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MARCH 2 (Meltdown Accident Response Characteristics) Code Description and User's Manual

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Battelle Columbus Laboratories

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ABSTRACT

MARCH 2 describes the response of water-cooled reactor systems to accidents which, because of failures in engineered safety features, lead to core meltdown. The code performs the calculations from the time of accident initiation through the stages of coolant blowdown and boiloff, core heat up and meltdown, pressure vessel bottom head melting and failure, and debris-water and debris-concrete interactions in the reactor cavity. Both the primary system and the containment building are modeled. Mass and energy additions to the containment building are evaluated and the pressure-temperature response of the containment with or without engineered safety features is calculated. A maximum of eight containment sub-volumes may be modeled. Engineered safety features modeled include emergency core cooling systems, containment sprays, building coolers and fans, suppression pool and ice condenser containments, and emergency core cooling and spray heat exchangers. Effects of metal-water reactions, combustion of hydrogen and carbon monoxide, heat losses to containment structures, and redistribution of the decay heat due to loss of volatile fission products from the core are considered.

MARCH 2 is an improved version of the earlier MARCH 1.1 code. MARCH 2 incorporates improvements in the areas of core heat transfer models prior to the core meltdown stage, primary system leakage, coolant properties, Zircaloy and iron metal-water reaction models, hydrogen and carbon monoxide combustion, use of debris bed models for debris-water interactions, timestep control, BWR core models, and conversion of the coding to Fortran-77 conventions to improve the code transportability, in addition to correction of errors identified in the earlier version of MARCH. In many cases, both the improved and simplified MARCH 1.1 models have been retained so the user can assess their effects on previously calculated results. The development of MARCH 2 was coordinated by Battelle-Columbus with contributions being made by workers at Sandia National Laboratories, Brookhaven National Laboratories, Oak Ridge National Laboratory, Tennessee Valley Authority, United Kingdom Atomic Energy Authority, and other organizations.

The present report describes the MARCH 2 models, the code input and output, machine requirements, and a discussion of several sample problems.

MARCH 2 ACKNOWLEDGEMENT

Contributions to the development of MARCH 2 have been made by workers at several laboratories including Battelle's Columbus Laboratories, Sandia National Laboratories, Brookhaven National Laboratory, Oak Ridge National Laboratory, Tennessee Valley Authority, and Culham Laboratory (UKAEA). Assessments of MARCH by Brookhaven National Laboratories and Sandia National Laboratories provided the technical bases or starting points for the improvement of MARCH 1.0.

A number of workers merit special mention for their efforts. R. O. Wooton had primary technical responsibility for collecting the contributions and suggestions, evaluating their correctness and compatibility with other contributions, and implementing and modifying them as required. He also provided the new primary system leak models and coded the energy balance audits. R. O. Wooton and P. Cybulskis almost completely rewrote the present MARCH 2 manual. S. F. Quayle performed the task of converting MARCH from the original Fortran-IV form into ANSI Standard Fortran-77, including partitioning of the larger subroutines, reorganizing the common blocks, and implementing the metric input/output options. M. P. Manahan added improved Zircaloy-steam reaction models using the most recent data and understanding. F. E. Haskin developed the new hydrogen and carbon monoxide combustion models and wrote the corresponding documentation. He also modified and edited an interim Fortran-77 version of MARCH. C. J. Shaffer provided the new core radiation and axial conduction models and the convection heat transfer correlations. L. J. Ott developed the BWR core models and provided a state-of-the-art steam and hydrogen properties routine. J. W. Yang programmed the debris bed and particle heat transfer correlations which have been implemented in the in-vessel and reactor cavity water-debris interactions models. W. S. Yu added iron-steam reaction to the reactor cavity model. Text processing contributions were made by Tina Payne and Angie Galleger.

Other developers of the original MARCH 1.0 code include A. M. Plummer, H. I. Avci, R. G. Jung, R. E. Kurth, G. T. Brooks, W. B. Murfin (Sandia), and typing contributions by L. L. Judd and E. R. Carey.

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MARCH 2 (MELTDOWN ACCIDENT RESPONSE CHARACTERISTICS) CODE DESCRIPTION AND USER'S MANUAL

by

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August 31, 1984

1.0 INTRODUCTION

The MARCH (Meltdown Accident Response Characteristics) code describes the physical processes governing the progression of core meltdown accidents, from the initiating event through attack of the concrete basemat by the molten core debris. The original MARCH code[1] was written shortly after the Reactor Safety Study[2] to computerize as well as extend the analytical models utilized in that effort. Its principal applications were intended to be the Reactor Safety Study Methodology Applications Program (RSSMAP)[3-6] and a series of uncertainty analyses.[7] The code attempts to treat a large number of complex and interrelated physical phenomena. Some of these phenomena are well understood and others are not (and may never be). In some cases the models used are simplifications of the actual processes, either because experimental data are lacking to provide the level of understanding necessary to improve the model or because the priority for funding in the past did not justify the effort. However, the level of sophistication was felt to be adequate for the initially intended applications, considering the state of understanding of the phenomena at the time.

Following the accident at Three Mile Island Unit No. 2, interest in the analyses of the phenomena of severe accidents increased significantly. In early 1980, a number of industrial groups as well as national laboratories were provided developmental versions of the MARCH code. In October 1980, MARCH 1.0 was released to the National Energy Software Center. A revision, MARCH 1.1, was issued in February 1981. Since then, the MARCH code has been used in a variety of applications far beyond its initially intended scope. These applications have included assessment of hydrogen control strategies,

evaluation of filtered-vented containment systems, consideration of alternative containment designs for severe accident mitigation, and emergency planning and siting studies. In using the MARCH code for this variety of applications, a number of limitations of the code (ranging from lack of treatment of some important phenomena to unnecessary simplifications, as well as some errors) have been identified; consequently, a number of ad hoc versions of the code were developed by individual users. In order to assess the needs for further development of meltdown accident analysis codes, Sandia National Laboratories was requested by the Office of Nuclear Regulatory Research of the NRC to perform a technical assessment of the MARCH code.[8] An assessment of the code was also undertaken at Brookhaven National Laboratory for the Office of Nuclear Reactor Regulation to examine the use of MARCH for licensing applications.[9] As a result of these and other inputs, the U.S. Nuclear Regulatory Commission began the development of an updated and improved version, MARCH 2, which removed a number of limitations in the original code. This effort was coordinated by Battelle's Columbus Laboratories, the original MARCH code developer, with the cooperation of a number of other institutions including: Brookhaven National Laboratories, Oak Ridge National Laboratories, Sandia National Laboratories, and the Tennessee Valley Authority. Each of these organizations provided improvements and suggestions for the code. This document describes the models in the code and how these models are implemented, and gives guidance for the implementation and application of the code.

In addition to the modeling changes associated with the development of MARCH 2, a major effort was undertaken to improve the transportability of the code between various computer systems. This is reflected in the use of FORTRAN-77[10] in MARCH 2 as well as improved modularity in the coding and the division of the major subroutines. The breakup of some of the previously very large subroutines in the code facilitates use of the code on some computer systems.

It should be noted that the scope of the effort associated with the development of MARCH 2 was restricted by the time available for its implementation. There were a number of existing, as well as on-going, model development efforts of substantial interest and significance to meltdown accident analyses that were considered for incorporation into MARCH 2. However, the

Nuclear Regulatory Commission schedule requirements for having a working version of an improved code were not consistent with the time required to complete all these model improvements and include them in MARCH 2. It is not presently planned to include these in later revisions of MARCH 2. Future efforts in this area are planned by the NRC to be incorporated in the MELCOR code under development at Sandia.(11)

2.0 GENERAL DESCRIPTION OF MARCH 2

The MARCH code has been developed to analyze the thermal-hydraulic response of the reactor core, the primary coolant system, and the containment system in light water reactor systems in response to accidents involving some level of engineered safety feature inoperability. While MARCH is primarily intended to address accidents leading to complete core meltdown, it can also be used to treat events involving only partial core degradation as well as for assessing the minimum levels of engineered safety feature operability required to cope with various accident events. Depending on the particular application, MARCH analyses can be conducted by themselves or in combination with fission product transport codes such as TRAP, CORRAL, and MATADOR[12,13,14]. In the latter case, MARCH would provide the essential thermal-hydraulic input conditions required by the fission product transport codes.

MARCH is designed to cover the entire accident sequence, from the initiating accident event through the attack of the containment basemat, for a variety of accident initiators and including coverage of a wide variety of reactor system designs. More specifically, depending on the reactor design and accident sequences, the code can evaluate:

(1) Heatup of the primary and secondary coolant inventories and pressure rise to the relief/safety valve settings with subsequent boiloff,

(2) Initial blowdown of the primary coolant for small and intermediate breaks in the primary system,

(3) Generation and transport of heat within the core and associated coolant, if any, including boiloff of water from the reactor vessel,

(4) Heatup of the fuel following core uncovery, including the effects of metal-water reactions,

(5) Melting and slumping of the fuel onto the lower core support structures and into the vessel bottom head,

(6) Interaction of the core debris with residual water in the reactor vessel,

(7) Interaction of the core debris with the reactor vessel bottom head and the meltthrough or pressure-driven failure of the head,

(8) Interaction of the core debris with the water in the reactor cavity, including effects of chemical reactions,

(9) Attack of the concrete basemat by the core and structural debris,

(10) The relocation of the decay heat source as fission products are released from the fuel and transported to the containment,

(11) Mass and energy additions to the containment associated with all the foregoing phenomena and their effect on the containment temperature and pressure response, including the effects of passive and active containment safety features, as appropriate,

(12) The effects on the containment pressure and temperature response of the burning of hydrogen and carbon monoxide, and

(13) Leakage to the environment after failure of the containment.

The above phenomena are treated in a self-consistent manner within the assumptions and approximations inherent in the code. The modeling approach is to treat well understood phenomena realistically on a level of sophistication consistent with the needs. For phenomena which are not well understood, there are a number of user-specified options in the code that may be selected to explore the effect of various modeling assumptions. In all cases, mass and energy are conserved so that calculated sequences are self-consistent. There is generally no deliberate bias in the coding to produce "conservative" results; however, the code user may by choice of input options produce "conservative" results. The choice of these user-specified options can in many instances greatly influence the results of the calculations.

2.1 Description of Major Subroutines

MARCH 2 consists of several major subroutines together with a large number of supporting subroutines and functions. Table 2.1 lists all the subroutines that comprise MARCH 2 together with brief descriptions of each.

TABLE 2.1 MARCH 2 FUNCTIONS AND SUBROUTINES

Subroutine Or Function	Description
ANSQ	Calculates the American Nuclear Society standard (ANS 5.1-1979) decay heat fraction as a function of time after shutdown and time at power. Called by MARCH, BOIL, BOILNT, HOTDRP, INTER, INTRNT, and MACE.
AXCOND	Calculates the axial conduction heat transfer in the fuel rods using the Fourier law of heat conduction and the BOIL calculated node temperatures. Called by BOIL (IAXC = 1).
AXIALC	BWR fuel rod, channel box, and control blade heatup and meltdown model. Called by BOIL if IBWR = 1.
BARREL	Calculates the core barrel heatup from radial thermal radiation heat transfer. Called by RHEAT.
BLOCK DATA	Collects all common blocks into one BLOCK DATA subroutine. Performs all initializations of values in common blocks.
BOIL	Primary system control routine. Controls: heat generation and transfer in the core, thermal-hydraulics of the primary system, boiloff of water from the reactor vessel, melting and slumping of the core material to the vessel bottom head, and metal-water reactions in the core and in the bottom head. Called by MARCH.
BOILEX	Called by BOIL to calculate core exit gas temperature and gas-space conditions. Calls EXITQ (structure temperatures), PRIMP (primary system pressure), and FPQSTR (fission product heating of EXITQ structures).
BOILLP	Writes Zr-H_2O reaction messages. Called by BOILP2.
BOILNT	Sets initial conditions for BOIL. Called by MARCH.
BOILP2	Prints some BOIL output. Called by BOILPR.
BOILPR	Prints BOIL output. Called by BOIL.
BURN	Burns hydrogen and carbon monoxide in containment volumes if their concentrations meet flammability criteria. Called from MACE.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
CHNG	Reduces the molten debris to single oxidic layer when all the metal has been used up by chemical reactions. Called by INTER.
CNVERT	Checks input values for errors; converts input values to internal units. Called by MARCH.
CONFAL	Calculates the mass and energy leakage to outside atmosphere through the break area when the containment fails. Called by MACEDT and MACETP.
CONV	Calculates steam and hydrogen gas properties. CONV is called by BOIL if CONV = 1.
CONVNT	Calculates inter-compartment orifice-flow type transfers. Called by MACE.
COOL	Calculates the rate at which the energy is extracted from the containment atmosphere by the coolers. Called by MACEDT, MACEND, and MACENT.
CPUSEC	Returns central processor time in seconds. Called by MARCH and PAGE.
CR1	Calculates the critical flow rate of saturated steam based on Moody tables. Called by BOILNT and PRIMP.
CSHX	Models the containment recirculation spray water heat exchanger. Called by MACEND and MACENT.
DBED	Calculates heat transfer rates to water from hot surfaces and from debris beds. Called by BOIL, HOTDRP, and QSLUMP.
DBPROP	Calculates the effective properties such as density, specific heat, thermal conductivity, and melting or freezing point in both the oxidic and metallic layers of the debris. Called by INTER.
DECOMP	Calculates the temperatures and energies associated with the decomposition of the constituents of concrete. Called by INTRNT and QINTER.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
ECC	Regulates Emergency Core Cooling system water flow. Called by MACEND and MACENT.
ECCHX	Models the Emergency Core Cooling recirculation flow heat exchanger. Called by MACEND and MACENT.
ECHO	Prints input data used in the MARCH calculation. Called by MARCH.
EFCRIT	Calculates the critical flow rate of subcooled and saturated (liquid) water using RETRAN curve fit to Henry-Fauske correlation. Called by PRIMP.
ENTH	Computes enthalpies of products passing into or out of melted debris which is in contact with the concrete containment floor. Called by INTER.
EQUIL	Finds the equilibrium temperature of a containment volume after the effect of the new mass and energy input/output to/from the same volume has been uniformly distributed over the volume. Called by MIXCTL.
EVENTS	Initiates and controls the "events" used in the input to MACE. Called by MACE.
EXITQ	Calculates the gas enthalpies and the heat transferred to structures in the gas flow path leaving the core. Called by BOILEX.
EXPFUN	Prevents calls to system function EXP from exceeding a set range. Called by several routines.
F235U	Thermal fission function exponential fit for U235, $F_1(t,T)$ which calculates the decay power t seconds after an operating period of T seconds at a constant fission rate of one ^{235}U fission per second in the absence of neutron capture in the fission product. Called by ANSQ.
FACTOR	Sets up conversion factors from internal units to desired output units. Called by MARCH.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
FENT	Enthalpy of saturated water at temperature T. Called by KOOLER, MACE, MACEND, and MACETP.
FLOW	The gas fraction which is available for reactions with the constituents of the metallic layer of the debris. $G = m/V_m$, where m is the mass rate of production of gases (CO_2 nad H_2O) and V_m is the volume of the metallic phase of the molten debris. Called by REACT.
FPLK	Calculates storage and leakage of fission product decay heat from the primary system gas space. Called by BOIL.
FPLOSS	Models the loss of volatile fission products from the melted fuel. Called by BOIL, HOTDRP, and INTER.
FPQSTR	Calculates heatup of primary system structures in the gas space due to decay heat of stored volatile fission products. Called by BOILEX.
FUNCAF	Wall condensing heat transfer coefficient correlation as a function of the air-to-steam weight ratio. Called by SLAB.
FVOL	Specific volume of saturated water at temperature T. Called by EVENTS and MACEND.
GENT	Enthalpy of saturated steam at temperature T. Called by KOOLER, MACE, MACEND, MACETP, SATEST, and TEMP.
GVOL	Specific volume of saturated steam at temperature T. Called by MACE, MACEND, MACENT, and MACETP.
HBOIL	Boiling heat transfer correlation for water which is in contact with molten debris. Called by INTER.
HCGAS	Calculates laminar/turbulent forced convection heat transfer coefficient. Called by AXIALC, BOIL, and EXITQ.
HEAD	Performs the heat transfer analysis between the melted core debris and the pressure vessel bottom head, and calculates the bottom head failure. Called by QSLUMP.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
HOTDRP	Analyzes the interaction of the core debris with water in the reactor cavity following the vessel bottom head meltthrough including such effects as debris fragmentation, heat transfer, and chemical reactions. Called by MARCH.
HRSTM	Calculates the rod-to-steam radiation heat transfer coefficients in the core. Called by AXIALC and BOIL.
INITL	Provides initial coolant blowdown into containment prior to start of BOIL. Normally used for large pipe break loss of coolant accidents. Called by MARCH.
INP	Reads the input data. Called by MARCH.
INTER	Analyzes the interaction between the molten debris and the concrete containment floor, and the penetration of the molten debris into concrete. Called by MARCH.
INTERP	Linear interpolation routine. Called by ANSQ and PROP.
INTRNT	Sets and prints out initial conditions in INTER. Called by INTER.
IOEND	Dummy subroutine which could be used to save files at the end of the calculations. Called by PERROR.
IOINIT	Dummy subroutine which could be used to open files at the start of the calculations. Called by MARCH.
KOOLER	Does the spray water droplet-containment atmosphere heat transfer analysis if the initial spray water temperature is greater than the containment temperature. Called by SPRAY.
MACE	Main control routine for the calculation of the containment response to mass and energy inputs from subroutines INITL, BOIL, HOTDRP, and INTER. Called by MARCH.
MACEDT	Calculates the MACE timestep based on energy addition rates. Called by MACE.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
MACEND	Calculates containment sump parameters, operation of ECC spray and heat exchangers, and timestep during containment failure. Prints MACE output. Called by MACE once per MARCH timestep.
MACENT	Sets initial conditions and flags in MACE. Called by MARCH.
MACEOT	Writes MACE output data on the plot file, Fortran unit "MACEPT". Called by MACE and MACENT.
MACETP	Calculates containment compartment temperatures before pressure equilibration transfer are made. Called by MACE.
MARNT1	Does some initializations. Called by MARCH.
MARNT2	Does some initializations. Called by MARCH.
MELT	Performs core meltdown model calculations. Called by BOIL.
MIXCTL	MIXCTL with its associated subroutines is used to uniformly mix any mass/energy additions to containment volumes and obtain a new uniform temperature and pressure for each volume. Called by MACE, MACEDT, and MACETP.
MWDRP	Analyzes the metal-water reactions taking place in the pressure vessel bottom head after the core slumps. Called by MELT.
OUTFLW	Writes mass flow rates at the top of the core to Fortran unit "FLOWS". Called by BOIL.
PAGE	Prints job title, MARCH version number, page number, and CPU time. Called by several routines.
PERROR	Prints error and normal problem termination messages. Called by several routines.
POLATE	Linear tabular interpolation routines. Called by THTRPH and THTRPS if ICONV > 1.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
PRIMP	Calculates the primary system pressure and the amount of water/steam/hydrogen leakage into containment through a pipe break and/or safety/relief valve. Called by BOILEX.
PROP	Calculates thermodynamic properties. Called by AXCOND, CONV, RHEAT, and ZRWATR.
PROPS	Contains a table of saturated water/steam thermodynamic properties between the pressures of 0.09 and 3200 psia. From a given value of pressure, temperature, or specific volume, it calculates the other properties by interpolating between the value in the table. The properties included in the table are pressure, temperature, specific volumes, specific enthalpies, and specific heat of water. Called by BOIL, BOILNT, DBED, EFCRIT, HOTDRP, MACE, MACEND, MACENT, PRIMP, QSLUMP, and SPHERE.
PRSS	Saturation pressure of steam at temperature T. Called by MACE and MACENT.
QINTER	Performs heat transfer analysis at the molten debris-concrete interface, and calculates the rate of penetration of the melt into concrete. Called by INTER.
QRAD	Calculates the heat radiated from the top surface of the molten debris to the walls of the cavity. Called by INTER.
QSLUMP	Calculates debris, water, grid plate, and head interactions for core material slumped into the bottom head. Called from BOIL.
RAD	Calculates parallel plane radiation heat transfer. Called by RHEAT.
RANGE	Function which constrains a variable to be in a given range. Called by several routines.
REACT	Performs mass and energy balances in chemical reactions $Fe + H_2O$, $Fe + CO_2$, $Zr + H_2O$, $Zr + FeO$, $Cr + FeO$, $Cr + H_2O$, and $Ni + H_2O$ during the time when the debris in melting the concrete floor of the containment. The reactions take place in the metallic layer of the debris. Called by INTER.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
REYN	Calculates the Reynold's number and the fall velocity associated with the spray water droplets in containment atmosphere. Called by MIXCTL and SPRAY.
RHEAT	Calculates the axial and radial core thermal radiation heat transfer among the core nodes and between the core nodes and the structure and water surfaces. Called by BOIL and BOILNT (IRAD = 1 or 2).
SATEST	Determines whether or not the steam in the containment atmosphere is superheated. Called by EQUIL, MACE, MACENT, MACETP, and MIXCTL.
SGEN	Calculates steam generator heat transfer. Called by BOIL.
SINK	Subroutines SINK and SLAB do heat transfer analysis between the containment atmosphere and the walls of the containment. They calculate wall temperatures, heat transfer to the walls, and an average wall surface temperature difference in each containment volume. Called by MACE and MACENT.
SLAB	Solves the wall conduction heat transfer equation for SINK. Called by SINK.
SOLINQ	Solves the simultaneous linear equations used to calculate MACE pressure-equilibration transfers. Called by MACE.
SOLLIQ	Calculates the effective melting point of the oxide layer of the debris which is penetrating into the concrete floor of the containment building. It also calculates the change in the effective specific heat of oxide layer due to melting or freezing of its constituents. Called by DBPROP.
SOURCE	Arranges the connected volumes in the order of decreasing pressure to determine intercompartment transfer directions. Called by MACE.
SPEEDY	Interpolates using a pressure index to calculate water/steam properties. Called by STEEM.

TABLE 2.1 (Continued)

Subroutine Or Function	Description
SPHERE	Calculates heat transfer from a hot sphere to water. Called by HOTDRP and QSLUMP.
SPRAY	Performs mass and heat transfer calculations between the spray water droplets and the containment atmosphere. It also calculates how much water and energy are added to the containment sump as a result of spray action. Called by EQUIL and MIXCTL.
STEAM	Calculates the primary system coolant flashing and boiling rates for subroutine BOIL. Called by BOIL.
STEEM	Calculates steam properties given the temperature and pressure. Called by STMH2P.
STEPS	Writes out the number of timesteps taken by BOIL and MACE. Called by PERROR.
STMH2P	Calculates steam - hydrogen gas properties using ASME and Vargaftik data for use in HCGAS convective heat transfer calculation. Called by AXIALC, BOIL (ICONV > 1), and EXITQ (ICONV > 10).
SUMHED	Prints headings for the MARCH summary page. Called by MARCH.
SUMOUT	Prints a line in the summary page. Called by several routines.
TEMP	Calculates containment thermodynamic properties such as partial pressure of steam, air, and its constituents, specific enthalpy, specific volume, and mass of steam and water droplets, gives the total energy and masses. Called by MIXCTL.
TGEOM	Calculates the thermal boundary layer thicknesses in the debris and the concrete. Called by INTER.
THTRPH	Calculates hydrogen properties for STMH2P (ICONV > 1). Called by STMH2P.
THTRPS	Numerical representation of IFC steam-water equations. Called by STEEM (ICONV > 1).

TABLE 2.1 (Continued)

Subroutine Or Function	Description
TVIEW	Calculates the modified radial node temperatures used in calculating the radial thermal radiation heat transfer. Called by RHEAT (IRAD = 2).
UNITS	Lists units used in the output from the code. Called by ECHO.
ZRWATR	Calculates the rate of zirconium clad oxidation in steam-rich/steam-deprived environments under laminar or turbulent flow conditions. Steam deprivation may be due to hydrogen blanketing and/or lack of steam. Called by BOIL.

Figures 2.1 to 2.5 are schematic illustrations of the relationship among the major subroutines in MARCH 2 and the sequence in which they are called. An overview of the functions of the major subroutines and their interrelationships follows; detailed descriptions of the phenomenological models in the various portions of the code are given in Sections 3.0 through 7.0.

MARCH is the driver routine which controls the information flow within the overall code and calls the other major subroutines. Input to MARCH defines the nature of the accident sequence to be considered and controls some of the code output. The input subroutine, INP, reads the inputs for all portions of the code. MARCH calls subroutine CNVERT to change input values to internal units. The input values are then printed by subroutine ECHO. The INITL subroutine uses initial primary system blowdown tables as input to the containment; it is normally used as the starting point for large loss-of-coolant accident (LOCA) initiated sequences. In such cases, the blowdown tables could be based on the results of detailed primary system blowdown calculations.

MACE and its associated subroutines comprise a major portion of MARCH. Figure 2.2 is a schematic illustration of the sequence of subroutine calls in MACE. Not all the subroutine calls are necessarily included in the treatment of each accident sequence. MACE evaluates the containment response to mass and energy inputs as calculated by the other principal subroutines in MARCH. MACE includes models for various containment engineered safety features and passive heat sinks and is capable of modeling a variety of containment designs and configurations. The modeling of the containment sumps is also included in MACE, as is the logic for certain engineered safety features such as the switchover from injection to recirculation.

The BOIL subroutines control the primary system calculations. BOIL evaluates heat generation and transfer within the core, thermal-hydraulics and pressurization of the primary system, boiloff and leakage of water from the reactor vessel, melting and subsequent slumping of the core material into the vessel bottom head, failure of the head, and the reaction of metals (Zircaloy and iron) with water in the core and bottom head.

MARCH

- IOINIT
- INP
- SUMHED
- FACTOR
- CNVERT
- ECHO
- MARNT1
- INITL
- MACENT
- MARNT2
- INITL
- MACE
- BOIL
- MACE
- HOTDRP
- MACE
- INTER
- MACE

FIGURE 2.1 MAJOR ROUTINES CALLED FROM THE MAIN PROGRAM MARCH

```
MACE      - MACEDT
          - MACENT
          - MACEOT
          - SINK      - SLAB        - FUNCAF
(MACEDT)  - ECC
(MACEND)  - ECCHX
(MACEND   - CSHX
(MACEND)  - COOL      - PROPS
          - GVOL
          - PRSS
          - SATEST
          - ANSQ
                      - F235U
                      - INTERP
          - EVENTS
                      - FENT
                      - FVOL
          - PROPS
          - MIXCTL
                      - SATEST
                      - TEMP      - GENT
                      - SPRAY
                                  - KOOLER
                                              - FENT
                                              - GENT
                                  - REYN
                      - EQUIL
                                  - SATEST
                                  - SPRAY
                                              - KOOLER
                                                          - FENT
                                                          - GENT
                                              - REYN
                      - REYN
(MACETP)  - CONFAL
          - CONVNT
          - FENT
          - GENT
          - SOLINQ
          - BURN
          - FVOL
```

FIGURE 2.2 MAJOR ROUTINES CALLED FROM THE CONTAINMENT ROUTINE MACE (MACE/MACEDT/MACEND/MACEOT/MACETP)

```
BOIL        - BOILPR
            - PROPS
            - CR1
            - ANSQ
                        - F235U
                        - INTERP
            - RHEAT
                        - PROP          - INTERP
                        - RAD
                        - TVIEW
                        - BARREL
            - AXIALC
            - SGEN
            - STEAM
            - DBED      - PROPS
            - CONV
                        - PROP          - INTERP
                        - HRSTM
            - STMH2P
            - HCGAS
            - HRSTM
            - AXCOND    - PROP          - INTERP
            - ZRWATR    - PROP          - INTERP
            - MELT
(QSLUMP)    - MWDRP
            - FPLOSS
            - FPLK
            - SPHERE    - PROPS
            - HEAD
(BOILEX)    - EXITQ     - STMH2P
                        - HCGAS
(BOILEX)    - PRIMP
                        - PROPS
                        - CR1
                        - EHCRIT        - PROPS
(BOILEX)    - FPQSTR
```

FIGURE 2.3 MAJOR ROUTINES CALLED FROM THE PRIMARY SYSTEM ROUTINE BOIL (BOILEX, MELT, QSLUMP)

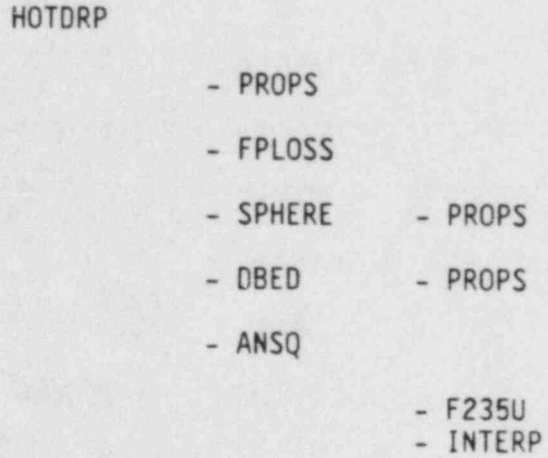

FIGURE 2.4 MAJOR ROUTINES CALLED BY THE REACTOR CAVITY DEBRIS-WATER INTERACTIONS ROUTINE HOTDRP.

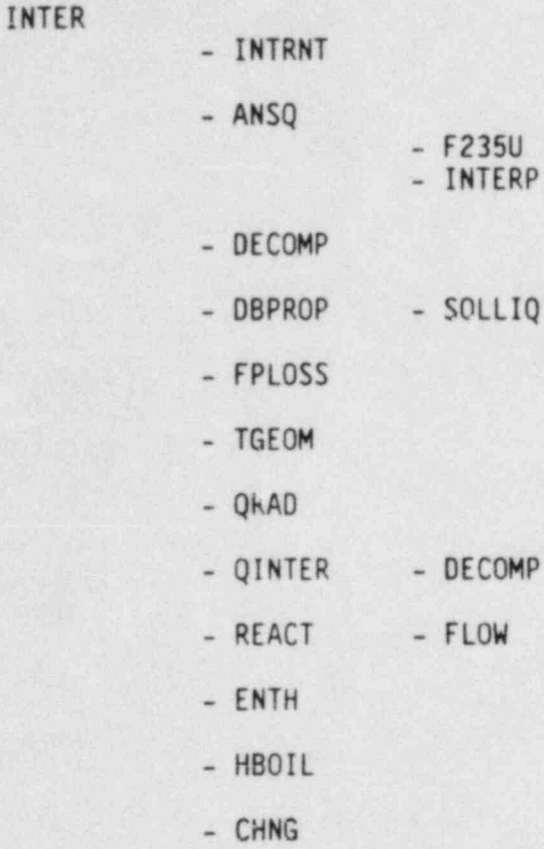

FIGURE 2.5 MAJOR ROUTINES CALLED BY THE DEBRIS-CONCRETE INTERACTIONS ROUTINE INTER

BOIL calls subroutine PRIMP for the evaluation of the primary system pressure and leakage through small pipe breaks and/or through relief/safety valves. BOIL calls subroutine HEAD to perform the heat transfer analysis between the core debris and the reactor vessel bottom head and to calculate bottom head failure. AXIALC contains the BWR core models. Figure 2.3 illustrates the sequence of subroutine calls in BOIL.

HOTDRP models the interaction of the core and structural debris with water in the reactor cavity following vessel failure, considering such effects as debris fragmentation, debris bed formation, heat transfer, and chemical reactions. The subroutines called by HOTDRP are shown in Figure 2.4.

INTER analyzes the interaction between molten core and structural debris and the concrete containment floor, including the penetration of the molten debris into the concrete. The subroutines comprising INTER are illustrated in Figure 2.5.

A number of supporting subroutines and functions are utilized throughout various portions of the code. ANSQ calculates fission product decay heat as a function of time after shutdown and time at power. BURN calculates hydrogen and carbon monoxide combustion if their concentrations meets flammability criteria. FPLOSS models the loss of fission product decay heat from the core debris during the meltdown accident. ZRWATR provides several modeling options for calculating the rate of Zircaloy reaction with water. A number of subroutines and functions are used to provide properties of steam and water including CONV, FENT, GENT, FVOL, GVOL, PROP, PROPS, PRSS, and STMH2P.

The following paragraphs describe how the MARCH code represents the various portions of the reactor system. Detailed descriptions of the input variables are given in Appendix A, Table A.1.

Core

The core is represented within the BOIL subroutines by a number of axial and radial regions or nodes. The core may be divided into a maximum of ten (10) radial zones and up to fifty (50) axial nodes. The sizes of the radial zones or regions are arbitrary, but would normally be selected in a

manner which conveniently describes the radial power distribution within the core. The in-core radiation heat transfer model assumes the radial regions are concentric. The core is divided into axial nodes of equal length. The user inputs, for each radial and axial region, a relative power level and the fraction of the core volume represented by the radial region. The BOIL routines then use this information to calculate the power generation in each of the core nodes. In addition to the above global core characteristics, BOIL requires as input the total number of fuel rods in the core, fuel and cladding dimensions, rod spacing, quantity of miscellaneous material (core barrel and grid supports in the core region), etc. Additionally, the BWR core model requires data on the channel boxes and control rod blades. A detailed description of all the input parameters required to describe the core is included in the namelist NLBOIL portion of Table A.1. Figure 2.6 illustrates the core region geometry in MARCH.

Core Support Structures

The BOIL subroutines model three separate structures as heat sinks below the core. One of these is required to be the reactor vessel head; the other two structures would typically be the core support plate and the lower core support structure. These structures are characterized by the following input parameters: initial temperature, mass times the heat capacity, heat transfer area, characteristic thickness, and location below the bottom of the core.

Heat Sinks in the Gas Space

The core exit gas stream is assumed to flow through as many as four series-connected heat sinks or structures. The first of these must be the structure immediately above the core--the upper grid plate. The other structures may be used to represent upper head internals, hot leg piping, pressurizer surge line, steam generator, etc. In the BOIL routines, each of these structures is characterized by an initial temperature, mass times the heat capacity, heat transfer area, flow equivalent diameter, flow area, and

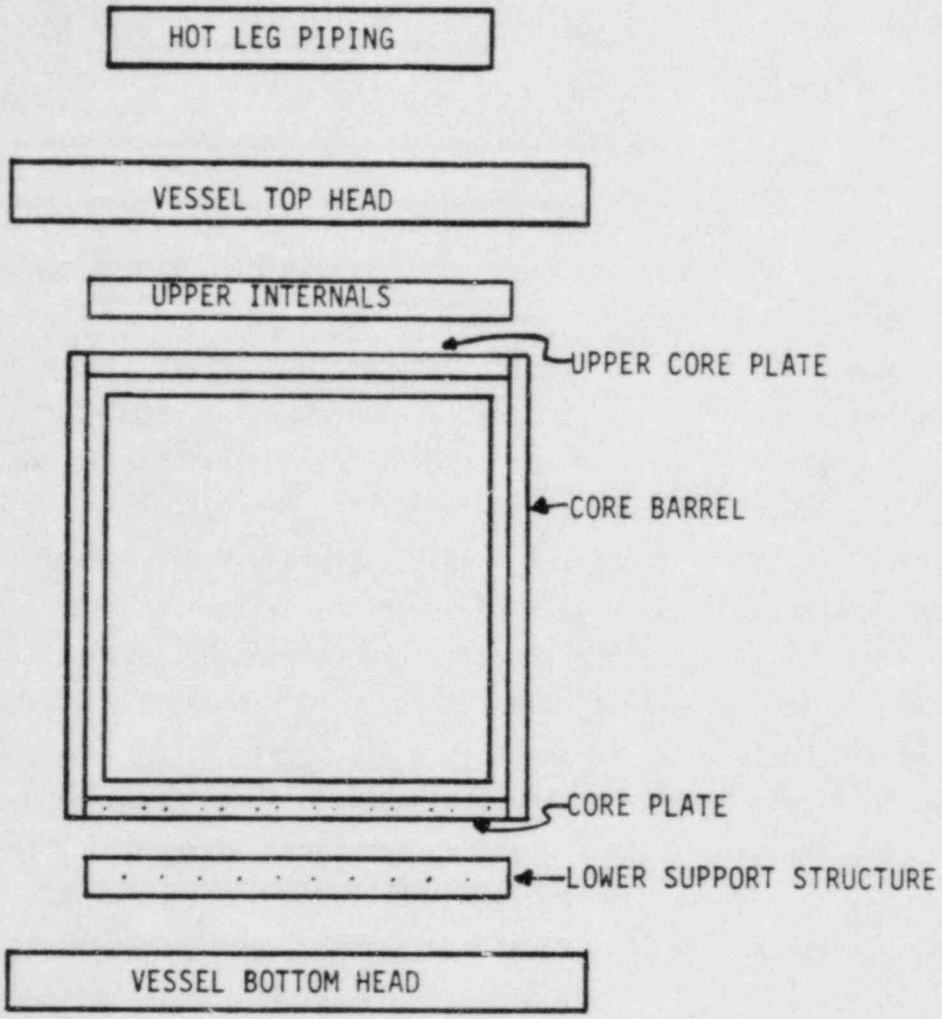

FIGURE 2.6. REPRESENTATION OF CORE REGION GEOMETRY USED IN MARCH

fraction of airborne fission product energy absorbed. An additional structure characterized by its mass times heat capacity can be used to represent the structures immediately surrounding the core, such as the core barrel. This structure serves as the heat sink for radiative heat losses from the core in the radial direction. Figure 2.6 is a schematic representation of the BOIL modeling of the structures within the reactor primary system. Also see Figures 2.7 and 2.3.

Primary System

MARCH models the primary system as a single cylindrical volume with liquid at the bottom and gases or vapors at the top. The cross sectional area of the cylinder is constant and is normally input as the actual area of water at the core midplane. Because of the constant area approximation, the liquid or two phase mixture levels calculated and used by the code have real physical significance only when these levels are between the top and bottom of the core. It is, of course, possible to relate the artificial levels used by the code to actual levels in a plant on the basis of coolant inventory. All elevations in the primary system are referenced to the bottom of the active core region. The initial description of the primary system requires as input the weight of water in the bottom head, the water cross sectional area in the assumed cylinder, the water cross sectional (flow) area within the core, the initial height of the liquid in the primary system, and the volume of steam initially present. Other required inputs are the elevations of the primary system breaks and relief/safety valves. Whether the discharge from the primary system is liquid or vapor is determined by the elevation of the opening (break or valve) relative to that of the liquid level. The initial primary and secondary water inventories are used in assessing steam generator performance. The steam generator heat removal capability is extrapolated from normal operating conditions. In those sequences where the steam generators are expected to function, additional required inputs are the time to start the auxiliary feedwater flow, auxiliary feedwater flow rate and temperature, and specification of steam generator modeling options. As part of the description of the primary system, a user-input volume (WDED in Figure 2.7) may be

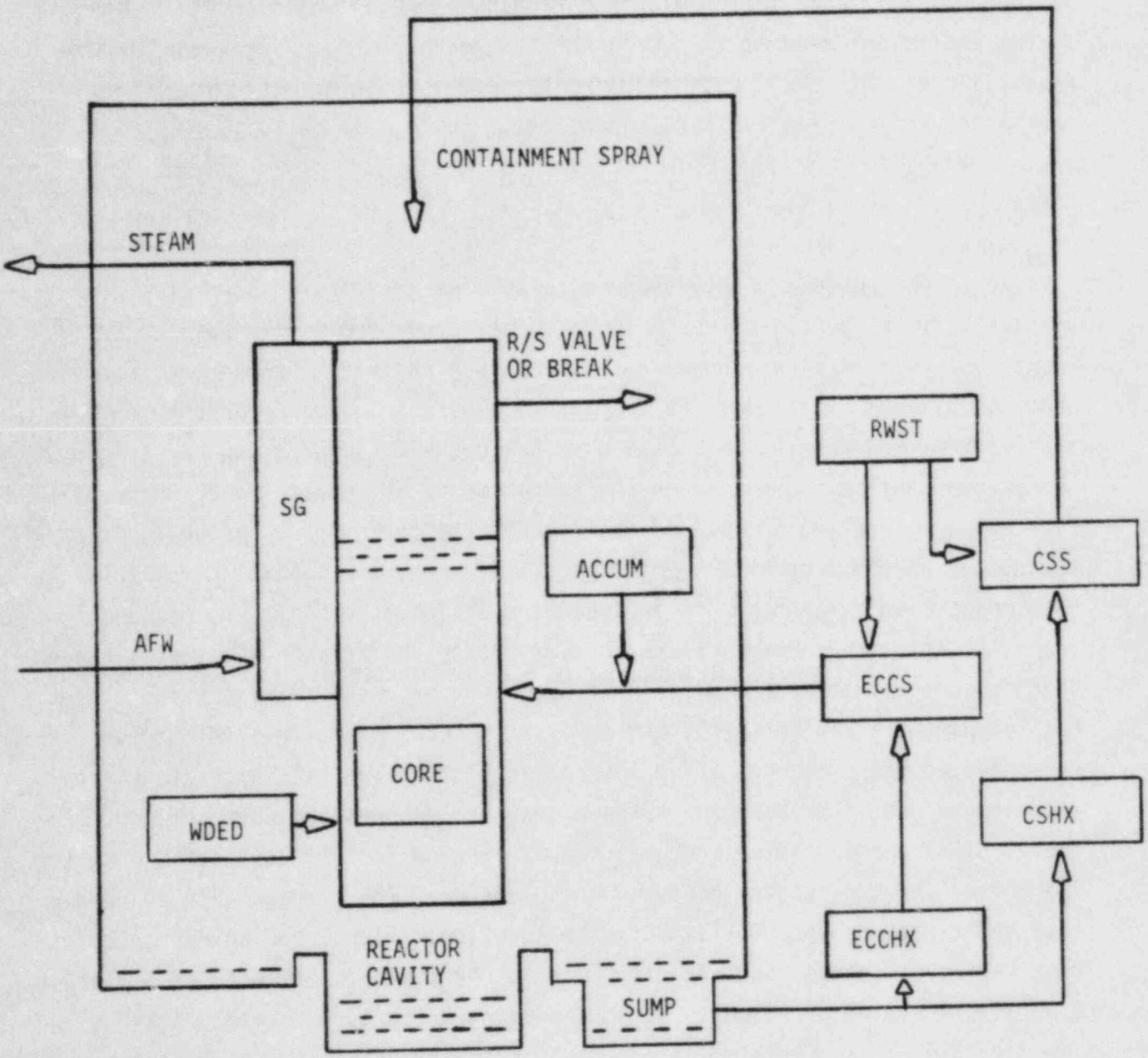

FIGURE 2.7. REPRESENTATION OF REACTOR PRIMARY AND CONTAINMENT SYSTEMS USED IN MARCH

specified to hold water trapped in low points in the primary system and which would not undergo boiloff during core uncovery. This water is assumed to be in thermodynamic equilibrium with the remainder of the water in the primary system and is released to the containment atmosphere following vessel bottom head failure. All the inputs required to describe the primary system are identified in the namelist NLBOIL portion of Table A.1.

Containment

MARCH models the containment system as a series of connected compartments, with up to eight such compartments permitted. With some exceptions, only series flow connections between the individual compartments are permitted. Some exceptions are the air return fans in ice condenser containment systems, and the vacuum breakers in BWR pressure suppression containments. The allowable flow paths between the compartments are specified by means of a flow matrix. The input required to describe the containment system include: the number of compartments; the volume, floor area, and initial conditions in each compartment; locations of engineered containment safety features and sumps; locations of primary system breaks and/or relief/safety valves; location of containment vents or failures; and vent or break characteristics. Each compartment may contain a number of structural heat sinks, either wholly or as the boundary between adjoining compartments. Special input flags are provided to identify ice condenser and pressure suppression containments. For these containments fission product decontamination factors associated with the ice bed or the suppression pool may be specified. The events table in namelist NLMACE may be used to identify the location, timing, and characteristics of a variety of containment events, such as the starting of containment sprays and fans, starting burn igniters, and containment failure characteristics. The modeling of the containment permits the specification of the location and connection of the containment sumps and the reactor cavity. Additionally, some fraction of the containment spray water may be directed to the reactor cavity. Also, the water in the containment sump can enter the reactor cavity when the core debris have penetrated a specified concrete wall thickness.

Figure 2.7 is a simplified schematic representation of the MARCH code modeling of the reactor primary as well as the containment systems. This is only an illustrative example and does not represent all the modeling options available to the user. The detailed description of all the input variables that must be specified to describe the containment is given in the namelists NLMACE, NLSLAB, NLECC, NLHX, and NLCOOL portions of Table A.1.

2.2. Comparison of MARCH 1.1 and MARCH 2

The differences between MARCH 1.1 and 2 include corrections of errors and changes in models, code structure, and programming language. The new models which are included in MARCH 2 were developed at a number of institutions including Battelle, Sandia National Laboratories, Oak Ridge National Laboratories, Brookhaven National Laboratory, and the Tennessee Valley Authority. These new models are in some cases provided as options to existing models. The changes in MARCH were largely undertaken to address some of the recognized deficiencies in the early version related to modeling approximations, time-step control, and transportability of the code to other installations.

MARCH 2 incorporates the current American National Standard for Decay Heat Power in Light Water Reactors[15] for evaluating fission product decay heating as a function of time after shutdown and time at power, including the contributions due to heavy element decay. This replaces the earlier, simplified version incorporated in MARCH 1.1. Alternatively, decay heat as a function of time may be input in tabular form; this approach would be particularly appropriate for transients in the absence of scram where the power history would be provided by more detailed systems codes.

The representation of the properties of water and steam in MARCH 2 has been improved over that in MARCH 1.1. This has included expansion of the property tables and correlations incorporated in the code such as additional properties required by the new phenomenological models.

The MARCH 2 treatment of the primary system includes improvements in both the initial (early) primary system response as well as the addition of several phenomenological models to treat the processes following core collapse

into the bottom head. Included are changes in the steam generator model to remove some of the restrictions and limitations of the earlier version, improved break flow models, changes in the flashing model in response to primary system pressure changes, provisions for simultaneous break and relief/safety valve flow, changes in the treatment of gas phase heat transfer to structures, and consideration of the holdup of released fission products within the primary system.

MARCH 2 retains the basic model of the core as developed for the earlier version, but incorporates a number of additional models for a more detailed treatment of heat transfer processes. The heat transfer between the fuel rods and the steam-hydrogen gas mixture is now calculated using either the full Dittus-Boelter correlation for turbulent flow or a laminar flow correlation. A subroutine has also been added to approximate axial conduction heat transfer in the fuel rods using the Fourier law of heat conduction and the BOIL-calculated node temepratures. The effect of axial and radial thermal radiation heat transfer within the core as well as between the core and surrounding structures and water surfaces can now be calculated. Included is the heatup of the core support barrel by thermal radiation. Additional changes have been made in the heat transfer analysis of partially covered core nodes and in the metal-water reaction model. A BWR core model providing an explicit treatment of channel boxes and control blades is incorporated.

A number of phenomenological models have been added for the treatment of core debris and water interactions in the reactor vessel. These range from a flat plate critical heat flux model, to a fragmented debris-to-water heat transfer correlation, to several options that consider formation of debris beds within the core and bottom head while water is still in the vessel. The bottom head heatup model utilizes a calculated heat transfer coefficient between the molten debris and the vessel head.

A major area of concern and controversy in the analysis of core meltdown accidents has been the behavior of core and structural debris upon contact with water in the reactor cavity. The isolated-particle models incorporated in MARCH 1.1 have been supplemented with the addition of the treatment of several debris configurations; these include a flat plate critical heat flux model, a particulate heat transfer model with improved heat transfer coefficients, and several debris bed heat transfer correlations. If

$$\begin{aligned} ROD(I,R) &= TR(I,R), && TR(I,R) < TMELT \\ ROD(I,R) &= TMELT, && TMELT < TR(I,R) < TFUS \\ ROD(I,R) &= TR(I,R) - \Delta T_{FUS}, && TFUS < TR(I,R). \end{aligned} \qquad \text{(E3.61)}$$

For temperatures between TMELT and TFUS, fractional node melting is calculated as

$$F_{NM}(I,R) = \frac{TR(I,R) - TMELT}{\Delta T_{FUS}} \quad . \qquad \text{(E3.62)}$$

BOIL also uses a third notation SOD(I,R) for rod temperature. ROD(I,R) and SOD(I,R) are the same, except that SOD(I,R) is set to zero as a flag to indicate that a node has fallen out of the core due to slumping. SOD(I,R) is printed in the output array of core temperatures. Note that ROD(I,R) is used to calculate rate processes, such as heat flux and metal-water reaction.

The calculation of the radiation heat transfer term differs for nodes inside and on the periphery of the core, and also depends on the input value of IRAD. For IRAD = 1 or 2:

$$QK_{RD} = \frac{RHT(I,R)}{(N_R\ V_F(R)\ \Delta Z)} \quad , \qquad \text{(E3.63)}$$

where

$V_F(R)$ = volume fraction of the core in radial zone R

ΔZ = axial mesh size, ft

and RHT(I,R) is calculated in subroutine RHEAT. RHEAT is discussed in Section 7.2. REHEAT models radiation heat transfer between adjacent core nodes, to the first structure above the core, to the core barrel, and to the water in or below the core.

For IRAD = 0, a simplified (MARCH 1.1) model is used and only radiation heat transfer to the structure above the core and to the water is modeled. Radiation heat transfer to the structure above the core is calculated using a parallel plane model:

2.3 MARCH 2 Validation and Assessment

A number of the physical properties, data correlations, and models in MARCH have an empirical basis or have been validated against experiments. The list of validated models and data includes properties of water and gases, heat transfer correlations, critical flow rates, combustion energy, and decay heat. However, some of the more important phenomena involving molten core debris, debris-water, debris-concrete interactions, and ignition of combustible gases are less well understood. Little effort has been performed to validate MARCH 2 against integral test data obtained under prototypic core melt conditions. This is primarily because few data of this type are available.

A comparison has been made between the MARCH 2 code and the results of the first severe fuel damage test (scoping test) in PBF.[16] Figures 2.8, 2.9, and 2.10 compare MARCH-calculated and measured temperatures and hydrogen generation in the PBF scoping test. The calculated steam temperature (Figure 2.8) is in excellent agreement with the experimental values. Calculated fuel rod temperatures (Figure 2.9) are generally high with a maximum deviation of about 400 K. The reason for the deviation is believed primarily to be due to mismatch of the experimental conditions during the initial core uncovery period between 0 and 3 minutes. (No attempt was made to fine-tune the initial conditions in the calculations, and nominal coolant makeup rates were employed.) The good agreement of the shape and trend of the curves in Figures 2.8 and 2.9 indicate the overall energy balance in MARCH is essentially correct. The calculated hydrogen generation is initially high, consistent with the high rod temperatures. The large increase in measured hydrogen generation after 200 minutes is due to failure of the housing (shroud) which allowed additional steam to enter the experiment.

These calculations indicate MARCH can do an adequate job of calculating core temperatures during the initial heatup phase prior to melting and gross core distortion. However, this agreement should not be extrapolated beyond the experimental data base into the melting and slumping phase. The meltdown models remain unsupported by direct experimental validation for this regime of behavior.

