PARET; up to 127 characters (must end in .inp)
2	input.scan	scratch file used for detection of illegal characters such as tabs in the input file
4	groenfilm2.bin	film boiling heat transfer tables from Groeneveld, in binary format
5	input.short	created by PARET from input.inp minus all comment lines with ! in column 1
6	abc.out	created by PARET as standard output. Must not exist prior to a computer run.
8	-	a scratch file containing water properties tables, generated automatically at the start of a run (light or heavy water, provided that IFLUID=0 or 1)
8	H2O.lib or D2O.lib	an "OLD" file containing water properties tables, generated previously by a stand-alone properties generator (light or heavy water, provided that IFLUID=2 or 3)
9	groen2006.2.bin	CHF lookup tables from Groeneveld, in binary format
10	SUMMARY	a binary output file of key time-dependent results: TIMES,POWER,REAC,(AMFR(I),I=1,NCHN),(BRM(I),I=1,NCHN), (TCOOL(I),I=1,NCHN),(TCLAD(I),I=1,NCHN),(TCNTR(I),I=1,NCHN), TCOUT(I),I=1,NCHN)

where

TIMES	=current time point, s
POWER	=total power, MW
REAC	=net reactivity, \$
AMFR	=mass flux, kg/m ² /s
BRM	=minimum burnout ratio
TCOUT	=coolant outlet temperature

The following temperatures are peak values located anywhere along a channel:

TCOOL	=coolant temperature
TCLAD	=clad surface temperature
TCNTR	=fuel centerline temperature

11	SUMMARY.short	a binary output file of key time-dependent results, thinned from file SUMMARY using a temperature tolerance of 0.5 C
12	RESTR1	a restart file
14	RESTR2	a second restart file
15	TBAR.out	contains core average fuel meat temperature, average clad temperature, etc. vs. time. The output is created if ISUPPR > 0
20	debug.out	a debug output file
41	OUTPUT.ch01	ASCII output like the SUMMARY file but specifically for channel 1, as a function of time, of key variables
40+nn	OUTPUT.chnn	like unit 41; characters nn are the channel number, $\leq$ NCHN
91	external.out	External loop time vs. temperature results (ASCII); created only if NLUP2>0
92	external.short	This is a shortened version of file external.out. Data are saved only if temperatures change at least 0.1 degree since the last saved data. This makes a much smaller file for use in any plotting program. This file is created after a successful run has reached completion.
101	101.short	Like unit 41, but shortened. ASCII output specifically for channel 1, as a function of time, of key variables (a shortened version of file 41 based on temperature changes being $\geq$ SUTOL from card 1116). That is, the differences between the present time point temperatures and the last saved time point temperatures are all at least SUTOL, for all four saved temperatures. Peak values are also collected for fuel, clad, coolant, and exit temperatures. In addition, the minimum positive period is also collected.
...		
100+nn	1nn.short	Like unit 40+nn, but shortened. Characters nn are the channel number: nn $\leq$ NCHN.

7 HOW TO RUN PARET/ANL

Open a Linux window (or DOS window). Create a working directory (e.g. run) in which to run the code. Copy the executable file (for example, paret76.x or paret76win.exe) to directory run. One can alternatively use the linux command `ln -s` to make a symbolic link to the executable file, rather than creating a copy in directory run.

Go to that working directory. Copy an input file of the form “abc.inp” in that directory. To run from the command line, in directory run, type:

```
paret76
```

Remember that the code will not overwrite a pre-existing file named abc.out, but will check if it already exists. If so, it will terminate the run immediately. Files debug.out, input.short, and external.out are opened with status=unknown, so it is not essential that they be deleted prior to a run because they will be automatically deleted before new information is written. Files RESTR1 and RESTR2 are checked for existence prior to being reopened. Hence they need not be deleted, but will be overwritten when used.

8 OUTPUT DESCRIPTION

8.1 MAIN OUTPUT

PARET/ANL generates several output files during each run. The main output file contains virtually all information produced by the code and requested by the user. Channel-specific output files contain tabulated data for a given channel at every time step.

The primary output file (unit 6) begins with date, time, and code version information. It then lists the input file. Next, the various input processor routines list the interpreted and expanded problem description derived from the input file.

Here is a sample (which is self-explanatory):

PARET/ANL Version=V7.6.0 Version Date=Tue Aug 26 12:07:1 Date=12/17/2014 TIME=6:41:50

test of December 2014, new ICLAD capability in IGEOM=2

0INPUT DATA		GENERAL INFORMATION	
+		_____	
=====			
0CHANNELS	= 4	AXIAL NODES	=
24			
0RADIAL NODES	= 12	GEOMETRY CODE	=
2			
0POWER-REAC CODE	= 1	R - X CALC. OPTION	=
1			
0PRESSURE OPTION	= 0	KINETICS TIME STEP	=
-1			
0DELAY GROUPS	= 6	KINETICS PRINT-OUT	=
-1			
0UBAR PRINT OPTION	= 0	MAX HEAT-1 CYCLES	=
20			
0INITIAL POWER	= 14.0000 (MW)	TOTAL FUEL VOLUME	=
0.398500E-02 (M**3)			
0OPERATING PRESSURE	= 434200. (PA)	INLET TEMPERATURE	=
62.7800 (DEG. C)			
0PIN SURFACE RADIUS	= 0.561600E-03 (M)	FUEL RADIUS	=
0.239600E-03 (M)			
0INSIDE CLAD RADIUS	= 0.265000E-03 (M)	TOTAL PLATE WIDTH	=
0.764000E-01 (M)			
0FUEL PLATE WIDTH	= 0.728400E-01 (M)	PIN LENGTH	=
0.609600 (M)			
0INLET DEAD LENGTH	= 0.190500E-01 (M)	EXIT DEAD LENGTH	=
0.190500E-01 (M)			
0EFF DLYD NEUT FRACT	= 0.765000E-02	PROMPT NEUT TIME	=
0.387000E-04 (SEC)			
0ACCEL. OF GRAVITY	= 9.80000 (M/S**2)	WATER SOURCE	=
0.00000			
0TRANSIENT TIME	= 0.160000 (SEC)	RX CONSTANT	=
0.800000			

```

ORX EXPONENT          =      1.00000          REFERENCE DENSITY      =
981.905      (KG/M**3)

ODOPP FDBK CONST (0)  =      0.00000          DOPP FDBK CONST (1)      =
0.911000E-03

ODOPP FDBK CONST (2)  =      0.00000          DOPP FDBK CONST (3)      =
0.00000

ODOPP FDBK CONST (4)  =      0.00000          DOPPLER EXPONENT        =
1.00000

OKINETICS TIME TEST   =      0.100000E-02      TRANSIENT DNB FLUX      =
0.00000      (W/M**2)

ONB BUBBLE LIFE-TIME  =      0.100000E-02      TB BUBBLE LIFE-TIME     =
0.100000E-02      (SEC)

ONB HEAT FRACTION     =      0.500000E-01      TB HEAT FRACTION        =
0.500000E-01

OFB HEAT FRACTION     =      0.500000E-01      HEAT TRANS CONST 1      =
1.40000

OHEAT TRANS CONST 2   =      0.330000

OTOTAL CORE FLOW AREA =      0.03350000      (M**2)          FLUX WEIGHTING FACTORS
= 1.0000  1.0000
1.0000  1.0000

```

```

1
PAGE      2

```

```

0
                                HEAT TRANSFER PARAMETERS
OSINGLE/TWO PHASE CORREL./MODE = 0/1/0  CHF CORREL. = 0  IHT = 2  ETA = 2.5000E+01  CP =
4.1870E+03  AVE. Q = 7.0016E+05

```

```

0
                                CORRELATION OPTIONS
0
SINGLE PHASE:      TWO PHASE:      MODE:      CRITICAL
HEAT FLUX:
0 - DITTUS-BOELTER  0 - JENS-LOTES      TRANSITION MODEL  0 - TONG      3 - FORGAN-
WHITTLE
1 - SIEDER-TATE      1 - MCADAMS      0 - NO      1 - BERNATH      4 - CEA
2 - PETUKHOV-7/23/96      1 - YES      2 - MIRSHAK      5/6- LUND
3 - COLBURN      2 - ATHENA      7 - GROENEVELD 2006
4 - RUSSIAN      3 - like 2+GROEN. FILM BOILING TABLE
5 - CIAE      4 - like 2 but ATHENA 101
6 - DB-MOD.      5 - like 3 but ATHENA 101

```

```

FLOW AND HEAT TRANSFER REGIME IDENTIFIER, JHT:

```

```

1 - LAMINAR      5 - NUCLEATE BOILING
2 - NATURAL CONVECTION      6 - TRANSITION BOILING
3 - TURBULENT      7 - FILM BOILING
4 - TRANSIENT      8 - USING HTRAN0(IHT=0)

```

```

REVISED SINGLE PHASE HEAT TRANSFER COEFFICIENT SUBROUTINE USED:  Nu = 1.400 FOR LAMINAR FLOW.
ENTRANCE EFFECTS WITH LAMINAR FLOW ARE INCLUDED.

```

```

0
                                SCRAM DATA

```

```

CONTROL INSERTION                                TRIP SET POINTS
0          INSERTION RATE (M/SEC) =  -1.0000E+00          OVER POWER TRIP
(MW) =    1.4460E+01
0          DELAY AFTER TRIP (SEC) =   1.5000E-01          LOW FLOW TRIP (%)
=    8.5500E+01
PREVIOUS OPERATING TIME (DAYS) =   6.5000E+00          OPERATING POWER (MW) =
1.4450E+01
INLK SETTING REL_T= 2300.000000000000  RET_T= 6000.000000000000  FINF= 1.000000000000000  PHI=
1.0000000000000000
0          HEIGHTS ABOVE AND BELOW REACTOR FOR NATURAL CONVECTION EFFECTS

ABOVE ACTIVE CORE =   1.8300E+00 M          BELOW ACTIVE CORE =   7.1000E-01 M

LAMINAR TO TURBULENT TRANSITION REYNOLDS NUMBER RANGE: 2300. TO 6000.

```

Next, card types 2000, 3000, and 4000 are interpreted to define the thermal properties of the compositions, the radial geometry, and the axial geometry.

Next, card types 5000 define properties specific to each channel, such as dimensions, reactivity feedback coefficients, and power shapes.

Here is sample output:

```

CHANNEL  1
0          FLOW PARAMETER = 1          PRESSURE DROP
=    0.000000
0          WATER NODE RADIUS = 0.1701100E-02          CHANNEL WEIGHTING FACTOR
=    0.9990100
0          ENTRANCE LOSS COEFFICIENT = 0.000000          EXIT LOSS COEFFICIENT
=    0.000000
0          ENTRANCE AREA RATIO = 1.000000          EXIT AREA RATIO
=    1.000000
0          INLET PLENUM LENGTH = 0.8890000E-01          EXIT PLENUM LENGTH
=    0.8890000E-01
0          INLET PLENUM EQUIV. DIAM. = 0.1646000          EXIT PLENUM EQUIV. DIAM.
=    0.1646000
0          COOLANT DENSITY/VOID COEF. = 0.3040000          COOLANT TEMPERATURE COEF.
=    0.1630000E-02

      RFW      RPW      RFLOW      ZQW      ZRS      ZRF      ZRC      FACT3
1.00000E+00  1.00000E+00  1.00000E+00  0.00000E+00  5.61560E-04  2.39643E-04  2.65043E-04
1.00000E+00

```

Next, edits are given regarding revising the axial mesh. Old and new mesh centers are given, and the result of cubic spline interpolation over the old mesh centers of the supplied relative axial power density is given as new values of PFQ. A sample output section is:

```

F500X: A NEW MESH WILL BE DEFINED
NEW INTERPOLATED PFQ=
  N      OLD Zmid      OLD PFQ      NEW Zmid      NEW PFQ
  1 1.27000E-02 3.75558E+03 6.62609E-03 3.95859E+03
  2 3.81000E-02 3.15132E+03 2.65043E-02 3.32780E+03
  3 6.35000E-02 3.53074E+03 5.30087E-02 3.30603E+03
  4 8.89000E-02 3.94178E+03 7.95130E-02 3.81122E+03
  5 1.14300E-01 4.25797E+03 1.06017E-01 4.15732E+03
  6 1.39700E-01 4.54956E+03 1.32522E-01 4.47393E+03
  7 1.65100E-01 4.76035E+03 1.59026E-01 4.71449E+03
  8 1.90500E-01 4.92547E+03 1.85530E-01 4.90062E+03
  9 2.15900E-01 4.98519E+03 2.12035E-01 4.97997E+03
 10 2.41300E-01 4.99925E+03 2.38539E-01 5.00144E+03
 11 2.66700E-01 4.92196E+03 2.65043E-01 4.92946E+03
 12 2.92100E-01 4.77089E+03 2.91548E-01 4.77501E+03
 13 3.17500E-01 4.51794E+03 3.18052E-01 4.51065E+03
 14 3.42900E-01 4.12798E+03 3.44557E-01 4.10165E+03
 15 3.68300E-01 3.74504E+03 3.71061E-01 3.70571E+03
 16 3.93700E-01 3.40427E+03 3.97565E-01 3.35770E+03
 17 4.19100E-01 3.10213E+03 4.24070E-01 3.03761E+03
 18 4.44500E-01 2.75082E+03 4.50574E-01 2.66376E+03
 19 4.69900E-01 2.38193E+03 4.77078E-01 2.27317E+03
 20 4.95300E-01 2.00954E+03 5.03583E-01 1.90717E+03
 21 5.20700E-01 1.72146E+03 5.30087E-01 1.62294E+03
 22 5.46100E-01 1.44391E+03 5.56591E-01 1.31982E+03
 23 5.71500E-01 1.21205E+03 5.83096E-01 1.24058E+03
 24 5.96900E-01 1.35609E+03 6.02974E-01 1.41245E+03

```

Next, power density information is presented for each channel:

```

AVG. FUEL MEAT POWER DENSITY= 3513.174565137049 MW/m^3
AVG. POWER DENSITY FOR EACH CHANNEL(MW/m^3)
  1 3.51320E+03  2 7.67201E+03  3 6.36325E+03  4 7.17755E+03
(Power Density/Core Avg. Power Density) For Each Channel
  1 1.00001E+00  2 2.18378E+00  3 1.81125E+00  4 2.04304E+00
PF= 2.42462E+07 POWER= 1.40000E+01
PFQ EDIT OF CHANNELS, SI MW/m^3; P= 1.40000E+01 MW
CHANNEL ->
      1          2          3          4
  1 3.9586E+03 8.6414E+03 6.8554E+03 7.2169E+03
  2 3.3278E+03 8.2196E+03 6.5345E+03 6.9340E+03
  3 3.3060E+03 8.5163E+03 6.7933E+03 7.3014E+03
  4 3.8112E+03 9.5521E+03 7.5722E+03 8.2037E+03

```

```

5 4.1573E+03 1.0492E+04 8.0594E+03 8.8435E+03
6 4.4739E+03 1.1039E+04 8.6367E+03 9.5028E+03
7 4.7145E+03 1.1693E+04 8.9070E+03 1.0040E+04
8 4.9006E+03 1.2060E+04 9.2442E+03 1.0422E+04
9 4.9800E+03 1.2311E+04 9.1831E+03 1.0592E+04
10 5.0014E+03 1.2183E+04 9.2669E+03 1.0692E+04
11 4.9295E+03 1.1959E+04 9.1531E+03 1.0679E+04
12 4.7750E+03 1.1402E+04 8.9335E+03 1.0510E+04
13 4.5107E+03 1.0361E+04 8.7803E+03 1.0111E+04
14 4.1016E+03 8.4874E+03 8.2640E+03 9.4797E+03
15 3.7057E+03 6.8702E+03 7.5034E+03 8.6174E+03
16 3.3577E+03 6.0669E+03 6.7265E+03 7.7485E+03
17 3.0376E+03 5.2440E+03 6.0742E+03 6.8170E+03
18 2.6638E+03 4.3298E+03 4.6956E+03 5.3724E+03
19 2.2732E+03 3.2065E+03 2.8510E+03 3.2076E+03
20 1.9072E+03 2.3648E+03 1.6746E+03 1.8945E+03
21 1.6229E+03 1.9670E+03 1.3878E+03 1.5551E+03
22 1.3198E+03 1.6113E+03 1.1055E+03 1.2378E+03
23 1.2406E+03 1.4648E+03 1.0454E+03 1.1222E+03
24 1.4124E+03 1.4677E+03 1.0693E+03 1.1842E+03

```

PFQ EDIT OF CHANNELS (EACH CHANNEL NORMALIZED TO 1.)

CHANNEL ->

	1	2	3	4
	3.5132E+03	7.6720E+03	6.3632E+03	7.1776E+03
1	1.1268E+00	1.1263E+00	1.0773E+00	1.0055E+00
2	9.4723E-01	1.0714E+00	1.0269E+00	9.6607E-01
3	9.4103E-01	1.1100E+00	1.0676E+00	1.0173E+00
4	1.0848E+00	1.2451E+00	1.1900E+00	1.1430E+00
5	1.1833E+00	1.3676E+00	1.2666E+00	1.2321E+00
6	1.2735E+00	1.4389E+00	1.3573E+00	1.3240E+00
7	1.3419E+00	1.5242E+00	1.3998E+00	1.3989E+00
8	1.3949E+00	1.5719E+00	1.4527E+00	1.4520E+00
9	1.4175E+00	1.6047E+00	1.4432E+00	1.4757E+00
10	1.4236E+00	1.5880E+00	1.4563E+00	1.4896E+00
11	1.4031E+00	1.5588E+00	1.4384E+00	1.4878E+00
12	1.3592E+00	1.4861E+00	1.4039E+00	1.4643E+00
13	1.2839E+00	1.3504E+00	1.3798E+00	1.4087E+00
14	1.1675E+00	1.1063E+00	1.2987E+00	1.3207E+00
15	1.0548E+00	8.9549E-01	1.1792E+00	1.2006E+00
16	9.5574E-01	7.9078E-01	1.0571E+00	1.0795E+00
17	8.6463E-01	6.8353E-01	9.5458E-01	9.4976E-01
18	7.5821E-01	5.6436E-01	7.3792E-01	7.4851E-01
19	6.4704E-01	4.1795E-01	4.4804E-01	4.4689E-01
20	5.4286E-01	3.0824E-01	2.6317E-01	2.6395E-01


```

21 4.6196E-01 2.5639E-01 2.1810E-01 2.1667E-01
22 3.7567E-01 2.1003E-01 1.7374E-01 1.7246E-01
23 3.5312E-01 1.9093E-01 1.6429E-01 1.5635E-01
24 4.0204E-01 1.9130E-01 1.6804E-01 1.6499E-01

```

The next edit is a table of fluid properties generated at the system pressure:

```

ENTERED SUBROUTINE WATER; IFLUID= 0 ICP= 0 PAVPA= 434200.0000000000
LIGHT      WATER PROPERTIES
subscripts f and l denote liquid; g and v denote vapor
units:      h[J/kg]      k[w/mK]      Cp[J/kgK]      rho[kg/m^3] [m^2/s]      [Pa
s]=[kg/ms]

      [C]  Hf      kl      Cpl      rho_l      nu=visc      Pr      mu=rho*nu
1      8.0 3.39778E+04 5.88064E-01 4.15617E+03 9.99470E+02 1.36942E-06 9.67332E+00 1.36869E-03
2     16.0 6.72405E+04 6.01141E-01 4.16053E+03 9.98603E+02 1.12026E-06 7.74255E+00 1.11870E-03
3     24.0 1.00545E+05 6.13312E-01 4.16517E+03 9.97170E+02 9.25046E-07 6.26446E+00 9.22429E-04
4     32.0 1.33884E+05 6.24588E-01 4.17011E+03 9.95180E+02 7.73723E-07 5.14092E+00 7.69994E-04
5     40.0 1.67265E+05 6.34982E-01 4.17538E+03 9.92643E+02 6.57312E-07 4.29041E+00 6.52476E-04
6     48.0 2.00687E+05 6.44509E-01 4.18103E+03 9.89574E+02 5.67999E-07 3.64628E+00 5.62077E-04
7     56.0 2.34165E+05 6.53182E-01 4.18707E+03 9.85991E+02 4.99047E-07 3.15421E+00 4.92055E-04
8     64.0 2.67685E+05 6.61012E-01 4.19356E+03 9.81917E+02 4.44872E-07 2.77130E+00 4.36827E-04
9     72.0 3.01260E+05 6.68013E-01 4.20053E+03 9.77378E+02 4.00194E-07 2.45953E+00 3.91140E-04
10    80.0 3.34897E+05 6.74199E-01 4.20804E+03 9.72403E+02 3.66081E-07 2.22186E+00 3.55978E-04
11    88.0 3.68591E+05 6.79580E-01 4.21615E+03 9.67028E+02 3.38358E-07 2.02998E+00 3.27201E-04
12    96.0 4.02353E+05 6.84170E-01 4.22493E+03 9.61289E+02 3.14131E-07 1.86475E+00 3.01971E-04
13   104.0 4.36192E+05 6.87981E-01 4.23446E+03 9.55229E+02 2.92208E-07 1.71799E+00 2.79125E-04
14   112.0 4.70107E+05 6.91024E-01 4.24481E+03 9.48895E+02 2.72564E-07 1.58874E+00 2.58635E-04
15   120.0 5.04113E+05 6.93312E-01 4.25611E+03 9.42336E+02 2.55001E-07 1.47514E+00 2.40297E-04
16   128.0 5.38209E+05 6.94854E-01 4.26848E+03 9.35609E+02 2.39337E-07 1.37557E+00 2.23926E-04
17   136.0 5.72409E+05 6.95663E-01 4.28205E+03 9.28773E+02 2.25390E-07 1.28854E+00 2.09336E-04
18   144.0 6.06727E+05 6.95748E-01 4.29700E+03 9.21894E+02 2.12991E-07 1.21271E+00 1.96355E-04
19   146.6 6.17939E+05 6.95620E-01 4.30221E+03 9.19653E+02 2.09257E-07 1.19021E+00 1.92444E-04
      T, C Hg      kv      Cpv      rhov      viscv      Prv      rhov*viscv
TSAT= 146.6083535023442
1   146.6 2.73920E+06 2.96137E-02 2.83628E+03 2.33041E+00 2.00411E-06 9.10523E-02 3.21027E-05
2   157.6 2.76425E+06 3.02870E-02 2.77208E+03 2.26038E+00 2.01010E-06 8.92576E-02 3.21988E-05
3   168.6 2.78912E+06 3.10777E-02 2.71113E+03 2.19487E+00 2.01598E-06 8.75502E-02 3.22928E-05
4   179.6 2.81382E+06 3.19492E-02 2.65320E+03 2.13346E+00 2.02175E-06 8.59250E-02 3.23854E-05
5   190.6 2.83837E+06 3.28791E-02 2.59805E+03 2.07577E+00 2.02744E-06 8.43753E-02 3.24764E-05
6   201.6 2.86275E+06 3.38539E-02 2.54548E+03 2.02146E+00 2.03305E-06 8.28968E-02 3.25663E-05
7   212.6 2.88697E+06 3.48648E-02 2.49532E+03 1.97025E+00 2.03860E-06 8.14853E-02 3.26553E-05
8   223.6 2.91104E+06 3.59059E-02 2.44740E+03 1.92187E+00 2.04411E-06 8.01364E-02 3.27435E-05
9   234.6 2.93495E+06 3.69733E-02 2.40157E+03 1.87609E+00 2.04957E-06 7.88459E-02 3.28310E-05
10  245.6 2.95872E+06 3.80642E-02 2.35769E+03 1.83271E+00 2.05500E-06 7.76105E-02 3.29180E-05

