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WREM: WATER REACTOR EVALUATION MODEL. (REVISION 1)

NUCLEAR REGULATORY COMMISSION,
WASHINGTON, D.C. OFFICE OF NUCLEAR
REACTOR REGULATION

MAY 1975



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WREM

Water Reactor Evaluation Model

[Revision 1]

MAY 1975

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FOREWORD

To improve the Nuclear Regulatory Commission (NRC) staff's capability to perform independent audits of vendor and applicant analyses, a series of computer programs have been generated to analyze the transient following a postulated loss-of-coolant accident. These computer programs can be used for both boiling and pressurized water reactors.

These computer programs were designed to comply with the requirements set forth in Appendix K to 10 CFR Part 50, but they also contain flexibility to perform other analyses. For example, data related to pump performance and fuel behavior are input by the user. Therefore, if these programs are used by applicants as part of a specific plant license application, further justification is required to demonstrate that the application of these programs in specific cases conforms to the Appendix K requirements.

The technology embodied within these programs represents the current capability in this field. In cases where the understanding of certain physical phenomena may be incomplete, conservative models have been adopted. Many experimental programs are being conducted to improve our understanding in these areas and to develop more sophisticated analysis techniques. While we believe the present computer analysis capabilities presented in this document are adequate for the purpose of evaluating the emergency core cooling systems, we wish to encourage and emphasize the need for additional work in this area. We anticipate that improved computer codes will be available in several years as a result of this continuing research and development activity.

ACKNOWLEDGEMENTS

The NRC Evaluation Model (Water Reactor Evaluation Model) was developed as a joint effort between Aerojet Nuclear Company (ANC) and the NRC staff. The NRC would like to thank the ANC personnel that worked on the Water Reactor Evaluation Model (WREM) computer code package. These people have given freely of personal time and have worked after normal working hours, weekends, and holidays. Without this effort, the WREM computer program package would not have been possible.

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1.0 INTRODUCTION

The Water Reactor Evaluation Model (WREM) consists of several computer programs developed to evaluate the consequence of a light-water-cooled power reactor when subjected to a postulated loss-of-coolant accident (LOCA) with emergency core coolant injection in accordance with current Commission acceptance criteria.^{1/} The WREM computer programs are almost entirely in FORTRAN IV and are programmed for the IBM digital computers. WREM was developed under the auspices of the NRC* staff, using the Aerojet Nuclear Company as its principal consultant.

The analytical techniques and assumptions used in the WREM computer programs are in accordance with 10 CFR Part 50 Appendix K - ECCS Evaluation Models.^{1/} WREM codes were developed based on existing computer programs modified to comply with the acceptance criteria. The purpose of this document is to provide general descriptions of the analytical models added or modified to make existing computer programs conform to the Commission criteria, and to provide the user with sufficient information to use the Evaluation Model programs. The fundamental capabilities of the base programs have not been altered, and the user must refer to the referenced program description documents for the base programs to obtain details of these capabilities. This document then supplements the base program manuals in providing the WREM description.

*Previously the AEC Regulatory staff.

This document is divided into several sections which discuss the Evaluation Model programs and the analytical models added to the existing computer programs. Section 1, "Introduction," provides a basic introduction and explanation of the PWR and BWR evaluation models. Section 2, "Basic Analytical Models," describes the analytical models and features that are common to each of the WREM computer programs. Sections 3 through 6 describe the WREM codes, modifications and analytical models. As previously discussed, this document does not attempt to provide a complete code description, but describes the added analytical models and modification. The user should refer to the original program description documents referenced to supplement this document.

Because of basic design differences and the resulting differences in expected LOCA behavior, the pressurized water reactors (PWRs) are analyzed using a different method than that used for the boiling water reactors (BWRs). Figures 1.1 and 1.2 show the WREM computer programs for PWRs and BWRs, respectively, and the portion of the LOCA transient to which they apply.

1.1 Pressurized Water Reactor Evaluation Model

For the evaluation of a postulated LOCA for a PWR, the Evaluation Model consists of the following three computer programs: (1) RELAP4-EM, (2) RELAP4-FLOOD, and (3) TOODEE2. The evaluation of a LOCA transient using the Evaluation Model is performed in four parts:

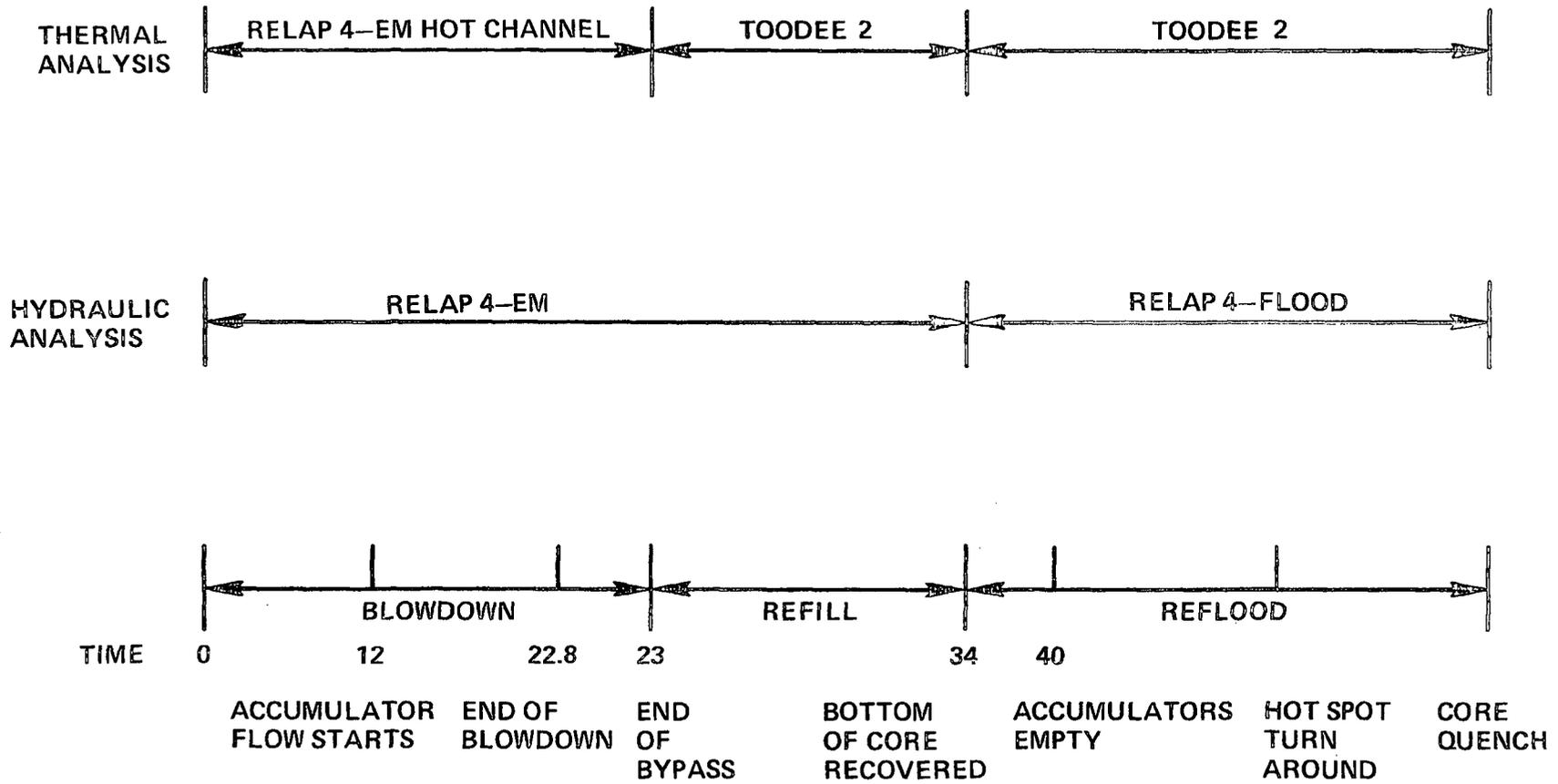


Figure 1.1 PWR LOCA Analysis

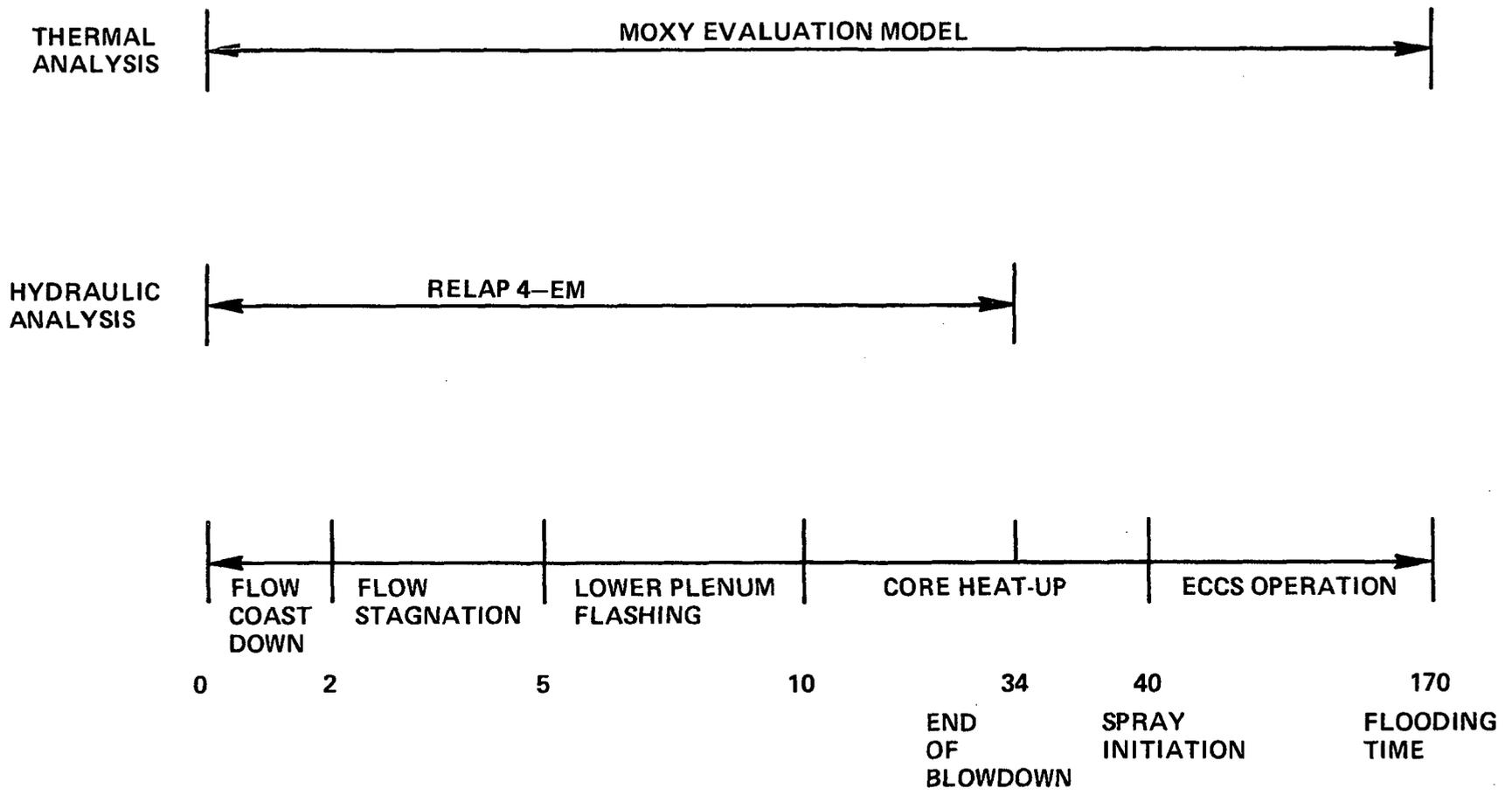


Figure 1.2 BWR LOCA Analysis

1. A system blowdown or decompression analysis calculation is made using a modified version of the RELAP4^{2/} program called RELAP4-Evaluation Model (RELAP4-EM, blowdown analysis).
2. A more detailed core thermal-hydraulic calculation is made by applying time-varying boundary conditions from the decompression program to a more detailed core model (hot channel analysis).
3. A reflood rate calculation is performed using the RELAP4-FLOOD program, which is a separate adaptation of the RELAP4-EM program (refill/reflood analysis).
4. A thermal analysis of a fuel rod during refill and reflood is made using the TOODEE2^{35/} program, which is a modification of the TOODEE^{3/} program.

The RELAP4-EM blowdown analysis provides a calculational model of the reactor primary and secondary systems, including the hot fuel assembly or assemblies in the core, the remainder of the core, the reactor vessel downcomer, upper head, upper plenum regions, secondary coolant systems, and emergency core coolant injection. The RELAP4-EM analysis begins from steady-state or assumed initial operating conditions and continues through pipe rupture and system decompression to the onset of the reactor core recovery with emergency coolant. RELAP4-EM computes the space and time variations of thermal-hydraulic conditions of the primary and secondary coolant systems. Included in

the calculation are coolant flows between regions; heat transfer between the primary and secondary coolant systems; heat transferred from system metal surfaces and the core to the coolant; hydraulic effects of system components such as pumps, valves, and the core; the temperature of the hot fuel assembly and the remainder of the core; fuel rod swelling and rupture; and emergency core coolant (ECC) bypass.

RELAP4-EM is then used to model the reactor core, including a hot fuel rod (hot channel analysis). Time dependent boundary conditions are supplied by the previous RELAP4-EM calculation to represent the fluid conditions in the adjacent upper and lower plenum regions. The RELAP4-EM program then performs a detailed calculation of the core and hot fuel rod temperature transient for the same time period as the system calculation previously performed by RELAP4-EM.

The RELAP4-FLOOD program performs essentially a continuation of the system blowdown calculation through the period of ECC reflood of the reactor core. The program itself is a special version of the RELAP4-EM program with modifications primarily in the core region to calculate reflooding rates and fluid conditions as required by the Commission acceptance criteria.

The fuel rod temperature calculation is provided during the blowdown period to the end-of-bypass period by the RELAP4-EM hot channel (a detailed core model). This calculation is continued during refill and reflood by a TOODEE2 calculation. The TOODEE2

calculation determines the temperature response of a single fuel rod with initial conditions obtained from the RELAP4-EM hot channel analysis. The hot channel analysis also provides detailed core and subsequent fluid conditions as a function of time to the end of bypass. The core reflooding rate is obtained from the RELAP4-FLOOD and is used with a modified version of the Westinghouse FLECHT correlation to obtain the temperature response during reflood. The TOODEE²^{35/} program is a special version of the TOODEE^{3/} program with modifications as required by the Commission acceptance criteria.

1.2 Boiling Water Reactor Evaluation Model

The evaluation of a postulated LOCA for a BWR requires the use of (1) RELAP4-EM and (2) MOXY-EM computer programs. The BWR Evaluation Model calculation is performed in two parts:

1. A system blowdown or depressurization is performed using RELAP4-EM.
2. A thermal analysis of a planar section of a fuel assembly is made using the MOXY-EM program, which is an adaptation of the MOXY^{4/} computer program.

The BWR Evaluation Model utilizes two interrelated programs to evaluate the response of a BWR to a postulated loss-of-coolant accident. These programs are RELAP4-EM and MOXY-EM. The RELAP4-EM computer program is used to model the hot fuel assembly and the remainder of the core, the fluid system within the reactor vessel, and the recirculating loops. The analysis begins with steady-state operating

conditions and is usually terminated at the end of lower plenum flashing unless further calculations are desired. The RELAP4-EM system analysis computes the space and time variation of thermal-hydraulic conditions of the fluid within the reactor vessel and recirculating loops, flows between system regions, heat transferred from system components and the core to the coolant, hydraulic effects of the pumps, fuel rod swelling and rupture, and power and temperature of the core and the hot fuel rod assembly.

The hydraulic conditions and heat transfer coefficient to be used in MOXY-EM are produced during the blowdown analysis. A separate hot channel using the plenums as boundary conditions is not required for the BWR Evaluation Model because of the BWR design. For the BWR analysis, the hot channel calculation is usually made concurrently with the system analysis but may be made as a separate calculation. The RELAP4-EM hot fuel assembly results provide (for the same time as analyzed by the RELAP4-EM system model) detailed information on the time-dependent normalized power, the average fluid conditions and convection heat transfer coefficients in the hot fuel assembly. The MOXY-EM program models in detail the geometry of the fuel rods and the canister at the hot axial level of the hot fuel assembly. This program is used to calculate the detailed thermal response of the fuel rods and canister, including the effects of radiation heat transfer. The MOXY-EM calculation begins with steady-state operating conditions and continues throughout the LOCA transient, including ECC injection. The calculational sequence is presented in Figure 1.2.

2.0 BASIC ANALYTICAL MODELS

Four computer programs form the basis of the analysis capability for the evaluation models. These programs are RELAP4-EM, RELAP4-FLOOD, TOODEE2 and MOXY-EM. Each of these computer programs is used in different parts of the blowdown analysis and together form a complete WREM code package. The WREM codes can be used to analyze both PWR and BWR postulated accidents.

Certain analytical models specified by the acceptance criteria are common among the WREM computer programs. In the development of each of these separate computer programs, consistency between common models was important. Because some of these programs actually restart an analysis at the end of a previous computer run, i.e., RELAP4-EM (hot channel) to TOODEE2 for determining the peak clad temperature in a PWR, consistency between these programs is necessary.

The basic analytical models used in three of the WREM computer programs are described in this section. The models discussed are radioactive decay heat, gap conductance, clad swelling and rupture, material properties and metal water reaction. (Of these, only decay heat is used in RELAP4-FLOOD.) These models are not programmed identically into each computer program, but the basic form of the analytical models is the same.

2.1 Fission Product Decay and Decay of Actinides

The Commission acceptance criteria require that several sources of neutron fission energy be considered in the Evaluation Model.

These are 1) fission heat, 2) decay of actinides, and 3) fission product decay. RELAP4-EM considers all three of these in calculating the neutron fission energy sources. RELAP4-FLOOD, TOODEE2 and MOXY-EM consider only the decay of actinides and fission product decay. These programs use the power vs time curve produced by RELAP4-EM or are initialized from the RELAP4-EM code.

For calculation of fission heat, the Commission criteria state:

"2. Fission Heat. Fission heat shall be calculated using reactivity and reactor kinetics. Shutdown reactivities resulting from temperatures and voids shall be given their minimum plausible values, including allowance for uncertainties, for the range of power distribution shapes and peaking factors indicated to be studied above. Rod trip and insertion may be assumed if they are calculated to occur."

The fission heat calculated by RELAP4-EM uses a reactor kinetics model and reactivity from time-dependent reactivity data (scram and borated water injections) and feedback effects from water density, fuel temperature, and water temperature. This model is described in the RELAP4^{2/} manual.

For large breaks in a PWR reactor, shutdown will usually occur because of void formation; and a reactor rod scram input may not be necessary. For this case, a density reactivity tabular function which is valid over the entire LOCA water density range must be

supplied by the user. For smaller breaks and BWRs, shutdown is caused by control rod action. The reactivity effects of control rods and boron injection are supplied by a tabular input of reactivity vs time. Doppler reactivity is also a tabular input as a function of fuel temperature.

The fuel temperature coefficient is normally input as zero, as this effect is considered in the Doppler relationship. Likewise, the water temperature coefficient can be input as zero since the density effect of water temperature is included in the density reactivity function. Weighting factors between core volumes are usually computed on a normalized flux (power) squared relationship.

Consideration of the other two energy sources required by the criteria, decay of actinides and fission product decay, require modification. In reference to these two energy sources the Commission criteria state:

"3. Decay of Actinides. *The heat from the radioactive decay of actinides, including neptunium and plutonium generated during operation, as well as isotopes of uranium, shall be calculated in accordance with fuel cycle calculations and known radioactive properties. The actinide decay heat chosen shall be that appropriate for the time in the fuel cycle that yields the highest calculated fuel temperature during the LOCA.*"

"4. Fission Product Decay. The heat generation rates from radioactive decay of fission products shall be assumed to be equal to 1.2 times the values for infinite operating time in the ANS Standard (Proposed American Nuclear Society Standards - 'Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors'. Approved by Subcommittee ANS-5, ANS Standards Committee, October 1971). The fraction of the locally generated gamma energy that is deposited in the fuel (including the cladding) may be different from 1.0; the value used shall be justified by a suitable calculation."

Decay of U_{235} fission products is computed by a relationship of the form of the summation of eleven decay equations. The equation is equivalent to:

$$P/P \text{ total} = \sum_{j=1}^{11} E_j \exp(-\lambda_j t) \quad (1)$$

where:

$P/P \text{ total}$ = fraction of operating power

E_j = yield fraction of decay heat group j

λ_j = decay constant of decay heat group j

t = shutdown time, sec

Values used in this relationship are given in Table 2.1.

TABLE 2.1
RADIOACTIVE DECAY CONSTANTS

Group	E_j	λ_j (sec ⁻¹)
1	0.00299	1.772
2	0.00825	0.5774
3	0.01550	6.743×10^{-2}
4	0.01935	6.214×10^{-3}
5	0.01165	4.739×10^{-4}
6	0.00645	4.810×10^{-5}
7	0.00231	5.344×10^{-6}
8	0.00164	5.726×10^{-7}
9	0.00085	1.036×10^{-7}
10	0.00043	2.959×10^{-8}
11	0.00057	7.585×10^{-10}

The fission product decay heat computed by the eleven group equations was evaluated and compared to the tabular values of the ANS standard^{24/} for infinite operating time. The comparison is shown in Table 2.2 along with the percentage error in the eleven group relationship relative to the ANS standard. As shown, agreement between the two relationships is within 4% over the entire range. Over the range of principal concern, 0.1 to 100 seconds, the eleven group calculation is within -1 to +2.1% of the ANS standard and is generally slightly higher. Based on this analysis, the ANS standard fission product decay heat data are well represented by this decay heat model.

Both TOODEE2 and MOXY-EM have options that allow time-dependent heat sources to be entered in the input with linear interpolation between values in the table. MOXY-EM also has the option of using

TABLE 2.2

COMPARISON OF RELAP4 AND ANS STANDARD DECAY HEAT CALCULATED RESULTS

<u>Time (sec)</u>	<u>RELAP4</u>	<u>ANS STD</u>	<u>% Error</u>
0.0000E+00	0.069900	- -	0.0000
1.0000E-01	0.068900	0.067500	2.0741
1.0000E+00	0.062800	0.062500	0.4800
2.0000E+00	0.059200	0.059000	0.3390
4.0000E+00	0.055400	0.055200	0.3623
6.0000E+00	0.053100	0.053300	- 0.3752
8.0000E+00	0.051400	0.051200	0.3906
1.0000E+01	0.049900	0.050000	- 0.2000
2.0000E+01	0.044900	0.045000	- 0.2222
4.0000E+01	0.039800	0.039600	0.5051
6.0000E+01	0.037200	0.036500	1.9178
8.0000E+01	0.035300	0.034600	2.0231
1.0000E+02	0.033700	0.033100	1.8127
2.0000E+02	0.028400	0.027500	3.2727
4.0000E+02	0.023400	0.023500	- 0.4255
6.0000E+02	0.021300	0.021100	0.9479
8.0000E+02	0.020100	0.019600	2.5510
1.0000E+03	0.019200	0.018500	3.7838
2.0000E+03	0.016100	0.015700	2.5478
4.0000E+03	0.012800	0.012800	0.0000
6.0000E+03	0.011200	0.011200	0.0000
8.0000E+03	0.010300	0.010500	- 1.9048
1.0000E+04	0.009760	0.009650	1.1399
2.0000E+04	0.008010	0.007950	0.7547
4.0000E+04	0.006260	0.006250	0.1600
6.0000E+04	0.005460	0.005660	- 3.5336
8.0000E+04	0.005050	0.005050	0.0000
1.0000E+05	0.004790	0.004750	0.8421
2.0000E+05	0.004090	0.004000	2.2500
4.0000E+05	0.003390	0.003390	0.0000
6.0000E+05	0.003050	0.003100	- 1.6129
8.0000E+05	0.002840	0.002820	0.7092
1.0000E+06	0.002690	0.002670	0.7491
2.0000E+06	0.002190	0.002150	1.8605
4.0000E+06	0.001680	0.001660	1.2048
6.0000E+06	0.001440	0.001430	0.6993
8.0000E+06	0.001290	0.001300	- 0.7692
1.0000E+07	0.001190	0.001170	1.7094
2.0000E+07	0.000906	0.000890	1.7978
4.0000E+07	0.000698	0.000680	2.6471
6.0000E+07	0.000619	0.000620	- 0.1613
8.0000E+07	0.000577	0.000570	1.2281
1.0000E+08	0.000551	0.000550	0.1818
2.0000E+08	0.000491	0.000485	1.2371
4.0000E+08	0.000421	0.000415	1.4458
6.0000E+08	0.000362	0.000360	0.5556
8.0000E+08	0.000311	0.000303	2.6403
1.0000E+09	0.000267	0.000267	0.0000

a built-in table based on the ANS^{25/} standard plus 20%, or using values stored on a RELAP4-EM plot-restart tape. When specifying the time dependent heat source for TOODEE2 and MOXY-EM, the RELAP4-EM generated values should be used during blowdown and then the ANS plus 20% including the decay of actinides should be used for the remainder of the transient.

The ANS standard equations^{24/} were added to RELAP4-EM to compute decay of U_{239} and Np_{239} . Assuming infinite operating time, the equations become:

$$\frac{P_{U_{239}}}{P_o} = 2.28 \times 10^{-3} C \frac{\sigma_{25}}{\sigma_{f^{25}}} (e^{-4.91 \times 10^{-4} t_s}) \quad (2)$$

$$\frac{P_{Np_{239}}}{P_o} = 2.17 \times 10^{-3} C \frac{\sigma_{25}}{\sigma_{f^{25}}} [7.0 \times 10^{-3} (e^{-3.41 \times 10^{-6} t_s} - e^{-4.91 \times 10^{-4} t_s}) + e^{-3.41 \times 10^{-6} t_s}] \quad (3)$$

where:

P = decay power

P_o = operating power

$C \frac{\sigma_{25}}{\sigma_{f^{25}}} = U_{238}$ atoms consumed per U_{235} atoms fissioned

t_s = shutdown time, sec.

Summing these expressions and combining like terms gives the actinide decay equations in the form:

$$\frac{P_{\text{actinide}}}{P_o} = \sum_{j=1}^2 E_j \exp(-\lambda_j t_s) \quad (4)$$

Thus the actinide decay was included in RELAP4-EM by adding two additional decay equation terms to the eleven equations for fission product decay. The constants for the equations are:

$$E_{j=1} = C \frac{\sigma_{25}}{\sigma_f 25} [2.28 \times 10^{-3} - 7 \times 10^{-3} (2.17 \times 10^{-3})] \quad (5)$$

$$E_{j=2} = C \frac{\sigma_{25}}{\sigma_f 25} (2.17 \times 10^{-3}) (1 + 7 \times 10^{-3}) \quad (6)$$

$$\lambda_1 = 4.91 \times 10^{-4} \text{ sec}^{-1} \quad (7)$$

$$\lambda_2 = 3.41 \times 10^{-6} \text{ sec}^{-1} \quad (8)$$

The quantity $C \frac{\sigma_{25}}{\sigma_f 25}$ is a user supplied input for the variable UDUF of the kinetics constant data (data card 140000) in the RELAP4-EM input.

The option to multiply the fission product decay energy by a factor of 1.2, as required by the Commission criteria, was added to RELAP4-EM and requires a non-zero input value for variable KMUL of the kinetics constant data.

In the RELAP4-EM computer program, reactor power as a function of time can be optionally (1) computed as described above, (2) supplied in tabular form by the user, or (3) obtained from the output tape of a previous RELAP4-EM calculation. Evaluation Model calculations have

to date calculated power for the blowdown calculation and used the output power from the previous blowdown tape for the PWR Hot Channel Analysis.

TOODEE2, MOXY-EM and RELAP4-FLOOD have as input the power vs time as calculated by RELAP4-EM or as normalized to ANS +20%, plus the actinides, using the RELAP4-EM power after the blowdown calculation. The normalization procedure allows the calculation to be continued after the end of a RELAP4-EM calculation.

2.2 Fuel-to-Cladding Gap Heat Transfer Model

The fuel-to-cladding gap heat transfer is provided to calculate initial stored energy and transient heat transfer across the gap. These two requirements are presented in the Commission criteria in two places. In reference to initial stored energy, the criteria state:

"1. The Initial Stored Energy in the Fuel. The steady-state temperature distribution and stored energy in the fuel before the hypothetical accident shall be calculated for the burn-up that yields the highest calculated cladding temperature (or, optionally, the highest calculated stored energy.) To accomplish this, the thermal conductivity of the UO_2 , shall be evaluated as a function of the burn-up and temperature, taking into consideration differences in initial density, and the thermal conductance of the gap between the UO_2 and the cladding shall be evaluated as a function of the burn-up,

taking into consideration fuel densification and expansion, the composition and pressure of the gases within the fuel rod, the initial cold gap dimension with its tolerances, and cladding creep."

In referencing the swelling and rupture criteria for the cladding, the criteria state:

"B. SWELLING AND RUPTURE OF THE CLADDING AND FUEL ROD THERMAL PARAMETERS

Each evaluation model shall include a provision for predicting cladding swelling and rupture from consideration of the axial temperature distribution of the cladding and from the difference in pressure between the inside and outside of the cladding, both as functions of time. To be acceptable the swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated. The degree of swelling and rupture shall be taken into account in calculations of gap conductance, cladding oxidation and embrittlement, and hydrogen generation.

The calculations of fuel and cladding temperatures as a function of time shall use values for gap conductance and other thermal parameters as functions of temperature and other applicable time-dependent variables. The gap conductance shall be varied in accordance with changes in gap dimensions and any other applicable variables."

The gap model selected is a modification of the Ross-Stoute model found in the GAPCON THERMAL-1^{5/} program. The gap conduction model accounts for (1) fuel-clad contact conduction heat transfer, (2) gas conduction, and (3) radiation heat transfer. The composition of the gap gas is input, and the conductivity is calculated as a function of temperature.

The following simplified GAPCON model has been incorporated into the WREM computer program package. The effective gap conductance can be expressed generally as the sum of three terms:

$$h_g = h_c + h_{gas} + h_{rad} \quad (9)$$

where:

h_g = effective gap conductance

h_c = effective conductance through points of contact of the cladding and fuel

h_{gas} = effective conductance through gas in the gap

h_{rad} = effective conductance due to radiation across the gap.

When the cladding is determined to be in contact with the fuel, the gap conductance equation is:

$$h_g = h_c + \frac{k_{gas}}{g + R} + h_{rad} \quad (10)$$

k_{gas} = conductivity of gas (BTU/hr-ft-°F)

g = combined jump distance (ft)

R = roughness factor (ft)

The roughness factor can be calculated by:

$$R = 0.165 (R_f + R_c) e^{-1.25 \times 10^{-3} P_i} \quad (11)$$

where:

P_i = fuel-to-cladding interfacial pressure (psi)

R_f = fuel arithmetic mean surface roughness (ft)

R_c = cladding arithmetic mean surface roughness (ft)

Since the roughness factor is a function of the interfacial pressure P_i which is not available, it must be estimated. For cases of interest, interfacial contact is not likely to be predicted and therefore the contact gap conduction will not be used.

The temperature jump distance is calculated by the user-supplied gas pressure and by using the code-computed gas mixture viscosity, temperature, and molecular weight to compute the temperature jump distance by the equation:

$$g = 0.1788 \left(\frac{\mu_{\text{gas}}}{P_{\text{gas}}} \right) \left(\frac{T_{\text{gas}}}{MW_{\text{gas}}} \right)^{0.5} \quad (12)$$

where:

μ_{gas} = gas viscosity $\left(\frac{\text{g}}{\text{cm-sec}} \right)$

P_{gas} = gas pressure (psi)

T_{gas} = gas temperature ($^{\circ}\text{F}$)

MW_{gas} = gas molecular weight $\left(\frac{\text{g}}{\text{g-mole}} \right)$

Gap conductance is predicted by the following equation for an annular gap (no contact):

$$h_g = \frac{k_g}{g + \Delta x} + h_{rad} \quad (13)$$

where:

Δx = the thickness of the annular gap (ft)

The radiation heat transfer term (h_{rad}) uses the conventional temperature to the fourth power relationship. The radiation gray body view factor used in the calculation is given by:

$$F_{12} = \frac{1}{1/\epsilon_1 + A_1/A_2(1/\epsilon_2 - 1)} \quad (14)$$

where:

ϵ_1 = fuel emissivity

ϵ_2 = cladding emissivity

A_1 = area of the fuel

A_2 = area of the cladding

The gas conductivity, k_g , of the gap mixture is computed based on the model used in GAPCON THERMAL-1;^{5/} wherein the thermal conductivity, viscosity, and mean molecular weight of a mixture of helium, oxygen, krypton, xenon, hydrogen and nitrogen are computed as a function of temperature and a user-supplied gas composition. After cladding rupture is calculated, the gap conductance in the ruptured heat slab (assumed to be a 3 inch segment as specified by the Commission rule) is calculated assuming the gap is filled with steam at the gap temperature and at a pressure equal to that in the associated fluid volume.

The hot gap dimensions are calculated on the basis of thermal expansion for both the fuel and cladding. The linear coefficients of thermal expansion for UO_2 and zircaloy are calculated in MOXY-EM by:

$$\epsilon_f = -1.723 \times 10^{-4} + 6.797 \times 10^{-6} T + 2.896 \times 10^{-9} T^2, \quad (T \equiv ^\circ C) \quad (15)$$

$$\epsilon_c = 3.2 \times 10^{-6} (T_2 - T_1), \quad T_2 \leq 1550^\circ F \quad (T \equiv ^\circ F) \quad (16)$$

$$\epsilon_c = 3.2 \times 10^{-6} (1550 - T_1), \quad 1550 < T_2 \leq 1775^\circ F \quad (T \equiv ^\circ F) \quad (17)$$

$$\epsilon_c = 3.2 \times 10^{-6} (1550 - T_1) + 5.3 \times 10^{-6} (T_2 - 1775), \quad T_2 > 1775^\circ F \quad (T \equiv ^\circ F) \quad (18)$$

where:

ϵ = linear coefficient of thermal expansion (in/in- $^\circ F$)

T = temperature (units as indicated)

f refers to fuel

c refers to clad

1 refers to initial

2 refers to final

In MOXY the average ϵ for fuel and cladding is obtained by evaluation of thermal expansion equations at the average temperature defined by the following equations for fuel and cladding:

$$T_{avg} = \frac{\sum_{i=1}^N V_i T_i}{\sum_{i=1}^N V_i} \quad (19)$$

where:

T_{avg} = volume weighted average temperature

V_i = volume of node i (in³)

T_i = temperature of node i

N = number of nodes in fuel or cladding

The clad linear expansion is evaluated using:

$$\frac{\Delta L}{L} = \epsilon_{avg} (T_{avg} - 68) \quad (20)$$

where:

ϵ_{avg} = average linear coefficient of thermal expansion
based on T_{avg} (in/in-°F)

$\frac{\Delta L}{L}$ = linear thermal expansion (in/in)

The hot fuel radius and cladding inside radius are obtained by

$$r_{hot} = r_{cold} \left(1 + \frac{\Delta L}{L}\right) \quad (21)$$

where:

r_{hot} = hot radius (ft)

r_{cold} = cold radius (ft)

2.3 Cladding Deformation and Rupture Model

One of the requirements of the new Commission criteria is the consideration of clad, swelling and rupture. The Evaluation Model must consider swelling and rupture of the cladding when they are calculated to occur, and inside oxidation is to be assumed in at least

a 3 inch length in the area of rupture after rupture has occurred. The specific requirements were stated previously and will be further stated in Section 2.5. Because of the difference between the PWR and BWR transients, the cladding deformation and rupture model will be discussed separately for MOXY and RELAP4-EM/TOODEE2.

2.3.1 Swelling and Rupture Model for RELAP4-EM and TOODEE2

The basic structure for calculating fuel pin deformation and rupture was taken from the FRAP^{6/} program. In particular, the subcode DEFORM and its associated subprograms are used to calculate all forms of pin deformation and make decisions on rupture. The subroutine GAPPERS from FRAP^{6/} calculates the internal pin pressure. Subroutines REFRAP and DEFRAP were written to make the arrays compatible between RELAP4-EM, TOODEE2 and FRAP and to calculate the required deformed geometry variable. Several minor differences between the RELAP4-EM and TOODEE2 swelling and rupture models should be noted. Since permanent deformation and/or rupture may have occurred prior to the commencement of the TOODEE2 calculation, a provision was made for initializing with these prior conditions. The rupture decision in TOODEE2 is made in a subroutine CLDRUP called from DEFORM; the rupture decision in RELAP is made prior to entry into the swelling and rupture subcodes.

Cladding Rupture Model

Rupture is predicted to occur from a correlation of ΔP (coolant pressure minus pin internal pressure) versus cladding temperature from various sources, notably ORNL^{7/}. This model requires the user to provide, from the available data, tabular values of rupture temperature as a function of pressure difference and of percentage blockage of flow area as a function of pin pressure differences. The clad surface temperature and the pressure difference between the internal fuel pin pressure and the pressure in the surrounding fluid are calculated and monitored during the transient and compared with tabular rupture data to determine when and if rupture occurs. The internal pin pressure calculation and the swelling before rupture are discussed in some detail in later sections.

If rupture is predicted, the following assumptions are used to calculate the ruptured pin conditions:

1. The pin internal pressure is reduced in one time step to that in the coolant channel adjacent to the failed slab and for the remainder of the calculation equals the coolant channel pressure. The gas composition is set equal to steam at the local pressure in the ruptured axial node or heat slab at the point of rupture.
2. The amount of blockage is determined from the selected tabular data of percent blockage as a function of pressure difference.
3. The metal-water reaction is continued on the outside surface with the oxide layer being thinned in accordance with the

calculated swelling. The metal-water reaction is assumed not to be steam limited.

4. The new rod radius is calculated assuming unrestricted swelling. Based on the new radius, the new surface area on the inside and the outside of the cladding is calculated. The length of the swollen zone is determined by the length of an axial node.
5. Metal-water reaction is started on the inside of the cladding, assuming no previous oxidation has occurred.
6. The new clad radius is calculated but limited to $0.2^{12/}$ of the increase predicted by the blockage. This is the limiting value of the plastic hoop strain before failure (uniform hoop strain), which is described in Fuel Rod Thermal and Pressure Response Model.

It is appropriate to discuss the models used in RELAP4-EM and TOODEE2. RELAP4-EM must consider two types of fuel pins because of the hydraulic calculations. One is a single fuel pin which is used to represent a hot pin in the hot assembly. The second is a "multiple" fuel pin which represents the average fuel pin in the remainder of the hot assembly or core. In the TOODEE2 computer code, only a single fuel pin is modeled. Therefore, RELAP4-EM will require the user to supply two sets of tables, one for multiple pin rupture criteria and one for single pin criteria. In addition to the six assumptions listed above, RELAP4-EM performs the following calculations for multiple pin rupture:

7. The friction is increased at the junctions above and below the swollen zone. The amount the friction is increased is calculated based on a sudden contraction and expansion. For example, if the flow is in the normal direction, a friction K factor based on a sudden contraction from the normal area to the blocked area is added to the friction terms in the junction immediately below the swollen zone. Likewise, a K factor based on a sudden expansion from the blocked area to the normal area is added at the junction above the swollen zone.

Three options are available for applying the swelling and rupture data to a RELAP4-EM model, and the user's choice is specified by the selection of a value for ISLBAJ (card 16XXX5).

These options are used to represent either a single rod, average rod in an assembly or assemblies, average rod in the average core, and fuel rod with an associated fluid channel. These options are:

1. Fuel Rod with an Associated Fluid Channel ISLBAJ = 0.

This option should be used when a small core region on the order of 3 inches of a fuel rod and the associated channel are being modeled. This option corresponds to a test section with a single rod in a close fitting tube and is not an EM option. The single rod blockage data should be selected for this option (ISWTAB = 1).

The options selected are:

- a. Internal pin pressure released after rupture,
- b. Blockage calculated,
- c. Metal-water reaction continued with oxide thinning,
- d. New rod radius calculated,
- e. Metal-water reaction started on inside, and
- f. Junction friction increased due to blockage.

2. Single Rod Analysis ISLBAJ = 1

This option should be used when a small core region such as a 3-inch fuel rod segment is modeled with bounding fluid conditions from a much larger volume. This option should select the single rod blockage data (ISWTAB = 1). The options used are:

- a. Internal pin pressure reduced after rupture,
- b. Blockage calculated,
- c. Metal-water reaction with oxide thinning,
- d. New rod radius calculated, and
- e. Metal-water reaction started on the inside.