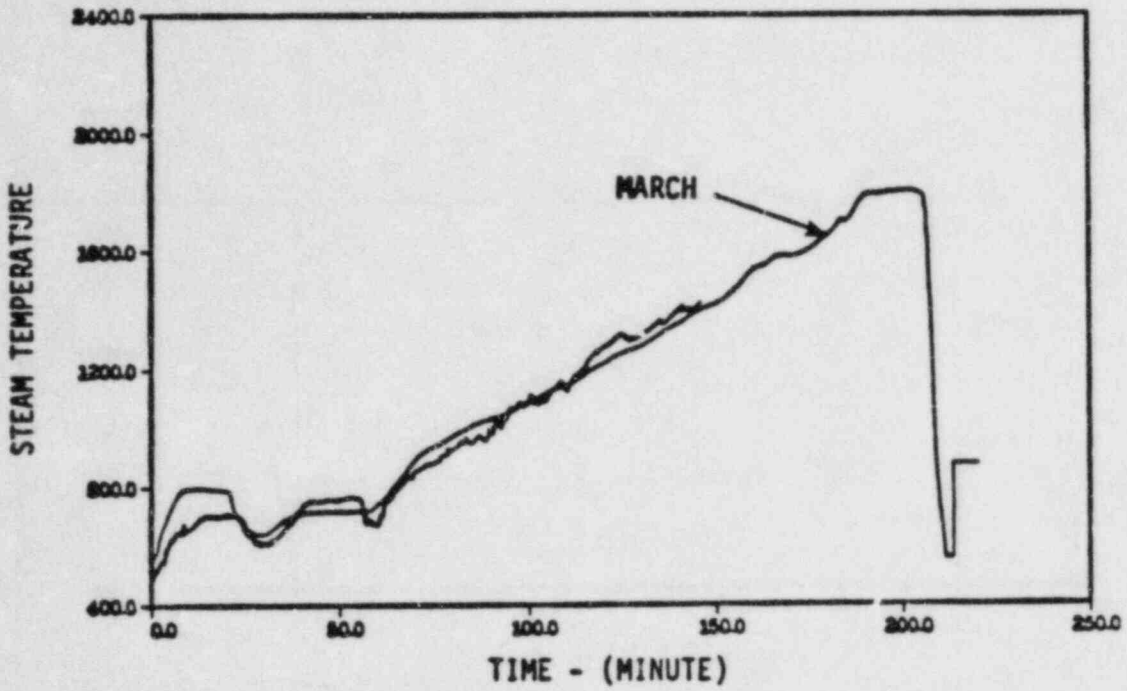

FIGURE 2.8 COMPARISON OF THE MARCH-CALCULATED AND MEASURED AVERAGE STEAM TEMPERATURE AT THE 0.91-M ELEVATION

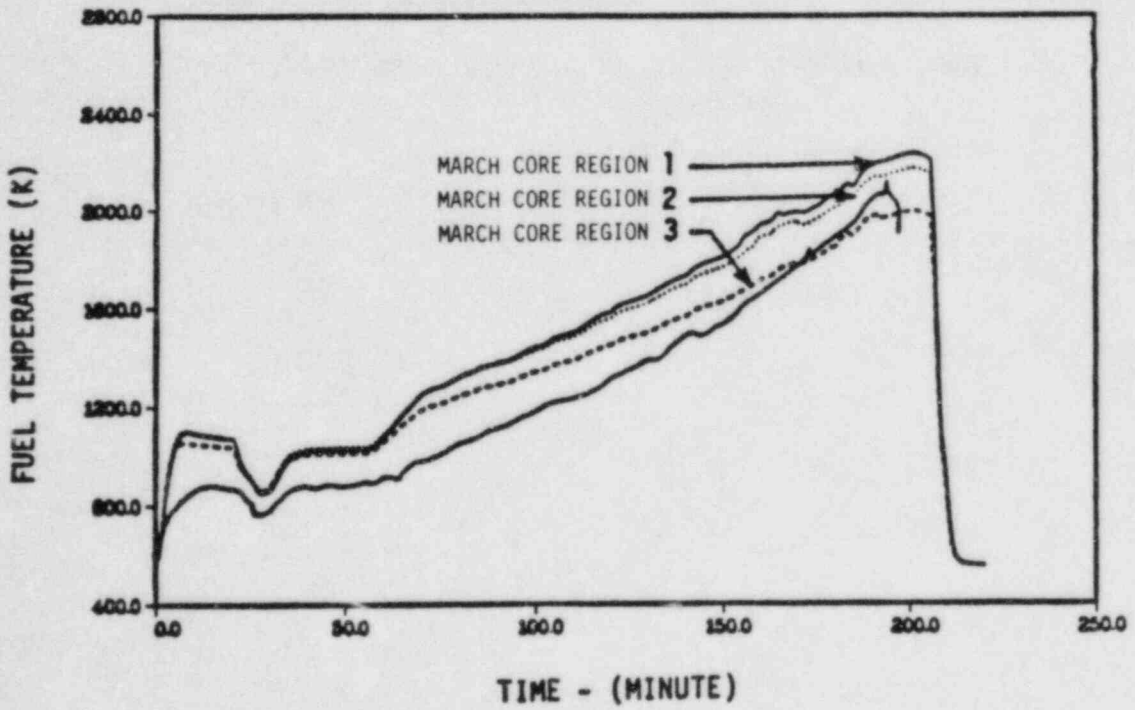

FIGURE 2.9 COMPARISON OF THE MARCH-CALCULATED AND MEASURED AVERAGE FUEL CENTERLINE TEMPERATURES AT THE 0.7-M ELEVATION

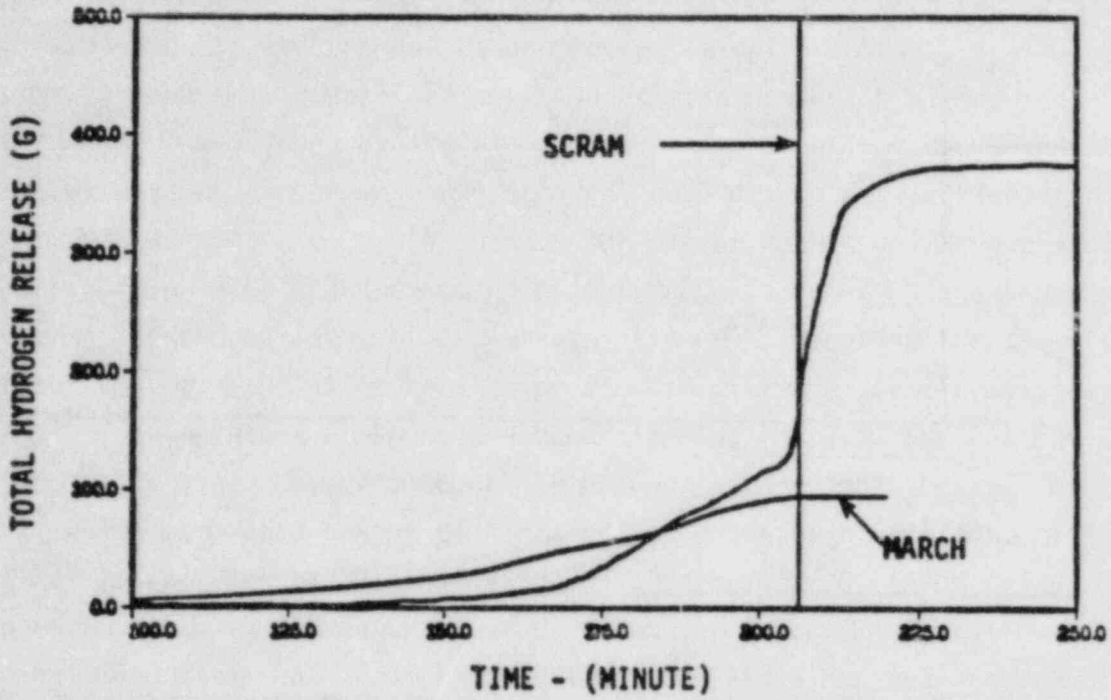

FIGURE 2.10 COMPARISON OF THE MARCH-CALCULATED AND MEASURED HYDROGEN PRODUCTION

Comparisons of MARCH 1.1, RELAP, and TRAC calculations are reported by Wooton[17] and Rogovin[18] for the TMI accident. These calculations indicated MARCH 1.1 models could explain many of the core uncovery and heatup, subsequent recovery, and thermal-hydraulic phenomena observed in the first 16 hours of the TMI transient.

In summary, the MARCH 2 computer code models a large number of complex interacting phenomena. In some cases, the basic processes are well known, and the models are supported by a significant data base. In general, however, there is very little experimental basis with prototypic materials and severe environments to support the modeling of the complex interacting phenomena associated with core meltdown itself. MARCH 2 was not developed with the intent of modeling all aspects of core meltdown accidents in detail. Rather, the intent was to provide a tool for risk analysis which described in reasonable detail the approximate timing and conditions of fuel degradation and containment failure. It is well suited for application to parameter and sensitivity studies. The user should be aware that because some of the important phenomena are not well understood, the uncertainties in the predictions of a given MARCH 2 calculation may be large. It should also be recognized that there are many assumptions not related to the MARCH code that are required in the analyses that may also introduce substantial uncertainties; among the latter are definition of the accident sequences including failure and success criteria for various engineered safety features, nature and timing of operator intervention, containment failure criteria, etc.

The major areas of uncertainty in the MARCH 2 models are believed to include:

1. Relocation and slumping of melted fuel as they affect steam and hydrogen generation
2. Debris behavior in the lower plenum of the reactor vessel
3. Vessel failure mode
4. Debris-coolant interactions in the reactor cavity
5. Ignition of combustible gases (hydrogen and carbon monoxide).

Many of the above phenomena will always have large associated uncertainties that cannot be eliminated by more sophisticated modeling. In general, however, we feel that the MARCH code predicts thermal-hydraulic conditions that are representative of those in severe accident sequences.

3.0 PRIMARY SYSTEMS MODELS

The core and primary system thermal-hydraulic conditions are calculated in subroutine BOIL and its associated subroutines. The following sections present the modeling details and equations. Input controlled modeling options are also discussed. In presenting the equations, an attempt is made to follow as closely as possible the notation, units, and the form of the equations as they are used in the coding. MARCH is generally coded in American Engineering units: lb, Btu, F, ft, etc. Consequently, the equations given in this report frequently contain unit conversion factors, which are superfluous for describing the physics. However, it is helpful for the user to see the equations as coded.

3.1 Summary of BOIL Calculations

Figure 2.3 shows BOIL and its associated subroutines. Table 2.1 briefly describes these subroutines. Not all of the subroutines and models are used in a given calculation, depending on the accident sequences, type of reactor, and user-selected input options. System-dependent models would include steam generators in PWR's and control blade and channel box models in BWR's. Examples of user-controlled models include the calculation of gas convective heat transfer coefficients, gas properties, radiation heat transfer, metal-water reaction, and meltdown models.

The major steps in the sequence of a BOIL calculation are listed below and details follow.

- Set the initial conditions (BOILNT)* and modify time dependent input parameters in subsequent timesteps.
- Calculate the core decay heat (ANSQ).
- Sum the heat input to the primary system water from the core decay heat, changes in stored energy from intact and slumped (QSLUMP) core regions, radiation (RHEAT) and axial conduction (AXCOND) heat transfer from the core, heat transfer from metal structures in the water, pump energy, ECC makeup, and steam generator heat transfer (SGEN).
- From a water mass and energy balance, calculate the water vaporization rate (STEAM), water temperature, and updated water inventory.
- Calculate the swollen mixture level and partition the core into gas-covered and mixture-covered regions.
- Calculate core temperatures and quenching (DBED) of nodes that are in the water but not slumped into the bottom head.
- For core nodes in the gas space, calculate gas properties (CONV or STMH2P), gas convection (HCGAS) and radiation (HRSTM) heat transfer, rod-to-rod radiation heat transfer (RHEAT), axial

*Subroutine names are indicated by parentheses.

conduction (AXCOND), the steam-cladding reaction rate (ZRWATR), and the rod temperatures.

- If the BWR core model has been selected, calculate rod, channel box, and control blade heat transfer, metal-water reaction, and core temperatures (AXIALC).
- Calculate the core exit gas temperature and steam-hydrogen composition
- Implement the core melting models (MELT) if required.
- Calculate the release of fission product decay heat from the core (FPLOSS) and storage of volatiles in the gas space (FPLK).
- (BOILEX) calculates the heating of structures in the gas space (EXITQ and FPQSTR) and the primary system leakage and pressure (PRIMP)
- (QSLUMP) calculates debris-water (DBED and SPHERE), debris-grid plate, and debris-head (HEAD) interactions for molten debris slumped out of the core into the bottom head.
- Total the primary system mass and energy balance audit parameters, and calculate the cumulative errors.
- Write to plot files (BOILPT) and print output (BOILPR and BOILP2).

3.2 Primary System Mass and Energy Balance

The primary system mass and energy balances, the water boiloff model, and the pressure and leakage calculations are described in this section. The first part of the section discusses the primary system nodalization, and defines input variables used in the nodalization.

3.2.1 Primary System Nodalization

The primary system in BOIL is modeled as a single volume which is partitioned into a gas (steam and hydrogen) region and a water region. Figure 3.1 illustrates features of the BOIL primary system geometry. Input required to describe the geometry includes the initial gas volume, the water

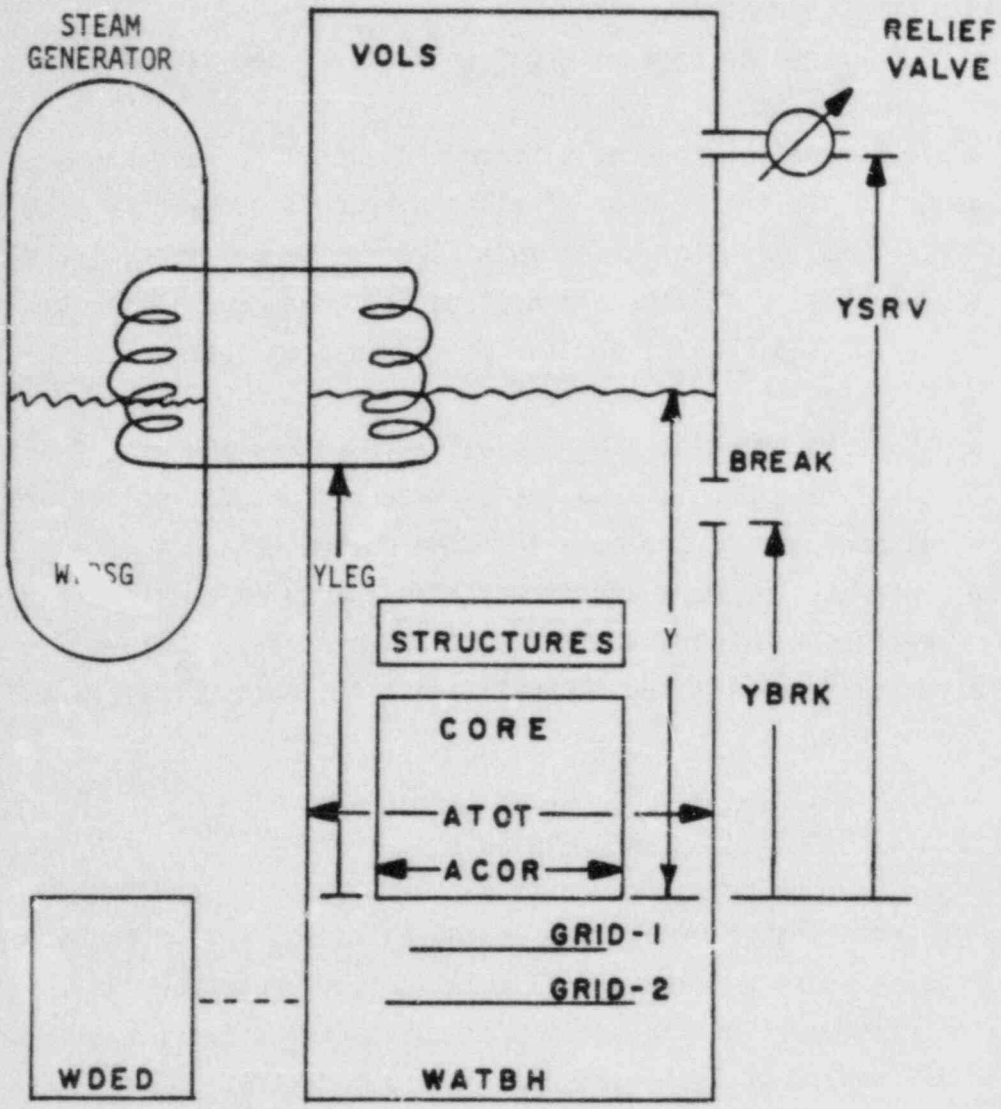

FIGURE 3.1 SKETCH OF BOIL PRIMARY SYSTEM GEOMETRY

area and height, elevations of the break, relief valve, and lower grid plates, and masses of water below the core and in dead-end volumes.

The primary system volume is calculated in PRIMP for transients and small LOCA's (input ITRAN = 1) and in BOIL for large LOCA's (ITRAN = 0). For ITRAN = 1, the total primary system is calculated in PRIMP:

$$V_P = VOLS + W_{TOT}/\rho_L \qquad (E3.1)$$

where

V_P = total primary system (water plus steam) volume, ft^3
VOLS = input initial steam volume, ft^3
W_{TOT} = initial mass of water in primary system, lb
ρ_L = water density calculated at the initial input temperature TGOO, lb/ft^3.

The initial mass of water in the primary system is

$$W_{TOT} = \rho_L A_{TOT} H_O + WATBHX + WDED \quad , \qquad (E3.2)$$

where

A_{TOT} = water occupied cross sectional area of vessel (input), ft^2
H_O = initial water height (input), ft^2
WATBHX = input mass of water in the bottom head, lb
WDED = input mass of water in dead-end volume, lb.

Note that Equation (E3.1) is used to define the primary system volume to assure consistency of Equations (E3.1) and (E3.2). The input primary system volume VOLP is not used if ITRAN = 1.

The WDED volume represents water which becomes isolated from the core during meltdown due to details of the primary system geometry. WDED may include water in loop seals, in the bottom of the steam generator, or the outer annular region below the top of the jet pumps in a BWR. WATBHX is the mass of water required to fill the lower head region. After the initial

input, water volumes are calculated from WATBHX and WDED so that subsequently the water masses are:

$$W_{BH} = VBH * \rho_L \tag{E3.3}$$

$$W_D = VDED * \rho_L \tag{E3.4}$$

where ρ_L is the density at the current water temperature and VBH and VDED are the volumes calculated from the input masses.

The cross-sectional area of the vessel, A_{TOT}, is normally selected to give a meaningful representation of the water level during core uncovery, that is, so the change in water level due to leakage ΔM is:

$$\Delta Y = \frac{\Delta M}{\rho_L \, A_{TOT}} \quad , \text{ ft} \quad . \tag{E3.5}$$

In general, the collapsed liquid height is calculated from:

$$Y_{LIQ} = \frac{W_M}{\rho_L \, A_{TOT}} \quad , \quad \text{ft} \tag{E3.6}$$

where

$$W_M = W_{TOT} - (VBH + VDED)\ \rho_L, \text{ lb} \tag{E3.7}$$

and W_M is the mass of water above the bottom of the core. Note that when the vessel is empty, $W_{TOT} = W_D$ and $Y_{LIQ} = -VBH/\rho_L \, A_{TOT}$. The swollen mixture level is calculated in Section 3.6. For a large LOCA (ITRAN = 0) the steam volume is calculated as

$$V_S = VOLP - W_{TOT}/\rho_L \quad , \text{ ft}^3 \quad , \tag{E3.8}$$

subsequent to initialization, and the input VOLSX is not used.

Other geometric specifications include the elevations of the breaks and grid plates. In general, the break elevations, YSRV and YBRK, should not have initial values outside the primary system. Also, the volume above the highest leak should not be less than 100 ft^3 and the lowest leak should leave a few hundred pounds of water in the vessel to avoid computational problems associated with zero steam volumes and masses. The lower grid plates must be below the core ($Y \leq 0$), and in the volume VBH. The first grid plate (Grid 1) may be at $Y = 0$.

3.2.2 Water Region Mass and Energy Balance

The initial mass of water in the primary system is determined by input parameters (HO, ATOT, TGOO, WATBHX, WDED), and is calculated from Equation (E3.2).

A mass balance on the liquid water in the primary gives:

$$W_{TOT} = W_{TOT1} + (W_{ECC} - W_{LBK} - W_{LRV} - W + W_{SGC})\ \Delta t \qquad (E3.9)$$

where

W_{TOT} = water mass, lb
W_{TOT1} = previous timestep value of W_{TOT}, lb
W_{ECC} = ECC injection rate, lb/min
W_{LBK} = break water leakage, lb/min
W_{LRV} = relief valve water leakage, lb/min
W = steam boiloff rate, lb/min
W_{SGC} = condensation (reflux) rate of steam in steam generator, lb/min
Δt = time step, min.

ECC injection is calculated in Section 3.7, and leakage in Section 3.2.5 below. Steam generator heat transfer and condensation are discussed in Section 3.8.

The BOIL energy balance equation for the water in the primary system is:

$$Q_{TOT}\,\Delta t = W_{TOT}\,C_{PL}\,\Delta T_{pool}\ , \qquad \text{(E3.10)}$$

where

Q_{TOT} = total heat input to water, Btu/min
C_{PL} = specific heat of water, Btu/lb
ΔT_{pool} = water temperature change, F.

An iteration is made to assure that $C_{PL}\Delta T_{pool}$ is consistent with the corresponding enthalpy change for the water properties in subroutine PROPS. If the new water temperature exceeds the saturation temperature at the total primary system pressure, primary system boiloff occurs. The boiling rate calculation is described in Section 3.2.3 below. Except in the steam generator, condensation is not modeled.

The energy input to the water is composed of that from the core (Q_{CORE}), heat transfer from structures in the vessel (Q_{SLB}), from the makeup/letdown system (Q_{MUP}), primary coolant pump energy (Q_{PMP}), from ECC injection (Q_{ECC}), and from steam generator heat transfer (Q_{SG}), thus:

$$Q_{TOT} = Q_{CORE} + Q_{SLB} + Q_{MUP} + Q_{PMP} + Q_{ECC} - Q_{SG},\ \text{Btu/min.} \qquad \text{(E3.11)}$$

The symbols used in Equation (E3.11) and the following are similar to those used in the BOIL programming. In some cases the units (power, energy, time) may be different than indicated here.

Heat transfer from the core to water is divided into five components:

$$Q_{CORE} = Q_{BL} + Q_{RADW} + Q_{AX} + Q_{NCH} + Q_{DRP} \qquad \text{(E3.12)}$$

where

Q_{BL} = decay heat below the mixture level, Btu/min
Q_{RADW} = heat radiated from the core, Btu/min

Q_{AX} = heat conducted along the fuel rods into the water, Btu/min

Q_{NCH} = heat from quenching the core material remaining in the core region, Btu/min

Q_{DRP} = heat from core debris in the bottom head and from bottom head structures after core slumping, Btu/min.

The terms in Equations (E3.11) and (E3.12) are defined later in this section. The equation numbers which define the variables are summarized below:

Q_{SLB} = Equation (E3.120)	Q_{BL} = Equation (E3.81)
Q_{MUP} = Equation (E3.110)	Q_{RADW} = Equation (E3.82)
Q_{PMP} = input	Q_{AX} = see after Equation (E3.82)
Q_{ECC} = Equation (E3.109)	Q_{NCH} = Equation (E3.83)
Q_{SG} = Equation (E3.116)	Q_{DRP} = Equation (E3.86)

3.2.3 Primary System Boiling Rate

In the absence of boiling, the increase in primary system water temperature due to all sources of heat is given by Equation (E3.10) as:

$$\Delta T = \frac{Q_{TOT}\ \Delta t}{C_{PL}\ W_{TOT}} \quad , \quad F \quad . \tag{E3.13}$$

If the new water temperature is greater than the saturation temperature, sufficient boiling will occur to reduce the water temperature to the saturation temperature. The boiling rate required to do this is:

$$W = (T_{pool} + \Delta T - T'_{sat})\ \frac{C_{PL}\ W_{TOT}}{h_{fg}\ \Delta t} \quad , \quad \text{lb/min} \quad , \tag{E3.14}$$

where

T_{pool} = water temperature at the end of the previous timestep, F

h_{fg} = heat of vaporization, Btu/lb

T'_{sat} = saturation temperature at the new total system pressure, F.

Equation (E3.14) cannot be used directly to calculate the boiling rate, however, because the new total system pressure, P', and the new saturation temperature, T'_{sat}, are not known. The calculation of P' requires knowledge of the boiling rate, heating of the gases in the core, composition of the gases, volumes of the water and gas, and leakage and ECC injection rates. An iterative solution technique is required in general. In principle, a numerical approach using small timesteps would also be feasible. The iterative and small-timestep approaches have the principal disadvantage of increased computer costs. It is also noted that some core melting and slumping processes in the present BOIL formulation are independent of timestep size which, without modification, would mitigate against proper convergence in all cases as $\Delta t \to 0$.

BOIL uses a simplified approach to estimate the coupling effects of W and P' so that iteration is not required and large timesteps can be taken. The boiling calculations are performed in subroutine STEAM. The boiling is divided into components W_B, the boiling which would occur in a closed system, and W_{flash}, the boiling required to compensate for changes in T_{SAT} due, for example, to depressurization caused by leakage.

The boiling which would occur in a closed system is calculated from Equation (E3.14) ignoring the effects of gas heating and metal-water reaction in the core; thus,

$$W_B = (T_{pool} + \Delta T - T'_s) \frac{C_{PL}\ W_{TOT}}{h_{fg}\ \Delta t} \qquad \text{(E3.15)}$$

where T'_s is the new saturation temperature resulting from the addition of a steam mass $W_B\ \Delta t$ to the gas space. T'_s is estimated from the relation

$$T'_s = T_{sat} + dT_s = T_{sat}\left(1 + \frac{dT_s}{T_s}\right) \quad , \quad F \qquad \text{(E3.16)}$$

where T_{sat} is the previous saturation temperature.

On the saturation line (within about a factor of two)

$$\frac{dT_s}{T_s} \sim \frac{1}{4.6} \frac{dP}{P} \qquad \text{(E3.17)}$$

where P is the total pressure (psia) and dP is the pressure change due to the addition of steam mass, $W_B \Delta t$. Replacing dP with

$$dP = \frac{W_B \Delta t}{STM} P_{sv} \qquad \text{(E3.18)}$$

where

STM = mass of steam in primary system, lb

P_{sv} = steam pressure, psia,

and combining Equations (E3.15), (E3.16), and (E3.17), W_B is found to be:

$$W_B = \Delta T_B \frac{C_{PL} W_{TOT}}{h_{fg} \Delta t} \qquad \text{(E3.19)}$$

where

$$\Delta T_B = \frac{(T_{pool} + \Delta T - T_{sat})}{(1 + \frac{C_{PL} T_{SAT} W_{TOT}}{4.6\ STM\ h_{fg}} \frac{P_{sv}}{P})} \qquad \text{(E3.20)}$$

The flashing component, W_{flash}, is set equal to the minimum of WF and FL; thus,

$$W_{flash} = \min(WF, FL) \qquad \text{(E3.21)}$$

where

$$WF = (T_{pool} + \Delta T - \Delta T_B - T_{sat}) \frac{C_{PL} W_{TOT}}{h_{fg} \Delta t} \qquad \text{(E3.22)}$$

and

$$FL = W_{SLK} + 9*W_{HLK} + (W_{LBK} - W_{ECC})\ \rho_S/\rho_L \qquad \text{(E3.23)}$$

where

W_{SLK} = steam leak rate, lb/min
W_{HLK} = hydrogen leak rate, lb/m
W_{LBK} = water leak rate, lb/min
W_{ECC} = ECC injection rate.

FL is evaluated using values calculated in the previous timestep. FL is approximately the boiling rate required to compensate for leakage; that is, to maintain a constant pressure with primary system leakage. WF is the additional boiling rate beyond W_B required to reduce the water temperature to the old saturation temperature, T_{sat}.

When the steam generator in a pressurized water is operating in a "steam condensation" mode (ICON = 1 in namelist NLBOIL), an additional steam flow rate, W_{SGC}, is assumed to be produced. The steam flow W_{SGC}, in effect, acts as a carrier to transport heat from the core to the steam generator. When the primary system is full, the steam generator would actually directly cool the primary system water and thus suppress boiling. Thus, in a full system, W_{SGC} may be an artificial parameter. However, in a partially filled system with an empty (primary side) steam generator, steam condensed in the steam generator represents potential core steam flow. Thus, the calculated W_{SGC} is meaningful during uncovering of the core. The calculation of W_{SGC} is discussed in Section 3. The steam flow rate W_{SGC} is assumed to flow through the core and structures above but is subsequently condensed so it does not contribute to the steam inventory in the primary system gas space.

The total steam generation rate is:

$$W = W_B + W_{flash} + W_{SGC},\ \text{lb/min} \quad . \qquad \text{(E3.24)}$$

The change in water temperature produced by the boiling is:

$$\Delta T_{TOT} = \frac{W \, \Delta t \, h_{fg}}{C_{PL} \, W_{TOT}} \ , \ F \qquad \text{(E3.25)}$$

and the new water temperature is:

$$T'_{pool} = T_{pool} + \Delta T - \Delta T_{TOT} \ , \ F \ . \qquad \text{(E3.26)}$$

This algorithm may produce values of T'_{pool} which may be either greater or less than T_{sat}. In practice, it is found that Equations (E3.19) and (E3.21) as given do not always produce smoothly varying boiling rates and close tracking of T'_{pool} and T_{sat}. Oscillations in the predicted boiling rates are found to occur during rapid transition states such as when the break flow changes from liquid to steam, when the break area is changed, and during core slumping, or when water levels are low so there is little heat input to the water.

In order to improve the smoothness, additional numerical restrictions are applied to Equations (E3.19) and (E3.21). The components of Equation (E3.24) are replaced with the sum of half the currently calculated value and half the previous value. For pipe break accidents (with ITRAN = 1) the boiling rate is restricted to 25 percent changes per timestep. Prior to core uncovery, and during core slumping, the boiling rate is increased if ΔT_{TOT} is less than 95 percent of ($T_{pool} + \Delta T - T_{sat}$). Subroutine BOIL prints a message* if a calculation of no boiling follows a timestep in which boiling occurred. Experience indicates the smoothing algorithm generally produces continuous boiling rates and that T_{pool} will normally track T_{sat} within about 1 F. The calculated boiling rate is relatively insensitive to the BOIL timestep size. For a 1.0 min timestep, one or two non-boiling timesteps have been observed at the end of core meltdown. For a 0.5 minute or smaller timestep, none were found.

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*"No core steam flow during MARCH timestep N, time = TIME".

3.2.4 Primary System Pressure Calculation

For large pipe break accidents (ITRAN = 0), the primary system pressure is assumed to be the same as the containment pressure. For transients and small LOCA's, the primary system pressure is calculated in subroutine PRIMP.

The pressure calculation in PRIMP assumes ideal gas behavior. The pressure is calculated from the relation:

$$P_{VSL} = P_{SV} + P_{H2} \quad , \text{psia} \tag{E3.27}$$

where

P_{SV} = steam partial pressure, psia
P_{H2} = hydrogen partial pressure, psia

and

$$P_{SV} = \frac{STM}{V_S} R_S \, (T + 460) \tag{E3.28}$$

$$P_{H2} = \frac{HYD}{V_S} R_H \, (T + 460) \tag{E3.29}$$

STM = mass of steam in gas volume, lb
HYD = mass of hydrogen in gas volume, lb
V_S = gas volume, ft^3
R_S = steam gas constant, $ft^3/in^2/F$
R_H = hydrogen gas constant, $ft^3/in^2/F$
T = mixed gas-space temperature, F.

For hydrogen, a constant $R_H = \frac{767}{144}$ $ft^3/in^2/F$ is used in PRIMP. For steam, R_S is calculated to give the correct pressure on the saturation line,

$$RS = \frac{P_{SAT}}{\rho_{SAT}(T_{SAT} + 460)} \tag{E3.30}$$

where ρ_{SAT} is the steam density. All properties in Equation (E3.30) are evaluated on the saturation line at a temperature $T_{SAT} = T_{pool}$, where T_{pool} is the water temperature. Thermodynamic properties are taken from subroutine PROPS (Section 7.6.1).

The gas volume is calculated from:

$$V_S = V_p - W_{TOT}/\rho L \qquad \text{(E3.31)}$$

where V_p is the total primary system volume and W_{TOT} is calculated in BOIL.

The masses of steam and hydrogen are obtained from mass balances:

$$STM = STM_B + (WS_N - WS_{BK} - WS_{RV})\Delta t \qquad \text{(E3.32)}$$

$$HYD = HYD_B + (WH - WH_{BK} - WH_{RV})\Delta t \qquad \text{(E3.33)}$$

where the B subscripts refer to old values and

WS_N = net steam flow rate into the gas space, lb/min
WH = hydrogen flow rate from the core, lb/min
WS_{BK}, WS_{RV} = break and relief valve steam leak rates, lb/min
WH_{BK}, WH_{RV} = hydrogen leak rates, lb/min.

The initial mass of steam in the pressure vessel required to initialize the pressure at the input P_{VSL} is:

$$STM_B = \frac{P_{VSL}}{P_{SAT}} \rho_{SAT} V_S, \text{ lb} \qquad \text{(E3.34)}$$

As discussed previously, the net steam flow into the gas space is:

$$WS_N = WS - W_{SGC}, \text{ lb/min} \qquad \text{(E3.35)}$$

where

W_{SGC} = the steam generator condensation rate, lb/min
WS = steam flow rate from core, lb/min.

The leak rate terms are discussed in Section 3.2.5.

The temperature of the gas space is calculated assuming a constant enthalpy mixing process of the gases from the core with those in the gas space. (A $\Delta(PV)$ term is neglected in the energy balance.) The gases coming from the core are assumed to transfer heat to the structures in the gas space before entering the gas volume. The gas space temperature is:

$$T = \frac{(MC)_B \, T_B + \Delta(MC) \, T_{GXS}}{(MC)_B + \Delta(MC)} \, , \, F \qquad \text{(E3.36)}$$

where

T_B = previous gas space temperatures, F

T_{GXS} = gas temperature at exit of last structure above the core (Section 3.9), F

$(MC)_B = STM_B \, C_{ps} + HYD_B \, C_{pH}$

$\Delta(MC) = (WS_N \, C_{ps} + WH \, C_{pH})\Delta t$

C_{ps} = steam specific heat, Btu/lb/F

C_{pH} = hydrogen specific heat, Btu/lb/F.

Since the leak rates in Equations (E3.32) and (E3.33) depend on the pressure P_{VSL} in Equation (E3.27), these equations are solved iteratively. The solution is assumed to have converged when the calculated steam and hydrogen masses do not change by more than 0.1 percent between iterations.

PRIMP also calculates the BOIL timestep size for small LOCA's. The calculated timestep size limits the vessel pressure change per timestep to the smaller of 10 psi or 2 percent of P_{VSL}. The timestep size may vary between 10^{-4} and 1.0 minute, depending on the break size and system pressure. The user may specify smaller timesteps than calculated in PRIMP by input TSB(I) in namelist NLBOIL, if desired.

3.2.5 Primary System Leak Rate

For large LOCA's (ITRAN = 0), the primary system leakage is calculated in BOIL. For large LOCA's only "break" flow is modeled. Relief valve flow is not modeled. The gas leakage calculation assumes storage and mixing

in the vessel prior to leakage. The leakage rate calculation assumes no pressure buildup in the vessel. For a constant pressure process, the leak rates for steam and hydrogen are found to be:

$$WS_{BK} = \frac{(WS + 9\ WH)\ F_T}{(1 + 9\ F_X)} \quad , \tag{E3.37}$$

$$WH_{BK} = F_X\ WS_{BK} \quad , \tag{E3.38}$$

where

$$F_T = \frac{T_{GXS} + 460}{T + 460} \quad , \tag{E3.39}$$

$$F_X = \frac{HYD + WH\ \Delta t}{STM + WS\ \Delta t} \quad . \tag{E3.40}$$

The derivation assumes the molar volumes of steam and hydrogen are in the ratio of 9:1. The parameters in Equations (E3.37) through (E3.40) were defined above. There is assumed to be no water leakage after blowdown for large LOCA's. Thus, if the ECC injection exceeds that required to compensate for boiloff, flow is diverted directly to the sump rather than flowing through the core and out the break. The vessel water level and ECC diversion are controlled by the inputs WVMAX and WVMAKS in namelist NLMACE.

For small LOCA's and transients (ITRAN = 1), the leakage calculations are done in PRIMP along with the vessel pressure calculation. Water leakage occurs when the break or relief valve is below the collapsed liquid level and gas leakage occurs when they are above the water level. Two-phase (liquid-steam) leakage is not modeled. Break flows are directed to containment compartment NRPV, and relief valve flows to compartment JRPV. If compartment JRPV is a suppression pool, the release point is in the pool. The break and relief valve elevations are illustrated in Figure 3.1. The elevations, break area, relief valve capacity and pressure setpoint, and NRPV and JRPV are specified by input.

The water leakage through a break is:

$$WL_{BK} = A_{BRK} \min\ (G_{LN}, G_{LC}),\ lb/min \quad , \tag{E3.41}$$

where

A_{BRK} = break area, ft^2
G_{LC} = liquid critical flow rate, $lb/min/ft^2$
G_{LN} = liquid orifice flow rate, $lb/min/ft^2$.

The orifice flow rate in PRIMP is:(20)

$$G_{LN} = 5778\ C_B \sqrt{\rho_L (P_{VSL} - P_N)},\ lb/min/ft^2 \qquad (E3.42)$$

where

C_B = 0.583
P_N = pressure in containment compartment NRPV, psia.

The critical flow rate, G_{LC}, is calculated in subroutine EFCRIT, Section 7.4.1, using the RETRAN fit to the subcooled Henry-Fauske correlation.(21a) The correlation is applicable to both saturated and subcooled liquid water.

Two valve models are available in MARCH. For one model, the valve is assumed to open just enough to maintain the primary system pressure at the relief valve setpoint. The second model allows valve cycling between fully-open and completely closed, depending on the pressure set-points. The second model may be more realistic. However, the first allows larger computational timesteps (thus saving computer costs) and is adequate for many applications.

For liquid flow through the relief valve, the flow rate is:

$$WL_{RV} = A_{SRV} \min (G_{LJ}, G_{LC}, WB3/A_{SRV}),\ lb/min \qquad (E3.43)$$

where

A_{SRV} = relief valve flow area, ft^2
G_{LJ} = the orifice flow rate into containment compartment JRPV
G_{LC} = the critical flow rate
WB3 = the flow required to maintain the vessel pressure at the relief valve setpoint (input option), lb/min.

Thus, G_{LJ} is given by Equation (E3.42) with P_N replaced by P_J, the pressure in compartment JRPV. G_{LC} is the same as for the break critical flow. The flow rate WB3 is:

$$WB3 = \left[\frac{(STM \times R_S + HYD \times R_H)(T + 460)}{(PSET + PJ + 5)} - V_S \right] \frac{\rho_L}{\Delta t}, \text{ lb/min} , \quad (E3.44)$$

where P_{SET} = relief valve pressure setpoint, psi. If P_{VSL} is less than $P_{SET} + P_J$, the valve is closed and WB3 = 0. Thus, valve closure is assumed to be controlled by gage pressure ($P_{VSL} - P_J$) rather than absolute pressure (P_{VSL}). The flow rate WB3 will maintain a vessel pressure of $P_{SET} + P_J + 5$ psia, or 5 psi above the absolute pressure setpoint. The 5 psi pressure differential is employed to avoid flow oscillations for small calculated changes in P_{VSL} and containment pressure.

The WB3 term is dropped from Equation (E3.43) if valve cycling is desired. In this case, the valve will leak through the area ASR when the primary system pressure reaches PSET and will reclose when the pressure falls below PSET-|PSR|, where PSR and ASR are input.

For gas (steam and hydrogen) leakage, the break flow is:

$$WG_{BK} = A_{BRK} \min (G_{GN}, G_{GC}), \text{ lb/min} . \quad (E3.45)$$

The orifice flow rate, G_{GN}, is given by Equation (E3.42) with ρ_L replaced by the gas density:

$$\rho = \frac{(STM + HYD)}{V_S} , \text{ lb/ft}^3 . \quad (E3.46)$$

The critical gas flow rate, G_{GC}, is:

$$G_{GC} = CF \sqrt{\rho/\rho_S} , \text{ lb/min/ft}^2 , \quad (E3.47)$$

where CF is the critical saturated steam flow rate at pressure P_{VSL}. CF is calculated in subroutine CR1, Section 7.4.2, using the RETRAN fit to the Moody correlation for saturated steam.(21b) The steam and hydrogen leak rates are assumed to be proportional to their mass fractions in the vessel. Thus:

$$WS_{BK} = F_S \, WG_{BK}, \text{ lb steam/min} \qquad \text{(E3.48)}$$

$$WH_{BK} = F_H \, WG_{BK}, \text{ lb hydrogen/min} , \qquad \text{(E3.49)}$$

where

$$F_S = STM/(STM + HYD) \qquad \text{(E3.50)}$$
$$F_H = HYD/(STM + HYD).$$

The relief valve gas flow is:

$$WG_{RV} = A_{SRV} \min (G_{GJ}, G_{GC}, WG/A_{SRV}), \text{ lb/min} , \qquad \text{(E3.51)}$$

where

G_{GJ} = given by Equation (E3.42) with ρ_L replaced with ρ and P_N by P_J
G_{GC} = given by Equation (E3.47), and
WG = the limiting flow rate to maintain a vessel pressure at the pressure setpoint (input option).

The limiting flow is:

$$WG = \frac{STM \times R_S + HYD \times R_H - \dfrac{V_S P_{LIM}}{(T + 460)}}{(F_S R_S + F_H R_H) \; \Delta t} , \text{ lb/min} , \qquad \text{(E3.52)}$$

where $P_{LIM} = P_{SET} + P_j + 5$, psia.

The steam and hydrogen flows through the relief valve are:

$$WS_{RV} = F_S \, WG_{RV}, \text{ lb steam/min} \qquad \text{(E3.53)}$$
$$WH_{RV} = F_H \, WG_{RV}, \text{ lb hydrogen/min.}$$

The full-open relief valve flow area, A_{SET}, is calculated in BOIL as:

$$A_{SRV} = A_{SET} = W_{SET}/CF \quad , \qquad \text{(E3.54)}$$

where

W_{SET} = the user-input rated relief valve capacity, lb steam/min, and
CF = saturated steam critical flow rate at pressure P_{SET}, $lb/ft^2/min$.

If a leak multiplier, TPM, is specified in the input, the water leak rates are multiplied by the factor $TPM^{-0.5}$ for orifice flow and $TPM^{-0.813}$ for critical flow for T_{pool} less than 20 F subcooled. The principal application of the TPM factor is for fine-tuning MARCH blowdown rates to agree with a particular set of experimental data or an independent blowdown calculation.

A_{BRK}, Y_{BRK}, A_{SRV}, Y_{SRV}, and P_{SET} may be changed during the calculation by arrays TB, ABR, YBR, ASR, YSR, and PSR in the namelist NLBOIL input. If PSR is negative (and $\neq -1$), vessel leakage occurs for pressures between PSET and PSET-|PSR|.

3.3 Core Heat Transfer

Core heat transfer, for fuel nodes which have not fallen into the bottom head after melting, is discussed in this section. Heat transfer from nodes above the mixture level is discussed in the first part of this section, and calculations for nodes in the water (mixture) are discussed in the second part. Meltdown models and heat transfer from fuel which has fallen into the bottom head are discussed in Sections 3.3.3 and 3.4.

3.3.1 Heat Transfer in Uncovered Core

Figure 3.2 illustrates the fuel rod modeling in BOIL. The fuel rod heat balance in the gas covered region considers fission product decay heat, energy from metal-water reaction, heat transfer by convection and radiation to the steam and hydrogen flowing through the channel, radiation heat transfer

to adjacent core nodes, and axial conduction. The top nodes in the core may radiate to a structure above the core. The nodes above the mixture level may radiate heat downward to the water. Nodes on the outer core periphery may radiate to the core barrel. Not all of these features are always modeled. Input options allow the user to skip certain features and to choose between different models for these features. The following discussion assumes that all core materials, including the BWR channel boxes and control blades, are included in lumped or average core properties rather than modeled separately. The BWR core model with explicit modeling of the channel boxes and control blades is discussed in Section 3.3.4.

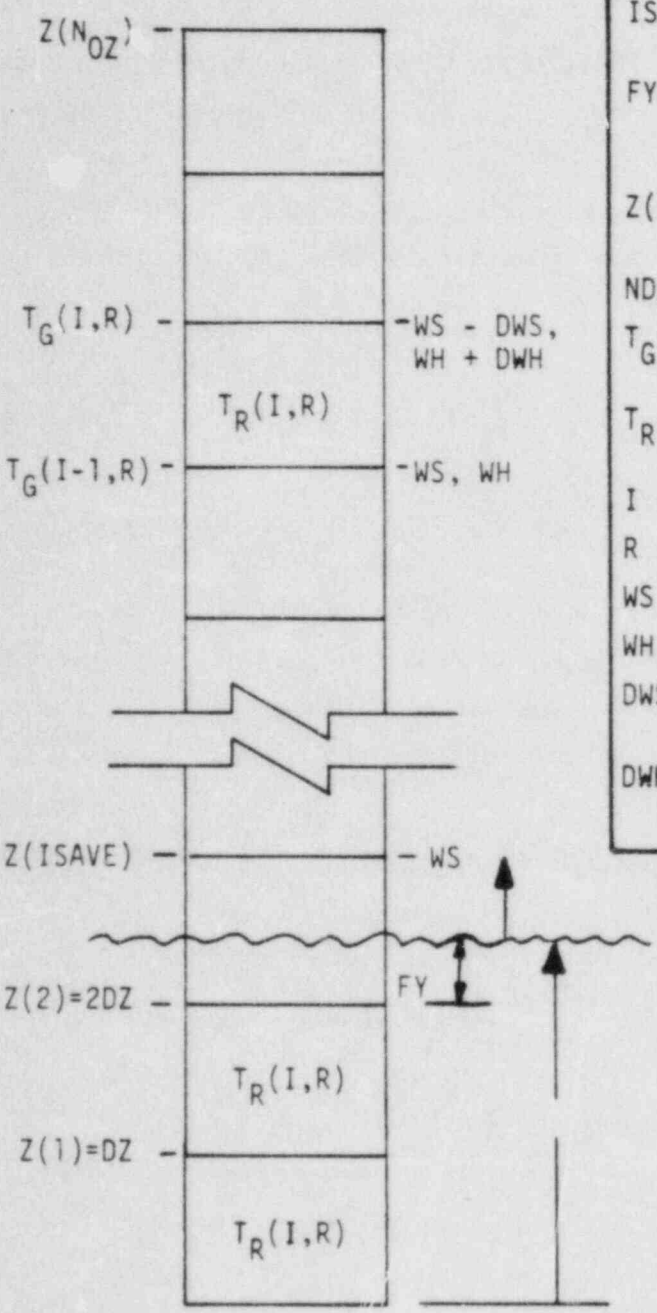
3.3.1.1 Fuel Rod Temperatures

The fuel rod temperature in the gas covered region is first calculated using an estimated convection component:

$$T_R(I,R) = T_{RO}(I,R) + (QK_{DK} + QK_{MW} - QK_{HC1} + QK_{RD} + QK_{AX}) \frac{\Delta t}{60(\rho C)A_R} \quad \text{(E3.55)}$$

where

$T_R(I,R)$ = new rod temperature, F
$T_{RO}(I,R)$ = rod temperature at the end of the previous timestep, F
I = axial node number
R = radial node number
(ρC) = rod volumetric heat capacity, Btu/ft^3/F
$A_R = \frac{\pi}{4}D^2$ = rod cross sectional area, ft^2
QK_{DK} = decay heat, Btu/hr/ft
QK_{MW} = heat from metal-water reaction, Btu/hr/ft
QK_{HC1} = first estimate of heat transfer to gas in channel, Btu/hr/ft



Y	= mixture level
ISAVE	= node which contains the mixture level
FY	= fraction of node ISAVE covered by mixture
Z(I)	= elevation of top of node I
NDZ	= node at top of core
$T_G(I,R)$	= gas temperature at top of rod node (I,R)
$T_R(I,R)$	= rod temperature for node (I,R)
I	= axial node number
R	= radial node number
WS	= steam flow rate
WH	= hydrogen flow rate
DWS	= steam consumed in metal-water reaction
DWH	= hydrogen consumed in metal-water reaction

FIGURE 3.2. BOIL MIXTURE LEVEL AND FUEL ROD SKETCH

QK_{RD} = radiation heat transfer to other rods, to structures outside the core, and to water, Btu/hr/ft

QK_{AX} = axial conduction heat transfer, Btu/hr/ft.

All of the QK values and (ρC) in Equation (E3.55) depend on the node index (I,R). Axial nodes are numbered from bottom to top, and radial nodes from inside to outside.

The local rod heat capacity is corrected to account for the increase in heat capacity due to the addition of oxygen to the cladding by metal-water reaction,

$$(\rho C) = \text{RHOCU}\left(1 + \frac{4\rho_{zr} C_{ox} X(I,R)}{D \times \text{RHOCU}} \frac{32}{91.22}\right) \qquad \text{(E3.56)}$$

where

RHOCU = input value of core heat capacity, Btu/ft^3/F

ρ_{zr} = 401.9 lb/ft^3 = zirconium density

C_{ox} = 0.218 Btu/lb/F = oxygen specific heat

X(I,R) = thickness of cladding reacted, ft.

RHOCU is calculated assuming the core heat capacity is distributed over N_R rods

$$\text{RHOCU} = \frac{\Sigma(\text{MC})\text{core}}{N_R\ A_R\ H}\ , \qquad \text{(E3.57)}$$

where

N_R = number of rods in core

H = core height, ft

MC = mass times heat capacity of core materials, Btu/F.

The core heat capacity (input RHOCU) is assumed to be temperature independent. Temperature dependence can be accounted for approximately in the calculations by using average heat capacities which give the correct enthalpy change over

the temperature range of interest. Section 7.6.6 contains core material density and heat capacity data suggested for use in MARCH.

The local decay heat is:

$$QK_{DK} = \frac{Q_{DK}}{V} P_F(R)\ F(I)\ FP(I,R)\ A_F \quad , \text{Btu/hr/ft} \quad , \qquad \text{(E3.58)}$$

where

Q_{DK} = core decay heat, Btu/hr

$P_F(R)$ = ratio of radial zone R power to average core power ($\Sigma P_F V_F = 1$)

$F(I)$ = ratio of axial node I power to average rod power ($\Sigma F = NDZ$)

$V_F(R)$ = volume fraction of core in radial zone R

$FP(I,R)$ = fraction of decay heat remaining in node (I,R)

$V = N_R A_F H$, ft^3

$A_F = \frac{\pi}{4} D_F^2$ = rod fuel area, ft^2.

The core decay heat is divided among N_R rods.

The metal-water reaction energy is given by Equation (E3.93). Because of the lumped node approximation used in BOIL, the energy is added to the whole node rather than being absorbed locally in the cladding. That is, the cladding and fuel are assumed to have the same temperature.

A first estimate of the heat transfer to the gas is made using old values of the rod temperature and the average of the old upstream and new downstream gas temperatures:

$$QK_{HC1} = (h_C + h_{rad})\ p(ROD(I,R) - TGAV), \text{ Btu/hr ft} \qquad \text{(E3.59)}$$

where

h_C = convective heat transfer coefficient, $Btu/hr/ft^2/F$

h_{rad} = gas radiation heat transfer coefficient, $Btu/hr/ft^2/F$

$p = \pi D$ = rod perimeter, ft

$TGAV = 1/2(T_{GO}(I,R) + T_{GO}(I-I,R))$.

The calculation of QK_{HC} is updated in a later step. The coding contains checks to assure that: QK_{HC1} does not predict heat fluxes which would cool the rod below the gas temperature, or heat the gas above the rod temperature, or exceed a gas-rod thermal equilibrium condition in one timestep. Similar (opposite) restrictions are applied when the rod is being heated by the gas.

Heat transfer coefficients are discussed in Section 7.1. h_C and h_{rad} depend on the input choices of ICONV and IHR. For ICONV > 0, h_C is given by Equation (E7.3) for turbulent flow and by Equation (E7.4) for laminar flow. For ICONV = 0, h_C is given by the maximum of h_C in Equation (E7.1) or $1/2(h_{nat})$ as given by Equation (E7.2). If IHR = 1, h_{rad} is given by Equation (E7.5) with $\epsilon_R = 0.7$. For IHR = 0, $h_{rad} = 0$. Use of ICONV $\geq$ 1 provides a complete turbulent and laminar flow correlation, while ICONV = 0 uses the simplified MARCH 1.1 correlation. For the BWR core model (IBWR = 1), only the ICONV > 1 option is available. Calculations indicate the choice of h_C (or ICONV) generally has little effect on the timing of core meltdown when radiation is included (IHR = 1), though it does effect the calculated core exit gas temperature.