```

```

11  256.6  2.98234E+06  3.91766E-02  2.31565E+03  1.79155E+00  2.06040E-06  7.64270E-02  3.30045E-05
12  267.6  3.00581E+06  4.03090E-02  2.27533E+03  1.75242E+00  2.06578E-06  7.52920E-02  3.30906E-05
13  278.6  3.02914E+06  4.14602E-02  2.23661E+03  1.71519E+00  2.07113E-06  7.42025E-02  3.31763E-05
14  289.6  3.05234E+06  4.26292E-02  2.19941E+03  1.67971E+00  2.07646E-06  7.31560E-02  3.32617E-05
15  300.6  3.07540E+06  4.38153E-02  2.16363E+03  1.64587E+00  2.08177E-06  7.21502E-02  3.33468E-05
16  311.6  3.09833E+06  4.50178E-02  2.12919E+03  1.61355E+00  2.08744E-06  7.11951E-02  3.34376E-05
17  322.6  3.12112E+06  4.62360E-02  2.09603E+03  1.58265E+00  2.09357E-06  7.02918E-02  3.35357E-05
18  333.6  3.14379E+06  4.74695E-02  2.06406E+03  1.55307E+00  2.09986E-06  6.94278E-02  3.36366E-05
19  344.6  3.16632E+06  4.87177E-02  2.03322E+03  1.52474E+00  2.10608E-06  6.85930E-02  3.37361E-05
20  355.6  3.18874E+06  4.99803E-02  2.00346E+03  1.49758E+00  2.11196E-06  6.77777E-02  3.38304E-05
21  366.6  3.21103E+06  5.12567E-02  1.97470E+03  1.47150E+00  2.11730E-06  6.69737E-02  3.39158E-05

END OF SUBROUTINE WATER

```

The next section of output concerns power normalization and checks that the reactor is specified accurately:

```

FUEL VOLUME IS BASED ON 2.*ZRF(J)*(FW*ZRFW(J))*AL
FUEL VOLUME BY CHANNEL=
2.128186278950400E-05  1.315290396510720E-06  1.315290396510720E-06  1.315290396510720E-06
CHECK OF TOTAL POWER: SUMPX= 2.586407710042880E-06
CHECK OF CHANNEL POWERS: 2.586385839018073E-06  7.910067578563821E-12  6.560690662436169E-12
7.400266565848406E-12
IGEOM=2: EXPECTED POWER FRACTIONS EXPECW ARE: 0.9999915438603425  3.058321991482418E-06
2.536603427588529E-06  2.861214238232269E-06
PBAR(M)= 3513.198643898371  7672.013460327878  6363.246150723338  7177.554949980793
ZCVOL(M)= 1.060395124855211E-04  4.066183227617280E-09  3.797651950202879E-09
3.934671755857920E-09
EXPECTED DIRECT HEAT FRACTIONS TO COOLANT:
0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
EXPECTED CONDUCTION HEAT FRACTIONS
9.99992E-01  3.05832E-06  2.53660E-06  2.86121E-06
EXPECTED TOTAL HEAT FRACTIONS
9.99992E-01  3.05832E-06  2.53660E-06  2.86121E-06
F500Y: EXPECW=
9.99992E-01  3.05832E-06  2.53660E-06  2.86121E-06
PFSI= 3.984999817239044E-03
CONSISTENCY CHECK: POWER FACTOR= 1.001009412098161
3.51320E+03  2.12608E-05
7.67201E+03  4.34046E-10
6.36325E+03  4.34046E-10
7.17755E+03  4.34046E-10
NORMALIZATION SCALE FACTOR (IF USED) = 0.9989916057871567
CHECK OF POWER NORMALIZATION
WARNING: THE REACTOR IS OVER-SPECIFIED. RENORMALIZATION MAY CORRECT IT.
CHANNEL POWER ALLOCATION WILL BE RENORMALIZED BY A FACTOR OF 0.9989916057871567

```

The next output section concerns establishing the steady-state solution:

STEADY-STATE SOLUTION

DEFAULT DURATION AND TIME STEP SIZE

NULL TRANSIENT DURATION 1.00000E+02 SEC

TIME STEP SIZE 1.00000E-03 SEC

CHANNEL NUMBER 1

OUTLET ENTHALPY RATE OF CHANGE (dH/dt): 4.83522E-02 (KJ/KG-SEC)

OUTLET MASS FLUX RATE OF CHANGE (dG/dt): 0.00000E+00 (KG/SEC**2-M**2)

MAXIMUM FUEL TEMPERATURE RATE OF CHANGE (dT/dt): 2.62622E-06 (C/SEC)

CONVERGENCE OF ENTHALPY: 3.38024E-07

CONVERGENCE OF MASS FLUX: 0.00000E+00

CONVERGENCE OF FUEL TEMP: 1.01209E-11

CHANNEL NUMBER 2

OUTLET ENTHALPY RATE OF CHANGE (dH/dt): 1.02477E-01 (KJ/KG-SEC)

OUTLET MASS FLUX RATE OF CHANGE (dG/dt): 0.00000E+00 (KG/SEC**2-M**2)

MAXIMUM FUEL TEMPERATURE RATE OF CHANGE (dT/dt): 6.59642E-06 (C/SEC)

CONVERGENCE OF ENTHALPY: 6.01620E-07

CONVERGENCE OF MASS FLUX: 0.00000E+00

CONVERGENCE OF FUEL TEMP: 1.94998E-11

CHANNEL NUMBER 3

OUTLET ENTHALPY RATE OF CHANGE (dH/dt): 1.38852E-01 (KJ/KG-SEC)

OUTLET MASS FLUX RATE OF CHANGE (dG/dt): 0.00000E+00 (KG/SEC**2-M**2)

MAXIMUM FUEL TEMPERATURE RATE OF CHANGE (dT/dt): 5.17485E-06 (C/SEC)

CONVERGENCE OF ENTHALPY: 8.47664E-07

CONVERGENCE OF MASS FLUX: 0.00000E+00

CONVERGENCE OF FUEL TEMP: 1.49679E-11

CHANNEL NUMBER 4

OUTLET ENTHALPY RATE OF CHANGE (dH/dt): 1.54556E-01 (KJ/KG-SEC)

OUTLET MASS FLUX RATE OF CHANGE (dG/dt): 0.00000E+00 (KG/SEC**2-M**2)
 MAXIMUM FUEL TEMPERATURE RATE OF CHANGE (dT/dt): 3.99072E-06 (C/SEC)

CONVERGENCE OF ENTHALPY: 9.18280E-07
 CONVERGENCE OF MASS FLUX: 0.00000E+00
 CONVERGENCE OF FUEL TEMP: 1.13338E-11

REACTIVITY OFFSET CONVERGENCE CRITERIA

MOEDRATOR EXPANSION & VOID: 7.42487E-12
 COOLANT TEMPERATURE: 5.13256E-13
 FUEL TEMPERATURE (DOPPLER): -3.96350E-14

1
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POINT KINETICS SOLUTION POWER SUMMED OVER CHANNELS= 1.40000E+01 MW AT TIME= 0.000000

CHANNEL FLOW AREAS AND AREA FRACTIONS

CHANNEL	AREA*BM	FRACTION	GAIN(MW)	BM
1	1.73949E-04	9.99889E-01	1.39819E+01	9.99010E-01
2	6.67025E-09	3.83417E-05	1.02134E-03	3.30000E-04
3	6.22974E-09	3.58096E-05	8.45498E-04	3.30000E-04
4	6.45451E-09	3.71016E-05	9.53538E-04	3.30000E-04

COOLANT POWER GAIN (IF IN STEADY STATE)= 1.39848E+01 MW

COOLANT FLOW, kg/s, BY CHANNEL (CORE refers to the whole reactor)

CHANNEL	OUT	IN	CORE OUT	CORE IN
1	1.06178E+00	1.06235E+00	1.98805E+02	1.98912E+02
2	1.23196E-01	1.23323E-01	7.61960E-03	7.62745E-03
3	1.15071E-01	1.15179E-01	7.11709E-03	7.12373E-03
4	1.19212E-01	1.19334E-01	7.37318E-03	7.38076E-03
			-1.98828E+02	-1.98934E+02
TOTAL CORE FLOW(kg/s)				

The transient begins, with results tabulated in time as Primary Edits and as Secondary Edits. A typical Primary Edit is:

POINT KINETICS SOLUTION POWER SUMMED OVER CHANNELS= 5.00086E+01 MW AT TIME= 0.160010

TIME	STEP	NUMBER	
Date=12/17/2014	TIME= 6:43:44		16001
		ELAPSED REACTOR TIME (SECONDS)	0.160010
		TIME STEP INCREMENT (SECONDS)	0.000010
		REACTIVITY (\$)	0.72821
		EXTERNALLY INSERTED	0.78400
		DOPPLER	0.02585
		ROD EXPANSION	0.00000
		MODERATOR EXPANSION AND VOIDS	0.02754

		MODERATOR TEMPERATURE			
		1	2	3	4
0	POWER (MW)		5.00081E+01	1.52942E-04	1.26852E-04
1.43085E-04	5.00086E+01				
0	DECAY POWER (MW)		9.24869E-01	2.82857E-06	2.34605E-06
2.64627E-06	9.24877E-01				
0	ENERGY GENERATED (MJ)		2.90918E+00	8.89729E-06	7.37950E-06
8.32386E-06	2.90921E+00				
0	ENERGY IN FUEL (MJ)		3.93725E-01	1.66214E-04	1.68483E-04
1.74656E-04	3.93336E-01				
0	COOLANT ENERGY (MJ)		7.06527E-01	1.56557E-08	1.29506E-08
1.49127E-08	7.06527E-01				
0	COOLANT ENERGY REMOVED (MJ)		2.26096E+00	5.47409E-08	4.51217E-08
5.09273E-08	2.26096E+00				

(MW sec)

1
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...CHANNEL 1...							
0 AXIAL	ENTHALPY	LIQUID(VAPOR)	LIQUID(VAPOR)	VOID	CLAD	SURFACE	FUEL
SURFACE	FUEL MAXIMUM	FUEL %					
NODE		TEMPERATURE	SPECIFIC VOL.	FRACTION	TEMPERATURE		
TEMPERATURE	TEMPERATURE	ENERGY					
	(kJ/Kg)	(DEG. C)	(m**3/Kg)*1000		(DEG. C)		(DEG.
C)	(DEG. C)	(MW sec)	QUAL.				
1	340.8642	81.4224	1.0293714	0.000000	130.9305		
137.5399	156.7112	0.00000 0.0000					
2	337.8651	80.7100	1.0288752	0.000000	122.1971		
127.7420	144.1094	0.01788 0.0000					
3	335.8638	80.2347	1.0285441	0.000000	121.4165		
126.9187	143.1898	0.01777 0.0000					
4	333.2167	79.6056	1.0281141	0.000000	127.3275		
133.6747	152.2202	0.01869 0.0000					
5	329.9705	78.8340	1.0275953	0.000000	131.1211		
138.0461	158.1257	0.01929 0.0000					
6	326.4275	77.9917	1.0270291	0.000000	134.5104		
141.9632	163.4280	0.01983 0.0000					
7	322.3297	77.0176	1.0263743	0.000000	136.8616		
144.7155	167.2278	0.02021 0.0000					
8	318.0452	75.9986	1.0257074	0.000000	138.5036		
146.6671	169.9880	0.02048 0.0000					
9	313.3137	74.8731	1.0249785	0.000000	138.7160		
147.0114	170.6917	0.02053 0.0000					
10	308.6029	73.7525	1.0242527	0.000000	138.1940		
146.5249	170.3218	0.02047 0.0000					
11	303.5765	72.5561	1.0235023	0.000000	136.4141		
144.6251	168.1485	0.02021 0.0000					
12	298.7482	71.4067	1.0227868	0.000000	133.5835		
141.5373	164.4367	0.01980 0.0000					
13	293.8233	70.2343	1.0220590	0.000000	129.2790		
136.7931	158.5935	0.01916 0.0000					
14	289.3474	69.1681	1.0214225	0.000000	123.1011		
129.9337	149.9846	0.01823 0.0000					

15	285.2002	68.1801	1.0208328	0.000000	117.1151	
123.2882	141.6076	0.01734 0.0000				
16	281.4817	67.2943	1.0203039	0.000000	111.8249	
117.4191	134.1865	0.01655 0.0000				
17	277.9661	66.4564	1.0198204	0.000000	106.9227	
111.9843	127.2973	0.01583 0.0000				
18	274.8061	65.7032	1.0193903	0.000000	101.3371	
105.7764	119.3530	0.01500 0.0000				
19	272.0048	65.0355	1.0190089	0.000000	95.5569	
99.3458	111.0658	0.01415 0.0000				
20	269.6419	64.4722	1.0186873	0.000000	90.1689	
93.3484	103.2898	0.01336 0.0000				
21	267.5936	63.9839	1.0184084	0.000000	85.9309	
88.6376	97.1723	0.01274 0.0000				
22	265.7882	63.5534	1.0181713	0.000000	81.4720	
83.6747	90.6820	0.01209 0.0000				
23	264.3494	63.2102	1.0179843	0.000000	80.1366	
82.2097	88.8186	0.01190 0.0000				
24	262.5678	62.7852	1.0177527	0.000000	82.2013	
84.5665	92.0660	0.01221 0.0000				
0 AXIAL PHASE	MASS FLOW DNB SURFACE	SURFACE HEAT J COOLANT	HEAT TRANSFER	BURN--OUT	MODERATOR	TWO
NODE TEMPERATURE	RATE TEMPERATURE	FLUX ENERGY	H	COEFFICIENT	RATIO	REGIME
	(Kg/s*m**2)	(W/m**2)	T			(DEG.
C)	(DEG. C)	(MW sec)	(W/m**2*K)			
1	-6101.20	1530609.	3	38933.35	4.6381	LIQUID
178.9847	194.7846	0.06315				
2	-6098.83	1278641.	3	38781.09	5.5678	LIQUID
177.5110	194.8198	0.06077				
3	-6095.95	1266421.	3	38673.00	5.6313	LIQUID
177.4343	194.8415	0.05918				
4	-6093.41	1463358.	3	38534.52	4.8853	LIQUID
178.6101	194.8718	0.05707				
5	-6090.89	1597751.	3	38365.57	4.4879	LIQUID
179.3467	194.9097	0.05449				
6	-6088.16	1720446.	3	38181.48	4.1816	LIQUID
179.9801	194.9509	0.05166				
7	-6085.58	1813676.	3	37971.52	3.9820	LIQUID
180.4394	194.9992	0.04839				
8	-6082.93	1885385.	3	37747.37	3.8460	LIQUID
180.7809	195.0497	0.04496				
9	-6080.54	1915664.	3	37500.51	3.8022	LIQUID
180.9222	195.1059	0.04117				
10	-6078.06	1923461.	3	37254.37	3.8036	LIQUID
180.9583	195.1615	0.03739				
11	-6075.98	1895088.	3	36987.53	3.8789	LIQUID
180.8263	195.2214	0.03334				
12	-6073.88	1834845.	3	36729.28	4.0245	LIQUID
180.5412	195.2786	0.02944				
13	-6072.16	1732420.	3	36467.40	4.2824	LIQUID
180.0401	195.3373	0.02546				
14	-6070.54	1573855.	3	36221.86	4.7337	LIQUID
179.2192	195.3904	0.02183				

15	-6069.15	1420790.	3	35994.98	5.2641	LIQUID
178.3664	195.4396	0.01847				
16	-6067.87	1287007.	3	35791.43	5.8315	LIQUID
177.5633	195.4835	0.01545				
17	-6066.87	1164144.	3	35587.08	6.4682	LIQUID
176.7692	195.5252	0.01258				
18	-6066.01	1020768.	3	35400.11	7.3985	LIQUID
175.7598	195.5627	0.01001				
19	-6065.32	871009.	3	35234.74	8.6934	LIQUID
174.5862	195.5959	0.00772				
20	-6064.73	730968.	3	35095.22	10.3817	LIQUID
173.3445	195.6239	0.00579				
21	-6064.27	622560.	3	34974.56	12.2128	LIQUID
172.2556	195.6482	0.00412				
22	-6063.98	507084.	3	34872.14	15.0194	LIQUID
170.9284	195.6697	0.00264				
23	-6063.62	478097.	3	34790.75	15.9514	LIQUID
170.5604	195.6867	0.00146				
24	-6063.47	547144.	3	34691.34	13.9618	LIQUID
171.4121	195.7080	0.00000				

A typical Secondary Edit is:

```

0*** STEP NO.      16000          SUMMARY NO.  1601
TIME=      0.16000000,  POWER=  5.001365E+01,  ENERGY=      2.909,  REACTIVITY=      0.728,
MFLOW(OUT)= -6.101E+03,  PERIOD=  2.6512E-02
DKPOW=  9.248772E-01
MIN. BR =    1.19  ETA =   67.87      MAX. TEMPS: COOLANT =   99.407      EDIT( 11)= 197.729
FUEL = 256.437      BOIL = 0/ 1/ 0/ 0
Tmax(C)  THUS FAR: COOL.=  9.9407E+01 at  1.6000E-01 s; EDIT( 11)= 1.9773E+02 at  1.6000E-01 s;
FUEL= 2.5644E+02 at  1.6000E-01 s
HOTTEST EXIT COOLANT T IS IN CHANNEL    2 ; Tmax(exit)=      99.41 C at t=      0.160 s; Thus
Far:      99.41 C at      0.160 s

```

The next section appears after the transient time specified is achieved. There is an edit for each channel of pressure drop, followed by key results for the run:

```

0                                     ...CHANNEL  4...
0PRESSURE DROP (KPa)
0 FRICTION    -61.107  ELEVATION      7.871  SPATIAL ACCELERATION      1.753  TRANSIENT
ACCELERATION    1.787  TOTAL    -49.697
0INTERNAL PRESSURES (KPa)

INLET PRESSURE=      434.20
24      433.35      431.23      429.11      427.01      424.94      422.90      420.88
418.87      416.87      414.86
14      412.85      410.82      408.77      406.68      404.53      402.34      400.08
397.75      395.32      392.79
4      390.20      387.60      384.99      382.37
OUTLET PRESSURE=      384.50  AVERAGE REYNOLDS NO.:      59734.99

```

```

MAXIMA THUS FAR:  0.50014E+02 MW at  0.16000E+00 s    0.29087E+01 MWs at  0.16000E+00 s
TIME=          0.16002000,    POWER=  5.000349E+01,    ENERGY=          2.910,    REACTIVITY=          0.728,
MFLOW(OUT)= -6.101E+03,    PERIOD=-9.6713E-02
DKPOW= 9.248772E-01
MIN. BR =      1.19    ETA =   67.77    MAX. TEMPS: COOLANT =   99.413    EDIT( 11)= 197.775
FUEL = 256.516    BOIL = 0/ 1/ 0/ 0
Tmax(C) THUS FAR: COOL.= 9.9413E+01 at  1.6002E-01 s; EDIT( 11)= 1.9778E+02 at  1.6002E-01 s;
FUEL= 2.5652E+02 at  1.6002E-01 s
HOTTEST EXIT COOLANT T IS IN CHANNEL    2 ; Tmax(exit)=          99.41 C at t=          0.160 s; Thus
Far:          99.41 C at          0.160 s

```

The next output is some final arrays of interest at the end of the run: coolant velocity and density by node, and the final power density (PFQ).