3. Average Rod in Hot Assembly or Average Core ISLBAJ = 2

This option should be used to model one assembly or more which will apply to large core volumes. It should use the multirod blockage tables ISWTAB = 0. The options selected are:

- a. Internal pressure reduced after rupture,
- b. Blockage calculated,
- c. Metal-water reaction continued with oxide thinning,

- d. New clad radius calculated but limited to 0.2 of the increase predicted by blockage table, and
- e. Junction friction increased.

In each case, swelling or rupture is tested on a stack of axial heat slabs and is allowed to occur at only one heat slab of an axial stack. In modeling the hot assembly, it is sometimes desirable to have more than one stack of heat slabs (i.e., the hot rod and an average hot assembly rod) connected to a given coolant volume. However, the code cannot handle rupture in more than one stack that might affect one junction, regardless of the value of ISLBAJ. If such multiple blockage of a junction is predicted, the problem is halted. Rupture in more than one stack is permitted if they are separated.

The TOODEE2 computer program considers only a single fuel pin but requires that three tables be entered as input. Tables consist of: (1) Rupture tables, (2) Multi-pin Blockage tables, and (3) Single-pin Blockage tables in the form of strain tables. If rupture is predicted to occur, the ruptured pin conditions are calculated as follows:

1. Internal pressure reduced,
2. Blockage calculated, the multipin blockage data is used for steam cooling calculations only,
3. Metal-water reaction continued with oxide thinning,
4. New rod radius calculated assuming unrestricted swelling,
5. Metal-water reactions started on the inside.

Fuel Rod Thermal and Pressure Response Model

The Fuel Rod Thermal and Pressure Response Model was adapted from the FRAP^{6/} code. The transient response of the rod includes the following features:

1. The expansion of the fuel material is based on the data of Conway^{13/} without allowance for melting. The curve used for T in °C is:

$$\epsilon = -1.723 \times 10^{-4} + 6.797 \times 10^{-6}T + 2.896 \times 10^{-9}T^2. \quad (22)$$
2. The expansion of the fuel pellet including allowance for cracking of the material follows the model used in GAPCON-THERMAL-1, in which free expansion is assumed outside the calculational node of maximum circumferential thermal expansion of the material.
3. Axial thermal expansion of the fuel pellet stack is calculated at a contact radius which is provided by the user. Normally this radius is that of the shoulder at the edge of the dished out portion of the ends of pellets.
4. The cladding expansion in both the radial and axial directions is calculated as the sum of a pressure-induced strain predicted by the thin wall formula plus thermal strain assuming an average temperature for the cladding. In addition, a plastic hoop strain is calculated as described in the next paragraph. The elastic modulus is obtained from an interpolation and extrapolation of available data:

$$E = (1.148 \times 10^{11} - 5.99 \times 10^7 T) \text{ N/m}^2, T \leq 750^\circ\text{K} \quad (23)$$

$$E = (1.07981 \times 10^{11} - 5.02236 \times 10^7 T) \text{ N/m}^2, T > 750^\circ\text{K} \quad (24)$$

The Poisson ratio for the cladding is calculated by:

$$\nu = 0.32 + 5 \times 10^{-5} T, \quad (25)$$

where T is the temperature in $^\circ\text{F}$. The cladding thermal strain for zircaloy clad when heated from temperature T_1 to T_2 is calculated as follows:

$$\epsilon = 3.2 \times 10^{-6} (T_2 - T_1), T_2 \leq 1550^\circ\text{F} \quad (26)$$

$$\epsilon = 3.2 \times 10^{-6} (1550 - T_1), 1550 < T_2 \leq 1775^\circ\text{F} \quad (27)$$

$$\epsilon = 3.2 \times 10^{-6} (1550 - T_1) + 5.3 \times 10^{-6} (T_2 - 1775), T_2 > 1775^\circ\text{F} \quad (28)$$

The clad thickness is decreased by the hoop strain assuming a constant cross sectional area, but is increased by the thermal strain in a first order calculation. The computer coding includes a check to insure the gap thickness cannot be negative.

5. The plastic hoop strain of the cladding before failure is calculated from a formulation using Hardy's ¹² data.

The following steps define the procedures of the model:

- a. From the table of rupture temperature versus pressure difference provided by the user for the fuel rod, determine T_{rupture} and $\Delta T = T_{\text{rupture}} - T_{\text{clad}}$. If ΔT is negative, rupture is predicted and the steps described in the cladding rupture model are taken.

- b. If ΔT is between 0° and 200°F , the user-provided table of flow blockage upon rupture is used to calculate the fractional change in the outer clad radius assuming rupture at the present pressure difference. Denote this fractional change by F ; then the plastic strain is calculated as:

$$\epsilon = 0.2 F \exp (- 0.0153 \Delta T). \quad (29)$$

The plastic strain behaves as a ratchet; once a given plastic strain is reached, no decrease of this component is allowed. Upon rupture of the clad, this ratchet is set to maintain the expanded condition. After rupture, the pressure strain is not calculated; but the thermal strain continues as a function of the transient temperature.

6. At each time step, the thickness of an oxide layer on the clad due to metal-water reaction (if any) is reduced according to any additional swelling of the slab.
7. The gas pressure inside the fuel rod is calculated using the ideal gas law from the number of moles of gas (a problem input value) and transient values of the temperature and volume in each fuel rod modeled. The volume available to the gas is determined in each slab from the thickness and average radius plus the volume of cracks in the fuel. The cold fuel rod plenum volumes are input by the user. Transient values

are obtained by adjusting for differential axial expansion of the cladding and fuel pellet stack. The plenum temperature used is that of the coolant volume for the top node of the fuel rod. The gas is assumed to flow freely between the gap and the plenum, and one pressure is calculated for all nodes in the axial direction.

After clad rupture, the gas pressure in the rod is set equal at each time step to the coolant pressure outside the ruptured node.

2.3.2 Swelling and Rupture Model For MOXY

Because of the difference in the BWR pin design, BWR LOCA transient, and the difference in code structure for MOXY, the swelling and rupture is based on a user input rupture temperature.

The rod swelling model is based on the following assumptions:

1. Rods retain original centers, and fuel and cladding are concentric after swelling.
2. The swollen rod diameter remains constant after swelling, and is not position-dependent.
3. Conduction between rods in contact is negligible.
4. The maximum rod diameter corresponds to contact between adjacent rods (60 percent reduction of the free flow area).
5. All rods in a single assembly are assumed to swell and rupture simultaneously. Rupture occurs at the time the maximum rod

temperature reaches a rupture temperature defined in the input data. Swelling begins when the maximum rod temperature reaches a swelling temperature, computed by subtracting a user-supplied value for swelling range from the rupture temperature.

Metal-water reaction on the cladding inside surface begins at the time of rod rupture, and fuel-to-cladding and cladding-to-surroundings heat transfer after swelling are based on the swollen rod dimensions. Thinning of cladding and of exterior surface oxide is considered, assuming constant cross-sectional area of cladding and of oxide.

While the hottest rod temperature is within the swelling temperature range (greater than the swelling temperature and less than the rupture temperature), the following equation is used to compute the rod radius.

$$\frac{r - r_i}{r_i} = 0.2 \frac{r_f - r_i}{r_i} \exp [- 0.0153 (T_r - T)] \quad (30)$$

where:

- r = current rod radius
- r_i = initial (unswollen) rod radius (in)
- r_f = final (fully swollen) rod radius (in)
- T_r = rupture temperature (°R)
- T = current peak rod temperature (°R)

When the hottest rod temperature equals or exceeds the rupture temperature, the rod radius is set equal to r_f.

2.4 Material Properties

There are no specific requirements set forth in the Commission criteria for material properties. The material properties for zircaloy and UO_2 presented have been reviewed by the Regulatory staff and were used in Evaluation Model computations.

1. Uranium Dioxide Thermal Conductivity

The thermal conductivity of UO_2 is taken from the Lyons^{8/} integral equal to 93. The Lyons integral is given by:

$$\int_{32}^{5037} k(T) dT = 93 \text{ watts/cm} \quad (31)$$

The porosity correction is the simplified MAXWELL-EUKEN^{9,10/} equation:

$$k_p/k_{95} = \frac{1.025 P}{0.95 (1 + (1-P)/2)} \quad (32)$$

where:

k_p = thermal conductivity at the current theoretical density

K_{95} = thermal conductivity at 95% theoretical density

P = fraction of theoretical density

The thermal conductivity of UO_2 95 percent density is given in Table 2.3 from 0° to 5100°F.

2. Uranium Dioxide Heat Capacity

The heat capacity of UO_2 is derived from the Brassfield^{11/} data.

The tabular values given by Brassfield are multiplied by the

Table 2.3

UO₂ THERMAL CONDUCTIVITY (95% THEORETICAL DENSITY)

<u>Temperature (°F)</u>	<u>Conductivity (BTU/hr-ft-°F)</u>
0	3.341
500	3.341
650	2.971
800	2.677
950	2.439
1100	2.242
1250	2.078
1400	1.940
1550	1.823
1700	1.724
1850	1.639
2000	1.568
2150	1.507
2300	1.457
2450	1.415
2600	1.382
3100	1.323
3600	1.333
4100	1.406
4600	1.538
5100	1.730

fraction of theoretical density over 0.95. The tabular volumetric heat capacities as a function of temperature from 0° to 8000°F are presented in Table 2.4.

3. Zircaloy Thermal Conductivity

The thermal conductivity of zircaloy is the curve recommended by Brassfield.^{11/} The zircaloy conductivity used is given in Table 2.5.

4. Zircaloy Heat Capacity

The heat capacity of zircaloy is obtained from the curve of Eldridge and Deem.^{33/} In order to account for the effect of the latent heat of phase change, a large increase in heat capacity is taken between 1480.3°F and 1787.5°F. The heat capacity for zircaloy used is presented in Table 2.6.

2.5 Metal-Water Reaction Rate

The rate of energy release and oxidation produced by cladding metal-water reactions is specified by the Commission criteria:

"5. Metal-Water Reaction Rate. *The rate of energy release, hydrogen generation, and cladding oxidation from the metal/water reaction shall be calculated using the Baker-Just equation (Baker, L., Just, L.C., "Studies of Metal Water Reactions at High Temperatures, III. Experimental and Theoretical Studies of the Zirconium-Water Reaction," ANL-6548, page 7, May 1962). The reaction shall be assumed not to be steam limited. For rods whose cladding is calculated to rupture during the LOCA, the inside of the cladding*

Table 2.4

UO₂ VOLUMETRIC HEAT CAPACITIES

<u>Temperature (°F)</u>	<u>Volumetric Capacity (BTU/ft³-°F)</u>
32	34.45
122	38.35
212	40.95
392	43.55
752	46.80
2012	51.35
2732	52.65
3092	56.55
3452	63.05
3812	72.80
4352	89.70
4532	94.25
4532	98.15
4892	100.10
5144	101.40
8000	101.40

Table 2.5

ZIRCALOY THERMAL CONDUCTIVITY

<u>Temperature</u>	<u>Thermal Conductivity (BTU/hr-ft-°F)</u>
32	7.812
212	7.992
392	8.208
572	8.784
752	9.540
932	10.404
1112	11.268
1292	12.492
1472	13.176
1652	13.968
1832	14.796
2012	16.128
2192	17.784
2372	19.656
2552	21.780
2732	24.048
3092	28.908
3360	33.120

Table 2.6

ZIRCALOY VOLUMETRIC HEAT CAPACITY

<u>Temperature (°F)</u>	<u>Volumetric Heat Capacity (BTU/ft³-°F)</u>
0.	28.392
1480.3	34.476
1675.0	85.176
1787.5	34.476
3500.0	34.476

shall also be assumed to react after the rupture. The calculation of the reaction rate on the inside of the cladding shall also follow the Baker-Just equation, starting at the time when the cladding is calculated to rupture, and extending around the cladding inner circumference and axially no less than 1.5 inches each way from the location of the rupture, with the reaction assumed not to be steam limited."

As required by the Commission criteria, energy released by metal-water reaction is applied to the outer surface of the cladding during the LOCA analysis. Once cladding rupture has been predicted, the inside reaction is assumed. If the internal reaction is to extend to a 3 inch segment, the axial rods or core heat slab must be modeled in 3 inch segments.

The reaction rate between zircaloy cladding and steam is assumed to follow the parabolic rate law of Baker and Just as specified by the criteria. Integration over a time step, Δt , and simplification of the parabolic rate law result in the following expressions for mass of zirconium reacted on the inside and outside surfaces of the cladding, MZR and MZR1, respectively:

$$MZR = \pi \rho_{zr} [2R_s (DRP1 - DRP) - AP] \quad (33)$$

$$MZR1 = \pi \rho_{zr} [2R_i (DRP2 - DRP1) + AP1] \quad (34)$$

where:

DRP1 = depth the reaction has penetrated the cladding exterior at the end of a time step (in)

DRP = depth the reaction has penetrated the cladding exterior at the beginning of a time step (in)

DRP2 = depth the reaction has penetrated the cladding interior at the end of a time step (in)

DRPI = depth the reaction has penetrated the cladding interior at the beginning of a time step (in)

ρ_{zr} = density of zirconium ($\frac{\text{lb}_m}{\text{in}^3}$)

R_s = initial rod radius (in)

R_i = inside cladding radius (in)

The quantities AP and AP1 are:

$$AP = DRP1^2 - DRP^2 = 0.123 \exp\left(\frac{41200}{T}\right) (XMWR) (\Delta t) \quad (35)$$

$$AP1 = DRP2^2 - DRPI^2 = 0.123 \exp\left(\frac{41200}{T_i}\right) (XMWR) (\Delta t) \quad (36)$$

where:

T = outside cladding surface temperature at the reacting metal-oxide interface ($^{\circ}R$)

T_i = inside cladding temperature ($^{\circ}R$)

Δt = time step size (sec)

XMWR = fraction of the parabolic rate (dimensionless)

The metal-water reaction heat flux is given by:

$$q_{mwr} = \frac{(\Delta H_r) (MZR + MZR1)}{(A_n) (\Delta t)} \quad (37)$$

where:

A_n = surface area of a node (in^2)

ΔH_r = heat of reaction (Btu/lbm)

In MOXY-EM, the heat of reaction can be computed by any of the four options:

1. A conservative constant value,
2. A slightly conservative temperature-dependent function,
3. A best-estimate temperature-dependent function, and
4. A user-supplied FORTRAN function of temperature.

The constant value is 2800 Btu/lbm; the value that has been used in all earlier versions of MOXY. The following equation gives a slightly conservative temperature-dependent function.

$$\Delta H_R = 2912 - 5.85 \times 10^{-2} T \quad (38)$$

The best-estimate temperature-dependent function computed from thermodynamic relationships is given by:

$$\Delta H_R = 2835 - 6.374 \times 10^{-3} T - 3.631 \times 10^{-5} T^2 - \frac{6312}{T} + 3.022 \times 10^{-9} T^3 \quad (39)$$

3.0 RELAP4-EM COMPUTER PROGRAM

The RELAP4-EM program is used to perform system thermal-hydraulic decompression analyses and detailed fuel rod thermal behavior calculations for both BWRs and PWRs. The RELAP4 computer program is the basis for RELAP4-EM. Most of the analytical model, input data, and format of the RELAP4^{2/} program remains unchanged for RELAP4-EM. Hence, the basic RELAP4 equations and models will not be repeated in this document. Only the modifications made to the RELAP4 program and the necessary revised input will be presented; therefore, a user must rely on both the RELAP4 program document^{2/} and this Evaluation Model supplement in preparing an Evaluation Model analysis.

3.1 Primary System Pump Model

The Commission acceptance criteria require that a dynamic model be considered for primary system pumps. In reference to the pump model to be used the criteria state:

"6. Pump Modeling. The characteristics of rotating primary system pumps (axial flow, turbine, or centrifugal) shall be derived from a dynamic model that includes momentum transfer between the fluid and the rotating member, with variable pump speed as a function of time. The pump model resistance used for analysis should be justified. The pump model for the two-phase region shall be verified by applicable two-phase pump performance data...."

In analyzing the available two-phase pump data, it was noted that when the fluid being pumped had a void fraction between 0.2 and 0.9, little head was developed by the pump being tested. Outside this range of void fraction, the pump developed head ranged from zero to undegraded single-phase performance. The limited available data indicate pump performance in the void fraction range 0.2 to 0.9 is significantly degraded from single-phase behavior. To consider the degraded performance, a set of dimensionless homologous curves was fitted to the head data in the fully-degraded void fraction range, and the difference between the undegraded single-phase and the fully degraded two-phase head was expressed as a function of the standard pump model arguments (v/a or a/v). To consider the ranges of void fraction where the pump was able to develop head (0 to 0.2 and 0.9 to 1.0), a multiplier* as a function of void fraction was employed. The multiplier varied from 0 to about 1.0 as the void fraction varied from 0 to 0.2, and the multiplier varied from about 1.0 to 0 as the void fraction varied from 0.9 to 1.0.

Two phase pump data available are limited. Pumps tested consist mainly of low specific speed and small scales. Table 3.1 presents the Westinghouse Canada Ltd. (WCL) and Semiscale pump characteristics. The specific speeds are much smaller than those for a reactor coolant system pump. The two-phase model generated has used the WCL and Semiscale pump test data.

*The two phase multiplier is a multiplier on the degradation curve where α denotes void fraction and a denotes speed ratio.

Table 3.1

PUMP CHARACTERISTICS

Pump	Flow (gpm)	Head (ft)	Speed (rpm)	Specific Speed
WCL	280	500	3560	550
Semiscale	189	192	3560	926

The RELAP4-EM pump model is the same as the pump model presented in the RELAP4 manual^{2/} except that a motor torque option, pump stop option, and dimensionless head ratio difference data have been built into pump curve Set 4 for the two-phase model. These modifications are described in the following sections.

3.1.1 Pump Model for Two-Phase Flow

Available pump data from the 1-1/2 Loop Model Semiscale and Westinghouse Canada Ltd. (WCL) experiments were used in developing the two-phase pump data for RELAP4-EM. Assumptions inherent in the pump model for two-phase flow include:

1. The head multiplier, $M(\alpha)$, that was determined empirically for the normal operating region of the pump is also valid as an interpolating factor in all other operating regions.
2. The relationship of the two-phase to the single-phase behavior of the semiscale pump is applicable to large reactor pumps. This assumption predicates a pump specific speed independence for the pump model for two-phase flow.

The single-phase pump head (dimensionless) curve for the semiscale pump is shown in Figure 3.1. The nomenclature is as follows:

$$h = H/H_r$$

$$\nu = Q/Q_r$$

$$\alpha = N/N_r$$

NORMAL PUMP	(+Q,+N)	{ HAN HVN
ENERGY DISSIPATION	(-Q,+N)	{ HAD HVD
NORMAL TURBINE	(-Q,-N)	{ HAT HVT
REVERSE PUMP	(+Q,-N)	{ HAR HVR

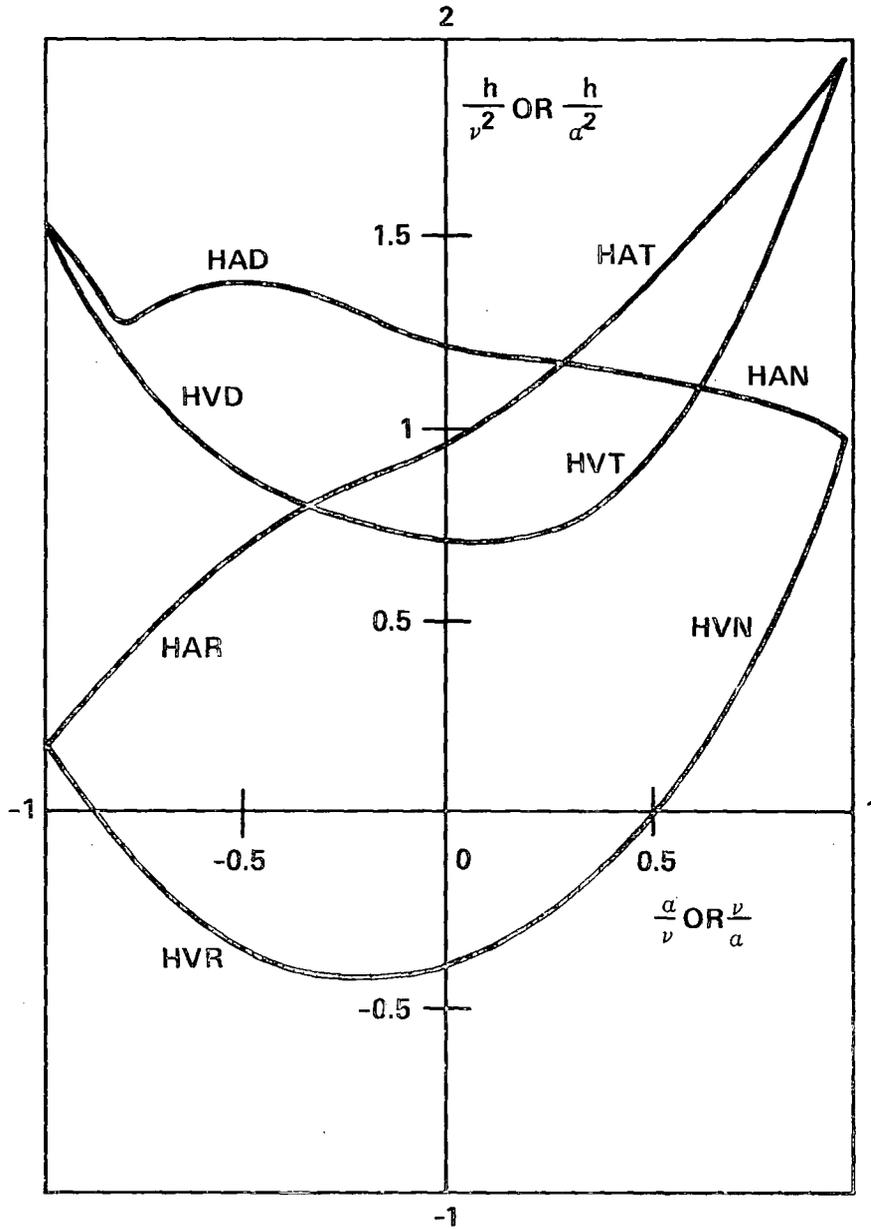


Figure 3.1 Single Phase Head Curves for 1-1/2 Loop Mod-1 Semiscale Pumps

H = head

Q = volumetric flow

N = angular speed

r = subscript denoting rated operating value.

The two-phase pump head curves shown in Figure 3.2 represent complete pump characteristics for the semiscale pump while operating under two-phase conditions when the average of the void fractions of the pump inlet and outlet mixtures is between 0.2 and 0.9. The lines drawn through the data were determined by least square polynomial fits to the data using known constraints.

A comparison of the two-phase data of Figure 3.2 with the single-phase data in Figure 3.1 shows that the dimensionless head ratio (h/v^2 or h/a^2) is significantly less than the single-phase dimensionless head ratio for the normal pump operation region (HAN and HVN). For negative ratios of v/a such as those which occur in the HAD region, the pump flow becomes negative. When the pump flow is negative, the two-phase dimensionless head ratio is greater than the single-phase dimensionless head ratio. Two-phase flow friction losses are generally greater than single-phase losses, and friction is controlling in this energy dissipation region (HAD). The other regions of the two-phase dimensionless head ratio data show similar deviations from single-phase data.

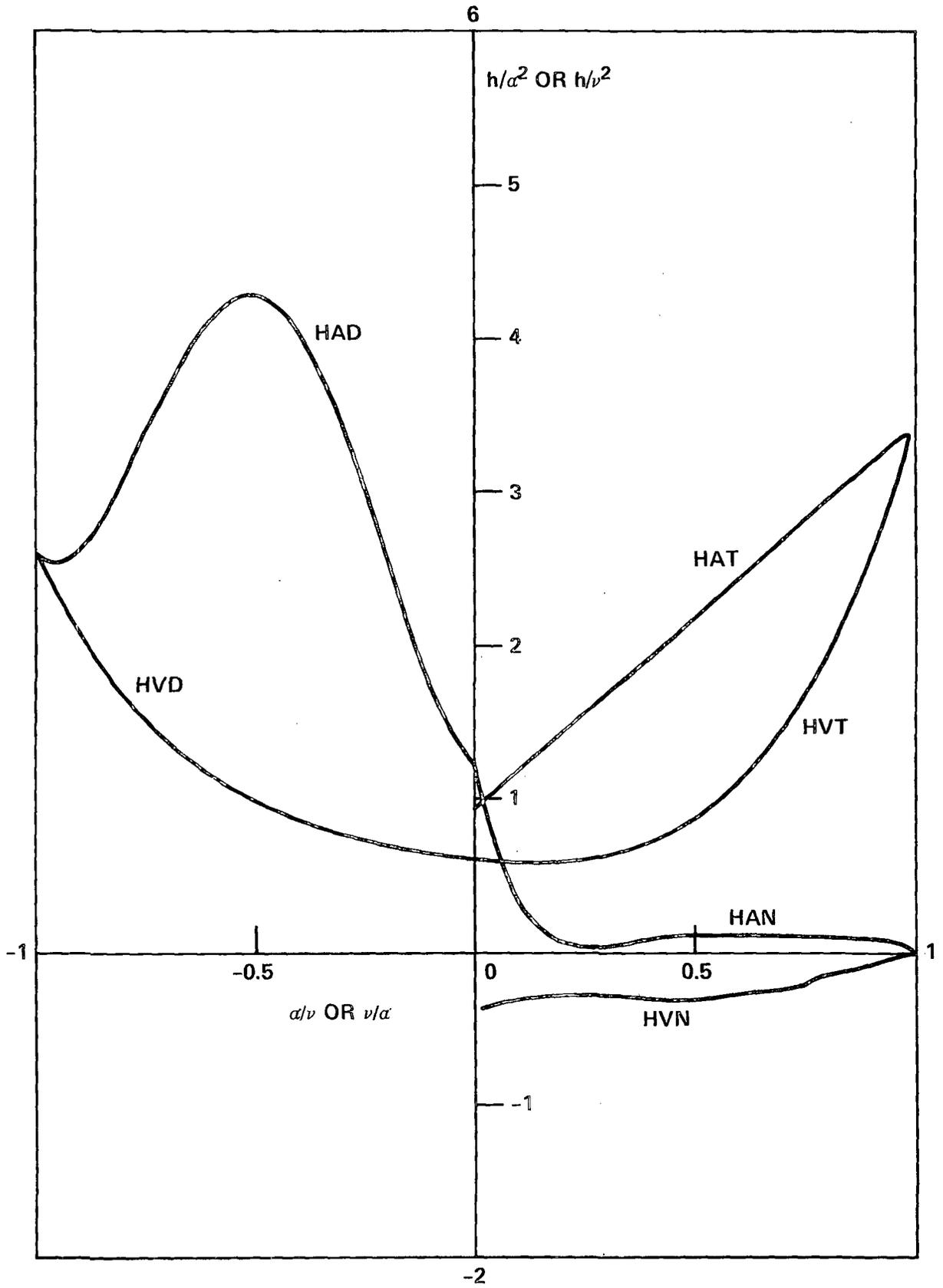


Figure 3.2 Two-Phase Homologous Head Curves for 1-1/2 Loop MOD-1 Semiscale Pump

Table 3.2 shows the difference between the single-phase and the two-phase dimensionless head ratio data as a function of v/a and a/v for the various pumping regions shown in Figures 3.1 and 3.2. The differences shown in Table 3.2 are for the eight curve types used in RELAP4 for determining pump head.

The head multiplier, $M(\alpha)$, and void fraction, α , data shown in Table 3.3 were obtained in the following manner. The semiscale and WCL pump data^{30/} were converted to dimensionless head ratios of h/a^2 or h/v^2 . Values of the dimensionless head ratios were obtained for those pump speeds and volumetric flow rates which were within 50% of the rated speed and flow rate for the pumps. The difference between the single-phase and two-phase dimensionless ratios was developed as a function of the average of the void fractions of the pump inlet and outlet mixtures. The difference between the single-phase dimensionless ratios was then normalized between 0 and 1.0 and the normalized result was tabulated as a function of the void fraction.

The two-phase pump model in RELAP4-EM calculates the pump head as follows:

$$H = H_1 - M(\alpha) (H_1 - H_2) \quad (40)$$

where:

$M(\alpha)$ = a multiplier which is a function of void fraction (α)

$$H_1 - H_2 = \left(\frac{h}{a^2} \Big|_1 - \frac{h}{a^2} \Big|_2 \right) a^2 H_R \text{ or } \left(\frac{h}{v^2} \Big|_1 - \frac{h}{v^2} \Big|_2 \right) v^2 H_R \quad (41)$$

Table 3.2

SEMISCALE DIMENSIONLESS HEAD RATIO DIFFERENCE(SINGLE-PHASE MINUS TWO-PHASE) DATA $x \equiv v/a$ or a/v

$$y \equiv \left(\frac{h}{a^2}\right)_1 - \left(\frac{h}{a^2}\right)_2 \text{ or } \left(\frac{h}{v^2}\right)_1 - \left(\frac{h}{v^2}\right)_2$$

Curve Type	x	y	Curve Type	x	y
1 (HAN)	0.00	0.00	4 (HVD)	-1.00	-1.16
	0.10	0.83		-0.90	-0.78
	0.20	1.09		-0.80	-0.50
	0.50	1.02		-0.70	-0.31
	0.70	1.01		-0.60	-0.17
	0.90	0.94		-0.50	-0.17
	1.00	1.00		-0.35	0.00
				-0.20	0.05
2 (HVN)	0.00	0.00	5 (HAT)	0.00	0.00
	0.10		0.20	-0.34	
	0.20	0.00	6 (HVT)	0.40	-0.65
	0.30	0.10	0.60	-0.93	
	0.40	0.21	0.80	-1.19	
	0.80	0.67	1.00	-1.47	
	0.90	0.80	6 (HVT)	0.00	0.11
	1.00	1.00	0.10	0.13	
			0.25	0.15	
			0.40	0.13	
3 (HAD)	-1.00	-1.06	0.50	0.07	
	0.90	-1.24	0.60	-0.04	
	-0.80	-1.77	0.70	-0.23	
	-0.70	-2.36	0.80	-0.51	
	-0.60	-2.79	0.90	-0.91	
	-0.50	-2.91	1.00	-1.47	
	-0.40	-2.67	7 (HAR)	-1.00	0.00
	-0.25	-1.69	0.00	0.00	
	-0.10	-0.50	8 (HVR)	-1.00	0.00
	0.00	0.00	0.00	0.00	

H_R = rated head

subscript 1 refers to single-phase head

subscript 2 refers to two-phase head.

The capability to calculate torque in a manner similar to the head relationships is available in RELAP4-EM.

The semiscale dimensionless head ratio difference data shown in Table 3.2 are built into the head portion of pump curve Set 4 in RELAP4-EM. A table of zeros is built into the torque portion of curve Set 4. Any of the data built into curve Set 4 may be overridden by input of other data.

To implement the two-phase model, the user must input to RELAP4-EM a table of multiplier, $M(\alpha)$, versus void fraction, α , of the type shown in Table 3.3 for head and torque. To date, zeros have been input for the torque multiplier because the torque portion of the two-phase pump model has not been approved for inclusion in RELAP4-EM.

3.1.2 Pump Motor Torque Model

The RELAP4-EM pump model has been modified to include the influence of the electric drive motor on the speed behavior of the pump while the motor remains connected to its power source. The effect of the motor is incorporated into the pump model by adding the value of motor torque to the angular momentum balance given by the following equation:

Table 3.3

HEAD MULTIPLIER AND VOID FRACTION DATA

α	M(α)
0.00	0.00
0.10	0.00
0.15	0.05
0.24	0.80
0.30	0.96
0.40	0.98
0.60	0.97
0.80	0.90
0.90	0.80
0.96	0.50
1.00	0.00

$$I \frac{dw}{dt} = \sum_{i=1}^N T_i \quad (42)$$

where:

I = moment of inertia of pump rotor and motor

$\frac{dw}{dt}$ = rate of change of angular velocity

T = torque

Prior to this modification, the components of the summation of torques consisted of the hydraulic torque, T_h , and the frictional torque, T_{fr} . With the inclusion of motor torque, T_m , the summation becomes:

$$\sum_{i=1}^N T_i = -T_h - T_{fr} + T_m \quad (43)$$

where the sign of the motor torque is in opposition to the hydraulic and frictional torque at normal operating conditions.

The motors used to drive primary coolant pumps are induction-type machines. At constant voltage, the motor torque is an explicit function of speed. This torque-speed relationship is normally available from the motor manufacturer.

Motor torque is supplied to the RELAP4-EM model as a tabular function of torque vs speed as defined by manufacturer's data. For illustration, a typical torque-speed curve for an induction motor is shown in Figure 3.3.

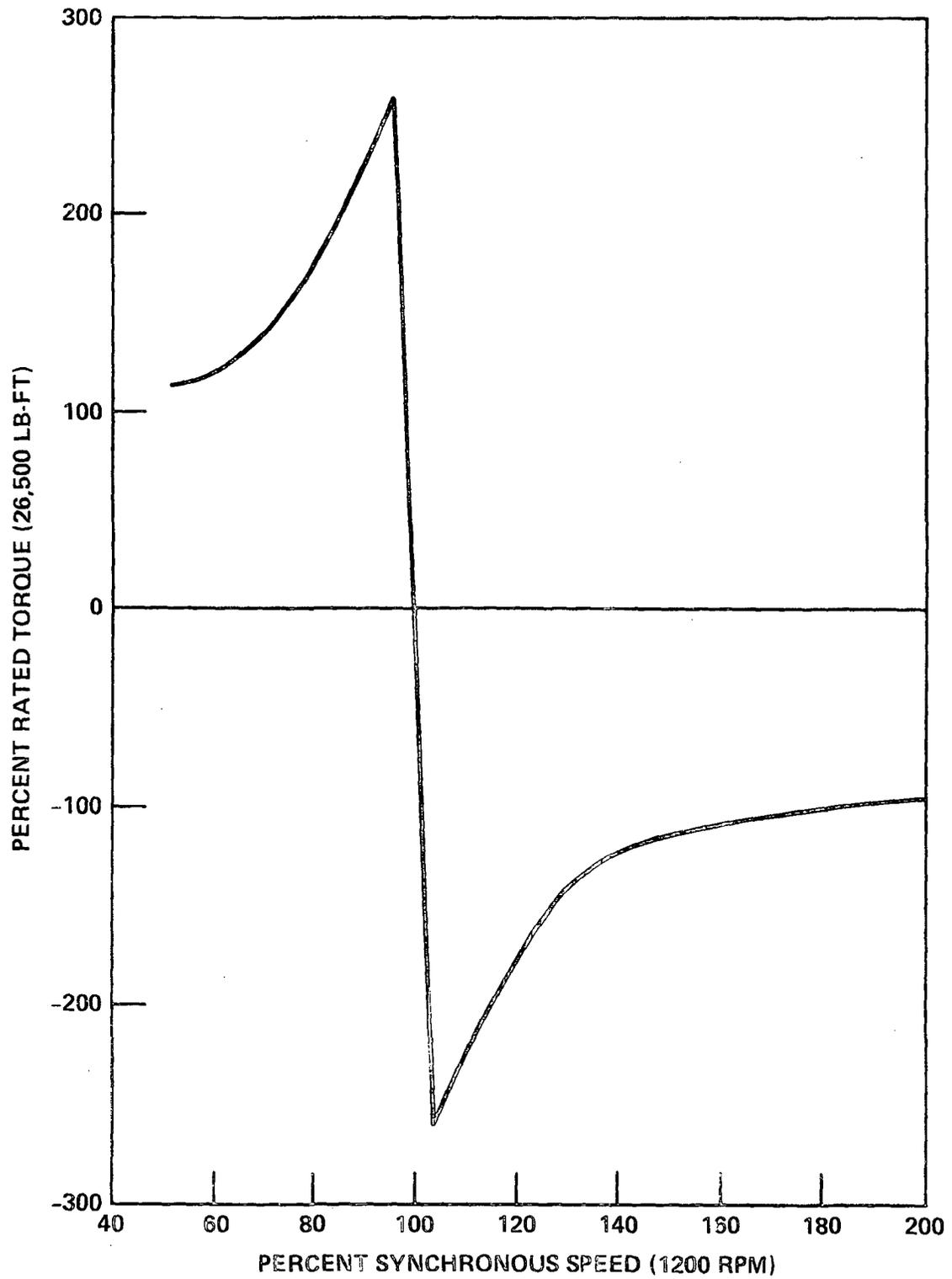


Figure 3.3 Torque Versus Speed Type 93A Pump Motor (Rated Voltage)

3.1.3 Pump Locked Rotor

The capability to simulate a locked rotor of the pump was included in the RELAP4-EM computer program. This option provides for simulating the locking of the pump rotor as a function of input elapsed time, maximum forward speed, or maximum reverse speed. At the time the rotor locks and at all times thereafter, the pump speed is set equal to zero. This option is called by inserting the Pump Stop Data Cards (093XX1) into the input deck as described in RELAP4-EM Input Data Description.

3.2 Discharge Model

The critical flow model in the two-phase region required by the Commission criteria is the Moody critical flow model. With respect to a discharge model the criteria state:

"b. Discharge Model. For all times after the discharging fluid has been calculated to be two-phase in composition, the discharge rate shall be calculated by use of the Moody model (F. J. Moody, "Maximum Flow Rate of a Single Component, Two-Phase Mixture," Journal of Heat Transfer, Trans American Society of Mechanical Engineers, 87, No. 1, February 1965). The calculation shall be conducted with at least three values of a discharge coefficient applied to the break area, these values spanning the range from 0.6 to 1.0. If the results indicate that the maximum clad temperature for the hypothetical accident is to be found at

an even lower value of the discharge coefficient, the range of discharge coefficients shall be extended until the maximum clad temperature calculated by this variation has been achieved."

The criteria require the Moody discharge model for the two-phase region. In the subcooled region, the criteria do not specify the discharge model to be used in constructing an Evaluation Model discharge model. The Henry-Fauske model and the Moody model were used for the subcooled and two phase regions, respectively.

The Moody critical flow model is an available option in RELAP4. However, changes in the subcooled critical flow model were made so that there would be a smooth transition between the subcooled and saturated regimes. In the subcooled region, the RELAP4-EM model uses the minimum of the flow calculated by the momentum equation (unchoked condition) or the Henry-Fauske model (choked condition). At saturation, the Moody model is used for the choked condition. The Henry-Fauske subcooled model gives slightly higher flow rates at the saturation point than the Moody model. However, in the code, they are forced to be equal as shown in Figure 3.4.

Critical flow at internal junctions is calculated in the same manner as it is calculated at the simulated break location. The flow is calculated using both the momentum equation and the tabulated critical flow values and the minimum of the two is used. If the tabulated critical flow rates are the minimum, the flow is considered to be choked.