As is apparent from Equations (E3.55) and (E3.59), BOIL uses more than one notation for rod temperature. In the BOIL notation, TR(I,R) is the "energy-equivalent" temperature; and ROD(I,R) is the actual or physical temperature. The difference between the two temperatures is that TR(I,R) includes the temperature equivalent of the heat of fusion to account for fuel rod melting. The temperature equivalence of the heat of fusion is defined as:

$$\Delta T_{FUS} = \frac{\Sigma(M\lambda)}{\Sigma(MC)} \qquad \text{(E3.60)}$$

where

λ = heat of fusion of core materials, Btu/lb

and the summation is over all core materials. Thus, depending on the extent of melting, TR(I,R) may exceed ROD(I,R) by as much as ΔT_{FUS}. (BOIL calculates ΔT_{FUS} from the input values of TMELT and TFUS; ΔT_{FUS} = TFUS-TMELT).
In general:

$$\begin{aligned} ROD(I,R) &= TR(I,R), && TR(I,R) < TMELT \\ ROD(I,R) &= TMELT, && TMELT < TR(I,R) < TFUS \\ ROD(I,R) &= TR(I,R) - \Delta T_{FUS}, && TFUS < TR(I,R). \end{aligned} \qquad \text{(E3.61)}$$

For temperatures between TMELT and TFUS, fractional node melting is calculated as

$$F_{NM}(I,R) = \frac{TR(I,R) - TMELT}{\Delta T_{FUS}} \quad . \qquad \text{(E3.62)}$$

BOIL also uses a third notation SOD(I,R) for rod temperature. ROD(I,R) and SOD(I,R) are the same, except that SOD(I,R) is set to zero as a flag to indicate that a node has fallen out of the core due to slumping. SOD(I,R) is printed in the output array of core temperatures. Note that ROD(I,R) is used to calculate rate processes, such as heat flux and metal-water reaction.

The calculation of the radiation heat transfer term differs for nodes inside and on the periphery of the core, and also depends on the input value of IRAD. For IRAD = 1 or 2:

$$QK_{RD} = \frac{RHT(I,R)}{(N_R \; V_F(R) \; \Delta Z)} \quad , \qquad \text{(E3.63)}$$

where

$V_F(R)$ = volume fraction of the core in radial zone R

ΔZ = axial mesh size, ft

and RHT(I,R) is calculated in subroutine RHEAT. RHEAT is discussed in Section 7.2. REHEAT models radiation heat transfer between adjacent core nodes, to the first structure above the core, to the core barrel, and to the water in or below the core.

For IRAD = 0, a simplified (MARCH 1.1) model is used and only radiation heat transfer to the structure above the core and to the water is modeled. Radiation heat transfer to the structure above the core is calculated using a parallel plane model:

$$Q_R = 0.173 \times 10^{-8} \, FA \left[\left(\frac{T_1 + 460}{100} \right)^4 - \left(\frac{T_2 + 460}{100} \right)^4 \right] \text{Btu/hr} \quad (E3.64)$$

where

$F = \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \right)^{-1}$ = F12 (input)

$A = V_F(R) A_{top}$ = fraction of area in radial zone R, ft^2

A_{top} = envelope area of top of core (πR^2 where R=core radius), ft^2

T_1 = ROD(ITOP,R), F

T_2 = structure temperature (TFEO), F

ITOP = highest non-slumped node in radial zone R.

The radiation to water for IRAD = 0 is calculated using Equation (E3.64) with:

T_1 = ROD(ISAVE,R), F

T_2 = water temperature (TPOOL), F

F = 0.5

ISAVE = axial node containing the mixture level (see Figure 3.2).

For IRAD = 0, the coding contains checks to assure that the heat radiated to water does not decrease the rod temperature more than halfway to the water temperature or vaporize the water to a level below the second grid plate in one timestep. For IRAD > 0, these checks are applied to RHT(ISAVE,R). For IRAD = 0, the highest non-slumped core node in each radial zone radiates to the structure above the core. For IRAD > 0, the top core node (I=NDZ) radiates to the upper structure, but if the top node has slumped from the core, the radiation heat transfer from the top of the core is set to zero. For IRAD = 0, the coding also contains a check to assure that the radiated heat does not increase the upper structure temperature above a heat capacity-weighted average of the top node and structure temperatures. For large timesteps (Δt = 1 minute), negative core temperatures are sometimes calculated for IRAD > 0, and are believed to be caused by the lack of an explicit check in the RHT(I,R) array to assure that the radiated heat fluxes

do not exceed those required to obtain thermal equilibrium, and thus reverse the source and receiver temperature differences. These difficulties can generally be eliminated by the use of smaller timesteps ($\Delta t < 0.1$ minutes) or by renoding the core so that adjacent nodes are of comparable size.

The radiation term in Equation (E3.55) for IRAD = 0 is:

$$QK_{RD} = -\frac{Q_R}{N_R \Delta Z} \quad \text{for I = ITOP or ISAVE} \qquad \text{(E3.65)}$$

$$= 0 \quad \text{for all other I.}$$

Use of the radiation heat transfer models for IRAD > 0 results in a smoothing of the core temperature distribution, more rapid heating of cooler nodes, extension of core meltdown by a few minutes, and a few percent increase in the metal-water reaction.

The RHEAT radiation heat transfer model (IRAD > 0) can also be used with the BWR core model (IBWR = 1). However, the effect of the presence of the channel boxes and control blades on radiation heat transfer between the core nodes is not modeled. That is, rod temperatures, ROD(I,R), are used in the calculations of the radiation heat flux. The use of rod temperatures is reasonable for the calculation of axial radiation heat transfer, but may overestimate radial heat transfer. Proper adjustment of the radial emissivity (ECROS) can partially compensate for the presence of the boxes and blades. Assuming equal emissisivities and that the boxes and blades act as simple baffles between adjacent fuel bundles, the input ECROS should be:

$$\text{ECROS} = 2\epsilon/(8 - 3\epsilon) \qquad \text{(E3.66)}$$

where ϵ is the surface emissivity.

The axial conduction term in Equation (E3.55) is:

$$QK_{AX} = QK_8 = \text{Btu/hr/ft} \qquad \text{(E3.67)}$$

where QK_8 is calculated in subroutine AXCOND Section 3.3 for IAXC = 1. For IAXC = 0, axial conduction is neglected, and $QK_{AK} = 0$. Axial conduction in

the fuel rods does not have a significant effect on the results. Axial conduction is not modeled if IBWR = 1.

As illustrated in Figure 3.2, the fuel rod node below the Z(ISAVE) elevation is partially covered with water (mixture). For I = ISAVE, the node is partitioned between the gas and water regions. Thus, for I = ISAVE, the QK values in Equation (E3.55) are multiplied by the fraction (1-FY), where FY is the water-covered fraction, to account for partial water coverage. The mixture level calculation is discussed in Section 3.6. For the BWR core model partial node covering is not accounted for, and the node at I = ISAVE is assumed to be in the gas region.

3.3.1.2 Gas Temperatures

With all the terms in Equation (E3.55) defined, the new rod temperature TR(I,R) can be calculated. The gas temperature is now calculated using the new rod temperature from the relationship:

$$TG(I,R) = ROD(I,R) - \left[ROD(I,R) - TG(I-1,R)\right] e^{-BB} \quad \text{(E3.68)}$$

where

$$BB = \frac{hp\Delta Z}{60(W_S C_{PS} + W_H C_{PH})}$$

$h = h_C + h_{rad}$, Btu/hr/ft^2/F
W_S = steam flow rate, lb/min per rod
W_H = hydrogen flow rate, lb/min per rod
C_{pS} = steam heat capacity, Btu/lb/F
C_{PH} = hydrogen heat capacity, Btu/lb/F

and BB is multiplied by (1-FY) if I = ISAVE. The form of Equation (E3.68) is derived as the solution of a differential equation of the form:

$$WC_P \frac{dT_G}{dZ} = hp(T_R - T_G) \quad , \quad \text{(E3.69)}$$

assuming constant T_R. For I = 1, TG(I-1,R) is set equal to the water temperature, TPOOL. For ICONV = 0, the specific heats are given by simplified Equations (E7.49) and (E7.50). For ICONV = 1, the gas properties are obtained from improved correlations in PROP. For ICONV > 1, and for the BWR core model, the gas properties are calculated in STMH2P. PROP and STMH2P are discussed in Section 7.6.1.

3.3.1.3 Final Rod Temperatures

Using the value of $T_G(I,R)$ obtained from Equation (E3.67), the updated convection heat transfer to the gas flowing past node (I,R) is:

$$QK_{HC2} = (W_S C_{PS} + W_H C_{PH})\ (TG(I,R) - TG(I-1,R))\ \frac{60}{\Delta Z}, \text{Btu/hr/ft} \qquad \text{(E3.70)}$$

In order to conserve energy, the difference in energy between QK_{HC2} and QK_{HC1} is added to the fuel rod. The corrected fuel rod temperature is

$$T_R(I,R) = T'_R(I,R) + \frac{(QK_{HC1} - QK_{HC2})\Delta t}{60(\rho C)\ A_R} \qquad \text{(E3.71)}$$

where T'_R is given by Equation (E3.55).

3.3.2 Heat Transfer in Water Covered Core

3.3.2.1 Rod Temperatures

Core temperatures in the mixture covered portion of the core are calculated in two steps.

In the first step, a rod temperature is calculated as if the fuel rod were in thermal equilibrium with the water at decay heat power levels. This equilibrium temperature is:

$$T_{R1} = T_{pool} + \frac{Q_{DK}\ P_F(R)\ F(I)\ FP(I,R)\ A_F}{p\ Vp\ h_W} \qquad \text{(E3.72)}$$

where h_W = rod-to-water heat transfer coefficient, Btu/hr/ft^2/F. Note that h_W is not a surface heat transfer coefficient; h_W is used with the average rod temperature rather than the surface temperature. In effect, h_W incorporates a rod conduction resistance. h_W is defined below.

For ITRAN = 1 (small LOCA's and transients), BOIL calculates the heat transfer coefficient, h_W, such that no temperature transient is induced on the first call to BOIL (that is, QZERO = $h_W A \Delta T$):

$$h_W = \frac{QZERO}{(TCAV - T_{pool})\ N_R \pi H} \quad , \quad Btu/hr/ft^2/F \ , \qquad (E3.73)$$

where

H = active fuel length, ft

TCAV = volume-average core temperature (input), F

QZERO = operating core power level (input), Btu/hr.

The user should input a value of TCAV which is consistent with the initial core stored energy. If time is greater than 0.002 minutes on the first call to BOIL, QZERO is replaced by the core decay heat. Equation (E3.73) normally yields heat transfer coefficients on the order of 300 Btu/hr/ft^2/F, and results in rod temperatures from Equation (E3.72) at decay heat levels about 20 F greater than the water temperature. If the accident time is greater than 0.002 minutes on the first call to BOIL, the user should input TCAV which is consistent with the core decay heat at that time. Otherwise, an unreasonable value of h_W may be calculated, and $T_{R1} - T_{pool}$ will be unrealistic. For ITRAN = 0 (large LOCA), h_W is input rather than calculated in BOIL.

Consistent with Equation (E3.72), it is assumed in the heat balance for the water in the primary system that all of the decay heat in fuel nodes below the mixture level is added to the water (see Equation E3.81).

In the second step of the rod temperature calculation, T_{R1} as calculated in Equation (E3.72) is compared with the previous value of the rod temperature $T_{RO}(I,R)$. T_{R1} may differ from $T_{RO}(I,R)$ for a number of reasons. These include: (1) rod temperatures are normally initialized a few hundred degrees hotter than the T_{R1} value after reactor scram, (2) T_{pool} may be

changing due to system pressure changes, (3) the node (I,R) may have previously been in the gas covered region of the core, (4) fuel slumping may have increased the temperature of the node, and (5) the core power is changing with time.

If $T_{RO}(I,R)$ exceeds T_{R1}, additional heat, Q_B, is removed from the rod. The heat, Q_B, is restricted to the minimum of Q_{B1}, Q_{B2}, or Q_{B3} (Btu per core node) where:

$$Q_B = \min (Q_{B1}, Q_{B2}, Q_{B3}) \qquad \text{(E3.74)}$$

$$Q_{B1} = (\rho C)\, N_R A_R V_F(R)\, \Delta z\, (T_{RO}(I,R) - T_{R1})\, \Delta t/\tau \ , \qquad \text{(E3.75)}$$

$$Q_{B2} = h_W\, p \Delta z N_R V_F(R) \left(T_{RO}(I,R) - T_{pool}\right) \Delta t/60 \ , \qquad \text{(E3.76)}$$

or

$$Q_{B2} = Q_{bed}\, A_{top}\, V_F(R) \Delta z \Delta t/60/H_{DB} \ , \qquad \text{(E3.77)}$$

$$Q_{B3} = A_C V_F(R)\, \Delta z \rho_L\, (1 - \alpha_z)\, (h_{fg} + C_p\, \Delta T)\, \Delta t/\tau, \qquad \text{(E3.78)}$$

where

Q_{bed} = debris bed heat flux, Btu/hr/ft^2
H_{DB} = debris bed height, ft
A_C = core water area (input ACOR), ft^2
α_z = void fraction at elevation z(I) - $\Delta z/2$
τ = time constant = 1 minute.

Q_{B1} is the heat from cooling the node to T_{R1}. Q_{B3} is the heat required to vaporize all the water in the adjacent channel. Q_{B1} and Q_{B3} are further restricted by the time constant τ such that $\Delta t/\tau \leq 1$. Since τ = 1 minute in the coding, this implies node quenching is required to take at least 1 minute. Q_{B2} restricts the cooling rate to that given by either the original heat transfer coefficient h_W or by a debris bed heat flux. Use of Equation (E3.76) to define Q_{B2} implies a core geometry as favorable for heat transfer as the original core geometry. Use of Equation (E3.77) implies a distorted geometry. Equation (E3.77) is used (input option IBEDC) to define Q_{B2} only after core melting. In the modeling, nodes below the mixture level, which are or were

previously melted, are assigned to the debris bed. If the debris bed option is not selected, melted core nodes recovered by ECC injection typically require about 10 minutes to cool to the temperature T_{R1}. Use of the debris bed option may substantially delay the cooling. In the BWR core model (IBWR = 1), in-core debris bed cooling of molten core materials is not modeled (IDBEDC = 0), and control blade and channel box material are assumed to be quenched in one timestep.

The rod temperature obtained after removing the heat Q_B is:

$$T_{R2} = T_{R0}(I,R) - \frac{Q_B}{(\rho C)\ N_R A_R \Delta z V_F(R)} \quad . \qquad \text{(E3.79)}$$

If the node (I,R) is partially covered with mixture (I = ISAVE), Q_B in Equation (E3.74) is first multiplied by the mixture covered fraction, FY. The new rod temperature for I=ISAVE is:

$$T_R(I,R) = FY\ T_{R2} + (1 - FY)\ T_{RG} \quad , \qquad \text{(E3.80)}$$

where T_{RG} is obtained from Equation (E3.71) for the gas covered fraction. If the node is completely covered, $T_R(I,R) = T_{R2}$.

3.3.2.2 Energy Transfer to Water

The total heat input to the water from the intact core is obtained by summing the radiation heat transfer and the energy terms in Equations (E3.72) and (E3.74). The decay heat input to the water is:

$$Q_{BL} = Q_{DK}\ \Sigma\ PF(R)\ F(I)\ FP(I,R)\ VF(R)/NDZ \quad , \qquad \text{(E3.81)}$$

where Q_{DK} is the total core decay heat, and the summation extends over all core nodes in the mixture. For the axial node which contains the mixture level, the node power is multiplied by FY, the fraction of the node which is covered by the mixture.

The radiation heat transfer to water from the core is given by:

$$Q_{RADW} = \Sigma\ RWAT(R)/60 \quad , \quad IRAD \neq 0$$

or (E3.82)

$$Q_{RADW} = \Sigma\ Q_R/60 \quad , \quad IRAD = 0$$

where RWAT(R) is calculated in subroutine RHEAT, Section 7.2, and Q_R is given by Equation (E3.64) with T_1 = ROD(ISAVE, R) and $T_2 = T_{POOL}$.

The axial heat conduction from the core into the water is calculated in subroutine AXCOND if IAXC = 1; otherwise, $Q_{AX} = 0$. The heat from quenching the core nodes not slumped into the heat is:

$$Q_{NCH} = \Sigma\ QB/\Delta t \quad , \qquad (E3.83)$$

where QB is given in Equation (E3.74).

3.3.3 Core Meltdown Models

Core melting models are incorporated in BOIL for the purpose of scoping the effects of melting on the core heatup. The models are not phenomenological in the sense that slumping is not based on calculations of stress levels, creep rates, or flow rates of molten materials. Fuel and cladding melting are not assumed, a priori, to cause channel blockage or stop metal-water reaction; rather blockage is largely input-controlled. Fuel slumping is triggered when a fuel node reaches the melting point of the core and absorbs additional energy equal to the latent heat of fusion. When certain input conditions relative to the extent of melting are satisfied, molten core material may fall out of the original core region and interact with water in the lower part of the reactor vessel. Two of the meltdown models assume temporary retention of portions of the molten fuel in the core as a continuous region. One model assumes the molten fuel falls into the bottom head as it melts. Calculations indicate that meltdown model input and modeling assumptions can significantly affect the predicted course of the core heatup, primarily

because of the influence of the meltdown model on the boil-off rate as molten material slumps into water and on the cladding-water reaction. This section of the report describes the meltdown models developed for BOIL.

Core melting usually starts at or above the center of the core in a coolant boiloff accident. This occurs because the top of the core is uncovered longer and core power distributions frequently peak in the central regions. Because of the power peaking and the presence of water in the bottom of the core, the core temperature a foot below the melted region is frequently calculated to be more than 1000 F below the melting point of the fuel. In these relatively cool regions, the UO_2 would remain solid although the cladding could be melted. Liquification of the debris would be expected over a range of temperatures depending on the local composition of UO_2, cladding, and ZrO_2. Because the fuel rods in the core are relatively closely packed, there is not room for solid fuel pellets to fall out of the core nor for gross distortion of the solid portions of the core. In this situation, it is believed a region of solid rubble would form under the molten fuel, and the molten fuel would tend to be retained in the core. However, since the rubble continues to generate heat, it will eventually melt, and the increasingly larger molten region will move downward. If the molten region moves downward fast enough, it will interact with the water in the bottom of the core. When this happens, the boiloff rate, and therefore the cladding-steam reaction rate, may increase. When the molten region grows to include 50 to 80 percent of the core, it becomes intuitively questionable whether the molten region can be retained inside the core. At this time, the molten pool in a typical 1000 Mw reactor will be 3 to 5 feet thick, and will presumably be held up by a layer of rubble. When large fractions of the core are molten, the core-suport plates and shrouds are also exposed to high thermal loadings. Failure of these major structural members could lead to core collapse or release of the molten material into the lower vessel region.

Meltdown Model A. In meltdown model A, it is assumed that a molten region forms in the core and grows downward in such a manner that the average temperature of the region remains just at the melting temperature. This model maximizes the downward movement of the molten pool. According to the model assumptions in BOIL, if the molten region moved downward any faster, it would

resolidify. In model A, each radial region is treated separately with no mixing between radial regions.

Meltdown Model B. In meltdown model B, growth of the molten region is in effect upward. The upward growth should be pictured to actually result from material falling from above into the molten region. The amount of solid material falling into the molten pool is sufficient to keep the homogenized temperature of the molten pool at the core melting point. Within the model B molten region, it is assumed heat may be transferred radially if the average temperature of a radial power region exceeds the melting temperature. When the top nodes in the core are melted, it is assumed that additional heat may be radiated to the support structures above the core. Models A and B yield similar results for core-meltdown fractions below about 50 percent. However, for larger core melt fractions, model A results in faster core heatup. In model A, the more rapid downward progression of the molten region generally results in increased metal-water reaction when the molten region intercepts the water level.

Meltdown Model C. In meltdown model C, it is assumed that when a fuel node melts, it immediately falls into the water in the bottom of the pressure vessel. The large boiloff rates obtained under these assumptions may result in very high heatup rates, due to the cladding-steam reaction. Early dry out of the reactor vessel may be indicated. Model C is not believed to give a realistic picture of meltdown in a large core.

Gradual Slumping. The meltdown models also provide for gradual dropping of molten material into the lower head. Gradual dropping or slumping is initiated when the extent of core melting satisfies certain input conditions. These gradual dropping models are modifications of models A and B which employ some of the model C features. Gradual slumping into the bottom head requires that the total core melt fraction exceed input FDROP. Then, if the core node in radial region R at axial elevation I = NDZDRP (input by user) is melted, all of the melted nodes in radial region R will fall into the bottom head. Core nodes in region R which are not melted will remain in the core region. Thus, it is possible for the model to predict, for example, that

the top and bottom nodes may remain in the core (if solid) while the central region falls out (if molten).

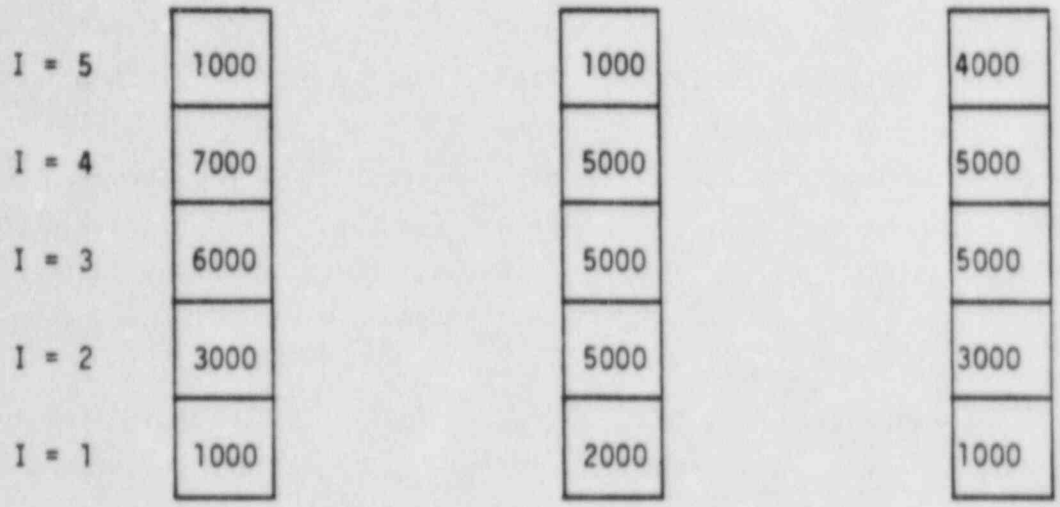
Finally, when the core melt fraction exceeds FCOL, the total core, including both the molten and remaining solid nodes, is dropped into the bottom head. At this time, the debris is assumed to begin to heat the bottom head as well as the water in the head. Head heating by core debris does not occur prior to this stage of meltdown in the BOIL models. Core collapse can also be triggered (input option) by high core barrel or by high lower grid plate temperatures.

Figure 3.3 illustrates the mixing computations in meltdown models A and B. Sketch (a) illustrates calculated rod temperatures prior to mixing. These temperatures are the result of solving Equations (E3.71) and (E3.80). Sketch (b) illustrates the downward redistribution of energy in meltdown model A. As seen in (a), melting starts at the highest melted node, I = 4. The mixing moves energy downward so that nodes 4, 3, and 2 are just at the fusion temperature so they are fully melted. The temperature of the bottom node is also increased to 2000 F by the downward mixing. The temperature mixing computation assumes the axial nodes within a given radial region have equal heat capacity.

For model B, the computation starts at the lowest fully melted node, I = 3. Upward mixing (or the f illing of node 5 into 4 and 3) results in nodes 3 and 4 being fully melted, and the node 5 temperature is increased to 4000 F. In model B, additional radiation heat transfer off the top of the core is modeled if the top node is fully molten. The additional radiation heat transfer is the smaller of that given by Equation (E3.64) to bring the temperature down to TFUS, or 10 percent of the total decay heat in the molten region of the radial zone modeled. If the temperature still exceeds TFUS, energy is moved outward to the next radial region. The large radiation heat fluxes predicted by model B may result in early melting of the structure above the core.

3.3.4 BWR Channel Box and Control Blade Models

The calculation of the BWR channel box and control blade temperatures uses modeling similar to that discussed above in Sections



(a) T_R prior to mixing. (b) T_R after Model A mixing (c) T_R after Model B mixing

TMELT = 4000

TFUS = 5000

FIGURE 3.3. ILLUSTRATION OF MODELS A AND B MELTDOWN COMPUTATION

3.3.1-3.3.3. However, not all modeling options and features are available in the BWR core model. The MARCH 2 BWR core model was originally supplied to Battelle-Columbus by L. J. Ott[22] of ORNL in April 1982. The original coding closely paralleled that in MARCH 1.1, and did not fully incorporate other MARCH 2 modifications under development elsewhere. After that time, both ORNL and Battelle-Columbus independently continued modification of the original model so that somewhat different versions have evolved. Although the present versions have the same origin, it is not expected they will produce identical results.

The development of the BWR channel box and control blade models begins by writing three separate equations similar to Equation (E3.55) for the fuel rods, the channel box, and the control blade. Since only the fuel rods are assumed to generate decay heat, $QK_{DK} = 0$ for the channel boxes and control blades. Metal-steam reaction (QK_{MW}) is modeled for the Zircaloy in the fuel rods and channel boxes and iron in control blades. Metal-water reaction is discussed in Section 3.5.3.

The convective heat transfer (QK_{HC}) for the BWR modeling involves two gas flow streams, one for the rod/channel box region and the second for the channel box/control blade region. Steam flow in the box/blade region is specified by an input fraction (FBP) of the total steam generation. Each gas stream has heat input from two surfaces. Thus, Equation (E3.59) for the rod/channel box region has two convective heat transfer terms; one for the rod and one for the box. A similar equation is written for the box/blade region. Ott[22] originally used an iterative solution to assure compatibility of Equations (E3.59) and (E3.70) and consistency of the calculated heat fluxes with the updated temperature differences. Because of computational difficulties and small timestep requirements with this approach, Battelle-Columbus subsequently replaced the iterative solution with an algebraic algorithm. The heat transfer correlations and gas properties correspond to the improved (ICONV = 2 or greater than 10) values. Thus, the simplified but fast-running options are not available.

Radiation heat transfer within a given radial core zone to surfaces ($QKRD$) is modeled between the fuel rods and channel boxes, between the channel boxes and control blades, and between the fuel rods and structures above the core and the water in the core. The original models of Ott[22] also

calculated radiation from the boxes and blades to the upper structures and to water. These were not implemented in MARCH 2 due to interfacing complications with other modifications for input IRAD > 0. The radiation heat transfer is modeled using Equation (E3.64) where the view factors (FRDBX and FBXCB) and heat transfer area (PBOX*NBOXS/NR*DZ) are input, and T_1 and T_2 are calculated source and receiver temperatures. Axial conduction heat transfer (QK_{AX}) is not modeled. Heat transfer in the mixture covered region of the core parallels the discussion in Section 3.3.2, except in-core debris bed quenching and partial node covering are not modeled.

Radiation heat transfer between axial and radial core nodes is modeled using the RHEAT models if input IRAD > 0. However, the modeling does not directly consider the effect of the presence of the boxes and blades on radiation transport. (The modeling continues to use fuel rod node temperatures.) As discussed in Section 3.3.1.1, the use of a modified radial emissivity, Equation (E3.66), improves the calculations of radial radiation heat transfer.

The channel box and control blade melting and slumping calculations prior to slumping into the bottom head are performed in a completely analogous manner to that described above. The boxes and blades have their own melting temperatures (user-input) which may be different from that of the fuel. However, slumping of box and blade material into the bottom head is controlled by the corresponding fuel rod node. When a fuel rod node (I,R) falls into the bottom head, the corresponding box and blade nodes also fall into the head.

The box, blade, and fuel rod nodes at a given position are assumed to remain thermally coupled (through radiation heat transfer) after melting. Box or blade melting is assumed to not physically move the molten material. Thus, calculated box and blade temperatures will closely follow the fuel rod temperatures because of the excellent coupling provided by radiation heat transfer. Molten boxes and blades, when used with meltdown Models A and B, act as heat pipes conducting heat to the top (Model B) or bottom (Model A) of the core. Since this is largely a modeling artifice and may be nonphysical, the user may turn off the box and blade Model A and B slumping while retaining them for the fuel rods. (See input MELMOD).

3.4 Debris, Gridplate, and Water Interactions in Bottom Head

Figure 3.4 illustrates the modeling in BOIL of the interactions of molten debris falling out of the core with the water in the bottom head of the reactor vessel. In sketch (a) molten material has fallen out of the core onto the first grid plate, but the water level remains above the grid plate elevation Y_{G1}. In sketch (b) sufficient material has fallen out of the core to reduce the water level below the first grid plate, but the first grid plate temperature remains above the failure temperature (input TFAIL). In sketch (c) the first grid plate has failed, and the grid plate and debris fall to the next lower level. At stage (c) both grid plates and the core material are combined into a common debris. The debris remains at stage (c) until the total core melt fraction exceeds FCOL (input), the core barrel temperature exceeds TFAILB (input), or the temperature TGR2 exceeds TFAIL2 (input). At the stage in sketch (d) the core debris is assumed to begin heating the bottom head. Delaying head heating until stage (d) may in reality underestimate the actual heating and failure, particularly if the failure is sensitive to local heating effects. The heating of the bottom head by the core debris is calculated in subroutine HEAD (Section 3.10). Note that water may remain in the bottom head during stage (d). Prior to core material falling out of the core, the grid plate and bottom head temperatures are calculated as discussed in Section 3.9.1.

The debris temperature is calculated from a lumped mass heat balance:

$$T_{FALL} = \frac{(Q_1 + DQ_{SL} + DQ_S + DQ_{DK} + DQ_{MW} - Q_{WTR} - Q_{HD})}{(FALL + GRID)} \qquad (E3.84)$$

where

Q_1 = (MC_pT_{GR}) of the grid plate included in the debris, Btu

DQ_S = $(MC_p\ T_R)$ of core debris slumped during current timestep, Btu

DQ_{SL} = $(MC_p\ T_R)$ of previously slumped core debris, Btu

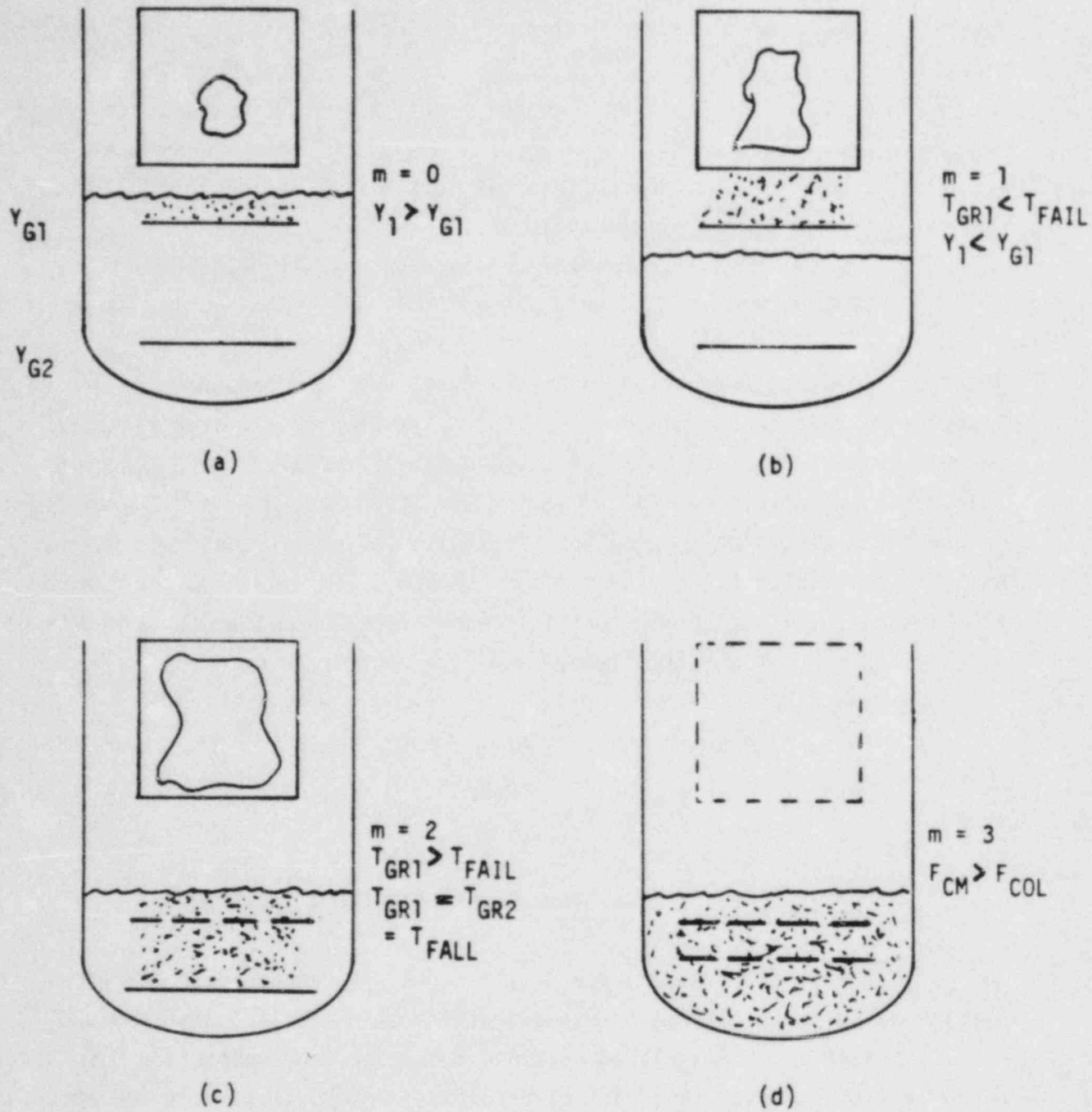


FIGURE 3.4. ILLUSTRATION OF DEBRIS AND GRIDPLATES IN BOTTOM HEAD

DQ_{DK} = decay heat of all slumped core debris, Btu

DQ_{MW} = metal water reaction in the debris during current timestep, Btu

Q_{WTR} = heat transfer from the debris to water in the bottom head, Btu

Q_{HD} = heat conducted into the bottom head and radiated from core debris slumped into head, Btu

FALL = (MC_p) of the total debris slumped into head, Btu/F

GRID = (MC_p) of the grid plates included in the debris, Btu/F.

The drop metal-water reaction, decay heat, masses, and temperatures are calculated using features of meltdown model C. The drop metal-water reaction is calculated in subroutine MWDRP or fixed by input (FDCR). The Q_{HD} term is calculated in subroutine HEAD. Q_{HD} includes the QRAD, QDB, and dX_m/dt terms on the right-hand-side of Equation (E3.134). The heat transfer to water, QWTR, is calculated using either (1) the MARCH 1.1 thermal-equilibrium model (IBEDS = -1), (2) an isolated particle model (IBEDS = 0), or (3) a debris bed model (IBEDS > 0). For the thermal equilibrium model:

$$Q_{WTR} = (DQ_S + DQ_{DK} + DQ_{MW} + D_{MS}\, T_{pool}) \text{ , Btu} \quad , \quad \text{(E3.85)}$$

where

D_{MS} = $(M\ C_p)$ of mass slumped during current timestep.

The particle models are similar to those described in HOTDRP, Section 4. Q_{WTR} is calculated using heat transfer coefficients from subroutine SPHERE for the isolated particle model and from subroutine DBED for the debris bed models. Restrictions are placed on Q_{WTR} based on the amount of water available for vaporization. In stage (a) Q_{WTR} is restricted to vaporizing the water above the first grid plate. In stages (b), (c), and (d), Q_{WTR} is limited to vaporizing 75 percent of the water in the bottom head per timestep. Water remaining in the head at head failure is added to the containment atmosphere.

The water heating rate from debris interactions in the bottom head is:

$$Q_{DRP} = Q_{WTR}/\Delta t, \qquad \text{Btu/min} \quad . \qquad \text{(E3.86)}$$

Equation (E3.86) defines the Q_{DRP} term in Equation (E3.12).

If the BWR core model is being used, additional terms accounting for the masses and temperatures of slumped box and blade material are added to Equation (E3.84). The drop metal-water reaction (DQ_{MW}) includes only the fuel rod cladding-steam reaction, and neglects additional box and blade reaction.

3.5 Metal-Water Reaction Model

BOIL calculates metal-water reaction in the uncovered portion of the core. Metal-water reaction below the mixture level is not modeled, except for those core nodes currently slumping into the bottom head. Thus, recovering an overheated or molten core region in BOIL will turn off the metal-water reaction below the mixture level. Only Zircaloy cladding reaction is calculated unless the BWR channel box and control blade model is selected. If the BWR model is not used, the masses of boxes and blades may be added to the core heat capacity and cladding thickness to simulate their effects. Distortions in core heating and metal-water reaction may result, however.

Metal-water reaction in the core is discussed in the first part of this section, and reaction during core slump in the second part.

3.5.1 In-Core

The zirconium steam reaction modeled is

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2.$$

The reaction rate is given by the minimum of a gaseous diffusion rate or a solid state diffusion rate. The gas diffusion limited cladding oxidation rate is:

$$\dot{X}_1 = 5.57 \times 10^{-6} \left(\frac{T_F}{d}\right)^{0.68} F_{H1}\, f(X, \frac{s}{D_H}, S_c, Re) \text{ , cm/sec} \qquad \text{(E3.87)}$$

where

Re = Reynolds number < 2100

Sc = Schmidt number

T_F = film temperature = $(\frac{T_R + T_G}{2} + 460)/1.8$, K

T_R = rod temperature, ROD(I,R), F

T_G = gas temperature, F

d = rod diameter, cm

X = distance from water level, ft

s/D_H = pitch/hydraulic diameter

f = function given in Reference 23

= a (s/D_H) [4.76 + g(X, Re, Sc)]

F_{H1} = hydrogen blanketing factor

For turbulent flow[23]

$$\dot{X}_1 = 1.28 \times 10^{-7}\, Re^{0.8}\, Sc^{0.4}\, F_{H1} \text{ , cm/sec} \qquad \text{(E3.88)}$$

where

Re > 2100.

The solid state limited rate is:

$$\dot{X}_2 = \frac{A}{X_o}\, e^{-\frac{B}{(T_R + 460)}}\, F_{H2} \text{ , cm/sec} \qquad \text{(E3.89)}$$

where

X_o = thickness of oxidized layer, cm

A, B = reaction constants in Table 3.1

F_{H2} = hydrogen blanketing factor.

The hydrogen blanketing factors are:

$$F_{H1} = PS'/P \text{ and } F_{H2} = 1 \text{ for } PS'/P > 0.5$$

$$F_{H1} = (PS'/P)^2 \text{ and } F_{H2} = PS'/P \text{ for } PS'/P < 0.5$$

where

PS' = steam partial pressure at the node elevation, psia

P = total pressure, psia.

TABLE 3.1 SOLID-STATE DIFFUSION CONSTANTS

Data	A, cm^2/sec	B, R	Range
Urbanic-Heidrick[24]	0.00353	30276	TR < 2876 F
	0.0104	29898	TR > 2876 F
Cathcart[25]	0.0373	36181	
Baker-Just[26]	0.394	41220	

The hydrogen blanketing factor, F_{H1}, in the steam deprived region ($PS'/P < 0.5$) is an approximation to the preliminary data of Chung and Thomas.[27]

Input options permit the user to replace the gas diffusion rates given by Equations (E3.87) and (E3.88) with the MARCH 1.1 model,[1,25]

$$\dot{X}_1 = 1.849 \times 10^{-7} \frac{R_P \, T_F^{0.68}}{(R_P - X_o/30.48)^2} \quad , \quad \text{cm/sec} \qquad \text{(E3.90)}$$

where

R_p = rod radius, ft

and the solid-state rate is given by Equation (E3.89) with $F_{H2} = 1$, and A and B are given by the Cathcart or Baker-Just constants.

Using the limiting $\dot{X}$ given above, the fuel rod volumetric heat generation rate is

$$Q_{MWV} = \frac{4\dot{X}}{D} \left(\rho_{zr} \Delta H \ 60/30.48\right) \qquad \text{(E3.91)}$$
$$= 8.742 \times 10^6 \ \dot{X}/D \quad , \text{Btu/min/ft}^3$$

where

$\dot{X}$ = oxidation rate, cm zr/sec

D = rod diameter, ft

ρ_{zr} = zirconium density = 401.9 lb/ft^3

ΔH = isothermal heat of reaction = 2762.6 Btu/lb Zr reacted.[28]

Additionally, a check is made to assure that the calculated QMWV does not increase the rod temperature above the input cutoff temperature, TMWOFF. The steam consumption rate per axial node consistent with the energy release in Equation (E3.91) is:

$$DW_S = \frac{Q_{MWV} \ A_R \ \Delta Z}{\Delta H(91.22/36)} \quad , \text{lb steam/min} \qquad \text{(E3.92)}$$

The coding contains checks to assure that DW_S does not exceed the steam supply and that $X_o + \dot{X} \ \Delta t$ does not exceed the cladding thickness.

The net energy addition to the rod is corrected to account for the enthalpy change associated with heating the steam from T_G to the rod temperature T_R and releasing hydrogen at temperature T_R. Thus, the net energy addition to the rod node is:

$$QK_{MW} = 60 Q_{MWV} \ A_R \ F_{ROD} \quad , \text{Btu/hr/ft} \qquad \text{(E3.93)}$$

where the correction for non-isothermal conditions is

$$F_{ROD} = \frac{(91.22/36)\Delta H + C_{PS} \ (T_G - 32) - 2/18 \ C_{PH} \ (T_R - 32)}{(91.22/36)\Delta H} \qquad \text{(E3.94)}$$

T_R = ROD(I,R) .

The derivation of Equation (E3.94) follows readily from mass and energy conservation and the stoichiometry of the reaction. Also, the calculation of the gas temperature in the core must account for the release of hot hydrogen from the fuel rods. The hydrogen is released at temperature ROD(I,R) and mixes with the other gases at temperature TG(I,R). Thus, the final gas temperature is

$$TG(I,R) = \left(F_{GAS}\ ROD(I,R) + TG(I,R)\right)/(1 + F_{GAS}) \quad , \tag{E3.95}$$

where

$$F_{GAS} = DW_S\ C_{PH}/\left(9\ (W_S\ C_{PS} + W_H\ C_{PH})\right) \tag{E3.96}$$

If the BWR core model is selected, the Zircaloy fuel rod cladding and channel box oxidation is calculated using the Cathcart or Baker-Just parameters. $\dot{X}_1$ is given by Equation (E3.90) with $F_{H2} = 1$, and $\dot{X}_2$ is given by Equation (E3.89) where A and B are either the Cathcart or Baker-Just constants. For the channel box, the rod temperature, T_2, is replaced by the box temperature, T_{BOX}, in Equations (E3.89) and (E3.90).

The iron-steam reaction modeled for the control blades is,

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2O$$

with an energy release of ΔH_{Fe} = 457.2 Btu/lb Fe. Baker[29] reports the Fe_3O_4 is characteristic of oxidation in a steam-rich environment, although other species are also observed. (Since the metal-water reaction in a meltdown accident is generally calculated to be steam-supply limited, modeling of a different reaction may be justified.) For the iron steam reaction, the reaction constants in Equation (E3.89) are A = 0.2662 x 10^6 cm^2/sec and B = 76411 R.[30] The constant in Equation (E3.90) contains the Zirconium density and is replaced by 1.515 x 10^{-7} to account for the larger density of iron. Equations (E3.91), (E3.92), and (E3.94) are similarly modified to account for differences in reaction stoichiometry.

The metal-water reaction may be turned off in molten nodes by input IMWA, IMWBOX, and IMWCB. Also, the zircalloy reaction in both the cladding and channel boxes may be turned off in nodes whose temperatures exceed input TMWOFF.

3.5.2 In Bottom Head

When a core node drops into the bottom head, the zirconium cladding in the node, which is generally partially oxidized, may react further with the water in the bottom head. Calculation of this reaction is done in subroutine MWDRP which is called by BOIL for each node for the timestep in which it falls into the head. The calculation in MWDRP assumes that all node material dropped into the bottom head takes the form of spheres. The diameter of these spheres is DPART, an input variable. The number of these spheres is NDROP, calculated from the total volume of the node and the sphere volume. The fuel volume per sphere, zirconium volume per sphere, and the zirconium oxide volume per sphere are calculated from the fuel rod dimensions, the number of fuel rods, axial node length, the volume fraction of the core in the node, and NDROP.

The spheres are assumed to be made up of a central core with zero, one, or two shells surrounding the core. All uranium oxide is put into the core. The core may also contain zirconium and zirconium oxide. The placement of the zirconium and the zirconium oxide is specified by input variables:

FZRCOR = the fraction of the zirconium in the particle core (the remainder goes into shell 1)

FZOCOR = the fraction of the zirconium oxide in the particle core (the remainder is shared by shells 1 and 2)

FZOS1 = the fraction of the zirconium oxide in shell 1 (the fraction 1-FZOCOR-FZOS1 will be placed in shell 2 if this is non-zero).

Values of FZRCOR = 1.0 and FZOCOR = 1.0 would simulate particles of homogeneous composition.

The oxidation reaction is assumed to take place in any layer which contains zirconium that has not been completely oxidized to zirconium dioxide. The rate at which the oxidation front advances in any mixture that exists in the sphere is assumed to be the same as that which would exist in pure zirconium, i.e., $\dot{X}$ is given by the smaller of the gaseous diffusion rate $\dot{X}_1$ and the solid-state diffusion rate $\dot{X}_2$ given by Equations (E3.90) and (E3.89). The quantity X_o used is the thickness of shell 2. The gas temperature, T_G, is replaced by TPOOL in the present calculations, where TPOOL is the temperature of the water in the bottom head. The heat released when the material being oxidized is not pure zirconium is multiplied by the volume fraction of zirconium that exists in the alloy being oxidized.

In general, the hot particles eventually cool as the thickness of the oxide layer builds up. When the sphere temperature drops to 2000 F, the calculation is ended. MWDRP returns the fraction of the previously unoxidized metal which is reacted in the bottom head. The oxidation rate during the core-slump timestep is:

$$\dot{X}_S = F_{DCR}\ (CLAD - X_o)\ /\ (60\ \Delta t)\ ,\ cm/sec \qquad (E3.97)$$

where

F_{DCR} = calculated fraction of the Zirconium reacted
CLAD = original Zirconium cladding thickness.

Input options allow the user to bypass the call to MWDRP and control F_{DCR} by input. These options allow the user to (1) stop the reaction during slumping after the total core reaction reaches FDCR (input value), or (2) force the total core reaction to a given value. The second option applies only to meltdown models A or B with input FDROP = FCOL, and may produce distortions in the spatial distribution of cladding oxidation. The distortion results from coding which redefines the input cladding thickness, and then forces the oxidation in the redefined thickness to completion.

Iron-steam reaction is not modeled in MWDRP. When the BWR core model is employed, the oxidation of channel box Zircaloy in the bottom head is neglected.

3.6 Steam-Water Mixture Level Calculation Model

The liquid level calculated in BOIL is given by Equation (E3.6) as:

$$Y_{LIQ} = W_M/\rho_L \, A_{TOT} \quad , \text{ ft} \qquad \text{(E3.6)}$$

where A_{TOT} is the total connected water cross sectional area of the reactor vessel in the active core region. W_M is the portion of the primary system water inventory located above the bottom of the core. When the calculated Y_{LIQ} is within the core region, Y_{LIQ} is the collapsed liquid level with a reference level of zero at the bottom of the core. When Y_{LIQ} is outside the core region, Y_{LIQ} is generally an artificial parameter since, in an actual reactor, A_{TOT} changes with elevation. The modeling of the liquid level assumes the liquid is at the bottom of the primary system.

When boiling occurs within the core region, level swell is calculated assuming a linear variation of void fraction with elevation. Thus, the steam generation rate, W, is related to the separation velocity, V, and core average void fraction α, by:

$$W = (2\alpha) \, \rho_S \, A_{COR} \, V \quad . \qquad \text{(E3.98)}$$

Note that (2α) is the void fraction at the top of the mixture. The Wilson[31] correlation for separation velocity and void fraction are used in BOIL. As recommended by Slifer and Hench[32], a minimum velocity of 1 ft/sec is specified. The Wilson correlation is:

$$V = \left(\frac{\alpha}{0.75 \times H \times F}\right)^{\frac{1}{0.78}} \left(D_H \times F^{\frac{1}{0.19}} \times g\right)^{0.5}, \text{ ft/sec} \, , \qquad \text{(E3.99)}$$

where

$$H = \left(\frac{\rho_S}{\rho_L - \rho_S} \right)^{0.32} \qquad \text{(E3.100)}$$

$$F = \left[\frac{1}{D_H} \left(\frac{\sigma}{\rho_L - \rho_S} \right)^{0.5} \right]^{0.19} \qquad \text{(E3.101)}$$

$$\sigma = 8.33 \times 10^{-6} \, (705 - T_{SAT}) \quad , \text{ lb/ft} \qquad \text{(E3.102)}$$

g = 32.2 ft/sec^2
D_H = hydraulic diamter, ft
T_{SAT} = saturation temperature, F.

The swollen mixture level is:

$$Y_M = Y_{LIQ}/(1 - \alpha) \quad , \qquad \text{(E3.103)}$$

for mixture levels below the top of the core ($Y_M < H$). As seen in Figure 3.2, the core node at the I=ISAVE axial level is partially covered. The fraction covered is:

$$FY = (Y_M - Z(ISAVE) + DZ)/DZ \qquad \text{(E3.104)}$$

Energy is partitioned between the water and gas according to the fraction FY. If the mixture level is above the top of the core, only level swell with the core region is modeled. Thus:

$$Y_M = Y_{LIQ} + \alpha H \quad , \qquad \text{(E3.105)}$$

for $Y_M > H$, where H is the core height.

As discussed in Section 3.3.2, core nodes within the mixture region are assumed to transfer heat to the water. Core nodes above the mixture level are assumed to be in the steam region. Thus, BOIL assumes a sharp decrease in heat transfer at the mixture/steam interface. In reality, a more gradual change would be expected. Entrainment of liquid droplets by the steam flowing up through the core is not modeled. In most coolant boiloff situations, the steam separation velocity is less than 10 ft/sec and is below velocities where significant entrainment would be expected.(33)

Level swell is neglected in the box-blade region of the BWR core model, as is partial covering of nodes.

3.7 Emergency Core Cooling System (ECCS) Model

In the MARCH model, there are three tanks that initially provide the ECCS water. Two of these tanks, the Upper Head Injection (UHI) tank and the accumulator are passive in nature and the third tank, the Refueling Water Storage Tank (RWST), provides suction for the ECCS pumps and the containment spray. It is possible to have up to six different injection rates and starting and stopping times for the pumps.

The input for the ECCS operation include the mass, temperature, and the pressure of water in the three tanks, nominal flow rate, high pressure set point, starting and stopping time, and low pressure shutoff point for each set of pumps. The fraction, ECCRC, of RWST mass at which the ECCS pump suction switches from the RWST to recirculation from the sump is also input. During recirculation, the ECCS water is chilled by an ECCS heat exchanger (see Section 6.6), if there is one, before being injected into the core.

Water from the Accumulator or the UHI tank is injected into the core according to:

$$W = A\sqrt{P - P_{VSL}} \qquad \text{(E3.106)}$$

where

W = water injection rate, lb/min

A = empirical constant

P = pressure in the tank, psia

P_{VSL} = pressure in the reactor pressure vessel, psia.

Based on the approximate time to empty accumulators in a large LOCA, the constant A is given the value 27,400 for the accumulator and 7,000 for the UHI. Also, the injection rate is not allowed to exceed that which would recover more than 20 percent of the core per timestep. The tank pressure is assumed to decrease during injection according to the relation:

$$P = PO/(2 - M/MO) \quad , \tag{E3.107}$$

where

PO = initial pressure in the tank, psia
M = mass of water in the tank
MO = initial mass of water in the tank.

Equation (E3.107) follows from an assumption that the initial water and gas volumes in the tanks are approximately equal. Water remaining in the accumulator or UHI tank is dumped into the reactor cavity when the bottom head fails.

The pumped injection rate into the core is the sum of injection rates for all the pumps specified. The pump flow can be either constant as specified in the input or it can be calculated using an assumed parabolic pump performance curve. The form of the equation used to calculate the pump flow rate is:

$$WPUMP_i = WPUMPO_i \sqrt{1 - \frac{\Delta P}{PH_i}} \tag{E3.108}$$

where

$WPUMP_i$ = flow rate for i-th set of pumps
$WPUMPO_i$ = run-out flow for a head of $\Delta P = 0$
PH_i = high pressure shutoff head for i-th set of pumps
ΔP = PVSL - PCON
PCON = containment pressure (recirculation mode) or RWST pressure (14.7 psia, injection mode).

If ECC operation continues after head failure (IECC = $\pm$ 3), the ECC water is assumed to be added directly to the reactor cavity. If the vessel pressure falls below the (user-specified) low pressure setpoint, the pump is turned off. The user may either stop ECC injection or divert flow directly to the sump if the mass of water in the primary system exceeds an input value (WVMAX or WVMAKS).

Water added to the primary system by either the ECC system or the makeup is assumed to mix uniformly with the water already in the primary system. The heat removed by ECC injection is:

$$Q_{ECC} = -W_{ECC} (h_L - h_{ECC}) \quad , \text{Btu/min} \qquad \text{(E3.109)}$$

where

W_{ECC} = accumulator plus pumped ECC injection rate, lb/min

h_L = primary system water enthalpy, Btu/lb

H_{ECC} = ECC water enthalpy, Btu/lb.