The next information is the final temperature array by channel, axial level, and radial node. Here is a sample:

```

EDIT OF U FOR CHANNEL  4
AXIAL LEVEL I= 1
      212.2760      211.1772      207.8610      202.2668      194.2892      183.7714      178.2352
176.0610      174.1231      172.4147
      170.9302      153.4022
AXIAL LEVEL I= 2
      206.8176      205.7547      202.5468      197.1359      189.4214      179.2533      173.9451
171.8539      169.9910      168.3497
      166.9249      150.1460
AXIAL LEVEL I= 3
      211.6996      210.5879      207.2327      201.5722      193.4992      182.8538      177.2593
175.0614      173.1038      171.3797
      169.8835      152.2416
AXIAL LEVEL I= 4
      224.8634      223.6360      219.9306      213.6766      204.7506      192.9684      186.6627
184.2027      182.0115      180.0813
      178.4061      158.5644
AXIAL LEVEL I= 5
      233.7677      232.4601      228.5120      221.8461      212.3277      199.7546      192.9451
190.3003      187.9446      185.8696
      184.0690      162.6835
AXIAL LEVEL I= 6
      242.9203      241.5319      237.3393      230.2586      220.1430      206.7719      199.4425
196.6079      194.0834      191.8599
      189.9306      166.9554
AXIAL LEVEL I= 7
      250.0753      248.6219      244.2327      236.8181      226.2215      212.2068      204.4541
201.4651      198.8034      196.4594
      194.4258      170.1621
AXIAL LEVEL I= 8

```


254.7958	253.2965	248.7680	241.1170	230.1795	215.7082	207.6559
204.5576	201.7988	199.3698				
197.2629	172.0966					
AXIAL LEVEL I= 9						
256.1729	254.6520	250.0584	242.2965	231.1990	216.5128	208.3296
205.1824	202.3805	199.9141				
197.7753	172.2270					
AXIAL LEVEL I= 10						
256.5163	254.9820	250.3475	242.5161	231.3179	216.4963	208.2374
205.0611	202.2338	199.7454				
197.5882	171.8264					
AXIAL LEVEL I= 11						
255.0610	253.5258	248.8888	241.0529	229.8478	215.0162	206.7711
203.5977	200.7733	198.2880				
196.1340	170.4310					
AXIAL LEVEL I= 12						
251.2114	249.6932	245.1073	237.3579	226.2772	211.6112	203.5033
200.3768	197.5946	195.1469				
193.0260	167.7575					
AXIAL LEVEL I= 13						
243.6566	242.1819	237.7277	230.2017	219.4423	205.2055	197.4182
194.4042	191.7224	189.3634				
187.3199	163.0412					
AXIAL LEVEL I= 14						
232.4023	230.9992	226.7620	219.6041	209.3745	195.8453	188.5625
185.7270	183.2043	180.9856				
179.0641	156.3280					
AXIAL LEVEL I= 15						
217.2923	215.9911	212.0620	205.4269	195.9493	183.4242	176.8285
174.2382	171.9339	169.9075				
168.1527	147.5093					
AXIAL LEVEL I= 16						
202.0133	200.8188	197.2128	191.1254	182.4353	170.9604	165.0552
162.7133	160.6302	158.7983				
157.2121	138.6645					
AXIAL LEVEL I= 17						
185.5228	184.4476	181.2023	175.7263	167.9143	157.6092	152.4404
150.3668	148.5221	146.8998				
145.4949	129.1786					
AXIAL LEVEL I= 17						
185.5228	184.4476	181.2023	175.7263	167.9143	157.6092	152.4404
150.3668	148.5221	146.8998				
145.4949	129.1786					
AXIAL LEVEL I= 18						
160.2196	159.3412	156.6908	152.2221	145.8551	137.4710	133.4349
131.7833	130.3140	129.0215				
127.9018	115.0423					
AXIAL LEVEL I= 19						

121.9481	121.3931	119.7197	116.9025	112.8976	107.6413	105.2736
104.2703	103.3777	102.5923				
101.9118	94.2390					
AXIAL LEVEL I= 20						
98.3157	97.9759	96.9518	95.2296	92.7855	89.5854	88.2057
87.6066	87.0737	86.6050				
86.1990	81.6793					
AXIAL LEVEL I= 21						
91.8526	91.5707	90.7215	89.2937	87.2686	84.6187	83.4906
82.9970	82.5579	82.1717				
81.8370	78.1238					
AXIAL LEVEL I= 22						
85.9066	85.6800	84.9976	83.8506	82.2244	80.0979	79.2031
78.8088	78.4580	78.1493				
77.8816	74.9212					
AXIAL LEVEL I= 23						
83.5535	83.3472	82.7259	81.6817	80.2015	78.2664	77.4560
77.0978	76.7789	76.4982				
76.2545	73.5622					
AXIAL LEVEL I= 24						
84.5106	84.2931	83.6378	82.5365	80.9751	78.9337	78.0771
77.6987	77.3617	77.0646				
76.8064	73.9498					

The next edit is useful for checking feedback coefficients. The system average temperature is obtained by volume-averaging over all volume elements in each fuel plate, for each channel:

```

TIME=      0.1600
SYSTEM AVG. TEMPERATURES(C) FOR EACH COMPOSITION
134.22      121.40      112.43      118.36

```

The next edit is of minimum Burnout Ratio, giving its value and time of occurrence for each channel:

```

CHANNEL  BR(MIN)      TIME(sec)
1      3.8010E+00  1.6002E-01
CHANNEL  BR(MIN)      TIME(sec)
2      1.1900E+00  1.6002E-01
CHANNEL  BR(MIN)      TIME(sec)
3      2.3330E+00  1.6002E-01
CHANNEL  BR(MIN)      TIME(sec)
4      2.1830E+00  1.6002E-01
GLOBAL MINIMUM BURNOUT RATIO=  1.1900E+00  AT TIME=  1.6002E-01 sec IN CHANNEL  2

```

The final edit lists key information about producing shortened output files, time, date, executable used, and execution time.

```

ENTERED SHORTSU WITH NSU= 10   NCHN= 4   SUTOL= 0.000000000000000E+00 0.000000000000000E+00
0.000000000000000E+00
SUMMARY file lines processed= 1603   lines saved= 1603   on SUMMARY.short
PARET/ANL Version=V7.6.0   Version Date= Tue Aug 26 12:07:1   Date=12/17/2014   TIME=
6:43:44
EXECUTION TIME =   2.004 MINUTES

```

8.2 CHANNEL OUTPUT

The PARET/ANL code writes a text (ASCII) summary file for each coolant channel (up to 50 available as NCHN cannot exceed 50). The files are called OUTPUT.ch01 through OUTPUT.chnn, where nn=NCHN. Also written are shortened text files, with the data "thinned". See discussion in Section 11. These files contain a record for each time step as follows:

TIME	=	Time, sec
POWER	=	Power, MW
ENRGYR	=	Energy, MWs
REAC	=	Net reactivity, \$
AMFRI	=	Mass flow rate, kg/s/m ² or lb _m /hr ft ²
BRM	=	Min. critical heat flux ratio
TCOOL	=	Max. coolant temperature, C or °F
TCLAD	=	Max. clad surface temperature, C or °F
TCNTR	=	Max. fuel center line temperature, C or °F
TCOUT	=	Coolant outlet temperature, C or °F
PERIOD	=	Reactor period, sec

This data is edited in FORMAT(1P,3E12.5,2E12.4,E10.3,5E11.4)

8.3 SUMMARY

The PARET/ANL code writes a binary SUMMARY file to facilitate post-processing of the large amount of data that is often generated. This file contains a record for each time step, written in the following format:

```

TIME, POWER, REAC, (AMFR(I), I=1, NCHN), (BRM (1), I=1, NCHN),
(TCOOL (I), I=1, NCHN), (TCLAD(I),I=1,NCHN),
(TCNTR(I),I=1,NCHN),(TCOUT(I),I=1,NCHN)

```

where

TIME	=	Time at each step, sec
POWER	=	Power at each step, MW
REAC	=	Net reactivity at each step, \$

and for each of the NCHN channels:

AMFR	=	Mass flow rate at each step, lb _m /hr ft ²
BRM	=	Min. critical heat flux ratio
TCOOL	=	Max. coolant temperature, C or °F
TCLAD	=	Max. clad surface temperature, C or °F
TCNTR	=	Max. fuel center line temperature, C or °F
TCOUT	=	Coolant outlet temperature, C or °F

An edit of this file provides a summary of the PARET/ANL results.

8.4 SHORT OUTPUT

This information is the same as in Section 8.3, but the changes from line to line are processed by a filter to reduce the number of lines retained. See Card Type 1116.

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APPENDIX I UNITS, CONSTANTS AND CONVERSION FACTORS

In PARET/ANL, the user has the option to specify quantity values in either one of the United States Customary unit system or the international system (SI) of units. Table I-1 lists the quantities used in PARET in both system of units and conversion factors to apply to convert from one system to the other. Table I-2 lists the constants defined and used by PARET.

Table I-1 Conversion table between United States Customary units and SI units

Quantity	United States Customary Unit	SI Unit	Conversion factors	Code Symbol
Conductivity	Btu/(hr·ft·°F)	W/(m·K)	1 Btu/(hr·ft·°F) = 1.730735 W/(m·K)	CON_K
Density	lb/ft ³	kg/m ³	1 lb/ft ³ = 16.01846 kg/m ³	CON_RHO
Energy	Btu	J	1 Btu = 1055.056 J	
Enthalpy	Btu/lb	J/kg	1 Btu/lb = 2326.00 J/kg	CON_H
Heat Flux	Btu/(hr·ft ²)	W/m ²	1 Btu/(hr·ft ²) = 3.1545906 W/m ²	CON_Q
Heat Transfer Coefficient	Btu/(hr·ft ² ·°F)	W/(m ² ·K)	1 Btu/(hr·ft ² ·°F) = 5.678263 W/(m ² ·K)	CON_HT
Length	ft	m	1 ft = 0.3048 m	CON_L
Mass Flow Rate	lb/(hr·ft ²)	kg/(s·m ²)	1 lb/(hr·ft ²) = 1.35623·10 ⁻³ kg/(s·m ²)	CON_MF
Power	Btu/hr	MW	1 MW = 3412141.2 Btu/hr	
Pressure	psi	Pa	1 psi = 6894.757 Pa	CON_P
Specific volume	ft ³ /lbm	m ³ /kg	1 ft ³ /lbm = 6.242797·10 ⁻² m ³ /kg	CON_V
Viscosity	lb/(ft·hr)	Pa·s	1 lb/(ft·hr) = 4.133789·10 ⁻⁴ Pa·s	CON_VIS
Volumetric Heat Capacity (ρC _p)	Btu/(ft ³ ·°F)	J/(m ³ ·K)	1 Btu/(ft ³ ·°F) = 6.706611·10 ⁴ J/(m ³ ·K)	CON_RCP
Specific Heat	Btu/(lb·°F)	J/(kg·K)	1 Btu/(lb·°F) = 4186.80 J/(kg·K)	1.8*CON_H

Table I-2 Constants defined and used by PARET/ANL

Quantity	Value
Gravitational constant	G = 9.80665 m/s ²

APPENDIX II EMPIRICAL CORRELATIONS

Several empirical correlations for the heat transfer at the clad-coolant interface are implemented in PARET/ANL. Table II-1 lists which correlations are available for each coolant regime. The remainder of this appendix defines the empirical correlations.

Table II-1 Heat Transfer Phenomena for the PARET/ANL options

Mode Number (IBOIL)	Heat Transfer Phenomena	Correlations
0	Single-phase liquid, no boiling	Dittus-Boelter [31], Petukhov [33], Sieder-Tate [32], Colburn [34], Russian, CIAE [7], ANL-modified Dittus-Boelter
1	Nucleate boiling	Jens-Lottes [18], McAdams [37]
2	Transition boiling	
3	Film boiling	Dittus-Boelter [20]
4	Bulk boiling	
-1	Pure vapor	

II-1 SINGLE PHASE LIQUID HEAT FLUX CORRELATIONS

The first item on card 1112 (IONEP, see section 5.4) determines the heat transfer correlation at the clad-coolant interface when the coolant is in single phase liquid regime. In the following relationships

- Re is the Reynolds number
- Pr is the Prandtl number
- L is the characteristic length of the channel
- De is the hydraulic diameter
- Nu is the Nusselt number
- h is the heat transfer coefficient
- k is the thermal conductivity of the fluid

The relationship between the Nusselt number and the heat transfer coefficient is

$$\text{Nu} = \frac{hL}{k} \quad (\text{II-1})$$

II-1.1 DITTUS BOELTER [31]

The Dittus-Boelter Eq. for the Nusselt number is:

$$\text{Nu} = 0.023\text{Re}^{0.8}\text{Pr}^{0.4} \quad (\text{II-2})$$

This relationship is valid as long as

- $0.7 < \text{Pr} < 160$ (i.e. valid for water at any temperature or pressure)
- $L/D > 60$, where D is the outer diameter of the pin
- $\text{Re} > 6000$

II-1.2 DITTUS-BOELTER MODIFIED BY ANL [31]

The modified Dittus-Boelter Eq. for the Nusselt number is:

$$\text{Nu} = 0.023\text{Re}^{0.8}\text{Pr}^{0.4} \left(\frac{\mu_b}{\mu_w} \right)^{0.11} \quad (\text{II-3})$$

This relationship is valid as long as

- $0.7 < \text{Pr} < 160$ (i.e. valid for water at any temperature or pressure)
- $L/D > 60$, where D is the outer diameter of the pin
- $\text{Re} > 6000$

II-1.3 SIEDER-TATE [32]

The Sieder-Tate Eq. for the Nusselt number is

$$\text{Nu} = 0.027\text{Re}^{0.8}\text{Pr}^{1/3} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \quad (\text{II-4})$$

This relationship is valid as long as

- $L/D > 60$, where D is the outer diameter of the plate
- $\text{Re} > 10000$

II-1.4 PETUKHOV & POPOV [33]

The Darcy friction factor f_D is approximated as

$$f_D = \frac{1.0875 - 0.1125\left(\frac{b}{s}\right)}{(1.82 \log \text{Re} - 1.64)^2} \quad (\text{II-5})$$

where

b is the gap of a rectangular channel or annulus (in m)

s is the span of the channel (in m)

Then the forced-convection heat transfer coefficient is:

$$h_{FC} = \frac{\frac{k_b f_D}{De} \frac{Re Pr}{8} \left(\frac{\mu_b}{\mu_w}\right)^{0.11}}{(1 + 3.4 f_D) + \left(11.7 + \frac{1.8}{Pr^{1/3}}\right) \left(\frac{f_D}{8}\right)^{1/2} (Pr^{1/3} - 1.0)} \quad (II-6)$$

where

μ_b and μ_w are liquid kinematic viscosities, (m²/s), for the bulk coolant and for the coolant at the wall temperature

k_b is the coolant conductivity, w/m K

De is hydraulic diameter, m

subscript b refers to bulk coolant

subscript w to coolant at the wall temperature

II-1.5 RUSSIAN

The “Russian” Eq. for the Nusselt number is

$$Nu = 0.021 Re^{0.8} Pr^{0.43} \left(\frac{\mu_b}{\mu_w}\right)^{0.25} \quad (II-7)$$

II-1.6 COLBURN [30]

The Colburn Eq. for the Nusselt number is

$$Nu = 0.023 Re^{0.8} Pr^{0.3} \quad (II-8)$$

This Eq. uses $T_{film} = (T_{surf} + T_{bulk})/2$ when obtaining fluid properties.

It is valid for fully developed turbulent flow.

II-1.7 CIAE

The CIAE equation for the Nusselt number is

$$\begin{cases} Nu = 0.68(Gr \cdot Pr)^{1/4} & , \text{ when } Gr \cdot Pr < 6 \cdot 10^6 \\ Nu = 0.174(Gr \cdot Pr)^{1/3} & , \text{ when } Gr \cdot Pr \geq 6 \cdot 10^6 \end{cases} \quad (II-9)$$

This equation is valid for $Re < 2300$

II-2 TWO-PHASE NUCLEATE BOILING HEAT FLUX CORRELATIONS

The second item on card 1112 (ITWOP, see section 5.4) determines the two phase nucleate boiling correlation for the heat transfer at the clad coolant interface.

II-2.1 ORIGINAL JENS-LOTTE [17]

$$2 \quad (q''_{NB})^{m+1} = (q''_{NB})^m \left[1 + \frac{4(u_s^{m+1} - u_s'^m)}{u_s'^m - u_{sat}} \right] \quad (\text{II-10})$$

where the superscript m, refers to the mth time node. This boundary condition is based on the Jens-Lottes correlation [18]

$$u_s' = u_{sat} + 60 \exp\left(-\frac{p}{900}\right) \left(\frac{q''}{10^6}\right)^{\frac{1}{4}} \quad (\text{II-11})$$

II-2.2 MCADAMS [37]

$$q'' = 0.074(T_w - T_{sat})^{3.86} \quad (\text{II-12})$$

where quantities are in United States Customary units (q'' in BTU/hr/ft². and temperatures in °F).

This correlation is valid for 2.06 - 6.21 Bar (30 - 90 psia), velocities from 0.3 - 11 m/s (1-36 ft/s), equivalent hydraulic diameter from 4.3 - 13.2 mm (0.17 - 0.52 in.), and subcooling from 11.1 - 83.3 C (20-150 ° F). The constant 0.074 varies with the extent of degassing of the water. It was found to be 0.074 at 0.06 ml. of air at standard conditions per liter of water.

II-3 CRITICAL HEAT FLUX CORRELATIONS

The fourth item on card 1112 (ICHF, see section 5.4) determines the critical heat flux correlations used by PARET. In the following relationships

- q_c is the critical heat flux in MW/m²

II-3.1 MIRSHAK-DURANT-TOWELL [36]

The Mirshak-Durant-Towell Eq. is

$$q_c = 1.51(1 + 0.1198U)(1 + 0.00914\Delta T_{sub})(1 + 0.19P) \quad (\text{II-13})$$

where

ΔT_{sub} is the subcooling at the channel exit (C)

U is the coolant velocity, m/s

P is the absolute pressure (bar) at the channel exit

This correlation is valid for downflow and

$$1.5 \text{ m/s} < U < 13.7 \text{ m/s}$$

$$5^\circ\text{C} < \Delta T_{sub} < 75^\circ\text{C}$$

$$1.72 \text{ bar} < P < 5.86 \text{ bar}$$

$$2.84 < q_c < 10.22 \text{ Mw/m}^2$$

Fitting error $\pm 16\%$, Standard deviation 8%, Downward flow, Based on 65 tests.

II-3.2 BERNATH [13]

The Bernath Eq. is

$$q_c = h_c[(T_w)_c - (T_b)_c] \quad (\text{II-14})$$

where

$$h_c = \frac{0.067D}{D + \frac{\xi}{\pi}} + 0.65 \times 10^{-4} \frac{U}{D^{0.6}} \quad (\text{II-15})$$

$$(T_w)_c = 57 \ln(14.5P) - \frac{54P}{P + 1.034214} - \frac{U}{1.2192} \quad (\text{II-16})$$

h_c is the (critical) heat transfer coefficient at burnout ($\text{MW/m}^2/\text{C}$)

$(T_w)_c$ is the (critical) wall temperature ($^{\circ}\text{C}$)

$(T_b)_c$ is the (critical) bulk coolant temperature ($^{\circ}\text{C}$)

D is the hydraulic diameter, m

ξ is the heated perimeter, m

U is the coolant velocity, m/s

P is the absolute pressure (bar)

This correlation is valid for $0 < V \leq 54$ ft/s; $23 < P < 3000$ psia; $0.143 < D < 0.66$ in

II-4 COMMENT ON "ATHENA" OPTIONS

ORNL created special heat transfer options for the RELAP code to use for the design of the Advanced Neutron Source Reactor (ANSR). The geometry of the coolant channel in the ANSR has an aspect ratio of about 68 in the inner fuel annulus and 55 in the outer fuel annulus. The heavy water coolant flow velocity is very high: 27.4 m/s. The inlet and outlet pressures are 3.7 and 1.9 MPa, respectively. The average and peak heat fluxes are 6.1 and 16.6 MW/m^2 . The stated range and conditions for CHF or Departure from Nucleate Boiling are [38]:

- subcooled water or heavy water
- Al or SS, tubes, annular or rectangular channels
- pressure of 0.1 - 8.4 MPa
- mass flux of 1.2 - 67.7 $\text{Mg/m}^2\text{s}$
- velocity of 1.1 - 61.9 m/s
- subcooling of 0.6 - 170.4 C
- heat flux of 3.2 - 130 MW/m^2
- equivalent hydraulic dia. of 2.1 - 25.4 mm

- L/D ratio of 6.56 - 191.0

For Turbulent Forced Convection, the stated range and conditions are:

- single-phase, fully developed, turbulent flow
- various fluids, including water
- friction factor corrected for rectangular channels
- corrected for variable properties

The accuracy of original correlation is

- 1 % for Re of 10,000 to 500,000 and Pr 0.5 – 200
- 1-2% for Re 500,000 to 5,000,000 and Pr 200 - 2000

range for variable physical properties correction $\mu_w/\mu_b = 0.08$ to 40, Re 10,000 to 125,000 and Pr = 2 - 140.

For Laminar Flow, the ANS option uses $Nu=7.63$ instead of 4.36.

For Natural Convection, the ANS option uses the Elenbaas correlation instead of correlations by Churchill-Chu or by McAdams.

II-5 FLOW INSTABILITY

The flow instability ratios (ICHF = 3 and 4) are defined as follows:

$$\mathbf{FIR} = \mathbf{q_{FI}} / \overline{\mathbf{q}}$$

$$\mathbf{q_{FI}} = \mathbf{R} \frac{\rho \mathbf{C_p} \mathbf{D_H}}{4 \mathbf{L_H}} \mathbf{v(T_{sat} - T_{in})}$$

$\overline{\mathbf{q}}$ = Average heat flux at normal steady-state power (QAVE) with peaking factors if the hot channel modeled.