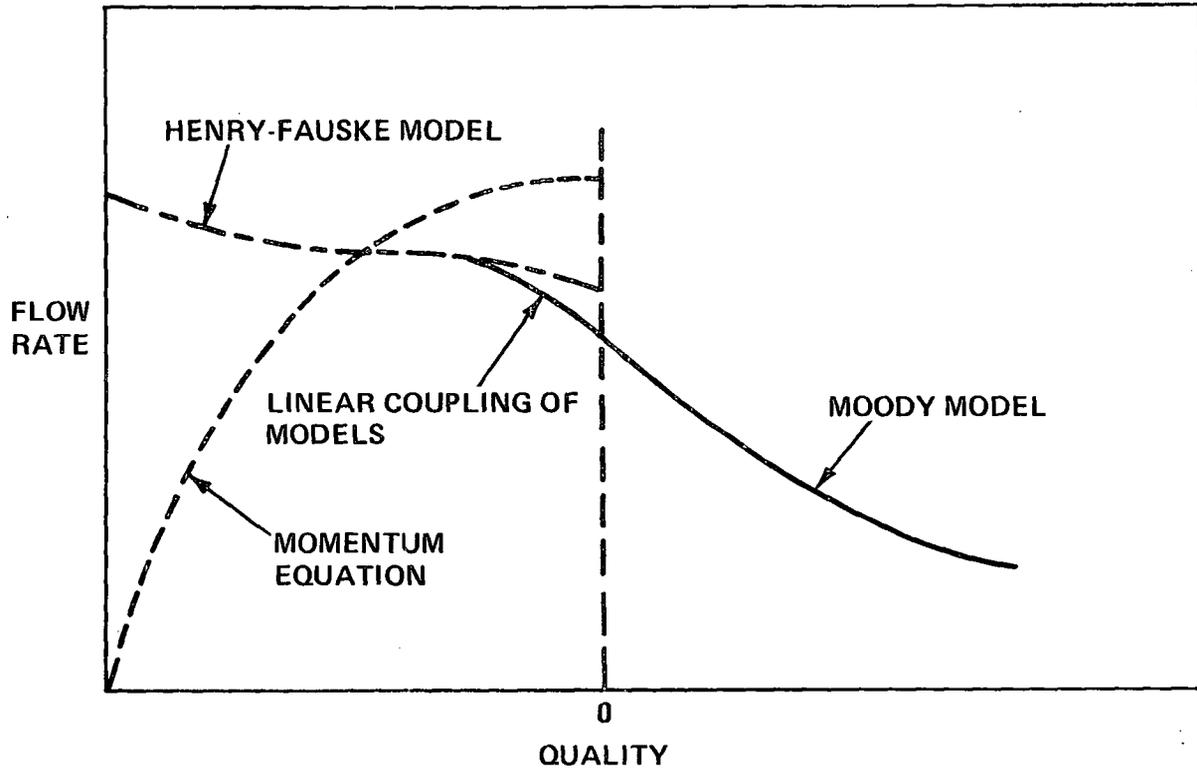


Figure 3.4 Critical Flow Model

In practice, several RELAP4 options for critical flow have been kept in RELAP4-EM for sensitivity studies and comparison purposes. The correct RELAP4-EM option must be selected by the user and is obtained by setting JCHOK (word 12) equal to zero and ICHOK (word 17) equal to eleven on card 08XXXX, as given in the RELAP4-EM input data description.

The critical flow option and the momentum equation are selected by three input variables. The selection of these variables is discussed in the Conservation of Momentum Equation section.

3.3 Critical Heat Flux

Steady-state and transient critical heat flux correlations are acceptable as specified by the Commission acceptance criteria:

"4. Critical Heat Flux. a. Correlations developed from appropriate steady-state and transient-state experimental data are acceptable for use in predicting the critical heat flux (CHF) during LOCA transients. The computer programs in which these correlations are used shall contain suitable checks to assure that the physical parameters are within the range of parameters specified for use of the correlations by their respective authors.

b. Steady-state CHF correlations acceptable for use in LOCA transients include, but are not limited to, the following:

(1) W-3. L. S. Tong, "Prediction of Departure from Nucleate Boiling for an Axially Non-uniform Heat Flux Distribution," Journal of Nuclear Energy, Vol. 21, 241-248, 1967.

(2) B&W-2. J. S. Gellerstedt, R. A. Lee, W. J. Oberjohn, R. H. Wilson, L. J. Stanek, "Correlation of Critical Heat Flux in a Bundle Cooled by Pressurized Water," Two-Phase Flow and Heat Transfer in Rod Bundles, ASME, New York, 1969.

(3) Hench-Levy. J. M. Healzer, J. E. Hench, E. Janssen, S. Levy, "Design Basis for Critical Heat Flux Condition in Boiling Water Reactors," APED-5186, GE Company Private report, July 1966.

(4) Macbeth. R. V. Macbeth, "An Appraisal of Forced Convection Burnout Data," Proceedings of the Institute of Mechanical Engineers 1965-1966.

(5) Barnett. P. G. Barnett, "A Correlation of Burnout Data for Uniformly Heated Annuli and Its Uses for Predicting Burnout in Uniformly Heated Rod Bundles," ABEW-R 463, 1966.

(6) Hughes. E. D. Hughes, "A Correlation of Rod Bundle Critical Heat Flux for Water in the Pressure Range 150 to 725 psia," IN-1412, Idaho Nuclear Corporation, July 1970.

c. Correlations of appropriate transient CHF data may be accepted for use in LOCA transient analyses if comparisons between the data and the correlations are provided to demonstrate that the correlations predict values of CHF which allow for uncertainty in the experimental data throughout the range of parameters for which the correlations are

to be used. Where appropriate, the comparisons shall use statistical uncertainty analysis of the data to demonstrate the conservatism of the transient correlation.

d. Transient CHF correlations acceptable for use in LOCA transients include, but are not limited to, the following:

(1) GE transient CHF. B. C. Slifer, J. E. Hench, "Loss-of-Coolant Accident and Emergency Core Cooling Models for General Electric Boiling Water Reactors," NEDO-10329, General Electric Company, Equation C-32, April 1977.

e. After CHF is first predicted at an axial fuel rod location during blowdown, the calculation shall not use nucleate boiling heat transfer correlations at that location subsequently during the blowdown even if the calculated local fluid and surface conditions would apparently justify the reestablishment of nucleate boiling. Heat transfer assumptions characteristic of return to nucleate boiling (rewetting) shall be permitted when justified by the calculated local fluid and surface conditions during the reflood portion of a LOCA."

Logic for selecting the CHF correlation in RELAP4-EM uses pressure and mass flow rates as a basis for choosing the appropriate correlation. Under some circumstances, a correlation may be used outside the original range of some of the experimental parameters used in developing the correlation. For example, correlations are lacking for two-phase entrance

conditions over the full range of pressures and mass flow rates expected in a LOCA, and thus extension of the correlations beyond the range of the data from which they were developed is necessary. The CHF correlations selection logic is based upon extensive comparison by ANC of existing CHF correlations with available data. The correlation scheme used gives the best approximation of existing data and is used in PWR analysis. The ANC analyses provided the basis for extending the range of the correlations.

The choice of a correlation for predicting the critical heat flux depends on the pressure and mass flow. The critical heat flux check is made for both noncore and core heat conductor slabs. The Babcock & Wilcox Company B&W-2, Barnett, and Modified Barnett correlations are used as follows:

P > 1500	B&W-2
1500 > P > 1300	Interpolation between B&W-2 and Barnett
1300 > P > 1000	Barnett
1000 > P > 725	Interpolation between Barnett and Modified Barnett
725 > P	Modified Barnett

A minimum critical heat flux value of 90,000 Btu/ft²-hr is set and used if the predicted value falls below this number.

For a mass flux, G, less than 200,000 lb_m/ft²-hr, the critical heat flux is interpolated between 90,000 Btu/ft²-hr and the value given

by the chosen correlation where the 90,000 Btu/ft²-hr corresponds to G=0 lb_m/ft²-hr and the latter corresponds to the value of CHF at G=200,000 lb_m/ft²-hr.

The inlet enthalpy used in the critical heat flux correlations is dependent on the flow direction and is determined in the following manner:

<u>Flow at Normal Inlet</u>	<u>Flow at Normal Outlet</u>	<u>H_{in}</u>
>0	≥0	H at normal inlet
<0	<0	H at normal outlet
All other cases		H at core volume

Critical heat flux correlations used in the RELAP4-EM PWR analysis have been discussed above. The correlations and the conditions under which they were obtained are given below:

1. Babcock & Wilcox Company, B&W-2^{14/}

$$q_{CHF} = \frac{1.15509 - 0.40703 \left(\frac{D_e}{12}\right)}{(12.71) (3.0545G')^A} (0.3702 \times 10^8) (0.59137G')^B - 0.15208 h_{fg} G' \quad (44)$$

where: A = 0.71186 + (2.0729 × 10⁻⁴) (P-2000)

and: B = 0.834 + (6.8479 × 10⁻⁴) (P-2000)

$$G' = G/10^6$$

h_{fg} = phase change enthalpy, Btu/lb

Water in rod bundles

Equivalent diameter D_e: 0.2 to 0.5 in.

Length: 72 in.

Pressure (P): 2000 to 2400 psia

Mass flux (G): 0.75×10^6 to 4.0×10^6 lb_m/ft² hr.

Burnout quality: 0.03 to 0.20

2. Barnett^{15/}

$$q_{CHF} = 10^6 \left[\frac{A + B(h_f - h_{in})}{C + L} \right] \quad (45)$$

where: $A = 67.45 D_{HE}^{0.68} G^{-0.192} [1.0 - 0.774e^{(-6.512 D_{HY} G^{-1})}]$ (46)

$$B = 0.2587 D_{HE}^{1.261} G^{-0.817} \quad (47)$$

$$C = 185.0 D_{HY}^{1.415} G^{-0.212} \quad (48)$$

D_{HE} = four times flow area divided by heated perimeter

$$D_{HY} = [D_r (D_r + D_{HE})]^{1/2} - D_r$$

D_r = rod diameter, in.

For a rectangular conductor geometry, D_{HE} is set equal to the input values for the right side hydraulic diameter for the conductor.

Water in annulus: applied to rod bundle using "equivalent" diameter

$$\text{Equivalent diameters: } 0.258 \text{ in.} < D_{HE} < 3.792 \text{ in.} \quad (49)$$

$$0.127 \text{ in.} < D_{HY} < 8.875 \text{ in.} \quad (50)$$

Length: 24 to 108 in.

Pressure: 1000 psia

Mass Flux: 0.14×10^6 to 6.20×10^6 $\text{lb}_m/\text{ft}^2\text{-hr.}$

Inlet Subcooling: 0 to 412 Btu/ lb_m

3. Modified Barnett^{31/}

$$q_{\text{CHF}} = 10^6 \left[\frac{A + B(h_f - h_{\text{in}})}{C + L} \right] \quad (51)$$

where:

$$A = 73.71 D_{\text{HE}}^{0.052} G^{-0.663} \left[1.0 = 0.315e^{(-11.34 D_{\text{HY}} G')} \right] \frac{888.6}{h_{\text{fg}}} \quad (52)$$

$$B = 0.104 D_{\text{HE}}^{1.445} G^{-0.691} \quad (53)$$

$$C = 45.55 D_{\text{HY}}^{0.0817} G^{-0.5866} \quad (54)$$

Water in rod bundles

Rod diameter: 0.395 to 0.543 in.

Length: 32.9 to 174.8 in.

Pressure: 150 to 725 psia

Mass Flux: 0.03×10^6 to 1.7×10^6 $\text{lb}_m/\text{ft}^2\text{-hr.}$

Inlet Subcooling: 6 to 373 Btu/ lb_m

The analysis of boiling water reactors (BWRs) uses the General Electric Company transient CHF correlation^{16/} as specified by the Commission acceptance criteria. This correlation was incorporated into the code as an optional replacement for the Barnett correlation

for BWR analysis. This option is exercised by using a negative value for the channel length in word 5 on Core Section Data Cards 16XXX0 as described in the Input Data Description. The correlation that was added to RELAP4-EM is:

$$q_{CHF} = 10^6 (0.8-x) \text{ for } G \geq 0.5 \times 10^6 \text{ lb}_m/\text{ft}^2\text{-hr} \quad (55)$$

$$q_{CHF} = 10^6 (0.84-x) \text{ for } G < 0.5 \times 10^6 \text{ lb}_m/\text{ft}^2\text{-hr} \quad (56)$$

but: $q_{CHF} \geq 90,000$ regardless

where: x = quality

G = mass flux

The above CHF correlation was used for all BWR LOCA analyses performed using RELAP4-EM.

3.4 Heat Transfer Correlations

The RELAP4-EM heat transfer correlation selection logic is based on the Commission acceptance criteria. Appropriate heat transfer correlations are specified in the criteria which state:

"5. Post-CHF Heat Transfer Correlations. a. *Correlations of heat transfer from the fuel cladding to the surrounding fluid in the post-CHF regimes of transition and film boiling shall be compared to applicable steady-state and transient-state data using statistical correlation and uncertainty analyses. Such comparison shall demonstrate that the correlations predict values of heat transfer coefficient equal to or less than the mean value of the applicable experimental heat*

transfer data throughout the range of parameters for which the correlations are to be used. The comparisons shall quantify the relation of the correlations to the statistical uncertainty of the applicable data.

b. The Groeneveld flow film boiling correlation (equation 5.7 of D. C. Groeneveld, "An Investigation of Heat Transfer in the Liquid Deficient Regime," AECL-3281, revised December 1969), the Dougall-Rohsenow flow film boiling correlation (R. S. Dougall and W. M. Rohsenow, "Film Boiling on the Inside of Vertical Tubes with Upward Flow of the Fluid at Low Qualities," MIT Report Number 9079-26, Cambridge, Massachusetts, September 1963), and the Westinghouse correlation of steady-state transition boiling ("Proprietary Redirect/ Rebuttal Testimony of Westinghouse Electric Corporation," U.S.A.E.C. Docket RM-50-1, page 25-1, October 26, 1972) are acceptable for use in the poast-CHF (SIC) boiling regimes. In addition the transition boiling correlation of McDonough, Milich and King (J. B. McDonough, W. Milich, E. C. King, "Partial Film Boiling with Water at 2000 psig in a Round Vertical Tube," MSA Research Corp. Technical Report 62 (NP-6976), (1958) is suitable for use between nucleate (SIC) and film boiling. Use of all these correlations shall be restricted as follows:

(1) The Groeneveld correlation shall not be used in the region near its low-pressure singularity,

(2) the first term (nucleate) of the Westinghouse correlation and the entire McDonough, Milich, and King correlation shall not be used during the blowdown after the temperature difference between the clad and the saturated fluid first exceeds 300°F,

(3) transition boiling heat transfer shall not be reapplied for the remainder of the LOCA blowdown, even if the clad superheat returns below 300°F, except for the reflood portion of the LOCA when justified by the calculated local fluid and surface conditions."

The heat transfer regimes which the core will experience during a typical LOCA are illustrated in Figure 3.5. Heat transfer mode numbers 1-9 are assigned to the various regimes and subregimes to identify the proper correlations to be used. Table 3.4 identifies these modes and lists the correlations as they are used in RELAP4-EM.

Reference to Figure 3.5 Regime A-B (subcooled forced convection, labeled mode 1 in RELAP4-EM) is characterized by the coolant bulk temperature less than saturation temperature and the surface temperature low enough that boiling does not occur. If the surface temperature is less than saturation temperature, no boiling is possible and the Dittus-Boelter subcooled forced convection correlation is used in RELAP4-EM. Point B of Figure 3.5 shows the beginning of the nucleate boiling regime; here the coolant may still be subcooled but the surface temperature is high enough that some boiling occurs. Thus, if the surface temperature is greater than saturation temperature, it is

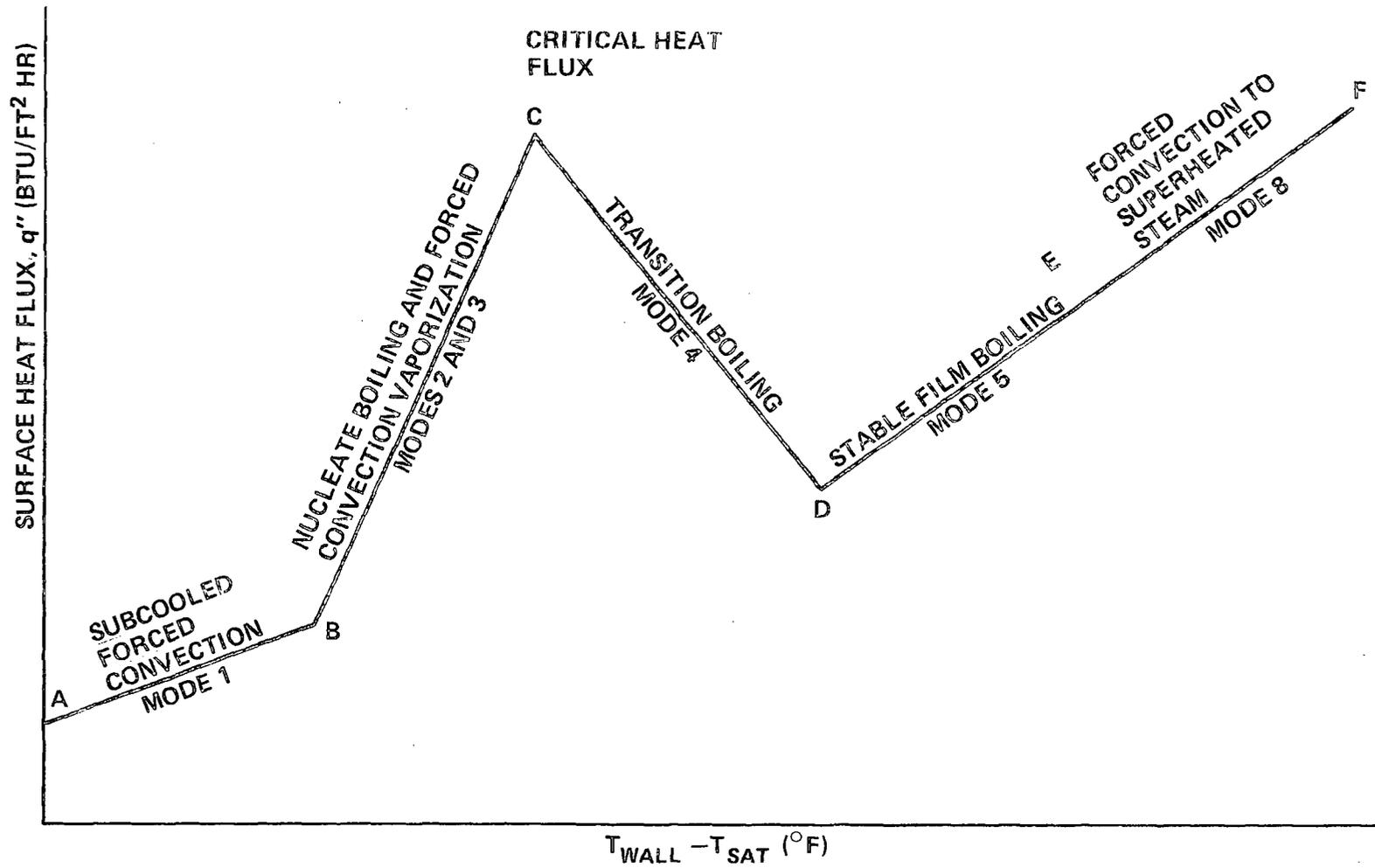


Figure 3.5 Heat Transfer Regimes

possible to be on either side of Point B. For this condition, both the Dittus-Boelter correlation and the Thom correlation are evaluated and the surface temperatures calculated. The correlation resulting in the lower surface temperature is selected and the proper mode number assigned.

Region B-C of Figure 3.5 is defined by two modes: nucleate boiling, mode 2, and forced convection vaporization, mode 3. If the void fraction is less than .80, the Thom nucleate boiling correlation is selected. For a void fraction above .90, the Schrock-Grossman forced convection vaporization correlation is used. For void fractions between .80 and .90, an interpolation between the two correlations is used in order to avoid a discontinuity between the nucleate boiling and forced convection vaporization regimes. The Schrock-Grossman correlation is applied until the quality reaches 95%. Above 100% quality, the Dittus-Boelter correlation for single phase forced convection to superheated steam (mode 8) is used. Between 95 and 100 percent quality, an interpolation technique based on quality is made to smooth the transition from forced convection vaporization (mode 3) to forced convection to superheated steam (mode 8).

The critical heat flux (Point C of Figure 3.5) is evaluated at each core heat slab location for each time step. If the heat flux, calculated by one of the above correlations, exceeds the calculated critical heat

TABLE 3.4

HEAT TRANSFER CORRELATIONS IN RELAP4-EM

Mode 1. Subcooled Liquid Forced Convection; Dittus - Boelter^{17/}

$$h = .023 \frac{k}{D_e} Pr^{0.4} Re^{0.8} \quad (57)$$

Mode 2. Nucleate Boiling; Thom^{18/}

$$q'' = \left[\frac{\Delta T_{sat} \exp(P/1260)}{.072} \right]^2 \quad (58)$$

Mode 3. Forced Convection Vaporization; Schrock - Grossman^{19/}

$$h = (2.5) (.023) \frac{k_f}{D_e} Pr_f^{0.4} \left[Re_f (1-X) \right]^{0.8} \quad (59)$$

$$\left[\left(\frac{X}{1-X} \right)^{0.9} \left(\frac{\mu_g}{\mu_f} \right)^{0.1} \left(\frac{\rho_f}{\rho_g} \right)^{0.5} \right]^{0.75} \quad (60)$$

Mode 4. Transition Boiling; McDonough, Milich, and King^{20/}

$$q'' = q''_{CHF} - C(P) (T_w - T_{w,CHF}) \quad (61)$$

Press, psi	C(P)
2000	979.2
1200	1180.8
800	1501.2

Mode 5. Stable Film Boiling - Groeneveld 5.7^{21/}

$$h = .052 \frac{k_g}{D_e} Pr_w^{1.26} \left\{ Re_g \left[X + \frac{\rho_g}{\rho_f} (1-X) \right] \right\}^{.688} \quad (62)$$

$$\left[1.0 - 0.1 (1-X)^{0.4} \left(\frac{\rho_f}{\rho_g} - 1 \right)^{0.4} \right]^{-1.06} \quad (63)$$

TABLE 3.4

HEAT TRANSFER CORRELATIONS IN RELAP4-EM (Cont'd)

Mode 6. Pool Film Boiling; Berenson^{22/}

$$q'' = F(P) (\Delta T_{\text{sat}})^{0.75} \quad (64)$$

Press, psi	F(P)
15	128
100	236
500	412
1000	510
1500	615
2000	705

Mode 7. Transition Pool Boiling

$$q'' = 20000 \frac{\Delta T_{\text{min}}}{\Delta T_{\text{sat}}} \frac{1.504}{\ln(\Delta T_{\text{min}}/20)} \quad (65)$$

$$\text{where: } \Delta T_{\text{min}} = \left[\frac{20,000}{F(P)} \right]^{4/3} \quad (66)$$

Mode 8. Superheated Vapor Forced Convection; Dittus - Boelter^{17/}

$$h = .023 \frac{k_g}{D_e} Pr^{0.4} Re^{0.8} \quad (67)$$

Mode 9. Low Pressure Flow Film Boiling; Dougall - Rohsenow^{23/}

$$h = .023 \frac{k_g}{D_e} Pr_g^{0.4} \left\{ Re_g \left[X + \frac{\rho_g}{\rho_f} (1-X) \right] \right\}^{0.8} \quad (68)$$

flux, the correlations for the transition regime (region C-D, of Figure 3.5, mode 4) and the stable film boiling regime (region D-E, mode 5) are evaluated.

The McDonough, Milich, and King correlation is used for the transition regime (mode 4) and either the Dougall-Rohsenow or the Groeneveld 5.7 may be specified for the stable film boiling regime (mode 5). Both the Dougall-Rohsenow and the Groeneveld 5.7 correlations are accepted by the criteria. Neither the Dougall-Rohsenow correlation nor the Groeneveld correlation is valid below 10% quality. Both correlations underpredict experimental data at low qualities. The data in this range indicate a tendency to rewet the surface with resulting heat transfer coefficients which are much higher than true film boiling. A reasonable lower limit to the heat transfer coefficient was provided by computing heat transfer coefficients using a 10% quality value in the correlations for all calculated qualities of 10% or less. The Dougall-Rohsenow correlation is always called if the pressure is less than 500 psi. In order to determine whether the transition or stable film boiling regime exists, the higher value of heat flux calculated from the correlations for modes 4 and 5 is used to identify the proper post CHF regime.

The Commission criteria disallow the return to nucleate boiling once the critical heat flux has been exceeded. To signal that CHF

has been calculated and the return to nucleate boiling is being precluded, a value of 10 is added to the heat transfer mode designator on the RELAP4-EM listings and plots.

In situations where the Thom correlation predicts heat fluxes less than the critical heat flux, indicating a return to nucleate boiling, both the Thom correlation and the McDonough, Milich, and King correlation are evaluated, and the smaller predicted heat flux is used.

When the coolant reaches 100% quality (Point E of Figure 3.5, mode 8), forced convection to superheated steam is initiated and the heat transfer coefficients are evaluated using the Dittus-Boelter correlation.

A discontinuity exists at the quality of 1.0 between the Groeneveld correlation and the Dittus-Boelter steam convection correlation. The Dougall-Rohsenow correlation is not discontinuous as this relationship becomes the Dittus-Boelter relationship at a quality of 1.0. To smooth the transition between regimes, an interpolation on quality is made over the range of .95 to 1.0 between the Groeneveld heat transfer correlation and the Dougall-Rohsenow correlation.

The criteria disallow the return to transition boiling (mode 4) if the cladding superheat exceeds 300°F. If the wall superheat drops below 300°F, the stable film boiling regime is assumed to continue. When the return to transition boiling is precluded, a value of 20 is added to the heat transfer mode printout and plot values to signal this occurrence.

If the mass flow drops below 0.2×10^6 lbm/hr-ft², pool film boiling is assumed (mode 6) and the Berenson correlation is applied. If the

heat flux predicted by the Berenson correlation is less than 20,000 Btu/hr-ft², then the correlation for transition pool boiling (mode 7) is used. For this regime, if the predicted wall superheat is less than 20°F, a heat flux of 90,000 Btu/hr-ft² is assigned.

3.5 ECC Bypass

The Commission acceptance criteria require that the Evaluation Model perform calculations to determine the end-of-bypass (EOB). The AEC model uses the conservative assumption that once downflow is established in the downcomer after ECC injection is started, ECC bypass will not occur further. However, the model will accept user input values of upflow velocity as an EOB criterion. If they are used, the user must provide justification. After the end-of-bypass has occurred, the injected ECC water is subtracted from the vessel inventory. The specific criteria concerning the end-of-blowdown, end-of-bypass, and subtraction of ECC water state:

"c. End of Blowdown. (Applies only to Pressurized Water Reactors.)
For postulated cold leg breaks, all emergency cooling water injected into the inlet lines or the reactor vessel during the bypass period shall in the calculations be subtracted from the reactor vessel calculated inventory. This may be executed in the calculation during the bypass period, or as an alternative the amount of emergency core cooling water calculated to be injected during the bypass period may be subtracted later in the calculation from the water remaining in the inlet lines, downcomer, and reactor vessel lower

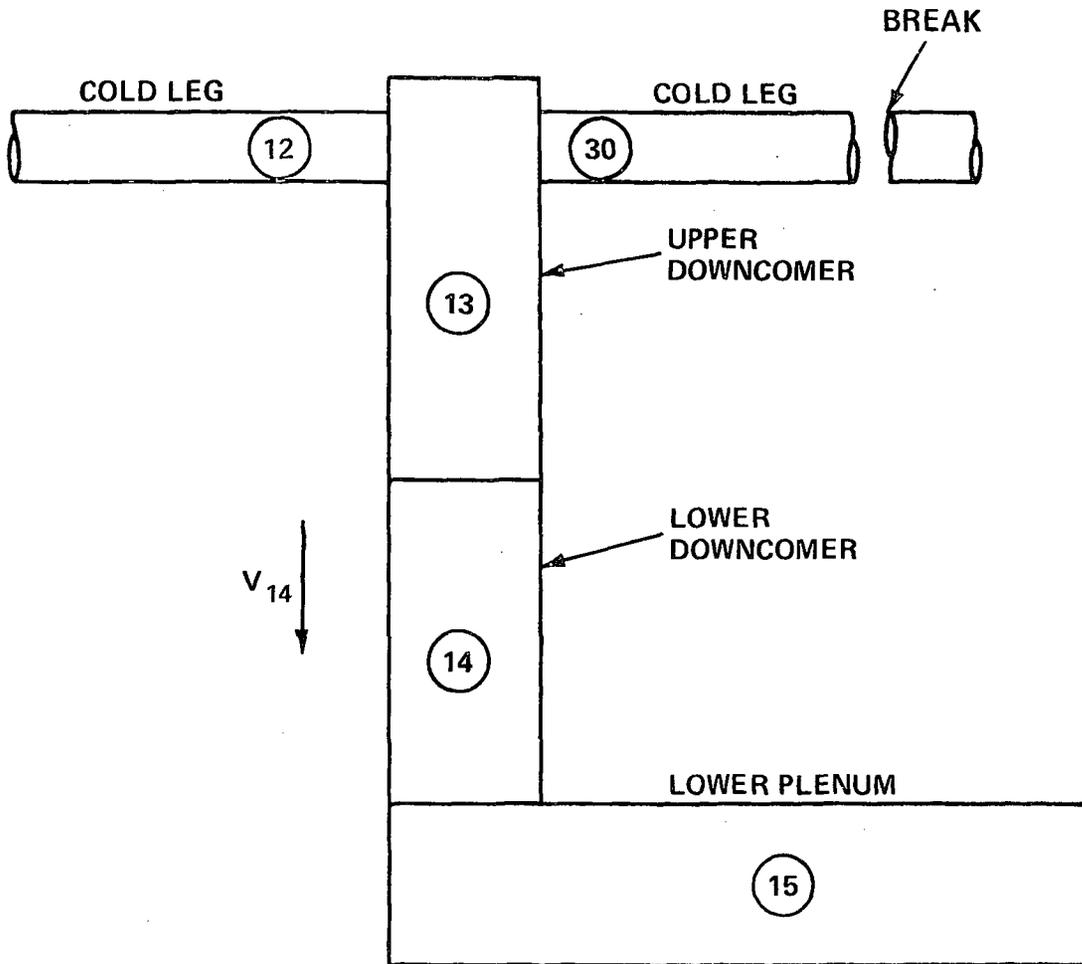
plenum after the bypass period. This bypassing shall end in the calculation at a time designated as the "end of bypass," after which the expulsion or entrainment mechanisms responsible for the bypassing are calculated not to be effective. The end of bypass definition used in the calculation shall be justified by a suitable combination of analysis and experimental data. Acceptable methods for defining "end of bypass" include, but are not limited to, the following: (1) Prediction of the blowdown calculation of downward flow in the downcomer for the remainder of the blowdown period; (2) Prediction of a threshold for droplet entrainment in the upward velocity, using local fluid conditions and a conservative critical Weber number."

The RELAP4 Evaluation Model contains the following model for computing ECC bypass. The check for end-of-bypass is initiated by user input trip identifications to the RELAP4-EM program. These trips are normally the trips initiating flow from the unbroken loop accumulators. This trip check serves two purposes: (1) end-of-bypass check will not be computed at input initial steady-state conditions, and (2) end-of-bypass check will not be tested until the bypass period has begun. At the time the trip is calculated to occur, the initial mass in the user specified volumes (accumulator volumes) is calculated and stored. After this time, the entrainment mechanisms that produce end-of-bypass are tested.

The end-of-bypass entrainment mechanism tested is a computed velocity in a user specified volume (a downcomer volume). This velocity is computed

based on the volume average mass flow rate, as described in the RELAP4 manual, divided by the volume-density area product. This calculated velocity is then compared with a user input end-of-bypass velocity and when the calculated velocity is greater than the input velocity, the time of end-of-bypass is established. To compute a proper volume velocity, a downcomer volume having a single inlet and outlet should be modeled and selected for this test. This model assumes the normal downward flow direction in the downcomer region as the positive flow direction, and input to RELAP4-EM must be consistent with this assumption. The input end-of-bypass velocity will normally be either zero (presently used by AEC-Regulatory) or an upward (negative) velocity, (which must be justified by the user). A calculated velocity greater than this value (in the algebraic sense) will be either a smaller upward velocity or a downward velocity. A typical PWR downcomer model for end-of-bypass is shown in Figure 3.6.

At the time of end-of-bypass, the mass of water remaining in the specified volumes (unbroken loop accumulators) is determined. This mass is then subtracted from the initial mass in the accumulator volumes, and the difference is the ECC mass lost according to the criteria. This difference or mass loss is then subtracted from the calculated mass in the reactor vessel lower plenum, downcomer regions and inlet line regions. The subtraction is made by progressively subtracting the mass loss difference from the specified regions in the order given by additional user



End of Bypass Defined as Time When Velocity in Volume 14 Reverses ($V_{14} > 0$)

$$\text{WHERE } V_{14} = \frac{\text{VOLUME AVERAGE MASS FLOW}_{14}}{\rho_{14} A_{14}}$$

Figure 3.6 Downcomer Bypass Model

input. If the liquid mass in a region is greater than the difference to be subtracted, the liquid mass in that region is reduced by the difference, and conditions for a saturated two-phase mixture with the remaining liquid mass at the existing calculated pressure are determined for that volume. If the liquid mass in a region is less than the difference to be subtracted, the liquid mass for the region is set to zero and the region is assumed to contain only saturated steam at the existing pressure. The mass loss difference is then reduced by the liquid mass removed, and the next region in the order of user input is tested. The mass removal is complete when the entire mass loss difference has been subtracted from the system or all the specified volumes contain only saturated steam. For large PWR inlet line breaks, the saturated steam conditions will usually be calculated for all the volumes.

These assumptions impose a severe condition on the system when they are implemented instantaneously, as the calculated mass flows are based on volume fluid densities which may be either liquid or two-phase. When these flows are instantaneously imposed on volumes with significantly reduced densities, the inconsistencies of flow, pressure distribution, and densities can create calculational instabilities. To make the conditions more representative, calculated flows from a volume at the end-of-bypass are modified by the ratio of volume densities after end-of-bypass to before end-of-bypass. Thus, volumetric flows are conserved while mass flows and densities are discontinuous.

After the end-of-bypass has been calculated, the RELAP4-EM calculation is continued with revised volume conditions. The arbitrary reduction of mass in a RELAP4-EM calculation can produce some effects which cause up flow in the downcomer region. This condition is produced by the injection of cold ECC liquid into cold leg volumes which at the end-of-bypass contain only saturated steam and leads to significant local depressurization. This rapid decompression causes calculated flow toward this point in the system. Thus, when end-of-bypass has been calculated by a downward flow in a downcomer region, the artificial assumptions for end-of-bypass mass loss can cause a flow reversal and subsequent upward flow in the downcomer. This condition is recognized as an artificial result of the ECC bypass assumptions, and subsequent further mass loss because of these effects is not considered by RELAP4-EM.

3.6 Core Flow Smoothing

Rapid oscillations with periods less than 0.1 seconds should be smoothed by an analytical technique as required by the Commission acceptance criteria. Requirements of the criteria are stated by:

"7. Core Flow Distribution During Blowdown. (Applies only to pressurized water reactors.)

a. The flow rate through the hot region of the core during blowdown shall be calculated as a function of time. For the purpose of these calculations, the hot region chosen shall not

be greater than the size of one fuel assembly. Calculations of average flow and flow in the hot region shall take into account cross flow between regions and any flow blockage calculated to occur during blowdown as a result of cladding swelling or rupture. The calculated flow shall be smoothed to eliminate any calculated rapid oscillations (period less than 0.1 seconds).

b. A method shall be specified for determining the enthalpy to be used as input data to the hot channel heatup analysis from quantities calculated in the blowdown analysis, consistent with the flow distribution calculations."

An extension has been made to the separate core calculation options in RELAP4-EM to allow smoothing oscillatory flows. A tape previously created by RELAP4 while performing the full primary system calculation is used as a data base. Volume conditions to be smoothed and reactor normalized power may be retrieved in the same way as without the flow smoothing option. To retrieve a junction flow, rescale the flow, and smooth the oscillations, the following changes are made.

To perform the flow smoothing calculation, a convolution integral may be performed for a junction for each time step using an input smoothing function and a junction flow retrieved from the tape of the reference calculation. The following equations define the convolution integrals performed during a separate core calculation using the flow smoothing option:

$$\text{FLOFAC}_i = \frac{\text{WP}_i(o)}{\text{WP}_j(o)} \quad (69)$$

$$\text{WFINT} = \int_0^{\tau_{\max}} \text{WFUN}(\tau) d\tau \quad (70)$$

$$\text{WP}_i(t) = \frac{\text{FLOFAC}_i}{\text{WFINT}} \int_0^{\tau_{\max}} \text{WP}_j(t-\tau) \text{WFUN}(\tau) d\tau \quad (71)$$

where:

- WP_j = flow in Junction j of the reference calculation
- WP_i = smoothed flow in Junction i of the separate core calculation
- WFUN = smoothing function
- FLOFAC = flow rescaling factor
- WFINT = smoothing function normalization factor

Figure 3.7 is a diagram of the smoothing process. An original and oscillatory flow is operated upon by a filter moving with time. A smoothed flow results.

The flow in junction i will be the smoothed flow of junction j of the reference calculation by setting the valve index (IVALVE) of junction i equal to -j (Section 3.9.3, item 14). The smoothing function is input on cards 080001 through 080009 in pairs of entries of τ and $f(\tau)$. Up to 20 pairs of entries are allowed in the smoothing function table. The table must be input if any valve index (IVALVE) of the separate core calculation is negative and must not be input if no valve index is negative. Up to 10 junction flows may be defined using flow smoothing.

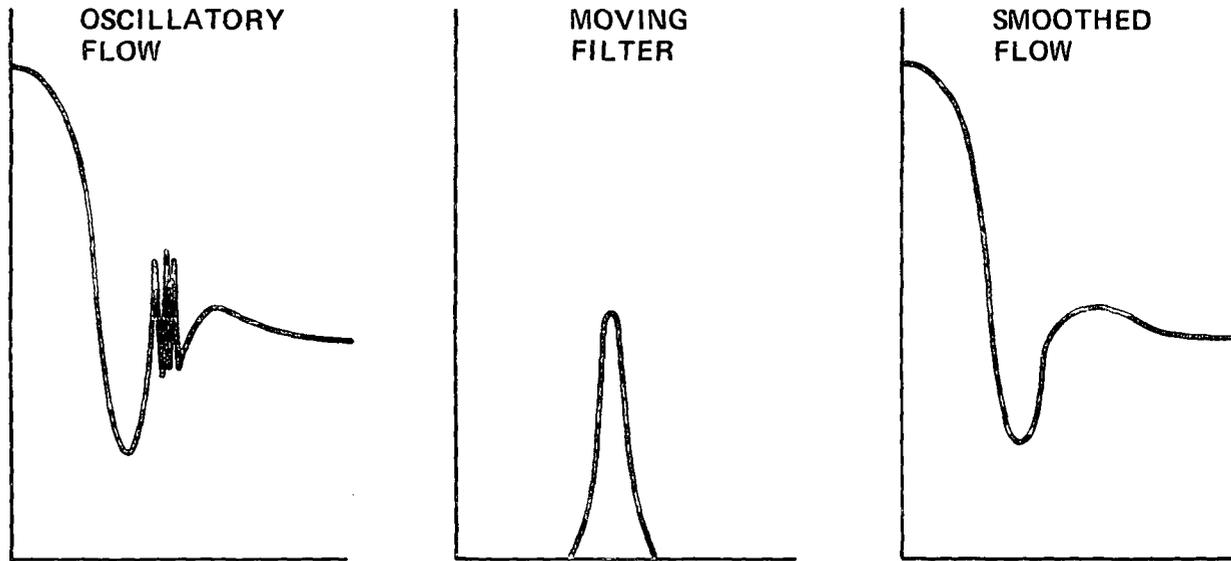


Figure 3.7 Core Flow Smoothing

3.7 Momentum Equation

The conservation of momentum equation to be used by the Evaluation Model computer programs should account for certain effects as specified by the acceptance criteria. The effects to be accounted for are given in the following paragraph from the Commission acceptance criteria:

"3. Momentum Equation. The following effects shall be taken into account in the conservation of momentum equation: (1) temporal change of momentum, (2) momentum convection, (3) area change momentum flux, (4) momentum change due to compressibility, (5) pressure loss resulting from wall friction, (6) pressure loss resulting from area change, and (7) gravitational acceleration. Any omission of one or more of these terms under stated circumstances shall be justified by comparative analyses or by experimental data."

Several options are available to the user* to select the form of the momentum equation that is desired. These equations are selected by the assigned value of the input variable MVMIX on the junction data cards (card 08XXXXY). This selection may be modified by the input value of the input variables JCHOKE and ICHOKE also on the junction data cards. The input variables JCHOKE and ICHOKE select the critical flow option as discussed in the critical flow section

*Presently (May 1975) the Regulatory staff uses the incompressible equation for "simple" nodes and no momentum flux equation for complex nodes for base-case PWR calculations (refer to the input Section 3.10). For further discussion of this point, the reader should refer to the staff report on momentum equation sensitivity studies^{34/}.

(Section 3.2). In addition to the six options available through the selections of MVMIX, the user must choose a momentum equation based on the complexity of the junctions that connect the volumes in question.

As stated earlier, the form of the momentum equation to be used in RELAP4-EM is selected by the value used for MVMIX. Momentum equations that can be used are presented in the form used for sudden expansions or sudden contractions. The geometry for the sudden expansion is presented in Figure 3.8.