The heat removed by the makeup/letdown system is:

$$Q_{MUP} = -W_{MUP}(h_L - h_{ECC}) \quad , \text{Btu/min} \quad , \qquad \text{(E3.110)}$$

where W_{MUP} is the makeup pump flow rate. Equations (E3.109) and (E3.110) are used in the BOIL energy balance, Equation (E3.11). The makeup and letdown flows are assumed equal so that W_{MUP} does not appear in the mass balance in Equation (E3.9). The temperature of the makeup water is assumed equal to the ECC water.

3.8 Steam Generator Heat Transfer

Steam generators are sized to remove the heat generated in the (PWR) primary system under full operating power levels. At decay heat power levels steam generators are very effective heat sinks, and the primary side temperatures will generally follow the secondary side temperature closely. As flow rates change, the primary and secondary coolant inventories decrease, and noncondensables (hydrogen) are produced in a reactor accident, the steam generator heat transfer is expected to degrade. In addition, the mode of heat

transfer may change from forced convection to one dominated by steam condensation. Steam generators were not intended to operate in a condensing mode; however, recent calculations and experiments[17,34] indicate good heat transfer is maintained in the condensing mode. Neither the BOIL primary nor secondary system models contain sufficient detail to model all of these complex interactions. Generally, detailed calculations are not necessary for most applications of MARCH. If more detail is necessary (prior to core meltdown), MARCH calculations can be supplemented by more sophisticated modeling (TRAC, RETRAN).

The BOIL steam generator model starts with the assumption that steam generators are more than adequately sized to handle decay heat power levels under normal conditions. A heat transfer coefficient is defined based on normal full power conditions and extrapolated to accident conditions. The principal scaling parameter is assumed to be the primary to secondary temperature difference. The heat transfer coefficient under normal conditions is:

$$H_{eff} = \frac{Q_O}{A_{SG}\,(T_{pool} - T_{SG})} \quad , \text{Btu/hr/ft}^2\text{/F} \qquad \text{(E3.111)}$$

where

Q_O = operating power level, Btu/hr
A_{SG} = steam generator heat transfer area, ft^2
T_{pool} = initial primary side water temperature, F
T_{SG} = initial secondary side water temperature, F.

In order to account for the presence of non-condensables, a condensing mass transfer coefficient is also defined as:

$$H_{KV} = \frac{1}{144A_{SG}} \frac{Q_O}{h_{fg}\,(P_{SV} - P_{SG})} \quad , \text{hr}^{-1} \qquad \text{(E3.112)}$$

where

H_{fg} = heat of vaporization, Btu/lb
P_{SV} = partial pressure of steam in primary, psia
P_{SG} = steam generator secondary saturation pressure, psia.

Calculations indicate that the steam generator heat transfer rates directly calculated from Equations (E3.111) and (E3.112) may significantly exceed the heat input to the primary system coolant from the core, which for large time-steps may result in oscillations in the primary to secondary temperature difference. In order to dampen these oscillations, the steam generator heat transfer rate is not allowed in the calculation to greatly exceed the core heat input. Thus, a first estimate of the steam generator heat transfer is

$$Q_{SG1} = \max (60Q_{TOT} , F_{HI} Q_{DK}), \text{ Btu/hr} \qquad \text{(E3.113)}$$

where

Q_{TOT} = total heat input to primary water, Equation (E3.11), Btu/min
Q_{DK} = core decay heat, Btu/hr.

The factor F_{HI} varies between 1 and 2 depending on $(T_{pool} - T_{SG})$ and the input value of ISG. The factor F_{HI} is employed as an input controled scaling factor on the decay heat. For ISG > 0, $1 < F_{HI} < 2$ and "high" heat transfer is obtained. For ISG < 0, $F_{HI} = 1$ and "low" heat transfer is obtained. Calculations indicate ISG > 0 and "high" heat transfer is more consistent with recent experimental and calculated information.

Use of the heat transfer coefficient in Equation (E3.111) gives:

$$Q_{SG2} = H_{eff} A_{SG} (T_{pool} - T_{SG}) , \text{ Btu/hr} \qquad \text{(E3.114)}$$

and the mass transfer coefficient in Equation (E3.112) gives:

$$Q_{SG3} = H_{KV} A_{SG} h_{fg} (P_{SV} - P_{SC}) , \text{ Btu/hr} . \qquad \text{(E3.115)}$$

Equation (E3.115) accounts for degradation of the heat transfer as non-condensable concentrations increase. The heat transfer from the primary to the secondary is the minimum:

$$Q_{SG} = \min (Q_{SG1}, Q_{SG2}, Q_{SG3}) \quad , \text{Btu/hr} \quad . \qquad \text{(E3.116)}$$

It is also required in the computations that Q_{SG} be positive when the steam generator is operating in a condensation mode (ICON $\geq$ 0) or when the core is uncovered. In order to account for the possibility of degraded heat transfer due to primary or secondary water depletion, Q_{SG} is multiplied by the factor:

$$F_{SG} = \min\left(\frac{M_{SG}}{M_{SG1}} , \frac{\Delta Y_{LIQ}}{\Delta Y_{LIQ1}}\right) \quad , \text{ISG} < 0 \text{ , or} \qquad \text{(E3.117)}$$

$$F_{SG} = M_{SG}/M_{SG1} \quad \text{when } F_{SG} < 0.1 \text{ and ISG} > 0 \quad , \qquad \text{(E3.118)}$$

where

M_{SG} = mass of water in secondary, lb

ΔY_{LIQ} = primary side water elevation above (user-input)

YLEG = $(Y_{LIQ} - Y_{LEG})$, ft.

In practice it is found that, for large timesteps, Q_{SG2} and Q_{SG3} are very sensitive to the small temperature and pressure differences after the primary and secondary sides approach thermal equilibrium. The coding contains smoothing functions proportional to the ΔT and ΔP differences to dampen oscillations in the direction of the heat transfer.

The steam generator secondary energy and mass balance considers both secondary boiloff and feedwater addition. The secondary steam relief valves are not explicitly modeled and are assumed to be large enough to accommodate the calculated boiloff. The secondary pressure and feedwater flow rate are input.

As discussed in Section 3.2.3, the steam generator modeling assumes that a steam vaporization rate:

$$W_{SGC} = \frac{Q_{SG}}{60\ h_{fg}} \quad , \text{lb/min} \qquad \text{(E3.119)}$$

is induced in the primary system water when ICON $\geq$ 0. The steam generator model permits operation either in a steam condensation mode (ICON $\geq$ 0) or in a mode which is assumed to remove heat by suppressing boiling (ICON = -1). In the steam suppression mode, no condensation is modeled and W_{SGC} = 0. Thus, for ICON = -1, heat is removed directly from the water, and boiling is reduced. For heat transfer in the steam condensation mode, Q_{SG} is dropped from the energy balance (Equation E3.11) prior to calculating the boiling rate. Thus, the boiling rate and steam flow through the core and structures (modeled in EXITQ) are increased. The steam W_{SGC} (or what is not consumed in metal-water reaction) is assumed to be removed (condensed) from the steam space so it does not contribute to the primary system pressure. The energy $Q_{SG}\ \Delta t$ is removed after calculating the boiling rate to maintain the correct water temperature and energy balance. For ICON = 0, the steam condensate is assumed to be lost; that is, it is not included in the mass balance in Equation (E3.9). Loss of the condensate implies that the water is prevented from draining back into the reactor vessel because of the system geometry and low water inventories.

3.9 Heat Transfer to Primary System Structures

Structures in the vessel, in addition to the core and steam generator, may also exchange heat with the water and gases in the primary system. Heat transfer to water is described in the first part and heat transfer to gases in the second part of this section.

3.9.1 Heat Transfer From Structures in Water

The portions of the primary system piping, reactor vessel, and internal structure immersed in water are potential heat sources. BOIL models three structures of this type. The three structures modeled are the bottom head and two additional grid plates or structures below the core. After core slumping into the bottom head, the heat transfer described in this section is bypassed and the models described in Section 3.4 are used.

The heat transfer from each structure is modeled as a lumped mass. A conduction resistance is incorporated in the effective heat transfer coefficient. The heat input to the water is:

$$Q_{SLB} = \Sigma\ hA(T_{SLB} - T_{pool})/60 \quad , \text{Btu/min} \qquad \text{(E3.120)}$$

where

$$h = \left(\frac{1}{h_C} + \frac{\Delta X}{2k}\right)^{-1}$$

h_C = Equation (E7.6)

ΔX = thickness of structure, ft

k = thermal conductivity ($k = 11$), Btu/hr/ft/F

A = heat transfer area, ft^2

T_{SLB} = structure temperature, F.

The summation in Equation (E3.120) is over the three structures. The new structure temperature is:

$$T_{SLB} = T_{SLB0} - \frac{Q_{SLB,I}\Delta t}{(MC_p)} \qquad \text{(E3.121)}$$

where MC_p = heat capacity of structure, Btu/F; and $Q_{SLB,I}$ is the heat transfer from structure I.

3.9.2 Heat Transfer to Structures in Gas Space

MARCH assumes that structures (heat sinks) in the primary system gas space are exposed to the hot gases leaving the top of the core. The structures are assumed to be connected in series. A maximum of four structures are permitted. The required input data for each structure include the initial temperature, heat capacity, heat transfer area, hydraulic diameter, flow area, and the fraction of the airborne fission product decay heat absorbed in the structure. The first structure is assumed to be directly above the core and also receives radiation heat transfer from the top of the core.

The gas-to-structures heat transfer analysis is done in subroutine EXITQ by solving the following equation for T_2, T_s', and Q for each structure as follows:

$$Q = \dot{m}\, C_{pm}\, (T_2 - T_1)\, \frac{\Delta t}{60} = hA_h\, \frac{\Delta t}{60}\, \left(\frac{T_2+T_1}{2} - \frac{T_s+T_s'}{2}\right) \qquad \text{(E3.122)}$$

$$= (MC_p)_s (T_s' - T_s)$$

where

Q = energy transferred from the flowing gas mixture to the structure during the timestep Δt

$\dot{m}$ = mass flow rate of steam and hydrogen gas mixture

C_{pm} = specific heat of gas mixture

T_1, T_2 = gas temperatures at the inlet and outlet of the structure

Δt = timestep

h = heat transfer coefficient

A_h = heat transfer area

T_s, T_s' = structure temperatures before and after the heat transfer

$(MC_p)_s$ = mass times the heat capacity of the structure.

The core exit gas temperature is:

$$T_{GAS} = \frac{\Sigma (W_s C_{ps} + W_H C_{pH})\, V_F(R)\, TG(NDZ, R)}{\Sigma\, (W_s C_{ps} + W_H C_{pH})\, V_F(R)} \quad ; \qquad \text{(E3.123)}$$

thus, $T_1 = T_{GAS}$ for the first structure. The heat transfer coefficient h is given by:

$$H = h_c + h_{nat} \quad , \text{ Btu/hr/ft}^2\text{/F} \qquad \text{(E3.124)}$$

where h_c = Equation (E7.1) and h_{nat} = Equation (E7.2) for ICONV $\leq$ 2, or by Equations (E7.3) through (E7.4) if ICONV > 10. Steam and hydrogen specific heats and enthalpies are given by Equations (E7.47) to (E7.50) for ICONV $\leq$ 2

or by STMH2P (Section 7.6.1.3) if ICONV > 10. The gas exiting the last structure is assumed to mix uniformly with the gases in the primary system. The mixed gas temperature is used in the calculation of primary system pressure in subroutine PRIMP.

In the EXITQ model, gas temperatures are not allowed to fall below the steam saturation temperature. Steam condensation is not modeled in EXITQ. Thus, EXITQ removes only the gas superheat, and may therefore underestimate structure temperatures.

The structure immediately above the core receives radiation heat transfer from the top of the core. The radiated heat is:

$$Q_{RAD} = \Sigma \text{ QRTOP(R)} \quad , \text{ Btu/hr} \quad , \tag{E3.125}$$

where QRTOP(R) is calculated in subroutine RHEAT for IRAD = 1 or 2, and QRTOP(R) is given by Equation (E3.64) for IRAD = 0 with F = F12 defined by user input. The temperature of structure 1 is increased by:

$$\Delta T_{s,1} = \frac{Q_{RAD}\ \Delta t/60}{(MC_p)_{s,1}} \quad , \text{ F} \tag{E3.126}$$

due to the radiated heat.

The structures are also heated due to the fission product decay heat stored in the primary system gas space. Each structure is assumed to absorb a fraction, FPV(I), of the stored decay heat. The decay heat produces a temperature increase:

$$\Delta T_{s,1} = \frac{\text{FPVSL} \times \text{FPV(I)}\ Q_{DK}\ \Delta t/60}{(MC_p)_{s,I}} \quad , \text{ F} \tag{E3.127}$$

where

FPVSL = fraction of decay heat stored in the vessel.
Note that energy conservation requires that (user-input)
ΣFPV(I) = 1.

The fission product heating of structures is calculated in subroutine FPQSTR.

3.10 Bottom Head Heatup and Failure Model (HEAD)

At some stage of the core melting and slumping process, core debris will fall into the bottom head and interact with the water, grid plates, and structures below the core. Subroutine HEAD calculates the heating and failure of the bottom head due to the slumped core debris. In the model, heating of the bottom head from slumped core debris is delayed until (1) the fraction of the core melted reaches a specified input value (FCOL), (2) the temperature of structure TGRID2 exceeds (input) TFAIL2, or (3) the temperature of the core barrel exceeds (input) TFAILB. Prior to reaching the specified core collapse flag, head heating occurs only by convection from the water in the head.

When the criteria for core collapse are reached, the total core including both melted and solid fuel material, is assumed to be relocated in the next timestep to the bottom head. The bottom of the core debris is in contact with the head, and the top of the debris may be covered with water. Heat transfer to the water, if present, is calculated using the models described in Section 3.4. When the water is vaporized, the debris is assumed to radiate heat to the core barrel. The bottom head failure criteria include stresses due to the vessel pressure, disjoint stresses, and the weight of the debris. Water, steam, and hydrogen remaining in the pressure vessel at the time of head failure are added to the containment atmosphere. Optional models allow either head failure or leakage of the water and gases prior to gross head failure based on overheating of the vessel at a specified head thickness. When the head fails, the core debris along with a portion of the head are assumed to be relocated to the reactor cavity. MARCH contains no modeling of this relocation process. Debris interactions after head failure are calculated in HOTDRP and INTER.

Subroutine HEAD models are described below.

3.10.1 HEAD Heat Transfer Model

The bottom head heatup model assumes an initially uniform wall temperature, TB. The outside of the head is assumed to be insulated. The initial core debris temperature TC is given by Equation (E3.84). The initial value of TB is given by Equation (E3.121) (for I=3) prior to the assumed total

core collapse into the bottom head. The debris may be either liquid or solid. The head heating model assumes one dimensional heat transfer with a uniform wall heat flux.

The bottom head is assumed to be a hemisphere joined to a cylinder. If the volume of the debris is insufficient to fill the hemisphere (see Figure 3.7), the radius of the top of the debris is given by

$$R_{POOL} = R_H \times SIN(ACOS(1 - H/R_H)) \qquad (E3.128)$$

where

R_H = head radius
H = height of debris above the bottom of the head,

and $R_{POOL} = R_H$ if $H \geq R_H$. The debris/head interface or contact area is

$$A_w = 2\pi R_{POOL} H \text{ for } H < R_H \qquad (E3.129)$$

or

$$A_w = 2\pi R_{POOL}^2 + 2\pi R_H (H - R_H) \text{ for } H > R_H$$

The conduction of heat into the bottom head is modeled using the concept of a thermal penetration distance. Suppose the inside surface temperature of the head is instantaneously increased from TB to TW. The heat flux required to maintain this temperature is:(35)

$$Q = k_H \frac{(TW - TB)}{\delta_H} , \qquad (E3.130)$$

where

TB = initial head temperature
TW = interface temperature
$\delta_H = \sqrt{\alpha \pi t}$ = thermal penetration distance
k_H = head thermal conductivity
$\alpha_H = k_H/(\rho c)$ = head thermal diffusivity

ρ = density of head

c = specific heat of head

t = time.

Differentiating δ_H, it is seen that the thermal front moves into the head with velocity:

$$\frac{d\delta_H}{dt} = \frac{\pi}{2} \frac{\alpha_H}{\delta_H} \quad . \tag{E3.132}$$

Figure 3.5 illustrates a case in which the head is melting. With melting, the thermal penetration distance increases at a rate of:

$$\frac{d\delta_H}{dt} = \frac{\pi}{2} \frac{\alpha_H}{\delta_H} - \frac{dX_m}{dt}$$

where X_m is the thickness of head melted. The heat input to the head during this melting process is:

$$QDB = (\rho C)_H A_H \frac{d}{dt} \left(\int_{X_m}^{L} T(x)dx \right) + (\rho\lambda)_H A_W \frac{dx_m}{dt} \quad , \tag{E3.133}$$

where

λ_H = head heat of fusion

A_W = debris-head interface area

T(x) = head temperature

QDB = heat transferred from the debris to the head.

It is assumed in the head heat balance, that the vessel is insulated on the outside and that the core debris separates the head from any water which may be present.

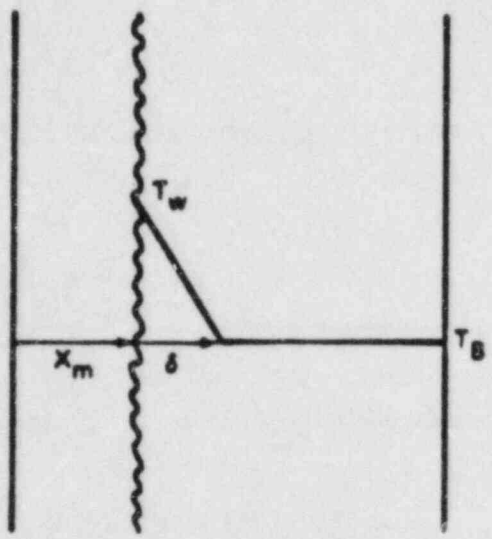


FIGURE 3.5. HEAD HEATUP WITH MELTING

3.10.2 Debris Heat Balance

A heat balance on the core debris can be written as:

$$(MC)_D \frac{dTED}{dt} = QDK - QRAD - QWTR - QDB - (\rho C)_H A_W \frac{dX_m}{dt} (TD - TMH) \quad , \tag{E3.134}$$

where

TED = "energy equivalent" debris temperature
TD = debris temperature
$(MC)_D$ = debris heat capacity
QDK = decay heat remaining in core debris
TMH = head melting point
QRAD = heat radiated to the core barrel
QWTR = heat transferred to the water on top of the debris.

The debris temperature is calculated using the concept of an energy equivalent debris temperature, which is the temperature corresponding to the debris enthalpy without phase change.

The debris temperature, TD, is calculated as,

$$TD = TED - \frac{DTFUSI \times \frac{FIM}{WFI} \times GDMC + DTFUSD \times \frac{FOM}{WFO} \times (DBMC-GDMC)}{DBMC} \tag{E3.135}$$

where

TED = equivalent debris temperature
DBMC = heat capacity of entire debris, Btu/F
GDMC = heat capacity of the grid plates (iron), Btu/F

DTFUSI = λ_H/C_H = temperature equivalent of the heat of fusion of iron

DTFUSD = temperature equivalent of the heat of fusion of the debris.

The terms represented by FIM divided by WFI and FOM divided by WFO are the fractions of grid plate and oxide debris which are molten. These are calculated as,

$$\frac{FIM}{WFI} = \frac{TED - TMLI}{DTFUSI} \qquad (E3.136)$$

$$\frac{FOM}{WFO} = \frac{TED - TMLD}{DTFUSI}$$

where

TMLI = iron melting point

TMLD = TMELT = debris melting point from namelist NLBOIL (or TMLT from namelist NLHEAD if negative).

QRAD in Equation (E3.134) is zero when QWTR > 0. Melted material is incorporated in the debris. The last term on the right of Equation (E3.134) is the energy required to heat the newly melted head material to the debris temperature. The debris is assumed to have a single, lumped temperature. The energy balance of the debris does not include modeling of metal-water reaction. Calculations using models in HOTDRP indicate metal-water reaction in debris beds can be significant. Thus, neglecting metal-water reaction at this point may not be appropriate. Heat transfer from the core debris to water is discussed in Section 3.4.

The heat radiated from the core debris after all the water is vaporized is:

$$QRAD = QRAD1 + QRAD2 \quad , \qquad (E3.137)$$

where

$$QRAD1 = 0.173\ \pi\ R_M^2\ F_{open}\ F_{12}\left[\left(\frac{TD + 460}{100}\right)^4 - \left(\frac{T_{bar} + 460}{100}\right)^4\right] \quad \text{(E3.138)}$$

$$QRAD2 = 0.173\ \pi R_H^2\ (1 - F_{open})\ F_{12}\left[\left(\frac{T_W + 460}{100}\right)^4 - \left(\frac{T_{bar} + 460}{100}\right)\right], \quad \text{(E3.139)}$$

πR_H^2 = top surface area of debris, ft^2

πR_M^2 = molten area, ft^2

R_H = radius of debris, ft

F_{open} = fraction of area radiating at debris temperature

T_W = debris-head interface temperatures, F

T_{bar} = core barrel temperature, F

$F_{12} = 1/[1/E_1 + 0.25(1/E_2 - 1)]$

E_1 = debris emmisivity

E_2 = core barrel emissivity

$QRAD \leq$ debris decay heat.

The melt radius, R_M, is based (input-controlled) on either the iron or debris melting points. Thus, R_M is defined as

$$R_M = R_{POOL}\ (F_M)^{1/3} \quad \text{(E3.140)}$$

where

F_M = FIM/WFI for input WUO2 > 0

F_M = FOM/WFO for input WUO2 < 0.

It is assumed that the radiated heat cannot exceed the debris decay heat. QRAD1 represents the amount of heat radiating from the molten debris at temperature TD, assuming no crust formation is on the surface. QRAD2 is the

heat radiating from the crust. If a crust forms, the radiating temperature will be less than TD. The debris-head interface temperature, TW, is assumed to represent the reduced radiating temperature. TW does not exceed the head melting point (2800 F). Heat radiated from the core debris is absorbed in the core barrel; thus:

$$TBAR = TBAR + QRAD*DT/(60*WBAR) \quad , \qquad (E3.141)$$

where

TBAR = barrel temperature, F

WBAR = heat capacity of barrel, Btu/F.

TBAR is calculated in RHEAT prior to core collapse if IRAD $\neq$ 0.

For molten debris, the rate of heat transfer between the debris and the head is calculated using a Rayleigh-number based heat transfer coefficient;[71] thus:

$$QDB = h_I A_W (TD - TW) \text{ , Btu/hr} \quad , \qquad (E3.142)$$

where

$$h_I = 0.55(Ra)^{0.15} \left(\frac{H}{R_H}\right)^{1.1} \left(\frac{1.935}{R_H}\right) \text{ , Btu/hr/ft}^2\text{/F} \quad , \qquad (E3.143)$$

$$Ra = 3.49 \times 10^7 \left(\frac{QDK}{VOL}\right) R_H^5$$

H = debris depth, ft.

For solid debris, convective heat transfer is suppressed. Conduction-limited heat transfer in the debris is modeled in a manner similar to that for the head:

$$QDB = k_D A_W \frac{(TD - TW)}{\delta_D} \qquad (E3.144)$$

and

$$\frac{d\delta_D}{dt} = \frac{\pi}{2}\,\alpha\,\frac{D}{\delta_D} - \frac{R_M}{dt} \quad , \qquad \text{(E3.145)}$$

where R_M is the debris melt radius.

For partially molten debris, the molten region is assumed to start at the center and grow outward. When the growth reaches the point where $R_H - R_M < \delta_D$, the heat transfer is assumed to become convection limited. (In the programming, δ_D is replaced by k_D/h_I).

The head heating rate predicted by Equation (E3.142) using the heat transfer coefficent h_I is generally only a fraction of the debris decay heat. Meltthrough time (where pressure stresses are negligible) on the order of 2 hours may be predicted. The coding contains an option to increase the heat input to the maximum of that given by Equation (E3.142) or QDB = QDK - QRAD - QWTR.

The initial contact temperature, TW, at the debris heat interface is obtained by equating the heat fluxes. Thus, from Equation (E3.130):

$$k_D\left(\frac{TD - TW}{\delta_D}\right) = k_H\left(\frac{TW - TB}{\delta_H}\right) \quad , \qquad \text{(E3.146)}$$

and

$$TW = \left(\frac{TD + A_O\,TB}{1 + A_O}\right) \quad , \qquad \text{(E3.147)}$$

where

$$A_O = \sqrt{\frac{(k\rho C)_H}{(k\rho C)_D}} \quad . \qquad \text{(E3.148)}$$

Equations (E3.131) through (E3.145) are solved iteratively. The solution is assumed converged when iterated temperatures agree within 2 F or when X_m is within 0.0005 ft.

3.10.3 Bottom Head Failure Model

The bottom head is assumed to fail if the total tensile stress exceeds the tensile strength at any location. The critical locations considered in subroutine HEAD are the points of maximum longitudinal and cylindrical stress in the cylindrical part of the vessel, and the horizontal circular cut in the pressure vessel along an imaginary plane containing the top surface of the molten pool. Temperature dependent tensile strength is assumed.

The tensile strength in the bottom head, SIG, is calculated as follows:

$$SIG = \frac{SIG1 \times X1 + SIG2 \times X2}{X1 + X2} \qquad (E3.149)$$

Using the schematic of Figure 3.6:

X_1 = thermal penetration distance in the bottom head
X_2 = THICK - X_m - X1
THICK = initial thickness of the bottom head
X_m = thickness of the melted portion of the bottom head
SIG1 = average tensile strength over the thermal penetration distance part of the bottom head, and
SIG2 = tensile strength over the uniform temperature part of the bottom head.

For temperatures below 1500 F, the tensile strength in psi is:[37]

$$\sigma = 1.49 \times 10^{16}\, T^{-3.91} \leq SIGF \text{ (input) for } T \leq 1500 \text{ F}, \qquad (E3.150a)$$

where SIGF is an input upper limit on tensile strength. The tensile strength is extrapolated to zero at the melting point; thus,

$$\sigma = 1.49 \times 10^{16}\, T^{-3.91} \frac{(TMLH - T)}{(TMLH - 1500)} \text{ , psi, for } T > 1500 \text{ F} \qquad (E3.150b)$$

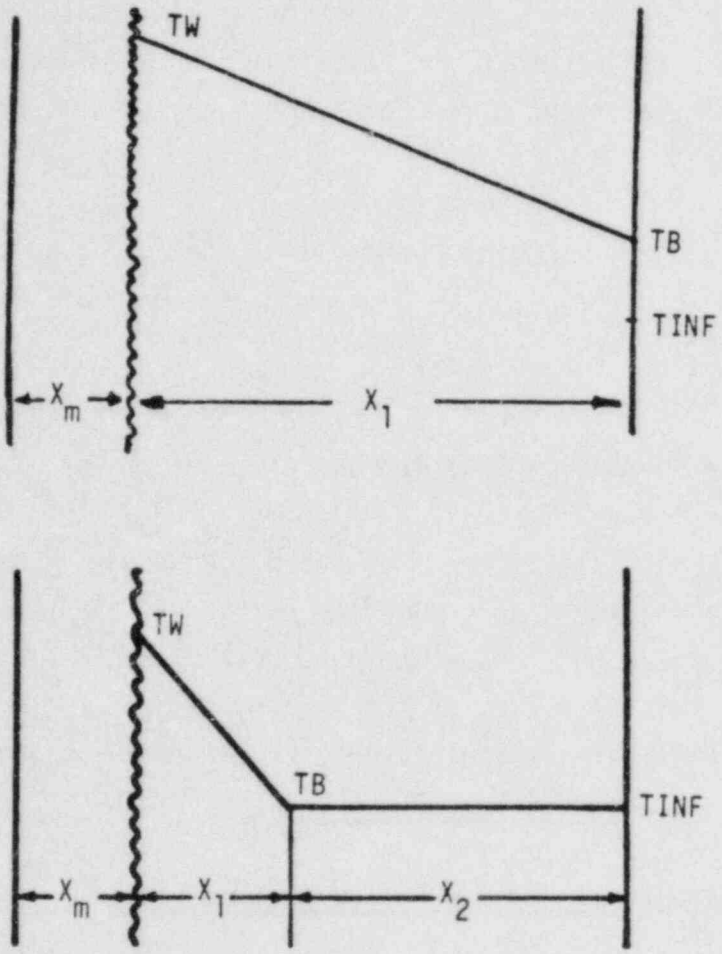


FIGURE 3.6. POSSIBLE TEMPERATURE PROFILES IN THE PARTIALLY MELTED BOTTOM HEAD

where

T = iron temperature = $(T_W + T_B)/2$
T_W = temperature at the debris-head boundary
T_B = temperature of the outside surface of the vessel
TMLH = melting point of the bottom head
TINF = head temperature at the start of HEAD calculations.

SIG1 is the value of σ evaluated in the X_1 interval of Figure 3.6 with $T = (T_W + T_B)/2$, and SIG2 is evaluated at the temperature T_B or TINF.

In calculating the stresses in the vessel and the bottom head, two cases are distinguished:

(a) The volume of the debris is less than the volume of the hemispherical section of the bottom head, and
(b) The volume of the debris is greater than the volume of the bottom head.

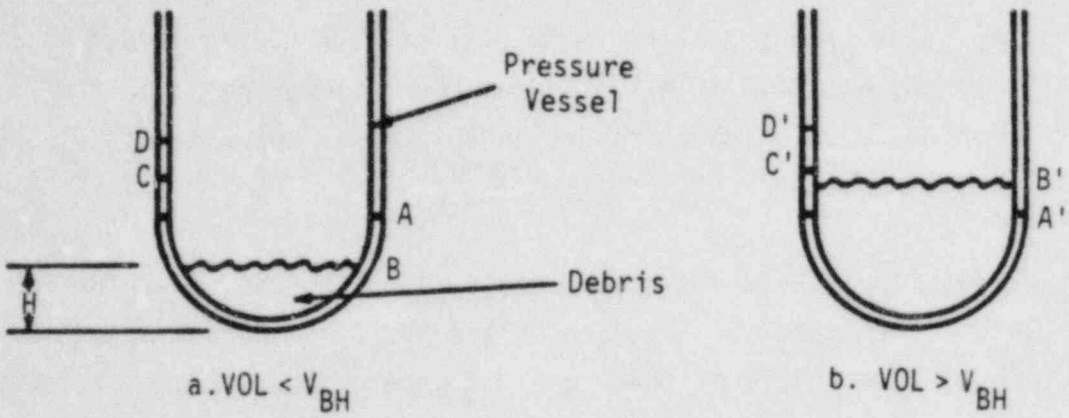
Cases (a) and (b) are shown schematically in Figure 3.7. For case (a) the maximum longitudinal and cylindrical stresses in the cylindrical part of the vessel are calculated as,[37]

$$\text{STRSL} = \frac{\text{DPRES} \times D}{4 \times \text{THICK}} + \frac{3 \times \text{DPRES} \times 0.3224}{4 \times \text{THICK}^2 \times \text{BETA}^2} + W \qquad \text{(E3.151)}$$

$$\text{STRSC} = \frac{\text{DPRES} \times D}{2 \times \text{THICK}} + \frac{3 \times 0.3 \times \text{DPRES} \times 0.2709}{4 \times \text{THICK}^2 \times \text{BETA}^2} - 0.3 \times W \qquad \text{(E3.152)}$$

where

STRSL, STRSC = the maximum longitudinal and circumferential tensile stresses in the cylindrical part of the vessel
DPRES = pressure difference between the vessel and the containment
D = diameter of the bottom head.



A = A' = Junction of cylindrical and hemispherical parts of the vessel.

B = B' = Point of the vessel corresponding to the debris top surface.

C = C' = Maximum longitudinal stress in the cylindrical part of the vessel.

D = D' = Maximum circumferential stress in the cylindrical part of the vessel.

FIGURE 3.7. MOLTEN DEBRIS IN PRESSURE VESSEL BOTTOM HEAD (VOL = VOLUME OF DEBRIS, V_{BH} = VOLUME OF BOTTOM HEAD)

$$BETA = \frac{1.285}{(\frac{D}{2} \times THICK)^{0.5}} \qquad (E3.153)$$

$$W = \frac{WGT}{144\pi\left[(\frac{D}{2} + THICK)^2 - (\frac{D}{2})^2\right]} \qquad (E3.154)$$

WGT = mass of debris falling into the head plus the mass of the bottom head.

The maximum stress in the cylindrical part of the vessel is the larger of STRSC and STRSL. It is compared with the tensile strength calculated using Equation (E3.150b), i.e.,

$$STRS1 = \max (STRSC, STRSL) \quad . \qquad (E3.155)$$

If STRS1 > SIG2, the bottom head is assumed to fail.

The stress at point B in case (a) is taken as:

$$STRS = \frac{DPRESS \times D}{4\ (THICK - XM)} + \frac{WGT}{144\pi\left[(\frac{D}{2} + THICK)^2 - (\frac{D}{2} + Xm)^2\right]} \qquad (E3.156)$$

If STRS > SIG, where SIG is calculated using Equation (E3.149), the bottom head is assumed to fail.

The criteria at locations B, C, and D are checked every timestep. Whenever the maximum stress in any location exceeds the tensile strength at that location, the bottom head is assumed to fail.

For case (b), the criteria at points C' and D' are more strict than at point B'. Therefore, only the conditions at C' and D' are checked. The stresses at these points are[37]

$$STRSL = \frac{DPRES \times DDH}{4 \times TTH} + \frac{3 \times DPRES \times 0.3224}{4 \times TTH^2 \times BETA^2} + W \qquad (E3.157)$$

$$STRSC = \frac{DPRES \times DDH}{2 \times TTH} + \frac{3 \times 0.3 \times DPRES \times 0.2709}{4 \times TTH^2 \times BETA^2} - 0.3W \qquad (E3.158)$$

where

$$DDH = D + 2 \times XM$$
$$TTH = THICK - XM$$

and now,

$$BETA = \frac{1.285}{\left(\frac{DDH}{2} \times TTH\right)^{0.5}} ,$$

$$W = \frac{WGT}{\pi\left[\left(\frac{D}{2} + THICK\right)^2 - \left(\frac{DDH}{2}\right)^2\right] \times 144} \text{ , and} \qquad (E3.159)$$

$$STRS1 = \max (STRSL, STRSC) \quad .$$

If STRS1 > SIG, where SIG is calculated using Equation (E3.149), the bottom head is assumed to fail.

3.10.4 Vessel Leakage Prior to Head Failure

An optional model allows leakage of the gases and water but not of the debris that remains in the vessel prior to gross head failure. Leakage starts when the head temperature at (user-input) thickness THKF exceeds 1600 F. The hole size and elevation are input as ABR(16) and YBR(16) in namelist NLBOIL. If THKF is input as a negative number, gross head failure is assumed based on overheating at thickness |THKF|.

4.0 REACTOR CAVITY DEBRIS INTERACTION MODELS (HOTDRP)

When the bottom head of the reactor pressure vessel fails, the core debris and any water, steam, and hydrogen left in the vessel will be released to the containment building. Accumulator water, if any remains, is assumed to dump into the reactor cavity. Depending on the nature of the vessel breach, the primary system pressure at the time of failure, the geometry of the reactor cavity, and the nature of the debris interaction with water which may be present in the reactor cavity, the core debris may fall to the reactor cavity floor or be swept out of the cavity region into the containment bulding. The HOTDRP subroutine in MARCH calculates the mass (steam hydrogen) and energy input rates to the containment from an assumed water-debris interaction in the reactor cavity following vessel failure. MARCH contains no modeling of debris entrainment, cavity sweep-out, or direct interactions between the core debris and containment atmosphere. The HOTDRP interaction is assumed to involve the total core debris and the steel in the lower grid plates and a portion of the bottom head. The mass of water involved includes any water which may remain in accumulators and water which has collected in the reactor cavity. The volume of the reactor cavity and whether additional water is added to the cavity during the interaction is controlled by user input. Pumped ECC water may be added to the reactor cavity if input IECCXX = $\pm$ 3. The location of the interaction, that is, which containment compartment receives the gases and energy produced in the interaction, is also input-controlled. The coding contains a number of user options on the use of isolated-sphere or debris bed heat transfer coefficients, the inclusion of iron oxidation, logic for switchover from isolated-sphere to debris bed heat transfer, inclusion of hydrogen production on debris bed flooding, and termination of the HOTDRP calculation. The HOTDRP calculation can also be effectively bypassed so that INTER concrete decomposition calculations may start immediately (actually, two small timesteps) after vessel failure.

4.1 Heat Transfer Models

4.1.1 Debris Particle Characterization

The debris is assumed to be in the form of spherical particles of diameter DP (input by the user). The steel (iron) is treated as a separate all-metal component. The Zircaloy cladding is included in the core fuel material. The steel volume is:

$$VOLF = (WFEC + WFEBLD + WGRID + WHEAD)/\rho_{FE} + WFEO/\rho_{FEO} \qquad (E4.1)$$

where the core steel (WFEC) and grid plate masses (WGRID) are input and WHEAD includes all of the molten head plus the user-input fraction FHEAD of the solid iron in the head. The head mass is calculated in HEAD based on the calculated interface area and input thickness (THICK). WFEBLD and WFEO are the non-oxidized and oxidized portions of the BWR control blade material. The non-steel debris volume is:

$$VOL = WUO2/\rho_{UO2} + WZR/\rho_{ZR} + WZRO2/\rho_{ZRO2} \quad , \qquad (E4.2)$$

where the fuel (WUO2) mass is input and the non-oxidized (WZR) and oxidized (WZRO2) Zircaloy masses are calculated in BOIL. The material densities (ρ_{FE}, ρ_{FEO}, ρ_{UO2}, ρ_{ZR}, and ρ_{ZRO2}) are stored in the code. The number of steel and core particles is calculated by dividing the respective total volume by the volume of a single particle. Similarly, the total particle surface area is the number of particles multiplied by the area of a single particle.

4.1.2 Debris-Water Heat Transfer

The steel and core debris particles are assumed to have the same uniform temperature (T). This is an important assumption, particularly if solid head material is included in the core debris (see namelist NLHEAD input FHEAD). Since the steel in the bottom head is relatively cool, the homogenization will increase the steel temperature and the oxidation rate. The rate of heat transfer from the particles to the water is:

$$QWTR = h_{eff}(AHS + AHZ)(T - TRC) \quad , \qquad (E4.3)$$

where

QWTR = heat transfer rate, Btu/hr
h_{eff} = effective head transfer coefficient, Btu/hr/ft^2/F
AHS = surface area of iron particles, ft^2
AHZ = surface area of fuel particles, ft^2
T = debris temperature, F
TRC = temperature of water in reactor cavity, F.

The effective heat transfer coefficient includes a single-node conduction resistance in the particle based on a steady-state conduction model; thus,

$$h_{eff} = \frac{1}{\frac{0.2\ R_p}{CON} + \frac{1}{h}} \quad , \qquad (E4.4)$$

where

R_p = particle radius, ft
CON = particle thermal conductivity, Btu/hr/ft/F
h = surface heat transfer coefficient, Btu/hr/ft^2/F.

The derivation of the conduction resistance in Equation (E4.4) is given on pages 3-83 and 3-84 of the MARCH 1.1 manual[10]. The same thermal conductivity is used for both the steel and fuel particles.

The heat transfer coefficient in HOTDRP may be calculated for an isolated particle model surrounded by water or for a debris bed model. For an isolated particle model, h in Equation (E4.4) is given by subroutine SPHERE for IDBED = 0 or by Equation (E7.6) (MARCH 1.1 model) for IDBED = -1. For a debris bed, the effective heat transfer coefficient is defined as:

$$h_{eff} = QDRY/[(AHS + AHZ)\ (T - TRC)] \quad , \qquad (E4.5)$$

where QDRY = debris bed dryout heat rate, Btu/hr. For IDBED = 1, a flat plate correlation is used, and for IDBED = 2, 3, or 4, a debris bed correlation is used. The correlations are programmed in subroutine DBED. The heat transfer correlations are discussed in Section 7.1.2. Of the debris bed correlations programmed, the Lipinski deep-bed model[38] (input IDBED = 3) appears to give the best representation (approximate factor of 2) of a variety of data. The Dhir-Cotton model[39] (IDBED = 2) as programmed should not be used for particle diameters greater than 1.0 mm.

4.1.3 Gas Heating and Cooling Models

Hydrogen generated by metal-water reaction in HOTDRP is assumed to be released from the debris at the debris temperature. For an isolated particle model, the hydrogen at temperature T is assumed to be mixed with the unreacted steam at temperature TSAT before release to the containment. It follows from the stoichiometry of the reaction that the hydrogen-steam mixture temperature (TGAS) is:

$$TGAS = (FAC*T + TSAT)/(1 + FAC) \quad , \qquad (E4.6)$$

where

FAC = CPH*DWS/(9*CPS*(WS - DWS))
CPH = specific heat of hydrogen, Btu/lb/F
CPS = specific heat of steam, Btu/lb/F
DWS = steam consumed, lb/min
WS = steam generation rate, lb/min.

When there is sufficient water in the reactor cavity, HOTDRP assumes that the hot gases produced in the bed will be cooled by the water in the reactor cavity. The heat absorbed in the water by cooling the gas is:

$$DQWTR = [(WS - DWS)*(HS - HSAT) + DWS/9*(HG - HG2)]\ 60, \text{ Btu/hr} \quad , \qquad (E4.7)$$

where

HS = steam enthalpy at temperature TGAS, Btu/lb
HSAT = saturation steam enthalpy, Btu/lb
HG = hydrogen enthalpy at temperature TGAS, Btu/lb
HG2 = hydrogen enthalpy at TSAT, Btu/lb.

It is assumed that the heat DQWTR is absorbed in the water on top of the bed. Thus, the steam produced by DQWTR is not available for metal-water reaction.

Experiments[40] indicate degraded debris bed heat transfer for shallow water pools. HOTDRP assumes that gases begin to break out or penetrate the cover water when the depth of the cover water is less than the bed height. When this occurs, the bed is assumed to heat the steam not consumed in metal-water reaction. The steam heating is calculated assuming flow through equivalent channels in the bed. The steam temperature at the top of the bed covered by a shallow pool is:

$$TGAS2 = T - (T - TSAT)e^{-BB} \quad , \qquad (E4.8)$$

where

T = bed temperature, F
BB = HC*AHB/(60*CPSH)
CPSH = (WS - DWS)*CPS
AHB = channel area, ft^2
HC = gas heat transfer coefficient, Equation (E7.1).

Mixing with the hydrogen is calculated by replacing TSAT in Equation (E4.6) with the TGAS2 above. The heat removed from the bed by the steam heating is:

$$DQHC = CPSH*(TGAS2 - TSAT)*60 \quad , \text{ Btu/hr.} \qquad (E4.9)$$

This steam heating model is bypassed if IDBED < 2 or for slab debris or when there is sufficient water to prevent break out.

4.1.4 Vaporization of Water in Reactor Cavity

The temperature increase of the water in the reactor cavity due to heat transfer from the debris is:

$$\Delta T = QWTR*DT/(60*CP*WRC) \quad , \quad F, \qquad (E4.10)$$

where

QWTR = Equation (E4.3)
WRC = mass of water in reactor cavity, lb
CP = specific heat or water, Btu/lb/F
DT = HOTDRP timestep, min.

The water vaporization rate is:

$$WSB = WRC*CP*(TRC + \Delta T - TSAT)/(HFG*DT), \text{ lb/min}, \qquad (E4.11)$$

where

HFG = heat of vaporization, Btu/lb
TSAT = saturation temperature at the total containment pressure, F.

The steam WSB is assumed to be available for metal-water reaction. If DQWTR (Equation E4.7) is greater than zero due to hydrogen evolution from a debris bed, the additional vaporization is DQWTR/HFG, and the total vaporization rate is:

$$WS = WSB + DQWTR/(HFG*60), \text{ lb/min} \qquad (E4.12)$$

When the boiling rate exceeds the water available (WS*DT > WRC), the boiling and heat transfer rates are redefined so that mass and energy balances are preserved.

During the time period prior to head failure, MACE uses a reactor cavity water vaporization model which maintains a partial pressure of

steam in the containment equal to the saturation pressure at the reactor cavity water temperature. The MACE vaporization model for the reactor cavity is bypassed during the HOTDRP and INTER calculations of bulk boiling at the total pressure.

4.1.5 Effect of Hydrogen Generation on Debris Bed Dryout

The Wallis flooding correlation,[14]

$$\sqrt{j_g^*} + m\sqrt{j_f^*} = C \qquad \text{(E4.13)}$$

is used to estimate the effect of hydrogen generation on debris bed dryout. At dryout, no water penetrates the bed so that $J_f^* = 0$, and:

$$j_g^* = \frac{WSBED}{60\ A\ \rho_s}\left(\frac{\rho_s}{gD(\rho_L - \rho_s)}\right)^{1/2} = C^2 \qquad \text{(E4.14)}$$

where

ρ_s = steam density, lb/ft^3
ρ_L = water density, lb/ft^3
g = 32.2 ft/sec^2
D = characteristic dimension, ft
A = characteristic flow area, ft^2
WSBED = steam flow rate leaving top of bed, lb/min.

Since the energy transferred from the bed to the water is:

$$QDRYB = WSBED*60*HFG,\ Btu/hr \quad , \qquad \text{(E4.15)}$$

equations (E4.14) and (E4.15) form the basis for a debris bed dryout correlation. With hydrogen generation in the bed, the combined steam and hydrogen momentum flux leaving the bed will remain constant at the value required to maintain no net water penetration. This is equivalent to the

statement that $j_g^* = C^2$ is a constant. Thus dropping common terms and assuming $\rho_L >> \rho_S$, the flooding limit with hydrogen generation is obtained from the relations:

$$\frac{WSOUT + WHOUT}{\sqrt{\rho_g}} = \frac{WSBED}{\sqrt{\rho_s}} \qquad (E4.16)$$

where

WSOUT = steam leaving the bed, lb/min
WHOUT = hydrogen leaving the bed, lb/min
$\rho g = (WSOUT*\rho_S + WHOUT*\rho_H)/(WSOUT + WHOUT)$.

With hydrogen generation, the water boiling in the bed produced by heat transfer from the bed is:

$$WSBP = WSOUT + DWS - WHOUT*CPH*(T-TSAT)/HFG \text{ , lb/min ,} \qquad (E4.17)$$

where DWS is the steam consumed in metal-water reactions. The last term on the right accounts for steam generation in the bed due to assumed cooling of the hydrogen from the debris temperature to the water temperature. Note that this assumption is inconsistent with the discussion in Section 4.1.3 where the hydrogen cooling is assumed to take place in the water above the bed. In terms of an energy balance on the water in the reactor cavity, the location of the hydrogen cooling is irrelevant. However, the location does impact the present calculation of dryout. Equation (E4.17) predicts bed dryout for:

$$QDRY = WSBP*60*HFG \quad \text{or} \quad = QDRYB*WSBP/WSBED \qquad (E4.18)$$

Assumptions are made in HOTDRP which have the effect of limiting the range of QDRY with hydrogen generation to values which are not greatly different from the experimental data base represented by QDRYB. HOTDRP calculations may predict metal-water reaction rates large enough to react all the steam in the

bed. However, it is assumed in HOTDRP that the steam consumption can not exceed the steam generation in the absence of metal-water reaction; thus,

$$DWS = 9*WHOUT \leq WSBED = QDRYB/(HFG*60) \quad . \quad (E4.19)$$

The first limit is obtained neglecting the hydrogen cooling term in Equation (E4.17). Then, by substituting $\rho_S/\rho_H = 9$, using Equation (E4.19) and (E4.17) to eliminate WSOUT, Equation (E4.16) can be solved by trial-and-error to give WSBP/WSBED ~ 1.835. Thus, this restriction limits QDRY to an 83.5 percent increase over QDRYB. The hydrogen cooling term in Equation (E4.17) has the effect of increasing the steam generation in the bed so that less water can enter the bed. Consequently, QDRY is reduced. The second HOTDRP limit assumes QDRYB cannot be reduced by more than 70 percent; that is, WSBP/WSBED > 0.3. This assumption, when combined with the restriction in Equation (E4.19), amounts to limiting the hydrogen cooling term to values of T-TSAT less than 3800 F. The model in this section is employed only during debris bed calculations when the input value of MWR is greater than 99.

4.2 Metal-Water Reaction

The HOTDRP metal-water reaction model assumes the debris is in the form of small spheres, the total area of all the spheres participates in the reaction, and the debris has a uniform temperature. The reaction rate is limited by the minimum of a solid-state diffusion rate, a gaseous diffusion rate, or by the steam supply. The steam supply limitation is assumed to be determined by the boiling rate predicted by an isolated particle model, a flat plate boiling rate, or be debris bed dryout. The modeling assumes the same surface area for all these cases.

The zirconium oxidation model assumes spherical particles with fuel material at the center, a shell of zirconium metal on the fuel, and an outer protective shell of zirconium oxide. The steel particles are treated separately as solid iron spheres with an initial oxide layer determined by the fraction of the BWR control blade reacted. The water-metal reaction energy from both types of particles is summed before inclusion in a lumped debris energy balance. The zirconium calculations are performed first in HOTDRP.

The steam not consumed by the zirconium calculation is assumed to be available for reaction with the steel. HOTDRP assumes all the steel is iron. Reactions with chromium and nickel are not modeled. (Note that this is inconsistent with INTER which assumes the unreacted steel is stainless steel with 70 percent iron, 18 percent chromium, and 10 percent nickel).

The zirconium reaction modeled is:

$$Zr + 2H_2O = ZrO_2 + 2H_2 \quad ,$$

with an energy release of:[11]

$$HZR = 2912.5 - 0.0585(T + 460), \text{ Btu/lb Zr} \quad .$$

The iron reaction is:[29]

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2 \quad ,$$

with an energy release of

$$HFE = 457.2 \text{ Btu/lb Fe} \quad .$$

The Fe_3O_4 species is believed to be characteristic of oxidation in a steam-rich environment.[29] (Note, however, that the Fe_3O_4 iron oxide is inconsistent with INTER which assumes an FeO iron oxide form.)

The metal oxidation rates for solid-state diffusion are given by relations of the form:

$$XDOT = \frac{Ae^{-\frac{B}{(T + 460)}}}{XO} \text{ , cm metal/sec} \quad , \qquad \text{(E4.20)}$$

where XO = oxide layer thickness, cm. The constants A and B depend on the MWR input flag for zirconium oxidation and are given in Table 3.2. For iron, $A = 0.2662 \times 10^6$ cm^2/sec and B = 76411 F.[30] For the iron reaction, the reaction rate is further limited by placing an upper limit (input TMS) on the

value of T used in Equation (E4.20). For input TMS = 0, the iron reaction is bypassed.

The gaseous diffusion rate for the zirconium is:[9]

$$XDOT1 = \frac{5.57 \times 10^{-8} \; Nu \cdot RP \cdot SUM^{0.68}}{(RP - XF)^2} \text{ , cm/sec} \qquad \text{(E4.21)}$$

where

XF = XO/30.48, oxide thickness, ft
Nu = Nusselt number = 2.0
RP = particle radius, ft
SUM = 2 x film temperature, (T + TRC + 960)/1.8, K.