- ICHF = 3

$$\mathbf{R} = \frac{1}{1 + \eta \frac{\mathbf{D_H}}{\mathbf{L_H}}}$$

- ICHF = 4

$$\mathbf{R} = \frac{1}{1 + 3.15(\mathbf{MFR})^{0.29} \frac{\mathbf{De}}{\mathbf{L_H}}}$$

$\square$ = Density of the coolant [g/cm³]

$\mathbf{C_p}$ = Specific heat of coolant (CP) [J/g °C]

$\mathbf{D_H}$ = Equivalent heated diameter [cm]

L_H	=	Heated length [cm]
v	=	Coolant flow-velocity [cm/s]
T_{sat}	=	Saturation temperature [°C]
T_{in}	=	Inlet temperature [°C]
□	=	Bubble detachment parameter (ETA) $\left[\frac{\text{cm}^3 \text{ } ^\circ\text{C}}{\text{J}} \right]$
De	=	Equivalent hydraulic wetted diameter [cm]
MFR	=	Absolute Value of Mass Flow Rate [g/cm ² s]

This form of the average heat flux at the onset of flow instability, q_{FI} , assumes that η is a minimum at the channel exit, and that the heat flux at the channel exit is representative of this average heat flux.

Table II-2 Heat Transfer Phenomena for the Athena (RELAP) Options

Mode Number (JHT)	Heat transfer phenomena	Correlations
0	Noncondensable-vapor-liquid	Dittus-Boelter[21], Petukhov [23], Churchill-Chu [40] Elenbaas [44]
1	Single-phase liquid or subcooled wall with void fraction < 0.1	Same as mode 0
2	Single-phase liquid or subcooled wall with void fraction < 0.1	Churchill-Chu [40]
3	Subcooled nucleate boiling	Chen [43]
4	Saturated nucleate boiling	Same as mode 3
5	Subcooled transition boiling	Chen-Sundaram-Ozkaynak [18]
6	Saturated transition boiling	Same as mode 5
7	Subcooled film boiling	Bromley [46]
8	Saturated film boiling	Same as mode 7
9	Single-phase vapor	Same as mode 0
10	Filmwise condensation with void fraction < 1.0	Shah
11	Condensation in vapor with void fraction = 1.0	Same as mode 10

APPENDIX III 10 MW IAEA BENCHMARK REACTOR HEU MODEL

The purpose of this appendix is to help clarify, by example, the meaning of some of the PARET input parameters. Input preparation for a typical PARET problem is discussed, and listing of input cards and a portion of the output are included for further clarification.

The excursion to be discussed is benchmark calculation of reactivity insertion transient of an idealized, light-water, pool-type reactor described in [39]. The transient is initiated by the ramp insertion of 1.5 \$ excess reactivity in 0.5 seconds at an operating pressure of 1.7 bar, an initial power of 1 W, an initial temperature of 38°C and a flow rate of 1000 m³/hr.

III-1 PREPARATION OF INPUT

An outline of the input data entered into PARET for the analysis under discussion is presented in Section III-1.1 through III-1.15 below. The complete input file for PARET/ANL is shown in Figure III-1.

III-1.1 GENERAL INFORMATION (1000-SERIES CARDS)

1. It was decided to represent the core with two channels (regions), with one channel representing the hottest channel and the other channel representing the remainder of the active core. The number entered is negative because the quantity entered on the remainder of the input will be given in SI units.
2. There is 22 axial node points. The plate is divided into 21 axial zones.
3. There is 7 radial node points. The plate is divided into 6 radial zones.
4. The geometry code is 0 because the reactor contains plate-type fuel.
5. The operation code is 1. This is a reactivity-specified input (1.5\$ ramp insertion)
6. Vapor fraction and quality option. The option 1 was chosen. This allows the code to calculate values of vapor fraction and quality in both the subcooled and saturated regions.
7. Moderator pressure code. The 0 option is applicable in this case since the inlet pressure is specified.
8. Kinetics time step parameter. Option 0 was chosen. The time step is reduced, when necessary, for the neutron kinetics calculation and then expanded to the input-specified or hydrodynamics-specified time-step, whichever controls. An integral number of neutron kinetics time steps are contained in each input-specified or hydrodynamics-specified time step.
9. The number of delayed neutron groups is six.
10. The print frequency. Since detailed printout was desired at the end of every time step, a -1 is appropriate here.
11. Average temperature printout option. Since no printout of average temperature was desired, a zero was entered here.

12. The maximum number of heat transfer code iterations. A value of 10 was selected.
13. Initial reactor power. This excursion was initiated from a power of 10^{-6} MW.
14. Total volume of fuel meat in the core. The core contains $10.62214\text{E-}3 \text{ m}^3$ of fuel meat.
15. Operating pressure was 1.7 bar.
16. Enthalpy of inlet moderator. At 1.7 bar and 38°C , the enthalpy of water is $1.58650\text{E}+5 \text{ J/kg}$.
17. Plate half-thickness is 0.635 mm.
18. Fuel meat half-thickness is 0.255 mm.
19. Half-distance to inner surface of clad. This is the same as item 18, since there is no intermediate region between the fuel and clad.
20. Fuel plate width is 6.65 cm.
21. Active fuel width is 6.30 cm.
22. Active fuel length is 60 cm.
23. Inlet non-fueled section length. There is no inlet non-fueled section in this model.
24. Outlet non-fueled section length. Same as item 23.
25. Effective delayed neutron fraction is 0.0076071.
26. Prompt neutron generation time is $5.5960\text{E-}5 \text{ s}$.
27. 27. Acceleration of gravity.
28. Heat source description for moderator. In specifying this parameter, it was assumed that 4.5% of the energy generated in the fuel is deposited promptly in the moderator.

$$Q_W = 0.045(V_f/V_{mod}) = 0.00975$$
 where
 V_f is the volume of fuel in the core.
 V_{mod} is the volume of moderator in the core.
29. Transient time. It was desired to investigate this transient over a time interval of 0.8 seconds.
30. Vapor volume fraction generation constant. The vapor volume fraction will be evaluated with Eq. (87). The constant was given a value of 0.8.
31. An exponent (dimensionless) used in Eq. (87), given a value of 1.0.
32. The moderator reference density at 1.7 bar and 38°C is 993.20 kg/m^3 .
33. Doppler coefficient constant term. The Doppler reactivity feedback is linear with the temperature.
34. Doppler coefficient linear term with temperature.
35. Doppler coefficient term varying as the square of temperature.
36. Doppler coefficient term varying as T^n .

37. Temperature offset used to select degrees K or R for temperature.
38. Doppler coefficient power, n, used with entry 36.
39. The upper limit for kinetics time step test, QH, was set to 0.001, as recommended in section 3.2.1.
40. Transient DNB heat flux. A value of zero was entered for this parameter. Thus, the code will calculate a steady-state DNB heat flux for each axial node at each time node.
41. Nucleate boiling bubble collapse time. Reliable values of this parameter cannot be predicted from fundamental considerations with any degree of assurance. Therefore, values should be derived from a parametric study of this parameter on a similar excursion experiment. A value of 0.5 ms is used here.
42. Transition boiling bubble collapse time. A value of 1 ms is used here.
43. Fraction of the clad surface heat flux which is utilized in producing vapor in the subcooled nucleate boiling region. A value of 0.03 is used here.
44. Fraction of the clad surface heat flux which is utilized in producing vapor in the subcooled transition boiling region. A value of 0.05 is used here.
45. Fraction of the clad surface heat flux which is utilized in producing vapor in the subcooled film boiling region. A value of 0.05 is used here.
46. Natural convection heat transfer constant. A value of 1.4 is given. The value used is of minor importance in this analysis, however, since the coolant is forced through the core at 1000 m³/hr. The natural convection heat transfer correlation will be used only if the flow is reduced at some point, or points, to a Reynold's number less than 2000.
47. Natural convection heat transfer constant. A value of 0.33 is given.

III-1.2 ADDITIONAL GENERAL INFORMATION (1100 SERIES CARDS)

1. The total cross-sectional area of all flow channels in core is 0.0857927 m². This parameter is no longer used.
2. The flux weighting factor is set to 1.0 for both channels. These factors have no effect on calculations and results. Its physical significance is not clear and has been taken as unity in ANL calculations
3. The single-phase correlation option is set to 1. The Sieder-Tate correlation will be used.
4. The two-phase correlation option is set to 1. The McAdams correlation will be used.
5. The transient two-phase scheme option is set to 1. The transition model, single-phase to two-phase will be used.
6. The DNB and flow instability correlations option is set to 0. The original DNB correlation is used.
7. The single-phase heat transfer subroutine option is set to 0. The original heat transfer subroutine is used. Therefore, entrance effects are included when the Reynolds is smaller than a specific threshold value.
8. The constant rate for control rod movement is set to 1.2 m/s. The control rod travels 0.6 m in 0.5 s when the reactor reaches the scram tripping point.

9. The delay time before rod starts in after trip is 25 ms.
10. The overpower trip point is 12.0 MW
11. The low flow trip point is set to 0%. This transient does not study a loss of flow accident.
12. The heights above and below the reactor for natural convection effects are set to 0.0.

III-1.3 THERMAL PROPERTIES OF FUEL ELEMENT MATERIALS

1. The thermal conductivity (k) and volumetric heat capacity (g) of the fuel are represented as a function of the temperature (T in Kelvin) by

$$k = 158.0 \text{ W/mK}$$

$$g = 1.0670 \cdot 10^3 T + 2.0721 \cdot 10^6 \text{ J/(m}^3\text{K)}$$
2. The thermal conductivity (k) and volumetric heat capacity (g) of the cladding are represented as a function of the temperature (T in Kelvin) by

$$k = 180.0 \text{ W/mK}$$

$$g = 1.0670 \cdot 10^3 T + 2.0721 \cdot 10^6 \text{ J/(m}^3\text{K)}$$

III-1.4 HALF-PLATE THICKNESS DESCRIPTION

In this problem the half-plate is divided into six radial intervals, four in the fuel and 2 in the cladding. A constant radial increment of $6.375 \cdot 10^{-2}$ mm is used in the fuel (nodes 1 through 5) and of $1.9 \cdot 10^{-1}$ mm in the cladding (nodes 6 and 7).

The source description has a constant value of 0.955 in the fuel and 0.0 in the cladding. 95.5% of the prompt energy is deposited in the fuel and none in the clad. The rest is deposited directly in the coolant.

III-1.5 AXIAL DESCRIPTION

The length of the active core (0.6 m) is divided into 21 axial regions of equal size ($2.85714 \cdot 10^{-2}$ m)

III-1.6 INDIVIDUAL CHANNEL INFORMATION

In this analysis channel 1 represents the hottest plate in the core and channel 2 represents the remainder of the active core. They are both treated as flow-forced channels. The differences between the two channels are:

1. The value of BM. Channel 1 represents only one plate and its associated coolant channel. Therefore its fraction of meat volume is much smaller than for channel 2.
2. Void and temperature reactivity feedback coefficient (DVOID and DTEMP). There is a spatial effect to take into account.
3. The axial power profile (PFQ).

It was assumed that there was no axial dependence for the temperature reactivity feedback and the axial dependence is identical in both channels for the void reactivity feedback. The values entered in this section are obtained with neutronics steady-state calculations using codes such as MCNP [40].

III-1.7 DELAYED NEUTRON INFORMATION

Delayed neutron fractions and decay constant are entered in pairs on the 6000-series card. As specified on the 1000-series card, there are six delayed neutron groups for this problem.

III-1.8 REACTIVITY VS TIME (TABLE 9000)

1.5\$ of excess reactivity is inserted at the beginning of the transient in 0.5 second. Those 1.5\$ excess reactivity are not removed or changed at any time during the transient.

III-1.9 COOLANT INLET MASS FLUX VS TIME (TABLE 10000)

The nominal flow rate of the coolant at the inlet is 1000 m³/hr and is constant throughout the transient. This is equivalent to a mass flow rate of 3.21580 10³ kg/s/m² at 38°C and 1.7 bar.

III-1.10 LINEAR THERMAL EXPANSION OF CLAD VS. TEMPERATURE (TABLE 11000)

In this problem we assume no thermal expansion of the clad.

III-1.11 TOTAL PRESSURE DROP VS TIME (TABLE 120000)

This is a flow-forced problem so we do not specify any pressure drop.

III-1.12 TIME INCREMENT VS TIME (TABLE 14000)

5 ms time increments are specified for the kinetics time step until 0.55 seconds into the transient. Then the time increment is reduced to 1 ms between 0.55 s and 0.75 s. Finally the time increment is reset to 5 ms until the end of the transient.

III-1.13 PRINT FREQUENCY VS TIME (TABLE 16000)

From 0.0 to 0.5 seconds, major output edits are printed every 0.10 seconds and intermediate output edits every 5 time steps. From 0.5 s to 0.6 s, major output edits are printed every 0.05 seconds and intermediate output edits every 2 time steps. From 0.6 s to 0.7 s, major output edits are printed every 0.05 seconds and intermediate output edits at every time step. From 0.7 seconds until the end of the reactor transient, major output edits are printed every 0.10 seconds and intermediate output edits every 5 time steps.

These settings will show the most output at the time of peak power, between 0.6 s and 0.7 s where changes in the variables of interest are most drastic.

III-1.14 PUMP MASS FLUX VS. TIME

The pump has a constant mass flux throughout the transient.

III-1.15 ROD WORTH VS. ROD LOCATION

Completer insertion of the control rod introduces 10\$ of negative reactivity into the core. This reactivity will scram the reactor when the overpower trip point is reached and the trip delay time is exceeded.

Figure III-1 Input listing for the IAEA 10 MW Benchmark HEU Reactor Core

```

0
* HEU Benchmark 2 Channel $1.50/0.5s ramp insertion
!
! 2 channel model of the 10 MW IAEA benchmark reactor with HEU fuel.
!
! Specifications for the safety-related benchmark problem are given in
! 'Research reactor core conversion guidebook', IAEA-TECDOC-643, vol 3.
!
! Fast reactivity insertion transient
!
!   - Reactor critical at an initial power of 1 W
!   - Safety system trip point: 1.2 P0 = 12 MW
!   - Time delay of 25 ms before linear shutdown reactivity insertion of
!     $10 in 0.5s
!   - Hot Channel Factors:
!     * Radial x Local Power Peaking Factor = 1.4
!     * Axial Power Peaking Factor = 1.5
!     * Engineering factor = 1.2
!   - Nominal flow rate: 1000 m^3/hr
!   - Coolant inlet temperature: 38 C
!   - Coolant inlet pressure: 1.7 bar (absolute)
!   - Thermal conductivity of UAlx-Al Fuel: 1.58 W/cm-K
!
! -----
!                                     GENERAL INFORMATION
!
! NCHN < 0
!   Use SI unit system
!
! |NCHN| = 2
!   2 channels model
!
! NZ = 21
!   21 axial node points
!
! NR = 7
!   7 radial node points in plate
!
! IGEOM = 0
!   slab geometry
!
! IPROP = 1
!   reactivity-specified operation (see Table 9)
!
! IRXSWT = 1
!   Subcooled vapor fraction and quality values are computed by the code
!
! IPOP = 0
!   Inlet coolant pressure will be specified (see PRESUR)
!
! KINTS = 0
!   Reduce and expand kinetics time step as needed
!
! IDLYGP = 6
!   6 groups of delayed neutrons
!
! KINPRT = -1
!   Print time, reactor power, reactivity, maximum outflow rate of all
!   channels and average reactor period after each kinetics time step
!
! ISUPPR = 0
!   Do not print average temperature
!

```

```

! MAXHCC = 10
!   Maximum iterations that the code should perform in the heat transfer
!   calculations. If the code detects that it should perform more iterations
!   to achieve convergence, the temperature printout is accompanied by an
!   asterix (*)
!
! POWER = 1.00000-6
!   Initial reactor power is 1W
!
! PF = .01062214
!   Total volume of fuel meat in the core is 1.062214E-02 m^3
!
! PRESUR = 1.70000+5
!   Inlet operating pressure is 1.7 bar (see IPOP)
!
! ENTHIN = 1.58650+5
!   The enthalpy of the inlet coolant is 1.58650E+5 (J/kg). This is equivalent
!   to a temperature of 38 C
!
! RS = 6.35000-4
!   Plate half-thickness (including clad) is 0.635 mm
!
! RF = 2.55000-4
!   Fuel half-thickness is 0.255 mm
!
! RC = 2.55000-4
!   Half distance to inner surface of clad is 2.55 mm. Same as RF because
!   there is no intermediate zone between the fuel and cladding.
!
! PW = 6.65000-2
!   Plate width is 6.65 cm
!
! FW = 6.30000-2
!   Fuel width is 6.3 cm
!
! AL = 0.6000
!   Active fuel length is 0.6 m
!
! ALDDIN = 0.0
!   Inlet non-fueled section length is 0.0 m
!
! ALDDEX = 0.0
!   Outlet non-fueled section length is 0.0 m
!
! BBEFF = 0.0076071
!   Effective delayed neutron fraction \beta=0.0076071
!
! EL = 55.960-6
!   Prompt neutron generation time is 55.960E-06 s
!
! GRAV = 9.80664
!   Acceleration due to gravity is 9.80664 m/s^2
!
! QW = 0.00975
!   Heat source description for coolant. It is the fraction of the heat
!   generated in the coolant multiplied by the ratio of the fuel meat volume
!   to the coolant volume (see card QR on card 3001 and 3002)
!
!   
$$QW = (V_f/V_c) * (1.0 - QR)$$

!
!   Vf is the volume of the fuel
!   Vc is the volume of the coolant
!   QR is the fraction of heat deposited directly in the plate
!

```

```

! TRANST = 0.80
!   The duration of the transient is 0.8 s
!
!
! RXXCON = 0.8, RXXEXP=1.0
!   The following Eq. will be used to evaluate the vapor volume fraction
!   (R) in sub-cooled regions:
!
!   
$$dR/dt + 0.8*V*dR/dZ + R/(\tau) = (\lambda)*K*(q'')^{(1.0)}$$

!
!   V is the fluid linear velocity
!   q'' is the surface heat flux
!   K is a constant
!   \tau is the bubble collapse time (see TAUUNB and TAUUTB)
!   \lambda is the fraction of the clad surface heat flux used in producing
!   vapor during boiling (see ALAMNB, ALAMTB and ALAMFB)
!
! RHOREF = 993.20
!   Coolant reference density (at t=0) is 993.20 kg/m^3
!
! GAMMA0 = 0.0, GAMMA1 = 3.60000-5, GAMMA2 = 0.0, GAMMA3 = 0.0, GAMMA4 = 0,
! DOPPN = 1.0
!   The following Eq. will be used to evaluate the fuel temperature
!   feedback
!
!   
$$\rho = 3.6E-05*T$$

!
!   \rho is the reactivity in $
!   T is the temperature in K
!
! EPS3 = 0.001
!   Threshold value used in kinetic time step error analysis
!
! DNBQDP = 0.0
!   The code will compute steady-state DNB heat flux values
!
! TAUUNB = 0.0005
!   Nucleate boiling bubble collapse time 0.5 ms (see RXXCON, RXXEXP)
!
! TAUUTB = 0.01
!   Transition boiling bubble collapse time 10 ms (see RXXCON, RXXEXP)
!
! ALAMNB = 0.03, ALAMTB = 0.05, ALAMFB = 0.05
!   Fraction of the clad surface heat flux utilized in producing vapor is
!   0.03 in the sub-cooled nucleate boiling region
!   0.05 in the sub-cooled transition boiling region
!   0.05 in the sub-cooled film boiling region
!
! HTTPCON = 1.4, HTTPEXP = 0.33
!   The following correlation is used for calculating the natural convection
!   heat transfer coefficients when Reynold's number is less than 2000:
!
!   
$$h = ((k/De)*(Re^{0.45})*(\xi/k)^{(5/6})*(\mu)^{(2/3})*(\mu/\mu_s)^{0.14})$$

!   
$$* 1.4*(u_s - u_b)^{0.33}$$

!
!   
$$\xi = k^{0.6} * (Cp/\mu)^{0.4}$$

!
!   k is the thermal conductivity
!   De is the equivalent diameter of the hydraulic channel
!   Re is the Reynold's number
!   u_s is the temperature of the outer surface clad
!   u_b is the bulk temperature of coolant
!   \mu is the coolant viscosity
!   \mu_s is the coolant viscosity at the temperature of the heating surface
!   Cp is the heat capacity at constant pressure

```



```

!
! -----1-----2-----3-----4-----5-----6-----7-----8-----9-----10-----11-----12-----
!      NCHN  NZ    NR    IGEOM  IPROP  IRXSWT
1001, -2    21    7      0      1      1
!      IPOP          IDLYGP      ISUPPR
!      |      KINTS |      KINPRT|      MAXHCC
1002, 0      0      6      -1     0      10
! -----1-----2-----3-----4-----5-----6-----
!      POWER      PF      PRESUR      ENTHIN
1003, 1.0E-6      .01062214  1.70000+5  1.58650+5
!      RS          RF      RC          PW          FW
1004, 6.35000-4  2.55000-4  2.55000-4  6.65000-2  6.30000-2
!      AL          ALDDIN  ALDDEX
1004, 0.6000      0.0      0.0
!      BBEFF      EL      GRAV      QW          TRANST
1005, 0.0076071  55.960-6  9.80664  0.00975  0.80
!      RXXCON      RXXEXP  RHOREF
1006, 0.800      1.0      993.20
!      GAMMA0      GAMMA1  GAMMA2      GAMMA3      GAMMA4      DOPPN
1007, 0.0      3.60000-5  0.0      0.0      0.0      1.0
!      EPS3      DNBQDP
1008, 0.001      0.0
!      TAUUNB      TAUUTB      ALAMNB      ALAMTB      ALAMFB
1009, 0.0005      0.001      0.03      0.05      0.05
!      HTTCON      HTTEXP
1010, 1.4      0.33
! -----
!
!                      ADDITIONAL GENERAL INFORMATION
!
! PSUBC = 0.0857927
!   The total cross-sectional area of all flow channels in core is
!   0.0857927 m^2. This parameter is no longer used.
!
! FACT2 = 1.00 1.00
!   The flux weighting factor is set to 1.0 for both channels
!
! IONEP = 1
!   The Sieder-Tate correlation will be used for single phase heat transfer
!   at the clad/coolant interface
!
! ITWOP = 1
!   The McAdams correlation will be used for two-phase heat transfer at the
!   clad/coolant interface
!
! IMODE = 1
!   The transition model will be used for the transient two-phase scheme
!
! ICHF = 0
!   The original DNB correlation is used
!
! IHT = 0
!   The original heat transfer subroutine is used
!
! QAVE = N/A, ETA=N/A and CP = N/A
!   These parameters are not relevant for ICHF=0
!
! RDRATE = 1.2
!   Control rod movement rate: 1.2 m/s
!
! TDLAY = 0.025
!   There is a 25 ms delay before rod starts after tripping point
!
! POWTP = 12.0
!   Overpower trip point in 12.0 MW