1. Compressible Mechanical Energy Balance Equation: MVMIX = 0

$$\begin{aligned}
 I_j \frac{dW_j}{dt} = & \left(P_K + \frac{\bar{v}_K \bar{W}_K}{A_K} + P_{Kgj} \right) - \left(P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgj} \right) \\
 & + \rho_{Li} (v_{Li}^2 + C_j^2) - \rho_{Ko} (v_{Ko}^2 + C_j^2) \\
 & - F_{fK} - F_{fL} - F_{K,j,L}
 \end{aligned} \quad (72)$$

where:

\bar{W} = volume average mass flow as previously defined for the energy equation

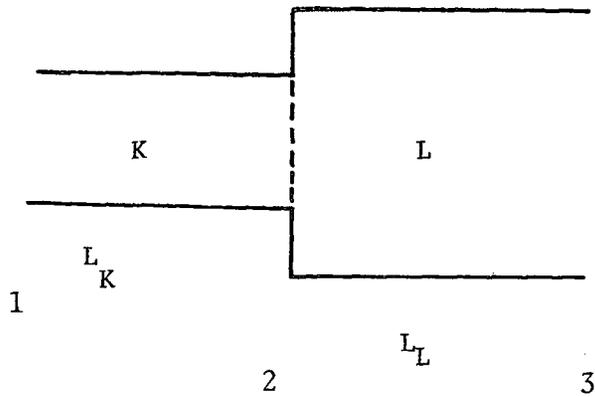
\bar{v} = volume average velocity

ρ_{Li} , ρ_{Ko} = fluid density at the inlet side of Volume L and the outlet side of Volume K, respectively

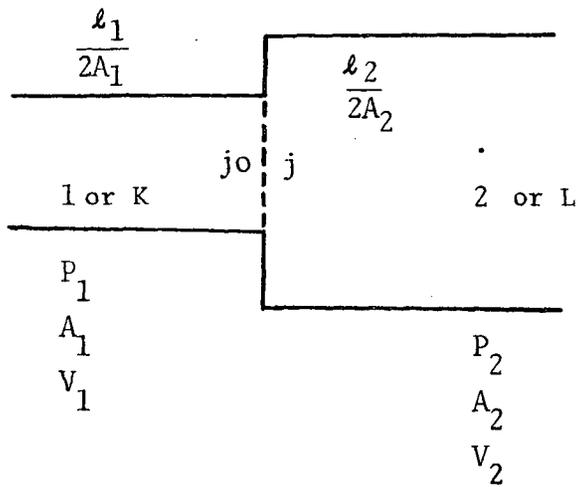
v_{Li} , v_{Ko} = fluid velocity at the inlet side of Volume L and the outlet side of Volume K, respectively

Figure 3.8

MOMENTUM EQUATION FOR SUDDEN EXPANSION



COMPRESSIBLE INTEGRAL MOMENTUM EQUATION



MECHANICAL ENERGY BALANCE EQUATION

$$C_j = \text{fluid sonic velocity} = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_S}$$

F_{fK}, F_{fL} = Fanning friction as previously defined

$F_{K,j,L}$ = frictional pressure loss from the outlet side of Volume K through Junction j into the inlet side of Volume L

S = subscript referring to constant entropy

I_j = geometric "inertia" for Junction j

W_j = mass flow at Junction j

P_1, P_2 = thermodynamic pressure in control volumes 1 and 2

v_1, v_2 = velocity in control volumes 1 and 2

A_1, A_2 = area in control volumes 1 and 2

P_{1g}, P_{2g} = gravitational pressure drops in control volumes 1 and 2

ℓ = length of control volume

D_h = diameter

K = loss coefficient

2. Mixed two stream compressible flow in the volume "from" side:

MVMIX = 1 (reference Figure 3.6 for definition of subscripts and model figure):

$$I_{j1} \frac{dW_{j1}}{dt} = -I'_{j2} \frac{dW_{j2}}{dt} + \left(P_K + \frac{\bar{v}_K \bar{W}_K}{A_K} + P_{Kgjl} \right) \quad (73)$$

$$- \left(P_L + \frac{\bar{v}_L \bar{W}_L}{A_L} + P_{Lgjl} \right) - F_{fK} - F_{fL} - F_{Kj1,j1, Lj1} + \Delta P_{j1}$$

where:

- W_{j1} = flow from Volume K through Junction j1 to Volume L
 W_{j2} = flow through Junction j2 that is mixed with W_{j1}
 I_{j1} = inertia for flow W_{j1}
 I_{j2} = half-volume inertia for flow W_{j2} in the volume common to flow W_{j1}
 $F_{Kj1,j1,Lj1}$ = friction loss for the flow through Junction j1
 ΔP_{j1} = Fanning friction, Volumes K and L
 P_{Kgj1}, P_{Lgj1} = elevation pressures for flow W_{j1} in Volumes K and L, respectively.

More details as to the form of the equation may be obtained from Section 2.32, "Compressible Two-Stream Flow with One-Dimensional Momentum Mixing," p. 24, of the RELAP4 manual.

3. Mixed two-stream compressible flow in the volume "to" side:

MVMIX = 2 The flow solution for the "to" side is obtained by appropriate changes in the subscripts of the above equation. More detail may be obtained from Section 2.32 of the RELAP4 manual.

4. Incompressible Mechanical Energy Balance Equation with no momentum flux (no Bernoulli effects): MVMIX = 3

$$I_j \frac{dW_j}{dt} = (P_K + P_{Kgj}) - (P_L + P_{Lgj}) - K_f \frac{\rho_j v_j |v_j|}{2} \phi_{2P} \quad (74)$$

5. Compressible Integral Momentum Equation, Single stream: MVMIX = 4

$$I_j \frac{dW_j}{dt} = (P_k + \frac{\bar{V}_k \bar{W}_k}{A_k} + P_{kgj}) - (P_L + \frac{\bar{V}_L \bar{W}_L}{A_L} + P_{Lgj}) - F_{fk} - F_{fL} - F_{k,j,L} \quad (75)$$

6. Special case of a fill with negative flow used to represent the outlet: A volume with no normal outlet junction, but with a negative fill position (flow is negative) as the actual volume outlet, constitutes a special case. In order for the correct volume flow to be calculated, the user must use MVMIX = -2 for the negative fill junction.

Through the selection of JCHOKE and ICHCKE, a seventh form of the momentum equation can be selected. If JCHOKE = 0 and ICHCKE = 11, the Incompressible Mechanical Energy balance momentum equation is used, this equation is given by:

$$\begin{aligned} I_j \frac{dW_j}{dt} = & (P_1 + \frac{v_1 W_1}{A_1} + P_{1g}) - (P_2 + \frac{v_2 W_2}{A_2} + P_{2g}) \\ & - \frac{W_j^2}{2} \left(\frac{1}{\rho_{j1} A_1^2} - \frac{1}{\rho_{j2} A_2^2} \right) \\ & - S_1 \left(\frac{4fL}{2D_h} \right)_1 \frac{W_1^2}{2\rho_1 A_1^2} - S_2 \left(\frac{4fL}{2D_h} \right)_2 \frac{W_2^2}{2\rho_2 A_2^2} - \frac{S_{jK} W_j^2}{2\rho_j A_j^2} \end{aligned} \quad (76)*$$

*Note that for this case $\rho_{j1} = \rho_{j2}$ and the middle term can be written as:

$$- \frac{W_j^2}{2\rho_j} \left(\frac{1}{A_1^2} - \frac{1}{A_2^2} \right)$$

where: f = friction factor

$S = 1$ for forward flow, -1 for reverse flow

This equation represents the incompressible form of the equation shown under item 1. Selection of JCHOKE=11 calls the evaluation model choking option using the MOODY model for the two-phase region. Therefore, the incompressible mechanical energy balance momentum equation represents the momentum equation used for all Evaluation Model calculations.

3.8 Liquid Level Calculation

The liquid level calculation option is not required by the Commission acceptance criteria but has been added to help define the beginning of core reflooding. An equivalent liquid level is defined such that an effective water level in the lower plenum can be calculated as a function of time. A conglomerate volume combining up to twenty RELAP-EM volumes may be described. The order of the RELAP4-EM volumes used to describe the conglomerate volume is arbitrary except that the first RELAP4-EM volume becomes the reference volume. The total liquid mass in the conglomerate volume is obtained by summing the liquid mass in each of the RELAP4-EM volumes. A total liquid volume is obtained by dividing the total liquid mass by the density of saturated liquid in the reference volume. The liquid level in the conglomerate volume is then calculated from the total liquid volume in all the RELAP4-EM volumes. Finally, the liquid level

in the conglomerate volume is compared to the elevation of the bottom of the reference volume and the result printed for each major edit. For the option to be used in determining the beginning of core reflooding, the reference volume would be chosen as the lowest core volume and other volumes would include downcomer volumes, lower plenum volumes, and the remaining core volumes.

3.9 Input Data Description for RELAP4-EM

The following description is for all input requirements for RELAP4-EM presented in a form necessary for the computer. Requirements for data deck organization, input data cards, tape editing, problem restart and control cards are presented. Control cards for execution and tape manipulation will not be discussed in detail.

3.9.1 Control Cards

The control cards necessary for input, output, tape setup, completion and execution of the RELAP4-EM code will not be discussed in detail. These control cards are computer system and installation dependent. General tape input and output needed are as follows:

Input Tape

1. Plot-Restart Tape - This tape contains information from a previous run that is to be restarted. Restart information is presented in Section 3.9.5.
2. Boundary Condition Tape - The tape is a plot-restart tape from a previous run to be used for volume data retrieval (boundary conditions) as specified in the junction data cards for this run.

Output Tape

The output tape to be generated will be a plot-restart tape if requested by the tape control variable on the Problem Dimension Data Card.

3.9.2 Data Deck Organization

A RELAP4-EM problem consists of a title card, comment cards (optional), data cards, and a terminator card. A listing of the cards is printed at the beginning of each RELAP4-EM problem. The order of the title, data, and comment cards is unimportant except that the last title card or the last data card with a duplicate card number will be used.

When a card format error is detected, a line containing a dollar sign (\$) located under the character causing the error, and a comment giving the card column of the error is printed. An error flag is set such that input processing continues, but the RELAP4 problem is aborted at the end of input processing. Usually another error comment is produced during input processing when the program attempts to process the erroneous data.

Title Card

A title card must be entered for each RELAP4-EM problem. A title card is identified by an equal sign (=) as the first nonblank character. The title (the remainder of the title card) is printed as the second line of every page. The title card is normally placed first in the problem.

Comment Cards

An asterisk (*) or a dollar sign (\$) appearing as the first nonblank character identifies the card as a comment card. Any information may be entered on the remainder of the card. Blank cards are treated as comment cards. The only processing of comment cards is printing of contents. Comment cards may be placed anywhere in the input deck.

Data Cards

The data cards contain a varying number of fields which may be integer, floating point, or alphanumeric. Blanks preceding and following fields are ignored.

The first field on a data card is a card number which must be an unsigned integer. If the first field has an error or is not an integer, an error flag is set. Consequently, data on the card are not used and the card will be identified by the card number in the list of unused data cards. After each card number and the accompanying data are read, the card number is compared to previously entered card numbers. If a matching card number is found, the data entered on the previous card is replaced by the data on the current card. If the card being processed contains only a card number, the card number and the data entered on the previous card are deleted. If a card causes replacement or deletion of data, a statement is printed indicating that the card is a replacement card.

Comment information may follow the data fields on any data card by preceding the comment with an asterisk or dollar sign.

A number field is started by either a digit (0 through 9), a sign (+ or -), or a decimal point(.). A comma or a blank (with one exception subsequently noted) terminates the number field. The number field has a number part, and optionally, an exponent part. A number field without a decimal point or an exponent is an integer field; a number field with either a decimal point, an exponent, or both is a floating-point field. A floating-point field without a decimal point is assumed to have a decimal point immediately in front of the first digit. The exponent denotes the power of ten to be applied to the number part of the field. The exponent part has an E or D, and a sign (+ or -) followed by a number giving the power of ten. These rules for floating-point numbers are identical to those for entering data in FORTRAN E or F format fields except that no blanks (one exception) are allowed between characters. Floating point data punched by FORTRAN programs can be read. To permit reading of floating-point data, a blank following an E or D denoting an exponent is treated as a plus sign. Acceptable ways of entering floating-point numbers are illustrated by the following six fields all containing the quantity 12.45:

12.45, +12.45 1245+2 1.245+1, 1.245E1 1.245E+1

A field starting with a letter is an alphanumeric field. The field is terminated by a comma, a blank, or the end of the card. All characters except commas and blanks are allowed.

Terminator Cards

The input data for RELAP4-EM problems are separated by slash cards; the final problem is terminated by a period card instead of a slash card. The period card also serves as the separator between problem sets. The slash and period cards have a (/) and (.), respectively, as the first nonblank character. Comments may follow the slash and period on the slash and period cards.

When a slash card is used as a terminator, the list of card numbers and associated data used in a problem is passed to the next problem. Cards entered for the next problem are added to the passed list or act as replacement cards depending on the card number. The resulting input is the same as if all previous slash cards were removed from the input to the problem set.

When a period card is used as a terminator, all previous input cards are erased before the input to the next problem is processed.

The ability to execute multiple problems and sets of input data is limited by magnetic tape usage. Only one of the problems can use restart capability if the restart file has multiple reels, and only one of the problems can generate a tape. Because of the limitations and the length of RELAP4 runs, the multiple problem and set capability will probably be of use only for input data checking.

3.9.3 Data Card Summary

In the following description of the data cards, the card number is given along with a descriptive title of the data contained on the card. Next is given an explanation of any variable data (such as volume number) which is included in the card number. Then, the order of the data (W1, W2, ...), the format (I, R, or A), the variable name, and the input data requirements are given where applicable. The format of the field, integer, real or floating, or alphanumeric is indicated by I, R, or A, respectively.

1. Title Card

The last title card entered for each case must have at least one nonblank character in Columns 1-72.

2. Problem Dimensions Data Card 010001

W1-I LDMP = Tape control (only one tape may be generated during a job)
 0 = no tape used
 -1 = store restart information on FORTRAN Unit 4
 -2 = store restart and plot information on FORTRAN Unit 4
 -3 = edit the tape on FORTRAN Unit 3
 N = restart at restart number N using the tape on FORTRAN Unit 3 (-3<LDMP<999)

W2-I NEDI = Number of minor edit variables desired
 (0<NEDI<9)

W3-I NTC = Time step card count
 (1<NTRP<20)

W4-I NTRP = Number of trip control cards
 (1<NTRP<20)

W5-I NVOL = Number of control volumes
 (1<NVOL<75)

- W6-I NBUB = Number of bubble-parameter sets.
A set may be used in several volumes.
(0<NBUB<5)
- W7-I NBDY = Number of time-dependent volume descriptions on cards
(0<NBDY<10)
- W8-I NJUN = Number of junctions or flow paths
(1<NJUN<100)
- W9-I NPMC = Number of pumps
(0<NPMC<12)
- W10-I NCKV = Number of check valve types. A parameter set may
be used for several junctions.
(0<NCKV<10)
- W11-I NLK = Number of normalized-leak-area versus time curves.
May be used many times.
(0<NLK<5)
- W12-I NFLL = Number of fill system curves. May be used many
times.
(0<NFLL<5)
- W13-I NSLB = Number of heat slabs
(0<NSLB<50)
- W14-I NGOM = Number of heat slab geometries
(M<NGOM<20)

For NSLB>0, M=1; for NSLB=0, M=0.
- W15-I NMAT = Number of heat slab materials
(M<NMAT<7)
- W16-I NCCR = Number of core sections
(0<NCCR<25)

If NSLB = 0, NCCR=0.
- W17-I NHTX = Number of data sets for heat exchangers without
conduction
(0<NHTX<20)

W18-I ISPROG = Program Option Flag.
 0 = RELAP4 with minimum controls
 1 = RELAP4-EM (option required by AEC acceptance
 criteria)
 2 = RELAP4-FLOOD

3. Problem Constants Data Card 010002

W1-R POWER = Initial power (megawatts)

W2-R OMEGA = Implicit-explicit proportion multiplier (dimensionless),

$0 < \text{OMEGA} < 1$

= 1.0, implicit

= 0.0, explicit

= 0.5, Crank Nicolson

4. Program Options Card 010003

This card is optional. The use of ISPROG = 1 on card 010001 requires the variables IEMHT, IEMPS, and IEMEC to be set to 1 if this card is used. If ISPROG = 1 and this card is not input, the program will set IEMHT, IEMPS, and IEMEC to 1.

W1-I IPROGM = Program Type.
 This variable is ignored unless ISPROG = 0 on card 010001.
 0 = RELAP4 type of problem
 1 = Nonstandard RELAP4-EM type of problem
 (This option does not meet the AEC Evaluation Model acceptance criteria.)

W2-I IEMHT = EM heat transfer logic flag.
 0 = do not use EM heat transfer logic
 1 = use EM heat transfer logic.

W3-I IEMPS = EM pin swelling and flow blockage flag.
 0 = do not include EM pin swelling and flow blockage.
 1 = include EM pin swelling and flow blockage.

W4-I IEMEC = EM ECC bypass logic flag.
 0 = do not include EM bypass logic
 1 = include EM bypass logic.

5. Edit Variable Data Card 020000

An Edit Variable Data card is required if NEDI (on Card 010001) is greater than zero. This card specifies the variables to be edited in the minor edits. NEDI specifications must be entered. Each specification consists of an alphanumeric entry and an integer entry as follows:

W1-A Variable symbol

W2-I Region number

Symbols of available minor edit variables

Symbol Variable (with reference to volume)*

AP	Average pressure
TM	Total mass
TE	Total energy
AT	Average temperature
AR	Average density
AH	Average enthalpy
AX	Average quality
BM	Bubble mass
ML	Mixture level
VF	Specific volume of saturated liquid
VG	Specific volume of saturated gas

* (For these variables, W2 is the volume number, $1 < W2 < 75$)

HF	Specific enthalpy of saturated liquid
HG	Specific enthalpy of saturated gas
TS	Saturation temperature
PS	Saturation pressure
WM	Liquid mass
WQ	Power into coolant
PR	Pump speed
PT	Normalized hydraulic pump torque

<u>Symbol</u>	<u>Variable (with reference to junctions)*</u>
JW	Junction flow
JH	Junction enthalpy
JX	Junction quality
TD	Total pressure differential
FD	Pressure differential due to friction
ED	Pressure differential due to elevation
PD	Pressure differential due to pump
AD	Pressure differential due to acceleration
JV	Junction specific volume
JC	Junction choking index

* (For these variables, W2 is the junction number, $1 < W2 < 100$)

<u>Symbol</u>	<u>Variable (with reference to heat slabs)*</u>
SL	Left surface temperature
SR	Right surface temperature
CL	Left heat transfer coefficient
CR	Right heat transfer coefficient
FL	Left heat flux
FR	Right heat flux
WL	Left heat transfer rate to coolant
WR	Right heat transfer rate to coolant
KL	Left heat transfer mode
KR	Right heat transfer mode
DL	Left critical heat flux
DR	Right critical heat flux
ST	Average slab temperature
SQ	Slab fuel power
DM	Depth of metal water reaction

* (For these variables, W2 is the heat slab number $1 < W2 < 50$)

<u>Symbol</u>	<u>Variable (with reference to the system)*</u>
NQ	Normalized power
AE	Total energy added during transient
FE	Energy stored in fuel
LE	Total energy leaked
HE	Energy removed by heat exchanger
EB	Energy balance term
LM	Total mass leaked
MB	Mass balance
TR	Total reactivity
RV	Reactivity due to coolant voids
RW	Reactivity due to temperature changes in coolant
RF	Reactivity due to temperature changes in fuel
RC	Reactivity due to control rod changes
RD	Reactivity due to Doppler effect (fuel temperature)
PO	Power
HL	Total heat removed
RP	Reactor period

* (These variables are system variables, W2=0)

6. Time Step Data Cards 03XXX0

NTC (on Card 010001) cards must be entered with XXX=001, 002, ..., NTC.

W1-I NMIN = Number of time steps per minor edit and number of
time steps per plot tape edit (0 is interpreted as 1)

W2-I NMAJ = Number of minor edits per major edit (0 is interpreted
as 50)

- W3-I NDMP = Number of major edits per restart tape edit (0 is interpreted as 20)
- W4-I NCHK = Option for time step control
 = -1, time step control on nonlinear conditions only
 = 0, time step control on linear and nonlinear conditions
 = 1, no time step control
- W5-R DELTM = Maximum time step size (sec)
 (0<DELTM)
- W6-R DTMIN = Minimum sub-time-step size when under time step control (0<DTMIN<DELTM) for NCHK=1, DTMIN must be C.O.
- W7-R TLAST = End of current time step data.
7. Detailed Edit Card 030002. This card is optional.
- W1-I IEVERY(1) = Detailed edit control
- W2-I IEVERY(2) = 0, no effect on the printed output for the time step indicated by the index, I, of IEVERY(I), where "I" refers back to the XXX of cards 03XXX0.
 = 1, a major edit will be obtained for every actual time step for the time-step card indicated by the index, I.
- WNTC-I IEVERY(NTC) Caution: The use of this option may result in up to DELTM/DTMIN times as much printed output as requesting a major edit every standard time step.
8. Trip Control Data Cards 04XXX0
- NTRP (on Card 010001) cards must be entered with XXX=001, 002, ..., NTRP.
- W1-I IDTRP = Action to be taken (1<IDTRP<20)
 (1 = End of problem, required for first card)
 IDTRP corresponds to entry on pertinent card elsewhere in input where trip action is desired.

W2-I	IDSIG = Signal being compared (1<IDSIG<10)	Trip Limit
	1 = Elapsed time	+HIGH, --HIGH
	2 = Normalized reactor power	+HIGH, --LOW
	3 = Reactor period	+HIGH, --LOW
	4 = Pressure (Vol IX1)	+HIGH, --LOW
	5 = Mixture level (Vol IX1)	+HIGH, --LOW
	6 = Liquid level (Vol IX1)	+HIGH, --LOW
	7 = Water temperature (Core Vol IX1)	+HIGH, --LOW
	8 = Metal temperature (Core Vol IX1)	+HIGH, --LOW
	9 = Flow (Junction IX1)	+HIGH, --LOW
	10 = Cladding surface temperature (Core Vol IX1)	+HIGH, --LOW
W3-I	IX1 = Volume or junction index (1<IX1<NCOR for IDSIG = 8 or 10) (1<IX1<NVOL for IDSIG = 4, 5, 6, or 7) (1<IX1<NJUN for IDSIG = 9)	
W4-I	IX2 = Optional volume If IX2 > 0 a ΔP or ΔT test is used (for IDSIG = 4, -4, 7, -7)	
W5-R	SETPT = Signal setpoint	
W6-R	DELAY = Delay time for initiation of action after reaching setpoint (sec)	

On the first trip card, a requirement is that IDTRP = IDSIG = 1.

9. Volume Data Cards 05XXXXY

NVOL (on Card 010001) sets of cards must be entered with XXX = 001, 002, ..., NVOL. Y is card sequence number for each set, starting at 1, and must be consecutive. The following items may be entered on up to nine cards.

W1-I IBUB = Bubble data index
(0<IBUB<NBUB)

W2-E	IRFAC	Volume data retrieval index = 0, no retrieval <, use the data pertaining to volume IRFAC stored on the plot-merest tape of a previous run. >, use set IRFAC of the time-dependent volume conditions
W3-E	P	Pressure (0.0 < P < 20.0) (psia)
W4-E	TEMP	Temperature (32.0 < TEMP < 327) (°F) (TEMP-0.0 used as logic control)
W5-E	HORE	Quality or relative humidity (dimensionless)
W6-E	V	Volume (ft ³) (0. < V)
W7-E	ZVOL	Volume height, bottom to top (ft) (0. < ZVOL)
W8-E	ZM	Mixture level (from bottom) (ft) (0. < ZM < ZVOL)
W9-E	JMPH7	Two-phase friction index = 0, use two-phase friction multiplier with Fanning friction losses = 1, no two-phase multiplier in Fanning type of friction losses
W10-E	FLOWA	Flow area of volume (ft ²)
W11-E	DIAMF	Equivalent diameter of flow area (ft) (For Fanning friction calculation only)
W12-E	ZBOT	Elevation at the bottom of the volume (ft)

10. Liquid Level Volume Calculation Card 060000

W1-I	ILVC(1)	Indices for the volumes over which liquid masses are to be summed to determine the equivalent liquid level. The bottom of the first volume is used as the reference elevation for the equivalent liquid level. A maximum of 20 volumes is allowed.
W2-I	ILVC(2)	
.		
.		
WN-I	ILVC(N)	

11. Bubble Data Cards 06XXX1

NBUB (on Card 010001) cards must be entered with XXX=001, 002, ..., NBUB.

W1-R ALPH = Bubble-gradient parameter
($0. < \text{ALPH} < 1.0$)

W2-R VBUB = Bubble velocity (ft/sec)
($0. < \text{VBUB}$)

Set Number 0 (ALPH=0., VBUB=0.) is built-in

12. Time-Dependent Volume Data Cards (07XXYY)

NTDV (from card 010001) sets of cards must be entered with the set number XX = 01, 02, ..., NTVD. Data points may be entered on cards ordered by YY, $00 \leq \text{YY} \leq 99$. YY need not be consecutive.

A data point consists of time, pressure, temperature, mixture quality, and mixture level. The first entry for a set is the number of data points (IRIN) contained in the set. Since the first data point (TIME = 0) has been read from the normal volume data, only IRIN-1 data points are entered in a set. An IRIN value of either 0 or 1 may be used to specify that the initial conditions of the volume are used throughout the transient. For a positive mixture quality, the pressure will be used if positive and the temperature ignored. Pressure, temperature, and zero quality should be used for subcooled liquid.

W1-I IRIN = Number of data points in the set
 (0 \leq IRIN \leq 20)

 W2-R TIMTBL(2) = Time (sec)

 W3-R PTABL(2) = Pressure (psia)

 W4-R TTABL(2) = Temperature ($^{\circ}$ F)

 W5-R XTABL(2) = Quality of mixture

 W6-R ZTABL(2) = Mixture level (from bottom of
 volume)(ft)

 W7-R,... TIMTBL(3), PTABL(3), TTABL(3), XTABL(3), ZTABL(3),
 W11-R,... ...

13. Flow Smoothing Data Card 080001 through 080009

This card is used with flow smoothing option.

W1-R TAU(1) = TAU(sec), where TAU(1) \geq 0
 W2-R WFUN(1) = Weighting function value at TAU(1)
 W3-R TAU(2) =
 W4-R WFUN(2) =
 .
 .
 .
 Up to 20 points (40 entries)*

14. Junction Data Cards 08XXXXY

NJUN (on Card 010001) sets of cards must be entered with XXX=001,
 002, ..., NJUN. The items listed below may be entered on up to
 nine cards. Y is a card sequence number for each set, starting
 at 1, and must be consecutive. All normal junctions must precede
 the leak and fill junctions when the junction data are input.

*A point in a table consists of one value for the independent variable and one value for each of the dependent variables.

- W1-I IW1 = Volume index at junction inlet
($0 \leq IW1 \leq NVOL$)
- W2-I IW2 = Volume index at junction exit
($0 \leq IW2 \leq NVOL$)
- W3-I IPUMP = (a) ($IW1 > 0, IW2 > 0$) Pump Index
($1 \leq IPUMP \leq NPUMPC$, and each IPUMP is unique). "Normal" junctions must precede leak and fill junctions.
(b) ($IW1 > 0, IW2 = 0$) Leak Index
($1 < IPUMP < NLK$)
(c) ($IW1 = 0, IW2 > 0$) Fill Index
($1 < IPUMP < NFLL$)

For the junctions connecting to the pump volume, the suction side junction should have a negative pump number and the discharge junction should have a positive pump number (IPUMP on the junction card). Flow in these junctions must be positive initially.

- W4-I IVALVE = Valve index
($0 < IVALVE < NCKV$)
(a) $IVALVE = 0$, No valve
(b) $1 < IVALVE < NCKV$, check valve
(c) $0 > IVALVE$, Negative of old junction number used in flow smoothing.
- W5-R WP = Flow (lb/sec)
- W6-R AJUN = Junction flow area in square feet and must be greater than zero. For a leak, AJUN is the full leak area.
- W7-R ZJUN = Junction elevation (ft)
- (a) $IW1 > 0, IW2 > 0$ the ZJUN must lie between the bottom and top of both volumes IW1 and IW2
- (b) $IW1 > 0, IW2 = 0$ the ZJUN must lie between the bottom and top of volume IW1
- (c) $IW1 = 0, IW2 > 0$ the ZJUN must lie between the bottom and top of volume IW2

W8-R INERTA = Junction effective $L/A(\text{ft}^{-1})$

(a) $IW1 > 0$, $IW2 > 0$
 INERTA > 0

(b) $IW1 \leq 0$ or $IW2 \leq 0$
 INERTA > 0

INERTA is calculated by the program if the input value is zero and JCALCI=2. The calculated value is one-half of the length of each adjacent volume divided by the volume flow area where volume length is V/FLOWA .

W9-R FJUNF = Forward flow "form loss coefficient."

This is either a dimensionless positive number dependent on geometric changes occurring within the flow control volume or zero. It is the standard head loss coefficient, as normally used in text books. The head loss is:

$$K \frac{v^2}{2}$$

where FJUNF is K, and the velocity, v, is based on the junction area.

W10-R FJUNR = Reverse flow "form-loss-coefficient."
 If FJUNR is entered as zero and FJUNF is nonzero, the FJUNR is set equal to FJUNF.

W11-I JVERTL = Vertical junction index

0 = Junction flow area is not distributed vertically and junction enthalpy is "smoothed" when the two-phase mixture interface is near the junction elevation

1 = Junction flow area is assumed to be a circular area centered and distributed vertically about ZJUN

2 = No bubble smoothing, junction flow area not distributed vertically

W12-I JCHOKE = Junction choking index

-1 = No choking

0 = Table choking or sonic choking as determined by code

1 = Table choking only (If MVMIX is #3, this flow solution corresponds to incompressible flow with Bernoulli effects)

2 = Sonic choking only

W13-I JCALCI = Initial condition calculation index

0 = Use input for inertia and form loss coefficients as given by user

1 = Calculate form loss coefficients (FJUNF and FJUNR) (for sharp-edge area changes)

+2 = Calculate inertias

+3 = Calculate both form loss coefficients and inertias

>3 = Frictionless junction except in mixed streams

W14-I MVMIX = Momentum Equation Type

0 = Compressible mechanical energy balance equation, single stream

1 = Mixed two-stream compressible mechanical energy balance flow equation in the volume "from" side

2 = Mixed two-stream compressible mechanical energy balance flow equation in the volume "to" side

3 = Incompressible mechanical energy balance equation with no momentum flux (no Bernoulli effects)

4 = Compressible integral momentum equation,
single stream

-2 = Special case of a fill with negative flow
used to represent the outlet junction

W15-R DIAMJ = Junction diameter

If $DIAMJ < 0.0$, the program will calculate
DIAMJ as $2\sqrt{AJUN/\pi}$, (used for junction
quality calculations)

W16-R CONCO = Contraction coefficient for leak (0. is
interpreted as 1.)

W17-I ICHOKE = Junction choking index to control table choking

0 = Table type choking will not be used in the
subcooled (liquid phase) region, i.e., Moody
or Henry data will not be used.

+1 = Use Moody table choking in the saturated region.

+2 = Use Henry table choking in the saturated region.

+3 = Use maximum value of Moody or Henry choking
in the saturated region.

+4 = Use minimum value of Moody or Henry choking
in the saturated region.

Notes:

In all cases above:

- a. If $ICHOKE > 0$, the flow in the subcooled region
will be the minimum of the specified table
choking and the momentum solution.
- b. If $ICHOKE < 0$, table choking will be used in
the saturated region only.
- c. By adding 10 to the absolute value of each of
the options above, the flow in the subcooled
region will be the minimum flow as determined

using either the Henry extended tables or a momentum solution. Also, sonic choking will not be allowed. Choking in the saturated region will be controlled by $|ICHOKE| \sim 10$.

If $|ICHOKE| \geq 10$, the negative option has no meaning and should not be used.

- d. If $JCHOKE = -1$ or 2 , $ICHOKE$ will be ignored.
- e. If $JCHOKE = 0$ or 1 , $ICHOKE \neq 0$.
- f. $JCHOKE = 0$ and $ICHOKE = 1$ is the Evaluation Model option.

W3-I INQOR = Machalpy transport index

0 = Both sides off

1 = Inlet side on, outlet side off

2 = Outlet side on, inlet side off

3 = Both sides on

15. Pump Curve Input Indicator Data Card 10000

This card is entered if NPMPG (on Card 010001) is greater than zero.

W1-I NC(1) = Numbers of pump curves to be read into curve Sets 1, 2, 3, and 4, respectively. If any pump used the two-phase option, single-phase minus two-phase difference curves should be read into Set 4. (For each set, $0 < NC < 16$.)

W4-I NG(4)

16. Pump Description Data Cards 090XXY

NPMPG (on Card 010001) sets of cards must be entered with XX =

01, 02, ..., NPMPG. The items subsequently listed may be entered

on one or two cards. Y is a card sequence number for each set,

Y = 1 for the first card and 2 for the second card, if used.

W1-1	IPG	* Curve set. If any pump uses the two-phase option, this is regarded as single-phase minus two-phase difference curves. ($1 \leq IPG \leq 4$)
W1-2	INITPR	* Index number to start pump off ($1 \leq INITPR \leq 20$)
W1-3	IMP	* Increase indication 0 = No increase allowed 1 = Increase allowed
W1-4	INA	* Index for two-phase option 0 = No two-phase option 1 = Two-phase option
W1-5	IMP	* Index for pump motor torque curve 0 = No curve 1 = Curve 1 2 = Curve 2
W1-6	FWGSA	* Rated speed (rev/min)
W1-7	PSRAT	* Pump speed ratio of initial speed-to-rated speed
W1-8	FFLOWR	* Rated flow (gal/min)
W1-9	PHEADR	* Rated head (ft)
W1-10	PTOWER	* Rated torque (lb_f-ft)
W1-11	PIINIA	* Moment of inertia (lb_m-ft^2)
W1-12	VNHON	* Rated density (lb_m/ft^3) If VNHON = 0, initial density is used
W1-13	TOMEX	* Frictional torque (lb_f-ft)
W1-14	TOMKWR	* Rated pump motor torque (lb_f-ft)

If $TORKMR = 0$, it is set to the sum of the frictional torque ($TORKF$) and the hydraulic torque at time $t = 0$.

17. Pump Head Multiplier Data Cards 0910YY

This curve is read if any IPM (on Cards 090XXY) equals unity. YY is a card sequence number, $00 \leq YY \leq 99$. The cards are ordered by YY, but YY need not start at 00 and need not be consecutive to facilitate additions or deletions from the table.

W1-I NPHM = Number of points on curve
 $(1 \leq |NPHM| \leq 20)$
 Positive value indicates no extrapolation,
 negative value permits extrapolation.

W2-R PHDM(1) = Void fraction

W3-R PHDM(2) = Head multiplier for difference curves in Set 4.

W4-R, PHDM(3),
 W5-R, PHDM(4),
 until NPHM points are entered (NPHM x 2 entries).
 Void fraction must be in ascending sequence.
 Normally, both void fraction and multiplier will
 range from 0.0 to 1.0.

18. Pump Torque Multiplier Data Cards 0920YY

This curve is also read if any IPM (on cards 090XXY) equals unity. YY is a card sequence number, the same as with cards 0910YY.

W1-I NPTM = Number of points on curve
 $(1 \leq |NPTM| \leq 20)$
 A negative value here also indicates that
 extrapolation is permitted.

W2-R PTKM(1) = Void fraction

W3-R PTKM(2) = Torque multiplier for difference curves in Set 4.

W4-R, PTKM(3),
 W5-R, PTKM(4),
 until NPTM points are entered (2xNPTM entries).
 Void fraction must be in ascending sequence.

19. Pump Stop Data Card 095XX1

This card must be present for each pump to which this option applies, where XX is the pump number between 01 and 12. Once any of the conditions below are met, the pump speed is set to 0.

W1-R CAVCON = Elapsed time (sec)
 <0.0, option not used
 >0.0, option used

W2-R FPUMP = Maximum forward speed (RPM)
 = 0.0, option not used
 ≠ 0.0, option used

W3-R SPUMP = Maximum reverse speed (RPM)
 = 0.0, option not used
 ≠ 0.0, option used
 (Note: Normally this number is negative.)

20. Pump Motor Torque Data Card 0970XY

X, $1 \leq X \leq 2$, indicates the curve number. Curve 09701Y is read if any IMT (on cards 090XXY) equals 1; curve 09702Y is read if any IMT = 2. Y is a card sequence number, $1 \leq Y \leq 9$.

W1-I NTMO = Number of points on curve
 ($1 \leq |NTMO| \leq 20$)
 A negative value indicates that extrapolation
 is permitted.

W2-R PTMO(1) = Pump speed (RPM)

W3-R PTMO(2) = Motor torque, normalized

W4-R PTMO(3)

W5-R PTMO(4)

... .. until NTMO points ($2 \times \text{NTMO}$ entries) are entered.
Speed must be in ascending sequence.

21. Pump Head and Torque Data Cards 10XYYZ

X, $1 \leq X \leq 4$, indicates the curve set number. NC (from Card 100000) total curves must be read for each set X. YY indicates the curve number, with YY = 01, 02, ..., NC. Z, $0 \leq Z \leq 9$, is the card sequence number for each curve. The cards are ordered by Z, but Z need not start at 0 and need not be consecutive. An arbitrary number of items may be entered on each card. At least one table pair must be entered. Any single-phase minus two-phase difference curves should be read into Set 4.

Curves for the following pumps are already built in:

Curve Set 1 - Bingham Pump Company pump, $N_S = 4200$

Curve Set 2 - Westinghouse Electric Corporation pump, $N_S = 5200$

W1-I IT = Head or torque indicator
1 = head
2 = torque

W2-I IC = Curve type
($1 \leq IC \leq 8$)

W3-I N = Number of data points
($1 \leq |N| \leq 20$)
Positive value indicates no extrapolation;
negative value permits extrapolation.

W4-R PHEAD(1)
or PTORK(1) = Independent Variable 1 (v/a for IC odd;
 a/v for IC even)

W5-R PHEAD(2)
or PTORK(2) = Dependent Variable 1 (h/a^2 or β/a^2 for IC odd;
 h/v^2 or β/v^2 for IC even)

W6-R, Independent Variable 2 and Dependent Variable 2,
 W7-R ..., until N pairs are entered, where Independent
 ... Variable $j < \text{Independent Variable } j+1$.
 v , h , a , and β are ratios of performance parameters
 to the rated parameters, where v = flow ratio,
 h = head ratio, a = speed ratio, and β = torque ratio.

22. Valve Data Cards 11XXX0

NCKV (on Card 010001) cards must be entered with XXX = 001, 002,
 ..., NCKV. The data on the card are interpreted according to the
 type of valve being described.

W1-I ITCV = Type of check valve
 -1 = inertial valve
 0 = Type 0 check valve
 1 = Type 1 check valve
 $-20 \leq \text{ITCV} \leq -2$ = a closed valve
 to open under control of trip ID = $|\text{ITCV}|$.
 $2 \leq \text{ITCV} \leq 20$ = an open valve to close
 under control of trip ID = ITCV.

W2-I IACV = Number of area-versus-angle table in the
 leak table data if ITCV = -1
 = Number of area-versus-time table in leak
 table data if $|\text{ITCV}| \geq 2$
 = 0 otherwise.

W3-R PCV = Back pressure for closure (psia)

W4-R CVI = Forward flow friction coefficient
 ITCV \neq -1 (dimensionless)
 Area moment arm ITCV = -1 (ft^3)

W5-R CV2 = Reverse flow friction coefficient valve
 open ITCV \neq -1 (dimensionless)
 Moment of Inertia ITCV = -1 (lb_m/ft^2)

W6-R CV3 = Reverse flow friction coefficient valve
 closed ITCV \neq -1 (dimensionless)
 Damping constant ITCV = -1.

23. Leak Table Data Cards 12XXYY

NLK (on Card 010001) sets of cards must be entered with XX=01,
 02, ..., NLK. YY is a card sequence number for each set, $00 \leq \text{YY} \leq 99$;

the cards are ordered by YY, but YY need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card. At least one table pair must be entered.

W1-I NAREA = Number of data points
 (1 \leq |NAREA| \leq 20)
 Positive value indicates no extrapolation;
 negative value permits extrapolation.

W2-I ITLEAK = Trip signal number to open leak
 (2 \leq ITLEAK \leq 20)

W3-R SINK = Sink pressure (psia)

W4-R TAREA(1)= Time (sec)

W5-R TAREA(2)= Leak area normalized to full open area AJUN

W6-R, TAREA(3), until NAREA points (2xNAREA entries) are
 W7-R, TAREA(4), entered, where the time values are in
 ascending order.