For the iron reaction, the constant in front of Equation (E4.21) is replaced with 4.134×10^{-8} to account for the larger density of iron. The reaction rate is then set to the minimum of the values given by Equations (E4.20) and (E4.21) (and multiplied by 3600/30.48 to convert the rate to ft/hr). Two energy production rates (Btu/hr) are then calculated:

$$QMW1 = HZR*DENZR*AHZ*XDOT \qquad \text{(E4.22)}$$

$$QMW2 = HZR*91.22/36*WBS*60 \qquad \text{(E4.23)}$$

QMW1 is the power given by the oxidation kinetics, and QMW2 is that given by the steam supply limitation. QMW is defined as the minimum of QMW1 and QMW2, and the actual steam consumption rate is calculated by recasting Equation (E4.23) in the form:

$$DWSZ = \frac{QMW}{HZR*152.03} \text{ , lb/min} \qquad \text{(E4.24)}$$

The steam not consumed (WSB - DWSZ) by the zirconium is assumed to be available for reaction with iron. Equations similar to Equations (E4.20) to (E4.24) are written for the iron reaction with the appropriate changes in energy

release, metal density, surface area, and stoichiometry. In addition, geometric corrections are made in the rate equations for iron. Equations (E4.20) and (E4.22) assume slab or thin shell geometry.* For the iron particles, spherical geometry is modeled. Thus, XDOT is divided by:

$$GEOM = \frac{[RP^3 - (RP - XS)^3](RP - XS)^2}{3 \cdot XS \cdot RP^4} \quad , \qquad (E4.25)$$

where XS = radial thickness of iron reacted, ft. The surface area AHS in the expression for QMW1 is multiplied by:

$$RAT = (1 - XS/RP)^2 \quad . \qquad (E4.26)$$

The fraction zirconium reacted for slab geometry is:

$$FZR = X/CLAD \quad , \qquad (E4.27)$$

and the fraction iron reacted for spherical geometry is:

$$FFE = 1 - (1 - XS/RP)^3 \quad . \qquad (E4.28)$$

The metal-water reaction energy is assumed to be added to the lumped debris. The net energy input to the debris accounts for the enthalpy flows associated with heating the steam to the debris temperature, retention of the oxygen, and release of the hydrogen at the debris temperature. The net metal-water reaction is:

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*The thin shell approximation for typical UO_2 and Zircaloy core volume fractions produces 10-30 percent errors in Equation (E4.20).

$$\begin{aligned} CLADMW = {} & 60*DWS*[16/18*CPOXY*(TSAT - 32) \\ & - 2/18*CPH*(T - TSAT)] \\ & + 60*[DWSZ*HZR*91.22/36 \\ & + DWSS*HFE*167.52/72], \text{ Btu/hr} \quad . \end{aligned} \tag{E4.29}$$

CLADMW is generally negative after all the zirconium is reacted. This occurs because, for the iron reaction, the energy required to heat the steam to the reaction temperature generally exceeds the isothermal energy release.

4.3 Debris Temperature

The debris "energy equivalent" temperature is given by:

$$TE = TE + (QDK*TFPL + CLADMW - QWTR - DQHC) *DT/(60*DBMC) \quad , \tag{E4.30}$$

where

QDK = core decay heat, Btu/hr
TFPL = fraction of decay heat remaining in debris
DBMC = heat capacity of debris, Btu/F

and CLADMW, QWTR, and DQHC are defined by Equations (E4.29), (E4.9), and (E4.3). The temperature TE may exceed the debris melting temperature. In this case, a melt fraction is calculated as:

$$FDM = (TE - TMLT)/(TFUS - TMLT) \quad , \tag{E4.31}$$

where

TMLT = melting temperature
TFUS = TMELT + DBLAM/DBMC
DBLAM = debris heat of fusion, Btu.

If no debris is melted, then the debris temperature is T = TE. If TE is between TMLT and TFUS, then T = TMLT. If TE is above TFUS, then T = TE - (TFUS - TMLT). If the melt fraction FDM exceeds the largest previous values, additional fission products are released from the debris.

4.4 Programmed Logic Switches

HOTDRP contains a number of logic switches set by input parameters which select model options and control the flow of the calculations. The input variable TCORM controls logic which switches the mode of heat transfer from isolated-particle to flat plate or debris bed. This switch is employed to examine a transition phase which may be postulated to occur between head failure and debris bed formation. If 0 < TCORM < 10,000 F, HOTDRP will use an isolated-particle model with heat transfer coefficients from subroutine SPHERE until the debris temperature falls below TCORM. For debris temperature below TCORM, a debris bed model is used. For input TCORM > 10,000 F, the code sets flags and replaces the input TCORM with TCORM - 10,000 F. For input TCORM > 10,000 F, a particle levitation calculation is performed. The model for TCORM > 10,000 F assumes the debris remains in the isolated-particle mode of heat transfer until the calculated steam flow rate falls below the velocity required to levitate an isolated particle. The isolated-particle steam generation rate used in the levitation test is:

$$WSP = \frac{HQNCH*(AHZ + AHS)*(T - TRC)}{60*HFG} \text{ , lb/min} \quad , \qquad (E4.32)$$

where HQNCH is given by Equation (E4.4) with h for an isolated sphere.

The flow rate required to levitate the particle is (Ref. 33, p. 177):

$$WLEV = \left(\frac{8}{3}*RP*32.2*\rho_p\rho_s/CD\right)^{1/2}*(60*PORO*ACAV), \text{ lb/min} \quad , \qquad (E4.33)$$

where

ρ_p = particle density, lb/ft^3

ρ_s = steam density, lb/ft^3

CD = drag coefficient = 0.5

ACAV = bed area, ft^2.

Debris bed formation is assumed when WSP < WLEV. Test calculations with a 300 ft^2 bed area using the levitation model indicate debris bed formation is precluded until 2-inch diameter debris particles cool to about 2800 F, 1-inch diameter particles to 1300 F, 0.5-inch diameter particles to 700 F, and 0.23-inch diameter particles remain levitated. Thus, the model indicates levitation is credible.

If the input TCORM is negative, the programming permits multiple switches between the debris bed and isolated particle modes if the debris bed cooling phase is not adequate to maintain the debris temperature below |TCORM| (or below the levitation velocity). If TCORM is positive and the debris bed is uncoolable, the calculation will switch to the concrete decomposition phase (INTER).

Input parameters IHOT, TQNCH, and NCAV (in namelist NLMACE) affect the timing of the change in accident phase from HOTDRP to INTER. IHOT and NCAV affect the amount of water entering the reactor cavity and vaporized in HOTDRP. The HOTDRP calculations may be terminated if desired after cooling the debris to TQNCH. The transfer to INTER is immediate if TQNCH is greater than 2500 F. Otherwise, the transfer is delayed until the debris reheats adiabatically to 2500 F. Use of IDBED or MWR greater than 100 activates gas heating and hydrogen flooding models.

4.5 HOTDRP Timestep

The HOTDRP timestep is calculated in the code and varies between 10 minutes and 0.0001 minutes depending on current events. Calculated timesteps allow 5 percent (or 100 F) changes in debris temperature, a 5 percent change in the fraction of metal reacted, or a 5 percent change in containment pressure per timestep.

4.6 Comment on HOTDRP

The user of MARCH should be aware that the outcome of a HOTDRP calculation is highly dependent on user-supplied input which selects the modeling assumptions. Reactor cavity debris-water interactions are not well-understood, and cannot at present be convincingly described by a single deterministic calculation. The options in HOTDRP are intended to allow the user to scope the consequences of a number of possible debris/water interaction possibilities. Not all possibilities are considered. For example, entrainment and sweep-out of the debris into the containment with direct debris-containment heating is not considered. Nor is the effect of debris-concrete interactions factored into HOTDRP. In any case, HOTDRP conserves mass and energy so that the predicted outcomes result from a consistent partition between the debris and water of the energy available.

5.0 THE DEBRIS-CONCRETE INTERACTION MODEL

Subroutine INTER and its associated subroutines models the interaction of the core debris with the concrete containment base pad (Figure 2.5). The INTER package was originally written by the Sandia National Laboratories as a separate code.[41] It has been incorporated in the MARCH code as a module by Battelle with modifications in the areas of debris decay heat calculation, radiation heat transfer from the top of the debris, treatment of solidified debris layers, the input initialization, and a number of error corrections.[42]

The INTER package will not be documented in detail here. Important modeling considerations and the changes made in the original INTER code will be highlighted. For more information on INTER, the reader is referred to Sandia publications.

5.1 Description of INTER

INTER models heat and mass transfer interactions between molten core debris and a concrete base pad. Depending on the curvature of the base pad, and the volume of the molten debris, the melt is geometrically described as either a nemisphere or a hemisphere attached to a cylinder. The melt is assumed to be separated into oxide and metal layers with the denser of the two layers being on the bottom.

Heat transfer takes place between the debris and the concrete, debris and the water or concrete wall above the debris, and between the two layers of the debris. A schematic of the concept is shown in Figure 5.1.* Each layer is assumed to be well mixed and isothermal in its interior as long as the layer is molten. Heat transfer from layer to layer or from a layer to surroundings takes place across a boundary layer or film whose thickness varies with the violence of mixing.

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*Figures 5.1, 5.2, and 5.3 are reproduced from Reference 41.

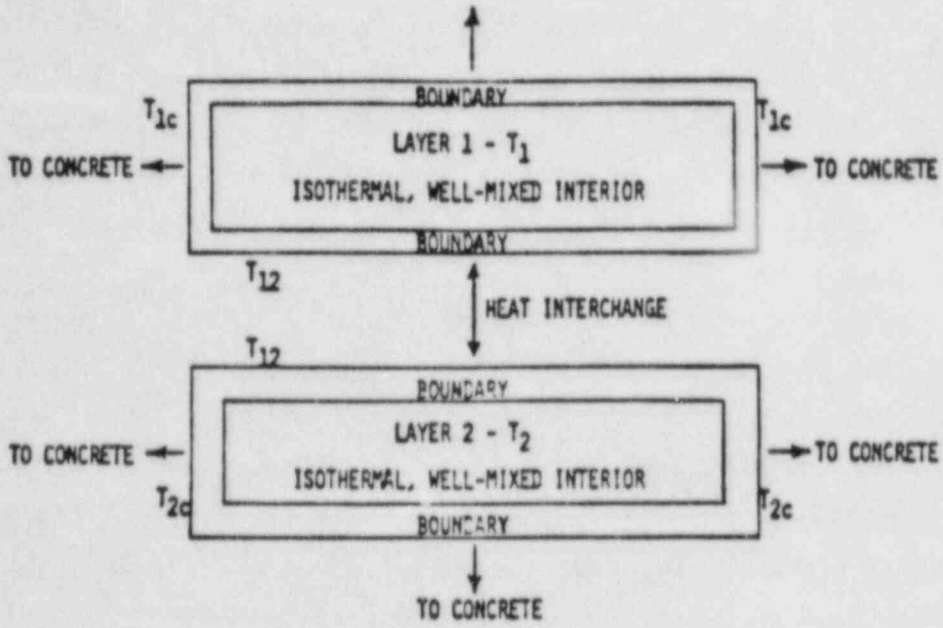


FIGURE 5.1 SCHEMATIC CONCEPTUALIZATION OF HEAT EXCHANGE IN DEBRIS-CONCRETE SYSTEM(41)

Energy conservation for each debris layer is expressed as:

$$d/dt\ (M_i\ C_{pi}\ T_i) = d/dt\ Q_i = \dot{q}_i \qquad \text{(E5.1)}$$

where

i = i, 2 (metal or oxide)

M_i = mass of i-th layer

C_{pi} = specific heat of i-th layer

T_i = temperature of the i-th layer

$d/dt\ Q_i = \dot{q}_i$ = net rate of heat added to i-th layer

t = time.

$\dot{q}_i$ is found from

$$\dot{q}_i = \dot{q}^i_{int} + \dot{q}^i_{ent} + \dot{q}^i_{react} + \dot{q}^{ji}_{cond} - \dot{q}^i_{leav} - \dot{q}^i_{rad} - \dot{q}^i_{conc} - \dot{q}^{ij}_{cond} - \dot{q}^i_D \ , \qquad \text{(E5.2)}$$

where

$\dot{q}^i_{int}$ = internal (fission-product decay) heating in layer

$\dot{q}^i_{ent}$ = rate of enthalpy addition due to materials entering the layer

$\dot{q}^i_{react}$ = net chemical reaction heat rate (the reactions considered are Fe + H_2O, Fe + CO_2, Zr + H_2O, Zr + FeO, Cr + H_2O, and Ni + H_2O)

$\dot{q}^{ji}_{cond}$ = rate of heat conduction from layer j (zero if $T_i > T_j$)

$\dot{q}^i_{leav}$ = rate of enthalpy loss due to materials leaving the layer

$\dot{q}^i_{rad}$ = radiation loss rate

$\dot{q}^i_{conc}$ = rate of heat lost to the concrete

$\dot{q}^{ij}_{cond}$ = rate of heat conduction to layer j (zero if $T_j > T_i$)

$\dot{q}_D^i$ = rate of heat of dissociation of concrete products not dissociated at the melt/concrete interface.

Mass balances on each layer consider decomposition of concrete and chemical reactions. Figure 5.2 shows schematically the flow paths of materials through the debris layers. Simplifying assumptions include:

- Newly incorporated oxides and metals are instantaneously transmitted to their respective layers
- Gases entering a layer leave the layer in the same timestep
- Gases generated at a vertical interface flow directly to the atmosphere without going through the melt
- Gases bypass frozen layers.

Figure 5.3 shows the expansion of the debris-concrete melt front in both the hemispherical segment, and the hemispherical plus cylindrical segments geometries.

5.2 MARCH Modifications to INTER

Modifications made in the original INTER code include: an internal calculation of the fission product decay heat, radiation heat transfer from the top of the debris, addition of a concrete heat sink above the debris, and treatment of solid layer behavior. Previously, the decay heat was supplied to the code as input. At present, it is calculated in the MARCH code in subroutines ANSQ and FPLOSS (see Section 7.5). A model for heat transfer from the top of the debris has been added which allows a user-specified portion of the debris to radiate at the internal debris temperature. Radiated energy either heats water on top of the debris or decomposes concrete. The mass of water on top of the debris is calculated in Section 6.4. The initial conditions in INTER, such as initial masses and temperatures are calculated in the earlier parts of the code and are passed to INTER.

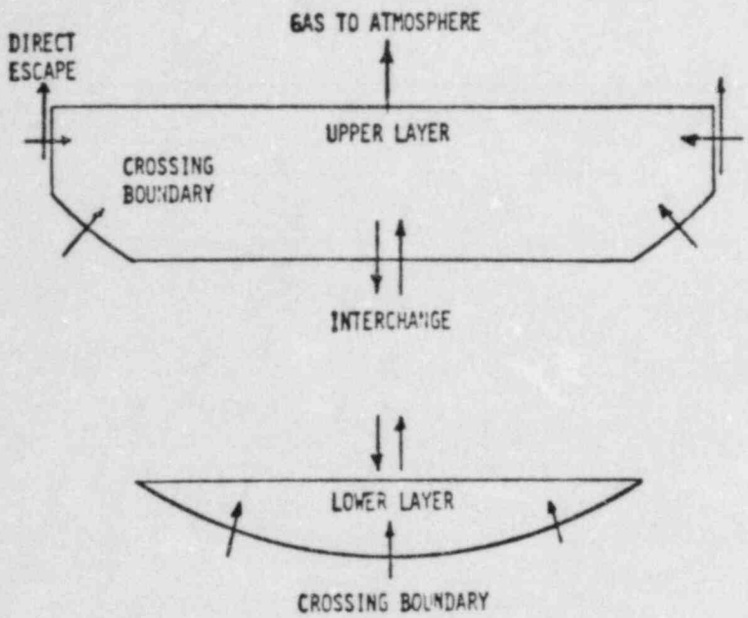
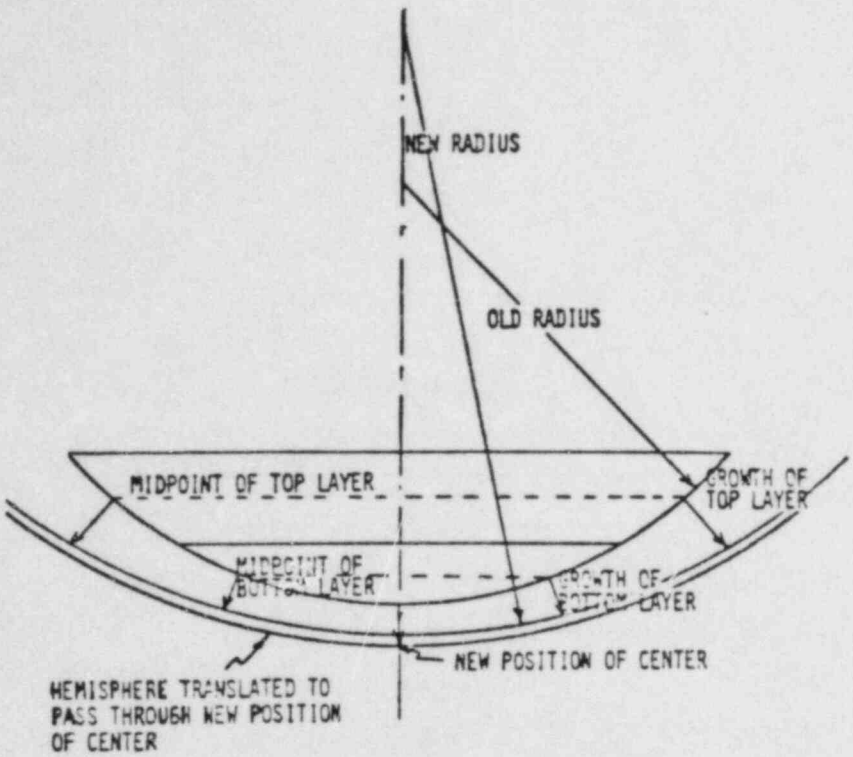
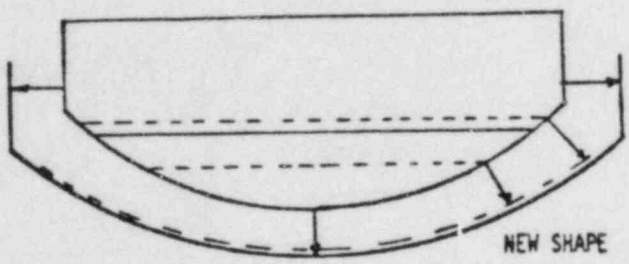


FIGURE 5.2. FLOW OF MATERIAL IN DEBRIS-CONCRETE SYSTEM(41)



a. Hemispherical Segment



b. Hemispherical/Cylindrical Segments

FIGURE 5.3 CHANGING SHAPE OF CAVITY IN CONCRETE MELTING[41]

When water covers the core debris, the concrete decomposition gases are assumed to be cooled to the water temperature. (An input option allows the gas to bypass the water.) The water is also heated by convection and radiation heat transfer from the top of the debris. The convective heat transfer is calculated assuming crust formation on the debris and using the boiling curve in function HBOIL. Radiation heat transfer to water is calculated assuming a fraction of the area (input FIOPEN) radiates at the internal debris temperature, and the original INTER model, which assumes radiation from the crust surface, is used only when there is no cover water. Because of the higher radiating temperature, significantly higher heat fluxes may be calculated. For purposes of calculating the vaporization of the water in the reactor cavity, the INTER boiling point is set equal to the value calculated in MACE. This is necessary to avoid vaporization oscillations since the programmed INTER boiling point is significantly greater than that used in other parts of MARCH, particularly for high containment pressures.

When there is no water in the reactor cavity, a user-specified fraction, FRCW, of the energy radiated from the top of the debris is assumed to decompose concrete. The model assumes all the energy leads to decomposition or ablation. None of the energy is re-radiated or conducted away from the surface. The fraction 1-FRCW of the radiated energy is lost from the system in the sense that the energy is not included in a modeled heat sink. The gases produced by concrete ablation are added to the containment atmosphere.

The ablation rate is:

$$W_{rad} = Q_R \, F_{RCW}/\Delta H_{CD} \text{ , gm concrete/sec} \qquad \text{(E5.3)}$$

where

Q_R = heat radiated from the top surface of the solid crust layer on the debris, W

F_{RCW} = fraction of Q_R which decomposes concrete (input)

$\Delta H_{CD} = Q_{CD} + C_{PC}(T_{DC} - 325)$, J/gm concrete

Q_{CD} = decomposition enthalpy from subroutine DECOMP

C_{PC} = specific heat of concrete, J/gm/K

T_{DC} = decomposition temperature, K.

The concrete decomposition is assumed to produce steam and CO_2 at the temperature T_{DC}. The fate of the solid decomposition products is not modeled. The steam and CO_2 production rates are:

$$W_{H_2O} = F_{H_2O} W_{rad} \text{ , gm } H_2O/\text{sec} \quad , \qquad \text{(E5.4)}$$

$$W_{CO_2} = F_{CO_2} W_{rad} \text{ , gm } CFO_2/\text{sec} \quad . \qquad \text{(E5.5)}$$

Where F_{H_2O} and F_{CO_2} are the masses of H_2O and CO_2 (from DECOMP) released per gram of concrete decomposed.

Two modifications were made in INTER which affect the debris-concrete heat transfer as the oxide and metal layers solidify. After both layers solidify, INTER will continue to predict both radial and vertical growth of the decomposed concrete region, while intuition would expect primarily vertical penetration. A negative value of input HIM sets a flag which suppresses radial heat transfer when both metal and oxide layers are solid. Input IGAS greater than 100 sets a flag which reduces both radial and vertical heat transfer coefficients when the layer temperatures are less than 100K above the melting temperature. The effect of the reduced heat transfer is that the debris will continue to remain slightly molten, which is more consistent with the INTER heat transfer models. However, since the concrete decomposition at this stage is primarily driven by the decay heat, regardless of other heat transfer assumptions, the modification has little effect.

Comparisons of CORCON and INTER indicate the early response of INTER is being driven by the highly exothermic Zr + FeO reaction. The CORCON chemistry model produces little energy from the reaction while INTER tries to react all the FeO in 1000 sec. Better agreement of CORCON and INTER are obtained by neglecting the reaction (input IZRFEO = 0).

6.0 CONTAINMENT RESPONSE MODELS

Subroutine MACE calculates the thermal-hydraulic response of the containment. MACE and its associated subroutines are shown in Figure 2.2, and the functions of subroutines are briefly described in Table 2.1. The containment response is calculated after each call to the source routines INITL, BOIL, and HOTDRP. The output from INTER is accumulated over a user-specified number of INTER timesteps before the call to MACE. MACE may divide the source routine timestep into smaller parts, depending on containment events and the energy addition rates.

The containment structure in MACE can be divided into 8 compartments.* If desired (and with the proper input), auxiliary buildings and the environment may be represented by one of these compartments. Containment safeguards (sprays, building coolers, etc), large dry containments as well as pressure suppression containments (ice condensers, suppression pools), and combustion of flammable gases (hydrogen and carbon monoxide) are modeled. MACE does not model the strength of the containment. Containment failure or leakage is initiated by user-specified criteria (pressure, temperature) and break or orifice parameters.

MACE permits only series-connected compartments. The present models contain no information on how to partition the flow among parallel paths. Inter-compartment flows are calculated using either the MACE "pressure equilibration" approach or through user specified orifices. Only two orifice-type flow paths are permitted. One may connect two compartments, and the other is reserved for containment failure or leakage to the environment. The orifice-type flow path connecting two compartments may contain a pressure suppression feature (ice bed or suppression pool). MACE "pressure-equilibration" transfers produce equal pressures in all compartments connected by this type of path. Many events in a core meltdown accident develop slowly over long periods of time, and neglecting intercompartment pressure drops is reasonable.

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*MACE is configured for 10 compartments. However, fission product information is stored in two of the positions so that the practical limit is 8 compartments.

However, equilibration transfers do not realistically model pressure drops for rapid transients such as large-LOCA blowdown or hydrogen burns. Frequently, however, even in rapid transients, it is adequate to know only the final state after equilibrium. Transfers by inter-compartment fans and through vacuum breakers (relieving high wetwell air space pressure to the drywell in a BWR) are also modeled.

A MACE calculation consists of the following steps:

- Calculate initial conditions and set flags to start containment sprays, hydrogen igniters, containment failure, ECC recirculation, etc.
- Based on containment events and the energy input rates, calculate the MACE timestep size (MACEDT).
- Sum all the energy and mass inputs, and calculate compartment pressures assuming no equilibration-type inter-compartment transfers. Orifice-type flows and inter-compartment fan flows are considered here, however (MACEPT).
- Calculate equilibration-type transfers and the final compartment conditions.

The last three steps above are repeated until a converged solution is found. After convergence, the following information is calculated once per MACE timestep:

- Calculate heat transfer to the containment walls (SINK).
- Distribute water on the floor among the sumps and the reactor cavity.
- Test criteria for combustion ignition, and calculate mass and energy inputs from hydrogen and carbon monoxide burning (BURN).

The above information is used in the next MACE timestep. The MACE timesteps are repeated until the controlling routine's timestep is filled. Some MACE information is calculated only once per controlling routine timestep. This information includes the following:

- Calculate sump and reactor cavity vaporization.
- Based on containment and reactor vessel conditions, calculate ECC injection and recirculation rates and heat transfer to ECC heat exchangers (ECC and ECCHX).
- Calculate spray injection flow rates and temperatures, and containment spray heat exchanger operation (CSHX).
- Calculate heat losses to building coolers (COOL).
- Check conditions for safeguards failure.
- Update sump conditions for ECC and spray recirculation.
- Calculate MARCH timestep limitation based on containment leak rate.

An energy audit calculation parallels the MACE calculation and is printed in the output. After processing output, MACE returns the control to MARCH for the next source routine timestep. Details of the calculations described above are given in the following sections.

6.1 Containment Mass and Energy Balance

Conservation of energy for the containment atmosphere may be stated as:

$$\Delta U = \Sigma W_i h_i \, dt + Q \, dt \qquad \text{(E6.1)}$$

where

ΔU = change in internal energy, Btu
$W_i h_i$ = enthalpy flow into compartment, Btu
W_i = mass flow into compartment, lb/min
h_i = enthalpy, Btu/lb
Q = energy input from walls, combustion, etc, Btu/min
dt = timestep, min.

Since $H = U + PV$, the enthalpy change is:

$$\Delta H = \Delta U + 0.1852 \, V \, \Delta P \qquad \text{(E6.2)}$$

where

ΔH = change in compartment enthalpy, Btu

V = compartment volume, ft^3

ΔP = change in compartment pressure, psia

and the constant 0.1852 is a units conversion factor. Combining Equations (E6.1) and (E6.2), the energy balance equation may be written in terms of the enthalpy change as:

$$\Delta H = \Sigma\ W_i h_i\ dt + Q\ dt + 0.1852\ V\ \Delta P, \qquad \text{(E6.3)}$$

or

$$H_2 = H_1 + \Sigma\ W_i h_i\ \Delta t + Q\ \Delta t + 0.1852\ V\ \Delta P\ , \qquad \text{(E6.4)}$$

where

H_2 = new compartment enthalpy, and

H_1 = old compartment enthalpy, and

ΔP = pressure change in timestep Δt.

Equation (E6.4) is the MACE energy conservation equation for the containment atmosphere.

Using the MACE notation* for Equation (E6.4), the energy balance equation is:

$$U_T = U_{TOT} + (R_{UG} + R_{US} + F_P\ Q_{DK}/60 - Q_H - Q_S + E_{SV})\ \Delta t + 0.1852\ V\Delta P + \Delta U_{BN} - \Delta U_{LK} - \Delta U_{TX} - \Sigma\ \Delta U\ ,\ \text{Btu}\ , \qquad \text{(E6.5)}$$

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*Note that MACE uses the notation UT, UTOT, UA, etc., for compartment enthalpy parameters, rather than the more conventional use of these symbols for internal energy. MARCH code users who examine the Fortran listing should be aware of this notation. Also, note that Equations E6.1-E6.4 are energy conservation equations. That is, they correctly conserve "internal energy" not "enthalpy".

where

U_T = new compartment enthalpy, Btu

U_{TOT} = enthalpy from previous timestep, Btu

and the sources of containment energy are:

R_{UG} = non-condensable gas energy flow into compartment, Btu/min

R_{US} = steam and water energy flow into compartment, Btu/min

Q_{DK} = total decay heat, Btu/hr

F_P = fraction of decay heat airborne in compartment

Q_H = heat removed by building coolers, Btu/min

Q_S = heat transfer to building walls, Btu/min

E_{SV} = energy added by sump water vaporization, Btu/min

ΔU_{BN} = energy added by hydrogen and CO combustion, Btu

ΔU_{LK} = energy flow leakage due to containment failure, Btu

ΔU_{TX} = net energy flow loss due to intercompartment transfers, Btu

$\Sigma\ \Delta U$ = others not specifically defined above (discussed later).

As discussed previously, MACE calculates equilibration-type inter-compartment transfers for multi-compartment containments in a two-step procedure. In the first step, the intercompartment transfers are ignored ($\Delta U_{TX} = 0$) and Equation (E6.5) is used along with a mass balance and equation of state to calculate the individual compartment pressures. The compartment pressures will generally be different because of the different source terms. In the second step, inter-compartment transfers, ΔU_{TX}, are calculated which equalize the pressures. The pressure equilibration calculation is discussed in Section 6.2.

The energy flows (R_{UG}, R_{US}) into the compartment are generally calculated in the source modules (INITL, BOIL, HOTDRP, INTER), but may also include additions from MACE "events" entries. Heat transfer to building coolers and walls are discussed in Sections 6.4 and 6.8.3, combustion in Section 6.9, and containment failure in Section 6.7.

The $V\Delta P$ term in Equation (E6.5) is calculated in MACE from old time-step containment pressures; that is, $\Delta P = P_1 - P_{-1}$, where P_1 is the previous pressure and P_{-1} is the pressure two timesteps back. In some cases, it is

observed that the inertia or "ancient" history of the VΔP term as calculated may have a small (~ 1 percent) effect on the shape of the containment pressure trace.

The last term in Equation (E6.5), ΣΔU, represents a number of additional energy transfer terms which may be present, but are not specifically included in other terms. The symbol ΣΔU is used here for the sake of brevity. ΣΔU includes energy transfer by (1) direct fallout from the atmosphere of a portion of the liquid blowdown included in R_{US}, (2) removal of liquid condensate from building coolers and on containment walls, (3) energy removed by direct blowdown through relief valves into the suppression pool, (4) energy transfer by intercompartment fans, (5) energy removal by containment sprays, and (6) energy removal by gravitational fallout of suspended water droplets from the atmosphere.

Energy removal from the atmosphere (to sumps) by fallout and condensation is:

$$\Delta U_F = \Delta M_F \, h_F, \text{ Btu} , \qquad \text{(E6.6)}$$

where

ΔM_F = mass of water falling out during the MACE timestep, lb

h_F = fallout water enthalpy, Btu/lb.

The coding contains checks to assure that energy removal by condensation and water fallout does not produce a superheated atmosphere. That is, condensation is not permitted to reduce the atmosphere steam density below that corresponding to the saturation density at the atmosphere steam partial pressure.

Mass balances are written for each component of the containment atmosphere. The mass balances parallel the energy terms included in Equation (E6.5). For example, the atmosphere steam (including suspended water) mass balance is:

$$W_S = M_{OS} + (R_{MS} + M_{SV})\,\Delta t + \Delta W_{BN} - \Delta W_{LK} - \Delta W_{TX} - \Sigma\,\Delta M, \text{ lb}, \qquad \text{(E6.7)}$$

where

W_S = current steam and water mass in atmosphere, lb
M_{OS} = previous timestep value of W_S, lb
R_{MS} = steam and water additions from source modules, lb/min
M_{SV} = steam from sump vaporization, lb/min
ΔW_{BN} = steam addition from combustion of hydrogen, lb
ΔW_{LK} = steam leaked, lb
ΔW_{TX} = net steam intercompartment transfer, lb
$\Sigma\ \Delta M$ = others, as discussed for Equation (E6.5).

6.2 Compartment Thermodynamic Model (Equation-of-State)

The MACE mass and energy balance calculations are described in the previous section. These relations along with thermodynamic state equations described below are used to calculate the compartment thermodynamic properties (temperature, pressure, and quality). These calculations utilize, in addition to MACE, subroutines MIXCTL, EQUIL, TEMP, and SATEST.

The first step in the calculation is a call to subroutine SATEST to determine if the atmosphere is superheated, that is, if the atmosphere contains liquid water. The atmosphere is superheated if the compartment enthalpy (known from the energy balance calculation) exceeds that for a saturated atmosphere; that is, if EXCESS > 0, where

$$\text{EXCESS} = \text{UTOT} - (MC_p)_{NC}\ (\text{TSAT} - 32) - \text{WS}\ h_g(\text{TSAT}), \qquad \text{(E6.8)}$$

where

UTOT = compartment enthalpy, Btu
$(MC_p)_{NC}$ = heat capacity of non-condensables, Btu/F
WS = total liquid plus vapor mass, lb
$h_g(TSAT)$ = saturated vapor enthalpy, Btu/lb
VC = compartment volume, ft^3.

TSAT is the saturation temperature corresponding to a saturated vapor density of WS/VC.

If it is not superheated (negative EXCESS), the compartment temperature, T_o, is calculated by iteration from the following equation (subroutine EQUIL):

$$UTOT = (MC_p)_{NC} (T_o - 32) + (WS - \frac{VC}{V_g(T_o)} h_f(T_o) + \frac{VC}{V_g(T_o)} h_g(T_o) \quad \text{(E6.9)}$$

where

T_o = compartment temperature, F

$V_g(T_o)$ = specific volume of steam at saturation temperature of T_o

$h_f(T_o)$ = specific enthalpy of water at saturation temperature of T_o.

$V_g(T_o)$, $h_f(T_o)$, and $h_g(T_o)$ are polynomial functions of T_o (given in Section 7.6.2). Once T_o is known, the partial pressure of steam is given by the polynomial function of Equation (E7.81).

However, if the compartment atmosphere is superheated (EXCESS >0), the temperature is found from (subroutine TEMP)

$$UTOT = (MC_p)_{NC} (T_o - 32) + WS\ H(T_o) \quad \text{(E6.10)}$$

where $H(T_o)$ is the superheated vapor enthalpy. $H(T_o)$ is derived from two equations of state that were obtained from curve fits to steam table data for saturated steam conditions[43]. These equations are:

$$P\ V_g = 1.34863\ H - 1157.716 \quad \text{(E6.11)}$$

$$\text{and } P\ V_g = 0.50662\ T_o + 282.4364 \quad \text{(E6.12)}$$

where

P = steam partial pressure, psia

V_g = specific volume, ft^3/lb

H = specific enthalpy, Btu/lb.

From Equations (E6.11) and (E6.12):

$$H = H(T_o) = (0.50662\ T_o + 1440.15)/1.3486 \quad . \quad \text{(E6.13)}$$

Substituting $H(T_o)$ in Equation (E6.10) and solving for T_o gives the compartment temperature.

The partial pressure of steam in the compartment atmosphere, P_s, is found from Equation (E6.12) with $V_g = VC/WS$ and the partial pressures of non-condensables are found from the ideal gas law, i.e.,

$$P_i = \frac{W_i R_i (T_o + 460)}{144\ VC} \qquad \text{(E6.14)}$$

where

$i = N_2, O_2, H_2, CO_2, CO$

W_i = weight of gas i

R_i = gas constant for gas i.

The total pressure in the compartment is the sum of partial pressures, i.e.,

$$P_{tot} = P_s + \sum_i P_i \qquad \text{(E6.15)}$$

where P_s is the vapor pressure.

The fraction of vapor (quality) of in the vapor-water mixture in the atmosphere is given by subroutine TEMP:

$$X = \frac{\frac{ENSX}{WS} - h_f(T_o)}{h_g(T_o) - h_f(T_o)} \qquad \text{(E6.16)}$$

where

$$ENSX = UTOT - UAIR \quad \text{(water + vapor enthalpy)}$$

$$UAIR = (MCp)_{NC}\ (T_o - 32) \quad \text{(non-condensables enthalpy)}$$

and the masses of steam and water droplets in atmosphere are

$$M_f = (1 - X)\ WS \quad , \text{ and} \qquad \text{(E6.17)}$$

$$M_g = WS - M_f \qquad \text{(E6.18)}$$

M_f and M_g are printed in the MACE output as MLIQ and MVAP.

6.3 Inter-Compartment Transfers

MACE models pressure-equilibration, orifice flow, and fan flow type intercompartment transfers. These are described below.

6.3.1 Pressure Equilibration Transfer

Compartment connections are specified by input. One connection may be of the orifice-type discussed in the next section. The equilibration transfer calculation discussed below allows MACE to bypass calculation of momentum conservation, and permits use of a large timestep. Pressures are first calculated in MACE ignoring equilibration type transfers. Orifice and fan flows are included in this first step, however. Compartment pressures will generally be different at this stage because of the differing energy inputs and losses.

Consider the simple three compartment containment sketched in Figure 6.1 connected by flow paths A and B. Let P_1, P_2, and P_3 be the pressures before transfer, and P_o be the (unknown) equilibrium pressure. In differential form the compartment pressure changes can be written

$$\begin{aligned} \Delta P_1 &= \left(\frac{dP}{dU}\right)_A \Delta U_A \\ \Delta P_2 &= \left(\frac{dP}{dU}\right)_A \Delta U_A + \left(\frac{dP}{dU}\right)_B \Delta U_B \\ \Delta P_3 &= \left(\frac{dP}{dU}\right)_B \Delta U_B \end{aligned} \qquad \text{(E6.19)}$$

where $\Delta P_i = P_i - P_o$ is the difference from equilibrium for compartment i, and ΔU_A and ΔU_B are the unknown enthalpy flows along paths A and B. The dP/dU terms are largely functions of the equation of state, and are obtained from the

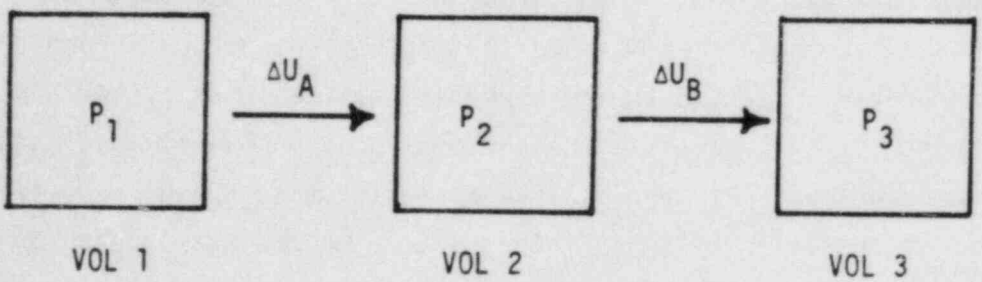

FIGURE 6.1. ILLUSTRATION OF THREE-COMPARTMENT FLOW CONNECTIONS

previous iteration. Thus, the three unknowns in Equation (E6.19) are the equilibrium pressure P_o and the transfers ΔU_A and ΔU_B which can be calculated from the three equations given. The generalized set of equations similar to Equation (E6.19) is solved in subroutine SOLINQ. Convergence is assumed in the iterative solution when the equilibrated compartment pressures agree within 0.01 psi.

Energy transfer to ice beds and suppression pools in pressure suppression containments is calculated by modifying one of the energy transfer terms, ΔU_i, in Equation (E6.19). Thus, the suppression function is assumed to be located, in effect, in the junction between two compartments. These calculations are discussed in Sections 6.8.4 and 6.8.5.

6.3.2 Orifice Flow Transfers

One inter-compartment flow path may be an orifice-flow type where the calculated flow depends on the pressure difference between compartments. The flow path may contain an ice bed or a pressure suppression pool. The orifice connected compartments are specified by the input IVENT. The sign ($\pm$) of IVENT controls switchover to the optional pressure-equilibration approach after the compartment pressure difference falls below 0.5 psi. Orifice flow transfers are initiated by input (high) source volume pressure or by high core exit gas temperature. (The orifice flow feature was initially intended to examine controlled containment venting options; however, it has other useful applications.)

The rate of gas flow between compartments is calculated in subroutine CONVNT as the minimum of the orifice flow rate as given by[20]

$$G1 = 5778\ AVBRK\ CVBRK\ (RHO\ \Delta P)^{1/2} \qquad \text{(E6.20)}$$

or the critical flow rate given by (see Equation E7.24)

$$G2 = 1642\ AVBRK\ (RHO\ P)^{1/2} \qquad \text{(E6.21)}$$

where

AVBRK = vent area

CVBRK = orifice coefficient

RHO = density of gas being vented

ΔP = pressure difference between compartments

P = pressure in the source compartment.

Individual flow rates of the gas constituents are assumed proportional to their mass fractions.

6.3.3 Inter-Compartment Fan Flow Transfers

Fans may also make transfers between two compartments. The fan flow is independent of whether or not the compartments are connected by another means (equilibration or orifice type or not connected). The fan can be turned on at an user-specified containment pressure, temperature, or time. Also supplied by the user are the fan flow rate and identification numbers for the source and receiver compartments.

After the fan has been turned on, FCFM*DTX ft^3 (FCFM is the fan flow rate specified by the user and DTX is the MACE timestep) is transferred from the fan source compartment to the receiver compartment. Transfers due to fan flow precede those that are driven by pressure gradients.

The fan may optionally be turned off when the containment fails.

6.4 Containment Wall Heat Transfer and Condensation Models

Containment walls and structures are modeled as one-dimensional slab geometry heat sinks (subroutines SINK and SLAB). The code allows a maximum of 15 heat sinks and 5 materials with a maximum 30 nodes per slab and a maximum of 200 total nodes. Material densities, heat capacities, thermal conductivities, as well as the location, composition, node coordinates, initial temperatures, and the heat transfer area of each heat sink are supplied by the user. The code uses a finite difference method to calculate the temperature profiles in the sinks.* Two adjacent slabs made up of two different materials

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*The method used to solve the conduction equation is the same as that described in the CONTEMPT-LT Manual, Appendix E (Reference 44.)

can be modeled as one heat sink, with a constant interface heat transfer coefficient. Heat transfer coefficients at the boundaries in contact with the containment atmosphere are calculated in the code. Ambient heat losses are not modeled.

The heat transfer coefficient, h_T, at the boundary between the containment atmosphere and the surface of the heat sink is calculated as:

$$h_T (T_b - T_w) = h_c (T_{sat} - T_w) + h_N (T_b - T_w)^{(44)} \qquad \text{(E6.22)}$$

where the term on the left side is the total heat transfer at the boundary. The first term on the right side accounts for steam condensation and the second for non-condensable natural convection. Rearranging this equation, the total heat transfer coefficient at the boundary, h_T, is:

$$h_T = h_c \frac{T_{sat} - T_w}{T_b - T_w} + h_N \qquad \text{(E6.23)}$$

where

h_c = condensing heat transfer coefficient
T_{sat} = saturation temperature of steam in containment atmosphere
T_w = heat sink surface temperature
T_b = temperature of containment atmosphere in the bulk
h_N = natural convection heat transfer coefficient.

h_c and h_N are calculated from Reference 45

$$h_c = 66.75\ ASWR^{-0.707},\ Btu/hr/ft^2/F \quad \text{for ASWR} < 20,$$

or

$$h_c = 12 - \frac{ASWR}{5},\ Btu/hr/ft^2/F,\ \text{(Ref. 42) for ASWR} > 20, \qquad \text{(E6.24)}$$

where ASWR = air-to-steam weight ratio in the containment atmosphere, and

$$h_N = 0.19 \, |T_b - T_w|^{1/3}, \text{ Btu/hr/ft}^2\text{/F (Ref. 31)} \; . \qquad \text{(E6.25)}$$

h_c is bounded between 2 and HMAX, where HMAX is an input number.

The boundary condition at the surface of the slab heat sink is

$$-k \frac{dT}{dX} = h_T \, (T_b - T_w) \quad , \qquad \text{(E6.26)}$$

where k is the thermal conductivity of the material in the slab and $\frac{dT}{dX}$ is the slope of the temperature profile into the slab at the surface.

At an insulated boundary

$$k \frac{dT}{dX} = 0 \text{ or } h_T = 0 \quad . \qquad \text{(E6.27)}$$

At the interface between two adjacent slabs, the boundary condition is

$$-k_1 \left.\frac{dT}{dX}\right|_{1R} = h_i (T_{1R} - T_{2L}) = -k_2 \left.\frac{dT}{dX}\right|_{2L} \quad , \qquad \text{(E6.28)}$$

where

k_1, k_2 = thermal conductivities of materials in slabs 1 and 2, respectively

$\left.\frac{dT}{dX}\right|_{1R}$, $\left.\frac{dT}{dX}\right|_{2L}$ = slopes of temperature profiles in slabs 1 and 2 at the interface, respectively

h_i = interface heat transfer coefficient (input value)

T_{1R} = temperature of last node in slab 1

T_{2L} = temperature of first node in slab 2.

The subroutine SLAB in the MARCH code calculates the node temperatures, the heat fluxes from each slab, and the total amounts of heat input to the compartment during each MACE timestep. An area-weighted temperature difference for use in CORRAL[13] is also calculated:

$$DTEM(J) = \left[\frac{\sum_{i=1}^{NSLAB} \Delta T_i^{1/3} \, AREA_i}{\sum_{i=1}^{NSLAB} AREA_i} \right]^3 , \qquad (E6.29)$$

where

DTEM(J) = average bulk-to-heat-sink surface temperature difference in containment compartment J

$\Delta T_i = T_b - T_w$ for slab i in compartment J

$AREA_i$ = surface area of slab i in compartment J

and the summations are over all slabs in compartment J. DTEM(J) is used in the CORRAL heat/mass transfer analogy calculations.

The total heat absorption rate in all slabs in compartment J, QRS(J), is:

$$QRS(J) = \sum_{i=1}^{NSLAB} (QL_i - QR_i) , \qquad (E6.30)$$

where QL_i and QR_i are rates of heat entering the left face and leaving the right face of slab i at the end of the timestep. QRS(J) is the Q_S term in Equation (E6.5).

Rate of steam condensation on the walls of the containment heat sinks is calculated in the subroutine MACEPT. MACEPT calls the subroutine MIXCTL, which, along with its own associated subroutines, calculates the equilibrium temperature, pressure, and atmospheric quality, with and without QRS(J)*DTX of energy removed from the atmosphere. (See Section 6.2 on compartment pressure and temperature equilibrium models). Then the rate of steam condensing on the structures in compartment J, MSCW(J), is:

$$MSCW(J) = \frac{WL_2 - WL_1}{DTX} , \qquad (E6.31)$$

where WL_1 and WL_2 are the masses of liquid water in the compartment J's atmosphere before and after QRS(J)*DTX of energy is removed.

6.5 Containment Sump Model

For a BWR, the drywell and the wetwell are modeled as separate compartments, each having its own sump. In the wetwell, the pressure suppression pool serves as the sump. In the drywell, water mass collects on the floor and when its volume exceeds an input specified value, it may overflow into the wetwell through the vent pipes.

For a PWR, the containment usually has only one sump and water from all compartments normally drains into that sump. The connection of the sumps is an input option.

Water may be added to a sump from one or more of the following sources:

- Containment sprays
- ECC overflow
- Direct fallout of the blowdown water
- Condensation on the walls and other structures in the containment
- Gravitational settling of water droplets suspended in the containment atmosphere
- Condensation in containment building coolers
- Condensation in ice condensers
- Ice melting.

The last two sources above are present only in an ice condenser containment and they provide water for the sump in the lower compartment (ICECUB - 1) only.

Water may leave a sump by:

- Flashing during containment depressurization
- Boiling due to fission product heating
- ECC recirculation
- Containment spray recirculation
- Vaporization

- Boiling if it comes in contact with fragmented core debris after reactor pressure vessel meltthrough (in subroutines HOTDRP and INTER).

Fission products scrubbed by ice beds or suppression pools are retained in the sump.

6.6 Reactor Cavity Model

The MARCH code models a reactor cavity that is located immediately under the reactor pressure vessel. Water from all sources first falls on the floor in compartment NCAV. After the volume of the water on the floor exceeds an user-specified value (VFLR), the water is assumed to overflow into the cavity. If the cavity also fills up (VCAV), the extra water drains back onto the floor. For a BWR, if both the floor and reactor cavity are filled, water is assumed to overflow into the suppression pool. A portion (input FSPRA) of the spray water can be directed to the reactor cavity. Water may also enter the reactor cavity by ECC injection after head failure or by meltthrough of the cavity walls in INTER.

When the pressure vessel bottom head fails, the debris is assumed to fall directly into the water in the cavity. The reactor cavity arrangement is illustrated in Figure 6.2.

6.7 Containment Failure and Leakage Models

In the MARCH code, containment failure is user-specified. Failure may be initiated by containment pressure, containment temperature, or accident time. The user specifies the compartment in which the failure occurs, the containment break area, and the orifice coefficient for the break.

Once the containment has failed, the leakage to outside is calculated as follows:

$$WBRK = ABRK*G \qquad (E6.32)$$

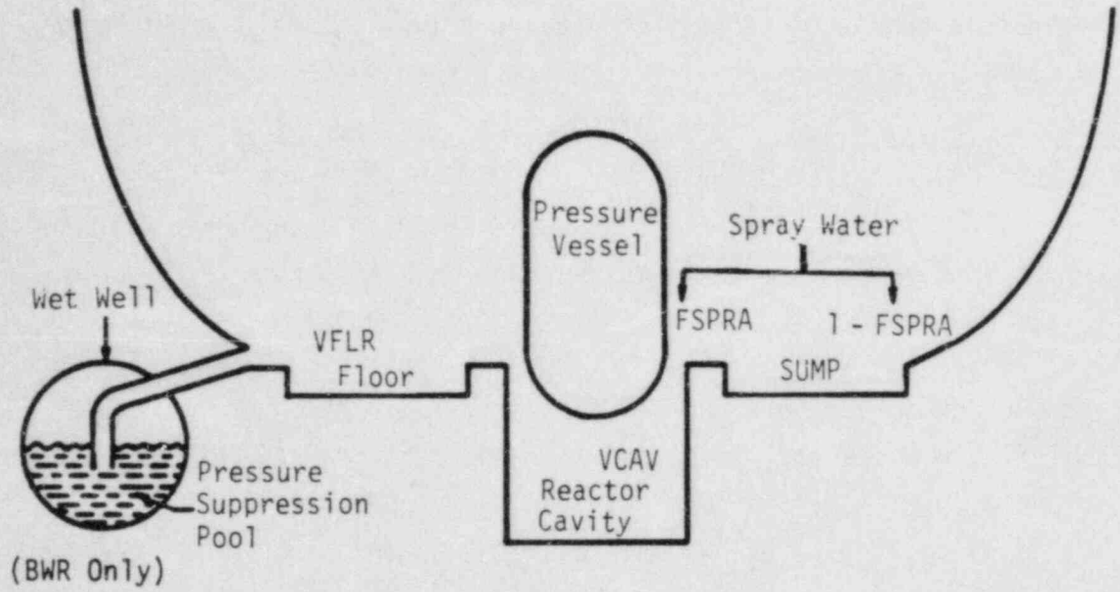

FIGURE 6.2. REACTOR CAVITY ARRANGEMENT

where WBRK = mass rate of leakage of the air-steam mixture in the containment (calculated in subroutine CONFAL), ABRK = break area, and G = mass flow velocity. G is taken as the smaller of G1 and G2, Equations (E6.20) and (E6.21).

The leakage of the compartment constituents is assumed proportional to their fraction in the failed compartment. If the pressure in the compartment is less than the atmospheric pressure, the leakage is assumed to be inwards with net addition of air to the compartment. The outside air is assumed to be at 70 F, 79 percent N_2 and 21 percent O_2. After the containment has depressurized, the user may optionally switch the calculated leakage from an orifice to a pressure-equilibration type transfer.

6.8 Containment Safety Features

6.8.1 Spray Droplet Heat Transfer Model

Heat and mass transfer between the containment sprays and the containment atmosphere are modeled in subroutine SPRAY. Heat transfer mechanisms are discussed in this section and mass transfer in Section 6.8.2 under the gravitational fallout modeling.

Spray flow rates, average diameter of the spray droplets, the logic to turn the sprays on and off and to set the spray mode to injection from the refueling water storage tank or recirculation from the containment sump, or both, are input by the user. The characteristics of the spray droplets (mass, volume, surface area, and number of droplets per unit time) are calculated in SPRAY.

It is assumed that:

- Spray droplets are spheres
- Spray droplets are at uniform temperature, i.e., there is no temperature gradient in the droplets
- Droplets fall with a constant average velocity
- All droplets are the same size
- There is no direct interaction among droplets, i.e., no droplet break-up or agglomeration.

Under these assumptions, the heat transfer coefficient, h, at the surface of the spray droplets is given by[46] (the following are in American engineering units):

$$h = \frac{k}{D} \left(2 + 0.54\ Re^{1/2}\right) , \qquad \text{(E6.33)}$$

where

k = thermal conductivity in droplets

D = diameter of droplets

Re = Reynolds number.

The Reynolds number is calculated in subroutine REYN as follows:

$$Re = \left(\frac{f}{15.71}\right)^{0.7057} \qquad \text{for } f < 10700, \qquad \text{(E6.34)}$$

$$Re = \left(\frac{f}{6.477}\right)^{0.6215} \qquad \text{for } f \geq 10700, \qquad \text{(E6.35)}$$

where

$$f = \frac{4}{3}\ \rho_D \rho_m D^3\ \frac{4.17 \times 10^8}{\mu_m^2} \qquad \text{(E6.36)}$$

where

ρ_D = density of spray droplet

ρ_m = density of air-steam mixture in compartment

D = droplet diameter

μ_m = viscosity of air-steam mixture.