```

```

!
! FLOTP = 0.0
!   There is no low flow trip point.
!
! OPT = N/A (default 24 days), POW0 = N/A (default same as POWER=1W)
!   Previous operating time and power of the reactor, used in decay heat power
!   after scram
!
! HNCTOP = 0.0, HNCBOT = 0.0
!   No height above or below the reactor.
!
! ----1-----2-----3-----4-----5-----6-----
!   PSUBC      FACT2
1111, 0.0857927  1.00      1.00
!   IONEP ITWOP IMODE ICHF  IHT      QAVE      ETA      CP
1112, 1      1      1      0      0
!   RDRATE      TDLAY      POWTP      FLOTP      OPT      POW0
1113, 1.2      0.025      12.0      0.0
!   HNCTOP      HNCBOT      REL_T      RET_T      FINF      PHI
1114, 0.0      0.0
! -----
!               THERMAL PROPERTIES OF FUEL ELEMENT MATERIALS
!
! thermal conductivity:      k = a1*T^2 + a2*T + a3 + a4/T      unit: W/(m*K)
! volumetric heat capacity: g = b1*T^2 + b2*T + b3 + b4/T      unit: J/(m^3*K)
!
! ----1-----2-----3-----4-----5-----
! FUEL MEAT
2001, 0.0      0.0      158.0      0.0      0.0
2002, 0.0      1.0670+3  2.0721+6  0.0      0.0
! CLAD
2003, 0.0      0.0      180.0      0.0      0.0
2004, 0.0      1.2420+3  2.0691+6  0.0      0.0
! -----
!               HALF-PLATE THICKNESS RADIAL DESCRIPTION
!
! The plate half-thickness (including clad) is 0.635 mm (see RS)
! The fuel half-thickness is 0.255 mm (see RF)
! There is no intermediate zone between the fuel and cladding (see RC)
!
! There are 7 radial node points (see NR) across the plates (6 intervals)
!   4 intervals in the fuel: 4 * 0.06375 = 0.255 mm
!   2 intervals in the clad: 2 * 0.19000 = 0.380 mm
!
! A fraction of 0.955 of the heat source is deposited directly in the fuel.
! None is deposited in the clad. The rest is deposited in the coolant (see QW)
!
! ----1-----2-----3-----4-----5-----
!   AINCR      KK      ICOMP QR      ICLAD
3001, 6.37500-5  5      1      0.955
3002, 1.90000-4  7      2      0.0000
! -----
!               AXIAL DESCRIPTION
!
! The active fuel length (0.6 m, see AL) is divided into 21 axial regions
! (see NZ).
! The same height is used for all the nodes: 21 * 0.0285714 = 0.6
! ----1-----2-----
4001, 2.85714-2  21
! -----
!               1st CHANNEL INFORMATION
!
! This channel represents the hottest plate
!
! IFLOW = 1, DELP = 0

```

```

!      flow-forced channel (see Table 10)
!
! RN = 1.75000-3
!      Distance from the center of the plate to the center of the coolant
!      channel is 1.75 mm.
!      The half-thickness of the coolant channel is 1.115 mm (1.75-0.635 = RN-RS)
!
! BM = 0.00181
!      Volume fraction of the core meat in this channel
!
! ALOSCN = 0.55, ALOSCX = 0.65
!      Unrecoverable pressure loss coefficient for abrupt change in the area at
!      the inlet (ALOSCN) and outlet (ALOSCX) of the channel
!
! SIGIN = 1.0, SIGEX = 1.0
!      Ratio of the channel area to the area of the associated plenum at the
!      inlet (SIGIN) and outlet (SIGEX) of the channel.
!
! DVOID = 0.2992
!      Overall density/void reactivity feedback coefficient
!
! DTMP = 1.6459-2
!      Overall temperature reactivity feedback coefficient
!
! ALPPIN = 0.0, ALPPEX = 0.0
!      Length of the inlet (ALPPIN) and outlet (ALPPEX) plenum
!
! DEEIN = 0.3048, DEEEX = 0.3048
!      Equivalent hydraulic parameter of the inlet (DEEIN) and outlet (DEEEX)
!      plenum
!
! PFQ
!      Axial source description for each axial node in the channel. It is the
!      ratio of the local fission power density to the core-average fission power
!      density.
!
! VOIDVC
!      Coolant density feedback weighting factor
!
! DOPPLR
!      Fuel temperature feedback weighting factor
!
! TEMPC
!      Coolant temperature feedback weighting factor
!
! ----1-----2-----3-----4-----5-----6-----
!      IFLOW DELP RN BM ALOSCN ALOSCX
5100, 1 0 1.75000-3 0.00181 0.55 0.65
!      SIGIN SIGEX DVOID DTMP
5100, 1.0 1.0 0.2992 1.6459-2
!      ALPPIN ALPPEX DEEIN DEEEX
5101, 0.0 0.0 0.3048 0.3048
!      PFQ VOIDVC DOPPLR TEMPC
5102, 0.1885 0.3617 1.0 0.4595
5103, 0.7172 0.5596 1.0 0.4136
5104, 1.0530 0.6938 1.0 0.5340
5105, 1.3674 0.8260 1.0 0.7074
5106, 1.6541 0.9585 1.0 0.8934
5107, 1.9073 1.0862 1.0 1.0740
5108, 2.1218 1.2021 1.0 1.2376
5109, 2.2934 1.2999 1.0 1.3751
5110, 2.4184 1.3740 1.0 1.4790
5111, 2.4945 1.4202 1.0 1.5436
5112, 2.5200 1.4358 1.0 1.5656
5113, 2.4945 1.4202 1.0 1.5436

```

```

5114, 2.4184      1.3740      1.0      1.4790
5115, 2.2934      1.2999      1.0      1.3751
5116, 2.1218      1.2021      1.0      1.2376
5117, 1.9073      1.0862      1.0      1.0740
5118, 1.6541      0.9585      1.0      0.8934
5119, 1.3674      0.8260      1.0      0.7074
5120, 1.0530      0.6938      1.0      0.5340
5121, 0.7172      0.5596      1.0      0.4136
5122, 0.1885      0.3617      1.0      0.4595
! -----
!
!                               2nd CHANNEL INFORMATION
!
! This channel represents the average plate
!
! IFLOW = 1, DELP = 0
!     flow-forced channel (see Table 10)
!
! RN = 1.75000-3
!     Distance from the center of the plate to the center of the coolant
!     channel is 1.75 mm.
!     The half-thickness of the coolant channel is 1.115 mm (1.75-0.635 = RN-RS)
!
! BM = 0.99819
!     Volume fraction of the core meat in this channel
!
! ALOSCN = 0.55, ALOSCX = 0.65
!     Unrecoverable pressure loss coefficient for abrupt change in the area at
!     the inlet (ALOSCN) and outlet (ALOSCX) of the channel
!
! SIGIN = 1.0, SIGEX = 1.0
!     Ratio of the channel area to the area of the associated plenum at the
!     inlet (SIGIN) and outlet (SIGEX) of the channel.
!
! DVOID = 0.3257
!     Overall density/void reactivity feedback coefficient
!
! DTMP = 1.5370-2
!     Overall temperature reactivity feedback coefficient
!
! ALPPIN = 0.0, ALPPEX = 0.0
!     Length of the inlet (ALPPIN) and outlet (ALPPEX) plenum
!
! DEEIN = 0.3048, DEEEX = 0.3048
!     Equivalent hydraulic parameter of the inlet (DEEIN) and outlet (DEEEX)
!     plenum
!
! PFQ
!     Axial source description for each axial node in the channel. It is the
!     ratio of the local fission power density to the core-average fission power
!     density.
!
! VOIDVC
!     Coolant density feedback weighting factor
!
! DOPPLR
!     Fuel temperature feedback weighting factor
!
! TEMPC
!     Coolant temperature feedback weighting factor
!
! -----1-----2-----3-----4-----5-----6-----
!     IFLOW DELP  RN      BM      ALOSCN  ALOSCX
5200, 1      0      1.75000-3  0.99819  0.55      0.65
!     SIGIN      SIGEX      DVOID      DTMP
5200, 1.0      1.0      0.3257      1.5370-2

```

```

!      ALPPIN      ALPPEX      DEEIN      DEEEX
5201, 0.0          0.0          0.3048    0.3048
!      PFQ         VOIDVC      DOPPLR      TEMPC
5202, 0.1122       0.3617      1.0        0.4595
5203, 0.4269       0.5596      1.0        0.4136
5204, 0.6268       0.6938      1.0        0.5340
5205, 0.8139       0.8260      1.0        0.7074
5206, 0.9846       0.9585      1.0        0.8934
5207, 1.1353       1.0862      1.0        1.0740
5208, 1.2630       1.2021      1.0        1.2376
5209, 1.3651       1.2999      1.0        1.3751
5210, 1.4395       1.3740      1.0        1.4790
5211, 1.4848       1.4202      1.0        1.5436
5212, 1.5000       1.4358      1.0        1.5656
5213, 1.4848       1.4202      1.0        1.5436
5214, 1.4395       1.3740      1.0        1.4790
5215, 1.3651       1.2999      1.0        1.3751
5216, 1.2630       1.2021      1.0        1.2376
5217, 1.1353       1.0862      1.0        1.0740
5218, 0.9846       0.9585      1.0        0.8934
5219, 0.8139       0.8260      1.0        0.7074
5220, 0.6268       0.6938      1.0        0.5340
5221, 0.4269       0.5596      1.0        0.4136
5222, 0.1122       0.3617      1.0        0.4595
! -----
!                               DELAYED NEUTRON INFORMATION
!
! Pair of delayed neutron fraction, delayed neutron constant (s^-1) for each
! delayed neutron group
! ----1-----2-----3-----4-----5-----6-----
6001, 0.04183      0.01334      0.19392      0.03274      0.15589      0.12078
6002, 0.38530      0.30278      0.15716      0.84950      0.06591      2.85308
! -----
!                               REACTIVITY VS TIME
!
! REACC: reactivity ($)
! TIME: reactor time (s)
!
! $1.5 of reactivity are inserted from time 0.0 to time 0.5 at a constant
! rate.
! -----
!      N
9000,      3
!      REACC      TIME
9001, 0.00      0.0
9002, 1.50      0.50
9003, 1.50      100.0
! -----
!                               COOLANT INLET MASS FLUX VS TIME
!
! AMFRIN: inlet mass flux (kg/s/m^2)
!         positive for up-flow, negative for down-flow
! TIME: reactor time (s)
!
! The nominal flow rate is 1000 m^3/hr
! -----
!      N
10000, 2
!      AMFRIN      TIME
10001, 3.21580+3  0.0
10002, 3.21580+3  100.0
! -----
!                               LINEAR THERMAL EXPANSION OF CLAD VS TEMPERATURE
!
! YYCLAD: percent linear thermal expansion of the clad (%)

```

```

! YCTEMP: temperature (K)
!
! Assume no clad expansion during this transient
! -----
!      N
11000, 2
!      YYCLAD      YCTEMP
11001, 0.0          98.0
11002, 0.0          1000.0
! -----
!
!                      TOTAL PRESSURE DROP VS TIME
!
! PRESSP: total pressure drop (Pa)
! TIME: reactor time (s)
! -----
!      N
12000, 2
!      PRESSP      TIME
12001, 0.0          0.0
12002, 0.0          100.0
! -----
!
!                      TIME INCREMENT VS TIME
!
! TINCRR: time increment (s)
! TIME: reactor time (s)
! -----
!      N
14000, 3
!      TINCRR      TIME
14001, 0.005        0.0
14002, 0.001        0.55
14003, 0.005        0.75
! -----
!
!                      PRINT FREQUENCY VS TIME (s)
!
! TOPFQ: print time increment (in seconds) for major output edits
! NPOFQ: frequency of intermediate printout (in steps)
! TIME: reactor time (s) at which print time increment goes into effect
! -----
!      N
16000, 4
!      TOPFQ      NPOFQ      TIME
16001, 0.10        5          0.0
16002, 0.05        2          0.50
16003, 0.05        1          0.60
16004, 0.10        5          0.70
! -----
!
!                      PUMP MASS FLUX VS TIME
!
! FLOWRT: mass flux fraction of the coolant to its initial value
! TIME: reactor time (s)
! -----
!      N
17000, 2
!      FLOWRT      TIME
17001, 1.0          0.0
17002, 1.0          100.0
! -----
!
!                      ROD WORTH VS ROD LOCATION
!
! RODWTH: reactivity ($) associated with the control rod
!          negative value should be entered
! RODLOC: rod position (m)
!
! The insertion rate is given by RDRATE=1.2 m/s such that 10$ of reactivity

```

```
! are inserted in 0.5s
! -----
!      N
18000, 2
!      RODWTH      RODLOC
18001,   0.0      0.0
18002, -10.0      0.6
```

APPENDIX IV USE OF AXIAL POWER PROFILES IN PARET

Previous Users Guides for PARET, and the original Obenchain [1] document, do not state clearly where the axial power profile supplied on card types 5k01 is located (variable PFQ), or how it is used. The purpose of Section IV-1 of this appendix is to make it clear how the code uses axial power profile information. The purpose of Section IV-2 is to document the self-consistency of input data arrays used to specify the power distribution among PARET channels, across the thickness or radius of the meat, and among the axial nodes over the fueled length.

IV-1 EDITED AXIAL MESH INFORMATION

When an input file is processed, the code edits axial profile location information under a centered title:

AXIAL DESCRIPTION

Here, one finds column headings of:

AXIAL NODE AXIAL LENGTH CALC. INTERVAL AXIAL INTERVAL

Values that follow under "AXIAL LENGTH" are the axial locations of the points in the z-direction at which the axial power profile is located. Also, the power that the code delivers to the coolant in each axial node is proportional to the average of the two interface values for PFQ at each end of that node.

If the mesh is optimal from the standpoint of numerical instability, then the fluid axial nodes will all be of the same length $[AL/(NZ-1)]$. The first and last fuel nodes will be half-sized, compared to all of the rest $[AL/(2(NZ-1))]$.

IV-1.1 TEST PROBLEM

As an example, a 2-channel case with $NZ=11$ axial nodes and an axial fueled length of 0.6 m was tested using a linear power profile that ranged over 1.0 to 2.0 in channel 1.(See Table IV-1).

Table IV-1 Enthalpy Rise at time $t=0.1$ second for a null transient

Node	Z, m	PFQ	Enthalpy at z, kJ (up-flow)	Enthalpy rise in node, kJ	Enthalpy at z, kJ (down- flow)	Enthalpy rise in node, kJ
1	0	1.0	146.1001	7.1155	247.4601	7.1037
2	.06	1.1	153.2156	7.7914	240.3564	7.7567
3	.12	1.2	161.0070	8.4693	232.5997	8.4534
4	.18	1.3	169.4763	9.1436	224.1463	9.1126
5	.24	1.4	178.6199	9.8228	215.0337	9.8041
6	.30	1.5	188.4427	10.4869	205.2296	10.4678

7	.36	1.6	198.9296	11.1743	194.7618	11.1554
8	.42	1.7	210.1039	11.8311	183.6064	11.8226
9	.48	1.8	221.9350	12.5266	171.7838	12.5072
10	.54	1.9	234.4616	13.1796	159.2766	13.1765
11	.60	2.0	247.6412		146.1001	

IV-1.2 DISCUSSION

Even though the PARET code should treat this problem identically for up-flow or for down-flow, there are small differences in the enthalpy rise in each node. One can ratio the enthalpy rise in various nodes, and compare that to the expected ratio, as shown in Table IV-2.

Table IV-2 Details of Enthalpy rise by node

Node Ratio	Enthalpy Rise Ratio Supplied and Expected		PARET edited Enthalpy Rise Ratio and % error (up-flow)	PARET edited Enthalpy Rise Ratio and % error (down-flow)
10:1	1.95/1.05 1.8571	or	1.8522 -0.27 %	1.8549 -0.12 %
9:2	1.85/1.15 1.6087	or	1.6077 -0.06 %	1.6124 +0.23 %
8:3	1.75/1.25 1.4000	or	1.39694 -0.22 %	1.3986 -0.10 %
7:4	1.65/1.35 1.2222	or	1.2221 -0.01 %	1.2242 +0.16 %
6:5	1.55/1.45 1.0690	or	1.0676 -0.13 %	1.0677 -0.12 %

It is clear from Table IV-2 that PARET computes the enthalpy rise for this linear power profile as expected. If there were any unknown treatment of first and last nodes, then the listed enthalpy rise ratios would not agree with those in column 2. The edited "ENERGY GAIN" at 0.1 sec is 1.04042 for up-flow, and 1.03511 for down-flow. The true power is 1.04000 MW. This comparison shows that the code is not exactly symmetric for up-flow vs. down-flow. It is more accurate for up-flow, in this case. One possibility is that the fluid density variation with pressure and height should be implemented.

IV-1.3 CONCLUSION

This investigation shows that the enthalpy rise calculation proceeds as expected for a linear power profile. There is a very minor difference between up-flow and down-flow that is not necessarily indicative of any error in coding. This investigation also found that PARET does not compute fluid density using local pressure, as the Obenchain report claims (Section 4, p. 8). It appears to be relatively simple to implement that feature, because the local pressure at each axial level is periodically computed throughout the transient event, accounting for up-flow vs. down-flow.

IV-2 SELF-CONSISTENCY OF ARRAYS BM AND PFQ FOR PARET CHANNELS AND NORMALIZATION OF POWER DENSITY DISTRIBUTION

IV-2.1 INTRODUCTION AND SUMMARY

The reactor core is modeled by dividing it into a maximum of 50 PARET/ANL channels (see input card series 5100 and 5101), where a channel is a specific group of fuel pins/plates with the associated coolant. All channels are axially divided into a maximum of 96 mesh intervals here referred to as axial nodes (see input card series 5102, 5103, etc.). The same axial mesh structure is used in all channels. As shown in Fig. 1, each fuel pin is radially divided into an input number of radial increments in the fuel meat, an input number of radial increments in the fuel-cladding gap, and an input number of radial increments in the cladding (specified on the input card series 3000). The power density distribution in a fuel pin is assumed to be separable into a function of time, a function of intra-pin radius, and a function of axial position.

It is shown below that a consistent normalization of reactor-wide power density distribution requires that the input array QR must average to $(1 - F_{cool})$ as shown by Eq.(IV-16), and the input arrays BM_k and $PFQ_{k,j}$ must satisfy Eq. (IV-26). The channel-wise power density in meat, $q_{chan,k,j,n}$, (excluding the power deposited directly in coolant) is shown to be related to the input data arrays by Eq. (IV-33). The channel-wise power density in coolant, $q_{chan,k,j}$, is shown to be related to the input data arrays by Eq. (IV-39). Here, $\bar{Q}$ is the core-average power density in meat assuming that all power is deposited in the meat, and Eq. (IV-1) and (IV-2) accounts for the fact that a fraction of power is deposited directly in the coolant.

$$q_{chan,k,j,n} = \bar{Q} \times PFQ_{k,j} \times QR_n \quad (IV-1)$$

$$q_{cool,k,j} = \bar{Q} \times PFQ_{k,j} \times QW \quad (IV-2)$$

IV-2.2 DEMONSTRATION OF THE SELF-CONSISTENCY OF ARRAYS BM AND PFQ

Let us assume a problem with NP fuel plates or pins discretized in NZ axial nodes, with (NN1-1) radial nodes in meat of each fuel pin as shown in Fig. Figure VII-1. From the physics-calculated power density distribution $Q_{i,j,n}$ in all fuel pins of the core, we need to calculate the channel-wise axial power density shapes $PFQ_{k,j}$ and describe the distribution of the total reactor power P_{tot} (input variable POWER) among the channels. First, the core average power

density in fuel meat is calculated by Eq.(IV-3), assuming the total power is produced and deposited in the total meat volume in core. The total meat volume V_{tot} is given by Eq. (IV-4) as the sum of meat node volumes ($\Delta A_n \Delta Z_j$) over all (NN1-1) nodes along meat thickness/radius, over all NP fuel plates/pins, and over all NZ axial nodes. The sum of all nodal powers $Q_{i,j,n} \times \Delta V_{i,j,n}$ (nodal power density $\times$ nodal volume) must be P_{tot} as shown by Eq. (IV-5).

$$\bar{Q} = \frac{P_{tot}}{V_{tot}} \quad (IV-3)$$

$$V_{tot} = \sum_{j=1}^{NZ} \sum_{i=1}^{NP} \sum_{n=1}^{NN1-1} \Delta V_{i,j,n} \quad \text{where} \quad \Delta V_{i,j,n} = \Delta A_n \Delta Z_j \quad (IV-4)$$

$$P_{tot} = \sum_{j=1}^{NZ} \sum_{i=1}^{NP} \sum_{n=1}^{NN1-1} Q_{i,j,n} \times \Delta V_{i,j,n} \quad (IV-5)$$

where

n = Intra-pin radial mesh index, or mesh index across plate thickness.

j = Axial segment index.

k = Channel number. Each channel models a different number of fuel pins of identical geometry, differing only in the coolant flow cross-sectional area.

The channel-wise flow area is determined by the coolant outer radius RN(K) (shown in Figure VII-1) that is entered on the input card series 5000.