24. Fill Table Data Cards 13XXYY

NFLL (on Card 010001) sets of cards must be entered with XX = 01, 02, ..., NFLL. YY is a card sequence number for each set, 00 \leq YY \leq 99; the cards are ordered by YY, but YY need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card. At least one table pair must be entered.

W1-I NFILL = Number of data points
 (1 < |NFILL| < 20)
 Positive value indicates no extrapolation;
 negative value permits extrapolation.

W2-I ITFILL = Trip signal to start
 (2 \leq ITFILL \leq 20)

W3-I IX = Independent variable
 IX = 0, time
 IX > 0, pressure ($P_{vol} + P_{grav}$) (psia)
 IX < 0, differential pressure
 ($P_{vol} + P_{grav} - P_{fill}$) (psia)

W4-I IY = Flow type
 IY \leq 0, flow in $lb_m/sec-ft^2$
 IY > 0, flow in gpm/ft^2

W5-R PORX = Pressure or quality in fill reservoir
 PORX = 0, saturated liquid
 0 < PORX < 1, mixture quality
 PORX = 1, saturated vapor
 PORX > 1, pressure (psi)

W6-R TEMP = Temperature ($^{\circ}F$)

W7-R FILTBL(1) = Time or pressure (sec or psia)

W8-R FILTBL(2) = Flow ($lb_m/sec-ft^2$ or gpm/ft^2)
 This flow is multiplied by junction area if nonzero.

W9-R FILTBL(3), until NFILL points are entered,
 W10-R FILTBL(4) where the time or pressure values are in
 ascending order.

25. Kinetics Constants Data Card 140000

This card is required if NCOR (on Card 010001) is greater than zero.

W1-I NODEL = Power calculation indicator

- 1 = Retrieve data from FORTRAN Unit 2
- 0 = Explicit power versus time
- 1 = One prompt neutron group plus six groups of delayed neutrons
- 2 = Same as 1 above plus eleven delayed gamma emitters
- 3 = Same as 2 above plus U-239 and Np-239.

W2-I KMUL = Multiplying factor for decay energy
 0 = Use ANS decay energy release rates
 0 \neq Multiply ANS rates by 1.2.

W3-R BCWL = β/Λ , the effective delayed neutron fraction over mean lifetime (sec^{-1})
 W4-R RHOIN = Initial reactivity (β)
 W5-R UDUF = U-238 atoms consumed per U-235 atoms fissioned. The default value is 1.0. The yield fractions for U-238 and Pu-239 are multiplied by UDUF.

26. Reactivity Coefficient Data Cards 140XX0

NCOR (on Card 010001) sets of cards are required if NOBEL (on Card 140000) is greater than zero with XX = 01, 02, ..., NCOR.

W1-R DENWT = Density weighting factor
 W2-R FTWT = Fuel temperature weighting factor
 W3-R ALPHTM = Fuel temperature coefficient ($\beta/^\circ\text{F}$)
 W4-R ALPHTW = Water temperature coefficient ($\beta/^\circ\text{F}$).

27. Scram Table Data Cards 1410XX

This set of cards is required if NCOR (on Card 010001) is greater than zero and NOBEL (on Card 140000) is zero or positive. XX, $00 \leq XX \leq 99$, is the card sequence number for the set; the cards are ordered by XX, but XX need not start at 00 and need not be consecutive.

W1-I NSCR = Number of data points
 $(|NSCR| \leq 20)$
 Positive value indicates no extrapolation;
 negative value permits extrapolation
 NSCR = 1, a constant value
 W2-I ITSCRM = Trip number for scram
 $(2 \leq ITSCRM \leq 20)$
 W3-R TSCR(1) = Time (sec)
 W4-R TSCR(2) = Reactivity or normalized power
 (β or dimensionless)
 W5-R, TSCR(3), until NSCR points are entered, where
 W6-R, TSCR(4), time values are in ascending order

28. Density Reactivity Table Data Cards 1420XX

This set of cards is required if NCOR (on Card 010001) and NOBEL (on Card 140000) are both greater than zero. XX, $00 \leq XX \leq 99$, is the card sequence number for the set; the cards are ordered by XX, but XX need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card.

W1-I NDEN = Number of data points
 ($|NDEN| \leq 20$)
 Positive value indicates no extrapolation;
 negative value permits extrapolation
 NDEN = 1, a constant value
 NDEN = 0, always zero

W2-R VOIDRO(1) = Density normalized to beginning value

W3-R VOIDRO(2) = Reactivity (\$)

W4-R, VOIDRO(3), until NDEN points are entered,
 W5-R, VOIDRO(4), density values in ascending
 order

29. Doppler Table Data Cards 1430XX

This set of cards is required if NCOR (on Card 010001) and NOBEL (on Card 140000) are both greater than zero. XX, $00 \leq XX \leq 99$, is the card sequence number for the set; the cards are ordered by XX, but XX need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card.

W1-I NDOP = Number of data points
 ($|NDOP| \leq 20$)
 Positive value indicates no extrapolation;
 negative value permits extrapolation
 NDOP = 1, a constant value
 NDOP = 0, always zero

W2-R DOPRO(1) = Temperature ($^{\circ}$ F)

W3-R DOPRO(2) = Reactivity (\$)

W4-R, DOPRO(3), until NDOP points are entered, where
 W5-R, DOPRO(4), temperature values are in ascending
 order

30. Heat Slab Data Cards 15XXX1

A zero value for either IVSL or IVSR means that the slab surface does not conduct heat. A -1 value for either IVSL or IVSR means that the slab is being used as a heat exchanger with constant sink conditions on the -1 side. For this case, two more input quantities are needed: a constant heat transfer coefficient and a removal fraction of the total power initially generated. The user can also model a heat exchanger slab using volumes on both sides of the slab. At least one of the quantities IVSL or IVSR must be greater than zero. If a heat slab is a core section, IVSL must be zero.

NSLB (on Card 010001) cards must be entered with XXX = 001, 002, ..., NSLB.

W1-I	IVSL	= Index number of volume at left slab surface (-1 ≤ IVSL ≤ NVOL)
W2-I	IVSR	= Index number of volume at right slab surface (-1 ≤ IVSR ≤ NVOL)
W3-I	IGOM	= Geometry index (1 < IGOM < NGOM)
W4-I	ISB	= Stack indicator 0 means that this slab is at the bottom of a stack. 1 means that this slab is stacked on top of the slab described by the previous card.

- W5-I IMCL = Indicator for flow film boiling heat transfer correlation at left surface.
 0 - use Groeneveld 5.9
 1 - use Groeneveld 5.7
 2 - use Dougall Rohsenow
 1X - use G.E. CHF Correlation (ten's place digit = 1)
- W6-I IMCR = Indicator for flow film boiling heat transfer correlation at right surface.
 Same as IMCL above.
- W7-R ASUL = Heat transfer area at left surface (ft²)
 ASUL = 0 if IVSL = 0
 ASUL > 0 if IVSL = 0
- W8-R ASUR = Heat transfer area at right surface (ft²)
 ASUR = 0 if IVSR = 0
 ASUR > 0 if IVSR ≠ 0
- W9-R VOLS = Total volume of slab (ft³)
 0 < VOLS
- W10-R HDML = Left side hydraulic diameter (ft)
 HDML ≥ 0. If HDML = 0 and IVSL > 0,
 HDML will be set equal to DIAMV
 (on Card 05XXXY) for volume IVSL.
- W11-R HDMR = Right side hydraulic diameter (ft)
 HDMR ≥ 0. If HDMR = 0 and IVSR > 0,
 HDMR will be set equal to DIAMV (on
 Card 05XXXY) for volume IVSR.
- W12-R DHEL = Left side heated equivalent diameter (ft)
 DHEL ≥ 0. If DHEL = 0 and IVSL > 0,
 DHEL will be set equal to HDML.
- W13-R DHER = Right side heated equivalent diameter (ft)
 DHER ≥ 0. If DHER = 0 and IVSR > 0,
 DHER will be set equal to HDMR.
- W14-R CHNL = Actual channel length on left side (ft)
 If CHNL = 0 and IVSL > 0, CHNL will be
 set equal to ZVOL (on card 05XXXY) for
 volume IVSL.

If CHNL < 0, the minus sign is used only as a flag calling for the following GE CHF correlations:

$$q_{CHF} = 10^6 (0.8-X) \text{ for } G \geq .5 \times 10^6 \frac{\text{lb}}{\text{ft}^2\text{-hr}}$$

$$q_{CHF} = 10^6 (0.84-X) \text{ for } G < .5 \times 10^6 \frac{\text{lb}}{\text{ft}^2\text{-hr}}$$

$$\text{but } q_{CHF} \geq 90,000 \frac{\text{Btu}}{\text{ft}^2\text{-hr}} \text{ regardless}$$

W15-R CHNR = Actual channel length on right side (ft)
 If CHNR = 0 and IVSR > 0, CHNR will be set
 equal to ZVOL (on card 05XXXY) for volume
 IVSR. If CHNR < 0, same as for CHNL above.

The following 2 quantities are required only if IVSL or IVSR is -1:

W16-R PFR = Fraction of total power generated removed by this
 slab ($0 \leq \text{PFR} \leq 1$)

W17-R HTC = Constant heat transfer coefficient
 (Btu/ft²-hr-°F)

31. Wall Temperature Reset Cards 15XXX3

This set of cards allows the initialization of slab wall temperature to values other than those determined by initial fluid conditions. The cards must satisfy $001 \leq \text{XXX} \leq \text{NSLB}$, but any or all cards may be omitted and the order is immaterial. Either the left or right slab temperature in each pair may be set to zero, in which case the temperature of the indicated slab is not reinitialized.

W1-R TP(1,XXX) = Temperature at the left side of the slab
 (°F)

W2-R TP(NODER,XXX) = Temperature at the right side of the slab
 (°F)
 NODER is the number of nodes for slab XXX.
 Temperatures at the inner slab nodes are
 obtained by linear interpolation.

32. Core Section Data Cards 16XXX0

NCOR (on Card 010001) cards must be entered with XXX=001, 002,
 ..., NCOR.

W1-I ISLB = Slab number
(1 < ISLB < NSLB)

W2-I
W3-I NODT = Node numbers at which temperatures
W4-I are to be printed on major edits

W5-R CLTI = Initial cladding thickness (ft)
If CLTI > 0, then metal-water reaction
is calculated for this core section.
If CLTI = 0, then no metal-water reaction
is calculated for this core section.

W6-R QFRAC = Fraction of power generated in core
section; $0 \leq QFRAC \leq 1.0$ and $\sum_{i=1}^{NCOR} QFRAC_i$
should = 1.0

33. Core Section Data Cards for Evaluation Model 16XXX5*

NCOR cards must be entered with XXX = 001, 002, ..., NCOR for
IEMPS = 1.

W1-I ISLBAJ= Flag to indicate what calculations to make after
a pin swelling event
0 = Swollen radius and area will be used in
generating M/W reaction data, heat trans-
fer data and adjusting flow friction in the
adjacent junctions.
1 = Swollen radius and area will be used in
generating M/W reaction data and heat
transfer data only. Junction flow will not
be restricted. (Hot pin option)
2 = Swollen radius will be used to adjust flow
friction in adjacent junctions only.

W2-I ISWEAB Indicates which table to use in determining
percent blockage after swelling event.
0 = Read in data for multiple pins
1 = Read in data for single pin

*The information on this card is used in conjunction with the pin swelling
logic. To prevent the pin from swelling in more than one place, the pin
should be set up as a stack. (ISB=1 on card 15XXX1)

W3-R*** GSMOL = Gram-moles of gas in pin gap and plenum
 W4-R EF = Emissivity of fuel (for effective radiation conductivity)
 W5-R EC = Emissivity of clad (for effective radiation conductivity)
 W6-R FRACT = Fraction of theoretical density (for fuel porosity adjustments)
 W7-R** AFR(1)= Mole fraction of Helium
 W8-R AFR(2)= Mole fraction of Argon
 W9-R AFR(3)= Mole fraction Hydrogen
 W10-R AFR(4)= Mole fraction of Nitrogen
 W11-R AFR(5)= Mole fraction of Krypton
 W12-R AFR(6)= Mole fraction of Xenon
 W13-R HCOND = Conductance term when fuel pin gap is closed (Btu/sec-ft²-°F)
 W14-R***VPLENI= Initial plenum volume for fuel rods (ft³)

** The information in words 7 to 17 is used in determining the conductivity in the gap in the fuel pin utilizing the GAPCON method, and to determine the internal pin pressure used in the clad geometry data cards 17XXYY.

*** For GSMOL and VPLENI, only the sum of the slab values for a stack of slabs is now used in any calculations. Thus the user can distribute the stack totals within the stack slabs as he wishes. One way is to use 0.0 for both values on all core slab cards except on the card for the last slab in the stack, where the stack totals would be used. The user should also remember that a pin-type slab includes all the pins, not just one, and input GSMOL and VPLENI accordingly.

- W15-R RSHD = Radius of shoulder for axial expansion of fuel (ft)
- W16-R EPSMXR= Permanent hoop strain of cladding (dimensionless, $\frac{\Delta R}{R}$)
- W17-R EPSMXA= Permanent axial pressure strain of cladding (dimensionless, $\frac{\Delta Z}{Z}$)

34. Slab Geometry Data Cards 17XXYY

NGOM (on Card 010001) sets of cards must be entered with XX = 01, 02, ..., NGOM. One card is required for each region and YY is the region number.

For YY = 01:

- W1-I IG = Geometry type
1 = Rectangular
2 = Cylindrical
- W2-I NR = Number of regions
($1 < NR < MAXREG = 6$)
- W3-I IM = Material index
($1 < IM < NMAT$)
- W4-I NDX = Number of space steps
 $1 < NDX$ and
 $\sum_{i=j}^{NR} NDX_j < MAXNOD = 21$
- W5-R XO = Radial distance to left surface (ft)
XO=0 for a solid rod
- W6-R XR = Region width (ft)
- W7-R PF = Fraction of slab power generated in region

For YY = 02, 03, ..., NR:

- W1-I IGP = Gap indicator
0 = No gap
1 = Gap expansion model desired

Two successive region cards cannot have IGP = 1, nor can the last card in the set.

W2-I	IM	} = As for the first region card
W3-I	NDX	
W4-R	XR	
W5-P	FFF	

35. Thermal Conductivity Data Cards 18XXYY

NMAT (on Card 010001) sets of data must be entered with XX indicating the material number, XX = 01, 02, ..., NMAT. YY is the card sequence number for each set, $00 \leq YY \leq 99$; the cards are ordered by YY, but YY need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card. At least one table pair must be entered.

W1-I NKP = Number of points in thermal conductivity table ($1 < |NKP| \leq 20$). Positive value indicates no extrapolation. Negative value indicates extrapolation.
NKP=1, a constant value

W2-R TPK(1)= Temperature ($^{\circ}$ F)

W3-R TPK(2)= Thermal conductivity (Btu/ft-hr- $^{\circ}$ F)

W4-R TPK(3), until NKP points are entered,

W5-R TPK(4), temperature values are in ascending order

36. Volumetric Heat Capacity Data Cards 19XXYY

NMAT (on Card 010001) sets of data must be entered with XX indicating the material number, XX = 01, 02, ..., NMAT. YY is the card sequence number for each set, $00 < YY < 99$; the cards are ordered by YY, but YY need not start at 00 and need not be consecutive. An arbitrary number of

items can be entered on each card. At least one table pair must be entered.

W1-I NCP = Number of points in heat capacity table
 ($1 < |NCP| < 20$)
 Positive value indicates no extrapolation;
 negative value permits extrapolation NCP = 1,
 a constant value

W2-I TPC(1)= Temperature ($^{\circ}$ F)

W3-R TPC(2)= Volumetric heat capacity (Btu/ $^{\circ}$ F-ft³)

W4-R TPC(3) Until NCP points are entered, where
 W5-R TPC(4) temperature values are in ascending
 order

37. Linear Expansion Coefficient Data Cards 20XXYY

These cards are required for each material only if any heat slab specifies the gap expansion model; that is, if IGP on any Card 17XXYY is 1. NMAT (on Card 010001) sets are entered with XX indicating the material number, XX = 01, 02, ..., NMAT. YY is the card sequence number for each set, $00 < YY < 99$; the cards are ordered by YY, but YY need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card.

W1-I NXP = Number of points in linear expansion coefficient
 table ($|NXP| < 20$)
 Positive value indicates no extrapolation;
 negative value permits extrapolation
 NXP=1, a constant value

W2-R TPX(1)= Temperature ($^{\circ}$ F)

W3-R TPX(2)= Linear expansion coefficient, ($^{\circ}$ F⁻¹)

W4-R TPX(3) until NXP points are entered, where
 W5-R TPX(4) temperature values are in ascending
 order.

38. Heat Exchanger Data Cards 21XXYY

This option provides two simplified heat exchanger models; neither model has heat conduction. NHTX (on Card 010001) sets of data must be entered with XX = 01, 02, ..., NHTX. YY is the card sequence number for each set, $00 < YY < 99$; the cards are ordered by YY, but YY need not start at 00 and need not be consecutive. An arbitrary number of items may be entered on each card; and if a table is entered, at least one table pair must be entered.

W1-I IHTX = Number of data points, 0 meaning flow and temperature dependent ($IHTX=0$ or $2 < |HTX| < 20$)
Positive value indicates no extrapolation; negative value permits extrapolation.
IHTX=1, a constant value

W2-I ITHTXQ= Trip number controlling heat exchanger
($2 < ITHTXQ < 20$)

W3-I JVOL = Volume number

If IHTX = 0:

W4-R HTQ = Fraction of power removed by heat exchanger

W5-R TSEC = Secondary side temperature ($^{\circ}F$)

W6-R HTXCO = Heat exchanger coefficient
($Btu\text{-}sec/hr\text{-}^{\circ}F\text{-}lb_m$)

If HTXCO is entered as zero, then the program calculates the steady state value as $HTXCO = \text{heat removal rate}/(\text{initial flow multiplied by the temperature difference between the primary fluid and secondary fluid})$.

If initial flow is zero, the user must put in a nonzero value for HTXCO.

The program will always use the input value of HTXCO if it is nonzero.

If IHTX > 0:

W4-R HTXTBL(1)=Time (sec)

W5-R HTXTBL(2)=Normalized power

W6-R HTXTBL(3) Until IHTX points are entered, where time values

W7-R HTXTBL(4) are in ascending order

39. Blockage, Swelling, Gap Reduction Data Card 250001 (if IEMPS = 1 on Card 010003)

W1-I IRGPIN= Number of external region of fuel pellet (defaults to 1)

W2-I IRGGAP= Region in heat slab where gap is present (defaults to 2)
Note: The EM model logic assumes a gap will be present.

W3-I IRGSW = Region in heat slab where clad swelling takes place (defaults to 3)

W4-R PITCH = Pin pitch in lattice (ft)

W5-R TDELT = Temperature increment to be added to actual temperature to obtain a swelling zone (°F)

40. ECC Bypass Input Data Card 260001 (if IEMEC = 1 on Card 010003)

W1-I	IACCV(1)	} Accumulator volumes
W2-I	IACCV(2)	
W3-I	IACCV(3)	
W4-I	IACCV(4)	

W5-I	ITRIP(1)	} Trip to open accumulator valve
W6-I	ITRIP(2)	
W7-I	ITRIP(3)	
W8-I	ITRIP(4)	

W9-I IDNCMV Volume monitored for end-of-bypass

W10-I VINPUT Velocity above which end-of-bypass occurs in volume IDNCMV (ft/sec) (downward flow is assumed positive direction)

W11-I	I REMV(1)	Volumes from which injected accumulator fluid is to be subtracted at end-of-bypass. (Volumes are adjusted in order as input)
↓	↓	
W20-I	I REMV(10)	

41. Multiple Pin Clad Rupture Data Cards 270001-270099 (if IEMPS = 1 on Card 010003)

W1-I NTAB1 = Number of points in table ($0 \leq |NTAB1| \leq 25$)
 Positive value indicates no extrapolation
 Negative value permits extrapolation

W2-R TAB1(1)=Average rupture temperature

W3-R TAB1(2)=Pressure differential across clad (psia)

W4-R TAB1(3) Until NTAB1 points have been entered

W5-R TAB1(4)

etc.

42. Multiple Pin Flow Blockage Data after Rupture: Cards 280001-280099 (if IEMPS=1 on Card 010003)

W1-I NTAB2 = Number of points in table
 ($0 \leq |NTAB2| \leq 25$)
 Positive value indicates no extrapolation
 Negative value permits extrapolation

W2-R TAB2(1)=Percent blockage of flow area

W3-R TAB2(2)=Pressure differential across clad (psia)

W4-R TAB2(3) until NTAB2 points have been entered

W5-R TAB2(4)

etc.

43. Single Pin Clad Rupture Data: Cards 290001-290099 (if IEMPS = 1 on Card 010003)

W1-I NTAB3 = Number of points in table ($0 \leq |NTAB3| \leq 25$)
 Positive value indicates no extrapolation
 Negative value permits extrapolation

W2-R TAB3(1)=Average rupture temperature

W3-R TAB3(2)=Pressure differential across clad (psia)

W4-R TAB3(3) Until NTAB3 points have been entered

W5-R TAB3(4)

etc.

44. Single Pin Flow Blockage Data after Rupture: Cards 300001-300099

W1-I NTAB4 = Number of points in table
 (0<NTAB4<25)
 Positive value indicates no extrapolation
 Negative value permits extrapolation

W2-R TAB4(1) = Percent blockage of flow area

W3-R TAB4(2) = Pressure differential across clad (PSIA)
 until NTAB4 points have been entered

W4-R TAB4(3)
 W5-R TAB4(4)
 etc.

3.9.4 Input for Tape Editing

An old plot tape must be mounted on FORTRAN Unit 3. The normal RELAP4 program is used with the following input definitions

Title Card

The first 12 columns of the last title must be identical to the first 12 columns of the title card of the problem which is to be edited.

Problem Dimensions Data Card 010001

W1-I LDMP = -3

W2-I NEDI = Number of minor edit variables
 (0<NEDI<9)

W3-I NTC = Edit frequency control card count
 (1<NTC<20)

W4-I NTRP = 0

These are the only control integers required for a tape edit.

Edit Variable Data Card 020000

One card is required if NEDI (on Card 010001) > 0, and the same rules apply as for the original problem. The quantities being edited need not have any relation to those of the original run.

Edit Frequency Control Data Cards 03XXX0)

NTC (on Card 010001) cards must be entered with XXX = 001, 002, ..., NTC.

W1-I NMIN = Number of plot records per minor edit
(0 is interpreted as 1)

W2-I NMAJ = Number of minor edits per major edit
(0 is interpreted as 50)

W3-R DELTM = Time step size (sec) between plot records; if known
(0<DELTM)

W4-R TLAST = End of Current edit frequency
control data (TLAST_{i-1} <TLAST_i)

3.9.5 Input for Restarting

An old restart data tape to be used must be mounted on FORTRAN Unit 3 and a blank tape must be mounted on Unit 4. The normal RELAP4 program is used with the following input definitions.

Title Card

The first 12 columns of the last title must be identical to the first 12 columns of the title card of the problem which is to be restarted.

Problem Dimensions Data Card 010001

W1-I LDMP = N, the restart number of the old
problem where restart is to begin
(1 <LDMP<999)

W2-I NEDI = Number of minor edit variables
(0<NEDI<9)

W3-I NTC = Time step card count
(1<NTC<20)

W4-I NTRP = Number of trip control cards
(0<NTR<20)
NTRP = 0 will cause the trip control values
from the restart tape to be used.
(See 04XXX0 Cards).

Edit Variable Data Cards 020000

One card is required if NEDI < 0 (on Card 010001), and the same rules apply as for the original problem. The quantities being edited on the new run need not have any relation to those of the original run.

Time Step Data Cards 03XXX0

NTC (on Card 010001) cards must be entered with XXX = 001, 002, ..., NTC. The same rules apply as for the original problem. The time-step sequence on the new run need not have any relation to that of the old run. No cards referring to problem times previous to the point of restart will be used, but they may be inputted. A TLAST equal to the transient time at restart causes difficulties unless that TLAST value was used in the old run to be restarted.

Trip Control Data Cards 04XXX0

NTRP (on Card 010001) cards must be entered with XXX = 001; 002, ..., NTRP. If no trip cards are submitted (NTRP=0), the trip information will be retrieved from tape as if no break in the problem has occurred. However, if any trip cards are submitted, all of the original specifications are erased and only a memory of the time of actuation of trips already triggered will be retained. Submission of new cards applying to a trip will turn the trip off and substitute the new specifications. Thus for a trip to remain actuated once the signal is received, no cards should be submitted for it; while for a trip not yet actuated, the specifications should be resubmitted.

3.10 Evaluation Model Options for RELAP4-EM

The AEC Evaluation Model is based on a set of computer programs that were available at the beginning of the Evaluation Model development. One of these codes was the RELAP4 computer program. Because RELAP4-EM was developed by adding models or changing presently available models in RELAP4^{2/} to comply with the Commission acceptance criteria, options exist which are not part of the Evaluation Model. A flag has been added to the RELAP4-EM input data to specify an Evaluation Model calculation. The flag is on the Problem Dimension Data Card (Card 010001), ISPROG, and should be specified as 1 to use all the Evaluation Model options.

Other options are available in the RELAP4-EM input data which are used to perform sensitivity analyses or check calculations. The options that must be specified for the Evaluation Models are listed below:

<u>OPTION</u>	<u>EVALUATION MODEL INPUT</u>	<u>COMMENT</u>
Card 0100001, Problem Dimension Data, ISPROG	ISPROG = 1	This is the flag that specifies all Evaluation Models to be used.
Card 08XXXXY, Junction Data Cards, JCHOKE, ICHOKE, MVMIX	JCHOKE = 0 ICHOKE = 11	The specification of JCHOKE and ICHOKE are used to specify the use of the Evaluation Model critical flow model.
	MVMIX = 0,1,2,3,4	This input variable specifies the type of momentum equation to be used. It should be selected on the type of geometry to be modeled.

Card 140000, Kinetics Constant
Data Card, NODEL, KMUL

NODEL = 3

Specifies the thermal
power calculation to be
used.

KMUL = 0

Specifies the ANS standard
to be multiplied by 1.2.

Card 15XXX1, Heat Slab Data
Cards IMCR

IMCR = 2 for PWR

Specifies the flow film
boiling correlation.

IMCR = 0 for BWR

Card 16XXX5, Core Section Data
Cards, ISLBAJ, ISWTAB

ISLBAJ = 2 for blowdown
run

Flag to indicate calculation
to be made after pin
swelling.

= 1 single pin

ISWTAB = 0 for blowdown
run

Indicates table to be
used for blockage data.

1 single pin

Card 260001, ECCS Bypass
Input Data

This card is required for
PWR only.

Card 270000 thru 300000, Pin Clad
Rupture and Blockage Data

Multiple and single pin
clad rupture and blockage
data.

4.0 MOXY-EM COMPUTER PROGRAM

For boiling water reactors (BWRs), the Commission acceptance criteria specify the manner by which certain aspects of the analysis shall be performed. A computer program, MOXY-EM, was developed to perform the BWR analysis as required by the acceptance criteria. Again MOXY-EM was developed by modifying the existing computer program MOXY^{4/} to provide the additional required capabilities. The modifications to and the use of the MOXY-EM program are presented in the following sections.

The MOXY-EM computer program computes the peak clad temperature in a boiling water reactor (BWR) fuel element composed of, at the user's option, either 49 zircaloy-clad fuel rods arranged in a 7x7 square array or 63 zircaloy-clad fuel rods and one hollow zircaloy rod arranged in an 8x8 square array. The fuel rod array in both cases is enclosed in an unperforated zircaloy canister that serves as a boundary for thermal radiation from the fuel rods. The fuel rods plus canister are represented, assuming diagonal symmetry, with 28 rods plus a half canister (Figure 4.1) in the case of the 7x7 array, and with 36 rods plus a half canister (Figure 4.2) in the case of the 8x8 array.

Conduction heat transfer is computed in each of the fuel rods, subject to the transient heat flux boundary condition of combined convection, radiation, and metal-water reaction. For initialization, the user can choose between a convection boundary condition and a temperature boundary condition.

(INTERSECTION
OF CONTROL
ROD BLADE)

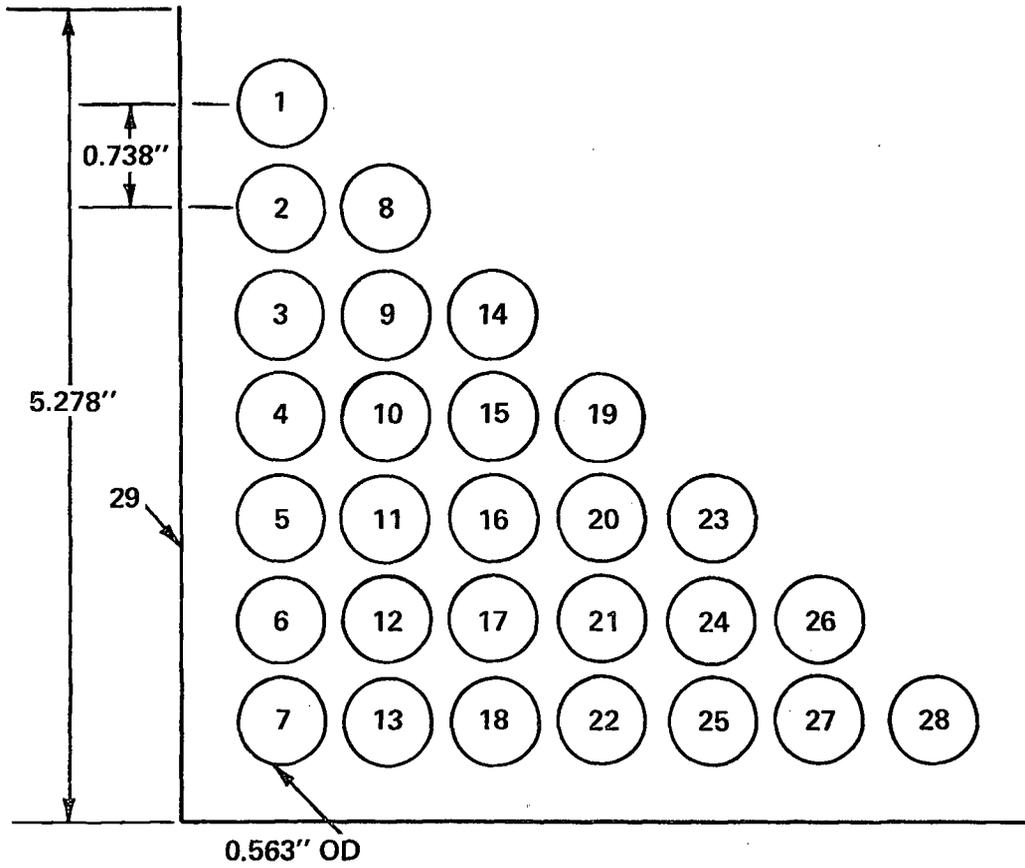


Figure 4.1 MOXY-EM Nodal Layout of 7x7 BWR Fuel Element

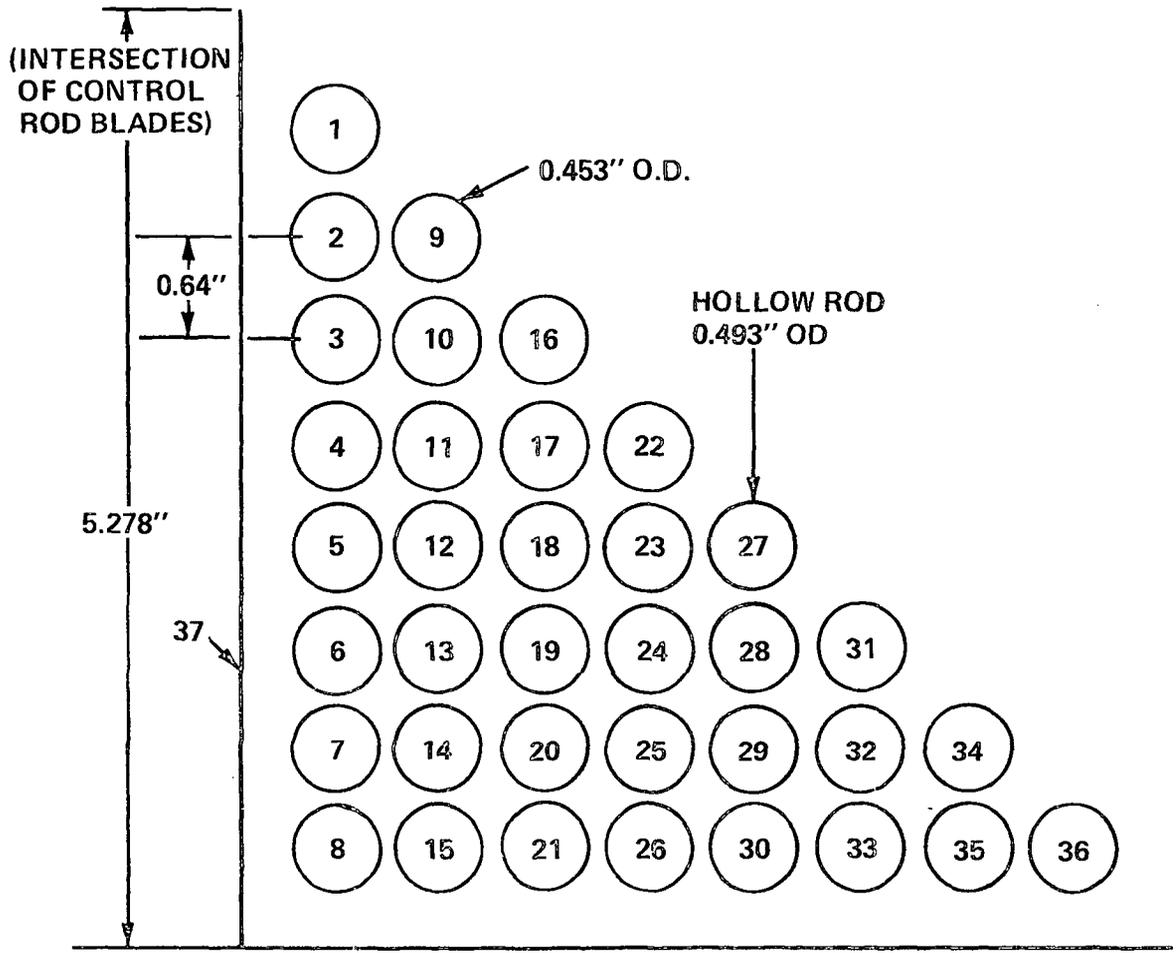


Figure 4.2 MOXY-EM Nodal Layout of 8x8 BWR Fuel Element

The canister and hollow rod are treated as a lumped mass that receives energy by thermal radiation and loses energy by convection to fluid flowing axially past it. The hollow rod also receives energy by metal-water reaction. The time of quenching can be input or computed internally. After quenching, the canister or hollow rod is maintained at the fluid equilibrium saturation temperature, and the emissivities are changed to values input by the user.

The basic MOXY-EM radiation and conduction heat transfer models are unchanged since publication of the original MOXY manual,^{4/} and their description will not be repeated here. The models added since the issuance of the MOXY manual are described in the following section.

4.1 Heat Sources and Sinks

4.1.1 Convective Heat Transfer Coefficient

Heat transfer for the channel box and rewetting criteria are specified by the Commission acceptance criteria. These criteria are outlined in Appendix K, Part D - Post-Blowdown Phenomena; Heat Removal by the ECCS, and are stated by:

"6. Convective Heat Transfer Coefficients for Boiling Water Reactor Fuel Rods Under Spray Cooling. Following the blowdown period, convective heat transfer shall be calculated using coefficients based on appropriate experimental data. For reactors with jet pumps and having fuel rods in a 7 x 7 fuel assembly array, the following convective coefficients are acceptable:

a. During the period following lower plenum flashing but prior to the core spray reaching rated flow, a convective heat transfer coefficient of zero shall be applied to all fuel rods.

b. During the period after core spray reaches rated flow but prior to reflooding, convective heat transfer coefficients of 3.0, 3.5, 1.5, and 1.5 $\text{Btu}\cdot\text{hr}^{-1}\cdot\text{ft}^{-2}\cdot\text{F}^{-1}$ shall be applied to the fuel rods in the outer corners, outer row, next to outer row, and to those remaining in the interior, respectively, of the assembly.

c. After the two-phase reflooding fluid reaches the level under consideration, a convective heat transfer coefficient of 25 $\text{Btu}\cdot\text{hr}^{-1}\cdot\text{ft}^{-2}\cdot\text{F}^{-1}$ shall be applied to all fuel rods.

7. The Boiling Water Reactor Channel Box Under Spray Cooling.

Following the blowdown period, heat transfer from, and wetting of, the channel box shall be based on appropriate experimental data. For reactors with jet pumps and fuel rods in a 7 x 7 fuel assembly array, the following heat transfer coefficients and wetting time correlation are acceptable.

a. During the period after lower plenum flashing, but prior to core spray reaching rated flow, a convective coefficient of zero shall be applied to the fuel assembly channel box.

b. During the period after core spray reaches rated flow, but prior to wetting of the channel, a convective heat transfer coefficient of 5 $\text{Btu}\cdot\text{hr}^{-1}\cdot\text{ft}^{-2}\cdot\text{F}^{-1}$ shall be applied to both sides of the channel box.

c. *Wetting of the channel box shall be assumed to occur 60 seconds after the time determined using the correlation based on the Yamanouchi analysis ("Loss-of-Coolant Accident and Emergency Core Cooling Models for General Electric Boiling Water Reactors," General Electric Company Report NEDO-10329, April 1971)."*

Since the blowdown heat transfer is specified by the criteria for both calculations of CHF and acceptable heat transfer correlations (see Sections 3.3 and 3.4), the convection heat transfer coefficient used in the Evaluation Model calculations is taken from the RELAP4-EM restart-plot tape. The source of heat transfer coefficient and core thermal power used is shown in Figure 4.3.

4.1.2 Convection Heat Transfer

The convection heat transfer coefficients are computed in RELAP4-EM for each of four groups of rods (shown in Figure 4.2) and for the canister. The user has the option of either supplying time-dependent heat transfer coefficients in the program input for each rod group and for the canister or using values from a RELAP4-EM generated plot tape. If values are input from a RELAP4-EM plot tape, the heat transfer coefficient is set to zero between the time lower plenum flashing ends and the time the core spray reached rated flow. Both times are user-supplied values.