μ_m is calculated from:

$$= \frac{\mu_{air}}{1 + \frac{VAP}{1 - VAP}\ \frac{\left(1 + \sqrt{\frac{\mu_{air}}{\mu_s} \cdot \frac{18}{29}}\right)^2}{4.5704}} + \frac{\mu_s}{1 + \frac{\left(1 + \sqrt{\frac{\mu_s}{\mu_{air}} \cdot \frac{29}{18}}\right)^2}{\frac{VAP}{1 - VAP}}} \qquad \text{(E6.37)}$$

where

μ_{air} = viscosity of air

μ_s = viscosity of steam

VAP = vapor mole fraction in the air-steam mixture

μ_{air} and μ_s are given as:

$$\mu_{air} = 0.0414 \left(\frac{TA}{492}\right)^{0.768}$$

$$\mu_s = 0.003339 \frac{TA \sqrt{TA}}{TA + 1224.2}$$

where

$TA = T_o + 460$, K

T_o = compartment temperature, F.

The droplet fall velocity, v_D, is calculated from the Reynolds number,

$$v_D = \frac{Re\ \mu_m}{\rho_D\ D} \qquad \text{(E6.38)}$$

The droplet temperature as a function of time is found by equating the droplet heat-up rate to the heat transfer rate between the droplet and the compartment atmosphere, i.e.,

$$m\ C_p\ \dot{T} = h\ A\ (T_o - T) \quad , \qquad \text{(E6.39)}$$

where

m = droplet mass

C_p = specific heat of droplet

T = T(t), temperature as a function of time

A = droplet surface area.

The equation above can be put into the form:

$$\dot{T} + \lambda T - \lambda T_o = 0 \quad , \quad \lambda = \frac{hA}{mC_p} \quad .$$

The solution to this equation with the initial condition $T(0) = T_i$ is:

$$T = T_i + (T_o - T_i)\ (1 - e^{-\lambda t}) \quad .$$

The final temperature of the droplet is found by subtracting in this equation the time it takes for the droplet to fall to the bottom of the compartment, i.e., for $t = t_f = \frac{HC}{v_D}$ where HC is the compartment height.

$$T_f = T_i + (T_o - T_i)\ (1 - e^{-\lambda t_f}) \quad . \qquad \text{(E6.40)}$$

If the initial temperature of the spray water, T_i, is less than the compartment temperature, T_o, the amount of heat, DEW, remaining in a droplet is:

$$DEW = mC_p(T_f - T_i) \text{ for } T_f \leq T_o < T_{sat} \text{ or } T_f \leq T_{sat} \leq T_o \qquad \text{(E6.41)}$$

or

$$DEW = mC_p(T_{sat} - T_i) - |DMW|\ h_\ell \text{ for } T_{sat} < T_f \leq T_o \ , \qquad \text{(E6.42)}$$

where

T_{sat} = saturation temperature of steam with specific volume WS/VC, where WS is the total steam mass in the compartment and VC is the compartment volume

DMW = evaporated mass of droplet (see section 6.8.2)

h_ℓ = specific enthalpy of water at saturation temperature, T_{sat}.

If $T_i > T_o$, the spray droplets are cooled by the compartment atmosphere, and the heat transferred is calculated in subroutine KOOLER as:

$$DEW = \frac{mC_p(T_i - T_{sat})}{h'_g - h'_\ell} \cdot h'_g \quad \text{for } T_f \geq T_{sat} \qquad \text{(E6.43)}$$

$$DEW = \frac{mC_p(T_i - T_{sat})}{h'_g - h'_\ell} \left[h'_g + m - \frac{mC_p(T_i - T_{sat})}{h'_g - h'_\ell} \right] C_p(T_{sat} - T_f) \quad \text{(E6.44)}$$

for $T_f < T_{sat}$

where h'_g and h'_ℓ are the specific enthalpies of steam and water at saturation temperature of $(T_i + T_{sat})/2$.

The total rate of heat exchange, EC, between the spray droplets and the compartment atmosphere is given by:

$$EC = DEW\ N \quad \text{(E6.45)}$$

where N is the total number of spray droplets flowing out of the spray headers per unit time.

6.8.2 Gravitational Fallout Model

There are two components to the water that falls out of the containment atmosphere due to gravity. One is associated with the containment sprays and the other is gravitational settling of the water droplets suspended in the atmosphere. Water from both sources is added to the containment sump.

The amount, CFALL, falling out of the atmosphere in a single compartment during a timestep is

$$CFALL = DMP + DMF \quad . \quad \text{(E6.46)}$$

DMP is the component associated with sprays, and is given by

$$DMP = N\ (M + DMW)\ DTX \quad , \quad \text{(E6.47)}$$

where

N = number of spray droplets coming out of the spray headers per unit time

M = average mass of each droplet

DMW = mass of steam condensed on each droplet or mass of water evaporated from each droplet depending on the compartment temperature and initial and final temperatures of spray droplets

DTX = timestep.

If the final temperature of the spray droplets is less than the saturation temperature of steam in the compartment atmosphere, DMW is the mass of steam condensed on a droplet and is given by

$$DMW = \frac{QC*STHR}{h_g - h_f} \quad , \tag{E6.48}$$

where

$$QC = M \cdot C_p \cdot (T_f - T_i) \tag{E6.49}$$

C_p = specific heat or spray water

T_f = final temperature of spray droplets (see Section 6.8.1 for the calculation of T_f)

T_i = initial temperature of spray droplets

STHR = ratio of the enthalpy of steam in the compartment atmosphere to the total enthalpy in the compartment atmosphere

h_g, h_f = specific enthalpies of steam and water at saturation temperature of T_0, where T_0 is the compartment temperature.

If T_f is less than the compartment temperature but greater than the steam saturation temperature, T_{sat}, corresponding to specific volume WS/VC (where WS is the total steam mass in the compartment and VC is the compartment volume) and if the timestep is larger than it takes the spray droplets to fall to the floor, DMW is the evaporated part of the mass of the spray droplet and is a negative number

$$DMW = \frac{-QC}{h_g - h_f} \quad , \tag{E6.50}$$

where

h_g, h_f are at the saturation temperature, T_{sat}.

DMF is due to gravitational falling of water droplets suspended in the atmosphere and is given by:

$$DMF = XMF \left(1 - e^{- \frac{V_D \ DTX}{HC}} \right), \qquad \text{(E6.51)}$$

where

XMF = mass of water droplets suspended in the atmosphere

V_D = droplet fall velocity

HC = compartment height.

V_D is given by

$$V_D = \frac{Re . \mu_m}{\rho_m . D} \qquad \text{(E6.52}$$

where

Re = Reynolds number

μ_m = viscosity of the steam-air mixture in the compartment

ρ_m = density of the steam-air mixture in the compartment

D = droplet diameter.

The calculations of Re and μ_m are shown in Section 6.8.1.

The gravitational fallout model normally uses a drop size of 4 microns, based on the data of Hilliard[47]. Experience with MARCH indicates the use of this small constant drop size may lead to the accumulation of large masses of suspended water droplets. In reality, growth of the drop size would be expected due to agglomeration. Agglomeration is not modeled in MARCH. However, an attempt is made to account for agglomeration by increasing the drop size from 4 to 400 microns as TSAT increases from T_o to T_o + 10 (F).

6.8.3 Containment Building Cooler Model

The required input for the containment building cooler model contained in subroutine COOL consist of:

QR = rated capacity, Btu/hr
CVAP = vapor mole fraction at rated conditions
WPR = rated fan flow rate, ft^3/min
TP1R = rated cooler inlet gas temperature, F
WSR = secondary flow rate, lb/min
TS1R = secondary water inlet temperature, F
TCOOL = time to start cooler, min.

The heat transfer coefficient correlation information is taken from the OCONEE Power Reactor Final Safety Analysis Report[48]:

$$h = 269 + 409.5\ (VAP - 0.26) \quad \text{for VAP} \geq 0.26\ , \qquad \text{(E6.53)}$$

$$h = 104 + 634.6\ VAP,\ Btu/hr/ft^2/F \quad \text{for VAP} < 0.26\ , \qquad \text{(E6.54)}$$

An effective heat transfer area for the cooler is calculated from rated conditions. Since

$$QR = h*AREA*\ (\bar{T}_p - \bar{T}_s) \qquad \text{(E6.55)}$$

where

$\bar{T}_p$ = TP1R - QR/(2 x 60 WPR), and
$\bar{T}_s$ = TS1R + QR/(2 x 60 WPR), (CP = 1)

the area is

$$AREA = \frac{QR}{h(TP1R - TS1R) - \frac{h\ QR}{120\ WSR}}\ ,\ ft^2 \qquad \text{(E6.56)}$$

In accident situations, the heat removal by the containment building cooler is:

$$QRH = h \times AREA \times \frac{TEM - TS1R}{\left(1 + \frac{h \times AREA}{WSR \times 120}\right) \times 60} \qquad (E6.57)$$

where h is calculated using the containment vapor mole fraction at present conditions and TEM is the containment atmospheric temperature. The containment cooler model described above is in subroutine COOL.

MACE input provides for a second type of building cooler (input option). The set-point pressure at which the cooler turns on and off and the constant cooler capacity (QRCOOL) are supplied as input by the user. Note that this type of cooler has constant capacity regardless of containment conditions, and may lead to unreasonable results. Because of coded limitations, the two types of coolers must not operate simultaneously in the same containment volume.

6.8.4 Ice Condenser Model

Ice condensers are used in some PWR containments to provide pressure suppression during the blowdown stage of a loss-of-coolant-accident. A schematic for an ice condenser building is given in Figure 6.3. In the MARCH code, an ice bed is modeled as being in the junction between two subvolumes ICECUB and ICECUB - 1. The reactor vessel is located in the lower compartment and any direct leakage into the containment from the primary system is directed to this lower compartment. Ice condenser containments also typically have fan flow directed from the upper to the lower compartment. Other compartments may be connected to the ICECUB and ICECUB - 1 compartments according to user needs.

The required input parameters for the modeling of an ice condenser are:

ICECUB = upper (receiver) compartment
WICE = mass of ice in ice bed
TICE = initial temperature of ice

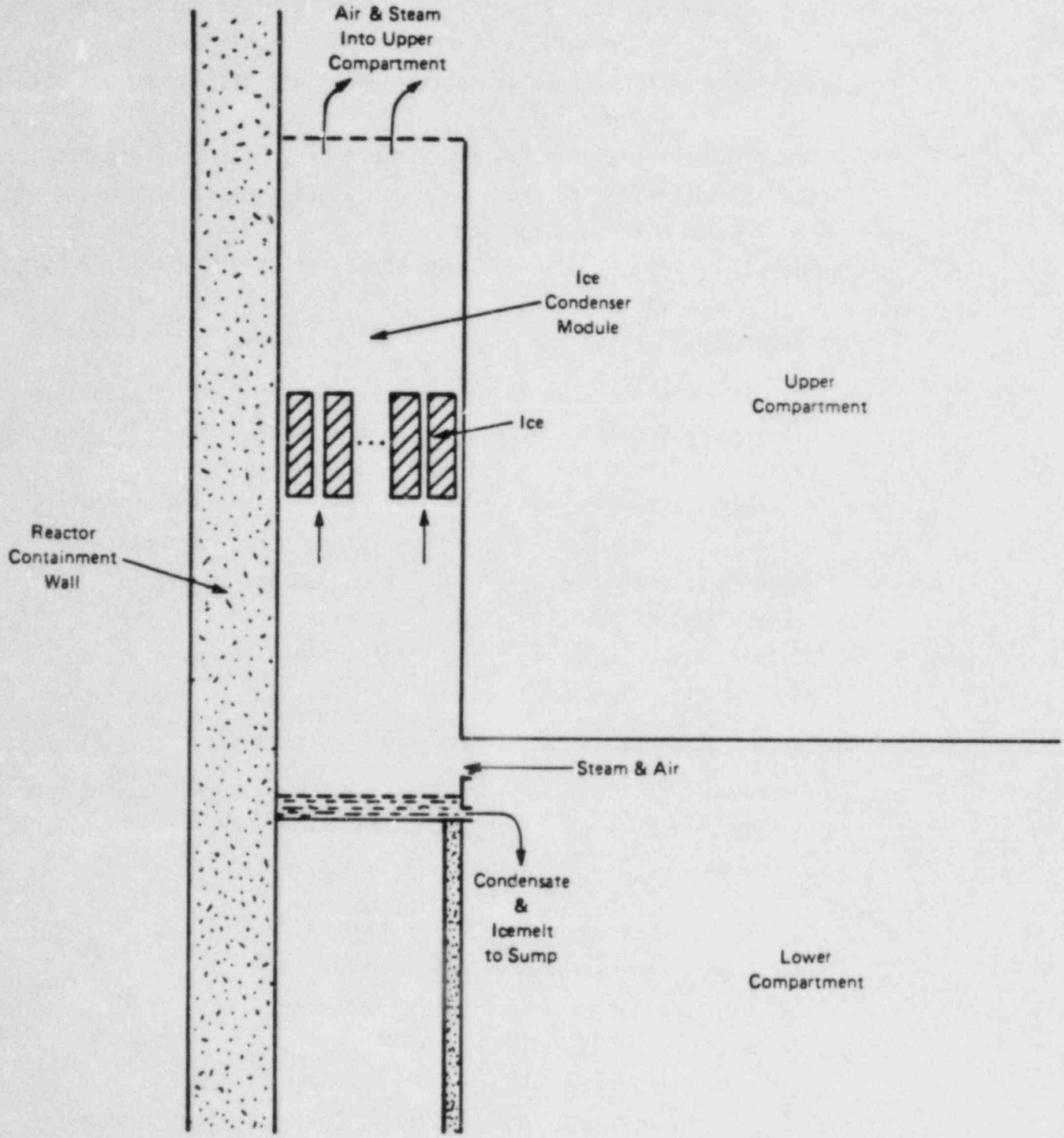

FIGURE 6.3 SCHEMATIC FOR AN ICE CONDENSER CONTAINMENT

TWTR = temperature of water draining from ice bed during blowdown (time < 1 minute)

TWTR2 = temperature of water draining from ice bed during boiloff (time > 1 minute)

TSTM = temperature of air-steam mixture exiting top of ice bed

DCFICE = decontamination factor for condensable fission products flowing through ice bed.

The default values used by the code for TICE, TWTR, TWTR2, and TSTM are taken from Reference 49.

The development of the ice condenser model assumes:

- Ice condenser doors do not interfere with the flow of steam and air mixture from one compartment to the other, and kinetic and transient effects on the ice condenser are negligible
- The temperature of steam-air mixture exiting the top of the ice cooler, and the temperature of the ice melt and condensate draining from the bottom of the ice cooler are constants independent of flow conditions
- Ice bed heat transfer is fully effective and is not degraded until all the ice is melted.

The steam condensation rate in the ice bed, MSCI, is:

$$MSCI = (\min (WSX, WS - VC\ \rho(TSTM))/DTX \qquad (E6.58)$$

where

WSX = mass of steam entering the ice bed

VC = upper compartment volume

WS = mass of steam in upper compartment

ρ(TSTM) = steam density at TSAT = TSTM

DTX = timestep size.

The fission product decay heat fraction, DFP, taken out of the atmosphere by the ice cooler, is:

$$DFP = FP\ FTX\ (1 - \frac{1}{DCFICE})\ CGF \quad , \qquad (E6.59)$$

where

FTX = fraction of lower compartment volume transferred

FP = fraction of fission product decay heat in the lower compartment before transfer

DCFICE = decontamination factor for condensable gaseous fission products (input)

CGF = the condensable fraction of fission products released from the fuel (from subroutine FPLOSS).

The rate at which energy enters the ice bed is UTX/DTX. The heat transfer to the ice bed is

$$QICE = \frac{UTX}{DTX} - \frac{CA\ (TSTM - 32)\ FTX}{DTX} + \left(\frac{WSX}{DTX} - MSCI\right)\ HTSTM \qquad (E6.60)$$

where

UTX = see Sections 4.3.1 and 4.3.2

CA = mass x specific heat of non-condensables in the lower compartment before transfer

HTSTM = specific enthalpy of steam at T = TSTM.

The term in bracket on the right hand side of Equation (E6.60) (QDEL in the output) is the rate at which energy enters the upper compartment.

The ice melting rate is:

$$DWI = \frac{QICE}{HICE} \qquad (E6.61)$$

where

HICE = the amount energy needed to heat a unit mass of ice from an initial temperature of TICE, melt it, and raise the temperature of the melt to TWTR or TWTR2.

The melted ice and steam condensate (DWI and MSCI) are added to the sump.

The grid and the structures used to hold up the ice blocks in the ice bed are treated as wall heat sinks with an initial temperature of TICE. Heat transfer to these structures is suppressed until ice bed melt is complete.

6.8.5 BWR Wet-Well Pressure Suppression Model

A BWR wetwell pressure suppression system is illustrated in Figure 6.4. When the pressure in the drywell increases due to the accumulation of steam which has leaked from the primary system, gases are driven from the drywell into the wetwell through the vent pipes and the pressure suppression pool. In the process, steam is condensed and energy transfered to the pool. Primary system coolant may also directly enter the pool through the relief valve system. Because of the large mass of the pool, low pressures are maintained. Heat exchangers are also provided for long term cooling of the suppression pool.

The required input data for the BWR pressure suppression system modeling calculations are:

IDRY = drywell volume number
IWET = wetwell volume number
WPOOL = initial mass of water in the pressure suppression pool
TPOOL = initial temperature of water in the pressure suppression pool
DCF = decontamination factor for condensable fission products in the pool.

Assumptions in the BWR pressure suppression system modeling in MARCH are:

- All steam entering the pressure suppression pool in a MACE timestep, DTX, is condensed; pool vaporization is calculated once per MARCH timestep, DTM
- Noncondensables leaving the pool leave at the pool temperature
- Steam leaking from the primary system through relief valves can be sent directly into the pressure suppression pool (input option)

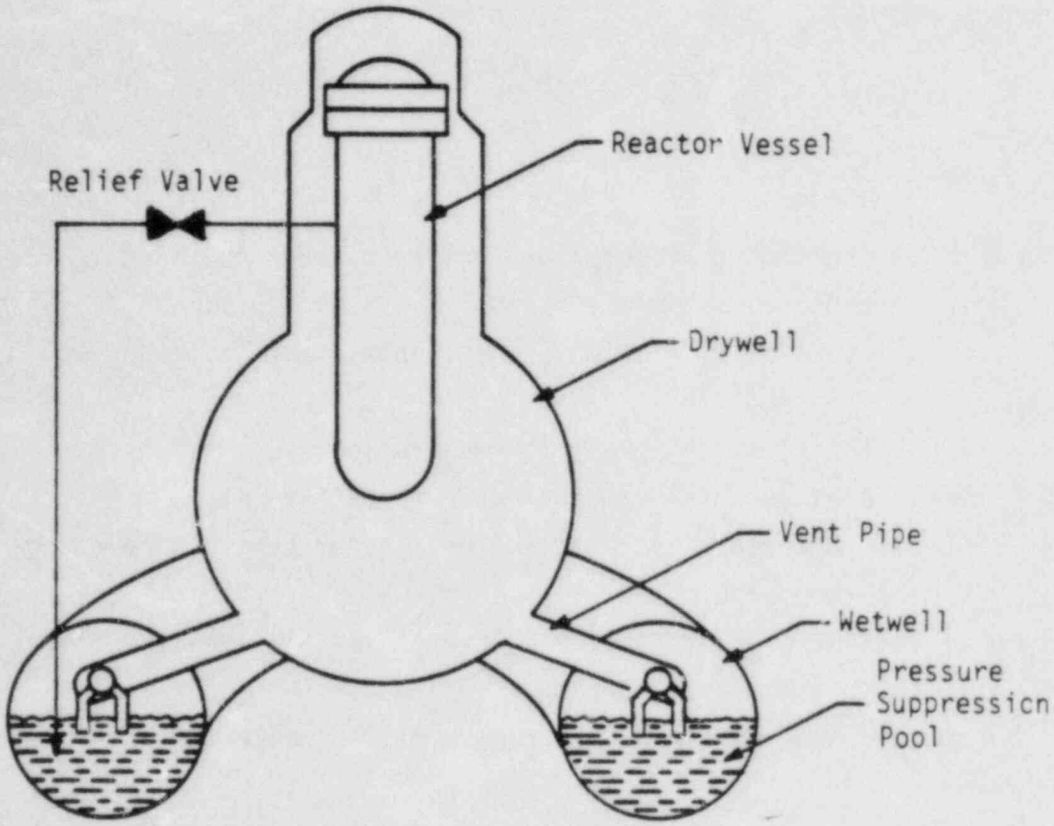

FIGURE 6.4. TYPICAL BWR PRESSURE SUPPRESSION SYSTEM

- Condensable airborne fission products flowing through the pressure suppression chamber as a result of inter-compartment transfers are retained in the pool according to:

$$DFP = FP\ FTX\ (1 - \frac{1}{DCF})\ CGF \qquad (E6.62)$$

where

DFP = fraction of fission product decay heat retained in the pressure suppression pool

FP = fraction of fission product decay heat in the drywell before transfer

FTX = fraction of drywell volume transferred

DCF = pool decontamination factor (input value)

CGF = condensable gas fraction of fission products released from fuel.

Scrubbing of fission products released through vent valves directly to the pool is modeled in a similar fashion.

Energy added to the pool during a MACE timestep by intercompartment transfers is

$$QPOOL = (UTX - CA\ FTX\ (TPOOL-32))/DTX \qquad (E6.63)$$

where

UTX = energy entering the pool from volume IDRY, Btu

FTX = fraction of IDRY entering the pool

CA = heat capacity of non-condensables in volume IDRY, Btu/F.

Pool vaporization is calculated once per MARCH timestep, DTM, and removes energy from the pool:

$$ESMP = WVAP\ DTM\ h_{fg}(TPOOL),\ Btu \qquad (E6.64)$$

where

WVAP = vaporization rate, lb/min

h_{fg}(TPOOL) = heat of vaporization, Btu/lb.

The energy ESMP is added to the wetwell atmosphere to complete the energy balance. Optionally, part of this energy may be added to the drywell atmosphere.

Suppression pool cooling is provided in MACE utilizing the containment sprays. The sprays may be utilized in one of two operational modes: to provide direct cooling of the suppression pool water (namelist NLMACE spray input NT = +1) or cooling of the wetwell atmosphere (input NT = -1). Additionally, operation of the Residual Heat Removal (RHR) system requires data be entered in namelist NLHX to model the containment spray heat exchanger with recirculation from the pool initiated by input CSPRC. When the NT = +1 option is used with ICECUB = -1 (BWR input flag), the spray water falls through the wetwell atmosphere with no heat or mass exchange; and, thus, directly enters the pool.

6.9 Combustion of Flammable Gases

The combustion of flammable gases (hydrogen and carbon monoxide) in MARCH is modeled in subroutine BURN. The flammability and flame propagation criteria are based on state-of-the-art models using best estimate data. The user may also supply flammability criteria if desired. BURN tests the compartment conditions to determine if flammability conditions are satisfied. However, actual ignition is largely user-controlled. Ignition may be initiated by igniters, by the phase of the meltdown (start of BOIL calculations, head failure, etc.), or immediately after the combustion criteria are satisfied. Alternatively, the user may calculate and output the adiabatic burn pressure at each timestep in the problem without actually burning the hydrogen and carbon monoxide. Thus, the user can monitor the effect of a burn of the combustible gases present at any stage of the accident, without actually burning the gases.

6.9.1 Heat of Reaction

The heat of reaction to be used in MACE depends on the point of zero internal energy selected for the chemical species involved and on the reference temperature actually used in MACE. MACE zeros the enthalpies of non-condensable gases and liquid water at 32 F. The reaction energy is derived below using JANAF table data(50).

Where an "energy-of-formation" scale is selected, as in the JANAF tables, the enthalpies of the elements are set equal to zero and the enthalpies of chemical compounds are set equal to their heats of formation at a common reference temperature (298 K). The following is a derivation for dT/dt in a given compartment using an "energy-of-formation" scale. The total number of moles in the compartment is the sum over all constituent chemical species:

$$n = \sum_i n_i \qquad \text{(E6.65)}$$

The rate of change of the number of moles in the compartment is the sum over all flow paths, ℓ, and chemical reactions, r:

$$\dot{n} = \sum_i \dot{n}_i = \sum_i \sum_\ell \dot{n}_{i\ell} + \sum_i \sum_r \dot{n}_{ir} \qquad \text{(E6.66)}$$

The internal energy is*

$$U = \sum_i n_i u_i \qquad \text{(E6.67)}$$

Where u_i is the internal energy per mole of species i. Differentiating,

$$\dot{U} = \sum_i n_i \dot{u}_i + \sum_i \dot{n}_i u_i$$

---

*Conventional notation is used here with U = internal energy, h = enthalpy, and C_v = constant volume specific heat.

But, by the chain rule,

$$\dot{u}_i = C_{V_i} \frac{dT}{dt} \tag{E6.69}$$

and since

$$C_V = \sum_i n_i C_{V_i} \tag{E6.70}$$

Equation E6.68 becomes

$$\dot{U} = C_V \frac{dT}{dt} + \sum_i \dot{n}_i u_i \tag{E6.71}$$

Now, from the first law of thermodynamics for an open system we know

$$\sum_i \sum_\ell n_{i\ell} h_{i\ell} + \dot{Q} - \dot{W} \tag{E6.72}$$

where $h_{i\ell}$ is the enthalpy of species i entering or leaving the compartment via flow path ℓ. $\dot{Q}$ is the rate or heat addition to the compartment from external sources, and $\dot{W}$ is the rate at which work is done by the system. Combining Equations (E6.66), (E6.71), and (E6.72) and solving for $C_V dT/dt$ yields

$$C_V \frac{dT}{dt} = \sum_i \sum_\ell \dot{n}_{i\ell} (h_{i\ell} - u_i) + \dot{Q} - \dot{W} - \sum_i \sum_r \dot{n}_{ir} u_i \tag{E6.73}$$

Now we can change the point of zero enthalpy for each species arbitrarily by defining

$$h_i^* = h_i + k_i \tag{E6.74}$$

$$h_{i\ell}^* = h_{i\ell} + k_i \tag{E6.75}$$

$$u_i^* = u_i + k_i \tag{E6.76}$$

Substituting Equations (E6.75) and (E6.76) into (E6.73) yields

$$C_V \frac{dT}{dt} = \sum_i \sum_\ell \dot{n}_{i\ell} (h_{i\ell}^* - u_i^*) + \dot{Q} - \dot{W} - \sum_i \sum_r \dot{n}_{ir} u_i^* + \sum_i \sum_r \dot{n}_{ir} k_r \tag{E6.77}$$

Equation (E6.77) shows that by changing from an energy-of-formation scale to an arbitrary scale, we introduce a heat of reaction term, $\sum_i \sum_r \dot{n}_{ir} k_r$, which must be added to the heat from external sources. The two reactions we are concerned with are

$$2H_2 + O_2 \rightarrow 2H_2O \qquad \text{(E6.78)}$$

and

$$2CO + O_2 \rightarrow 2CO_2 \qquad \text{(E6.79)}$$

so that

$$\sum_i \sum_r \dot{n}_{ir} k_r = \dot{n}_{H_2O} \left(k_{H_2O} - k_{H_2} - \tfrac{1}{2} k_{O_2}\right) + \dot{n}_{CO_2} \left(k_{CO_2} - k_{CO} - \tfrac{1}{2} k_{O_2}\right) \qquad \text{(E6.80)}$$

MACE employs a scale in which the enthalpies of noncondensable gases and liquid water are zero at 32 F. Using Equation (E6.74)

$$k_i = -h_i(32\ F) \qquad \text{for noncondensable gases,} \qquad \text{(E6.81)}$$

$$k_{H_2O} = -h_{H_2O(\ell)}(32\ F), \qquad \text{(E6.82)}$$

and

$$\sum_i \sum_r \dot{n}_{ir} k_r = -\dot{n}_{H_2O} \left(h_{H_2O(\ell)} - h_{H_2} - \tfrac{1}{2} h_{O_2}\right) \Big|_{32\ F} - \dot{n}_{CO_2} \left(h_{CO_2} - h_{CO} - \tfrac{1}{2} h_{O_2}\right) \Big|_{32\ F} .$$

The terms within brackets are molar heats of formation of liquid water and carbon dioxide at 32 F. Using data from the JANAF thermochemical tables and introducing the MACE Fortran nomenclature,

$$\text{DELEN} = -\text{DNS}*\text{HTL32F} - \text{DND}*\text{HTD32F} \quad , \qquad \text{(E6.84)}$$

where

$$DELEN = \sum_i \sum_r \dot{n}_{ir} k_r \qquad (E6.85)$$

$$DND = \dot{n}_{CO_2} \qquad (E6.86)$$

$$DNS = \dot{n}_{H_2O} \qquad (E6.87)$$

$$HTD32F = -122{,}022 \ Btu_{TH}/lb\text{-}mole \qquad (E6.88)$$

$$HTL32F = -105{,}938 \ Btu_{TH}/lb\text{-}mole \ . \qquad (E6.89)$$

6.9.2 Flammability Limits

A simple formula proposed by LeChatelier has been shown to predict the lower limits of flammability (upward flame propagation) for air-hydrogen-carbon monoxide mixtures to within 0.4 percent.(51) Modifying and expanding on an approach proposed in Reference (52), we have used the following form of LeChatelier's formula to characterize the thresholds for the MACE combustion events:

$$x_{H_2} + \frac{L_{H_2}}{L_{CO}} x_{CO} \geq L_{H_2} \ . \qquad (E6.90)$$

Here, the x's denote the mole fractions of hydrogen and carbon monoxide in the gas mixture. The L's denote the threshold mole fractions for the combustion event being considered, in gas mixtures containing only one (the subscripted) combustible gas. We have applied LeChatelier's formula in tests for ignition, propagation, and completeness. The default limiting mole fractions used for the various events are summarized in Table 6.1.

As discussed later, we make use of the variable y, based on the left hand side of LeChatelier's formula:

$$y = x_{H_2} + \frac{L^*_{H_2}}{L^*_{CO}} x_{CO} \qquad (E6.91)$$

in our estimate of the extent of reaction and the linear burning rate (flame speed). Here the L*'s denote combustible mole fractions above which burning

TABLE 6.1 DEFAULT LIMITING MOLE FRACTIONS FOR TESTS BASED ON LeCHATELIER'S FORMULA

Combustion "Event"	L_{H_2}	L_{CO}	L_{H_2}/L_{CO}
Upward Propagation	H2UP = 0.041	CMUP = 0.125	0.328
Horizontal Propagation	H2HZ = 0.06	CMHZ = 0.138	0.435
Ignition with Igniters	H2ON = 0.08	CMON = 0.148	0.541
Complete Combustion	H2XX = 0.08	CMXX = 0.148	0.541
Downward Propagation	H2DN = 0.09	CMDN = 0.150	0.600
Ignition Without Igniters	H2HI = 0.10	CMHI = 0.167	0.600

is likely to be complete in mixtures containing only one (the subscripted) combustible gas ($L^*_{H_2}$ = H2XX and L^*_{CO} = CMXX; see Table 6.1). In the absence of carbon monoxide, y is equal to the hydrogen mole fraction, x_{H_2}.

Ignition

One test for ignition in our model requires that the mole fractions of hydrogen and carbon monoxide satisfy LeChatelier's formula. The limits, as indicated in Table 6.1, depend on whether the user wants to approximate ignition with or without igniters. In addition to sufficient combustible gases, ignition requires sufficient oxygen.

$$x_{O_2} \geq \text{HIOXY (0.05 default)} \qquad \text{(E6.92)}$$

Also, the mole fractions of steam and carbon monoxide must be sufficiently low to preclude inerting:

$$x_{H_2O} + x_{CO_2} \leq \text{HIG (0.55 default)} \quad . \qquad \text{(E6.93)}$$

A specific test for inerting due to the presence of large amounts of nitrogen is not included. However, nitrogen inerting frequently implies insufficient oxygen, and Equation (E6.92) precludes burning for such cases.

Propagation

The ignition tests are applied to each nonburning compartment at the beginning of each timestep. After ignition in any compartment, burn propagation to a connected compartment is precluded if the atmosphere in that compartment is inerted per Equation (E6.92) or (E6.93). The user may specify nonmechanistic burn propagation to all connected compartments which are not inert by setting input parameter IBURNJ = 2. Alternatively, the user may (by setting IBURNJ = 1) have the code test the combustible mole fractions in noninert, connected compartments using Equation (E6.90) to determine if burn propagation is possible. The option of precluding the possibility of burn propagation by setting IBURNJ = 0 is also available to the user.

The code logic for propagation testing is summarized in follows. The user specifies, through an input flow matrix BK(I,J), whether there is a flow path from compartment I to compartment J; whether the flow from compartment I to compartment J is directed upward, horizontally, or downward; and the fraction of a characteristic distance, H2DIST(I), which a burn in compartment I must traverse before propagation into compartment J can occur. The characteristic distance H2DIST(I) is also user-specified and represents the distance traversed by a complete burn in compartment I.

Combustion Rate

The burning model in MARCH tests for a change in the rate of combustion at each MACE timestep based on the mole fractions at the beginning of the timestep. The molar combustion rates of hydrogen and carbon monoxide in compartment I are:

$$\dot{n}_{H_2} = n_T \dot{y} x_{H_2}/y \qquad \text{(E6.94)}$$

$$\dot{n}_{CO} = n_T \dot{y} x_{CO}/y \qquad \text{(E6.95)}$$

where

$$\dot{y} = -y_{max} v/H2DIST(I) \qquad \text{(E6.96)}$$

n_T = moles of gas in compartment I
Y_{max} = maximum value of y, as defined in Equation (E6.91) since beginning of the burn
v = flame speed.

The flame speed has experimentally been observed to be a function of the initial combustible gas concentration. The function in our model is:

$$v = v(Y_{max}) = H2_{VO} + H2_{VX} Y_{max} \qquad \text{(E6.97)}$$

with defaults of $H2_{VO}$ = 352.8 ft/min and $H2_{VX}$ = 11630 ft/min.

This expression is derived from turbulent hydrogen flame experiments performed at Sandia(53) and is applicable for hydrogen mole fractions below about 10 percent. The application of Equation (E6.97) to gases containing both hydrogen and carbon monoxide is a modeling hypothesis which has not been tested experimentally.

Extent of Reaction

Once combustion is started in a given compartment, it continues until y, as defined by Equation (E6.91), decreases to a user-specified or code-computed level, y_{min}. The value of y_{min} depends on the burn limit option specified via the input parameters IBURNL. For IBURNL = 0, continuous burning is approximated and y_{min} = 0. For IBURNL = 1, y_{min} = H2LO, a user-specified

mole fraction with a default value of zero. For IBURNL = 2, y_{min} is calculated as a function of y_{max} to approximate a linear variation in the extent of reaction from zero percent at $y_{max} = 0$ to 100 percent at $y_{max} = L^*_{H_2}$.

$$y_{min} = \max \left[0, \; y_{max} \left(1 - y_{max}/L^*_{H_2}\right) \right] \qquad \text{(E6.98)}$$

7.0 SUPPORT MODELS AND FUNCTIONS

This section contains discussions of supporting models and functions used in MARCH not discussed elsewhere. Models discussed here include heat transfer correlations, critical fluid flow correlations, fission product decay heat and loss models, and thermodynamic property data for water and gases. Both simplified and more complete correlations are given when the user has an input choice. In some cases, the necessary support functions are presented elsewhere in the discussion of specific subroutines.

7.1 Heat Transfer Correlations

Correlations used in the primary system and reactor cavity models of heat transfer to water and gases are discussed in this part of Section 7. Containment, molten debris, and INTER models are discussed elsewhere.

7.1.1 Heat Transfer to Gases

Heat transfer to gases is modeled in the uncovered portion of the core in BOIL, for primary system structures in EXITQ, and from the core debris in HOTDRP.

7.1.1.1 Simplified Correlation, Forced Convection

McAdams(36) gives a simplified turbulent flow heat transfer coefficient for gases as:

$$h_c = 0.0144\ C_p\ G^{0.8} / D^{0.2} \quad , \text{Btu/hr/ft}^2\text{/F} \quad , \qquad \text{(E7.1)}$$

where

C_p = specific heat of gas mixture, Btu/lb/F
G = flow rate, lb/hr/ft^2
D = equivalent diameter, ft.

The specific heats are calculated from Equations (E7.49) and (E7.50).

The correlation is stated to be applicable to common gases for moderate ΔT, at distances 60 diameters from entrance effects. The correlation is used in BOIL (ICONV = 0), EXITQ (ICONV < 10), and HOTDRP (IDBED > 101) without testing for Re or ΔT.

7.1.1.2 Simplified Correlation, Natural Convection

McAdams(36) also gives a simplified correlation for vertical plates in air in the turbulent flow regime as:

$$h_{nat} = 0.19\ \Delta T^{1/3} \quad , \text{Btu/hr/ft}^2\text{/F} \quad , \tag{E7.2}$$

where ΔT is the surface-to-gas temperature difference. The correlation is used in BOIL (ICONV = 0) and EXITQ (ICONV < 10) when Equation (E7.1) predicts $h_C = 0$.

7.1.1.3 Complete Forced Convection Correlation

Turbulent and laminar heat transfer coefficient are calculated in subroutine HCGAS when ICONV > 0 or IBWR > 0 in BOIL and ICONV > 10 in EXITQ. The Dittus-Boelter(54) correlation for turbulent flow is:

$$h_T \frac{D}{k} = 0.023\ Re^{0.8}\ Pr^{0.4} \tag{E7.3}$$

where

$$Re = \frac{GD}{\mu} = \text{Reynolds number}$$

$$Pr = \frac{C\ \mu}{\frac{p}{k}} = \text{Prandtl number}$$

μ = viscosity, lb/hr/ft

k = thermal conductivity, Btu/hr/ft/F.

The laminar flow correlation of Holman(55) is

$$h_L \frac{D}{K} = 3.66 + \frac{0.0668\ C_x}{(1 + 0.04\ C_x^{2/3})} \qquad \text{(E7.4)}$$

where

$C_x = (\frac{D}{x})\ Re\ Pr$

x = distance from the entrance, ft.

For Reynolds numbers below 2300, the heat transfer coefficient is given by the smaller of h_L from Equation (E7.4) or h_T from Equation (E7.3), evaluated at Re = 2300. For mixtures of gases, the specific heats of the components are summed using mass fraction weighting, and thermal conductivities and viscosities are mole-fraction weighted. Properties are calculated in subroutine PROP for ICONV = 1 or from STMH2P for ICONV > 1.

7.1.1.4 Gas Radiation Heat Transfer

The gas radiation heat transfer coefficient of Krieth[56] is

$$h_{rad} = 0.173 \times 10^{-8} \frac{(\epsilon_{SR} T_R^4 - \epsilon_{SG} T_G^4)}{(T_R - T_G)} (1 + \epsilon_R)/2\ , \qquad \text{(E7.5)}$$

$$\text{Btu/hr/ft}^2\text{/F}\ ,$$

where

ϵ_{SR} = gas emissivity at temperature T_R
ϵ_{SG} = gas emissivity at temperature T_G
ϵ_R = surface emissivity
T_R = surface temperature, R
T_G = gas temperature, R.

Equation (E7.5) is used in BOIL to model heat transfer to the steam-hydrogen mixture flowing through the uncovered portion of the core. Hydrogen is assumed to be transparent. The gas emissivities are thus evaluated at an optical thickness $P_S D$, where P_S is the local steam partial pressure and D is the hydraulic diameter. The heat transfer coefficient is calculated in

subroutine HRSTM using the low pressure data of McAdams[36]. The low pressure data of McAdams indicate that gas radiation in the core is negligible at low pressures. Extrapolation of the data to high pressures, such as those prevailing in transients, predicts that the radiation heat transfer coefficients may exceed the convection coefficient by an order of magnitude. Kinsman[57] reports that use of the more recent data of of Baynton[58] and an improved data interpolation technique produces heat transfer coefficients about a factor of 2 higher than those calculated in HRSTM.

7.1.2 Heat Transfer to Water

Heat transfer to water is modeled in BOIL for core material and for structures below the core, in HOTDRP for debris-water interaction processes, and in INTER for heat transfer to water over the debris. The heat transfer correlations used in these models are discussed below.

7.1.2.1 Simplified Boiling Curve

Pool boiling data presented by McAdams[36] (p. 380) can be approximated by the expressions:

$$h_B = 44.5\ \Delta T^{1.523}\ P_x \text{ Btu/hr/ft}^2\text{/F} \qquad \Delta T < 42 \text{ F} \qquad \text{(E7.6)}$$

$$h_B = 2.02 \times 10^8\ \Delta T^{-2.575}\ P_x, \text{ Btu/hr /ft}^2\text{/F} \quad \Delta T > 42 \text{ F},$$

where

$P_x = (P/15)^{0.25}$

P = pressure, psia

ΔT = temperature difference = $T - T_{WTR}$, F°.

Equation (E7.6) is used in BOIL to calculate heat transfer to the structures below the core and in HOTDRP (IDBED = -1). When used in HOTDRP, the total heat transfer coefficient is obtained by adding a radiation term given by Equation (E7.16) with F = 0.4.

7.1.2.2 Pool Boiling from Spheres

Subroutine SPHERE provides a complete pool boiling heat transfer curve for isolated spheres in water. Yang[59] has recommended the following correlations.

Temperature Difference	Regime	Heat Transfer Coefficient	Data	Eq. #
$\Delta T > \Delta T_{film}$	film boiling	H_{FB}	Farahat & Halfawy[60]	7.7
$\Delta T_{CHF} < \Delta T_{film}$	transition	H_{TR}	Interpolation	---
$\Delta T = \Delta T_{CHF}$	critical heat flux	Q_{CR}	Ded & Lienhard[61]	7.8
$\Delta T < \Delta T_{CHF}$	nucleate boiling	H_{NB}	Rohsenow[62]	7.9

The minimum film boiling temperature of ΔT_{film} = 110 F is based on the data of Dhir and Purohit[63]. The temperature difference at the critical heat flux is ΔT_{CHF} = 42.5 F. For temperature differences between ΔT_{CHF} and ΔT_{film} a logarithmic interpolation between the film boiling and critical heat fluxes is performed. A radiation heat transfer term is added to the total film boiling correlation using Equation (E7.16) with F = 0.75. These correlations are used in BOIL (IBEDS = 0) and HOTDRP (IDBED = 0) to calculate debris-water interactions. Property data used in these correlation are coded in subroutine SPHERE.

Film boiling:

$$H_{FB} = 0.75 \left[\frac{g k_s^3}{\mu_s} \frac{\rho_s(\rho_L - \rho_s)}{D\ \Delta T} \right] (h_{fg} + 0.5\ C_{Ps}\ \Delta T)^{0.25} \qquad \text{(E7.7)}$$

Critical heat flux:

$$Q_{CR} = 0.84\ Q_f\ ,\ R_p > 4.26$$

$$Q_{CR} = 1.734\ Q_f\ /\ R_p\ ,\ R_p < 4.26 \qquad \text{(E7.8)}$$

where

$$Q_f = \frac{\pi}{24} h_{fg} \left(\sigma g^2 \rho_s^2 (\rho_L - \rho_s)\right)^{0.25}$$

$$R_p = D/2B$$

$$B = \left(\frac{\sigma}{\rho_L - \rho_s}\right)^{0.5} \quad \text{(dimension = length)}$$

Nucleate boiling:

$$H_{NB} = \frac{C_{PL}\,\Delta T}{0.0132\, h_{fg}} \left(\frac{\mu_L h_{fg}}{B \Delta T}\right)^{1/3} \left(\frac{1}{P_{r_L}^{1.7}}\right)^3 \qquad \text{(E7.9)}$$

7.1.2.3 Debris Bed Heat Transfer

Subroutine DBED calculates debris bed dryout. Four correlations are provided for this purpose. The correlations are accessed by user option in BOIL and HOTDRP. The correlations provided are the Berenson[64] flat plate and the Dhir-Catton[39], Lipinski deep bed[38], and Ostensen-Lipinski[65] flooding models for debris beds. The property data used by DBED are coded in the subroutine. The correlations follow.

Berensen flat-plate:[64]

$$H_{CB} = 0.425 \left(\frac{g k_s^3 \rho_s (\rho_L - \rho_s)}{\mu_s B \Delta T}\right)^{0.25} (h_{fg} + 0.5\, C_{ps} \Delta T) \qquad \text{(E7.10)}$$

where B is defined above in Equation E7.8.

A radiation term, H_R, is added in the following formula to obtain a total coefficient, H_T.

$$H_T = H_{CB} + 0.75\ H_R, \qquad H_{CB} > H_R \ ,$$

$$H_T = H_{CB} + H_R\ (0.75 + \frac{0.25\ H_x}{2.62 + H_x}) \ , \qquad H_{CB} < H_R \ , \tag{E7.11}$$

where

$$H_x = H_R \ / \ H_{CB}.$$

The radiation term is given by Equation (E7.16) with F = 0.8.

Dhir-Catton Debris Bed:[39]

$$q_{DC} = C_3 \frac{\varepsilon^3 D^2}{(1-\varepsilon)^2} \frac{\rho_L}{\mu_L} (\rho_L - \rho_s)\ g h_{fg} \ , \quad \text{Btu/hr/ft}^2 \tag{E7.12}$$

where

$$C_3 = \pi\ 7.5 \times 10^{-4} \ / \ 24$$

ε = bed porosity.

The Dhir-Catton model as programmed is not recommended for particle diameters greater than 1.0 mm.

Lipinski Deep Bed Model:[38]

The dryout heat flux for small diameter particles where capillary effects are important is:

$$q_L = \rho_s\ h_{fg}\ ((V_L^2 + V_T^2)^{1/2} - V_L) \tag{E7.13}$$

where V_L and V_T are functions of the average liquid fraction in the bed, γ, the particle size, bed depth, bed porosity, surface tension, and the vapor and liquid densities and viscosities. See Reference 38 for the definitions of functions V_L and V_T. The dryout flux is found by maximizing q_L with respect to γ. For larger particles:

$$q_L = h_{fg} \frac{(\rho_s(\rho_L-\rho_s)g\eta(1+\lambda/H))^{0.5}}{(1 + (\frac{\rho_s}{\rho_L})0.25)^2} \quad , \qquad \text{(E7.14)}$$

where

H = bed depth

$$\lambda = \frac{6\sigma(1-\varepsilon)}{D\varepsilon(\rho_L-\rho_s)}$$

$$\eta = \frac{D}{1.75} \cdot \frac{\varepsilon^3}{(1-\varepsilon)}$$

DBED uses Equation (E7.14) for particle diameters greater than 1.0 cm.

Ostensen-Lipinski Flooding Model:(65)

$$q_{OL} = \frac{0.25\ h_{fg}(\rho_L\rho_s gD\varepsilon^3/(1-\varepsilon))^{0.5}}{1 + (\frac{\rho_s}{\rho_L})0.25^2} \qquad \text{(E7.15)}$$

For subcooled water, the dryout heat fluxes given by Equation (E7.6) to Equation (E7.15) are increased by the factor:

$$(1 + C_{pL}(TSAT - T_{WTR})/h_{fg}) \quad .$$

7.1.2.4 Radiation Heat Transfer

For heat transfer surfaces above about 1000 F, radiation heat transfer is significant. Radiation heat transfer is modeled by a parallel-plane model

$$h_{rad} = 0.173 \times 10^{-8} \frac{F\ (T + 460)^4 - (T_w + 460)^4}{(T - T_w)} \quad , \qquad \text{(E7.16)}$$

$$\text{Btu/hr/ft}^2\text{/F}$$

where

$$F = \frac{1}{(\frac{1}{\varepsilon} + \frac{1}{\varepsilon_w} - 1)}$$

ε = emissivity of surface
ε_w = emissivity of water
T = surface temperature, F
T_w = water temperature, F.

Different values of F are programmed in different subroutines. When used in HOTDRP with h_c given by Equation (E7.6), F = 0.4; in subroutine SPHERE, F = 0.75; and F = 0.8 when used with the Berensen correlation in DBF. Since to good approximation $\varepsilon_w \approx 1$, the debris surface emissivities are assumed to range between 0.4 and 0.8. Emissivities in this range are reasonable for oxidized or damaged surfaces. In subroutine INTER, the emissivities are input as well as the fraction of the area radiating at temperature T.

7.2 In-Core Radiation Heat Transfer

Subroutine RHEAT models radiation heat transfer between adjacent core nodes and radiation heat transfer from the core to structures above the core, to the core barrel, and to water. The RHEAT model is used by BOIL when input IRAD $\neq$ 0.

RHEAT models the rate of radiative heat transfer between adjacent volume nodes using the expression:

$$\dot{Q}_{mn} = \sigma AF(T_m^{*4} - T_n^{*4}) \quad , \qquad \text{(E7.17)}$$

where

$\dot{Q}_{mn}$ = rate of radiative heat transfer from node m to adjacent node n, Btu/hr
A = area of contact between nodes m and n, ft^2
σ = Stefan-Boltzmann constant, 1.714×10^{-9} Btu/hr/ft^2/R^4

F = radiation exchange resistance term, dimensionless

T_m^*, T_n^* = effective radiating temperatures of the adjacent node surfaces, R.

The net heat flux for a given node includes contributions from the four adjacent nodes: the axial nodes above and below, and the inner and outer radial nodes. The effective radiating surface areas for the radial calculations are adjacent cylinders one node high with radii corresponding to the intersections between the adjacent nodes. The effective radiating surfaces for the axial calculations are the flow channel areas associated with the nodes. Because the effective radiating surfaces are in contact, all radiation leaving one surface reaches the adjacent surface, the radiation view factor is unity, and the radiation exchange resistance term, F, is given by:

$$\frac{1}{F} = \frac{1}{\varepsilon_m} + \frac{1}{\varepsilon_n} - 1 \quad , \tag{E7.18}$$

where

ε_m, ε_n = emissivities of the two adjacent surfaces, dimensionless.

The emissivities are for the effective radiating surfaces, which are not necessarily actual heat transfer surfaces. The effective radiating surfaces are defined by the planes or cylinders which separate the nodes axially and radially, respectively. When one of the planes or cylinders coincides with an actual heat transfer surface such as the water surface or the surface of an upper or outer heat sink, then the actual material emissivity should be used. But when a plane or cylinder does not coincide with an actual material surface, an effective emissivity should be used. The effective emissivity is equal to the absorptivity of that imaginary surface to thermal radiation impinging upon it. Based on the analysis of Shaffer[66], the following emissivity values are recommended for use in the RHEAT model for a PWR core:

ELONG = $0.121\ (H/NDZ)^{-0.822}$ (axial)

ECROS = 0.7 (radial)

ESTRU = 0.6 (structures)
EWAT = 0.95 (water).

where H = core height in feet and NDZ = number of axial core nodes.

The BWR core model accounts for radial radiation heat transfer between the fuel rod, channel box, and control blade nodes at a given nodal position (I,R), but does not account for radiation transport between different nodal positions. For a BWR core, the primary effect of the boxes and blades on the RHEAT model is to block radial radiation heat transfer between the fuel rod nodes in adjacent core regions. (The T_m^* and T_n^* in Equation 7.17 are full node temperatures.) The radial blocking effect may be accounted for approximately by appropriate reduction of ECROS. Based on Equation 3.66, a value of ECROS = 0.237 (with E = 0.7) is recommended when the BWR core model (IBWR = 1) is used.

The effective radiating temperatures for the radial heat transfer calculations are determined by one of the following two schemes as specified by the user via input variable IRAD in namelist NLBOIL.

(1) For IRAD = 1, the BOIL-calculated node temperatures are used.
(2) For IRAD = 2, radial radiating temperatures approximating those of rods close to the node interfaces are used.

Because the radiation view factors from one rod to the others effectively extends to rods only three or four rows away, the IRAD=2 option provides more realistic temperatures for the parallel planes equation (Equation E7.17). Temperatures N rod pitches from the interface are estimated to include some allowance for reflected thermal radiation from rods further away from the interface. The effective radiating temperatures are determined by linear interpolation between the adjacent node centers which are assumed to be at the node average temperatures. The value recommended by Shaffer is N=2 (input as VIEW=2). The effective radiating temperatures for the axial radiative heat transfer calculations are the BOIL calculated node temperatures.

Radiative heat transfer to the residual water includes the contribution from the partially uncovered axial node and from the node immediately above that node. The radiative heat transfer to the upper structures includes

radiation from only the upper node. The core barrel is modeled as a single mass receiving radiation from only the outer radial node.

During meltdown, core nodes may fall out of the core. The net radiation heat flux in RHEAT is set to zero if the heat flux involves any node or adjacent node which has slumped into the bottom head. Section 3.3.1 contains further comments on the RHEAT model.