A_{cool} = coolant flow area associated with a fuel plate/pin

$A_{meat} = \sum_{n=1}^{NN1-1} \Delta A_n$ = fuel meat cross sectional area in fuel plate/pin

ΔA_n = (plate width) $\times\Delta X_n$ in slab geometry (IGEOM = 0) where ΔX_n is the n^{th} mesh interval in the thickness of a fuel plate, or

= $\pi(r_{n+1}^2 - r_n^2)$ in cylindrical geometry (IGEOM = 1) as shown in Fig. 1

$F_{cool} = (\text{input QW}) \times (A_{cool}/A_{meat})$ = fraction of P_{tot} that is deposited directly in the coolant

NZ = Number of axial node boundaries. (input card series 1000)

NN1 = Input radial node number out to which is fuel meat. The meat consists of the Radial *mesh intervals* $I = 1, 2, \dots (NN1-1)$. In the special case of Figure VII-1, NN1 = 6 and the meat consists of 5 mesh intervals. (input card series 3000)

NN2 = Input radial node number out to which is fuel-cladding gap. In Figure VII-1, NN2 = 8.

(input card series 3000)

NN3 = Input radial node number out to which is cladding. In Figure VII-1, NN3 = 10. (input card series 3000)

P_{tot} = total reactor power (input variable POWER). It includes the power deposited

directly in the coolant.

$P_{\text{tot},k}$ = total power in meat and coolant of PARET/ANL channel k

P_k = $P_{\text{tot},k}(1 - F_{\text{cool}})$ = power in fuel meat in PARET/ANL channel k

$\bar{Q}$ = core-average power density in meat assuming that all power is deposited in the meat

$Q_{\text{avg},i,j}$ = power density averaged over fuel meat cross-section in axial segment j of pin/plate i assuming that all power is deposited in the meat

$q_{i,j,n}$ = nodal power density in fuel meat volume $\Delta V_{i,j,n}$. It does not include the power deposited directly in the coolant. It only includes the power deposited in the meat.

$q_{\text{chan},k,j,n}$ = channel-wise power density in fuel meat, excluding the power deposited directly in the coolant.

$q_{\text{cool},i,j}$ = nodal power density in coolant volume $A_{\text{cool}}\Delta Z_j$ of the i^{th} pin/plate in the j^{th} axial segment. It only includes the power deposited directly in the coolant.

QW = $q_{\text{cool},i,j} / Q_{\text{avg},i,j}$ = Ratio of power density in coolant to the total power density averaged over fuel meat cross-section. (input card series 1000). The value of this input fraction must be such that

$$[\text{averaged value of } QR(I)] + QW \cdot (\text{coolant volume}) / (\text{fuel meat volume}) = 1$$

RF = Fuel meat outer radius, m. (input card series 1000)

RC = Cladding inner radius, m. (input card series 1000)

RS = Cladding outer radius, m. (input card series 1000)

V_{tot} = total meat volume in core

$\Delta V_{i,j,n} = \Delta A_n \times \Delta Z_j$ = volume of meat in intra-meat radial node n of axial node j of fuel pin i.

Eq. (IV-6) defines a power density $Q_{\text{avg},i,j}$ averaged over fuel meat cross-section in axial segment j of pin/plate i assuming that all power is deposited in the meat.

$$Q_{\text{avg},i,j} = \frac{\sum_{n=1}^{NN1-1} Q_{i,j,n} \times \Delta A_n}{\sum_{n=1}^{NN1-1} \Delta A_n} = \frac{\sum_{n=1}^{NN1-1} Q_{i,j,n} \times \Delta A_n}{A_{\text{meat}}} \quad (\text{IV-6})$$

$$Q_{\text{avg},i,j} A_{\text{meat}} = \sum_{n=1}^{NN1-1} Q_{i,j,n} \times \Delta A_n \quad (\text{IV-7})$$

Eq. (IV-3) for the core-average power density $\bar{Q}$ assuming that all power is deposited in the meat can be written as Eq.(IV-8). Using Eq. (IV-7), Eq. (IV-8) can be written in terms of $Q_{\text{avg},i,j}$ as shown by Eq. (IV-9).

$$\bar{Q} = \frac{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \sum_{n=1}^{NN1-1} Q_{i,j,n} \times \Delta A_n \Delta Z_j}{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \sum_{n=1}^{NN1-1} \Delta A_n \Delta Z_j} = \frac{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \Delta Z_j \sum_{n=1}^{NN1-1} Q_{i,j,n} \times \Delta A_n}{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \Delta Z_j \sum_{n=1}^{NN1-1} \Delta A_n} \quad (IV-8)$$

$$\bar{Q} = \frac{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \Delta Z_j Q_{avg,i,j} A_{meat}}{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \Delta Z_j A_{meat}} = \frac{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \Delta Z_j Q_{avg,i,j}}{\sum_{j=1}^{NZ} \sum_{i=1}^{NP} \Delta Z_j} \quad (IV-9)$$

The code makes the following two assumptions regarding the power split between the meat and the coolant:

- (1) It is assumed that the ratio $q_{cool,i,j}/Q_{avg,i,j}$ is constant. This assumption means that the nodal power density in the coolant associated with *each pin/plate* has the same axial shape as that of the total power density averaged over meat cross-section.

$$\frac{q_{cool,i,j}}{Q_{avg,i,j}} = QW, \text{ where } QW \text{ is an input datum} \quad (IV-10)$$

- (2) It is assumed that the nodal power density $q_{i,j,n}$ deposited in meat is the product of array $Q_{avg,i,j}$ and an input array QR_n of intra-meat index n , as shown by Eq. (8). The current code assumes a single intra-meat radial profile QR_n for all pins/plates and for all axial nodes.

$$q_{i,j,n} = Q_{avg,i,j} \times QR_n \quad (IV-11)$$

Multiplying Eq. (IV-11) by nodal volume $\Delta A_n \Delta Z_j$ and summing over the meat cross section, the power ($P_{meat,i,j}$) deposited in meat in the j^{th} axial segment of the i^{th} plate/pin is found as follows.

Here the average of array QR_n is defined by $\sum_{n=1}^{NN1-1} QR_n \Delta A_n = A_{meat} \bar{QR}$.

$$P_{meat,i,j} = \sum_{n=1}^{NN1-1} q_{i,j,n} \Delta A_n \Delta Z_j = Q_{avg,i,j} \Delta Z_j \sum_{n=1}^{NN1-1} QR_n \Delta A_n \quad (IV-12)$$

$$P_{meat,i,j} = Q_{avg,i,j} \Delta Z_j A_{meat} \bar{QR} \quad (IV-13)$$

The sum of the power ($P_{meat,i,j}$) deposited in meat [given by Eq. (IV-13)] and the power deposited directly in the coolant must equal the total power in an axial segment of each plate/pin, which is given by $P_{i,j} = Q_{avg,i,j} \times A_{meat} \Delta Z_j$. The power deposited directly in the coolant is given by $q_{cool,i,j} \times A_{cool} \Delta Z_j$. This power balance is expressed as follows.

$$Q_{avg,i,j} \Delta Z_j A_{meat} \bar{QR} + q_{cool,i,j} \times A_{cool} \Delta Z_j = Q_{avg,i,j} \times A_{meat} \Delta Z_j \quad (IV-14)$$

Dividing this power balance Eq. by $A_{meat} \Delta Z_j$, and using Eq. (IV-11), one obtains Eq. (IV-15).

$$\overline{QR} + QW \times \left(\frac{A_{cool}}{A_{meat}} \right) = 1 \quad (IV-15)$$

The PARET/ANL input data description specifies that Eq. (IV-15) must be satisfied. This Eq. can be rewritten as a normalization condition for the input array QR_n , as given by Eq.(IV-16). Here $(input\ QW) \times (A_{cool}/A_{meat})$ is the fraction of total power that is deposited in coolant.

$$\overline{QR} = \frac{\sum_{n=1}^{NN1-1} QR_n \Delta A_n}{\sum_{n=1}^{NN1-1} \Delta A_n} = 1 - F_{cool} \quad \text{where} \quad F_{cool} = (input\ QW) \times (A_{cool}/A_{meat}) \quad (IV-16)$$

PARET/ANL model requires the calculation of local-to-average power density ratios, $PFQ_{k,j}$ for each channel k . So let us start with the local-to-average power density ratios for each nodal volume in the reactor. The local power density used in the ratio is the value averaged over meat cross section.

$$f_{i,j} = \frac{Q_{avg,i,j}}{Q} \quad (IV-17)$$

For each channel of PARET/ANL model, the $PFQ_{k,j}$ of an axial node j is the average of all the $f_{i,j}$ at that axial location in fuel plates/pins represented by that channel. Let us assume that PARET/ANL channel k represents the fuel plates/pins 1 to M .

$$PFQ_{k,j} = \frac{\sum_{i=1}^M f_{i,j} \times A_{meat} \Delta Z_j}{V_{k,j}} \quad (IV-18)$$

where the denominator $V_{k,j} = \sum_{i=1}^M A_{meat} \Delta Z_j$ is the sum of all fuel volumes in channel k for a given axial node j . For that channel, the axially averaged PFQ is

$$\overline{PFQ}_k = \frac{\sum_{j=1}^{NZ} PFQ_{k,j} \times V_{k,j}}{V_k} \quad (IV-19)$$

where the denominator $V_k = \sum_{j=1}^{NZ} V_{k,j}$ is the fuel meat volume in PARET/ANL channel k . The fuel meat volume fraction array BM_k by channel (an input data) is defined in terms of V_k as follows.

$$BM_k = \frac{V_k}{V_{tot}} \quad (IV-20)$$

Using Eqs. (IV-19) and (IV-20), let us evaluate

$$\overline{PFQ}_k \times BM_k = \frac{\sum_{j=1}^{NZ} PFQ_{k,j} \times V_{k,j}}{V_k} \times \frac{V_k}{V_{tot}} = \frac{\sum_{j=1}^{NZ} PFQ_{k,j} \times V_{k,j}}{V_{tot}} \quad (IV-21)$$

Eq. (IV-18) can be rewritten as $\text{PFQ}_{k,j} \times V_{k,j} = \sum_{i=1}^M f_{i,j} \times A_{\text{meat}} \Delta Z_j$. Using this in Eq. (IV-21)

$$\overline{\text{PFQ}}_k \times \text{BM}_k = \frac{\sum_{j=1}^{\text{NZ}} \text{PFQ}_{k,j} \times V_{k,j}}{V_k} \times \frac{V_k}{V_{\text{tot}}} = \frac{\sum_{j=1}^{\text{NZ}} \text{PFQ}_{k,j} \times V_{k,j}}{V_{\text{tot}}} \quad (\text{IV-22})$$

$$\overline{\text{PFQ}}_k \times \text{BM}_k = \frac{\sum_{j=1}^{\text{NZ}} \sum_{i=1}^M f_{i,j} \times A_{\text{meat}} \Delta Z_j}{V_{\text{tot}}} \quad (\text{IV-23})$$

Replacing Eq. (IV-17) in Eq. (IV-23)

$$\overline{\text{PFQ}}_k \times \text{BM}_k = \frac{\sum_{j=1}^{\text{NZ}} \sum_{i=1}^M Q_{\text{avg},i,j} \times A_{\text{meat}} \Delta Z_j}{V_{\text{tot}} \bar{Q}} \quad (\text{IV-24})$$

The denominator of Eq. (IV-24) is $V_{\text{tot}} \bar{Q} = P_{\text{tot}}$. The numerator is the total power (including the power in coolant) in PARET/ANL channel k, $P_{\text{tot},k}$, as defined by Eq. (IV-25). Replacing Eq. (IV-25) in Eq. (IV-24), we get Eq.(IV-26).

$$P_{\text{tot},k} = \sum_{j=1}^{\text{NZ}} \sum_{i=1}^M Q_{\text{avg},i,j} \times A_{\text{meat}} \Delta Z_j \quad (\text{IV-25})$$

$$\overline{\text{PFQ}}_k \times \text{BM}_k = \frac{P_{\text{tot},k}}{P_{\text{tot}}} \quad (\text{IV-26})$$

Eq. (IV-26) indicates that in order for the input arrays BM_k and $\text{PFQ}_{k,j}$ to be self-consistent, the product of the axial average of $\text{PFQ}_{k,j}$ in a PARET/ANL channel times its BM must equal the fraction of power in that channel. The axial average of $\text{PFQ}_{k,j}$ in a PARET/ANL channel is found by Eq. (IV-19) which can be rewritten as Eq. (IV-27).

$$\overline{\text{PFQ}}_k = \frac{\sum_{j=1}^{\text{NZ}} \text{PFQ}_{k,j} \times \Delta Z_j}{\sum_{j=1}^{\text{NZ}} \Delta Z_j} \quad (\text{IV-27})$$

IV-2.3 CHANNEL-WISE POWER DENSITY IN FUEL MEAT:

The code uses channel-wise power density in meat, $q_{\text{chan},k,j,n}$, excluding the power deposited directly in the coolant. This is basically the average of pin-wise (or plate-wise) nodal power density in meat $q_{i,j,n}$, over all the pins/plates ($i=1$ to M) constituting a channel k.

$$q_{\text{chan},k,j,n} = \frac{\sum_{i=1}^M q_{i,j,n} \Delta A_n \times \Delta Z_j}{\sum_{i=1}^M \Delta A_n \times \Delta Z_j} \quad (\text{IV-28})$$

Using Eq. (IV-11) in Eq. (IV-28)

$$q_{\text{chan},k,j,n} = \frac{\sum_{i=1}^M Q_{\text{avg},i,j} \times QR_n \Delta A_n \times \Delta Z_j}{\sum_{i=1}^M \Delta A_n \times \Delta Z_j} = \frac{QR_n}{M} \sum_{i=1}^M Q_{\text{avg},i,j} \quad (\text{IV-29})$$

Using Eq. (IV-17) in Eq. (IV-29)

$$q_{\text{chan},k,j,n} = \frac{\bar{Q} \times QR_n}{M} \sum_{i=1}^M f_{i,j} \quad (\text{IV-30})$$

The sum $\sum_{i=1}^M f_{i,j}$ is obtained from Eq. (IV-18).

$$\sum_{i=1}^M f_{i,j} = \frac{PFQ_{k,j} \times V_{k,j}}{A_{\text{meat}} \Delta Z_j} = \frac{PFQ_{k,j} \times \sum_{i=1}^M A_{\text{meat}} \Delta Z_j}{A_{\text{meat}} \Delta Z_j} \quad (\text{IV-31})$$

$$\sum_{i=1}^M f_{i,j} = PFQ_{k,j} \times M \quad (\text{IV-32})$$

Using Eq. (IV-32) in Eq. (IV-28), the channel-wise power density in meat is given by Eq. (IV-33):

$$q_{\text{chan},k,j,n} = \bar{Q} \times PFQ_{k,j} \times QR_n \quad (\text{IV-33})$$

IV-2.4 POWER DENSITY IN COOLANT

Eq. (IV-33) can be used to find the pin/plate linear power in meat in axial node j of PARET/ANL channel k , as shown by Eq. (IV-34). Dividing this linear power by $(1 - F_{\text{cool}})$, one gets the total linear power (i.e., including the power deposited in coolant), as shown in Eq. (IV-35). Multiplying the total linear power of Eq. (IV-35) by F_{cool} , one gets the linear power in the coolant, as shown in Eq. (IV-36). Dividing Eq. (IV-36) by the coolant flow area associated with a pin/plate gives the power density in coolant, as shown by Eq. (IV-37).

$$\text{Pin/plate linear power in meat of channel } k = \sum_{n=1}^{NN1-1} q_{\text{chan},j,k,n} \times \Delta A_n \quad (\text{IV-34})$$

$$\text{Pin/plate total linear power of channel } k = \frac{1}{(1 - F_{\text{cool}})} \sum_{n=1}^{NN1-1} q_{\text{chan},j,k,n} \times \Delta A_n \quad (\text{IV-35})$$

$$\text{Pin/plate linear power in coolant of channel } k = \frac{F_{\text{cool}}}{(1-F_{\text{cool}})} \sum_{n=1}^{NN1-1} q_{\text{chan},j,k,n} \times \Delta A_n \quad (\text{IV-36})$$

$$q_{\text{cool},k,j} = \frac{F_{\text{cool}}}{A_{\text{cool}} \times (1-F_{\text{cool}})} \sum_{n=1}^{NN1-1} q_{\text{chan},j,k,n} \times \Delta A_n \quad (\text{IV-37})$$

Replacing Eqs. (IV-33) and (IV-16), Eq. (IV-37) becomes Eq. (IV-38). Noting that the input datum $QW = F_{\text{cool}} \times A_{\text{meat}} / A_{\text{cool}}$, Eq. (IV-38) becomes Eq. (IV-39)

$$q_{\text{cool},k,j} = \frac{F_{\text{cool}} \times \bar{Q} \times \text{PFQ}_{k,j}}{A_{\text{cool}} \times (1-F_{\text{cool}})} \sum_{n=1}^{NN1-1} QR_n \times \Delta A_n = \frac{F_{\text{cool}} \times \bar{Q} \times \text{PFQ}_{k,j}}{A_{\text{cool}} \times (1-F_{\text{cool}})} A_{\text{meat}} \times (1-F_{\text{cool}}) \quad (\text{IV-38})$$

$$q_{\text{cool},k,j} = \frac{F_{\text{cool}} \times \bar{Q} \times \text{PFQ}_{k,j}}{A_{\text{cool}}} A_{\text{meat}} = \bar{Q} \times \text{PFQ}_{k,j} \times QW \quad (\text{IV-39})$$

IV-2.5 CHECK THAT EQ. (IV-33) IS CONSISTENT WITH EQ. (IV-27)

To show this, the power in PARET/ANL channel k found from Eq. (IV-33) will be shown to equal to $P_{\text{tot},k}$ given by Eq. (IV-27). The sum over indices j and n of Eq. (IV-33) times the nodal meat volume in channel k equals the power in meat of channel k , as shown by Eq. (IV-40). The power in meat is not the total power in the channel given by Eq. (IV-27), rather a fraction $(1-F_{\text{cool}})$ of $P_{\text{tot},k}$. To show the consistency, the right hand side of Eq. (IV-40) should equal $(1-F_{\text{cool}}) P_{\text{tot},k}$.

$$\begin{aligned} \text{Power in meat of channel } k &= \sum_{j=1}^{NZ} \sum_{n=1}^{NN1-1} M \Delta A_n \Delta Z_j \times q_{\text{chan},k,j,n} \\ &= \sum_{j=1}^{NZ} \sum_{n=1}^{NN1-1} M \Delta A_n \Delta Z_j \times \bar{Q} \times \text{PFQ}_{k,j} \times QR_n \end{aligned} \quad (\text{IV-40})$$

Substituting Eq. (IV-16) in Eq. (IV-40)

$$\begin{aligned} \text{Power in meat of channel } k &= M \times \bar{Q} \sum_{j=1}^{NZ} \Delta Z_j \times \text{PFQ}_{k,j} \sum_{n=1}^{NN1-1} \Delta A_n \times QR_n \\ &= M \times \bar{Q} \sum_{j=1}^{NZ} \Delta Z_j \times \text{PFQ}_{k,j} (1-F_{\text{cool}}) A_{\text{meat}} = M \times \bar{Q} (1-F_{\text{cool}}) A_{\text{meat}} \sum_{j=1}^{NZ} \Delta Z_j \times \text{PFQ}_{k,j} \end{aligned} \quad (\text{IV-41})$$

Eq. (IV-19) can be rewritten as $\bar{\text{PFQ}}_k \times L_h = \sum_{j=1}^{NZ} \text{PFQ}_{k,j} \times \Delta Z_j$ where L_h is fueled length of each plate/pin. Using this, Eq. (IV-41) becomes Eq. (IV-42). Using Eq. (IV-3), Eq. (IV-42) becomes Eq. (IV-43).

$$\text{Power in meat of channel } k = M \times \bar{Q} (1-F_{\text{cool}}) A_{\text{meat}} \times L_h \times \bar{\text{PFQ}} \quad (\text{IV-42})$$

$$\text{Power in meat of channel } k = M \times \frac{P_{\text{tot}}}{V_{\text{tot}}} (1-F_{\text{cool}}) A_{\text{meat}} \times L_h \times \bar{\text{PFQ}} \quad (\text{IV-43})$$

Noting that the volume of meat in channel k is given by $V_k = M \times A_{\text{meat}} \times L_h$, Eq. (IV-43) can be rewritten as Eq. (IV-38). Using Eq. (IV-20), Eq. (IV-44) becomes Eq. (IV-45).

$$\text{Power in meat of channel } k = V_k \times \frac{P_{\text{tot}}}{V_{\text{tot}}} (1 - F_{\text{cool}}) \times \overline{\text{PFQ}} \quad (\text{IV-44})$$

$$\begin{aligned} \text{Power in meat of channel } k &= P_{\text{tot}} (1 - F_{\text{cool}}) \times \overline{\text{PFQ}} \times \text{BM}_k \\ &= (1 - F_{\text{cool}}) \times P_{\text{tot}} \text{ given by Eq. (20)} \end{aligned} \quad (\text{IV-45})$$

The right hand side of Eq. (IV-40) is shown to equal $(1 - F_{\text{cool}}) P_{\text{tot},k}$ as required for consistency.

Figure IV-1 Radial and Axial Mesh structure used by PARET/ANL in a Fuel Pin

APPENDIX V COOLANT PROPERTIES GENERATORS FOR PARET

This documents how the coolant properties subroutines used in PARET/ANL V7.5 were obtained from original PARET/ANL Version 5 software. The original stand-alone coolant properties generators in PARET are:

light water source code: proph2og.for, dated 8/12/2004

heavy water source code: propd2og.for, dated 12/6/2001

There is also a readable text version of the library for heavy water called propd2o.prt which was created when the code was executed. The FORTRAN source file proph2og.for was changed to a subroutine, to be called by PARET. This stand-alone code had no PROGRAM statement, so it was only necessary to add a SUBROUTINE statement to make it useable by PARET. The actual statement is:

```
SUBROUTINE PROPH2O(N8)
```

The argument N8 is the unit number of the binary file to be created. The PARET main program opens this file and calls either PROPH2O or PROPD2O, as directed by input parameter IFLUID.