The user can choose internally computed heat transfer coefficients for spray cooling according to either of two General Electric Company (GE) models, one based on an emissivity of 0.9, the other on 0.7 (the

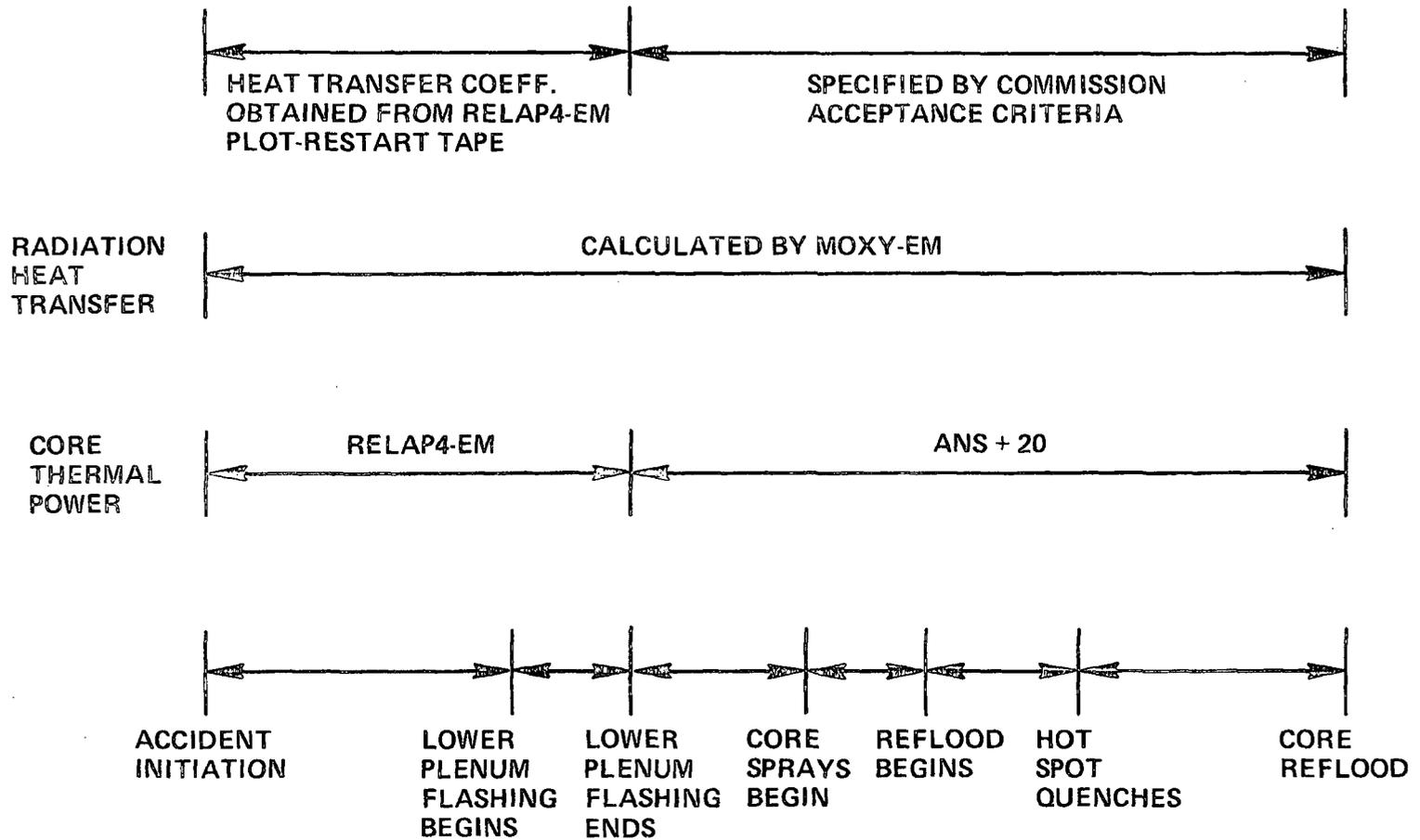


Figure 4.3 MOXY-EM Heat Sources and Sinks

model specified in the acceptance criteria), the ANC-3 model; or a user-supplied FORTRAN subroutine; or the user can supply spray cooling heat transfer coefficients in the program input. Time-dependent fluid temperatures can be input either from a RELAP4-EM plot tape or by the user. The program interpolates linearly between points in the tables.

The GE models are given in Table 4.1, and the ANC-3 model is given in Table 4.2. At a user-supplied time when core spray reaches its rated flow rate, the coefficients in Tables 4.1 or 4.2 are applied to their respective rod groups.

The above paragraph describes the options that are available in MOXY-EM. In performing evaluation model calculations, the convection heat transfer coefficients for the 4 groups are specified as shown below:

1. Blowdown Convection Heat Transfer Coefficients

(Initiation of Blowdown to End of Lower Plenum Flashing)

These are obtained from the RELAP4-EM plot-restart tape for all 4 rod groups.

2. Post-Blowdown Convection Heat Transfer Coefficients

- a. End of Lower Plenum Flashing to attainment of Rated Flow on Core Spray. Apply convection heat transfer coefficient of $h = 0$ to all rods and channel box.
- b. Rated Flow on Core Spray to Beginning of Reflood Apply convection heat transfer coefficients of:

TABLE 4.1

GE SPRAY COOLING HEAT TRANSFER MODELS

Rod Group Number	Heat Transfer Coefficient	
	$\epsilon = 0.9$	$\epsilon = 0.7$
1	2.0	3.0
2	3.2	3.5
3	1.5	1.5
4	1.7	1.5
Canister	5(a,b)	5(a,b)

TABLE 4.2

ANC-3 SPRAY COOLING HEAT TRANSFER MODEL

Time from Canister Quenching (Sec)	Heat Transfer Coefficient $\left(\frac{\text{Btu}}{\text{hr-ft}^2-\text{°F}} \right)$				
	Rod Group 1	Rod Group 2	Rod Group 3	Rod Group 4	Canister
- ∞	2.3	2.3	2.3	2.3	5(a)
- 40	2.3	2.3	2.3	2.3	5
0	3.05	3.05	2.8	2.6	(b)
200	3.6	3.6	0	0	(b)
∞	3.6	3.6	0	0	(b)

(a) The coefficient is applied to both the inside and the outside canister surfaces.

(b) At quenching the canister temperature is set to the fluid saturation temperature, and the canister emissivity is raised to that of liquid water, $\epsilon = 0.96$.

At a user-supplied time when the rod bundle is flooded, the heat transfer coefficient on all surfaces is increased to 25 Btu/hr-ft²-°F.

Rods

$h = 3.0$	Btu/hr-ft ² -°F	outer corner
$h = 3.5$	"	outer row
$h = 1.5$	"	next to outer row
$h = 1.5$	"	remaining in the interior

Channel Box (prior to wetting), both sides

$$h = 5 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

c. After two phase level is on rods

Rods

$$h = 25 \text{ Btu/hr-ft}^{-1}\text{-}^\circ\text{R}$$

Channel Box

for channel box wetting time uses Yamanouchi

Analysis + 60 seconds

4.2 Canister and Hollow Rod Quenching Model

The model used to compute the time at which the canister or the hollow rod quenches is based on Yamanouchi's analysis of the velocity of a wetting front as specified in the criteria. Based on the assumption of a linear axial temperature gradient, the wetting front velocity equation of Yamanouchi can be integrated to give an expression for quenching time. An empirical fit of the integrated equation to FLECHT data gives the following equation:

$$t_w = \frac{0.259 \gamma c}{T_o - T_s} \frac{\delta}{h_f k} T_{BM} - T_o - \frac{dT}{dx} \frac{X_M}{2} X_M + 12$$

where:

$$t_w = \text{time to wetting (sec)}$$

γ = specific weight $\left(\frac{\text{lbm}}{\text{in}^3}\right)$

c = specific heat $\left(\frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)$

h_f = heat transfer coefficient on wetted surface $\left(\frac{\text{Btu}}{\text{sec-in}^2\text{-}^\circ\text{F}}\right)$

k = thermal conductivity $\left(\frac{\text{Btu}}{\text{sec-in-}^\circ\text{F}}\right)$

δ = thickness (in)

T_o = Leidenfrost temperature ($^\circ\text{R}$)

T_s = saturation temperature ($^\circ\text{R}$)

$T_{\infty M}$ = maximum temperature of the non-wetted surface ($^\circ\text{R}$)

X_M = axial distance below the top to the maximum temperature (in)

$\frac{dT}{dx}$ = slope of temperature vs axial position $\left(\frac{^\circ\text{R}}{\text{in}}\right)$

As specified by the criteria, 60 seconds is added to the time determined by the Yamanouchi correlation. This model is then used to determine the time that both canister and hollow rod quench.

4.3 Canister and Hollow Rod Energy Balance

No specific model is specified by the Commission criteria for performing an energy balance on a canister or hollow rod. The assumptions used in the development of the model are:

1. No metal-water reaction takes place on the canister but is considered as occurring on both inside and outside surfaces on the water rod.
2. The canister and hollow rod are at a uniform temperature throughout.
3. The canister is square in cross-section.

4. No energy is lost from the exterior surface of the canister or from the interior surface of the hollow rod.

Expressing the canister and hollow rod energy balances based on the above assumptions in finite difference form results in a quartic equation in temperature that can be solved iteratively using a Newton-Raphson scheme:

$$[T_i^{m+1}]^4 + RT_i^{m+1} + S = 0 \quad (77)$$

$$R = \frac{\rho_i C_i V_i}{\Delta t} + h_i A_i \quad (78)$$

$$S = - \frac{A_i \left(\frac{\epsilon_i}{1-\epsilon_i} \right) \sum_{j=1}^N G I_{ij} A_j \left(\frac{\epsilon_j}{1-\epsilon_j} \right) \sigma (T_j^m)^4 + \frac{\rho_i C_i V_i}{\Delta t} T_i^m + h_i A_i T_w + q_{mwr_i}}{\text{DENOM}} \quad (79)$$

$$\text{DENOM} = \left[1 - A_i \left(\frac{\epsilon_i}{1-\epsilon_i} \right) G I_{ii} \right] A_i \left(\frac{\epsilon_i}{1-\epsilon_i} \right) \sigma \quad (80)$$

where:

T_i = temperature ($^{\circ}\text{R}$)

ρ_i = density ($\frac{\text{lbm}}{\text{ft}^3}$)

C_i = heat capacity, ($\frac{\text{Btu}}{\text{lbm } ^{\circ}\text{R}}$)

V_i = volume (ft^3)

q_{mwr_1} = metal-water reaction heating rate $\left(\frac{\text{Btu}}{\text{sec}}\right)$

Δt = time step size (sec)

A_i = area (ft^2)

ϵ_i = total hemispherical emissivity (dimensionless)

σ = Stefan-Boltzmann constant = $4.758 \times 10^{-13} \left(\frac{\text{Btu}}{\text{sec-ft}^2-\text{R}^4}\right)$

h_i = heat transfer coefficient $\left(\frac{\text{Btu}}{\text{sec-ft}^2-\text{F}}\right)$

T_w = water temperature ($^{\circ}\text{R}$)

GI_{ij} = elements of inverse-radiation matrix F^{-1} (ft^{-2})

G_{ij} = elements of radiation matrix $A_j - \left(\frac{\delta_{ij}}{1-\epsilon_j} - F_{ij}\right)(\text{ft}^2)$

δ_{ij} = 1 when $k = j$

= 0 when $i \neq j$

F_{ij} = view factor from node i to node j (dimensionless)

Subscripts refer to node number.

Superscripts refer to time step number.

4.4

Fuel Assembly Geometry

As mentioned earlier, MOXY-EM has the capability to consider either a 7x7 or an 8x8 BWR fuel element as a user option. The code has provision for internally computing view factors as a function of rod diameter and pitch using subroutines extracted from the VIEWPIN code. The geometries for the 7x7 and 8x8 arrangements are presented in Figures 4.1 and 4.2.

4.5 Input Data Description for MOXY-EM

Information required to execute the MOXY-EM computer program includes job control cards and punched-card input data. Because job control cards are facility-dependent, they are not presented herein. The required punched-card input data are defined in terms of the overall organization of a data deck, the options required to meet the Evaluation Model requirements, and a data card summary.

4.5.1 Data Deck Organization

A MOXY case consists of a title card, optional comment cards, data cards, and a terminator card. A listing of the cards is printed at the beginning of each MOXY case. The order of the title, data, and comment cards is unimportant except that the last title card or the last data card with a duplicate card number will be used.

When a card format error is detected, a line containing a dollar sign (\$) located under the character causing the error and a comment giving the card column of the error is printed. An error flag is set such that input processing continues, but the case is aborted at the end of input processing. Often another error comment is produced during input processing when the program attempts to process the erroneous data.

Title Card

A title card must be entered for each case. A title card is identified by an equal sign (=) as the first nonblank character. The title (the remainder of the title card) is printed as the second line

of every page. The title card is normally placed first in the problem.

Comment Cards

An asterisk (*) or a dollar sign (\$) appearing as the first nonblank character identifies the card as a comment card. Any information may be entered on the remainder of the card. Blank cards are treated as comment cards. The only processing of comment cards is printing of contents. Comment cards may be placed anywhere in the input deck.

Data Cards

The data cards contain a varying number of fields which may be integer, floating point, or alphanumeric. Blanks preceding and following fields are ignored.

The first field on a data card is a card number which must be an unsigned integer. If the first field has an error or is not an integer, an error flag is set. Consequently, data on the card are not used and the card will be identified by the card number in the list of unused data cards. After each card number and the accompanying data are read, the card number is compared to previously entered card numbers. If a matching card number is found, the data entered on the previous card are replaced by the data on the current card. If the card being processed contains only a card number, the card number and the data entered on the previous card are deleted. If a card causes replacement or deletion of data, a statement is printed indicating that the card is a replacement card.

Comment information may follow the data fields on any data card by preceding the comment with an asterisk or dollar sign.

A number field is started by either a digit (0 through 9), a sign (+ or -), or a decimal point(.). A comma or a blank (with one exception subsequently noted) terminates the number field. The number field has a number part, and optionally, an exponent part. A number field without a decimal point or an exponent is an integer field; a number field with either a decimal point, an exponent, or both is a floating-point field. A floating-point field without a decimal point is assumed to have a decimal point immediately in front of the first digit. The exponent denotes the power of ten to be applied to the number part of the field. The exponent part is a sign, an E or D, or an E or D and a sign followed by a number giving the power of ten. These rules for floating-point numbers are identical to those for entering data in FORTRAN E or F formatted fields except that no blanks (one exception noted later) are allowed between characters. Floating-point data punched by FORTRAN programs can be read. To permit reading of such data, a blank following an E or D denoting an exponent is treated as a plus sign. Acceptable ways of entering floating-point numbers are illustrated by the following six fields all containing the quantity 12.45:

12.45,+12.45,1245+2,1.245+1,1.245E1,1.245E+1

A field starting with a letter is an alphanumeric field. The field is terminated by a comma, a blank, or the end of the card. All characters except commas and blanks are allowed.

Terminator Cards

The input data for cases are separated by slash cards; the final problem is terminated by a period card instead of a slash card. The period card also serves as the separator between problem sets. The slash and period cards have a (/) and (.), respectively, as the first nonblank character. Comments may follow the slash and period on the slash and period cards.

When a slash card is used as a terminator, the list of card numbers and associated data used in a case is passed to the next case. Cards entered for the next problem are added to the passed list or act as replacement cards depending on the card number. The resulting input is the same as if all previous slash cards were removed from the input to the problem set.

When a period card is used as a terminator, all previous input cards are erased before the input to the next problem is processed.

4.5.2 Evaluation Model Options for MOXY-EM

The Evaluation Model was developed to calculate the peak cladding temperature for a BWR; the previously developed MOXY computer program^{4/} was used as a basis for this development. Since MOXY-EM was developed by adding analytical models and modifying

previous developed models to conform with the Commission acceptance criteria, options are available which are not part of the Evaluation Model. These options were made available to perform either studies of sensitivity to certain models or to audit calculations. The options that must be used for an Evaluation Model calculation are:

<u>Option</u>	<u>Evaluation Model Selection</u>	<u>Non-EM Alternatives Possible</u>
Source term	Time-dependent	Can be constant
Metal-water reaction	Calculated	Can neglect
Convection heat transfer	Calculated	Can neglect
Initial surface temperature distribution	Computed from surface heat transfer coefficient	Can input initial surface temperature distribution
Fluid temperature	Time-dependent	Can be constant
Convection heat transfer coefficient	Time-dependent	Can be constant
Normalized power, heat transfer coefficient, fluid temperature	Input from direct-access files that are derived from a RELAP4-EM plot tape	Can be input with punched card data
Gap conductance	Internally computed	Can be input with punched card data
Metal-water reaction multiplier	1.0	Any positive number
Spray cooling model	GE model ($\epsilon = .7$)	Can be input with punched card data, can select GE model for $\epsilon = 0.9$ can select ANC-3 model, or can provide own model as FORTRAN subroutine

<u>Option</u>	<u>Evaluation Model Selection</u>	<u>Non-EM Alternatives Possible</u>
Quenching Time	Internally computed by Yamanouchi correlation	Can be input with punched card data
Hollow rod and solid rod quenching time	Internally computed by Yamanouchi correlation	Can be input with punched card data
Temperature jump distance	Value input	Can be computed internally
Time lag to be added to Yamanouchi calculated quenching time	60 sec	Any finite number
Heat of reaction for zirconium-water reaction	2800 Btu/lb _m	Can select one of two different temperature-dependent functions or provide own function as FORTRAN subroutine

When the user makes the complete set of Evaluation Model selections itemized above, the page heading label is changed to reflect the fact that an Evaluation Model calculation is being performed. (MOXY/MOD030 becomes MOXY-EM/030.) The user can make each selection directly through the punched card data, or he can have the program make the appropriate selections for him. In either case, the input data are extensively checked for errors and for whether the Evaluation Model selections have been made correctly. If no errors have been found, and if the Evaluation Model selections have been made correctly, the page heading label is changed and a message advising that the Evaluation Model assumptions have been met appears in the printed output data. The

page heading label also appears on any plots made from the resulting plot tape. Thus, only when the Evaluation Model assumptions are met will MOXY-EM program output be flagged as EM output.

4.5.3 Data Card Summary

In the following description of the data cards, the card number is given along with a description of the data contained on the card. Next is given an explanation of the data on the card and a designation whether the data item is integer, real, or alphanumeric as I, R, or A, respectively. Units, unless otherwise designated, are specified as length in inches, mass and force in pounds, time in seconds, energy in Btu, and temperature in degrees Fahrenheit.

1. Title Card

The title (with the equal sign replaced by a blank) is printed as the second line on each page of printed output data.

2. T or F Option Card 010001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	A	ABRV	T to print only surface mesh-point temperatures, F to print all mesh-point temperatures
2	A	EQSWLR	T to force all swollen rods to have the same final radius, F to input values for final radius
3	A	ARYNAM	BWR5 to select 7x7 array with all active rods, BWR6 to select 8x8 array with 63 active rods and one hollow zircaloy inactive rod, IIIF to select 7x7 array with 48 active rods and one solid zircaloy inactive rod, VB to select 8x8 array with 60 active rods and four solid zircaloy inactive rods, and anything else to select a general array

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
4	A	SRCE	T for time-dependent decay heating, F for constant
5	A	LMWR	T to consider metal-water reaction, F to ignore
6	A	LCONV	T to consider convection, F to ignore
7	A	LCON	T to internally compute rod initial surface temperature, F to provide as punched-card input data
8	A	LCS	T for time-dependent fluid temperature, F for constant
9	A	LSTM	T for time-dependent heat transfer coefficient, F for constant
10	A	THETDA	T to select time-dependent normalized power, surface heat transfer coefficient, and fluid temperature from direct access devices; F to provide in punched card input
11	A	GAPCAL	T to internally compute gap heat transfer coefficient, F to provide as punched card input data

Fields 4-11 can be omitted. This will give the Evaluation Model

Values of T for each parameter.

Skip to card 010101 if general array was not selected.

3. Rod Type Cards 010011 - 010020

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	I	RODTYP(1)	Type of rod 1.
...
N-1	I	RODTYP(N-1)	Type of rod N-1.

There are N-1 rods. The canister is referred to by the designation N.

Up to 9 types of active rods (Types 1-9) and two types of inactive rods (Type 10 - hollow rod and Type 11 - solid rod) are allowed.

4. Rod Length Card 010021

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	RODL	Fuel rod length in feet.

If card is not present, or if no entries are made on card, RODL is set to 12 feet.

5. Integer Option Card 010101

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	I	NTSETS	Number of time step sets, (≤ 10)
2	I	NOSETS	Number of print interval sets, (≤ 10)
3	I	M	Number of decay heating-time pairs in considering time-dependent decay heating (≤ 50) - Must equal 1 if SRCE is F. Uses built in ANS+20% values if 0. Ignored if THETDA is T.

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
4	I	L	Number of heat transfer coefficient - time pairs in considering time-dependent heat transfer coefficients (≤ 50) - must equal 1 if LSTM is false. Ignored if THETDA is T.
5	I	LL	Number of fluid temperature-time pairs in considering time-dependent fluid temperature - (≤ 50) - must equal 1 if LCS is F. Ignored if THETDA is T.
6	I	NRECYC	Maximum number of outer iterations to balance canister temperature with rod temperatures.
7	I	ITM	Maximum number of inner iterations allowed to balance temperatures of rods and canister individually.
8	I	LINPG	Selects 60 or 80 lines per page of printed output. Any value chosen other than 60 or 80 causes printer to print over perforations between pages.
9	I	IHGR	Sets option for volumetric heat generation rate. If 1, value is input directly in Btu/sec in ³ . If 2, value is computed from kW/ft (MAPLHGR); if 3, value is computed from reactor thermal power in MW, number of fuel elements, and bundle and axial peaking factors.
10	I	ISPR	Sets option for spray cooling model. If 0, input own tables with heat transfer coefficients; if 1, uses GE model with $\epsilon = 0.9$; if 2, uses GE model with $\epsilon = 0.7$; if 3, uses ANC3; if 4, uses user-supplied FORTRAN subprogram.

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
11	I	IHR	Sets option for metal-water heat of reaction computation. If 1, uses constant value; if 2, uses slightly conservative temperature-dependent function; if 3, uses best estimate temperature-dependent function; if 4, uses user-supplied FORTRAN subprogram.
12	I	IQUEN	Sets option for canister and inactive rod quenching model. If 1, uses Yamanouchi, if 2, allows user-supplied model.

Fields 10-12 can be omitted, giving Evaluation Model values for parameters.

6. Time Step Data Cards 020001 - 020100

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	DT1(1)	First time step size
2	R	TDT(1)	Time to change from first time step size to second time step size
3	R	DT1(2)	
4	R	TDT(2)	
...	
2(NTSETS)-1	R	DT1(NTSETS)	
2(NTSETS)	R	(TDT(NTSETS))	

TDT(NTSETS) is transient end time. Up to 10 time step sizes are allowed.

7. Print Interval Data Cards 020101 - 020200

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	I	NOUTP(1)	First printing interval
2	R	TOUT(1)	Time to change from first printing interval to second printing interval
3	I	NOUTP(2)	
4	R	TOUT(2)	
...	
2(NOSETS)-1I		NOUTP(NOSETS)	
2(NOSETS) R		TOUT(NOSETS)	

Up to 10 printing intervals are allowed.

8. Geometry Data Card 030001**

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	I	NDR(I,1)	Number of space steps in fuel
2	I	NDR(I,2)	Number of space steps in gap
3	I	NDR(I,3)	Number of space steps in cladding

9. Fuel Rod Geometry Data Cards 030101 - 030109*,**

Card Number 030101:

* The card number for items 9 and 10 is effectively 0301II subject to the restriction $01 < II < 11$.

** The variable I is set within the Code according to the Rod Type Card information (Item 3).

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	REGSZE(I,1)	Radius of fuel pellet (Rod Type 1)
2	R	REGSZE(I,2)	Radial gap thickness (Rod Type 1)
3	R	REGSZE(I,3)	Radial cladding thickness (Rod Type 1)
...

Card Number 030100 + II:

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	REGSZE(I,1)	Radius of fuel pellet (Rod Type II)
2	R	REGSZE(I,2)	Radial gap thickness (Rod Type II)
3	R	REGSZE(I,3)	Radial cladding thickness (Rod Type II)

Cards in this group must be in serial order. One card must be provided for each unique rod type used.

10. Geometry Data Cards 030110 - 030111

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	REGSZE(I,1)	Radius of solid inactive rod (II=11) or inside radius of hollow rod (II=10).
2	R	REGSZE(I,2)	Radial hollow rod wall thickness (II=10).

11. Geometry Data Card 030201

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	P	Rod pitch
2	R	SL	Distance between inside flat surfaces of canister
3	R	REGSZE(N,1)	Thickness of canister

12. Geometry Data Cards 030301 - 030400

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	R3(1)	Ruptured rod radius of Rod 1
2	R	R3(2)	Ruptured rod Radius of Rod 2
...	
N	R	R3(N-1)	Ruptured rod radius of Rod N-1

N is number of rods. If EQSWLR is T, card can be omitted or one entry can be made. Omitting the card gives a rupture rod radius for all rods equal to half the pitch, and making an entry gives a ruptured rod radius equal to that value. If EQSWLR is F, N-1 entries must be made.

13. Core Spray Initiation Time Data Card 040001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	TSPRAY	Time at which core spray reaches rated flow rate

14. Inactive Rod Quenching Time Data Card 040101

(Omit if array contains all active rods)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	TQR or HF	Rod quenching time or heat transfer coefficient on wetted portion of hollow rod in Btu/hr-ft ² -°F
2	R	RDTD	Axial Temperature gradient on hollow rod
3	R	XM	Distance from top of core to axial hot spot
4	R	TLEID	Leidenfrost temperature
5	R	DTIME	Time lag to be added to Yamanouchi-calculated quenching time, 60 if omitted

If rod quenching time is to be input, it should be the only number on the card. At least four fields are used if the rod quenching time is to be internally computed.

15. Canister Quenching Time Data Card 040201

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	TQ or HF	Canister quenching time. Heat transfer coefficient on wetted portion of canister in Btu/hr-ft ² -°F
2	R	DTD	Axial temperature gradient on canister

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
3	R	XM	Distance from top of core to axial hot spot
4	R	TLEID	Leidenfrost temperature
5	R	DTIME	Time lag to be added to Yamanouchi calculated quenching time, 60 if omitted

If canister quenching time is to be input, it should be the only number on the card. At least four fields are used if the rod quenching time is to be internally computed.

16. Reflooding Time Data Card 040301

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	TFLOOD or FLDRT	Reflooding time, volumetric reflooding rate
2	R	PLNVOL	Volume to be refilled

If only one entry is made, it is taken as the reflooding time.

If two entries are made, reflooding time is PLNVOL/FLDRT.

17. Initial Surface Temperature Data Cards 050001 - 050100 (Omit if LCON is T)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	T(1,NN)	Initial surface temperature of Rod 1
2	R	T(2,NN)	Initial surface temperature of Rod 2
...	
N	R	T(N,NN)	Initial surface temperature of canister

18. Power Data Cards 060001 - 060100 (Omit is THETDA is T or M = 0)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	SORDK(1)	First value of normalized power
2	R	DKTIM(1)	First value of time
...	
2M-1	R	SORDK(M)	Mth value of normalized power
2M	R	DKTIM(M)	Mth value of time

Up to 50 points are allowed.

19. Rod Group 1 Heat Transfer Coefficient Data Cards 070001 - 070100

(Omit if THETDA is T)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	HZ5(1)	First value of heat transfer coefficient for rod group 1 (heat transfer coefficient in Btu/hr-ft ² -°F)
2	R	TZ5(1)	First value of time
...	
2L-1	R	HZ5(L)	Lth value of heat transfer coefficient for rod group 1
2L	R	TZ5(L)	Lth value of time

Up to 50 points are allowed.

20. Rod Groups 2 - 4 and Canister Heat Transfer Coefficient Data Cards 070101 - 070500

(Omit if ISPR > 0 or THETDA is T)

Same as Rod Group 1 for Rod Groups 2 - 4 and canister.

21. Fluid Temperature Data Cards 080001 - 080100 (Omit if THETDA is T)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	TSINK(1)	First value of fluid temperature
2	R	TME(1)	First value of time
...	
2(LL)-1	R	TSINK(LL)	LLth point of fluid temperature
2(LL)	R	TME(LL)	LLth point of time

Up to 50 points are allowed.

22. Volumetric Heat Generation Rate Data Card 090001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	QVA	See below
2	I	NBNDLS	Number of bundles in the reactor

If IHGR is 1 or 2, only one value should be on the card. If IHGR is 1, the value should be QVA in Btu/sec-in³; if 2, the value should be the value for maximum average peak linear heat generation rate (MAPLHGR) in kW/ft; if 3, two values should be on the card: the first field is reactor thermal power in MW, and the second field is the number of bundles in the reactor. In all cases, the power applied to the fuel of Rod I is (QVA)(RPF)(APF) W(I).

23. Bundle and Axial Peaking Factor Data Card 090101

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	RPF	Bundle peaking factor
2	R	APF	Axial peaking factor

If IHGR is 1 or 2, this card may be omitted, with RPF and APF assuming values of unity, or a single peaking factor may be provided, with the other peaking factor becoming unity. If IHGR is 3, both peaking factors must be provided.

24. Local Peaking Factor Data Cards 090201 - 090400

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	W(1)	Peaking factor of Rod 1
2	R	W(2)	Peaking factor of Rod 2
...	
N-1	R	W(N-1)	Peaking factor of Rod N-1

25. Rod Swelling and Rupture Data Card (100001)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	TRUPT	Rupture temperature
2	R	DTSWL	Swelling temperature range - swelling temperature is (TRUPT - DTSWL)

26. Emissivity Data Card 110001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	EROD	Emissivity of fuel rods
2	R	ECAR	Emissivity of canister prior to quenching
3	R	ER20	Emissivity of quenched canister and hollow rod
4	R	EUR	Emissivity of hollow rod prior to quenching. (Omit if BWR6 is F)

The card can contain one, two, three or four values. If one, all emissivities prior to and after quenching are set to that value. If two, fuel rods and hollow rod emissivities are set to the first value, and pre-quench and quenched canister emissivities are set equal to the second value. If three, the hollow rod emissivity is set equal to that of the fuel rods. If four, all values are set according to the values on the data card.

27. Metal-Water Reaction Data Card 120001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	XMWR	Metal water reaction rate multiplier
2	R	CXTK	Initial external oxide thickness
3	R	CXTKIN	Initial internal oxide thickness

The card can contain one, two or three entries or it can be omitted. If one, distribution of CXTK and CXTKIN can be entered on subsequent

cards. If two, a uniform oxide thickness equal to the second value is applied to the interior and exterior of all rods. If three, a uniform oxide thickness equal to the second value is applied to the exterior of all rods, and a uniform oxide thickness equal to the third value is applied to the interior of all rods. If the card is omitted, the effect is the same as for one entry, except that XMWR assumes a value of unity.

28. External Oxide Thickness Data Card 120101 - 120200 (Omit if more than one entry on card 120001)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	OXTK(1)	Initial external oxide thickness of Rod 1
2	R	OXTK(2)	Initial external oxide thickness of Rod 2
...	
N-1	R	OXTK(N-1)	Initial external axial thickness of Rod N-1

29. Internal Oxide Thickness Data Card 120201 - 120300 (Omit if more than one entry on card 120001)

Same as external oxide thickness.

30. Fuel Fractional Density Data Card 130001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	FRDEN	Fraction of theoretical fuel density of fuel in rods

31. Steam Pressure Data Card 140001

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	STPR	Steam pressure in core

32. Cap Coefficient Data Card 150001 (Omit if GAPCAL is F)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	CONCON	Contact conductance for fuel and cladding in Btu/hr-ft ² -°F
2	R	E1	Emissivity of fuel surface
3	R	E2	Emissivity of cladding interior surface
4	R	PGAS	Fission gas pressure
5	R	RUFF	Arithmetic average surface roughness for fuel
6	R	RUFCL	Arithmetic average surface roughness for cladding
7	R	TJUMP	Temperature jump distance, can be set to zero by omitting.

33. Fission Gas Composition Data Cards 150101 - 150200 (Omit if GAPCAL is F)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	MOLEFR(1,1)	Mole fraction of helium in fission gas of Rod 1
2	R	MOLEFR(2,1)	Mole fraction of argon in fission gas of Rod 1

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
3	R	MOLEFR(3,1)	Mole fraction of hydrogen in fission gas of Rod 1
4	R	MOLEFR(4,1)	Mole fraction of nitrogen in fission gas of Rod 1
5	R	MOLEFR(5,1)	Mole fraction of krypton in fission gas of Rod 1
6	R	MOLEFR(6,1)	Mole fraction of xenon in fission gas of Rod 1
...	
6(N-1)-5	R	MOLEFR(1,N-1)	Mole fraction of helium in fission gas of Rod N-1
6(N-1)-4	R	MOLEFR(2,N-1)	Mole fraction of argon in fission gas of Rod N-1
6(N-1)-3	R	MOLEFR(3,N-1)	Mole fraction of hydrogen in fission gas of Rod N-1
6(N-1)-2	R	MOLEFR(4,N-1)	Mole fraction of nitrogen in fission gas of Rod N-1
6(N-1)-1	R	MOLEFR(5,N-1)	Mole fraction of krypton in fission gas of Rod N-1
6(N-1)	R	MOLEFR(6,N-1)	Mole fraction of xenon in fission gas of Rod N-1

If only six values are provided, all rods are assumed to have the same fission gas composition.

34. Initial Fuel-Cladding Gap Heat Transfer Coefficient Data
Cards 160001 - 160100 (Omit if GAPCAL is T)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	GAPCON(1)	Initial gap heat transfer coefficient for Rod 1

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
2	R	GAPCON(2)	Initial gap heat transfer coefficient for Rod 2
...	
N-1	R	GAPCON(N-1)	Initial gap heat transfer coefficient for Rod N-1

35. Post-rupture Fuel-Cladding Gap Heat Transfer Coefficient Data Cards 160101 - 160200 (Omit if GAPCAL is T)

<u>Field Number</u>	<u>Field Format</u>	<u>Name of Parameter</u>	<u>Function of Parameter</u>
1	R	GAPC2(1)	Post-rupture gap heat transfer coefficient for Rod 1
2	R	GAPC2(2)	Post-rupture gap heat transfer coefficient for Rod 2
...	
N-1	R	GAPC2(N-1)	Post-rupture gap heat transfer coefficient for Rod N-1

5.0 RELAP4-FLOOD COMPUTER PROGRAM

The Commission acceptance criteria for acceptable Evaluation Models specify several special capabilities related only to the reflooding portion of a PWR LOCA analysis. To perform a reflooding analysis as required by the Commission criteria, the RELAP4-FLOOD computer program was developed. The RELAP4-FLOOD computer program is a special adaptation of the RELAP4-EM computer program designed to predict the thermal and hydraulic response of a pressurized water reactor (PWR) during the reflood phase of a loss-of-coolant accident. Again much of the basic RELAP4-EM input (Section 3.9) structure is maintained and only the modifications are presented here. Modifications to the RELAP4-EM program were required to account for the nonequilibrium effects upon the core heat transfer and carryover rate fraction. Special models were also developed for the steam generator secondary system heat transfer as required by the acceptance criteria and to better represent the separated two-phase flow in the broken loop cold leg nozzle.

The RELAP4-FLOOD program uses the basic RELAP4-EM program capabilities to calculate the thermal and hydraulic response in the primary system during reflood. RELAP4-EM provides many capabilities desirable for the reflood calculations, including:

1. Solution of the mass, momentum and energy conservation equations for compressible flow,

2. Solution for wall friction as a function of Reynolds number and a two-phase multiplier,
3. Calculation of pressure changes for area changes,
4. Pump model capabilities to simulate pump coastdown or locked rotors (pump assumed to be running with a very low pump speed),
5. Calculation of momentum flux in the momentum equation and kinetic energy terms in the energy equation,
6. Calculation of heat transfer from hot surfaces and steam generators.

To meet the Commission criteria, modification or expansion of the RELAP4-EM calculation procedures were necessary in several key areas. These areas include core heat transfer, core carryover rate fraction, steam generator secondary heat transfer, and stratified two-phase flow in the broken loop cold leg nozzle. These modifications are discussed in the following sections.

5.1 Core Model

The Commission acceptance criteria specify certain models that should be used during core reflooding rate calculation. The criteria applicable to the reflood portion of a LOCA are:

"3. Calculation of Reflood Rate for Pressurized Water Reactors.

The refilling of the reactor vessel and the time and rate of reflooding of the core shall be calculated by an acceptable model that takes into consideration the thermal and hydraulic characteristics of the core and

of the reactor system. The primary system coolant pump shall be assumed to have locked impellers if this assumption leads to the maximum calculated cladding temperature; otherwise the pump motor shall be assumed to be running free. The ratio of the total fluid flow at the core exit plane to the total liquid flow at the core inlet plane (carryover fraction) shall be used to determine the core exit flow and shall be determined in accordance with applicable experimental data (for example, "PWR FLECHT (Full Length Emergency Cooling Heat Transfer) Final Report," Westinghouse Report WCAP-7665, April 1971; "PWR Full Length Emergency Cooling Heat Transfer (FLECHT) Group I Test Report," Westinghouse Report WCAP-7435, January 1970; "PWR FLECHT (Full Length Emergency Cooling Heat Transfer) Group II Test Report," Westinghouse Report WCAP-7544, September 1970; "PWR FLECHT Final Report Supplement," Westinghouse Report WCAP-7931, October 1972).

The effects on reflooding rate of the compressed gas in the accumulator which is discharged following accumulator water discharge shall also be taken into account."

A carryover fraction should be used to determine the core exit flow. RELAP4-FLCOD has three models that are based on experimental data. The B&W carryover rate fraction correlation has been used for all Evaluation Model calculations. Carryover rate fraction models are discussed in Subsection 3.1.2.

Experimental studies of reflood core heat transfer have shown that the fluid phases are not in equilibrium. Conventional heat transfer models in RELAP4-EM cannot predict core heat transfer during reflood due to the non-equilibrium between phases. In addition, the advancing front and flow regime boundaries which are known to occur during reflood result in transient liquid entrainment and mass storage effects which cannot be accurately predicted using the RELAP4 homogeneous assumptions. Consequently, empirical correlations are used and a core model was developed to account for the experimentally observed phenomena. The core model output includes the core heat transfer, the core outlet enthalpy, the core pressure, and the core outlet flow rate.

The reactor core is represented by a single fluid volume and up to 12 axially stacked heat slabs with the exact number being the user's option.

5.1.1. Core Heat Transfer

The core heat transfer coefficients are calculated from two empirical heat transfer correlations which were developed from data obtained in the PWR FLECHT program. The correlation reported by Westinghouse Electric Corporation in the PWR FLECHT documents^{26,27/} is used for core heat slabs at elevations of 3 feet or greater. A correlation developed at Aerojet Nuclear Company is used for heat slabs at elevations of less than 3 feet. Both correlations are of the form:

$$h = h (V_{in}, Q_{max}, P, T_{init}, \Delta T_{sub}, B, t) \quad (81)$$

where:

h = heat transfer coefficient, Btu/hr-ft²-°F

V_{in} = core inlet flow velocity, in/sec (referred to herein as flooding rate)

Q_{max} = peak power density, kW/ft

P = pressure, psia

T_{init} = initial peak cladding temperature, °F

ΔT_{sub} = ECC subcooling, °F

B = fraction of channel blockage

t = time after start of reflood, seconds

The following restrictions have been applied when calling the subroutine that computes the heat transfer coefficient for the PWR FLECHT heat transfer correlation referenced above:

$$V_{in} > 10 \text{ in/sec, } V_{in} = 10 \text{ in/sec} \quad (82)$$

$$V_{in} < .4 \text{ in/sec, } V_{in} = .4 \text{ in/sec} \quad (83)$$

$$Z > 8 \text{ ft, } Z = 8 \text{ ft} \quad (84)$$

$$Z < 4 \text{ ft, } Z = 4 \text{ ft} \quad (85)$$

The Aerojet heat transfer coefficient is used for core elevations less than 3.0 ft. The correlation is:

$$h = HA + HB + HC \quad (86)$$

where:

$$HA = 2. + (11t_p / (Z+1))^{2.5} [V_{in}]^{.467 + .0583Z} \quad (87)$$

$$HB = (.05Z+3) t_p V_{in}^8 \exp \left[- \frac{t_p V_{in}^3}{3Z + 13} \right] \quad (88)$$

$$HC = A \left[\frac{t_p - t_z}{C_t/2} \right]^2 \quad (89)$$

with definitions:

$$A = 22 \cdot 9 \quad (90)$$

$$t_z = 9Z^{1.7} \left(\frac{Q_{\max}}{G_{\max}} \right)^{-0.35} / V_{in}^{1-0.1(V_{in}-1)} \quad (91)$$

$$C_t = 27Z \cdot 6 / V_{in}^5 \quad (92)$$

and:

t_p = adjusted time (sec)

Z = core elevation (<3.0) (ft)

V_{in} = flooding velocity (in/sec)

Q_{\max} = power density (kw/ft)

with the additional restrictions of :

$$\text{if } t_p < t_z \quad HC = 0 \quad (93)$$

$$\text{if } t_p \geq t_z + C_t \quad HC = 0 \quad (94)$$

RELAP4-FLOOD input requires a FLECHT heat transfer data card which includes the core inlet subcooling, maximum initial cladding temperature at bottom of core recovery (BOCREC), peak power density (kw/ft), channel blockage fraction, and heat transfer due to radiation immediately preceding reflood. Both correlations are valid only until the heat transfer coefficient reaches 50 Btu/hr-ft²-°F, after which the coefficient remains constant at this value until the slab begins to quench. The RELAP4-FLOOD core model assumes that the cladding temperature must be

less than or equal to a defined quench temperature before quenching can begin. The heat transfer coefficient, therefore, is not allowed to exceed 50 Btu/hr-ft²-°F before the quench temperature is reached. After the quench temperature is reached, the heat transfer coefficient is increased to 1000 Btu/hr-ft²-°F over a time period which approximates the time required for the quench front to move the length of the heat slab. The reflood heat transfer coefficient and the assumption presented are not used to generate a peak clad temperature. This model is used to calculate the steam generation rate in the core during reflood only. The peak clad temperature analysis is performed using the TOODEE2 program and the reflood rates generated from RELAP4-FLOOD. TOODEE2 uses the flooding rates and a modified Westinghouse FLECET correlation to calculate the heat transfer coefficients used for the hot pin analysis.