7.3 Axial Fuel Rod Conduction

Subroutine AXCOND models axial fuel rod conduction. The AXCOND model is used by BOIL when input IAXC = 1. For the BWR core model, axial conduction is not modeled (IAXC = 0).

The heat added to the node I by axial conduction is:

$$Q_{AX} = Q_{I+1,I} - Q_{I,I-1} \quad , \tag{E7.19}$$

where

$$\dot{Q}_{mn} = -(k_f A_f + k_c A_c)\ \Delta T/\Delta z \tag{E7.20}$$

$\dot{Q}_{mn}$ = rate of heat conduction from node m to axially adjacent node n, Btu/hr (W)

k_f = thermal conductivity of the fuel, Btu/hr/ft/F (W/m/K)

k_c = thermal conductivity of the cladding, Btu/hr/ft/F (W/m/K)

A_f = cross-sectional area of fuel at horizontal interface between nodes m and n, ft^2 (m^2)

A_c = cross-sectional area of cladding at horizontal interface between nodes m and n, ft^2 (m^2)

$\Delta T = T_n - T_m$ where T_m and T_n are BOIL-calculated node temperatures, F (K)

Δz = axial distance between the adjacent nodes, ft (m).

Temperature dependent thermal conductivities for the UO_2 fuel and the Zircaloy cladding are calculated in the subroutine PROP, Section 7.6.1.2. If the node m or n has fallen out of the core due to slumping, $\dot{Q}_{mn}$ is set to zero.

7.4 Critical Flow of Fluids

7.4.1 Critical Flow of Water

The critical flow rate of water in the MARCH primary system model is calculated in subroutine EFCRIT using the RETRAN[21] polynomial fit to the extended Henry-Fauske model for subcooled water. The model also predicts flow rates within the scatter band of other correlations for saturated water. Thus, the Henry-Fauske model is used for both saturated and subcooled liquid blowdown.

The RETRAN polynomial curve fit to the Henry-Fauske correlation is:

$$G = 60 \sum_{\substack{I=1-6 \\ J=1-6}} HK_{I,J} \, p^{J-1} \, H^{I-1} \quad , \text{lb/min/ft}^2 \quad , \qquad \text{(E7.21)}$$

where

P = vessel pressure, psia

H = water enthalpy, Btu/lb, and

$HK_{I,J}$ = correlation constants.

The correlation constants are given in Table IV.3-2 of the RETRAN manual and are not repeated here. The correlation applies to short pipes and does not account for friction or long-pipe effects. The RETRAN correlation is limited to vessel pressures between 15 and 3000 psia. For pressures below 15 psia, MARCH uses the predicted flow rate at 15 psia. For pressures above 3000 psia, MARCH multiplies the RETRAN-polynomial flow rate at 3000 psia by $\sqrt{P/3000}$.

For saturated water, the RETRAN polynomial predicts about the same blowdown rate as the correlation in MARCH 1.1[1a]. However, for water which is subcooled by, for example, 200 Btu/lb, the blowdown rate will be two to three times greater than that for MARCH 1.1. Water enthalpies are obtained from subroutine PROPS evaluated at the water temperature.

7.4.2 Critical Flow of Gases

Critical flow of gases is modeled in both the MARCH containment and primary system models. In the containment models, the leak rate of gases between compartments (for IVENT ≠ 0) and the leak rate after containment failure may be limited by critical flow. In the primary system models, the leak rate of steam and hydrogen through breaks and relief valves may be limited by critical flow.

Critical flow of saturated steam in the primary system model (subroutine PRIMP) is calculated using the Moody correlation.[72] The Moody correlation is contained in subroutine CR1 in the form of 28 table entries between pressures of 50 and 3000 psia. Data tables entries are made for values of the friction factor (f L/D) = 0, 5, and 10. Flow rates are calculated by linear interpolation between the data entries. For pressures below 50 psia, the flow is calculated by extrapolation, using the data entries at 50 and 100 psia. For pressures above 3000 psia, ideal gas behavior is assumed and the leak rate at 3000 psia is multiplied by P/3000.

For a mixture of steam and hydrogen or for superheated gases, the critical flow used in PRIMP is:

$$G = C_F \sqrt{\rho/\rho_s}, \quad \text{lb/min/ft}^2 \quad , \qquad \text{(E7.22)}$$

where

ρ = gas mixture density, lb/ft^3

ρ_S = saturated steam density, lb/ft^3

C_F = saturated steam critical flow rate from Moody tables, lb/min ft^2.

The Moody critical flow rate for saturated steam for f L/D = 0 can be represented approximately by the relation:

$$G_C = 2800 \sqrt{P\rho_s}, \quad \text{lb/min/ft}^2 \qquad \text{(E7.23)}$$

The MARCH 1.1 steam critical flow rate is (1b, 67)

$$G_C = 1642 \sqrt{P\rho_s} \quad , \quad \text{lb/min/ft}^2 \qquad \text{(E7.24)}$$

It is seen by comparing Equations (E7.23) and (E7.24) that the Moody critical flow rate is 70 percent greater than the MARCH 1.1 flow rate. The flow rate in Equation (E7.24) corresponds approximately to the Moody table entries for a friction factor of f L/D ~3.4. A friction factor of 3.4 implies flow through either a long pipe or a path containing significant turning losses.

Equation (E7.24) has been retained for the calculation of critical gas flow rates in the containment models in MARCH 2. Based on comparison with the Moody data, containment leak rates may be underestimated, depending on the nature of the leak path.

7.5 Fission Product Decay Heat

7.5.1 ANS Standard Decay Heat

The fission product decay heat is calculated in subroutine ANSQ using the 1979 ANS-5.1 standard[15]. The core power may also be supplied by an optional input decay heat table (IDECAY > 0) or by an input constant (KRPSXX > 0) in namelist NLBOIL.

The decay heat power fraction is:

$$\text{ANS} = \frac{1}{Q_1} \quad 1.02 \quad F_1(t,\infty) - F_1(t+T,\infty) \quad G_{max}(t) \qquad \text{(E7.25)}$$

$$+ F_{U239}(t,T) + F_{NP239}(t,T) \quad ,$$

where

t = time after shutdown, cooling time, s

T = total operating time, s

TABLE 7.1 PARAMETERS FOR U235 THERMAL FISSION FUNCTION $F_1(t,T)$

i	α_i (sec^{-1})	β_i (MeV/fission sec)
1	6.5057E-01	2.2138E+01
2	5.1264E-01	5.1587E-01
3	2.4384E-01	1.9594E-01
4	1.3850E-01	1.0314E-01
5	5.5440E-02	3.3656E-02
6	2.2225E-02	1.1681E-02
7	3.3088E-03	3.5870E-03
8	9.3015E-04	1.3930E-03
9	8.0943E-04	6.2630E-04
10	1.9567E-04	1.8906E-04
11	3.2535E-05	5.4988E-05
12	7.5595E-06	2.0958E-05
13	2.5232E-06	1.0010E-05
14	4.9948E-07	2.5438E-06
15	1.8531E-07	6.6361E-07
16	2.6608E-08	1.2290E-07
17	2.2398E-09	2.7213E-08
18	8.1641E-12	4.3714E-09
19	8.7797E-11	7.5780E-10
20	2.5131E-14	2.4786E-10
21	3.2176E-16	2.2384E-13
22	4.5038E-17	2.4600E-14
23	7.4791E-17	1.5699E-14

Q_1 = total recoverable energy associated with one fission of U^{235}, (input Q235U, default is 200 MeV/fission)

$$F_1(t,T) = \sum_{i-1}^{23} \frac{\alpha_i}{\lambda_i} \exp(-\lambda_i T) \quad 1 - \exp(-\lambda_i T) \qquad \text{(E7.26)}$$

= fission product decay power t seconds after operating at a constant rate of one U^{235} fission per second for T seconds in the absence of neutron capture in fission products, (MeV/s)/(fission/s)

α_i = constant from Table 7.1, MeV/fission/sec

λ_i = constant from Table 7.1, sec^{-1}

$G_{max}(t)$ = correction factor which accounts for neutron capture in fission products, Table 7.2

$$F_{U239}(t,T) = E_{U239}\, R\, (1 - \exp(-\lambda_1 T))\, \exp(-\lambda_1 t) \qquad \text{(E7.27)}$$

= U^{239} decay power t seconds after operating at a constant rate of one U^{235} fission per second for T seconds, (MeV/s)/(fission/s)

$$F_{NP239}(t,T) = E_{NP239} R \quad \frac{\lambda_1 (1 - \exp(-\lambda_2 T))\, \exp(-\lambda_2 t)}{\lambda \; -_1 \lambda \quad _2} - \frac{\lambda_2 (1 - \exp(-\lambda_1 T))\, \exp(-\lambda_1 t)}{\lambda_1 - \lambda_2} \qquad \text{(E7.28)}$$

= Np239 decay power t seconds after operating at a constant rate of one U^{235} fission per second for T seconds, (MeV/s)/(fission/s)

E_{U239} = average energy from the decay of one U^{239} atom, 0.474 MeV

E_{NP239} = average energy from the decay of one Np^{239} atom, 0.419 MeV

R = atoms of U^{239} produced per U^{235} fission evaluated for the reactor composition at the time of shutdown, dimensionless, (input R239U, default is 0.8)

λ_1 = decay constant for U^{239}, 4.91E x 10^{-4} s^{-1}

λ_2 = decay constant for Np^{239}, 3.41 x 10^{-6} s^{-1}.

March 1.1 used the 1971 ANS standard[68] to calculate the decay heat, neglecting heavy element decay. Equation (E7.25) from the 1979 standard predicts an integrated decay heat over the first hour after shutdown about 20 percent greater than that in MARCH 1.1.

7.5.2 Fuel Meltdown Fission Product Release

During core meltdown, fission products are released from the fuel. The release of fission products reduces the decay heat source for the core. The released fission products may, in general, be deposited on cooler primary system surfaces, retained by water remaining in the primary system, or be released to the containment atmosphere. MARCH accounts for fission product scrubbing by suppression pools and ice beds using input decontamination factors. However, in general, MARCH does not perform a fission product removal evaluation; it treats the transport of the released fission products in an approximate fashion as a means of tracking the redistribution of the fission product decay heat source. Fission products released upon the initial melting of the core are released to the primary system gas (vapor) space and are assumed to behave as perfect gases. The release of the fission products from the primary system is taken to be proportional to the gas flows from the primary system. The decay heat associated with the released volatiles may be absorbed by primary system structures. Additional fission products are lost from the melt during the concrete interaction phase of the accident due to scrubbing by gases released from the concrete. These releases are known as vaporization releases.

Subroutine FPLOSS calculates the loss of volatile fission products from the melted fuel including vaporization releases from the core-concrete interaction. Note that FPLOSS merely partitions the decay heat between that retained in the debris and that released. The absolute value of the decay heat is calculated in subroutine ANSQ.

TABLE 7.2 $G_{max}(t)$, RATIO OF DECAY HEAT WITH ABSORPTION TO VALUES WITHOUT ABSORPTION

Time After Shutdown (sec)	$G_{max}(t)$	Time After Shutdown (sec)	$G_{max}(t)$
1.0	1.020	1.5E+5	1.130
1.5	1.020	2.0E+5	1.131
2.0	1.020	4.0E+5	1.126
4.0	1.021	6.0E+5	1.124
6.0	1.022	8.0E+5	1.123
8.0	1.022	1.0E+6	1.124
1.0E+1	1.002	1.5E+6	1.125
1.5E+1	1.022	2.0E+6	1.127
2.0E+1	1.022	4.0E+6	1.134
4.0E+1	1.022	6.0E+6	1.146
6.0E+1	1.022	8.0E+6	1.162
8.0E+1	1.022	1.0E+7	1.181
1.0E+2	1.023	1.5E+7	1.233
1.5E+2	1.024	2.0E+7	1.284
2.0E+2	1.025	4.0E+7	1.444
4.0E+2	1.028	6.0E+7	1.535
6.0E+2	1.030	8.0E+7	1.586
8.0E+2	1.032	1.0E+8	1.598
1.0E+3	1.033	1.5E+8	1.498
1.5E+3	1.037	2.0E+8	1.343
2.0E+3	1.039	4.0E+8	1.065
4.0E+3	1.048	6.0E+8	1.021
6.0E+3	1.054	8.0E+8	1.012
8.0E+3	1.060	1.0E+9	1.007
1.0E+4	1.064		
1.5E+4	1.074		
2.0E+4	1.081		
4.0E+4	1.098		
6.0E+4	1.111		
8.0E+4	1.119		
1.0E+5	1.124		

FPLOSS assumes that the fission products are initially distributed throughout the core with the same distribution as the power peaking factors and noding specified as input to subroutine BOIL. The fission products are divided into seven groups, represented by Xenon, Iodine, Cesium, Tellurium, Strontium, Ruthenium and Lanthanum. Each of these groups is further subdivided into metal (FMET) and oxide (FOX) phases. The total fractional releases during the core meltdown (RF) may be selected by one of three data sets. These data sets are internally-coded and correspond to small, best-estimate and large melt releases. The best-estimate values are the WASH-1400[2] values. The desired data-set is chosen by setting IFPSM in Namelist NLMAR. Values for IFPSM of 1, 2 and 3 correspond to small, best-estimate, and large melt-releases, respectively. Tables (7.3) to (7.5) give the melt-release fractions available. The melt release estimates given in Tables (7.3) to (7.5) include the WASH-1400 gap releases of fission products which have been released from the fuel pellets during normal operation, and which occupy the free volume of fuel pins.

Fission Product Loss During Meltdown

The release of fission products from a node is assumed proportional to the fraction of the node melted. The fractional release of a node (I, R) for a given fission product group J is therefore given as,

$$DRF(I,R) = FF(I) \times PF(R) \times \frac{VF(R)}{NDZ} \times RF(J) \times FNM(I,R) \quad . \qquad \text{(E7.29)}$$

Where RF(J) is the total melt-release fraction for the fission product group J, and FNM(I,R) is the fraction of the node melted.

To obtain the total fraction of group J fission products released from the core, CRF(J), Equation (E7.29) is summed over all nodes i.e.,

$$CRF(J) = \sum_{R=R1}^{R2} \sum_{I=1}^{NDZ} FF(I) \times PF(R) \times \frac{VF(R)}{NDZ} \times RF(J) \times FNM(I,R) \quad . \qquad \text{(E7.30)}$$

TABLE 7.3 SMALL ESTIMATE FISSION PRODUCT MELT-RELEASES (IFPSM = 1)

J	Group	Melt-Release (RF)
1,	Xe	RF(1) = 0.51
2,	I	RF(2) = 0.501
3,	Cs	RF(3) = 0.404
4,	Te	RF(4) = 0.05
5,	Sr	RF(5) = 0.02
6,	Ru	RF(6) = 0.01
7,	La	RF(7) = 0.0001

TABLE 7.4 BEST-EFFORT ESTIMATES FISSION PRODUCT MELT-RELEASE (IFPSM = 2)

J	Group	Melt-Release (RF)
1,	Xe	RF(1) = 0.9
2,	I	RF(2) = 0.9
3,	Cs	RF(3) = 0.31
4,	Te	RF(4) = 0.1501
5,	Sr	RF(5) = 0.1
6,	Ru	RF(6) = 0.03
7,	La	RF(7) = 0.003

TABLE 7.5 LARGE ESTIMATE FISSION PRODUCT MELT-RELEASES (IFPSM = 3)

J	Group	Melt-Release (RF)
1,	Xe	RF(1) = 1.0
2,	I	RF(2) = 1.0
3,	Cs	RF(3) = 1.0
4,	Te	RF(4) = 0.29
5,	Sr	RF(5) = 0.2004
6,	Ru	RF(6) = 0.1
7,	La	RF(7) = 0.01

TABLE 7.6 PERCENTAGE FISSION PRODUCT DECAY HEATS

J	Group	Percentage of Total Decay Heat Q(J,1) 10^2sec	Q(J,2) 10^4sec	Q(J,3) 10^6sec
1,	Xe	5.5	4.3	0.85
2,	I	9.3	16.0	4.3
3,	Cs	9.9	3.3	5.7
4,	Te	6.1	2.9	0.93
5,	Sr	7.2	8.9	16.5
6,	Ru	16.3	58.0	65.0

The fraction of decay heat in each fission product group before accounting for losses is,

$$QF = Ce^{-\lambda t} \qquad \text{(E7.31)}$$

Where t is time in seconds, C(J) is a normalized constant of proportionality and $\lambda(J)$ is obtained by interpolation of data given in Table 7.6. This data specifies, at three different decay times, the percentage decay heat associated with each fission product group. The percentage decay heat is called Q(J,K), with K = 1, 2 or 3 corresponding to 10^2, 10^4 and 10^6 seconds respectively. For decay times less than 10^4 seconds, $\lambda(J)$ is calculated using,

$$\lambda(J) = \frac{\text{Log}_e \frac{Q(J,1)}{Q(J,2)}}{10^4 - 10^2} \qquad \text{(E7.32)}$$

and for decay times greater than 10^4 seconds as,

$$\lambda(J) = \frac{\text{Log}_e \frac{Q(J,2)}{Q(J,3)}}{10^6 - 10^4} \qquad \text{(E7.33)}$$

The decay heat lost, due to the release of fission products from a node, for group J fission products is,

$$DFPL(I,R) = QF(J) \times DRF(I,R) \qquad \text{(E7.34)}$$

Where DRF(I,R) is the fractional release of fission products from a node, as given in Equation (E7.29).

The fraction of fission product decay heat, of a given group, left with the node is therefore (1 - DFPL). The total fraction of fission product decay heat left with the core is therefore,

$$TFPL=1 - \sum_{J=1}^{7} \sum_{R=R1}^{R2} \sum_{1=1}^{NDZ} QF(J)xFF(I)xPF(R)x \qquad \text{(E7.35)}$$

$$\frac{VF(R)}{NDZ}xRF(J)xFNM(I,R)$$

$$\text{Since} \sum_{R=R1}^{R2} \sum_{I=1}^{NDZ} FF(I) \times PF(R) \times \frac{VF(R)}{NDZ} = 1,$$

Equation (E7.35) may be written as

$$TFPL = \sum_{R=R1}^{R2} \sum_{I=1}^{NDZ} FF(I) \times PF(R) \times \frac{VF(R)}{NDZ} \left[1 - \sum_{J=1}^{7} QF(J) \times RF(J) \times FNM(I,R) \right] . \qquad \text{(E7.36)}$$

It is this expression for the fraction of fission product decay heat remaining in the core which is coded in FPLOSS.

After vessel failure and MARCH has transferred control from BOIL to HOTDRP, the release of fission products and the associated decay heat is calculated, using Equations (E7.30) and (E7.36) given above, by considering the core debris as a single node. In these equations the radial and axial power peaking factors are set to unity, and the debris temperature is used as the node temperature.

When MARCH progresses to the core-concrete interaction phase of the accident which is modeled in Subroutine INTER, the loss of fission products is calculated somewhat differently. The model coded into FPLOSS includes vaporization releases due to the scrubbing by gases released from the concrete. The fractional vaporization releases, RFV, are included in FPLOSS in a similar manner to the fractional melt releases, RF, i.e. the values used may be selected as one of three data-sets. Like the melt release estimates these data-sets represent small, best-estimate (WASH-1400), and large estimate vaporization releases. The required data-set is selected according to the value specified for IFPSV in Namelist NLMAR. Tables (7.7) to (7.9) detail the three available data-sets. It should be noted that Table 7.8 implies that the best-estimate vaporization release estimates <u>should not</u> be used in conjunction with the large melt release estimates since this would clearly lead to total fractional releases of greater than one, which is not physically possible.

The vaporization model assumes an exponential release with time constants TAUOX and TAUM for the oxide and metallic debris layers

respectively. TAUOX and TAUM are set equal in INTER unless one layer is solid and the other liquid. Solid and liquid time constants are usersupplied in Namelist NLINTR as TAUS and TAUL respectively. The fractional vaporization release per group is

$$DRFV(J) = 0.693 \times DT \times (RF(J)+RFV(J)-CRF(J)) \left(\frac{FOX(J)}{TAUOX} + \frac{FMET(J)}{TAUM} \right) . \quad \text{(E7.37)}$$

Where DT is the timestep in hours, FMET(J) = 1 - FOX(J), and FOX(J) is the fraction of group J which is oxide. The values of FOX(J) used by FPLOSS are given in Table 7.10.

The total fractional fission product loss per group, CRF(J), is therefore calculated as,

$$CRF(J) = CRF'(J) + DRFV(J) \quad , \quad \text{(E7.38)}$$

where CRF'(J) is the total fractional melt release as calculated in Equation (E7.30). This total fractional fission product release is subject to the condition that CRF(J) cannot be greater than the sum of the melt and vaporization releases.

The total fraction of fission product decay heat remaining with the debris is simply,

$$TFPL = \sum_{J=1}^{7} (1 - CRF(J)) \times QF(J) \quad . \quad \text{(E7.39)}$$

Similarly, the total fraction of decay heat remaining with the oxide debris, SOX, is calculated as,

$$SOX = \sum_{J=1}^{7} (1 - CRF(J)) \times QF(J) \times FOX(J) \; . \quad \text{(E7.40)}$$

For the fraction of decay heat remaining in the metallic debris, SMET, the code uses the following,

$$SMET = TFPL - SOX \quad . \quad \text{(E7.41)}$$

TABLE 7.7 SMALL ESTIMATE FISSION PRODUCT VAPORIZATION RELEASES (IFPSV = 1)

J	Group	Vaporization-Release (RFV)
1,	Xe	RFV(1) = 1-RF(1)
2,	I	RFV(2) = 1-RF(2)
3,	Cs	RFV(3) = 1-RF(3)
4,	Te	RFV(4) = 1-RF(4)
5,	Sr	RFV(5) = 0.002
6,	Ru	RFV(6) = 0.01
7,	La	RFV(7) = 0.002

TABLE 7.8 BEST ESTIMATE FISSION PRODUCT VAPORIZATION RELEASES (IFPSV = 2)

J	Group	Vaporization-Release (RFV)
1,	Xe	RFV(1) = 0.1
2,	I	RFV(2) = 0.1
3,	Cs	RFV(3) = 0.19
4,	Te	RFV(4) = 0.85
5,	Sr	RFV(5) = 0.01
6,	Ru	RFV(6) = 0.05
7,	La	RFV(7) = 0.01

TABLE 7.9 LARGE ESTIMATE FISSION PRODUCT VAPORIZATION RELEASES (IFPSV = 3)

J	Group	Vaporization-Release (RFV)
1,	Xe	RFV(1) = 1-RF(1)
2,	I	RFV(2) = 1-RF(2)
3,	Cs	RFV(3) = 1-RF(3)
4,	Te	RFV(4) = 1-RF(4)
5,	Sr	RFV(5) = 0.04
6,	Ru	RFV(6) = 0.225
7,	La	RFV(7) = 0.05

TABLE 7.10 FRACTION OF RELEASE WHICH IS OXIDE

J	Group	Vaporization-Release (RFV)
1,	Xe	FOX(1) = 0.5
2,	I	FOX(2) = 0.5
3,	Cs	FOX(3) = 0.5
4,	Te	(a)
5,	Sr	FOX(5) = 1.0
6,	Ru	FOX(6) = 0.0
7,	La	(b)

(a) FOX(4) = Fraction of Fuel Cladding Which has reacted (FZR)

(b) FOX(7) = 0.87 + 0.13 x FZR

The condensable gas fraction, CGF, is the fraction of released fission product decay heat produced by fission products that are condensable. FPLOSS assumes that the xenon group fission products are not condensable but all other groups are, thus

$$CGF = 1 - \frac{CRF(1) \times QF(1)}{1 - TFPL} \qquad (E7.42)$$

$$= 1 - \frac{(\text{Xenon decay heat lost})}{(\text{Total decay heat lost})}$$

7.5.3 Storage and Transport of Released Volatiles

Volatile fission products released from the core during meltdown are assumed to be stored in the primary system gas space. The storage and release calculation tracks only the decay heat associated with the volatile fission products. The concentrations of individual species are not monitored, and plate-out is not modeled. However, the decay heat of the stored volatiles is added to the structures in the primary system gas space while the volatiles remain in the vessel.

The heat-up of the primary system structures is calculated by Subroutine FPQSTR and the storage and leakage of fission product decay heat from the primary system is calculated by Subroutine FPLK.

The fractions of the decay heat leaked from the primary system to containment volumes NRPV and JRPV during timestep Δt are:

$$FP_{LKN} = FP_{VSL}\, F_N, \text{ and} \qquad (E7.43)$$

$$FP_{LKJ} = FP_{VSL}\, F_J \quad , \qquad (E7.44)$$

where

FP_{VSL} = fraction of decay heat stored in the primary system gas space,

$$F_N = \frac{WS_{BK}\, \Delta t}{STM} \quad , \qquad (E7.45)$$

$$F_J = \frac{WS_{RV}\ \Delta t}{STM} \quad , \qquad \text{(E7.46)}$$

WS_{BK}, WS_{RV} = break and relief valve steam leakage, lb/min, and
STM = mass of steam in primary, lb.

Note that it is assumed water leakage does not produce fission product leakage.

Fission product decay heat transport within the containment building is also assumed to follow the transport of the containment gases. Containment plate-out is not modeled in MARCH. However, ice beds and suppression pools are assumed to remove fission products, other than the noble gases, from the atmosphere, and the removed decay heat is added to the containment sump. The removal is calculated using a user supplied decontamination factor. Fission product decay heat removal by sprays is not modeled. The decay heat of the airborne fission products is added to the containment atmosphere.

7.6 Thermal Properties Data

Thermal properties data are discussed in this part of Section 7. MARCH properties correlations are not contained in a single subroutine devoted to properties. Frequently, MARCH subroutines contain their own coding of the specific properties needed. Data sources are not always consistent and the functional forms may not be identical. Although consistency would be desirable, lack of consistency is not believed to be a significant source of error. Primary system and HOTDRP water and gas properties are given in the first part of this section and containment code water and gas properties in the second part. Subroutines PROP, SPHERE, and DBED contain additional property data, most of which is used locally for calculations of heat transfer coefficients. Section 7.6.1.6 contains a list of recommended input properties for core and structure materials.

7.6.1 BOIL and HOTDRP Properties

The primary system and HOTDRP generally contain consistent properties for the water saturation properties: pressure, temperature, and water and steam density. Specific heats, enthalpies, viscosities, thermal conductivities, and surface tension may differ in the various subroutines.

7.6.1.1 Subroutine PROPS

PROPS provides water and steam properties on the saturation line using the 1967 ASME data tables[69]. PROPS provides pressure, temperature, water and vapor density and enthalpy, and water specific heat. The properties are calculated by interpolation between 33 sets of ASME data between 0.0887 and 3208.2 psia. Both linear and logarithmic interpolations are utilized, depending on the property. The water specific heat is obtained from the slope of the enthalpy-temperature curve, rather than from direct use of specific heat data, for improved accuracy in the primary system water energy balance. PROPS may be called by specifying either the saturation pressure, temperature, or steam density.

PROPS data are always used in the primary system pressure calculations and mass and energy balances. PROPS also provides saturation temperature, densities, and enthalpies to HOTDRP and other subroutines.

7.6.1.2 Subroutine PROP

Subroutine PROP provides properties data for the gas heat transfer coefficient calculations if input ICONV = 1, the gaseous diffusion rate parameters in ZRWATR, and thermal conductivity data for use in subroutine AXCOND. The PROP data are obtained by specifying a property flag and the pressure and temperatures. The flags and properties are listed in Table 7.11.

7.6.1.3 Gas Enthalpy and Specific Heat

In the primary system models (BOIL and EXITQ), the steam (h_S) and hydrogen (h_H) enthalpies at temperature T are:

$$h_s(T) = h_{SAT} + \int_{T=T_{SAT}}^{T} C_{ps}\, dT \quad , \text{Btu/lb} \quad , \tag{E7.47}$$

$$h_H(T) = \int_{t=32}^{T} C_{pH}\, dT \quad , \text{Btu/lb} \quad , \tag{E7.48}$$

where

$$C_{ps} = 0.43 + 8 \times 10^{-5}\, T, \quad \text{Btu/lb/F} \tag{E7.49}$$

$$\begin{aligned} C_{pH} &= 3.4 + 1.1 \times 10^{-4}\, T, \; T < 1000 \text{ F}, \text{ Btu/lb/F} \quad , \\ &= 3.26 + 2.48 \times 10^{-4}\, T, \; T > 1000 \text{ F}, \text{ Btu/lb/F} \end{aligned} \tag{E7.50}$$

T_{SAT} = saturation temperature corresponding to the system water temperature, F

h_{SAT} = saturated steam enthalpy, Btu/lb.

TABLE 7.11. PROP DATA

Flag	Data
1	none
2	none
3	water density, lb/ft^3
4	none
5	hydrogen specific heat, Btu/lb/F
6	hydrogen thermal conductivity, Btu/hr ft/F
7	hydrogen viscosity*
8	steam specific heat, Btu/lb/F
9	steam thermal conductivity, Btu/hr/ft/F
10	steam viscosity*
11	UO_2 thermal conductivity, Btu/hr/ft/F
12	Zr thermal conductivity, Btu/hr/ft

*32.2 x 3600 x VIS has units of lb/hr/ft, where VIS is calculated in PROP.

The primary system reference temperature of 32 F is consistent with that in the containment.

The specific heats given by Equations (E7.49) and (E7.50) are always used in the primary system gas enthalpy calculations. However, if input ICONV = 1, the specific heats used elsewhere in BOIL will be obtained from subroutine PROP. If ICONV > 1 and in the BWR core model (IBWR = 1), specific heat properties are obtained from STMH2P in BOIL; and if ICONV > 10, STMH2P properties are also used in EXITQ. Equations (E7.49) and (E7.50) are used in EXITQ (ICONV < 10) and in HOTDRP.

7.6.1.4 Subroutine STMH2P

Subroutine STMH2P and its associated subroutines calculate steam and hydrogen properties for use in BOIL (for input ICONV > 1 and in the BWR core model) and in EXITQ (for input ICONV > 10). STMH2P uses the same IFC equations which were used to generate the ASME tables. Steam properties are obtained from the 1967 IFC formulation for temperatures below 1500 F. For steam temperatures above 1500 F and for hydrogen, properties are taken from Vargaftik.[70] Ott[22] has compared the steam specific heat obtained from STMH2P, PROP, and from MARCH 1.1 (Equations E7.49 and E7.50) with the ASME values. His calculations indicate the PROP values are accurate for gas temperatures about 200 F above the saturation temperature, while the MARCH 1.1 correlation is accurate only at low pressures. At 1500 psia and a gas temperature below 800 F, the MARCH 1.1 steam specific heat is about 40 percent too small. The computational time for the use of STMH2P, PROP, and MARCH 1.1 gas properties are in the ratio 2.0/1.5/1.0.

In subroutine HOTDRP, the enthalpy calculation takes the specific heats outside the integral so that:

$$h_s(T) = h_{SAT} + C_{ps}(T - T_{SAT}) \quad , \text{ Btu/lb} \quad , \qquad \text{(E7.51)}$$

$$h_H(T) = C_{pH}(T - 32) \quad , \text{ Btu/lb} \quad , \qquad \text{(E7.52)}$$

where C_{ps} and C_{pH} are given by Equations (E7.49) and (E7.50) evaluated at the temperature T.

For a mixture of steam and gas, the mixture enthalpies and specific heats are obtained by summing the mass-fraction-weighted components.

7.6.1.5 Debris Beds

Subroutines SPHERE and DBED contain their own property correlations for vapor and liquid thermal conductivities, specific heats, viscosities, and surface tension. The correlations are used locally and are not repeated here. Subroutine PROPS is called to determine the saturation temperature, densities, and enthalpies.

7.6.1.6 Core and Structure Properties (Input)

Subroutine BOIL, HEAD, and HOTDRP is some cases contain hard-coded values for the densities and heat capacities of core and structural materials. However, some of these same parameters are required as input. For consistency, the input and hard-coded values should be in agreement. With the exception of subroutine INTER, MARCH generally assumes temperature independent densities and heat capacities for core debris materials. A reasonable choice of constant heat capacity for a core material is one which gives the correct enthalpy change over a temperature range of interest. Table 7.12 lists core debris material properties either hard-coded or recommended for use in preparation of BOIL, HEAD, and HOTDRP input.

7.6.2 Containment Model Properties

The gas and vapor properties used in the various containment subroutines are self-consistent. However, the property data correlations and functions differ from those in the other parts of MARCH. They may also have a smaller range of validity, for example, between 40 and 400 F for water saturation properties.

TABLE 7.12 CORE DEBRIS PROPERTIES

Material	Density, lb/ft^3	Heat Capacity,[30] Btu/lb/F	Heat Capacity, Btu/ft/F	Heat of Fusion,[30] Btu/lb*
Zircaloy	401.9	0.09**	36.17	97
Iron/Steel	490.5	0.12	58.86	118
UO_2	626.7	0.10**	62.67	121

*Subroutine HEAD uses a constant heat of fusion for all materials of 118 Btu/lb.

**Average value for temperature changes from 500 F to the melting point.

7.6.2.1 Gas Enthalpy

The enthalpy at a temperature T of gases of other than steam is given by:

$$h_A = C_{pA} (T - 32) \quad , \text{Btu/lb} \quad , \tag{E7.53}$$

where the gas specific heat, C_{pA}, is given in Table 7.13. (Note: MACE uses the notation CVNTR, CVOXY, etc. for the constant pressure specific heat.)

The steam enthalpy is calculated in subroutine TEMP as

$$h_v = \text{GENT}(T_{sat}) \text{ for } T = T_{sat} \tag{E7.54}$$

$$h_v = (0.50662\ T + 1440.15)/1.3486 \text{ for}$$

$$T > T_{sat}, \text{ Btu/lb} . \tag{E7.55}$$

TABLE 7.13 GAS SPECIFIC HEATS IN MACE*

Gas	Specific Heat, Btu/lb/F
Nitrogen	0.245
Oxygen	0.218
Hydrogen	3.41
Carbon Dioxide	0.203
Carbon Monoxide	0.246

*Reference 36, STP conditions.

The saturation steam enthalpy is given by the function GENT (Equation E7.65). Equation (E7.55) for superheated steam was derived from two equations of state:

$$PV = A_1 h_v + B_1 \qquad \text{(E7.56)}$$

$$PV = A_2 T + B_2 \quad , \qquad \text{(E7.57)}$$

where

$A_1 = 1.34863$
$B_1 = 1157.716$
$A_2 = 0.50662$
$B_2 = 282.4364$
V = steam specific volume, ft^3/lb
P = steam pressure, psia.

The constants A_1, B_1, A_2, and B_2 were obtained by a least-mean-squares curve fit to steam properties[43] on the saturation line.

7.6.2.2 Water Enthalpy

The water enthalpy in the MACE atmosphere energy balance routines is given by

$$h_L = \text{FENT}(T), \text{ Btu/lb} \quad , \tag{E7.58}$$

where the function FENT is the water saturation enthalpy at temperature T. FENT is given by Equation (E7.54).

The enthalpy of water in sumps is generally given by:

$$h_L = C_{pw} (T - 32), \text{ Btu/lb} \quad , \tag{E7.59}$$

where

C_{pw} = 1.0 Btu/lb/F
T = water temperature.

For temperatures below 300 F (P_{sat} = 67 psia) the error in Equation (E7.59) is less than 0.6 percent, and at 400 F (247 psia) the enthalpy error is about 1.8 percent. Since containment pressures are usually less than 250 psia, Equation (E7.59) is normally a good approximation.

7.6.2.3 Functions

The containment routines use several polynomial functions for water and vapor properties on the saturation line. The functions were obtained by fitting the data in steam tables[43] by use of regression analysis. Their range of validity is between 40 F and 400 F. These functions are:

$$\log(\text{TSAT}) = 6.11067 - 0.180564\ V - 0.0292964\ V^2 + 0.00629137\ V^3 - 0.59749 \times 10^{-3}\ V^4 \tag{E7.60}$$

$$\log(\text{PRSS}) = 27.7630 + 23.7433\ X - 8.69638\ X^2 + 1.41067\ X^3 - 0.0777638\ X^4 \tag{E7.61}$$

$$FVOL = 0.0903737 - 0.0694378\ X + 0.0242644\ X^2 - 0.00376979\ X^3 + 0.000220413\ X^4 \quad \text{(E7.62)}$$

$$\log(GVOL) = 25.9245 - 16.8828\ X + 6.35612\ X^2 - 1.006006\ X^3 + 0.0587298\ X^4 \quad \text{(E7.63)}$$

$$FENT = 2068.48 - 2011.26\ X + 726.624\ X^2 - 117.646\ X^3 + 7.43066\ X^4 \quad \text{(E7.64)}$$

$$GENT = 1043.94 + 1910.76\ X - 640.327\ X^2 + 93.7205\ X^3 - 4.94574\ X^4 \ , \quad \text{(E7.65)}$$

where

V = log(VC/WS)
X = log(T)
VC/WS = vapor specific volume, ft^3/lb
T = saturation temperature, F
TSAT(VC/WS) = saturation temperature, F
PRSS(T) = saturation pressure, psia
FVOL(T) = water specific volume, ft^3/lb
GVOL(T) = vapor specific volume, ft^3/lb
FENT(T) = water enthalpy, Btu/lb
GENT(T) = vapor enthalpy, Btu/lb.

7.6.2.4 INTER Properties

INTER contains its own gas enthalpy functions. These enthalpies are used as generated by INTER except for a correction, which zeros the enthalpies at the MACE reference point of 32 F, rather than at absolute zero before transfer to MACE.

The boiling point of water in INTER is coded as:

$$T_{vw} = 373 + 12.31\ (P_{ATM} - 1) \quad . \quad \text{(E7.66)}$$

At a pressure of P_{ATM} = 10 atm (147 psia), Equation (E7.66) overpredicts the boiling point by about 50 F. This inconsistency in the INTER and MACE boiling points could potentially produce oscillations in the boiling of water over the core debris in INTER. In order to remove this oscillation, the INTER sump boiling point is set equal to the MACE boiling point. For all other uses of T_{vw} in INTER the Equation (E7.66) value is retained.

8.0 MASS AND ENERGY BALANCE AUDIT

BOIL and MACE contain time-integrated energy balance audits. BOIL contains a mass balance audit similar to the energy audit. MACE contains mass inventory summaries at each printout, but does not contain a time-integrated mass balance audit. The audit calculations are performed independently of the normal BOIL and MACE calculations. Thus, the integral mass and energy balance audits parallel the normal BOIL and MACE calculations but have no feedback to the system response.

8.1 BOIL Energy Balance Audit

In the BOIL energy balance audit, all of the energy input to the primary system is summed over time and compared with the change in stored energy since the beginning of the calculation. In order to provide meaningful reference points, the energy imbalance or error is expressed in the output as percent of the integrated core decay, the stored energy in the core, and the energy leaked from the system.

Energy input to the primary system includes that from (1) the core decay heat, (2) metal-water reaction, (3) ECC injection, (4) primary system leakage, and (5) energy from pumps. Energy is stored (1) in the water, (2) in the gas (steam and hydrogen), (3) in the core, and (4) in other structures in the primary system.

The decay heat energy (E_{DK}) added to the primary system is:

$$E_{DK} = E_{DK} + Q_{DK} (f_C + f_G) dt/60 \quad , \quad B^{\prime} \qquad \text{(E8.1)}$$

where

dt = BOIL timestep, min

Q_{DK} = core decay heat, Btu/hr

f_C = fraction of decay heat retained in the core

f_G = fraction of decay heat in the gas space.

The energy, E_{MW}, from metal-steam reaction is:

$$E_{MW} = E_{MW} + \Delta H_{zr}\, f_{zr}\, W_{zr} + \Delta H_{Fe}\, f_{Fe}\, W_{ss},\ \text{Btu}\ , \quad \text{(E8.2)}$$

where

ΔH_{zr} = zirconium reaction energy = 2739.2 Btu/lb zirconium
f_{zr} = fraction of zirconium reacted
W_{zr} = calculated mass of cladding and channel box zirconium in the core, lb
ΔH_{Fe} = iron reaction energy = 457.2 Btu/lb Fe
f_{Fe} = fraction blade reacted
W_{ss} = mass of steel sheath on control blades, lb.

Energy, E_{in}, added to the primary system by water additions is:

$$E_{in} = E_{in} + (W_{ECC} + W_{MUP})\ dt\ h_{ECC}\ ,\ \text{Btu}\quad , \quad \text{(E8.3)}$$

where

W_{ECC} = ECC injection rate, lb/min
W_{MUP} = makeup pump flow rate, lb/min
h_{ECC} = enthalpy of injection water, Btu/lb.

The energy, E_{LK}, leaked from the primary system is:

$$E_{LK} = E_{LK} - (W_{LK}\, h_L + W_{SLK}\, h_S + W_{HLK}\, h_H)\ dt,\ \text{Btu}, \quad \text{(E8.4)}$$

where

$W_{LK} = W_{LBK} + W_{LRV} + W_{MUP}$
$W_{SLK} = W_{SBK} + W_{SRV}$
$W_{HLK} = W_{HBK} + W_{HRV}$
W_{LBK} = liquid flow out break, lb/min
W_{LRV} = liquid flow out relief valve, lb/min
W_{SBK} = steam flow out break, lb/min
W_{SRV} = steam flow out relief valve, lb/min
W_{HBK} = hydrogen flow out break, lb/min

W_{HRV} = hydrogen flow out relief valve, lb/min
h_L = primary system water enthalpy, Btu/lb
h_S = enthalpy of steam in gas space, Btu/lb
h_H = hydrogen enthalpy in gas space, Btu/lb.

h_L is evaluated at the water temperature, and h_S and h_H at the gas space temperature. Leaked energy in Equation (E8.4) is treated as negative.

The energy, E_{PMP}, from primary system pumps is:

$$E_{PMP} = E_{PMP} + Q_{pump}\, dt/60, \text{ Btu} \quad , \tag{E8.5}$$

where

Q_{pump} = pump power, Btu/hr.

The change, ΔE_{WTR}, in stored energy of the water is:

$$\Delta E_{WTR} = E_{WTR} - E_{WTR1} \quad , \text{ Btu}, \tag{E8.6}$$

where

$E_{WTR} = W_{TOT}\, h_L$, Btu
E_{WTR1} = initial value of E_{WTR}, Btu
W_{TOT} = mass of water in primary system, lb.

The change, ΔE_G, in stored energy of the gas (steam and hydrogen) in the primary system is:

$$\Delta E_G = E_G - E_{G1}, \text{ Btu} \quad , \tag{E8.7}$$

where

$E_G = W_S h_S + W_H h_H - 0.1852\, P\, V_G$, Btu
E_{G1} = initial value of E_G, Btu
W_S = mass of steam in the gas space, lb
W_H = mass of hydrogen in the gas space, lb
P = primary system pressure, psia
V_G = volume of the gas space, ft^3.

The constant 0.1852 in the gas internal energy term is a units conversion factor.

The change, ΔE_C, in stored energy of the core is:

$$\Delta E_C = E_C - E_{C1}, \quad \text{Btu} \quad , \qquad \text{(E8.8)}$$

where

$E_C = \Sigma(MCp)\ V_r\ (T_{i,r} - 32.0);\ i = 1, NDZ;\ r = 1, R$

E_{C1} = initial value of E_C

(MCp) = core node heat capacity = $(MC)_1 + (MC_{ox}/t_{zr})\ X_{i,r}$, Btu/F per node

$(MC)_1$ = core nodal heat capacity before cladding oxidation

(MC_{ox}) = nodal heat capacity of oxygen associated with ZrO_2, Btu/F

$X_{i,r}$ = oxidized cladding thickness, ft

V_r = volume fraction of core in radial zone r

$T_{i,r}$ = temperature of core node (i,r), F

NDZ = number of axial core nodes

R = number of radial core zones

t_{zr} = cladding thickness

N_R = total number of rods

D = rod diameter, ft

H = active fuel lengths, ft

ρ_{zr} = zirconium density = 401.9 lb/ft^3.

The nodal heat capacities are:

$$(MC)_1 = N_R\ \frac{\pi}{4}\ D^2\ \left(\frac{H}{NDZ}\right)\ (\rho C)_{core} \quad ,$$

$(\rho C)_{core}$ = core heat capacity, $Btu/ft^3/F$ = input RHOCU

$$(MC_{ox}) = N_R\ \pi\ D\ \left(\frac{H}{NDZ}\right)\ t_{zr}\ \rho_{zr}\ \left(C_{ox}\ \frac{32}{91.22}\right)$$

C_{cx} = 0.218 Btu/lb(ox)/F.

For the BWR core model, the summation in E_C includes the box and blade nodes.

The energy stored in structures is assumed to include heat transfer to the steam generator in addition to that transferred in the structures in the gas space, lower support structures, and the core barrel. After core collapse, heat transfer from the core debris to the bottom head and to the support structures is incorporated. The change, ΔE_S, in stored energy in the structures is:

$$\Delta E_S = \Sigma(E_{S,i} - E_{S,1}) \text{ , Btu ,} \qquad \text{(E8.9)}$$

where

$E_{S,i}$ = energy stored in structure i, Btu
$= (CM)_i (T_i - 32.0)$
$E_{S,1}$ = initial value of $E_{S,i}$, Btu
$(CM)_i$ = heat capacity of structure i, Btu/F
T_i = temperature of structure i, F.

The summation is over all non-core structures. $E_{S,i}$ is redefined for special cases. For the steam generator, $E_{S,i}$ is the total heat input to the steam generator:

$$E_{S,ISG} = E_{S,ISG} + Q_{SG}\, dt/60, \text{ Btu} \text{ ,} \qquad \text{(E8.10)}$$

where

Q_{SG} = heat transfer from the primary to the secondary, Btu/hr.

After core collapse, heat is conducted from the core debris into the head; and the total energy stored in the head is:

$$E_{S,I3} = E_{S,I3} + Q_K\, dt/60 \text{ , Btu ,} \qquad \text{(E8.11)}$$

where

Q_K = heat conducted from the core debris into the head, Btu/hr.

For the core barrel, $(CM)_i$ = WBAR and T_i = TBAR.

When the temperature of the structure immediately above the core exceeds 2800 F, it is optionally replaced by another structure at the initial structure temperature, and:

$$E_{S,1} = W_{Fe} (T_1 - 32) + CM_1 (2800 - 32) \quad , \text{Btu} \quad . \qquad (E8.12)$$

The total energy input to the primary system is given by the sum of Equations (E8.1) through (E8.5):

$$E = E_{DK} + E_{MW} + E_{in} + E_{LK} + E_{PMP} \quad , \text{Btu} \quad . \qquad (E8.13)$$

The change in stored energy is given by the sum of Equations (E8.6) through (E8.9):

$$\Delta S = \Delta E_{WTR} + \Delta E_G + \Delta E_C + \Delta E_S \quad , \quad \text{Btu}, \qquad (E8.14)$$

Errors in the energy balance are expressed as:

$$E_{DK} = \frac{100\ (E - \Delta s)}{E_{DK}} \quad \text{(percent decay heat)}$$

$$E_S = \frac{100\ (E - \Delta s)}{E_C} \quad \text{(percent core stored energy)} \qquad (E8.15)$$

and

$$E_{LK} = \frac{100\ (E - \Delta s)}{E_{LK}} \quad \text{(percent leaked energy)}$$

Calculated results for input IBWR = 0 typically indicate errors in the range of $\pm$ 3 percent, depending on accident time and the basis for comparison. The decay-heat-based error is generally positive at the start of a problem and trends to negative values at the time of head failure. Discontinuities are oberved during transition phases, such as during a change of break flow from liquid to steam, a change in break flow area, and at the time of core collapse. The sources of the discontinuities and error are not known. Suspected sources are the calculation of the gas stored energy (E_G) and the metal-water reaction (E_{MW} and E_C). Larger errors are obtained for the BWR core model (IBWR = 1) and generally have a positive bias.

The magnitude of the apparent error indicates an adequate energy balance for most applications of BOIL. It should be emphasized that the calculated energy balance is only a test of the internal consistency of the physics and does not necessarily demonstrate the correctness of the physics. Undoubtedly, phenomenological uncertainties in the modeling are much greater than the apparent errors in energy balance.

8.2 BOIL Mass Balance Audit

The BOIL mass balance audit parallels the approach taken in the energy balance audit. All the mass additions to the system are summed and compared with the change in mass stored in the primary system.

The total mass of water in the form of either liquid or vapor added to the primary system is:

$$S_{WTR} = W_{WTR} + (W_{ECC} - W_{LBK} - W_{LRV} - W_{SBK} - W_{SRV})\,dt - f_{zr}\,W_{zr}\,\left(\frac{36}{91.22}\right) - f_{Fe}\,W_{SS}\,\frac{72}{167.55}\ , \text{lb}, \qquad \text{(E8.16)}$$

The last terms account for the destruction of water due to metal-water reaction.

The hydrogen mass added to the primary system is:

$$S_H = S_H - (W_{HBK} + W_{HRV})\,dt + f_{zr}\,W_{zr}\,\left(\frac{4}{91.22}\right) + f_{FE}\,W_{SS}\,\frac{8}{167.55}\ , \text{lb}, \qquad \text{(E8.17)}$$

where the last terms account for hydrogen production by metal-water reaction.

The change in mass of stored water is:

$$\Delta W_{WTR} = W_{TOT} + W_S - W_{TOT1} - W_{S1}\ , \qquad \text{(E8.18)}$$

where W_{TOT1} and W_{S1} are initial values of W_{TOT} and W_S.

The change in stored mass of hydrogen is:

$$\Delta W_H = W_H\ , \qquad \text{(E8.19)}$$

where W_H is the current value of the hydrogen mass.

The water mass balance error is:

$$G_{WTR} = S_{WTR} - \Delta W_{WTR}\ , \qquad \text{(E8.20)}$$

and the hydrogen mass balance error is:

$$E_H = S_H - \Delta W_H \quad . \qquad \text{(E8.21)}$$

Calculated results indicate mass balance errors on the order of $\pm$ 10 lb hydrogen and -1000 $\pm$ 500 lb water/steam. Errors of this magnitude are not significant and would not have a significant impact on the containment response.

8.3 MACE Energy Balance Audit

The MACE energy balance audit is similar to that in BOIL. The energy input to the containment building is summed over time and compared with the change in stored energy since the beginning of the calculation. The energy input to the containment is composed of:

(1) E_{DK} = decay heat released to the containment
(2) E_{BN} = energy from hydrogen and CO burns
(3) E_{BD} = energy added to the containment by MACE "event" data and by the source routines (INITL, BOIL, HOTDRP, INTER)
(4) E_{SI} = energy added by containment sprays operating in the injection mode from an external storage tank
(5) E_{ECI} = energy added by direct spill-over of ECC water from the primary system
(6) E_{ECO} = energy removed by ECC pumps operating in the recirculation mode from a containment sump
(7) U_{LK} = energy loss by containment leakage
(8) E_{WL} = energy loss to structures (walls) in the containment
(9) E_{HX} = heat transfer to heat exchangers
(10) E_{QW} = direct energy additions from core debris to sump water by HOTDRP and INTER
(11) E_{IC} = the net energy loss to ice beds.

Energy is assumed to be stored in the containment atmosphere and in sump water. The containment walls and ice beds and modeled in the energy balance as containment boundary heat fluxes. Energy balance errors are expressed in terms of percent stored energy in the containment atmosphere.

The integrated decay heat is:

$$E_{DK} = E_{DK} + (f_A + f_{LK} + f_{SMP})\ Q_{DK}\ dt/60,\ Btu \quad , \qquad (E8.22)$$

where

f_A = airborne fraction

f_{LK} = fraction leaked

f_{SMP} = fraction in the sump

and the implied summation is over time.

The energy input to the containment during hydrogen and CO burning is:

$$E_{BN} = E_{BN} + f_B\ \Delta E_B,\ Btu \quad , \qquad (E8.23)$$

where

f_B = fraction of H_2 and CO burned per timestep

ΔE_B = burn energy release, Btu.

The burn fraction and energy release are discussed in Section 6.9.

The blowdown energy input to the containment is:

$$E_{BD} = E_{BD} + \Sigma w_i\ h_i\ dt \quad , \qquad (E8.24)$$

where the sum represents all the enthalpy flows into the containment from INITL (blowdown table), BOIL (break and relief valve flow), HOTDRP (steam from water vaporization and hydrogen), INTER (steam from boiling water in the reactor cavity and steam, hydrogen, CO, and CO_2 from concrete decomposition), and from MACE "event" data.