The same process was applied for heavy water, using file propd2og.for as the starting point for PARET file propd2o.f. The actual statement is:

```
SUBROUTINE PROPD2O(N8)
```

The coding involved to make the binary library was unchanged. Tests were performed at that time to assure that the new library from PARET was the same as before, and that sample problems produced identical results. Similar tests were conducted in December 2009 to verify that the code produced identical results with different libraries.

The heavy water library is generated by functions that are valid from 0-100 MPa, and 0-800 C.

The light water library is set up to create the default library that goes from 14.6959 psia to 50.304 psia. For HFIR or for BR2, we currently have to change some parameters to increase the pressure range, and recompile subroutine proph2o.f. In Version 7.5, the code checks the operating pressure supplied and generates a library structured accordingly. Then one executable will handle all reactors. Note that the accuracy of interpolation within the library is decreased as the pressure range is increased. We could consider increasing the number of tabulated points in the tables, to overcome this.

Version 7.5 has a new fluid properties option: it now optionally can read a supplied binary coolant properties file, instead of creating it. This option assists in code verification.

APPENDIX VI ENERGY CONSERVATION IN PARET 7

P. Garner (ANL, private communication) provided a sample 2-channel case with complex axial power shapes. Now it will be shown that increasing the number of axial nodes, coupled with retaining the complex axial power shapes, leads to significant improvements in the accuracy of the energy gain in the coolant.

A *Mathematica* notebook was created that interpolated Garner's power shapes and edited new nodal powers for any desired number of axial mesh nodes. The number of axial nodes was increased from the original 11 to 21, and then to 41. These choices halved the mesh spacing, and halved it again.

Figure VI-1 shows the original 11-point power shape in the hot channel. Also shown is the fitted interpolated curve, and the 21 fitted points. Figure VI-2 is the same, but for a 41-node fit. Table VI-1 shows how the energy gain in the coolant varied in time over the first second of operation. The input model defines that there is no introduction of any change over the first second of time--hence in that interval it is a "null transient".

CONCLUSIONS

It can be seen that the numerical scheme for computing the energy gain in the coolant becomes very stable at all edited times during the first second of operation, when the number of axial nodes is increased to 41. This problem is quite complex. For the 41-node case, one can see that the edit of "ENERGY GAIN IN THE COOLANT" is within 0.013% over $0.2 \leq t \leq 1$ second. These results indicate that the energy gain edits are probably correct for this problem.

Table VI-1 Energy Gain for Real Axial Power Profile (from P. Garner)

Time, s	21 Axial Nodes: Gain, MW	41 Axial Nodes: Gain, MW
.1	1.03902	1.03900
.2	1.04053	1.03996
.3	1.03923	1.03987
.4	1.03931	1.03990
.5	1.03924	1.03994
.6	1.03919	1.03995
.7	1.03914	1.03997
.8	1.03910	1.03997
.9	1.03908	1.03998
1.0	1.03905	1.03997

Figure VI-1 Axial Power Shape in the Hot Channel (21 nodes) Small dots are interpolated points on the fitted curve through the large dots.

Figure VI-2 Axial Power Shape in the Hot Channel (41 nodes) Small dots are interpolated points on the fitted curve through the large dots.

APPENDIX VII AXIAL NODALIZATION

PARET has always used two sets of axial nodes: the given set on card types 3000 (increments DZ in the code), and a fluid node set made from the first by placing mesh interfaces at the centers of all nodes DZ(j) for $1 < j < NZ$. There are NZ axial nodes in the fuel for the heat source. The user normally specifies these to be of the same axial length. With this construction, there are NZ-1 axial nodes in the coolant, separated by distances DELZ(j). Note that the first and last axial nodes in the coolant are larger than the others: node 1 has $\Delta z_1 = \text{DELZ}(1) = \text{DZ}(1) + 0.5 * \text{DZ}(2)$, and node NZ-1 has $\Delta z_{NZ-1} = \text{DELZ}(NZ-1) = \text{DZ}(NZ) + 0.5 * \text{DZ}(NZ-1)$. Enthalpy rise and fluid temperature edits by PARET are at the end points of the unequally-spaced nodes collected into vector DELZ. See Fig. 5 of the Obenchain document [1]. The conservation of energy Eq. is given in Eq. (107) by Obenchain. This Eq. uses DZ and Δ to identify spatial increments.

It was found that by replacing the usage of DZ by DELZ, the error in the energy conservation was greatly reduced. Results with and without this change are shown in Figure VII-1 for a simple 1-channel test. Similar behavior is obtained for a 12-channel test. As the number of axial nodes is increased, the error clearly diminishes. But there is an unexpected result that the trend is different for even numbers of nodes vs. odd numbers of nodes. In fact, the odd number choice is very much better than is the even number choice, for the revised V7.4, while the opposite is true for older uncorrected versions. This behavior most likely is associated with the "four point explicit" difference representation used to solve the energy conservation equation.

Figure VII-1 Effect of Increasing Axial Nodes on Energy Conservation

Table VII-1 and Table VII-2 show the effect of changing integration time step size, on the fraction of energy delivered to the coolant in a null transient.

Table VII-1 Fraction of Energy to Coolant; 1 Channel Test, Flat Axial Profile

Time step size, s	Old Versions	Version 7.4
0.002	0.954	0.987

0.0001	0.9382	0.9966
0.00001	0.9398	0.9979

Table VII-2 Fraction of Energy to Coolant; 12 Channel Test, Flat Axial Profile

Time step size, s	Old Versions	Version 7.4
0.0001	0.9383	0.9965
0.00001	0.9341	0.9923
0.000001	0.9398	0.9920

VII-1 CHOOSING A "BEST" AXIAL MESH

Within that subject, the issue of stability has undergone a great deal of research. PARET uses a standard criterion for stability to determine if the enthalpy calculations are to remain stable in time. If that criterion is violated at any axial node in any channel, at any time, the calculation terminates with an error message. This check takes care of instability in time only. The subjects of stability in time and monotonic error growth due to centered advection differencing are discussed by Roache in [41]. The latter is a so-called static instability, not in time, but in space. This type of error is introduced by changes in mesh node lengths. The comment is made by Roache that "unless the mesh spacing is changed slowly, the formal truncation error is actually deteriorated, rather than improved." This comment was in the context of attempts to locally improve the quality of a solution by deviating from a uniform mesh.

The PARET user typically selects uniform length nodes for the heat source. PARET internally creates a fluid node set in which the first and last nodes are 50% larger than the others. One finds oscillations in the enthalpy solution. For example, the enthalpy rise across a set of interior nodes should always be the same, if the fluid remains single-phase liquid and the axial power profile is flat. And yet the code produces results that show a "pairing" effect where pairs of axial nodes have the correct total enthalpy rise, but one of the pair is too low, and the other is too high. This pairing effect occurs for both the old and for the revised coding in subroutine enthal. It shows an oscillating error about the true solution, where the magnitude of the oscillation is quite large.

The question that comes to mind is: What is the best mesh? What mesh is minimally subject to static instability? If the heat source nodes are selected to be of uniform length, what would happen if the fluid nodes were of equal length? The heat source nodes have to be chosen to assure that condition. One simply sets the heat source nodes to be of size

$$L/(NZ-1), 1 < j < NZ; \text{ and } L/[2(NZ-1)] \text{ for } j=1, \text{ or } j=NZ$$

Tests were run with various numbers of axial nodes, for the standard 1-channel case with a flat axial profile. The results obtained for energy conservation are amazing, as shown in Table VII-3. There is essentially no error at all, for any choice from 9 to 21 axial nodes! Furthermore,

the enthalpy solution shows consistent heat additions to every node, whether the model has even or odd numbers of nodes. I believe this confirms the conclusion that the non-uniform fluid node spacing is the source of a static instability that does not damp out over time, but in fact grows to some limiting oscillatory error from node to node.

As for older versions of PARET, how will they perform with this special axial mesh? As it turns out, they will do just the same as Version 7.5 because the logical error in subroutine enthal is fortuitously corrected. Note, however, that in general the old PARET versions will perform substantially less accurately for any other choice of axial nodalization than does Version 7.4.

Table VII-3 Fraction of Energy to Coolant, 1 Channel Test, Flat Axial Profile; Uniform Fluid Node Spacing; PARET 7.4

Number of Axial Nodes	Error in Energy Conservation, %
9	-0.0021
10	+0.0019
15	-0.0015
20	-0.0012
21	-0.0014

APPENDIX VIII USERS' GUIDELINES

The purpose of this chapter is to help PARET/ANL users by providing:

1. an overview of the code and the information needed to determine its applicability to model a given reactor and/or transients of interest (Section XII.1),
2. a summary of the lessons learned from comparisons with reactivity insertion experiments (SPERT-III and SPERT-I reactors) and with the RELAP5 code (Section XII.2 and XII.3),
3. recommendations and guidelines about modeling choices based on the experience of the developers and various experienced users (Sections XII.4 to XII.11),
4. clarifications about some input options (Sections XII.12 to XII.15)

VIII-1 GENERAL OVERVIEW OF PARET/ANL

The original PARET code was designed for predicting the course of nondestructive (events in which fuel or structural deformation does not occurs) reactivity accidents in small reactor cores in which there are no space-time effects on the neutron flux (i.e., point-kinetics where only the neutron flux magnitude changes with time) [XII-1]. More specifically, the code was designed to analyze reactivity insertion transients in the light-water-cooled plate-type and rod-type cores tested in the SPERT-III reactor. Since then, PARET/ANL has been used routinely to analyze transients in research reactor cores with similar fuel designs (flat plate, curved plate, tube, and pin) using light or heavy water coolant.

PARET/ANL models the fuel assemblies of a reactor core as one or more channels. Each of these channels consists of a half fuel plate or a pin (which can be composed of multiple layers/rings to represent cladding, gap, oxide layer, and other laminated fuel designs) and a half coolant channel. Each channel is thermal-hydraulically independent but coupled through reactivity feedback effects (from coolant density and temperature changes as well as fuel temperature changes and fuel plate thermal expansion) to the whole core. The code also contains logic models for automatic trips on period, power, and flow as well as models for decay heat after shutdown and control rod reactivity versus time or position. More details about PARET/ANL's one-dimensional hydrodynamic momentum integral model, heat transfer models and point-kinetics model can be found in Ref. XII-1.

PARET/ANL core representation by channels is adequate for the simulation of transients affecting mainly the core region. System transients requiring the simulation of coolant regions other than the core cannot be modeled with PARET/ANL due to the lack of representation of components such as valves, piping, heat exchangers, etc. However, three simplified models have been implemented in PARET/ANL to approximate three types of transients under specific conditions: two different models to estimate buoyancy-driven flow in pool-type reactors, and a loss-of-flow model.

To evaluate the applicability of PARET/ANL to model a given reactor and/or transient, the user should take into consideration the assumptions used in the thermal-hydraulics and point-kinetics solutions as well as in the various other models. Therefore the remainder of this section discusses these assumptions.

The main assumptions in the PARET/ANL thermal-hydraulic solution are:

1. A thermal-hydraulic solution is obtained for each PARET/ANL channel independently
2. The radial heat conduction is modeled (axial and lateral heat conduction are neglected).
3. The radial heat flux is assumed symmetric, i.e., half of the heat goes out of each side of the plate
4. Each coolant channel is assumed heated by two half-plates at the same power
5. Core internal structures cannot be modeled (grid plate, side plates, core shroud, fuel assembly cans or channel walls, solid moderator or reflector).
6. The use of steady-state heat transfer correlations, a simplified boiling model considered in the developmental stage and an incompressible hydrodynamic model.

A few comments about the impact of the thermal-hydraulics assumptions on the simulation of typical events in research reactors:

1. For longer transients and for steady-state, the user should review the implications of neglecting the thermal-hydraulic coupling between channels. For most transient events lasting up to a few seconds, the channels are effectively thermal-hydraulically decoupled since the event is terminated before any potential coupling could take place. Reactor designs using fuel pins can be modeled as long as there is no significant cross-flow between the sub-channels.
2. Axial heat conduction is typically important only for transients which involve steep axial temperature gradients due to large differences in coolant voiding conditions. Lateral conduction near the fuel plate unheated edge can be important if the power peak occurs in the same region. However, both the lateral and axial heat conduction can conservatively be ignored.
3. The heat flux is nearly symmetric for fuel assemblies using flat or slightly curved thin fuel plates when the flow conditions on each side of a fuel plate are similar. For a fuel assembly design with different flow conditions in both channels, this assumption is conservative when modeling the hot side of a fuel plate. The symmetry assumption is less accurate for tubes when the ratio of tube radius to tube thickness is less than 10. Note that variations in that symmetry are typically of the order of a few percent, i.e., small compared to the other uncertainties associated with modeling transients.
4. The heat flux symmetry assumption is always conservative when modeling the hot plate/channel.
5. The importance of modeling internal core structures depends on their contributions to heat removal and/or reactivity feedback for a transient in a given reactor. For most transients, the heat removal contribution of these structures can be conservatively ignored. For slow transients, the user should pay attention to the potential reactivity feedback of heating the reflector region.
6. The prediction by PARET/ANL of a thermal and/or hydraulic crisis should be interpreted as a qualitative indication rather than a reliable quantitative prediction [XII-1].

Based on the various assumptions discussed up to this point, PARET/ANL can model adequately reactivity insertions resulting in limiting voiding. **These assumptions also imply**

that the code cannot be recommended for quantitative analyses of reactivity insertions resulting in significant voiding of the coolant channels since modeling accurately such events requires good predictive capabilities of phenomena such as: 1) the impact of the void distribution in the various fuel assemblies on the power shapes and reactivity feedback coefficients, 2) the onset of thermal-hydraulic crises and possibly the resulting cladding and/or fuel melting, and 3) fuel deformation including the impact of reflooding (“quenching”). The user should read Section XII.2.2 to understand the level of agreement between calculation and measurements that have been historically achieved for this type of events.

The rest of this section provides a description of the approximate system-type transient models and their assumptions. These models are designed to simulate the expected stable, dominant core flow pattern of upflow everywhere in the heated channels, at all times.

The first model (IFLOW=4, NLUP2=0) is designed to estimate buoyancy-driven flow in a reactor submerged in an infinite pool (good assumption when the pool water’s heat capacity is very large compared to the energy release of the event). The model assumes that the coolant flows only through the fuel assembly inlets and outlets which are opened directly to the pool. The coolant is assumed to be drawn only from the pool which remains at constant temperature throughout the transient. This model does not take into account any return flow path other than through the pool.

The second model (IFLOW=4, NLUP2=1) is designed to estimate the buoyancy-driven flow in a Miniature Neutron Source Reactor (MNSR). The reactor core is contained in a closed tank which is submerged in a very large but not infinite pool. In an MNSR, when operating at power, the coolant flows through the core and returns to the inlet by a complex downcomer between the core inner tank and the outer tank wall. The model approximates this flow path using an equivalent hydraulic resistance. It assumes that this region is unheated (no gamma heating or conduction through the inner tank). In the model, the coolant entering the downcomer is the same as the coolant exiting the core. The initial unheated water in the downcomer flows over time to the core inlet and is followed by the heated water. The small heat exchange through the tank wall between the coolant in the downcomer and the pool water is taken into account. The flow resistance in the downcomer region is approximated through the use of inlet and outlet unrecoverable pressure loss coefficients. The model also has provision for representing heat removal from the pool by air flow over the pool. The variation in the pool water temperature is accounted for by a simple enthalpy balance.

The loss-of-flow model (IFLOW=3, NLUP2=0) combines the forced flow from a pump coast-down with the estimated buoyancy-driven flow (calculated like in option IFLOW=4). If a flow reversal is detected (coolant mass flux sign switching from negative to positive), the channel outlet becomes the inlet and time-dependent coolant mixing fractions are used. These coolant mixing fractions approximate the transition period when hot water from the outlet plenum is mixed with the colder pool water and drawn back into the core.

VIII-2 LESSONS LEARNED FROM COMPARISONS REACTIVITY INSERTION EXPERIMENTS IN THE SPERT CORES

One of the objectives of the SPERT program was to determine experimentally the maximum equivalent step reactivity that could be inserted safely, i.e., relying only on the self-limiting behavior of the core to halt the excursion and stabilize the power to a level limited by feedback without damaging the fuel. Comparison of PARET predictions with measurements from the

SPERT-III transients was part of the original validation [XII-1] of the code performed in 1969. This validation was later extended [XII-2] to include comparisons with SPERT-I experimental data. These comparisons studied the applicability of the code to model feedback effects in a wide variety of transients performed without scram (unprotected transients). A discussion about the use of PARET/ANL to model protected transients (i.e. with a reactor trip followed by a scram) is presented in Section XII.3.

It is recommended that the user review the discussions presented below in order to get a sense of the type of uncertainties that are expected when modeling reactivity insertion transients.

VIII-2.1 SPERT-III REACTOR TRANSIENTS

The SPERT-III cores and experiments were designed to measure the effects of changing the following parameters on the core behavior following various reactivity insertions: initial power, coolant inlet temperature and pressure, and coolant velocity. The range of these parameters covered the operating environment found in a typical unborated PWR (of that era) without fission products. Therefore many of these tests were performed at operating conditions relatively far from those of most typical research reactors. The operating regimes were: coolant temperature up to 260°C (500°F), pressure up to 10.34 MPa (1500 psig), coolant velocity up to 7.31 m/s (24 ft/sec) and initial power up to 20 MW. The initial periods associated with the reactivity insertions ranged from 2.26 sec to 9.7 msec. These experiments covered a major part of the range of reactor accident severity that is of interest in reactor analyses.

Two types of cores were studied [XII-1, XII-6] as part of this validation, the E-cores and the C-cores. The E-cores used fuel rods with 4.8% enriched UO_2 pellets clad in stainless steel with a helium-filled gap. The reactivity insertions for the E-core ranged from 0.5 to 1.3\$. For the E-core, 129 of 256 total tests were for initial pressures not exceeding 200 psig. The C-cores used fuel plates with 93% enriched UO_2 dispersed in stainless steel and also clad in stainless steel. However, application of PARET to the SPERT-III C-cores was not as extensive as for the E-cores in this study. It should also be mentioned that this validation study performed no comparisons with E-cores' transients in which boiling occurred. Only limited boiling occurred in C-core transients.

One of the first lessons drawn from the comparison between PARET and SPERT-III measurements is that the code requires the calibration of its boiling model parameters: (1) an exponent (input option RXXEXP), (2) a dimensionless constant (input option RXXCON), the bubble collapse times in the sub-cooled and transition boiling regimes (input options TAUUNB, and TAUUTB) as well as the fractions of the heat transfer area contributing to producing bubbles in the sub-cooled, transition and film boiling regimes (input options ALAMNB, ALAMTB and ALAMFB). More details about the PARET/ANL boiling model can be obtained in Ref. XII-1.

These boiling model parameters were obtained through a parametric study in order to represent the experimental results of a given SPERT-III C-19/52 core transients since no values was available from theory or experimental measurements. Note that the topic of boiling and bubble formation remains a topic of much research to this day. The selected values for those parameters remain the basis for the current recommended values in the manual. (RXXEXP=1, RXXCON=0.8, TAUUNB=TAUUTB=0.001, ALAMNB=ALAMTB=ALAMFB=0.05)

The overall time-dependent behavior of the power, peak clad temperature and the energy generation was well predicted by the code. For the LEU oxides cores, discrepancies of 10 % to 30% between the predicted and measured values were observed. The calculated results from PARET (IDO-17270, June 1968) required a good estimate of the helium gap conductance in order to best match experiment. In addition, it was found that direct heating by gammas to clad and water was important. For plate-type cores, discrepancies of 20% to 40% have been observed. To put these discrepancies into context, some of the reported experimental errors were: $\pm 10\%$ on the power calibration, $\pm 7\text{-}10\%$ on the reproducibility of the power for a given reactivity insertion, $\pm 5\%$ due to the dynamic error of the temperature response, and $\pm 4\%$ on the initial reactivity insertion. Similarly, Ref. XII-6 reports that the PARET results were within 30% or less for the SPERT-III experiments.

VIII-2.2 SPERT-I REACTOR TRANSIENTS

The SPERT-I experimental facility used pool-type cores without forced circulation or pressurization other than the static pressure head. The SPERT-I cores used plate-type fuel assemblies using 93% enriched uranium-aluminum alloy meat clad in aluminum. Two of the SPERT-I B-series cores (B-24/32 and B-12/64) as well as the D-12/25 core (used in the final destructive test) were analyzed using PARET/ANL. All transients were initiated at 20°C and from a nominal power level of 5 W. The initial periods associated with the reactivity insertions ranged from 930 ms to 3.2 ms (destructive test).

A two-channel model was developed [XII-2] to compare PARET/ANL predictions with measured data from these tests. A ramp of 70ms was used to insert the specified amount of reactivity (same assumption as in the analysis of the SPERT-III tests discussed in Section XII.2.1). The experimental time taken to fully insert the reactivity is not clearly defined. The transient rod drop time is given (IDO-17036, p. 101, SPERT-III Reactor Facility: E-Core Revision, J. Dugone, Editor, TID=4500, Nov. 1965) as 0.2 seconds, for a 45" maximum drop, from initiation of scram signal to full travel. In general, the tests did not require a maximum drop therefore the drop time should be less. However, the evolution of the transient is not sensitive to the ramp duration or profile since the initial power is very low and the insertion time is short. A forced flow problem was specified with an inlet velocity of 0.3 cm/s to approximate the expected steady-state buoyancy-driven flow at the beginning of the event. More details about the modeling choices used in these analyses can be found in Ref. XII-2.

In this analysis, the Rosenthal and Miller [XII-3] approximation of the heat transfer coefficient was selected in order to obtain better cladding temperature in the natural circulation regime ($Re < 2000$).