The quench temperature model used is one developed by Henry^{32/} and is a function of pressure. RELAP4-FLOOD approximates Henry's equation in tabular form for water. The quench time for the heat slabs is calculated from the carryover rate fraction (CRF) correlation used. The carryover rate fraction correlations in RELAP4-FLOOD account only for mass storage below the quench front and thus the CRF can be expressed as:

$$CRF = 1 - \frac{V}{V_{in}} \quad (95)$$

where:

V_{in} = core inlet velocity

V_c = velocity of the quench front

Solving for V_q gives:

$$V_q = V_{in} (1 - CRF). \quad (96)$$

The time required to quench a heat slab of length ΔL is given by

$$t_q = \Delta L / V_{in} (1 - CRF). \quad (97)$$

The heat transfer coefficient correlations were developed from data obtained with constant flooding rates. The flooding rates during an actual reflood transient are expected to vary with time; therefore, the heat transfer correlations were modified to allow for variable flooding rates. The mass integral method and equations given in the PWR FLECHT documents^{26,27/} were extended to utilize the time-dependent integral of a continuously changing flooding rate as opposed to the step change in flooding rate analyzed in the PWR FLECHT Report.^{26,27/}

5.1.2 Core Outlet Enthalpy

Two core outlet enthalpy model options are provided in RELAP4-FLOOD. The first option allows the user to specify a core outlet enthalpy which is held constant through the run. The second option utilizes a model which was developed to account for liquid storage in the core below the moving quench front. The option on core outlet enthalpy model is specified by IHM on the program option card described in the input section. If the constant outlet enthalpy option is selected, the desired enthalpy must be specified on the core outlet enthalpy data card.

5.1.3 Core Pressure

The thermodynamic equilibrium pressure which is calculated in RELAP4-EM may be significantly different from the non-equilibrium core pressures expected during reflood. Thermodynamic equilibrium will, however, be reached in the upper plenum during reflood. RELAP4-FLOOD, therefore, sets the core pressure equal to the upper plenum pressure plus the appropriate friction gain and gravity head.

5.1.4 Core Outlet Flow Rate

The core outlet flow rate during reflood has been correlated from experimental data as a function of the carryover-rate fraction (CRF). The CRF is defined as:

$$\text{CRF}(t) = \frac{W_{\text{out}}(t)}{W_{\text{in}}(t)} \quad (98)$$

where W_{in} is the mass flow rate into the core and W_{out} is the mass flow rate out of the core. Subroutines have been written to provide the three optional CRF correlations. The subroutine to be used is specified as IENT on the program option card described.

Each of the correlations assumes a small CRF until a critical water level in the core is reached, after which the CRF increases rapidly until a maximum is reached.

Two of the correlations were developed by the Aerojet Nuclear Company. These correlations result in the CRF as shown in Figure 5.1. The Aerojet Nuclear Company correlation A requires that the final

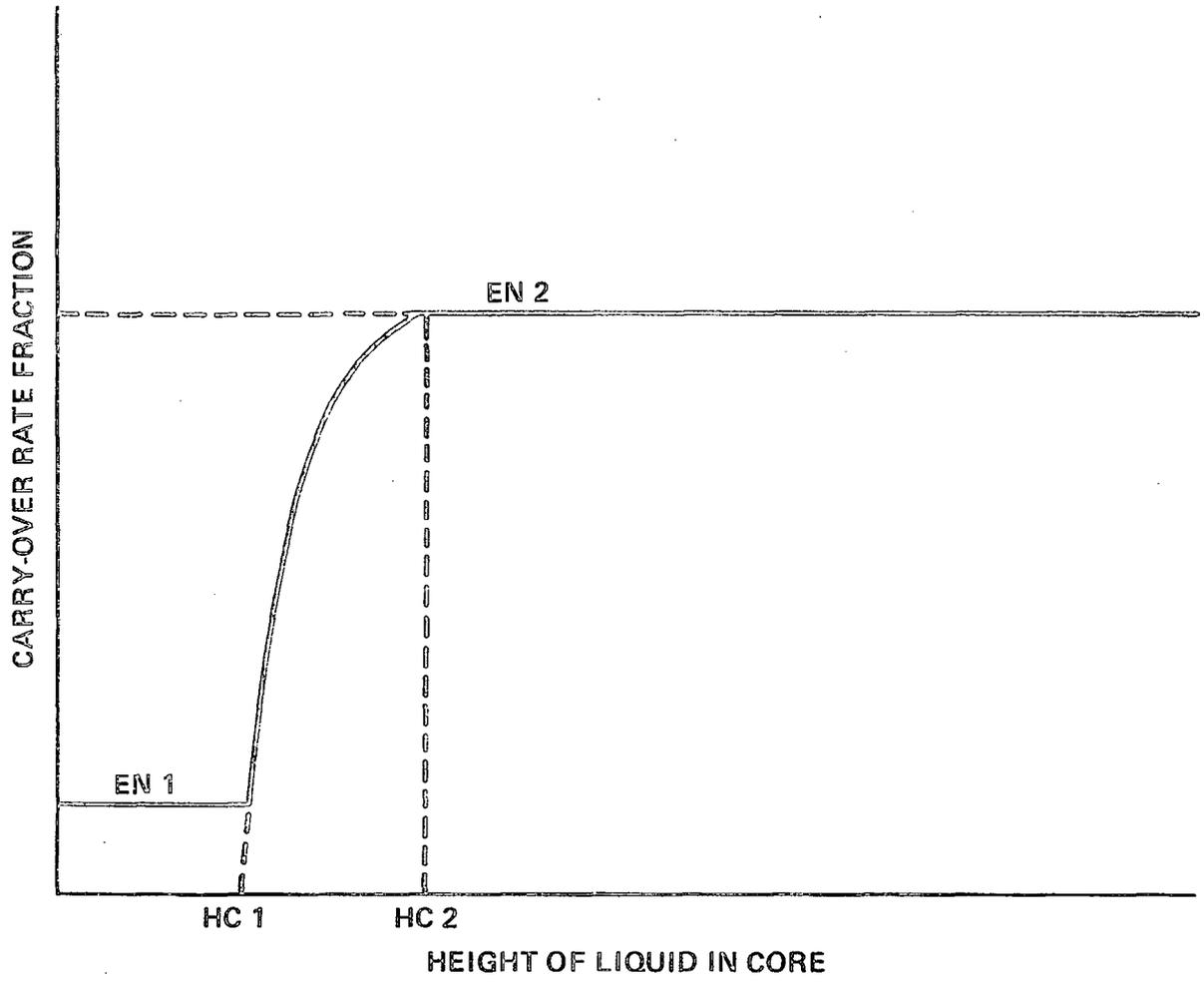


Figure 5.1 ANC Carryover-Rate-Fraction Model

CRF (EN2) and the controlling core liquid levels (HC1 and HC2) be input by the user. EN1 is set internally to approximate the steam displacement. The Aerojet correlation B requires no input.

The following correlation is for Aerojet model A where HC1, HC2, and EN2 are input values. Defining the mixture level in the core as HC; then if $HC \leq HC1$, CRF is defined by:

$$CRF = \frac{EN2 - .0024}{HC1} * HC + .0024 \quad (99)$$

If $HC1 < HC < HC2$:

$$CRF = .0024 + \frac{EN2 - .0024}{\exp(HC1 - HC2) - 1} [\exp(HC1 - HC) - 1] \quad (100)$$

If $HC \geq HC2$:

$$CRF = EN2 \quad (101)$$

where:

HC = mixture level in core (ft)

HC1 = level for entrainment initiation (ft)

HC2 = level for maximum entrainment (ft)

EN2 = maximum entrainment value

The entrainment calculated by the Aerojet correlation B is determined using the following equations. The maximum entrainment value is computed by:

$$EN2 = 1 - \frac{57.49}{T q_6 V_{in}} \quad (102)$$

and the critical height for entrainment initiation is:

$$HC1 = 1.04V_{in}^{0.67} \quad (103)$$

and:

$$HC2 = HC1 + 0.5 \quad (104)$$

where:

V_{in} = core inlet velocity (in/sec)

T_{q6} = estimated quench time (seconds) for the six foot elevation.

These data define the CRF value:

$$CRF = \frac{EN2 - .0024}{\exp(HC1-HC2) - 1} [\exp(HC1-HC)-1] + .0024 \quad (105)$$

The 6 ft quench time T_{q6} is obtained from the expression given by the Westinghouse heat transfer correlation.

The third correlation was developed by Babcock and Wilcox Company^{28/} and requires no input. The carryover rate fraction is defined by:

$$CRF = H * T_1 * T_2 * T_3 * T_4 * T_5 \quad (106)$$

where:

$$T_1 = A_o \exp \left[-A_1 \left(\frac{P}{60} \right)^2 \right] \quad (107)$$

$$T_2 = 1 - \exp \left[\frac{-A_2 Q}{1.24} \right] \quad (108)$$

$$T_3 = 1 - \exp \left[\frac{-A_3 v}{6} \right] \quad (109)$$

$$T_4 = \exp \left[-A_4 \left(\frac{\Delta t}{140} \right)^2 \right] \quad (110)$$

$$T_5 = 1 - \exp \left[-A_5 \frac{Z-1.5}{6} \right] \quad (111)$$

$$A_0 = .9739 \qquad A_3 = 12.6124 \qquad (112)$$

$$A_1 = .0209 \qquad A_4 = .0558 \qquad (113)$$

$$A_2 = 4.3648 \qquad A_5 = 23.5254 \qquad (114)$$

P = core pressure (psi)

Q = core power density (peak) (kw/ft)

V = flooding velocity (in/sec)

Δt = mixture level in core (ft)

Z = mixture level in core (ft)

T = term (a temporary storage location in the computer program)

$$H = 0 \text{ if } Z < 1.0 \text{ ft} \qquad (115)$$

$$H = 1 \text{ if } Z \geq 1.0 \text{ ft} \qquad (116)$$

The RELAP4-FLOOD program sets the core outlet flow rate equal to the product of the core inlet flow rate and the carryover rate fraction.

5.2 Steam Generator Primary-to-Secondary Heat Transfer

A requirement of the Commission acceptance criteria is that heat transfer between the primary and secondary system be considered.

Requirements are given in the criteria by:

"7. Pressurized Water Reactor Primary-to-Secondary Heat Transfer. Heat transferred between primary and secondary systems through heat exchangers (steam generators) shall be taken into account. (Not applicable to Boiling Water Reactors.)"

In the reflood portion of the LOCA, heat is transferred in the steam generator from the secondary to primary side. A two-phase mixture from the core enters the inlet side of the steam generator and is converted to superheated steam. This conversion process leads to the "steam binding" effect which effectively limits the flood rate.

During the reflood phase of a loss-of-coolant accident, water flow in the secondary side of the steam generators is negligible. The secondary side heat transfer mode is therefore natural convection. Since the RELAP4-EM program does not have the natural convection mode, modifications were required to include this heat transfer mode in RELAP4-FLOOD. The RELAP4-FLOOD program requires two volumes for the secondary side of each steam generator. One volume initially contains only water and the other only steam. The water volume height is assumed to be equal to the total height of the primary side volumes (not including the inlet or outlet plenums). Heat is transferred from the primary side to the secondary side water. A typical steam generator nodalization is shown in Figure 5.2.

The secondary side heat transfer coefficient is calculated using an equation given by Brown and Marco^{29/} for long vertical cylinders as:

$$h = 0.13 k (a\Delta t)^{1/3} \quad (117)$$

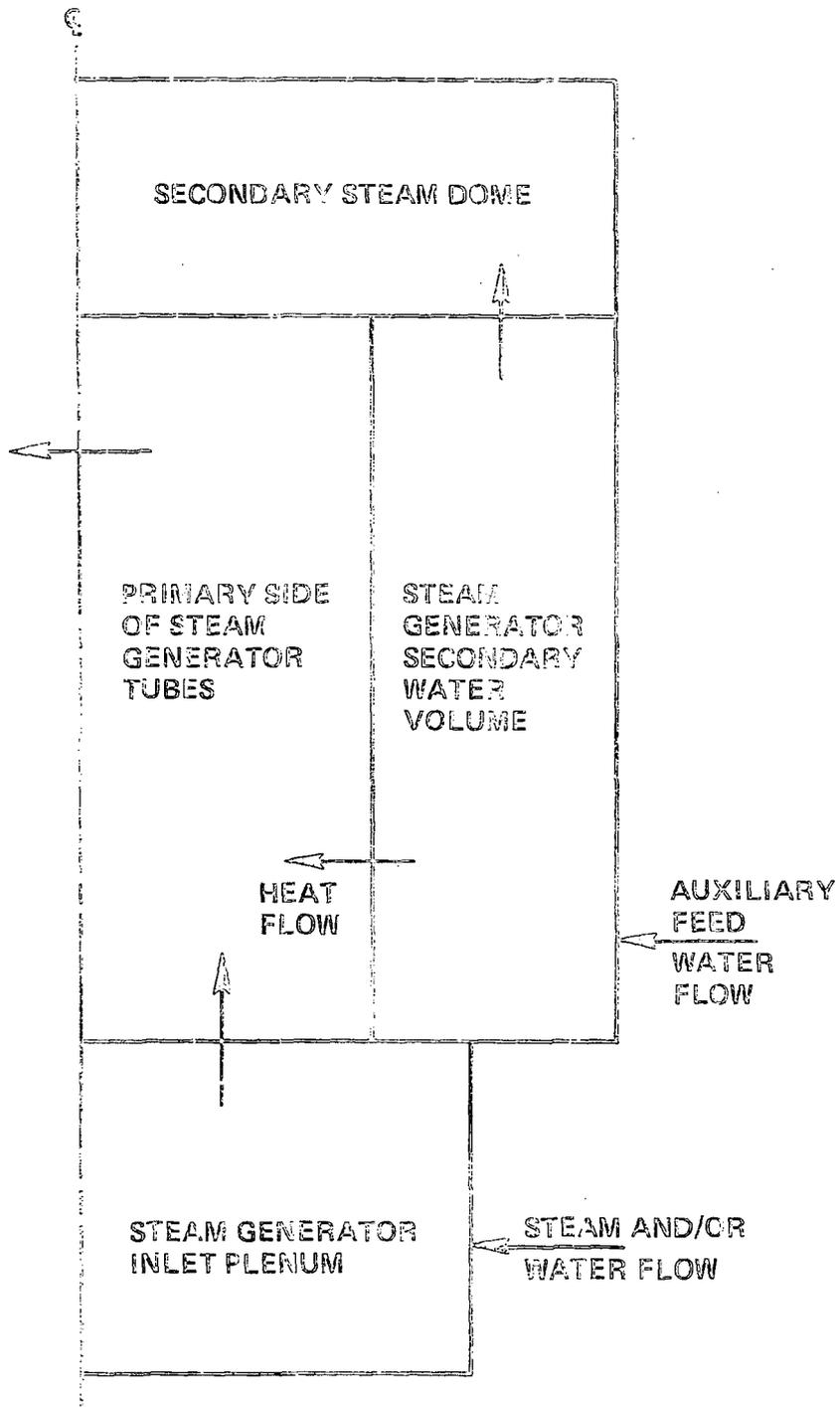


Figure 5.2 Typical Steam Generator Nodalization for RELAP4-FLOOD

where:

k = thermal conductivity of water, Btu/hr-ft $^{\circ}$ F

Δt = temperature difference, $^{\circ}$ F

$$a = \frac{g\beta\rho^2 C_p}{\mu k} \quad (118)$$

g = acceleration of gravity, ft/sec 2

β = coefficient of expansion, $^{\circ}$ F $^{-1}$

ρ = density, lbm/ft 3

C_p = specific heat at constant pressure, BTu/lbm $^{\circ}$ F

μ = viscosity, lbm/ft-hr

If the user desires to use the natural convection option, NSGV on the RELAP4-FLOOD program option input data cards is the number of steam generator primary volumes (not including inlet and outlet plenums) and the steam generator volume data card must be supplied. If NSGV is zero, the standard RELAP4-EM correlations are used for the secondary side heat transfer.

5.3 Broken Loop Cold Leg Nozzle Model

Part of the steam which is generated in the core during reflood passes through the intact loops to the downcomer and then flows around the top of the downcomer and out the broken loop cold leg nozzle to the containment. In some cases, the downcomer water level will exceed the elevation of the cold leg nozzles. If this happens, the normal RELAP4-EM calculation assumes a homogeneous mixing of the intact loop steam flow with the water above the bottom of the cold leg nozzle. The resulting

two-phase mixture then flows to the containment with no slip between the phases. This phenomenon was observed in early calculations to result in unreasonably large pressure drops between the downcomer and containment.

The two-phase flow regime expected when the downcomer fills and begins to overflow is that of a separated flow with slip between the phases as shown in Figure 5.3. Since RELAP4-EM currently has no provision for slip flow of this type, a special model was developed for RELAP4-FLOOD to simulate slip flow. The model is shown in Figure 5.4. The broken loop cold leg nozzle is divided into two pipes or RELAP4-EM junctions, each of which has a variable area. The area of the liquid slip junction is calculated as a function of the height of the mixture level above the bottom of the cold leg nozzle, i.e., H_f in Figure 5.3. The steam slip junction area is, thus, the true junction flow area minus the liquid slip junction area. The elevation of the intact loop nozzle is artificially raised by one-half the nozzle diameter to prevent mixing of the steam with the water in the downcomer. Since each junction now has a common pressure drop to the containment, each will flow at the velocity required to reach that pressure drop, thus simulating slip between phases for separated flow in a single pipe. The friction at the liquid-vapor interface is neglected in the model.

The junction and volume numbers input card described in the Input Data Section requires the downcomer volume number and the junction numbers for the steam and water slip junction. The user should also be

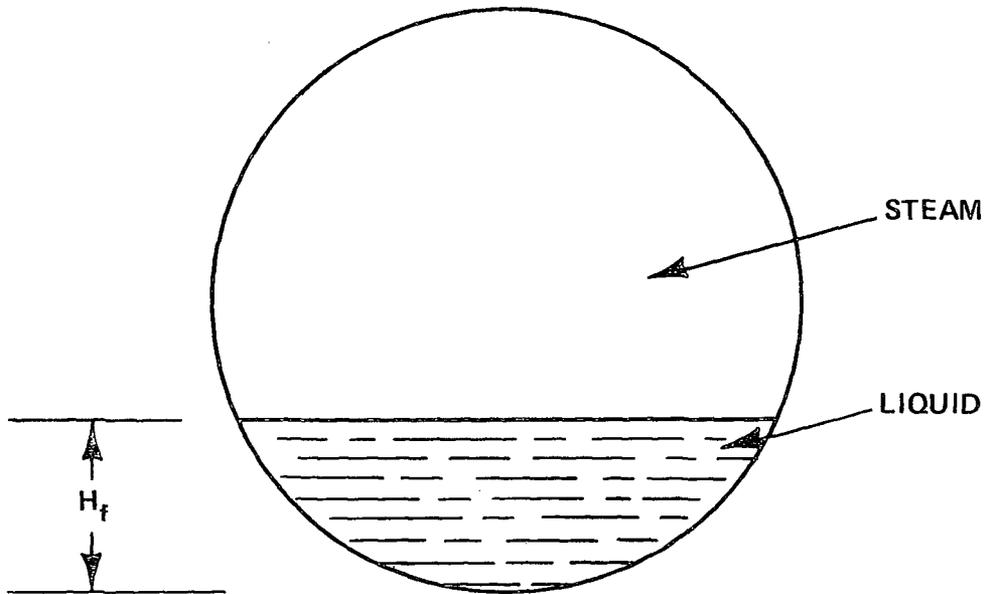


Figure 5.3 Flow Separation in Cold Leg Nozzle

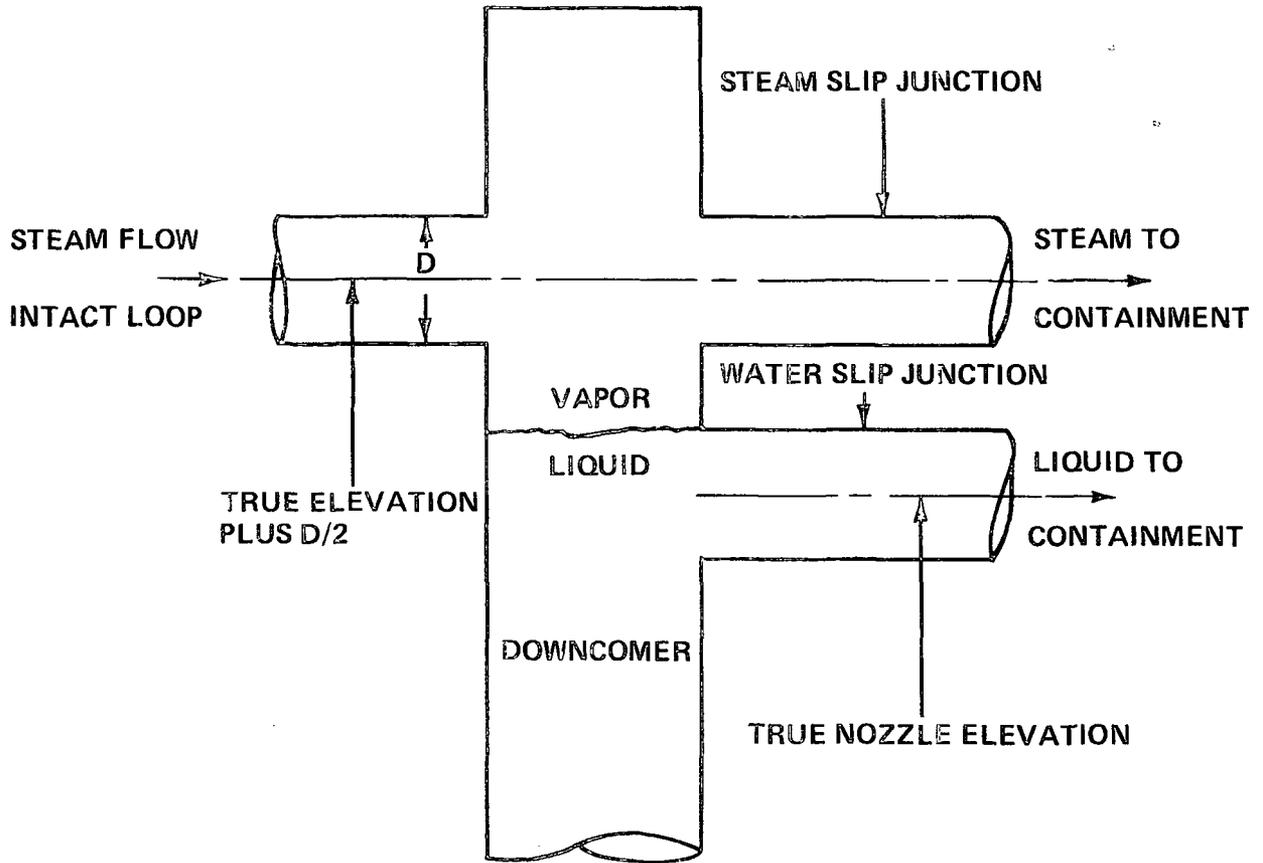


Figure 5.4 Upper Downcomer Nodalization for Cold Leg Nozzle Slip Flow

certain to specify the junction elevations on the RELAP4-EM junction data cards as shown on Figure 5.4. The junction areas on the RELAP-EM junction data cards for the slip junctions must sum to the true junction area.

5.4 Input Data Description for RELAP4-FLOOD

Input requirements for RELAP4-FLOOD consist of a complete RELAP4-EM input data deck as described in Section 3.10, Input Data Description for RELAP4-EM, and several additional input cards required for the RELAP4-FLOOD models as described below. The RELAP4-FLOOD program may be restarted as described in the RELAP4-EM Input Data Description.

Entrainment Correlation Option, 400001

W1 -I	IENT	=	entrainment correlation
		=	1, Babcock and Wilcox
		=	2, Aerojet A
		=	3, Aerojet B

FLECHT Heat Transfer Correlation Data, 400002

W1-R	DTSUB	=	subcooling temperature (°F)
W2-R	TINIT	=	maximum initial clad temperature (°F)
W3-R	QMAXFD	=	peak power input (kw/ft)
W4-R	BFFF	=	fraction of channel blockage
W5-R	HRAD	=	radiation heat transfer coefficient (Btu/hr-ft ² -°F). If HRAD = 0., code will compute a value
W6-R	CØRCHL	=	core channel length (ft)

Initial Clad Surface Temperatures, 4001YY

YY, 01 <YY< R, indicates the axial core slab number

W1-R TS(1) = surface temperatures

W1-R TS(2)

... ..

Steam Generator Volume Data, 4002YY

YY, 01 <YY< 12, indicates the steam generator primary volume number

W1-I NSGVOL(1) = steam generator secondary volume number
for each steam generator primary volume
number. A secondary volume number must
be input for each primary volume, even
if this volume is common to several
primary volumes.

W2-I NSGVOL(2)

... ..

Aerojet A Entrainment Correlation (if IENT = 2), 400003

W1-R EN2 = = entrainment fraction at liquid level = HC2

W2-R HC1 = liquid level (ft)

W3-R HC2 = liquid level (ft)

Core Outlet Enthalpy, 400004 (optional)

W1-R HCOUT = core outlet enthalpy (Btu/lbm)

Junction and Volume Numbers, 400005

W1-I JUNIN = core inlet junction number

W2-I JUNOUT = core outlet junction number

W3-I JUNWSL = water slip junction number

W4-I JUNSSL = steam slip junction number
 W5-I NCVOL = core volume number
 W6-I NUPVOL = upper plenum volume number
 W7-I NLPVOL = lower plenum volume number
 W8-I NDCVOL = downcomer volume number

5.5 Evaluation Model Options for RELAP4-FLOOD

The RELAP4-FLOOD computer program was developed to calculate the reflooding transient for a PWR. RELAP4-EM was the basic computer program that was used for the RELAP4-FLOOD code. Evaluation Model option flag, ISPRØG specified on the Problem Dimension Data Card (card 010001) should be set to two. By setting ISPRØG=2 all the Evaluation Model options are skipped. This option is used because the RELAP4-FLOOD computer program is used to calculate core flooding rate only. The peak cladding temperature for the refill and reflood portions of the transient are calculated by the TOODEE2 computer program. The Evaluation Model options that should be selected are described below.

<u>Option</u>	<u>Evaluation Model</u> <u>Input</u>	<u>Comment</u>
IENT (400001 card)	IENT = 1	Selects the Babcock and Wilcox entrainment correlation
NSGV (4002YY card)	NSGV ≠ 0	Selects the RELAP4-FLOOD steam generator heat transfer model
IHM (no input required)	IHM = 2	Uses Core model to compute core exit enthalpy

FLECHT Heat Transfer Correlation Data

BFFF BFFF = 0.0 Selects the fraction of channel blockage

Card C10001 Problem Dimension Data

ISPROG ISPROG = 2 Flag to select none of the evaluation model options to be used, only REFLOOD

6.0 TOODEE2 COMPUTER PROGRAM

TOODEE2^{35/} is a two dimensional, time-dependent fuel element thermal analysis program developed by the AEC Regulatory staff from the TOODEE^{34/} code. The current version of TOODEE2 was developed primarily as an evaluation tool to calculate fuel element thermal analysis during post-LOCA refill and reflood in a PWR. TOODEE2 used as an Evaluation Model tool does not take as its point of departure another current version of the program in the way that RELAP4-EM is a version of RELAP4. Rather, certain options are exercised in TOODEE2 which qualify as Evaluation Model options. In particular, a small break mixture level model, small and large break blowdown heat transfer models, and a radiation model exist in the program. These models are not currently qualified as Evaluation Models. No attempt has been made to run the program in anything but the r, z geometry with the current modifications. The modifications require operation with only 2 clad nodes. Film heat transfer considerations have been limited to one channel.

6.1 Cladding Computational Model

TOODEE2 considers r, z type geometry where the maximum numbers of radial and axial nodes are 12 and 50, respectively. One outer radial node represents the fluid channel. Two outer axial nodes provide the boundary condition at the inlet and outlet of the flow channel. Therefore, the maximum solid node matrix is 10 radial and 48 axial nodes.

TOODEE2 allows only two nodes in the fuel rod cladding. Details of these nodes are shown in Figure 6.1. The two cladding nodes are established such that variations in heat capacity and thermal conductivity reflect changing thickness of the inside and outside zircaloy oxide. The time-dependent thickness of the oxide layer is calculated and the thermal conductivity and heat capacity are modified to reflect the composition of oxide and zirconium properties. When the material properties are assigned in the input, the oxide material should be assigned to the outer clad node and the zircaloy metal properties assigned to the inner node. Composite heat capacities are then calculated by the program for the heat capacities and thermal conductivities.

6.2 Heat Transfer Correlations

TOODEE2 is principally used to calculate the fuel rod temperature response during the refill and reflood portion of a LOCA. For the reflood portion of the transient, the Commission acceptance criteria specify the heat transfer coefficient to be used. The criteria state for the reflood period:

"5. Refill and Reflood Heat Transfer for Pressurized Water Reactors. For reflood rates of one inch per second or higher, reflood heat transfer coefficients shall be based on applicable experimental data for unblocked cores including FLECHT results ("PWR FLECHT (Full Length Emergency Cooling Heat Transfer) Final Report," Westinghouse Report WCAP-7665, April 1971).

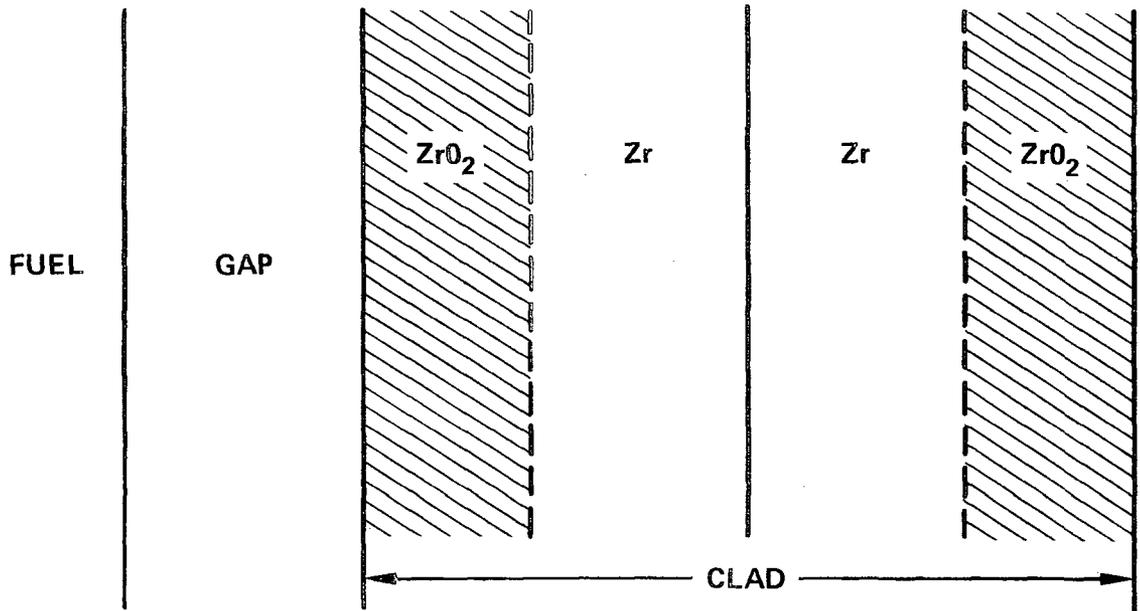


Figure 6.1 TOODEE 2 Fuel Rod Cladding Nodes

The use of a correlation derived from FLECHT data shall be demonstrated to be conservative for the transient to which it is applied; presently available FLECHT heat transfer correlations ("PWR Full Length Emergency Cooling Heat Transfer (FLECHT) Group I Test Report," Westinghouse Report WCAP-7544, September 1970; "PWR FLECHT Final Report supplement." Westinghouse Report WCAP-793L, October 1972) are not acceptable. New correlations or modifications to the FLECHT heat transfer correlations are acceptable only after they are demonstrated to be conservative, by comparison with FLECHT data, for a range of parameters consistent with the transient to which they are applied.

During refill and during reflood when reflood rates are less than one inch per second, heat transfer calculations shall be based on the assumption that cooling is only by steam, and shall take into account any flow blockage calculated to occur as a result of cladding swelling or rupture as such blockage might affect both local steam flow and heat transfer."

As specified by the criteria, the heat transfer during refill and reflood, when reflood rates are less than one inch per second, shall be based on steam cooling only. For Evaluation Model calculations, two heat transfer correlations are used. For steam cooling, the Dittus-Boelter heat transfer correlation is used, and for reflood heat transfer, a modified FLECHT correlation is used. Each of these will be discussed in more detail.

Because TOODEE2 has been used for other fuel rod temperature profile calculations, a number of other heat transfer correlations is available to the user. The heat transfer logic from RELAP⁴ has largely been adopted for blowdown calculations in TOODEE2. For a full discussion of fluid properties, blowdown heat transfer logic, and surface heat flux convergence methods, the reader is referred to the TOODEE2^{35/} document.

Calculation of the reflood heat transfer coefficient uses a correlation devised in the Westinghouse PWR FLECHT program^{26/} and modified to account for variable flooding rate. The variable flooding rate correction is that suggested in the final FLECHT report.^{27/} Three options are available if the flooding rate falls below one inch/sec:

1. Use the FLECHT correlation.
2. Use the FLECHT correlation below the quench front and steam cooling at or above the quench front. (The quench front here is assumed to be $h \geq 50$ BTU/hr-ft $^{-\circ}\text{F}$ as calculated by the FLECHT correlations.)
3. Use the FLECHT correlation below the blockage plane and steam cooling at or above the blockage plane.

The steaming rate used for the steam cooling calculation is the user-supplied inlet flow rate in lbs/hr. If blockage has been predicted (after rupture) then the mass velocity in the blocked region is modified

to approximate the results of COBRA calculations performed for blocked subassemblies. The mass velocity fraction as a function of axial elevation is given in Figure 6.2.

When the FLECHT correlation is used, the sink temperature is set to saturation. When steam cooling is used, the adjacent node quality is set to 1., and a steam energy balance is performed. An input option determines whether or not blockage shall be considered in the FLECHT correlations.

If heat transfer coefficients are determined from tabular values, a minus sign prefixes the overall HTR integer.

6.3 Surface Radiation Model

A surface radiation model is provided in the TOODEE2 computer program. This model is not presently part of the Evaluation Models, but was incorporated to perform sensitivity studies. The model is used to simulate radiation from a hot ruptured node to a cooler unruptured node that is adjacent. Radiation from a rupture node surface is determined by the equation

$$q'' = F_{so} (T_s^4 - T_o^4) \quad (117)$$

where:

q'' = surface radiation heat flux

F_{so} = radiation interchange factor

T_s = surface temperature of ruptured node

T_o = surface temperature of unruptured adjacent node.

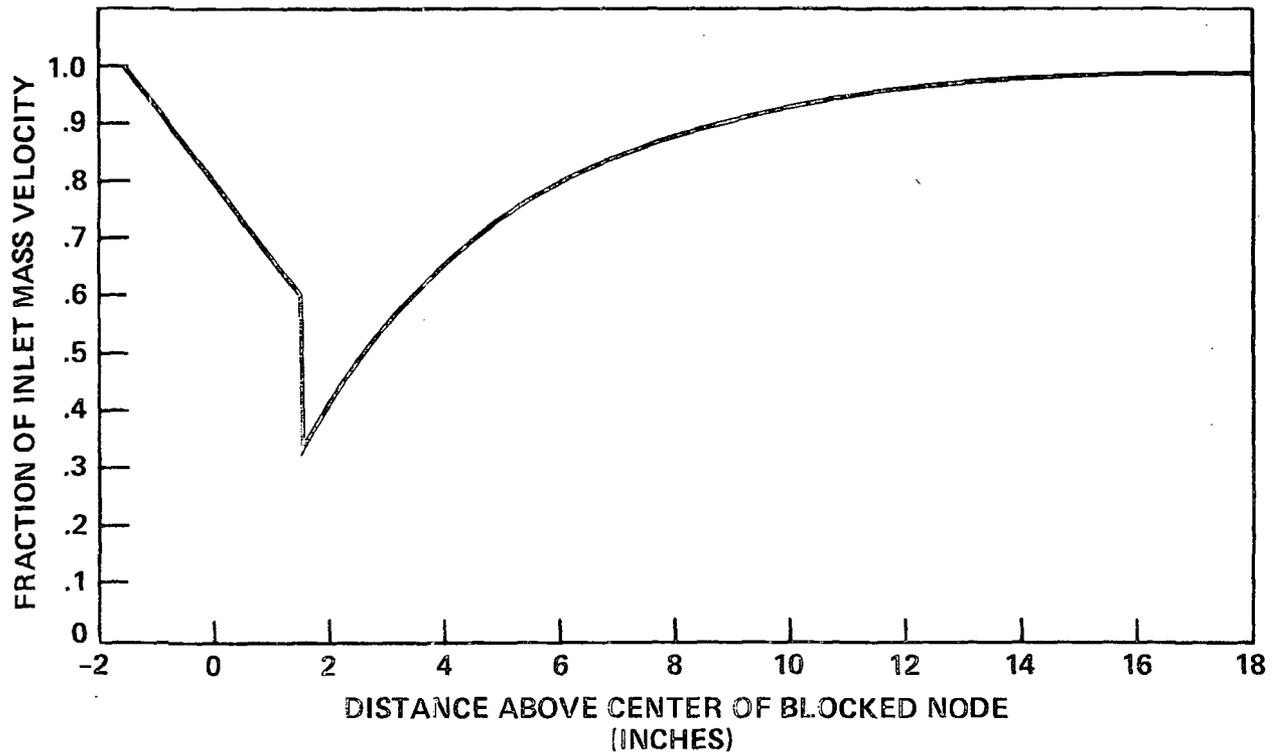


Figure 6.2 Fraction of Inlet Mass Velocity
vs.
Distance from Center of Blocked Node

The intention of using the unruptured adjacent node is to simulate an unruptured node of a pin adjacent to the hot pin. The radiation interchange factor is:

$$F_{so} = 1/[1/\epsilon_s + R_s/R_o(1/\epsilon_o - 1)] \quad (118)$$

where:

ϵ_s = emissivity of the ruptured cladding node

ϵ_o = emissivity of the adjacent cladding node

R_s = clad radius (inches)

R_o = effective radius of radiation sink (inches)

The effective radius of the radiation sink can be input or determined in the following manner. The radiation sink geometry for the ruptured core is shown in Figure 6.3. A subassembly containing the ruptured rod of interest (RR) and its immediate neighbors (RD and RA) is considered. The ruptured rod is assumed to swell according to the radial expansion data given in Table 6.1. Half-rods (RA) immediately adjacent to RR are not considered to swell. Diagonal quarter rods (RD) are considered to swell an amount such that the blockage in the subassembly is that specified by Table 6.2 for the rupture ΔP in rod RR (the ruptured rod). The rods RD are considered to be at the temperature of the ruptured rod RR whereas unruptured rods RA are at the adjacent node temperature.

Thus, the rod radius ratio R_s/R_o is given by:

$$R_s/R_o = (R_{RR} + R_{RD})/2R_{ra} \quad (119)$$

where R represents the respective rod radii.

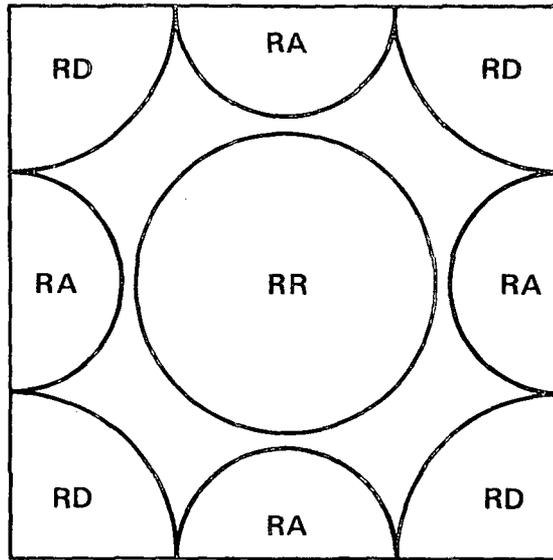


Figure 6.3 Radiation Sink Geometry

TABLE 6.1
RADIAL EXPANSION VS. ΔP

<u>Pressure Difference Across Cladding</u>	<u>Best Estimate Radial Expansion</u>
0 psig	60%
100	60%
200	32%
400	25%
600	35%
800	46%
1000	54%
1200	60%
1400	62%
1600	60%
1800	56%
2000	48%
2200	38%
2400	30%

TABLE 6.2

ASSEMBLY AVERAGE FLOW BLOCKAGE VS. ΔP

<u>Pressure Difference Across Cladding</u>	<u>Maximum Assembly^{2/} Average Flow Blockage</u>
0 psig	80%
100	80
200	60
400	30
600	35
800	55
1000	70
1200	78
1400	77
1600	73
1800	67
2000	57
2200	52
2400	30

The above surface radiation model has been used to evaluate the effect of unruptured rods at lower temperature in the region of ruptured rods.