It was found that the energy release and clad temperatures were the most sensitive to the choice of the void generation model parameters. To obtain better agreement for transients reaching the nucleate boiling regime, the bubble collapse time and the fraction of the heat transfer area contributing to producing bubbles were changed for that regime ($TAUUNB=0.0005$ and $ALAMNB=0.03$).

For these tests, the overall time-dependent behavior of the power, peak clad temperature and the energy generation were predicted well by the code.

For the SPERT-I B-24/32 core, comparisons between the PARET/ANL predictions and the measurements showed that:

- Discrepancies between 10% and 40% (on average 20%) for the peak power for most transients were observed. Peak powers were overestimated for events with initial periods less than 0.02 sec and underestimated for the other events.
- Discrepancies of up to 30% (on average 10%) for the energy release at the time of peak power were observed. The largest discrepancy was observed for an event with an initial period of about 0.01 second. Transients with initial periods larger than 0.15 seconds have discrepancies around 20%. For this core, the predicted energies releases were both underestimated and overestimated.
- Discrepancies of up to 20% (on average 10%) in the peak cladding temperatures were observed. For events with initial periods larger than 0.15 seconds and smaller than 0.05 second, the discrepancies were typically of the order of 15%. The peak clad temperatures were overestimated for events with initial periods larger than 0.15 second and smaller than 0.02 seconds. For the other events, the peak clad temperatures were underestimated.
- For one of the events (initial period greater than 0.5s), the discrepancy in the peak power was larger than 80% but the peak cladding temperature and energy released agreed within 20%.

For the SPERT-I B-12/64 core, comparisons between the PARET/ANL predictions and the measurements showed that:

- Discrepancies of about 10% for the peak power for most transients were observed. The peak powers were typically overestimated.
- Discrepancies of up to 50% (on average 20%) for the energy release at the time of the peak power were observed. For transients with an initial period below about 20 ms, the energies released at the time of the power peak were overestimated. For the other transients, the energy released was underestimated.
- Discrepancies of up to 30% (on average 10%) in the peak cladding temperatures. Peak clad temperatures are typically overestimated.
- For one of the event (initial period of about 50 ms), the peak power and energy released were overestimated by about 70% and 50% respectively. For that event, the peak cladding temperature was overestimated by about 20%.

For the SPERT-I D-12/25, the following observation about the comparisons between PARET/ANL predictions and the measurements can be made:

- Discrepancies of up to 60% (on average 30%) for the peak power for most transients were observed. The peak powers were all overestimated.
- Discrepancies of up to 80% (on average 30%) for the energy release at the time of the peak power were observed. Most of the energies released were overestimated.
- Discrepancies of up to 50% (on average 30%) in the peak cladding temperatures were observed. Peak clad temperatures were almost all overestimated.
- For one event with an initial period near 50 ms, the peak power and energy released were overestimated by about 110% and 90% respectively. For that event, the peak cladding temperature was overestimated by about 30%.

It should be noted that numerical difficulties in the hydraulic solution were experienced for reactivity insertions large enough to result in significant void generation. For those cases, significant short-lived unphysical oscillations² in the mass flow rate resulted in an unphysical enthalpy calculation. Consequently, the simulations of many of the shortest period transients failed at or slightly after the power peak.

Mass flow rate oscillations can be prevented, to some extent, by reducing the time step size (see Section XII.7). However, results may differ significantly since in those cases, stable transition or film boiling can be predicted by the code even though it is questionable that such stable conditions actually occurred during the experiments based on the measured cladding temperatures. It was found that the selection of the heat transfer correlations as well as the correlation used to define the boundaries of the various regimes (including DNB) affects significantly the prediction of the code for those types of events.

VIII-2.3 SUMMARY

The analyses of SPERT-III and SPERT-I experiments showed that the boiling model parameters for the nucleate boiling regime may need to be calibrated to reflect the operating conditions of the core. **In absence of reactor-specific experiments, it is recommended that the user select values based on the analysis of the SPERT core most similar to their reactor: SPERT-I for reactors with natural circulation and near atmospheric pressure and SPERT-III for reactors with forced flow and pressurized.** The values selected for the boiling model parameters will affect the predictions of the code for transients where the presence of void is a significant feedback effect. **It is recommended that a sensitivity study be performed to understand the impact of those parameters for a given reactor and transients of interest.**

The comparisons with measurements performed for a wide range of reactivity insertions in five SPERT cores have shown that the overall time-dependent behavior of the power, peak clad temperature and the energy released were adequately predicted by the code. For these same three parameters, the discrepancies between the predictions from the code and the measurements were generally between 10% and 50%. For the SPERT-I cores, about one tenth of the events modeled have shown discrepancies between 50%-80%.

For the 2-channel model used in the SPERT-I transient analyses, most of the measured parameter (peak power, energy release at time of peak power and peak clad surface temperature) were overestimated and therefore conservative.

VIII-3 LESSONS LEARNED FROM COMPARISONS WITH RELAP5

Many comparisons between RELAP5 and PARET/ANL have been performed over the years. This section presents several to illustrate the lessons learned.

Reference XII-4 performed a comparison between PARET/ANL and RELAP5/MOD3 for the following events in an idealized reactor (IAEA 10MW benchmark reactor):

² Mass flow rates orders of magnitude larger than steady-state values fluctuating between upflow and downflow at each time step

- fast and slow loss-of-flow followed by a flow reversal
- fast and slow reactivity insertion followed by an overpower scram at 120% of full power

Comparisons of the flow reversal events showed that:

- the results were nearly identical while the pump coast-down curve dominated the buoyancy effects,
- the time of flow reversal as well as the peak clad temperatures at time of flow reversal agreed relatively well: within 1 or 2 seconds for the time of flow reversal and within a few degrees for peak clad temperature,
- PARET/ANL predicted a slightly higher coolant temperature,
- Small discrepancies of 5°C were observed after flow reversal when buoyancy effects drive the flow solution.

Comparisons for reactivity insertion events followed by an overpower scram at 120% showed that the results were nearly identical for the slow reactivity insertion event studied. For the fast reactivity insertion event, the largest discrepancy in peak cladding temperature was about 12°C.

It was concluded that for the IAEA benchmark reactor, the overall agreement between the codes was generally good.

Reference VIII-4 compared RELAP5 and PARET/ANL simulations of IAEA benchmark reactor transients. Note that the Rosenthal and Miller correlation was implemented in an ANL test version of RELAP5 for this analysis.

The comparisons showed that:

- Up to 1.2\$ reactivity insertion, the two codes agree well when the same natural circulation heat transfer correlation is used (i.e., Rosenthal and Miller).
- For reactivity insertion above 1.2\$ (point at which significant nucleate boiling occurs), the discrepancy between the two codes increases significantly due to different predicted void fraction, flow regimes and reactivity feedback. For those higher reactivity events, PARET/ANL predictions were closer to the experimental values.

VIII-4 RECOMMENDATIONS FOR SELECTING AN AXIAL NODALIZATION

Due to the numerical scheme used within PARET/ANL, it is best to use axial nodes with the first and last nodes defined to be half the length in the inner nodes. By this means, the fluid nodes are all of the same length, which is advantageous for numerical accuracy and stability of the enthalpy solution in space and time. Even though the current code can re-nodalize any problem not meeting that criteria (user option), **it is recommended that the user define such a nodalization explicitly in order to avoid unintended consequences** (see APPENDICES X and XI for more discussion about axial nodalization in PARET/ANL).

A sensitivity study can then be performed to study the numerical effect of the number of axial nodes. It is recommended that the user select as many axial nodes as necessary to adequately capture the axial power peak.

VIII-5 XII.5. RECOMMENDATIONS FOR STEADY-STATE INITIALIZATION

At the beginning of a PARET/ANL transient, thermal-hydraulics properties are initialized to their steady-state values. In recent versions of the code, this initialization was improved such that reactivity insertion could be defined starting a time zero. **However, it is still recommended to perform a “null” transient (i.e., no reactivity insertion) for the first second of the simulation in order to verify that the steady-state conditions (flow and temperatures) are as expected and remain stable.**

The user should look for the message of “STEADY-STATE INITIALIZATION CONVERGED AT MPASS= NNN” where NNN is the number of passes needed to ensure that the steady-state initialization was successful.

It is also recommended that the steady-state conditions be compared with either experimental data or a more detailed steady-state thermal-hydraulic code if possible.

VIII-6 RECOMMENDATIONS FOR FLOW-FORCED, PRESSURE-DROP-FORCED OR BUOYANCY DRIVEN CALCULATIONS

When possible, it is recommended that the user select IFLOW=1 (forced flow calculation) since the other flow options have not received as much verification.

IFLOW=2 (pressure-drop flow calculation) should not be used as it is known to fail to converge (see Section XII.9).

IFLOW=3 (buoyancy driven with pump coast down flow superimposed) received some verification but is not fully qualified yet.

Therefore, for events terminated before the buoyancy effects can change significantly the flow conditions, it is recommended that a forced flow calculation (IFLOW=1) be performed even for reactors cooled by natural circulation. The value of the mass flux should correspond to the expected steady-state natural circulation values (experimental data or other values obtained from another code). The buoyancy-driven flow rate for a given steady-state power can be approximated using IFLOW=4 without reactivity feedback by setting the Doppler, coolant void and coolant temperature feedback coefficients to zero and specifying a null transient or by setting IPROP=0 to perform a power-level specified calculation. A long “transient” time should be specified (possibly of the order of 100 seconds) to allow for the convergence of the flow solution.

If the assumptions used in the buoyancy-driven flow model (see Section XII.1) are appropriate, the user can also select IFLOW=4 (and NLUP2=0) to approximate the response of the flow conditions during a slow event. Note that this utilization of IFLOW=4 has received limited verification at this time. For MNSRs (NLUP2=1), slower events are modeled more accurately due to the reactor-specific natural circulation model in the code.

VIII-7 XII.7. RECOMMENDATIONS FOR SELECTING THE TIME STEP SIZE

It is important to understand that the hydrodynamics and point-kinetics solutions from PARET/ANL are sensitive to time step size. PARET/ANL uses a simple algorithm to control the time step to ensure the numerical stability of the enthalpy solutions. Special attention should be given to the selection of the time step size.

If computing time constraints permit, it is recommended that the user specify a uniform time step sufficiently small to model adequately the kinetics and hydraulics transient behaviors. This will simplify the use of the following guidelines since it may be necessary to run the simulation multiple times.

PARET/ANL v 7.5 does not ensure that the time step is at or below the Courant limit. The user must therefore ensure that the selection of the time step size meets this criterion (see Eq.(VIII-1)) during the whole transient.

$$\Delta t \leq \min \left(\frac{\rho_{i,m} \cdot \Delta z_i}{\dot{m}_{i,m}} \right) \quad (\text{VIII-1})$$

The above criterion is theoretically necessary but not sufficient to ensure a well-behaved solution. It is recommended that the user set the time step size to about $\Delta t / 5$.

Moreover, this version of the code does not have an algorithm to adjust the time step size to prevent the fluid density from changing too drastically over a time step. If it does, it can result in stability issues when significant boiling occurs. In that event, further reduction in the time step size is required. For example, the occurrence of "BULK BOILING" and "FILM BOILING" involves the creation of significant steam void and can challenge the PARET/ANL hydraulic solution. Should numerical stability fail, the error message "ENTH<0" (i.e., that the fluid enthalpy of a given node has been computed in error) may be generated. The code terminates the run at that time. The onset of numerical instability is typically preceded by large mass flux oscillations.

To select an appropriate time step size based on Eq. XII-1, it is helpful to proceed as follows. The first calculation should be performed with a time step size evaluated from Eq. XII-1 using the initial conditions (input parameters). The results from that calculation should be inspected to evaluate the minimum time step size for the whole transient using Eq. XII-1. The calculation can then be repeated with the new time step size. **If significant oscillations are observed in the flow solution, it is recommended that the time step size be further reduced based on the above criterion evaluated using the unphysical values.** This should help prevent the onset of these instabilities.

Secondly, **it is recommended to use option KINTS=-1 to force the code to use the same time steps for both the thermal-hydraulic and point-kinetics solutions**, to prevent extrapolation of the reactivity over a time step and warn the user that the time step has to be reduced to meet the point-kinetics solution error criterion (see Ref. XII-1). In that case, the user should look for "NEXT TIME-STEP WAS FORCED" statements in the output. If they occur,

the user should reduce the time step size in half and rerun the simulation. This process should be repeated until no such statement appears in the output.

Finally, PARET/ANL assumes that all clad surface temperatures must satisfy a relative change of less than 0.001 within MAXHCC iterations in order to consider the thermal solution converged. Issues with the thermal solution are flagged in the output file and preceded by the label "HEAT2". For convergence problems, the time, channel, axial node, and radial node numbers where the convergence was worst are printed. Note that any issue with the thermal solution can be an indication that the time step size is inappropriate, or that MAXHCC needs to be larger.

If PARET/ANL cannot obtain a converged thermal solution within MAXHCC iterations, the code relaxes the convergence criterion to 0.008 for 1% of the transient time requested, and then restores the original criterion. **However, if possible, it is recommended that the user try to avoid this type of relaxation of the convergence criterion by reducing the time step size further and rerunning the problem.**

VIII-8 RECOMMENDATIONS ABOUT OUTPUT VERIFICATION

Errors in processing the supplied input are sometimes fatal, and sometimes not. Not all card type sequence numbers within a given card type such as 14000 cards, are checked. But input is checked for integer vs. floating point, for complete pairs of data when it should be in pairs, and for the correct number of data values for a given card type. Detected errors will cause various messages, including the word "DUMP" when an input line image is edited that does not conform to expectations

The user can search for the label "ERROR" in the output file in order to identify the source of the problem.

If a job fails to complete, it is recommended that the user look at the last time step by searching up from the end of the output file for "THUS FAR" in order to diagnose the issue.

In general, it is good practice to look for the label "WARNING" in the output file to see if any questionable conditions were detected.

One such warning relates to PARET/ANL renormalization of the power distribution if normalization discrepancy larger than 0.1% is detected. The user should always look for that warning since it might be due to a user input error rather than a round-off error.

Channel files provide an output for the peak properties only. **It is recommended to review/study/plot the properties (clad and fuel properties as well as coolant temperature and density) in the whole channel using the information in the main output file to verify that a stable/physical solution was obtained.**

The power peaks can be identified by searching for "PERIOD=-" in the output file. The first occurrence of a negative period marks the power peak. Subsequent peaks can also be located in the same way.

Review the average Reynolds number of each channel, which is printed at the end of every major edit. Heat transfer correlations have limits of applicability, such as the Reynolds number, L/D, pressure, coolant velocity, up-flow or down-flow, or the Prandtl number. A warning is printed to inform the user when a limit of applicability has been violated. APPENDIX II

provides those limits where known. **The user should use caution when the known limits of applicability of a selected correlation are violated during the transient.**

VIII-9 RECOMMENDATIONS ABOUT THE DEVELOPMENTAL OPTIONS

A number of options in PARET/ANL v7.5 are in their developmental state and/or have received minimal testing. Consequently, it is recommended that users do not utilize the following options:

- IFLOW=2 (pressure drop driven flow solution)
- IGEOM=2 (nested tube modeled as two half-plates per tube)
- IMODE=2, 3, 4 and 5 (transient two-phase schemes)
- INORM=1 and 2 (power distribution renormalization options)
- IONEP=5 (CIAE MNSR natural circulation correlation)

The manual also specifies that the developmental option IGEOM=2 allows for different meat and coolant channel dimensions as well as for different forced flow rate in each channel. **If the user needs to specify different types of fuel assemblies in the same core, it is recommended that each type of fuel assembly in the core be simulated as a separate run using IGEOM=0.** Various approaches can be used to partition the core into “PARET” channels for each type of fuel. Appropriate power fraction and feedback coefficients are needed for each “channel”. At this point, there is no generic recommendation on how to proceed to partition the reactor core. The following reference contains an example of an analysis for two different fuel types in the same core:

P.L. Garner and N. A. Hanan, “Transient Analyses for the Uzbekistan VVR-SM Reactor with IRT-3M HEU Fuel and IRT-4M LEU Fuel: Independent Verification Results,” ANL-07/26, Argonne National Laboratory, (2007).

VIII-10 RECOMMENDATIONS FOR MASS FLOW SPECIFICATION USING IGEOM=0 OR 1

The recommended geometry options in PARET/ANL v7.5 (IGEOM=0 or 1) with IFLOW=1 use a single mass flux for all channels. It is therefore recommended to use the best estimate of the coolant mass flux in the hot channel in order to better reflect the peak clad temperature. If the mass flux in the hot channel is significantly different than the other channels, it is recommended that a sensitivity study be performed to evaluate the impact of the coolant mass flux on the transient behavior due to change in the coolant feedback.

For IFLOW=3 and IFLOW=4, the flow in each channel will be based on each specified power.

VIII-11 RECOMMENDATIONS FOR MULTI-CHANNEL CORE PARTITIONING

It is recommended that a PARET/ANL model have at least 2 channels, i.e., one channel representing the hot coolant channel (typically the coolant channel where the peak clad

temperature occurs at steady-state) and one other channel representing the remainder of the core to model the core average feedback.

It is expected that 2-channel models will provide a conservative estimate of the peak clad temperatures. Engineering judgment suggests that the overall reactivity insertion from the coolant and fuel feedback could be better represented by modeling core regions with similar power as different equivalent PARET channels. In theory, this should allow for high power regions to introduce negative reactivity feedback earlier during the transient and possibly improve comparisons to experiments. However, absent of detailed and successful comparisons to experimental data for different nodalizations, it is difficult to recommend an appropriate level of detail. Note that, as mentioned in Section XII.1, the predicted clad temperatures in channels other than the hot channel may not be conservative.

It is useful to perform a nodalization sensitivity study analyzing the impact of the number of the channels. If the number of channels in the model has a large impact on the predicted transient behavior, it is possible that the core for this specific transient has a strong space-time dependency for the coolant and fuel reactivity feedback. This can potentially invalidate the approximations used in the point-kinetics model that predicts the power excursion. **The user should be very careful when relying on the code predictions for cases where the channel nodalization has a strong impact on the results.**

The user should also be aware that increasing the number of PARET/ANL channels affects only the evaluation of the effective core feedback and not the thermal-hydraulics solution since, as noted previously, the channels are not thermal-hydraulically coupled.

VIII-12 CLARIFICATION ABOUT USING THE DECAY HEAT MODEL

PARET/ANL has a decay heat model based on the ANS-5.1-1973 draft decay heat standard.

If a decay power contribution from prior operation at a given power (card POW0) for a given number of days (card OPT) is specified, it is assumed that this contribution is part of the initial steady-state power (card POWER) and is not updated based on the change in power during the transient. This last assumption is valid for all transients except the very long events involving a major change in power. For such cases, the decay power contribution after scram can be modeled by adjusting the cards POW0 and OPT to reflect the conditions at the time of the trip.

In addition to providing the proper cards to input previous operating time and power, it is necessary to set up trip points and control rod reactivity insertion cards in order to activate the decay heat model. The decay heat contribution will be added to the residual neutronics power once a trip is detected (T_{trip}) and a scram is initiated following a user-specified control system response delay (T_{delay}).

VIII-13 CLARIFICATION ABOUT WATER PROPERTY TABLES

The water properties tables (used for interpolated properties during the simulation of a transient) are automatically generated for a fixed number of points based on the original library range of pressure (0 to 50 psi). Version 7.5 allows for the use of any pressure but the user should be aware that the table of properties will contain the same number of points no matter the range of pressure specified. If the code is to be applied to pressures well beyond 50 psi, then the user could request an update to the number of points.

It should also be noted that pressure drop calculations reported by PARET/ANL are not used to evaluate the water properties at different axial locations in the coolant channel. The water properties are always evaluated at the initial pressure specified by the input variable PRESUR. Note that the change in pressure due to the change in static pressure head and friction loss along a fuel assembly has only a negligible impact on the water properties in research reactors.

VIII-14 CLARIFICATION ON PARET/ANL AXIAL NODALIZATION CONVENTION

The convention used in PARET/ANL is that axial node 1 is always located at the bottom of the fuel assemblies. This convention is used anytime axially dependent properties need to be specified in the 5000-series cards (5kXX cards with $XX \geq 02$) as well as in the output file.

VIII-15 CLARIFICATION ABOUT SPECIFYING FLOW CONDITIONS

Some comment is appropriate regarding orientation of PARET input/output (sign conventions for gravity and mass flow rate) and the axial source distribution sequence. PARET models either up flow or down flow by user input specifications for Table 10, i.e., the Coolant Inlet Mass flux vs. Time data supplied on cards 10000 and 10XXX. Positive values for input variable AMFRIN denote up flow, while negative values denote down flow. The acceleration of gravity, GRAV, should be >0 regardless of flow direction, to account correctly for static pressure head changes.

VIII-16 DISCUSSION ABOUT TWO-PHASE FLOW HEAT TRANSFER CORRELATIONS AND TRANSITION MODELS

The boiling transition models (IMODE=0 or IMODE=1) are used to evaluate the two-phase heat transfer coefficients in the partial boiling regime (after onset of nucleate boiling but before fully developed boiling occurs) and smoothly transition from one heat transfer mode to the other. **At this point, it is recommended that the user select IMODE = 1 to use the approach developed by Bergles & Rosenhow.** A generic recommendation for the selection of a two-phase heat transfer correlation (ITWOP = 0 or ITWOP = 1) cannot be made. **The user should be careful to select a correlation that was developed for pressures close to their operating pressure (see comments for the ITWOP option written in the 1112 Card section) and perform a sensitivity study of the impact of this selection.** For transients with limited boiling, the impact of selecting either the Jens-Lottes correlation (ITWOP = 0) or the McAdams (ITWOP = 1) is expected to be small (the single-phase heat transfer coefficient still dominates the overall two-phase heat transfer coefficient obtained through the transition formula).

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