6.4 Input Data Description for TOODEE2

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
1	I1,12A6	1	ISHAPE	Geometry selection 1 = R- θ , 2 = R-Z, 3 = X-Y
		2-13	TITLE(I)	Alphanumeric title information
1A	12A6	1-12	ZZ(I)	Optional additional title information
2	-	-	-	Blank card
3	6E12.6	1-6	RA(I)	Radial grid line locations in ascending order on consecutive cards until list is complete (inches)
4	-	-	-	Blank card
5	6E12.6	1-6	AX(J)	Axial grid line locations in ascending order on consecutive cards until list is complete (inches)
6	-	-	-	Blank card
7	4E12.6	1 2-4	CW(1) CW(N)	Pitch of channel 1 (inches) Unused channel widths
8	-	-	-	Blank card
9	I1,E11.6,	1	II	1 designates block
	5E12.6	2	RBLD(1,K)	Location of radial grid line forming left boundary of block (inches)
		3	RBLD(2,K)	Location of radial grid line forming right boundary of block (inches)

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
		4	ABLD(1,K)	Location of axial grid line forming lower boundary of block (inches)
		5	ABLD(2,K)	Location of axial grid line forming upper boundary of block (inches)
		6	MB(K)	Material number of block
9A	I1,E11.6,	1	I1	2 designates gap
	5E12.6	2	RBLD(3,K)	Radial gap width (inches)
		3	MGR(K)	Material number of gas in gap
		4	CCR(K)	Radial contact coefficient (Btu/hr-ft ² -F) (Default to 1.0 x 10 ⁵)
		5	ABLD(3,K)	Axial gap width (inches)
		6	MGA(K)	Material number of gas in gap
		7	CCA(K)	Axial contact coefficient (Btu/hr-ft ² -°F)

Note: Up to 36 blocks may be assigned in any order. Requirements are that each block be homogeneous in composition and its boundaries coincide with grid lines. Properties are assigned only as follows:

UO₂ - material 1

Zr - material 3

ZrO₂ - material 4

Gas gap - material 2

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
				Because of specialized calculational schemes, the last three radial grid lines must be material boundaries. Blocks encompassing the last radial mesh space are material 4. Blocks encompassing the next to last mesh space are material 3. All other internal spaces are assigned material 1. Blocks with material 1 are assigned a radial gap. No other gaps are assigned.
10	-	-	-	Blank
11	2I6	1	JX	Lowest axial position of initial plastic strain.
		2	JY	Highest axial position of initial plastic strain.
11A	6E12.6	odd	EPR(J)	Radial strain at consecutive ascending axial positions from JX to JY.
		even	EPA(J)	Axial strain of consecutive ascending axial positions from JX to JY.
				Note: As many cards of type 11A to satisfy JX to JY.
12	-	-	-	Blank
13	6E12.6	1	RMIN	Left radial temperature block boundary (inches)
		2	RMAX	Right radial temperature block boundary (inches)
		3	AMIN	Lower axial temperature block boundary (inches)

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
		4	AMAX	Upper axial temperature block boundary (inches)
		5	T	Temperature with specified block (°F).
				Note: As many cards as needed to specify entire mesh. Assignments to sink or coolant are made by setting both boundary assignments in one direction equal to the proper exterior boundary. The remaining boundaries specify the interval for which the given temperature applies. This card group may be overridden by group 27.
14	-	-	-	Blank Card
15	8X,I4,	1	NZP	Non-zero punch
	4E12.6	2-5	TSAT(N)	Steady state saturation temperature. Only channel 1 of interest
15A	8X,I4,	1		Nonzero punch
	4E12.6	25	FILML(N)	Lower film boiling limit. Not used in TOODEE2.
16	-	-	-	Blank
17	8X,I4,	1	NI	Material number
	4E12.6	2	RMELT(NI,1)	Melting temperature (°F)
		3	RMELT(NI,2)	Heat of fusion (Btu/ft ³)
		4	RMELT(NI,3)	Vaporization temperature (°F)

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
		5	RMELT(NI,4)	Heat of vaporization (Btu/ft ³) Note: One card for each material. Temperature boundaries in ascending order.
18	-	-	-	Blank
19	2I6, 5E12.6	1 2	II JJ	Location of first datum on card Number of entries on card
		3-7	AVAIL(K)	Data. All defaults are 0.0 except as noted.

Note: As many cards as needed to specify stated options. A data list follows wherein the location number refers to the subscript of AVAIL(K).

Location NumberData

1	Initial time (sec)
2	Initial pin average linear heat generation rate (kw/ft)
3	Metric-English energy conversion 3412.75 Btu/hr-kw
4	Point-to-average power distribution base 0.0 - Unity average in fuel area 1.0 - Unity average at a particular point -1.0 - Use as specified
5	X or R point number at which power distribution is unity

<u>Location Number</u>	<u>Data</u>
6	Y, Z, or θ point at which power distribution is unity
7	Number of time steps between print out of results
8	Number of transient time-power data pairs (-0.0 for s.s) Any negative number at this location will allow reading in eight tables: time-quality, time-flow (lbs/sec), time-inlet temperature ($^{\circ}$ F), time-relative power, time-saturation temperature ($^{\circ}$ F), time-flooding rate (in./sec), time-mixture level (ft), and time-steaming rate (lbs/sec).
9	Initial time increment for calculation (sec)
10	Time at which use of second time increment is begun (sec)
11	Second time increment (sec)
12	Time at which use of third time increment is begun (sec)
13	Third time increment (sec)
14	Time at which use of fourth time increment is begun (sec)
15	Fourth time increment (sec)
16	Problem termination time (sec)
17	Final temperature distribution punch control 0.0 - No punch 1.0 - Punch requested

<u>Location Number</u>	<u>Data</u>
18	Radial point (X or R) for maximum temperature test. No test if = 0.0
19	Y, Z, or θ point for maximum temperature test
20	Maximum temperature allowed at specified point ($^{\circ}$ F). Program stops if this value is reached.
21	Convergence criterion for surface heat flux
22	Nonzero to suppress gap width print out
23	The initial constant thickness of ZrO_2 (mils).
24	Steady state value for inlet quality. Not needed if location 8 is negative and $NXQ > 0$
25	Steady state value for inlet mass flow (lbs/sec). Not needed if location 8 is negative and $NFL > 0$
26	Steady state value for inlet temperature ($^{\circ}$ F). Not needed if location 8 is negative and $NTI > 0$
27	Effective core flow area (ft^2). Adjustment of this factor allows for a flow factor such as 0.8.
28	Blowdown heat transfer correlations. The number determines the two phase post DNB turbulent correlation as follows: <ul style="list-style-type: none"> 0. - Groeneveld (5.9) 1. - Groeneveld (5.7) 2. - Dougall-Rohsenow 3. - Condie-Bengston (Presently not available)

<u>Location Number</u>	<u>Data</u>
29	Effective roughness (mils) in the sum of the arithmetic mean roughness heights of the fuel and cladding.
30	UO ₂ percent theoretical density.
31	Reflood inlet sub-cooling (°F). If number is negative sub-cooling is calculated by subtracting inlet temperature from saturation temperature.
32	Flow blockage fraction $\leq 0.$, blockage calculated from Table 6.2 after rupture.
33	Time of DNB (seconds).
34	Start time for adiabatic heatup (seconds).
35	Start time for reflood (BOCREC) (seconds).
36	Reflood heat transfer correlation. Only correlation is option 0.0. at this time. <0 , neglect blockage in FLECHT correlation. Any decimal fraction specifies future low flood rate correlation. Presently ignored.
37	Initial reflood coefficient, H_o or H_{rad} (Btu/hr-ft ² -°F).
38	Estimated hot gas pressure (p.s.i.a.)
39	Mole fraction helium in gap.
40	Mole fraction argon in gap.
41	Mole fraction hydrogen in gap.

<u>Location Number</u>	<u>Data</u>
42	Mole fraction nitrogen in gap.
43	Mole fraction krypton in gap.
44	Mole fraction xenon in gap.
45	Axial node which has ruptured. If rupture has not occurred value should be 0.0.
46	Mean outside swollen radius of ruptured node (inches). ≤ 0 , swollen radius calculated from Table 6.1
47	Cold fuel plenum volume (cubic inches).
48	Axial Conduction option: 0.0 - No axial conduction 1.0 - Axial conduction included.
49	Preset rupture time. If < 0 , rupture calculated from Table 6.3.
50	Low Flood rate options: 1.0 - Use FLECHT correlation 0. - Use low flood rate methods .0 - Entrainment (FLECHT correlation) only below ruptured node. .1 - Entrainment (FLECHT correlation) only below quench front.
51	Steady state flooding rate (inches/sec). Not needed if AVAIL (8) < 0 . and NFR > 0 .
52	Effective external radiation sink radius (inches) (> 0). Calculation ignored ($= 0$) Calculated as per Section 6.3 (< 0)

TABLE 6.3

RUPTURE TEMPERATURE VS. ΔP

<u>Pressure Difference Across Cladding</u>	<u>Average Rupture Temperature</u>
0 psi	2500°F
100	2200
200	1820
400	1730
600	1660
800	1600
1000	1540
1200	1480
1400	1440
1600	1400
1800	1370
2000	1335
2200	1310
2400	1280

<u>Location Number</u>	<u>Data</u>
53	Cladding emissivity
54	Fuel pellet emissivity
55, 56, 57	Reflood heat transfer factors for periods I, II, and III, respectively.
58	Number of gram moles of gas in pin.
59	Fuel plenum temperature, °F (>0) Constant whose absolute value is added to upper coolant temperature to obtain plenum temperature (<u><</u> 0)
60	Pellet shoulder radius (inches).
61	Plot scan parameter. Number before decimal is lower axial range. Number after is one one-hundredth of upper range, (e.g., 6.111 means save fuel and clad temperatures between nodes 6 and 11 for plot selection.
62	Gap convergence criterion. Fuel surface temperatures must converge within this value.
63	Lower X value of plot. If <u><</u> 0, default value is start time of calculation.
64	Upper X value of plot. If <u><</u> 0, default value is end time of calculation.
65	Lower Y value of plot. If <u><</u> 0, default value is 200°F.

<u>Location Number</u>	<u>Data</u>
66	Upper Y value of plot. If ≤ 0 , default value is 3200°F.
67	Minimum flood rate for using high flood rate FLECHT correlations if integer part of location 50 is 0.
68	Steady state steaming rate (lbs/sec). Not needed if AVAIL (8) < 0 and NSR > 0 or if NML=0.

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
20	-	-	-	Blank Card
				Note: Card groups 21, 23 & 25 are power distribution data. Where distribution is separable, i.e., can be specified as a product of functions in each direction, use 21 and 23. For non-separable distributions, use 25. Power distribution data defined only at internal mesh points.
21	2I6,5E12.6, 1	1	I	Axial coordinate of first datum on card.
		2	JJ	Number of entries on card.
		3-7	AXPOW(J)	Axial power distribution in ascending order of J.
				Note: As many cards as needed to satisfy desired axial power distribution.
22	-	-	-	Blank Card
23	2I6,5E12.6, 1	1	I	Radial coordinate of first datum on card.

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
		2	II	Number of entries on card.
		3-7	RAPOW(I)	Radial power distribution in ascending order of I. Note: As many cards as needed to satisfy desired radial power distribution.
24	-	-	-	Blank Card
25	314,5E12.6,	1	I	Radial coordinate of all data on card.
		2	J	Axial coordinate of first datum on card. Data in ascending order of J on each card.
		3	JJ	Number of entries on card
		4-8	POW(I,J)	Non-separable power distribution data. Note: As many cards as needed to satisfy desired power distribution.
26	-	-	-	Blank Card
27	10X,3110	1	IMAX	Number of radial nodes
		2	JMAX	Number of axial nodes
		3	NIT	Temperature distribution type <0 - Parabolic fit (data described in group 27A.) >0 - Point-by-point (data described in group 27B.)
27A	5E12.6	1	TBP(J)	Volumetric average fuel temperature (°F).
		2	STH(J)	Fuel surface temperature (°F)
		3	STL(J)	Clad inside surface temperature (°F).

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
		4	STR(J,1)	Clad outside surface temperature (°F)
		5	TE(IMAX,J)	Fluid temperature (°F)
				Note: One type 27A card for each axial distribution.
27B	6E12.6	1-6	TE(I,J)	Temperatures in °R for every point in the mesh from point (1,1) to (IMAX, JMAX) in ascending order of I and J, respectively. All fields must be full up to (IMAX, JMAX). Use as many cards as needed.
				Note: If card 27 calls for temperature data, the data obtained from 27A or 27B supercedes that obtained in group 13.
28	-	-	-	Blank Card
29	2I6	1	JX	Lower axial node point of first outside oxide thickness specified.
		2	JY	Upper axial node point of last outside oxide specified.
29A	6E12.6	1-6	XRI(J)	Oxide thickness (ft.) at each node point inclusive of numbers specified in Card 31. As many cards are used as are needed to satisfy Card 29.
				Note: If no value is specified for an axial elevation or if group 29 is omitted default is to thickness specified by AVAIL (23).
30	-	-	-	Blank Card
31	2I6	1-2	JX,JY	Same as card 29 for inside oxide

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
31A	6E12.6	1-2	XR2(J)	Same as card 29A for inside oxide
32	-	-	-	Blank Card
33	I12	1	NHT	Number of entries in table (<u><</u> 100) (Optional table)
33A	10x, 2E16.8	1	CHT(Even)	Time (sec.)
			CHT (Odd)	Heat transfer coefficient (Btu/ hr-ft ² -°F).
				Note: One card of type 35A for each time in the table for first channel.
34	-	-	-	Blank Card
				Note: The following card group reads in transient data. If AVAIL (8) = 0.0 this group should not be included. If AVAIL (8) >0.0 only subgroup 35 is used. If AVAIL (8) <0.0 then subgroups 35A through 35G are used and not 35.
35	10X,2E16.8	1	CBP	Time (seconds)
		2	DRP	Fraction of full power
				Note: Number of cards equal to AVAIL (8)
35A	I12	1	NXQ	Number of pairs in time-quality table.
35A1	10X,2E16.8	1	CXQ(even)	Time (sec.)
		2	CXQ(odd)	Quality
				Note: Number of 35A1 cards equals NXQ. If NXQ <u>≤</u> 1. AVAIL (24) used for constant quality.

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
35B	I12	1	NFL	Number of pairs in time-flow table
35B1	10X,2E16.8	1	CFL(even)	Time (sec.)
		2	CFL(odd)	Flow (lbs/sec.)
				Note: Number of 35B1 cards equals NFL. If NFL \leq 1, AVAIL (25) used for constant flow.
35C	I12	1	NTI	Number of pairs in time-inlet temperature table
35C1	10X,2E16.8	1	CTI(even)	Time (sec.)
		2	CTI(odd)	Inlet temperature ($^{\circ}$ F)
				Note: Number of 35C1 cards equals NTI. If NTI \leq 1 AVAIL (26) used for constant inlet temperature.
35D	I12	1	NPO	Number of pairs in time-power table.
35D1	10X,2E16.8	1	CPO(even)	Time (sec.)
		2	CPO(odd)	Fraction of full power
				Note: Number of 35D1 cards equals NPO.
35E	I12	1	NTS	Number of pairs in time-saturation temperature table.
35E1	10X,2E16.8	1	CTS(even)	Time (sec.)
		2	CTS(odd)	Saturation temperature ($^{\circ}$ F)
				Note: Number of 35E1 cards equals NTS. If NTS \leq 1, TSAT(N) from card 15 is used for constant saturation temperature. If the time on

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
				the last card in this group is less than the time on the last card in group 35C1, the saturation temperature is set equal to the inlet temperature determined from the 35C1 table.
35F	I12	1	NFR	Number of pairs in time-flood rate table.
35F1	10X,2E16.8	1	CFR(even)	Time (sec.)
		2	CFR(odd)	Flooding rate (in./sec.)
				Note: Number of 35F1 cards equal NFR. If NFR \leq 1, AVAIL (51) used for constant flooding rate.
35G	I12	1	NML	Number of pairs in time-mixture level table.
35G1	10X,2E16.8	1	CML(even)	Time (sec.)
		2	CML(odd)	Mixture level (feet)
				Note: Number of 35G1 cards equals NML.
35H	I12	1	NSR	Number of pairs in time-steaming rate table.
35H1	10X,2E16.8	1	CSR(even)	Time (sec.)
		2	CSR(odd)	Steaming rate (lbs/sec.)
				Note: Number of 35H1 cards equals NSR. If NSR $<$ 1, AVAIL (68) used for constant steam flow.
36	-	-	-	Blank Card
37A	I12	1	NR	Number of rupture temperature - ΔP pairs

<u>Card Number</u>	<u>Card Format</u>	<u>Field Number</u>	<u>Variable Name</u>	<u>Description</u>
37A1	6E12.6	odd	DRP(even)	Pressure difference (psid)
		even	DRP(odd)	Rupture temperature (°F)
37B	I12	1	NA	Number of blockage fraction - ΔP pairs.
37B1	6E12.6	odd	DPA(even)	Pressure difference (psid)
		even	DPA(odd)	Blockage fraction
37C	I12	1	NU	Number of plastic strain - ΔP pairs
37C1	6E12.6	odd	DPU(even)	Pressure difference (psid)
		even	DPU(odd)	Plastic strain at rupture ($\Delta D/D$)

Note: In groups 37A1, B1, C1 there are three pairs per card. Sufficient cards are required to satisfy NR, NA, & NU. Current tables for 37A1, B1, C1 are tables 6.1, 6.2 and 6.3.

6.5 Evaluation Model Options for TOODEE2

The TOODEE2 computer program was developed from the TOODEE computer code. Many options available in the original TOODEE program³ have been mentioned and new options added for Evaluation Model calculations. Many of these options do not necessarily comply with the analytical models developed for the NRC Evaluation Model, but have been included in the program to perform sensitivity analyses or to audit calculations. The following list of input variables is included to specify options that were used for the Evaluation Model. Since TOODEE2 is initialized from RELAP4-EM at the "end of bypass" much of the input data is taken from the RELAP4-EM output.

<u>Option</u>	<u>Evaluation Model Selection</u>
Radial Grid Line Location	Third from last entry must be the cold clad inside diameter. Last entry must be the cold clad outside diameter. NOTE: this requires that the clad consist of two and only two clad nodes.
Block Data	
Block 1 (Material number 1) <u>Fuel Material</u>	The right boundary must coincide with cladding inside diameter.
Block 1 (Material number 2) <u>Gap</u>	The gap size must be the same as the cold gap size in RELAP-4EM.
Block 2 (Material number 3) <u>Cladding Material(Zr)</u>	The right boundary must be the same as the middle node in the cladding.

Block 3 (Material number 4) <u>Cladding</u> <u>Oxidized Material</u> (ZrO ₂)	The right boundary must be the same as the cladding outside diameter.
Initial Permanent Strain	Strain values should be obtained directly from the RELAP4-EM hot channel calculation at the "end of bypass."
Initial Time	The problem start time in the nearest major edit to the end of bypass from the RELAP4-EM output.
Initial pin average linear heat generation rate	The average kW/ft obtained from the RELAP4-EM hot channel calculation at the end of bypass.
UO ₂ percent theoretical density	The density used that corresponds to that required by densification.
Inlet Subcooling	The value is obtained from the RELAP4-FLOOD run.
Start Time for Adiabatic Heatup	The time of end of bypass should be used which eliminates the steam cooling calculation.
Start of Reflood	Determined from the RELAP4-EM accumulator delivery calculation.
Reflood Heat Transfer Correlation	Should input -0.1 so that no blockage is used in the FLECHT correlation.
Initial Reflood Coefficient	Determine the value from the FLECHT data.
Estimated Hot Gas Pressure	Determine the gas pressure from the RELAP4-EM hot channel calculation.
Mole Fraction for Gap Gas	The mole fraction should be determined from a fuel pin design code and should be the same as the RELAP4-EM input.

Axial Node that has ruptured	If rupture has occurred in the RELAP4-EM hot channel calculation value corresponding to RELAP node should be used. If rupture has not occurred use 0.0.
Mean Outside Swollen Radius	Only ≤ 0 option is needed if prior rupture has not occurred. If prior rupture has occurred, number ignored and plastic strain tables are used.
Cold Fuel Plenum Volume	Should be determined from a fuel pin design code and should be the same as the RELAP-EM hot channel, hot pin.
Axial Conduction Option	Select no axial conduction.
Preset Rupture Time	<u>Unruptured</u> < 0 <u>Rupture</u> the time of rupture as determined by RELAP4-EM hot channel must be <time of end of bypass.
Beginning of Entrainment	The time at which entrainment is assumed to begin. The value is obtained from the RELAP4-FLOOD code and the FLECHT data.
External Radiation Sink Radius	Value should be zero so that surface radiation is not used.
Number of Gram Moles of Gas in Pin	Value should be obtained from a fuel design code and should be the same as the value in RELAP-EM hot channel (the hot rod).
Initial Temperature Distribution	The temperatures from the RELAP4-EM hot channel-hot pin are used, at the time that end of bypass occurs.
Outside and Inside Oxide Distribution	The values are determined from the RELAP4-EM hot channel, the hot pin oxidation thickness.
Transient Data	The following tables are used in the present Evaluation Model 1) Time-Power Data 2) Time-Saturation Temperature Data 3) Time-Flooding Rate Data 4) Rupture Table 5) Blockage Table 6) Unit Plastic Strain Table

Time-Power Data	The normalized power should be obtained from a RELAP4-EM calculation.
Time-Saturation Temperature Data	Pressure is obtained from the RELAP4-EM and RELAP4-FLOOD computer programs.
Time-Flooding Rate Data	Flooding rate data are obtained from the RELAP4-FLOOD calculation.
Rupture Tables	Data are obtained from the RELAP4-EM swelling table for a single pin.
Blockage Table	Data are obtained from the RELAP4-EM multiple pin blockage data table.
Unit Plastic Strain Table	The data are obtained from converting the single pin blockage data in the RELAP4-EM data to a strain equivalent to unit blockage.

6.6

Error Messages

The input data for TOODEE are checked for self-consistency and compatibility with the program at the beginning of a problem. Certain quantities are also checked during program execution to avoid using undefined values for them. Whenever an error is detected, an error identification number and an index number are printed in the program output and the problem is terminated by an overflow trip. The error identification numbers and their respective causes are listed in this section.

The index number is an aid for determining which data were in error or the location in the mesh where an error was detected. An index of zero is given to errors which have either an obvious location or where the location is not relevant. Where a single index is described, the index number will be a one- or two-digit number. For example, if the material number assigned to block four exceeded eight, the following message would be written:

ERROR 1302 INDEX 4

where two index numbers are described, the first one is given by the first one or two digits in the number printed (since leading zeros are suppressed), and the second is given by the last two digits printed. For example, if the point (3,4) was interior to more than one block, the following error message would be written:

ERROR 1510 INDEX 304

<u>Error Number</u>	<u>Cause of Error</u>
1200	Improper geometry specification; index=0
1201	There are too many grid lines in the X-direction; possible missing blank card; index=grid line number I.
1202	There are too many grid lines in the Y-direction; possible missing blank card; index=grid line number I.
1300	An upper block boundary in X-direction is smaller than the corresponding lower boundary; index=block number K.
1301	An upper block boundary in Y-direction is smaller than the corresponding lower boundary; index=block number K.
1302	A block material number is too large; index=block number K.
1303	A block material number is too low; index=block number K.
1304	The material number of the gas in a gap along the X-boundary of a block is too large; index=block number K.
1305	The material number of the gas in a gap along the X-boundary of a block is too low; index=block number K.
1306	The material number of the gas in a gap along the Y-boundary of a block is too large; index=block number K.
1307	The material number of the gas in a gap along the Y-boundary of a block is too low; index=block number K.
1308	There are too many blocks; index=0.

<u>Error Number</u>	<u>Cause of Error</u>
1309	The X-grid lines are not in ascending sequence; index=grid line number I which is out of order.
1310	The Y-grid lines are not in ascending sequence; index=grid line number J which is out of order.
1311	There are too many X-grid lines; index=0.
1312	There are too many Y-grid lines; index=0.
1402	There are too many X-grid lines designated as block boundaries; index=0.
1405	There are too many Y-grid lines designated as block boundaries; index=0.
1408	A block boundary in the X-direction does not coincide with any boundary grid line; index=number of boundary IG.
1410	A block boundary in the Y-direction does not coincide with any boundary grid line; index=number of boundary JG.
1500	There are less than two block boundaries in the X- direction; index=0.
1501	A low block boundary in the X-direction does not correspond to any boundary grid line; index=block number K.
1504	An upper block boundary in the X-direction does not correspond to any boundary grid line; index=block number K.

<u>Error Number</u>	<u>Cause of Error</u>
1505	There are less than two block boundaries in the Y-direction; index=0.
1506	A low block boundary in the Y-direction does not correspond to any boundary grid line; index=block number K.
1509	An upper block boundary in the Y-direction does not correspond to any boundary grid line; index=block number K.
1510	The point (I,J) in the mesh is interior to more than one block; index=point coordinates I, J.
1511	A gap along an X-grid line is in more than one block; index=X-boundary number, Y-point number.
1512	A gap along a Y-grid line is in more than one block; index=Y-boundary number, X-point number.
1513	A point in the mesh is not in any block; index=point coordinates I, J.
1600	A boundary location in the X-direction was negative; index=boundary number IG.
1601	A boundary location in the Y-direction was negative; index=boundary number JG.
1700	An upper temperature block boundary in the X-direction is smaller than the lower boundary; index=initial temperature card number.

<u>Error Number</u>	<u>Cause of Error</u>
1701	An upper temperature block boundary in the Y-direction is smaller than the lower boundary; index=initial temperature card number.
1702	The sink temperature boundary is not in the system; index = initial temperature card number.
1703	The sink temperature boundary is interior to the mesh; index = initial temperature card number.
1704	A temperature block boundary in the X-direction does not coincide with any grid line; index=initial temperature card number.
1707	A temperature block boundary in the Y-direction does not coincide with any grid line; index=initial temperature card number.
1708	An internal point temperature has not been assigned; index = coordinates of point I, J.
1709	The material phase change temperature boundaries are not in ascending order; index=material number Jth temperature boundary.
1710	There are too many power distribution data points in the Y-direction; index=number of data points.
1711	There are too many power distribution data points in the X-direction; index=number of data points.
1712	Array size from temperature distribution does not fit mesh; index=0.

<u>Error Number</u>	<u>Cause of Error</u>
1800	Low exterior boundary in X-direction is negative; index=0.
1801	Low exterior boundary in X-direction positive but less than 0.00001 ft; index=0.
1802	A gap width along a Y-boundary is equal to or greater than half the width of its bounding grid lines; index=boundary number JG.
1803	A gap width along an X-boundary is equal to or greater than half the width of its bounding grid lines; index=boundary number IG.
3300	A boundary number in the X-direction is negative; index=boundary number IG.
3301	A gap width along an X-boundary is negative; index = boundary number IG.
3302	Surface temperatures on either side of a gap along an X-boundary were not converged in 100 iterations. Temperature instabilities resulting from too large a time step may be present; index=boundary number IG.
3303	A boundary number in the Y-direction is negative; index=boundary number JG.
3304	A gap width along a Y-boundary is negative; index= boundary number JG.

<u>Error Number</u>	<u>Cause of Error</u>
3305	Surface temperatures on either side of a gap along a Y-boundary were not converged in 10 iterations. Temperature instabilities resulting from too large a time step may be present; index=boundary number JG.
3600	Point was not in any block; index=point coordinates I,J.
4102	The heat transfer coefficient is negative; index=channel number, point in channel.

6.7 Evaluation Model Messages

Some of the input data for TOODEE2 are checked for compliance with 10 CFR 50.46 Appendix K. If the input does not comply, a message is printed and the calculation continues. The message identification number and an index are printed. The I. D. number, index and cause for the message are listed in this appendix.

<u>Message Number</u>	<u>Cause for Message</u>
8000	Axisymmetric geometry was not chosen; index=0
8001	Channel 1 has not been specified; index=0
8002	The following channel has been improperly selected; index=channel number (2, 3, or 4)
8010	There are axial gaps; index=block number where axial gap appears
8011	There is a radial gap which does not have material 2. Index=block which has the stated gap.
8022	The second radial material boundary is not the third last grid line; index=0
8023	The third radial material boundary is not the second last grid line. Index=0
8032	There is no radial gap between fuel and clad. Index=0
8033	There is a radial gap within the clad. Index=0
8041	UO ₂ is not specified for fuel. Index=0
8043	Zircaloy is not specified for clad. Index=0

<u>Message Number</u>	<u>Cause for Message</u>
8044	ZrO ₂ is not specified for clad. Index=0.
8103	Metric-English conversion less than 3412 BTU/kw-hr. Index=0.
8108	Provision not made for transient data. Index=0.
8134	Adiabatic regime does not begin transient. Index=0.
8136	Blockage not neglected in FLECHT correlation. Index=0.
8137	h_o is too high (> 4). Index=0.
8145	Prior rupture has occurred but ruptured node was not specified. Index=0.
8149	Prior rupture has not occurred but ruptured node has been specified. Index=0.
8146	Strain tables have been incorrectly optioned out. Index=0.
8150	Low flood rate option not invoked. Index=0.
8152	Unapproved radiation option invoked. Index=0.
8155	Regime I reflood factor $> .85$. Index=0.
8156	Regime II reflood factor $> .99$. Index=0.
8157	Regime III reflood factor $> .85$. Index=0.
8167	FLECHT correlation used improperly below 1 in/sec. Index=0.

6.8 Data Selection for EM Refill-Reflood Calculations

This section describes the data selection made by the Staff for making TOODEE2 calculations. The card groups, location numbers and formats are defined in Section 6.4. Variables which are plant dependent, the result of sensitivity studies or not used for Evaluation Model refill-reflood studies are not presented here.

<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
1	ISHAPE = 2	Specifies R-Z geometry
3	RA(IM2) = clad I. R. RA(IM) = clad O.R.	See section 6.4
5	AX(J)	Chosen to be same as RELAP since TOODEE2 is a continuation of RELAP hot channel
7	CW(1)	Same as RELAP
9	DII = 1 RBLD (1,1) = 0.0 RBLD (2,1) = clad I.R. ABLD (1,1) = 0.0 ABLD (2,1) = T.A.F. MB (1) = 1	Denotes solid block Center line See section 6.4 Bottom of active fuel Top of active fuel Denotes UO ₂ (see section 6.4)
9A	II = 2 RBLD (3,1) = gap MGR (1) = 2 CCR(k) = h _c	Denotes gap Radial gap size Specifies gas (see section 6.4) Contact term of gap conductance.

<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
9	II = 1	Solid block
(repeat)	RBLD (1,2) = clad I.R.	See section 6.4
	RBLD (2,2)	Specify near middle of cladding (see section 6.4).
	ABLD (1,2) = 0.0	
	ABLD (2,2) = T.A.F.	
	MB(2) =3	Specifies zircaloy (see section 6.4).
9	II = 1	
(repeat)	RBLD 91,3) = RBLD (2,2)	
	RBLD (2,3) = clad O.R.	See section 6.4
	ABLD (1,3) = 0.0	
	ABLD (2,3) = T.A.F.	
	MB (3) = 4	Specifies ZrO_2 (see section 6.4).
11	JX, JY	strain values obtained from
11A	EPR(J)	RELAP 4 hot channel calculation at end of bypass.
13		Temperatures are overridden by group 27 so are not im- portant. However 1 dummy block must be specified.

<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
15	NZP = 1 TSAT(1)	Constant value from FLOOD calculation may be input here.
17		Any high values can be input for each solid material.
19	AVAIL(1) = t_{EOBY} AVAIL(2) AVAIL(3) = 3413 AVAIL(4) = -1 AVAIL(8) < 0 AVAIL(23) = 0.0 AVAIL(24) = 1.E-5 AVAIL(26) AVAIL(27) AVAIL(30)	Time of end of bypass Average pin kw/ft same as RELAP, value is steady state value. BTU/kw-hr Specified power distribution Transient tables will be used In effect, this specifies 0.0 initial oxide thickness for unruptured nodes when RELAP thicknesses are input in groups 29A and 31A. Should be $0 < AVAIL(24) < 1$. Should correspond to TSAT(1) for reflood calculations unless sub-cooling justified. Channel flow area should be consistent with any flow rate used so that mass velocity is correct. 96.5% density used to correspond to densification requirements.

<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
	AVAIL(31)	75°F used based on FLECHT experiments.
	AVAIL(32) < 0	So that blockage is calculated if rupture has not occurred. If rupture has occurred and radiation or steam cooling is required use value determined in RELAP4 hot channel.
	AVAIL(34) < AVAIL(1)	Required for REFILL-REFLOOD
	AVAIL(35) = t_{BOCREC}	Bottom of core recovery time.
	AVAIL(36) = -.1	Negative value required to neglect blockage in FLECHT correlation.
	AVAIL(37) = 1.67	Recommended value.
	AVAIL(38) →	Pin pressure from RELAP hot channel at end of bypass.
	AVAIL(39-44)	Gas mol fractions should be the same as RELAP.
	AVAIL(45) →	Number is 0.0 if rupture has not occurred. RELAP4 hot channel hot pin. If rupture has occurred numbers should correspond to ruptured node.

<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
	AVAIL(46) →	≤ 0.0 if rupture has not occurred. If rupture has occurred in preceding RELAP4 hot channel number ignored and strain table (group 11A) used.
	AVAIL(47) →	Same as RELAP4 hot pin
	AVAIL(49) < 0. < AVAIL(1) but > 0.0	If rupture has not occurred in RELAP If rupture has occurred
	AVAIL(50) = 1	Only FLECHT correlation has been used to date for EM calculations
	AVAIL(51) →	Flooding rate from FLOOD calculation
	AVAIL(52) = 0	Radiation option ignored
	AVAIL(53) = .67	Cladding emissivity
	AVAIL(54) = .80	fuel emissivity
	AVAIL(55) = .85	FLECHT region I recommended factor
	AVAIL(56) = .99	FLECHT region II recommended factor
	AVAIL(57) = .85	FLECHT region III recommended factor
	AVAIL(58) →	Same as RELAP4 input
	AVAIL(59) = -2	Make fuel plenum 2°F hotter than fluid
	AVAIL(60) →	Same as RELAP4 input
	AVAIL(62) = 2°F	2°F gap heat transfer convergence.
	AVAIL(67) = 1	1 in/sec FLECHT limit required by rule.
	AVAIL(68) →	Appropriate steaming rate if required. (See explanation for cards 35H and 35HI)

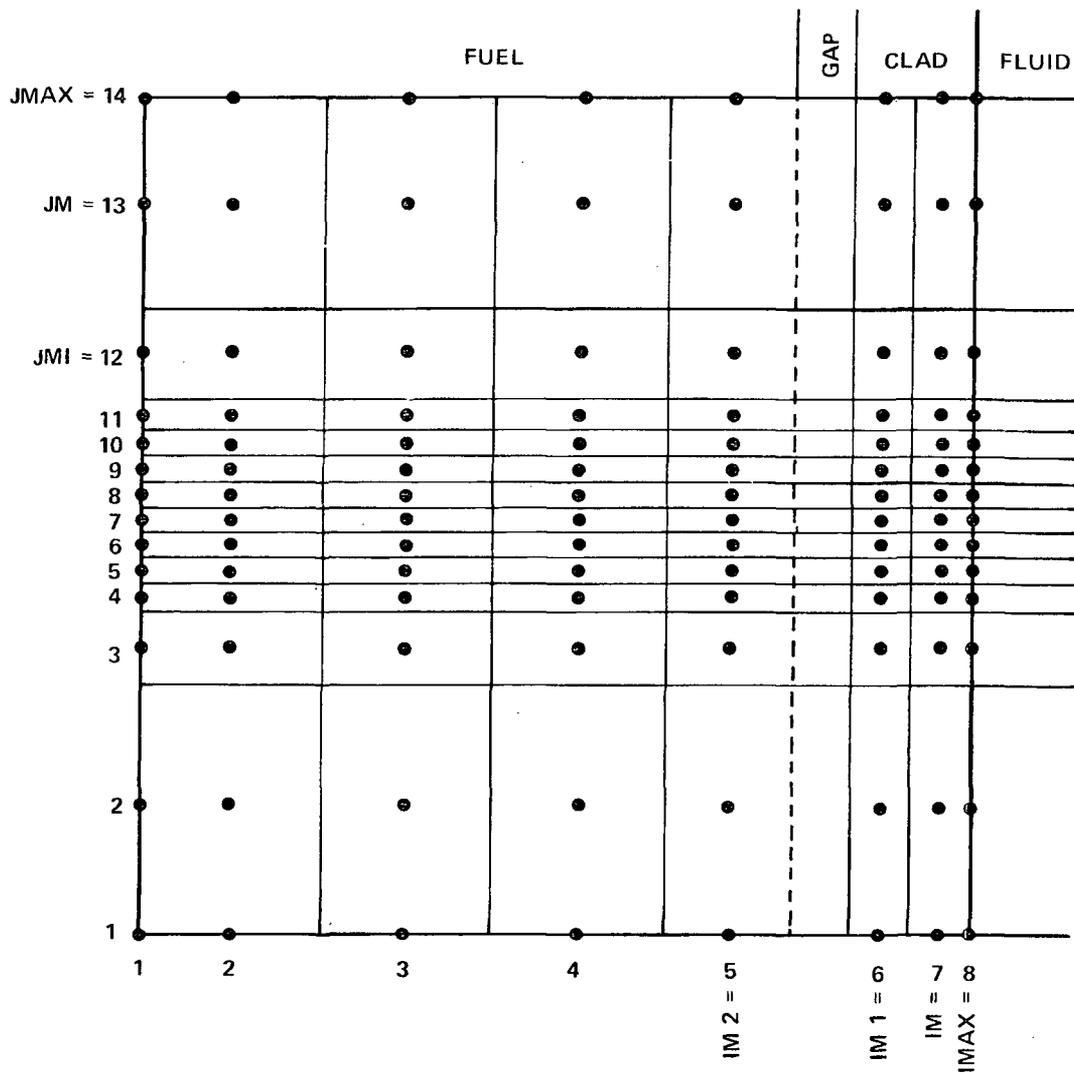
<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
21	AXPOW(J) →	Axial power same RELAP4 input.
23	RAPOW(J) = 1.0	No radial gradient assumed in fuel
27	NIT = 0	Parabolic fit used
27A	TBP, STH, STL, STR, TE	Temperatures from RELAP4 hot pin at end of bypass.
29	JX, JY	Outside oxide distribution from RELAP4
29A	XRI(J)	hot pin at end-of-bypass.
31	JX, JY	Inside oxide distribution from RELAP4.
31A	XRI(J)	Only rupture node need be specified if other constant inside values represented by AVAIL(23).
35A	NXQ	Table not needed for REFILL- REFLOOD
35A1	CXQ	
35B	NFL	Need for table dependent on steam
35B1	CFL	cooling requirements during refill.

<u>Card Number</u>	<u>Variable Specification</u>	<u>Explanation</u>
35C	NTI	Need for table dependent on FLOOD
35C1	CTI	calculated pressure transient and sub-cooling allowed.
35D	NPO	Power table normalized to time of
35D1	CPO	break is required. Use ANS + 20 or FLOOD calculated values.
35E	NTS	Comment same as 37C & C1.
35E1	CTS	
35F	NFR	Flood rate tables required for variable
35F1	CFR	flooding rate, from FLOOD calculated output.
35G	NML, CML	Mixture level table from RELAP analysis
35G1		required for small break.
35H	NSR, CSR	Appropriate steaming rates required for
35HI		reflood less than 1 in/sec. and small break.
37		All group 37 tables required. Should be as given in tables 6.1, 6.2, & 6.3

6.9 Typical Moding Schematic

A typical moding schematic diagram for TOODEE2 is illustrated in Figure 6.4.

Figure 6.4 TYPICAL TOODEE2 NODING SCHEMATIC



Note: Axial nodes 1 and JMAX and radial node 1 are dummy nodes at adiabatic boundaries. All exterior mesh points coincide with grid lines.

7.0

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