Energy from the injection spray is:

$$E_{SI} = E_{SI} + \dot{m}_{SP}\ h_{SP}\ dt,\ Btu \quad , \qquad (E8.25)$$

where

$\dot{m}_{SP}$ = spray flow rate, lb/min

h_{SP} = spray enthalpy, Btu/lb.

In subroutine MACE, $\dot{m}_{SP}\, h_{SP}\, dt$ is known as DUSPI.

A portion of the ECC flow may spill directly into the sump rather than being added to the primary system. The spill-over adds energy:

$$E_{ECI} = E_{ECI} + \Delta E_{ECI}\ ,\ \text{Btu}\ , \qquad \text{(E8.26)}$$

where

$\Delta E_{ECI} = (W_{PMP} - W_{INJ})\, h_{ECC}\, dt$, (coded as DUECI*DTX/DTM in MACE)

W_{PMP} = ECC pump flow rate, lb/min

W_{INJ} = ECC water added to vessel, lb/min

h_{ECC} = enthalpy of ECC water, Btu/lb.

Energy removed from the sump by ECC recirculation is:

$$E_{ECO} = E_{ECO} - \Delta E_{ECO},\ \text{Btu}\ , \qquad \text{(E8.27)}$$

where

$E_{ECO} = W_{PMP}\, h_{SMP}\, dt$, (coded as DUECO*DTX/DTM in MACE)

h_{SMP} = sump water enthalpy, Btu/lb.

Energy from the containment is:

$$U_{LK} = U_{LK} - \Delta U_{LK},\ \text{Btu}\ , \qquad \text{(E8.28)}$$

where

$\Delta U_{LK} = f_{TX}\, U_{T,J}$

f_{TX} = fraction of compartment J leaked to outside

$U_{T,J} = U_J + f_J\, Q_{DK}\, dt/60$

U_J = total atmosphere enthalpy of compartment J, Btu

f_J = airborne decay heat fraction in compartment J.

ΔU_{LK} is coded in MACE as UTLK = UTX(I), where UTX(I) is the enthalpy leaked through failure path I.

Energy loss to structures is:

$$E_{WL} = E_{WL} - Q_{RS}\, dt, \text{ Btu} \quad , \qquad \text{(E8.29)}$$

where Q_{RS} = heat transfer rate to walls, Btu/min.

Note that Q_{RS} is treated as a boundary heat loss. Thus, the MACE energy balance audit does not make an independent test of whether E_{WL} is consistent with the change in stored energy in the walls themselves.

The heat loss to heat exchangers is:

$$E_{HX} = E_{HX} - (Q_{cool} + Q_{SHX}/60)\, dt, \text{ Btu} \quad , \qquad \text{(E8.30)}$$

where

Q_{cool} = heat transfer to building coolers, Btu/min

Q_{SHX} = heat transfer to containment spray heat exchangers, Btu/hr.

Note that heat transfer to ECC heat exchangers does not directly appear in the MACE energy audit. Their effect appears in the difference in energy removed from the sump, Equation (E8.27) and that returned from BOIL, Equation (E8.24).

In addition to the energy sources given by Equation (E8.24), HOTDRP and INTER also supply energy to the containment by direct heating of the water in the reactor cavity. The energy is added to the water (that is, the accumulative change in water enthalpy) is:

$$E_{QW} = E_{QW} + M_{RC2}\, h_{RC2} - M_{RC1}\, h_{RC1}, \text{ Btu} \quad , \qquad \text{(E8.31)}$$

where

M_{RC2}, M_{RC1} = final and initial masses of water in the reactor cavity, lb

h_{RC2}, h_{RC1} = final and initial water enthalpies, Btu/lb.

The net energy loss to an ice bed is:

$$E_{IC} = E_{IC} - (Q_{ICE} - \dot{m}_I C_p (T_{WTR} - 32))\, dt, \text{ Btu} \quad , \qquad (8.32)$$

where

Q_{ICE} = energy removed from atmosphere, Btu/min ,

$\dot{m}_I$ = water (condensate and melt) draining from the ice bed, lb/min

T_{WTR} = temperature of water draining from the ice bed, F.

Q_{ICE} is defined in Section 6.6.1. The last term on the right is the energy added to the containment sump by the water draining from the ice bed due to steam condensation and ice melting.

The total energy input is given by the sum of the terms in Equations (E8.22) through (E8.32).

$$E = E_{DK} + E_{BN} + E_{BD} + E_{SI} + E_{ECI} + E_{ECO} + U_{LK} + E_{WL} + E_{HX} + E_{QW} + E_{IC} \quad . \qquad (E8.33)$$

The change in stored energy is:

$$\Delta E_S = \Delta E_{AT} + \Delta E_{SMP} + M_{RC}\, h_{RC} - DUSMP3 \quad , \qquad (E8.34)$$

where

$\Delta E_{AT} = E_{AT} - E_{AT1}$

$\Delta E_{SMP} = E_{SMP} - E_{SMP1}$

$E_{AT} = \Sigma(UT_i - 0.1852\, P_i V_i)$, Btu

$E_{SMP} = \Sigma(EP_i)$, Btu

UT_i = compartment i enthalpy

P_i = compartment i pressure, psia

V_i = compartment i volume, ft^3

EP_i = total enthalpy of water in compartment i sump, Btu

M_{RC} = mass of water in reactor cavity, lb

h_{RC} = enthalpy of water in reactor cavity, Btu/lb

DUSMP3 = enthalpy removed from the containment sump by the recirculation spray in the current timestep, Btu.

E_{AT1} is the initial value of E_{AT}, the stored energy in the containment atmosphere. E_{SMP1} is the initial value of E_{SMP}, the stored energy in the containment sumps. ΔE_{AT} is the change in atmosphere internal energy. ΔE_{SMP} is approximated by the change in enthalpy of the water. The initial value of $M_{RC}\ h_{RC}$ is zero, so that $M_{RC}\ h_{RC}$ is the change in enthalpy for the reactor cavity water. The last term, DUSMP3, corrects E_{SMP} for sump water removed by the recirculation spray.

The MACE energy balance error is expressed as a percent of the stored energy in the atmosphere:

$$\varepsilon_{AT} = 100\ (E - E_S)/E_{AT} \qquad \text{(E8.35)}$$

ε_{AT} is a measure of the potential error in containment pressure due to energy balance errors.

Calculated results generally indicate errors on the order of $\pm$ 0.3 percent. Larger errors are calculated after containment failure and when containment sprays are on, partially because E_{AT} is smaller because of the reduced containment pressures. Errors of this magnitude are not significant in terms of their effect on containment pressure.

9.0 MARCH 2 IMPLEMENTATION

This section summarizes the information necessary for successful operation of MARCH 2. Knowledge of Fortran-77 and its use on the target system is assumed.

9.1 Language and Machine Requirements

With few exceptions, MARCH 2 is written in the Fortran-77 programming language, ANSI Standard X3.9-1978 (full subset). This permits easier transport than ever before possible. The only major exception is the use of the Namelist feature in MARCH 2. However, Namelist is found in almost all Fortran compilers. Required computer resources are highly dependent on the computer, compiler, compiler options, operating system, and input problem.

9.1.1 BCL CDC Systems

The final development of MARCH 2 was performed on a Cyber 180-815 at Battelle-Columbus. The operating system is NOS 2.2-605/587, with Fortran compiler FTN 5.1+587.

When compiled with optimization OPT = 0, the code requires 321100 (octal) CDC words to load.

The code also compiles and executes on the Battelle-Columbus NOS/BE-1.5 577 system.

9.1.2 BCL VAX System

MARCH 2 runs on the Battelle-Columbus VAX/VMS system. Function CPUSEC required minor recoding. References to CDC system subroutines "STRACE" and "REMARK" were deleted.

9.1.3 INEL CDC Systems

MARCH 2 is operational on both the NOS and NOS/BE systems at INEL. No changes were required.

9.1.4 Other Systems

ORNL has successfully compiled an interim version of MARCH 2 on their IBM system. That same version was segmented, compiled, and executed at BNL on a CDC machine. SNL has compiled and executed versions of MARCH 2 on a Cray-1.

9.1.5 Compiler Options

Tests of various optimization on the CDC systems were conducted at Battelle-Columbus. The code executes normally with OPT = 0 (minimal optimization). A bug in the compiler causes the code compiled under OPT = 1 to execute normally for a while, followed by an address-out-of-range error. Other optimizations were not tested.

The CDC compiler permits users to choose the treatment of low-order bits when they cannot be kept due to limits on precision. CDC recommends the use of ROUND = A/S/M/-D, which causes rounding to take place for all operations except division.

Selecting different options can be expected to change results slightly, since the order of calculation may be changed. This should only cause problems when a calculated value is used to "trigger" an option or select a different path.

9.2 Implementing MARCH 2 Under Fortran-77

MARCH 2 has several programming features that speed implementation. No assumptions are made regarding word length on the target system. All COMMON blocks are referenced in the BLOCK DATA subroutine. There is a single definition for each COMMON block, so all instances of that block are identical.

The only extensions to Fortran-77 are found in routines INP, CPUSEC, PERROR, and STEPS:

(1) Namelist input is used for much of the input data. Although this is non-ANSI, it offers great flexibility in the input data. This should present no problem since most Fortran-77 compilers have a Namelist facility. However, check the reference manual for the target system, since there may be differences in usage.

(2) Function CPUSEC references a CDC intrinsic function called SECOND. SECOND returns the number of central processor (CP) seconds that elapsed since the start of the job. CPUSEC subtracts an appropriate starting value to determine the number of CP seconds since start of the program.

    The target system may not have the SECOND function, or at least not by that name. If there is a facility to determine the elapsed CP time, CPUSEC can be re-coded to operate in the proper fashion. If a CP time function is not available, but the time of day is available, CPUSEC can be re-coded to return elapsed real time. Either CP or real time will allow the graceful exit provided by the CPSTP input parameter. If neither function is available, CPUSEC should be coded to return a value of zero.

(3) Subroutines PERROR and STEPS reference CDC subroutines REMARK and STRACE. They may be deleted. Subroutine REMARK is used to write a message to the job log ("dayfile"). Subroutine STRACE forces a "traceback" of the subroutine which caused PERROR to exit.

If the code is implemented on a non-CDC system, the values of "BIG" and "SMALL" in function EXPFUN should be changed. "BIG" is the largest value that can be passed to Fortran function EXP without causing an error. If EXPFUN is called with an argument smaller than "SMALL", zero is returned.

9.3 Implementing MARCH Under Fortran IV

Compiling MARCH 2 with a Fortran IV compiler is not recommended. Depending on the extensions available on the target compiler, the following may have to be done:

(1) Character strings delimited by single quote marks ('): Some compilers require a different delimiter. Other compilers may require that Hollerith format be used.

(2) Expressions in output statements: local temporary variables should be used to hold the values before output.

(3) Generic functions: for example, "AMAX1" should replace "MAX".

(4) IF-THEN-ELSE statements: these statements should be replaced by a series of GO TO's.

(5) CHARACTER variables: change to INTEGER arrays of the proper lengths. These lengths are machine-dependent. Corresponding FORMAT statements must be changed.

(6) PARAMETER statements: replace with variables of the same names, with a DATA statement to hold the values.

(7) END= and ERR= on I/O: replace with corresponding function references.

9.4 Decreasing the Size of the Code

If the program is too large to fit into available memory, the following actions may be taken:

(1) Subroutine UNITS may be deleted. This subroutine serves only a documentation function.

(2) Subroutines INP, ECHO, and CNVERT can be moved to a separate program which produces an unformatted file containing all input data. A new INP subroutine would then be added to MARCH 2 to read the unformatted data.

(3) Much of the program does not have to be resident in the memory continuously. The target system will usually have a way to divide the program into segments or overlays.

If the program is overlayed or segmented, it may be necessary to insert SAVE statements into each subroutine. The SAVE statements will retain the status of the variables local to each routine while that routine is not active.

9.5 Enhancements

Several changes can be made to the code fairly easily which, for some users, can greatly increase the utility of the program.

(1) All REAL variables can be declared to be DOUBLE PRECISION. On systems with short word lengths, this permits increased accuracy. Output from systems with larger word lengths can then be compared more easily. This will greatly increase the size of the program.

(2) Subroutines IOINIT and IOEND can be modified to save, destroy, or otherwise manipulate the input and output files. IOINIT is called before any file operations are done; IOEND is called just before the program exits. For example, an output file could be sent to a printer directly from MARCH.

(3) Additional error messages could be generated. If the user elects to modify MARCH 2, any new error messages can be added to the error message file. This allows addition of messages with "ad hoc" code.

(4) When adding code that uses the exponential function (EXP), call function EXPFUN instead. EXPFUN traps errors if the argument is outside of the legal range.

(5) Several useful constants are available. Refer to the BLOCK DATA routine for locations.

ONTHRD	1/3
TWTHRD	2/3
FRTHRD	4/3
CMPRFT	Number of centimeters per foot
EBOLTZ	American Engineering Stefan-Boltzmann constant
GRAV	Acceleration due to gravity, ft/sec^2

H2H2O	Ratio of molecular weights of hydrogen and water
PI	Needs no introduction
SBOLTZ	SI Stefan-Boltzmann constant
TFUSEN	Freezing point of water, F
aTObC	Temperature conversion factors. Use
aTObM	T*aTObM + aTObC to convert T from units "a" to units "b". Values of "a" and "b" are:

C Celcius
F Farenheit
K Kelvin
R Rankine

If the multiplier is 1 or constant is 0, there is no corresponding constant.

9.6 File Structures

The following files are used in MARCH 2.

Unit	Type	Purpose
2	Input	Default data values. Optional.
3	Input	Namelist NLINTL. Required only if IBLDF=1.
4	Input	Error message texts. Required.
5	Input	Problem data values. Required.
1*	Output	Mass flow rates at top of core.
6	Output	Normal ("print") output.
7*	Output	Output for CORRAL code.
9*	Output	BOIL plot file.
11*	Output	MACE plot file.
12	Output	Summary of problem, error messages.
20*	Output	Output for MERGE code.
25*	Output	Output for CORSOR code.

The user must determine how to connect his data with the Fortran unit numbers above. The formats of the input and output files can be found in Appendices A and B, respectively.

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*Default value. May be changed by user input. The user may suppress creation of the file by specifying a unit number $\leq$ 0.

The user is encouraged to develop one or more sets of default values. Since the defaults file is read before the input file, deviations from the "defaults" can be made.

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APPENDIX A

INPUT GUIDE

APPENDIX A

INPUT GUIDE

Introduction

Table A.1 describes input to MARCH. The first record read is a title. The remaining input variables are grouped into 12 namelists: NLMAR, NLINTL, NLSLAB, NLECC, NLHX, NLCOOL, NLMACE, NLBOIL, NLBWR, NLHEAD, NLHOT, and NLINTR. A brief description introduces each namelist. For the longer namelists, a logical grouping of the input preceeds an alphabetic listing of all input variables. The user may prefer to prepare the input using the logical grouping as a guide while referring to the alphabetical listing as needed for definitions of variables.

In addition to definitions, the alphabetic listing incorporates assigned default values. The default values are coded in the BLOCK DATA subroutine. The default values have been selected to simplify input preparation, but are not necessarily recommended values. Most default values are based largely on experiment or are recommended by the model developers, but the user is cautioned to scrutinize all input. Most input variables have been left deliberately undefined to force the user to carefully provide input for his own problem and to make decisions on important modeling choices and assumptions.

Variables which do not have default values should be entered even though not used for model description. On computers which identify "undefined" values, the program may fail while converting the undefined values to the output units.

Subroutine INTER input units are always as indicated. Otherwise, units are controlled by input "IU" in namelist NLMAR. The units of the default values also depend on input "IU". For many inputs, the default values should be modified when using SI input.

Table A.2 describes the format required for the error message file. This file contains the texts of all the possible error messages. When an error occurs, the file is consulted for severity and the corresponding text.

TABLE A.1 DEFINITION OF INPUT VARIABLES

Variable	Description	Default
	Title	
	MARCH reads the first record of the input file as the problem title. The title appears on all printed output. To specify a blank title, make the first record in the input file blank.	
	Namelist NLMAR	
	NLMAR primarily contains data on problem execution or termination control and problem sequence flags. Other problem termination control variables include DTS in namelist NLMACE, NDTM in namelist NLBOIL, NSTOP in namelist NLHOT, and TF in namelist NLINTR.	
	Execution Control Variables:	
	ICHECK, CPSTP, IS, PRST, TRST	
	Output File Unit Numbers:	
	BOILPT, CORRAL, CORSOR, FLOWS, MACEPT, MERGE	
	Note: To speed execution and save disk space on small computers, the above output files should not be written unless needed. Setting a unit number to zero will suppress the corresponding output file.	
	Time:	
	ATIME, DTINITL, TAP	
	Sequence Flags:	
	IBLDF, IBLDI, IBLDP, IBRK, ICBRK, ICE , ICKV, IECCXX, IFPSM, IFPSV, IPDTL, ISPRA, ITRAN, IU, IXPL, NINTRL, NPAIRL	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMAR (Continued)	
ATIME	= time at start of accident; min (s).	None
BOILPT	= the Fortran unit number for the BOIL plot file = 0, do not produce a BOIL plot file.	9
CORRAL	= the Fortran unit number for the CORRAL output = 0, do not produce a CORRAL output file.	7
CORSOR	= the Fortran unit number for the CORSOR output = 0, do not produce a CORSOR output file.	25
CPSTP	= CPU time at which problem execution is to be stopped; sec.	1.0
DTINITL	= timestep between calls to subroutine INITIL; min (s).	10.0
FLOWS	= the Fortran unit number for the mass flow rate output = 0, do not produce a mass flow rate output file.	1
IBLDF	= 0, namelist NLINTL is read from the standard input file (Fortran unit "INFILE") = 1, namelist NLINTL is read from input unit BLODWN.	0
IBLDI	= 0, linear interpolation of blowdown table = 1, histogram interpolation of blowdown table.	0
IBLDP	= number of calls to subroutine INITL per printed MACE output.	1

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMAR (Continued)	
IBRK	= 0, not a small break LOCA	None
	= 1, small break LOCA (ABRK or ASRV > 0 in namelist NLBOIL).	
ICBRK	= 0, ECC and containment spray recirculation fail when containment fails	None
	= 1, ECC and containment spray recirculation do not fail when containment fails.	None
ICE	= 0, not an ice condenser containment	None
	= 1, ice condenser containment.	
ICHECK	= 0, normal execution	1
	= 2, print all namelist data; process and print input; do not execute	
	≠ 0 and ≠ 2, process and print input; do not execute.	
ICKV	= sets special V-sequence LOCA flags (blowdown outside containment) which disallows intercompartment transfer prior to head failure.	
	= -1, blowdown to auxiliary building	0
	= +1, direct blowdown to atmosphere	
	= 0, skip ICKV model.	
	For ICKV = +1, coding sets NRPV1 = NCUB + 1. Do not use ICKV = +1 with ITRAN = 0. Suggested alternative modeling is to set ICKV = 0 and use IVENT in namelist NLMACE features to control compartment transfer.	
IECCXX	= 0, no ECC	2
	= ± 1, ECC works until head failure; ECC water saturated at vessel pressure	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMAR (Continued)	
IECCXX (Cont'd)	= ± 2, ECC works until head failure; ECC water at source (RWST or sump) temperature	
	= ± 3, same as ± 2 except ECC works after head failure.	
	For negative IECCXX, the pumps fail on switchover to recirculation.	
IFPSM	= 1, small melt fission product release	2
	= 2, reference (WASH-1400) melt fission product release	
	= 3, large melt fission product release.	
IFPSV	= 1, small vaporization fission product release	2
	= 2, reference (WASH-1400) vaporization fission product release	
	= 3, large vaporization fission product release.	
IPDTL	= 0, regular printout (included for all values of IPDTL)	7
	= 1, detailed printout from MACE	
	= 2, detailed printout from BOIL	
	= 3, not used	
	= 4, detailed printout from HEAD	
	= 5, detailed printout from HOTDRP	
	= 6, detailed printout from INTER	
	= 7, detailed printout	
	= 17, detailed printout plus MACE energy balance audit diagnostics.	
IS	= value of NUPLAC at which problem execution will be stopped:	7

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMAR (Continued)	
IS (Cont'd)	NUPLAC — Before Subroutine 1 — INITIL 2 — BOIL 3,4 — HEAD 5 — HOTDRP 6 — INTER 7 — No effect	
ISPRA	= -1, containment spray injection is operable, failure on switchover to recirculation = 0, containment sprays inoperable = 1, containment sprays operable.	None
ITRAN	= 0, large LOCA with blowdown data in namelist NLINTL = 1, MARCH-calculated blowdown	None
IU	= designates units to be used in input and output from the following table: IU — Input Units — Output Units = 0 American Engineering (AE) — AE = 1 International System (SI) — AE = 2 SI — SI = 3 AE — SI For negative IU, Fortran unit "CORRAL" output is written in American Engineering units for compatibility with CORRAL.	0
IXPL	= 0, no in-vessel steam explosion = 1, in-vessel steam explosion is assumed to fail vessel and containment when core slumping starts. (See parameters NDZDRP, FDROP, FCOL, and TMELT in namelist NLBOIL).	0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMAR (Continued)	
MACEPT	= the Fortran unit number for the MACE plot file = 0, do not produce a MACE plot file.	11
MERGE	= the Fortran unit number for the MERGE output = 0, do not produce a MERGE output file.	20
NINTRL	= number of INTER timesteps performed before call to MACE. (INTER output is averaged over NINTRL timesteps before call to MACE).	12
NPAIRL	= 0, no blowdown table, subroutine INITL bypassed and subroutine BOIL calculations start immediately = 2 to 200, number of blowdown table entries in namelist NLINTL.	0
PRST	= containment pressure at which the calculation is stopped; psia (MPa).	1.0E10
TAP	= time at power; min (s).	None
TRST	= problem execution is stopped when accident time reaches TRST; min (s).	1.0
	Namelist NLINTL	
	If NPAIRL ≠ 0, this namelist may be used to enter a blowdown table characterizing the initial mass and energy release from the primary system prior to start of the BOIL calculations. Otherwise, the blowdown is calculated in subroutine PRIMP. See namelist NLMAR above for definitions of related variables DTINITL, IBLDF, IBLDI, IBLDP, and NPAIRL.	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLINTL (Continued)	
EW(I)	= specific enthalpy of blowdown fluid; I ≤ 200; Btu/lb (J/kg).	200*0.0
T(I)	= accident time; I ≤ 200; min (s). Units are seconds if IBLDF = 1.	200*0.0
W(I)	= mass flow rate; I ≤ 200; lb/min (kg/s). Units are lb/sec (kg/s) is IBLDF = 1.	200*0.0
	Namelist NLSLAB	
	NLSLAB contains information on the containment wall heat sinks. It is recommended that the user define the side of a slab exposed to the atmosphere as "left", regardless of the actual orientation of the slab. If both sides of the slab are exposed to the atmosphere, either may be chosen as "left".	
	Wall Material Variables:	
	IMAT, NMAT DEN, HC, TC	
	Slab Variables:	
	ISLAB, NSLAB IVL, IVR, MAT1, MAT2, NNO1, NNO2 DTDX, HIF, SAREA	
	Mesh Variables:	
	TEMP, X, NOD	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLSLAB (Continued)	
DEN(NM)	= density of material NM; NM ≤ 5; lb/ft^3 (kg/m^3).	None
DTDX(NS)	= 0, right hand boundary of slab NS is insulated. May also be used to model center line symmetry if the face area SAREA is doubled and the slab thickness halved	None
	= 1, right hand boundary of slab NS is in contact with containment volume IVR(NS); NS ≤ 15.	
HC(NM)	= heat capacity of material NM; NM ≤ 5; Btu/lb/F (J/kg/K).	None
HIF(NS)	= interface heat transfer coefficient for heat sinks which have two material regions; NS ≤ 15; Btu/hr/ft^2/F (W/m^2/K).	None
	= 0 for slabs which have a single material region.	
IMAT(I)	= containment material names; I ≤ NMAT; enter as Fortran character strings, maximum of 10 characters each.	None
ISLAB(I)	= containment wall names; I ≤ NSLAB; enter as Fortran character strings, maximum of 10 characters each.	None
IVL(NS)	= containment compartment number adjacent to the left boundary of slab NS; NS ≤ 15.	None
IVR(NS)	= containment compartment number adjacent to the right boundary of slab NS; for an insulated right boundary (DTDX(NS) = 0), enter IVR = IVL; NS ≤ 15.	None
MAT1(NS)	= material number in left material region of slab NS; NS ≤ 15.	None
MAT2(NS)	= material number in right material region of slab NS; for a one material slab, enter MAT2 = MAT1; NS ≤ 15.	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLSLAB (Continued)	
NMAT	= number of materials in the slabs; NMAT ≤ 5.	None
NNO1(NS)	= number of nodes in the left material region of slab NS; NS ≤ 15.	None
NNO2(NS)	= number of nodes in the right material region of slab NS; for a one material slab enter NNO2 = 0. The total number of nodes per slab is limited to NNO1(NS) + NNO2(NS) ≤ 30; total for all slabs is limited to 200 nodes; NS ≤ 15.	None
NOD(I)	= node numbers for which temperatures are written to Fortran unit "MACEPT"; NOD(4) is saved on Fortran unit "CORRAL" for an ice condenser; if NOD(5) < 0, heat flux rather than temperature for NOD(5) is written to "MACEPT"; I ≤ 5.	None
NSLAB	= number of slabs; NSLAB ≤ 15.	None
SAREA(NS)	= area of one face of slab NS; NS ≤ 15; ft^2 (m^2).	None
TC(NM)	= thermal conductivity of material NM; NM ≤ 5; Btu/hr/ft/F (W/m/K).	None
TEMP(N)	= initial temperature of node N; N ≤ 200; nodes in the ice basket of an ice condenser must be at 20 F and be in the last slab entered; F (K).	None
X(N)	= coordinate of node N; that is, the distance from the left boundary of the slab to node N. For a concrete wall a surface mesh interval [X(N) - X(N-1)] less than 0.01 ft is recommended. Mesh size may double toward the interior. The left hand coodinate of each slab may start at zero. The total number of nodes is limited to 200, with no more than 30 per slab; N ≤ 200; ft (m).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLECC	
	NLECC contains data on the ECC injection and storage tanks (RWST), ECC pumps, recirculation setpoints, and pump failure criteria. Variables IECCXX in namelist NLMAR and STPECC, WVMAKS, and WVMAX in namelist NLMACE also affect ECC operation.	
	Injection and Storage Tanks:	
	ACMO, PACMO, TACM, UHIO, PUHIO, TUHI RWSTM, TRWSTX	
	Recirculation and Failure Setpoints:	
	CSPRC, ECCRC DTSUBX, WTCAVX	
	ECC Pump Data:	
	NPUMP P, PLO, STP, TM, WEC	
ACMO	= initial mass of water in accumulator. Any water remaining in accumulators is added to reactor cavity when the head fails; lb (kg).	0.0
CSPRC	= fraction of initial RWST water left when switchover to containment spray recirculation is started.	None
DTSUBX	= subcooling of water in containment sump (TSAT-TSUMP) below which recirculation pump cavitation and failure occur; F° (K°).	None
ECCRC	= fraction of initial RWST water left when switchover to ECC recirculation is started.	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLECC (Continued)	
NPUMP	= number of ECC pumps modeled; $0 \leq$ NPUMP ≤ 6.	0
P(N)	= high pressure shutoff head for N-th ECC pump if WEC(N) is negative. Nominal pressure setpoint if WEC(N) is positive; N ≤ 6; psia (MPa).	6*0.0
PACMO	= initial accumulator pressure; psia (MPa).	0.0
PLO(N)	= low pressure shutoff for N-th ECC pump; N ≤ 6; psia (MPa).	6*0.0
PUHIO	= initial pressure of upper head injection tank; psia (MPa).	0.0
RWSTM	= initial mass of water in the spray and ECC water storage tank (RWST); lb (kg).	None
STP(N)	= stop time for N-th ECC pump; N ≤ 6; min (s).	6*1.0E+10
TACM	= accumulator water temperature; F (K).	None
TM(N)	= start time for N-th ECC pump; N ≤ 6; min (s).	6*1.0E+10
TRWSTX	= temperature of water in RWST; F (K).	None
TUHI	= temperature of water in upper head injection tank; F (K).	None
UHIO	= initial mass of water in the upper head injection tank; lb (kg).	0.0
WEC(N)	= if positive, nominal flow rate of N-th ECC pump; if negative, maximum or run-out flow rate. Negative WEC triggers use of parabolic flow rate curve; N ≤ 6; gpm (m^3/sec). Note that this value is converted to ft^3/min (m^3/sec) on output.	6*0.0
WTCAVX	= minimum mass of water in containment sump to avoid recirculation pump cavitation; lb (kg).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLHX	
	NLHX contains ECC and containment spray heat exchanger data.	
EQR	= rated ECC heat exchanger capacity; Btu/hr (W).	0.0
ETP1R	= rated ECC heat exchanger primary side inlet (hot) temperature; F (K).	0.0
ETS1R	= rated ECC heat exchanger secondary side inlet (cold) temperature; F (K).	0.0
EWPR	= rated ECC heat exchanger primary side flow rate; lb/min (kg/s).	0.0
EWSR	= rated ECC heat exchanger secondary side flow rate; lb/min (kg/s).	0.0
SQR	= rated containment spray heat exchanger capacity; Btu/hr (W).	0.0
STP1R	= rated containment spray heat exchanger primary side inlet (hot) temperature; F (K).	0.0
STS1R	= rated containment spray heat exchanger secondary side inlet (cold) temperature; F (K).	0.0
SWPR	= rated containment spray head exchanger primary side flow rate; lb/min (kg/s).	0.0
SWSR	= rated containment spray heat exchanger secondary side flow rate; lb/min (kg/s).	0.0
	Namelist NLCOOL	
	NLCOOL contains input data needed for the description of building coolers. Parameters	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLCOOL (Continued)	
	NCOOL, PCOOL, POFF, and QRCOOL describe a constant capacity cooler. The remaining parameters describe a fan cooler heat exchanger. JCOOL and NCOOL must be different compartment numbers if the two fans operate simultaneously.	
CQR	= rated capacity of containment fan cooler; Btu/hr (W).	0.0
CTPR	= rated air inlet temperature for containment fan coolers; F (K).	0.0
CTSR	= rated cooling water inlet temperature for containment fan coolers; F (K).	0.0
CVAP	= rated vapor mole fraction for containment fan coolers.	0.693
CWPR	= rated air flow rate of containment fan coolers; ft^3/min (m^3/s).	0.0
CWSR	= rated cooling water flow rate for containment fan coolers; lb/min (kg/s).	0.0
JCOOL	= number of the containment compartment which contains the fan coolers.	0
NCOOL	= number of the containment compartment which contains a constant capacity containment fan cooler that turns on and off with containment pressure.	0
PCOOL	= containment pressure at which constant capacity fan cooler is turned on (i.e., for $P \geq$ PCOOL); psia (MPa).	0.0
POFF	= containment pressure at which constant capacity fan cooler is turned off (i.e., for $P \leq$ POFF); psia (MPa).	0.0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLCOOL (Continued)	
QRCOOL	= capacity of constant capacity fan cooler; Btu/hr (W).	0.0
TCOOL	= time at which containment fan coolers start; min (s).	1.0E+10
	Namelist NLMACE	
	NLMACE contains containment input parameters including descriptions of containment events, initial conditions, pressure suppression features, compartment connections, and combustion model parameters.	
	Containment Flags:	
	IBETA, NCUB, JRPV1, JRPV3, NRPV1, NRPV2	
	Output and Miscellaneous Data:	
	DTO, DTPNT, DTS, FALL, HMAXX	
	Sump and Cavity Parameters:	
	NCAV, NSMP, NSMP2, VCAV, VFLR	
	Pressure Suppression Data:	
	ICECUB, IDRY, IWET DCF, TPOOL, WPOOL DCFICE, TICE, TSTM, TWTR, TWTR2, WICE	

TABLE A.1 (CONTINUED)

Variable	Description	Default

Namelist NLMACE (Continued)

Spray and ECC Control:

FSPRA, STPECC, STPSPR, WVMAKS, WVMAX

Compartment Initial Conditions:

PO
VC, AREA, HUM, TEMPO, WCDO, WCMO,
WHYD, WNTR, WOXY

Containment Events:

N, NC, NS, NT, C1, C2, C3, C4

Compartment Transfer Data:

BK (burn data), KT, PRESS
IVENT, JRPV1, JRPV3, AVBRK, CVBRK, TVNT1, TVNT2

Burn Flags:

IBURN, IBURNJ, IBURNL, IBURNM
IGNITE

Burn Model Data:

BK, H2DIST
CMDN, CMHI, CMHZ, CMLO, CMON, CMUP, CMXX,
H2DN, H2HI, H2HZ, H2LO, H2ON, H2UP, H2VO,
H2VX, H2XX, HIG, HIOXY

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
AREA(I)	= floor area of compartment I; I ≤ 10; ft^2 (m^2).	None
AVBRK	= flow area of inter-compartment flow restriction; ft^2 (m^2).	0.0
BK(I,J)	= 0, KT(I,J) is used to specify containment connections.	100*0.0
	= 10.X, mass transfer from compartment I downward to compartment J. X is the fraction of H2DIST(I) which burn in compartment I must travel before downward burn propagation into compartment J can take place.	
	= 20.X, mass transfer from compartment I horizontally to compartment J. X is the fraction of H2DIST(I) which burn originating in compartment I must traverse before horizontal burn propagation into compartment J can take place.	
	= 30.X, mass transfer from compartment I upward to compartment J. X is the fraction of H2DIST(I) which burn originating in compartment I must traverse before upward burn propagation into compartment J can take place.	
	I ≤ 10; J ≤ 10.	
C1(L)	= switch parameter which initiates event L	None
	= time; min (s) - for NS(L) = 1	
	= pressure; psia (MPa) - for NS(L) = 2	
	= temperature; F (K) - for NS(L) = 3	
	Negative pressure or temperature initiates on declining pressure or temperature.	
	L ≤ 10.	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
C2(L)	= spray flow rate; gpm (m^3/s) - for NT(L) = 1 Note that this value is converted to ft^3/min (m^3/s) on output. = heat removal rate; do not use if coolers are on; Btu/min (W) - for NT(L) = 2 = steam input rate; lb/min (kg/s) - for NT(L) = 3 = hydrogen input rate; lb/min (kg/s) - for NT(L) = 4 = CO_2 input rate; lb/min (kg/s) - for NT(L) = 5 = CO input rate; lb/min (kg/s) - for NT(L) = 6 = containment break orifice coefficient - for NT(L) = 7 = fan flow rate; ft^3/min (m^3/s) - for NT(L) = 8 = 0 for other values of NT(L). $L \leq 10$.	None
C3(L)	= spray temperature; F (K) - for NT(L) = 1 = steam enthalpy; Btu/lb (J/kg) - for NT(L) = 3 = hydrogen temperature; F (K) - for NT(L) = 4 = CO_2 temperature; F (K) - for NT(L) = 5 = CO temperature; F (K) - for NT(L) = 6 = containment break area; ft^2 (m^2) - for NT(L) = 7	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
C3(L) (Cont'd)	= fan source volume number - for NT(L) = 8 = 0 for other values of NT(L). L ≤ 10.	
C4(L)	= spray droplet diameter; ft (m) - for NT(L) = 1 = containment break or vent closing pressure; psia (MPa) - for NT(L) = 7 = 0 for other values of NT(L) L ≤ 10. For a containment failure event, C1 is the failure pressure if NS = 2. If NS = 1 or 3, the failure pressure is set in the code to the containment pressure when the switch parameter is reached. If C4 = 0, inward leakage can occur. If C4 ≠ 0, it is the break (controlled vent) closing pressure. Positive C4 delays start of leakage until next MARCH timestep; negative or zero C4 starts leakage at the next MACE timestep.	None
CMDN	= CO mole fraction at which downward flame propagation into adjoining compartments becomes possible.	0.15
CMHI	= CO mole fraction at which ignition occurs in the absence of igniters.	0.167
CMHZ	= CO mole fraction at which horizontal flame propagation into adjoining compartments becomes possible.	0.138
CMLO	= CO mole fraction at which burning is stopped.	0.003
CMON	= CO mole fraction at which ignition occurs with igniters.	0.148

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
CMUP	= CO mole fraction at which upward flame propagation into adjoining compartments becomes possible.	0.125
CMXX	= CO mole fraction above which complete combustion occurs.	0.148
CVBRK	= orifice coefficient for inter-compartment flow area AVBRK.	0.0
DCF	= suppression pool decontamination factor for halogens and particulates; DCF $\geq$ 1.	None
DCFICE	= decontamination factor for halogens and particulates flowing through ice bed; DCFICE $\geq$ 1.	None
DTO	= small timestep used by subroutine MACEDT to calculate MACE timestep size.	0.05
DTPNT	= time interval between printed MACE outputs; min (s).	10.0
DTS	= stop time for calculation; min (s).	1.0E+4
FALL	= fraction of non-flashed blowdown water falling directly to sump.	None
FSPRA	= fraction of containment spray falling directly into reactor cavity.	None
H2DIST(I)	= characteristic burn distance in compartment I; I $\leq$ 10; ft (m).	None
H2DN	= hydrogen mole fraction at which downward flame propagation into adjoining compartments becomes possible.	0.09
H2HI	= hydrogen mole fraction at which ignition occurs in the absence of igniters.	0.10

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
H2HZ	= hydrogen mole fraction at which horizontal flame propagation into adjoining compartments becomes possible.	0.06
H2LO	= hydrogen mole fraction at which burning is stopped.	0.001
H2ON	= hydrogen mole fraction at which ignition occurs with igniters.	0.08
H2UP	= hydrogen mole fraction at which upward flame propagation into adjoining compartments becomes possible.	0.041
H2VO H2VX	= constants in linear burn velocity correlation; velocity = H2VO + H2VX * XHMAX where XHMAX is the combustible gas concentration; ft/min (m/s).	352.8 11630.0
H2XX	= hydrogen mole fraction above which complete combustion occurs.	0.08
HIG	= inerting gas (CO_2 + steam) equivalent mole fraction required to suppress burning.	0.55
HIOXY	= oxygen mole fraction required to start burning.	0.05
HMAXX	= maximum atmosphere to wall condensing heat transfer coefficient; Btu/hr/ft^2/F (W/m^2/K).	280.0
HUM(I)	= initial relative humidity in compartment I; I $\leq$ 10.	None
IBETA	= 0, no steam explosion in the reactor cavity = 1, steam explosion in the reactor cavity is assumed to fail containment at start of HOTDRP.	0
IBURN	= -1, call subroutine BURN but do not actually burn the hydrogen, calculate adiabatic burn pressure = 0, no hydrogen burn calculation	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
IBURN (Cont'd)	= 1 to 6, hydrogen burns in flammable compartments are permitted when NUPLAC (defined under namelist NLMAR variable IS) reaches IBURN.	
IBURNJ	= 0, no burn propagation	None
	= 1, apply burn propagation tests which depend on direction of flow from burning compartment (downward, horizontal, or upward)	
	= 2, burn in all compartments upon ignition in any compartment.	
IBURNL	= 0, continuous burning	None
	= 1, burn until the hydrogen mole fraction is reduced to H2LO	
	= 2, burn the hydrogen to a calculated mole fraction which is a function of H2XX.	
IBURNM	= 0, do not burn carbon monoxide	None
	= 1, burn until the carbon monoxide mole fraction is reduced to CMLO.	
ICECUB	= -1, BWR suppression pool modeled	None
	= 0, no ice bed or suppression pool	
	= > 1, compartment which receives the gases leaving the ice bed in an ice condenser containment.	
IDRY	= BWR drywell compartment number. For negative value, suppression pool vaporizes into both wetwell and drywell.	0
IGNITE(I)	= 1, burn igniter in compartment I	10*0
	= 0, no igniter in compartment I.	
	I ≤ 10.	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
IVENT	= 0, skip calculation of inter-compartment transfer through an orifice flow resistance (containment venting)	0
	= integer, JK, compartment J will depressurize into a suppression pool or through an ice bed, if present, in initially isolated compartment K. For example, if JK = 12, volume 1 will vent into volume 2. Pressure drop through orifice (AVBRK) is calculated. For positive JK, orifice pressure drop is neglected after compartment pressure equilibration. For negative JK, orifice calculation is always performed. Also, enter data for TVNT1, TVNT2, AVBRK, and CVBRK.	
IWET	= BWR wetwell compartment number. IDRY and IWET must be directly connected compartments; the suppression pool is modeled in the junction between IDRY and IWET.	0
JRPV1	= containment compartment which receives the primary system relief valve flow.	None
JRPV3	= compartment which receives primary system relief valve flow initiated by TVNT2 parameter.	0
KT(I,J)	= 0, no transfer from compartment I to compartment J	100*0
	= 1, transfer from compartment I to compartment J is permitted; specify series flowpaths with no loops	
	= 2, transfers from J to K are suppressed unless the compartment pressure difference before equilibration transfers exceeds PRESS (J,K)	
	Note: compartment connections are specified in BK array if BK $\neq$ 0 and corresponding KT are defaulted to 1.	
	I $\leq$ 10; J $\leq$ 10.	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
N	= number of containment "events"; $0 < N \leq 10$. For each event, variables C1, C2, C3, C4, NC, NS, and NT must be defined.	None
NC(L)	= compartment number in which event L occurs. For an intercompartment fan, NC is the receiver compartment. The containment spray and break events may have multiple starting triggers but NC(L) cannot change; $L \leq 10$.	None
NCAV	= two digit number IJ. I is the containment compartment which contains the reactor cavity. J is the compartment from which water comes into the cavity when the cavity wall melts through. See namelist NLINTR variables WALL and ZF. In a BWR, overflow from the drywell to wetwell occurs when the drywell water volume exceeds VCAV + VFLR. For negative NCAV, cavity does not refill during subroutine HOTDRP and only the water initially there is vaporized. Also, specify VCAV, VFLR, and FSPRA.	None
NCUB	= number of compartments in containment; $NCUB \leq 8$.	None
NRPV1	= compartment which receives initial primary system breakflow. For an ice condenser containment use NRPV1 = ICECUB - 1 or a lower compartment.	None
NRPV2	= compartment which receives breakflow after bottom head failure; negative value bypasses BWR pressure suppression after bottom head failure; if NRPV2 > 100 and concrete melt exceeds WALL or ZF, BWR pressure suppression is skipped.	None
NS(L)	= 1, event L initiated when accident time reaches C1(L) = 2, event L initiated when compartment reaches pressure C1(L)	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
NS(L) (Cont'd)	= 3, event L initiated when compartment reaches temperature C1(L). For negative 2 or 3, event L is initiated on declining pressure or temperature, respectively. L ≤ 10.	
NSMP	= compartment which contains suppression pool, if present; otherwise, compartment which contains containment sump. For negative NSMP, water does not drain into a common sump.	None
NSMP2	= compartment which contains recirculation sump; normally the same as |NSMP|.	None
NT(L)	= event type index = -1, spray recirculation initiation = 1, spray injection initiation The modeling of wetwell spray (NC = IWET) in a BWR depends on NT = ± 1. For NT = + 1, the spray water directly enters the suppression pool (not the atmosphere). For NT = -1, the spray enters the atmosphere. The RHR heat exchanger may be modeled using spray with NT = +1, NC = IWET, and namelist NLHX spray data. = 2, heat removal system initiation (do not use if coolers are on) = 3, steam source initiation = 4, hydrogen source initiation = 5, carbon dioxide source initiation = 6, carbon monoxide source initiation = 7, containment failure or leakage (-7 holds compartment pressure at 14.7 psia after initial depressurization following a containment failure) = 8, intercompartment fan initiation (negative NT fails fan on containment failure)	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
NT(L) (Cont'd)	= 9, turns burn igniters on at time C1(L) in compartment NC(L). L ≤ 10.	
PO	= initial containment pressure; psia (MPa).	None
PRESS(J,K)	= for KT(J,K) = 2 and bK(J,K) = 0, transfers from J to K are stopped unless the pressure difference before transfer exceeds PRESS(J,K); J ≤ 10; K ≤ 10; psia (MPa).	100*0.0
STPECC	= accident time at which all ECC injection (pumps and accumulator) is stopped; min (s).	1.0E+10
STPSPR	= accident time at which containment sprays and fan coolers are stopped; min (s).	1.0E+10
TEMPO(I)	= initial temperature in compartment I; I ≤ 10; F (K).	None
TICE	= initial temperature of ice in ice bed; F (K). 20 F (266.5 K) required. Unexpected results may occur if TICE ≠ 20 F.	20.0
TPOOL	= initial temperature of water in pressure suppression pool; F (K).	0.0
TSTM	= temperature of air-steam mixture exiting top of ice bed; F (K).	105.0
TVNT1	> 0, core exit temperature at which transfers from compartment J to compartment K are initiated (if IVENT ≠ 0); F (K).	1.0E+10
	< 0, initiates transfers from J to K when the pressure in compartment J exceeds |TVNT1|; psia (MPa).	
TVNT2	= core exit temperature at which primary system depressurization directly into the suppression pool (if present) in compartment JRPV3 is initiated if IVENT ≠ 0; F (K).	1.0E+10

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
TWTR	= temperature of water draining from ice bed during first minute of blowdown; F (K).	190.0
TWTR2	= temperature of water draining from ice bed after first minute of blowdown; F (K).	130.0
VC(I)	= volume of compartment I; I ≤ 10; ft^3 (m^3).	None
VCAV	= maximum water volume in reactor cavity; ft^3 (m^3).	None
VFLR	= maximum water volume on compartment NCAV floor before overflow to reactor cavity; water volume in excess of VCAV + VFLR will remain on floor or (for a BWR) drain into suppression pool; ft^3 (m^3).	None
WCDO(I)	= initial fraction CO_2 in the atmosphere of compartment I; mole fraction if WCDO, WCMO, WHYD, WNTR, WOXY are negative; mass fraction if positive. Default is standard air. I ≤ 10.	10*-3.32E-4
WCMO(I)	= initial fraction CO in the atmosphere of compartment I; I ≤ 10.	10*0.0
WHYD(I)	= initial fraction H_2 in the atmosphere of compartment I; I ≤ 10.	10*-4.99E-7
WICE	= initial mass of ice in the ice bed, lb (kg).	0.0
WNTR(I)	= initial fraction of N_2 in the atmosphere of compartment I; I ≤ 10.	10*-0.79
WOXY(I)	= initial fraction of O_2 in the atmosphere of compartment I; I ≤ 10.	10*-0.21
WPOOL	= initial mass of water in pressure suppression pool; lb (kg). If WPOOL < 0, inhibits all suppression functions including that from sparger flow when the containment fails.	0.0

TABLE A.i (CONTINUED)

Variable	Description	Default
	Namelist NLMACE (Continued)	
WVMAKS	= primary water inventory which is maintained by reducing ECC injection to the vessel and increasing the overflow to the containment sump; skipped if the accumulators are not empty or if WVMAKS = 0; lb (kg).	None
WVMAX	= primary water inventory which is maintained by reducing ECC pump flow; skipped if WVMAX = 0; lb (kg).	None
	Namelist NLBOIL	
	Namelist NLBOIL contains input data describing the core, primary system, steam generator (if present), pipe breaks and valves, and melt-down and heat transfer models. Additional (optional) BWR core model input data describing the channel boxes and control blades are contained in namelist NLBWR.	
	If NPAIRL ≥ 2 in namelist NLMAR, the BOIL calculations start at the end of the blowdown data in namelist NLINTL and the BOIL input must correspond to end-of-blowdown conditions. Initial conditions are defined by FM, FR, HO, PVSL, TCAV, TFEOO, TGOO TT(I), VOLSX, VOLPX, WATBHX, WDED, and WTRSG.	
	Heat Transfer Flags:	
	IAXC, ICONV, IHC, IHR, IRAD, ISTM, ISAT	

TABLE A.1 (CONTINUED)

Variable	Description	Default

Namelist NLBOIL (Continued)

Timestep and Output Control:

NDTM
IPRIMP, AB
DTKXXX, DTPN, DTPNTB, TPN
TSB, TSCT
NRPLT, NZPLT

Core Power:

IFP, QZERO, Q235U, R239U
KRPSXX, ANSK, TDK, TRPS, YT, YB
FZ, PF, VF
IDECAY, DHEAT

Core Parameters:

NDZ, NR, R1, R2
ACOR, ATOT, DC, H, D, DF, DH, PITCH
CLAD, XOO, RHOCU, TCAV, HW
ECROS, ELONG, ESTRU, EWAT, VIEW
TALF1, TALF2

Meltdown and Metal-Water Reaction:

MELMOD, NDZDRP, FCOL, FDROP, TFUS, TMELT
TFAIL2, TFAILB, TFAILX
IMWA, MWORNL, FDCR, TMWOFF
IBEDC, IBEDS, CONB, DPART, PORB, TCORMB
DUO2, FZMCR, FZOCR, FZOS1
IMZ, FM, FR

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
	Primary System:	
	PVSL, TGOO, F12, TFEOO, WBAR, WFE2 HO, VOLPX, VOLSX, WATBHX, WDED QPUMP1, QPUMP2, TPUMP1, TPUMP2 TMUP1, TMUP2, WMUP1, WMUP2 ISTR, AH, ARSTR, CM, DD, FPV	
	Steam Generator:	
	ICON, ISG, FULSG, WTRSG, YLEG, YLEG2, TMLEG TAFW, TMAFW, WAFW, WCST PSG, TMSG1, TMSG2	
	Break and Valve Parameters:	
	ABRK, YBRK, YBRK2, TMYBK, FLD, TPM ASRV, YSRV, PSETX, WSETX TB, ABR, YBR, ASR, YSR, PSR	
AB(I)	= flags for diagnostic printout; see Table B.2 for lists of variables printed; I ≤ 16.	16*0.0
ABR(I)	= break area used for time greater than TB(I); I ≤ 16; ft^2 (m^2).	16*-1.0
ABR(16)	= hole size prior to head failure if THKF (namelist NLHEAD) > 0; ft^2 (m^2).	
ABRK	= initial area of break for small LOCA's; ft^2 (m^2). Use zero if ITRAN = 0 in namelist NLMAR.	None
ACOR	= core flow area; ft^2 (m^2).	None
AH(I)	= heat transfer area of I-th structure in reactor coolant system; see discussion of ISTR; I ≤ ISTR+3; ft^2 (m^2).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
ANSK	= fractional power level used for time < TDK if KRPSXX > 0 and ANSK > subroutine ANSQ decay power fraction.	0.0
ARSTR(I)	= flow area of exit gas stream when moving across I-th structure above core; I ≤ ISTR; ft^2 (m^2). = distance from bottom of active core to I-th structure for I > ISTR; ft (m).	None
ASR(I)	= relief valve flow area for time greater than TB(I); I ≤ 16; ft^2 (m^2).	16*-1.0
ASRV	= initial relief valve open flow area; ASRV = 0 if initially closed; ft^2 (m^2).	None
ATOT	= total cross sectional area of water in vessel in the active core region; see definition of HO; ft^2 (m^2).	None
CLAD	= effective clad thickness = WZRCXX/(NR*π*D*H*ρ_{Zr}) where WZRCXX is the total mass of Zircaloy in the core as input to namelist NLHEAD. The masses of spacers, channel boxes, endpieces, etc., may be included in CLAD; however, only rod surface area is modeled; also see namelist NLBWR if IBWR = 1; ft (m).	None
CM(I)	= mass times heat capacity of I-th structure in reactor coolant system. For the steam generator, I = ISG, CM should include the water in the secondary; I ≤ ISTR + 3; Btu/F (J/K).	None
CONB	= debris bed particle thermal conductivity; Btu/hr/ft/F (W/m/K).	2.0
D	= fuel rod diameter; ft (m).	None
DC	= core diameter; ft (m).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NiBOIL (Continued)	
DD(I)	= equivalent flow diameter for I-th structure in exit gas stream above core; I ≤ ISTR; ft (m). = grid plate or bottom head thickness for I > ISTR; ft (m).	None
DF	= fuel pellet diameter; ft (m).	None
DH	= core hydraulic diameter; ft (m).	None
DHEAT	= tabular decay heat data input in pairs of time and power fraction (if DHEAT(2) < 0) or power level (if DHEAT(2) > 0); min (s) and fraction or Btu/hr (W) for a total for IDECAY pairs.	0.0
DPART	= diameter of debris particles in the bottom head; used in subroutine MWDRP and in-vessel debris quenching models; ft (m).	None
DTKXXX	= maximum BOIL timestep size for KRPS > 0 and time < TDK; min (s).	0.1
DTPN	= BOIL printout interval is changed to DTPN for time greater than TPN, or when the core uncovers if DTPN is negative; min (s).	-5.0
DTPNTB	= initial time interval between BOIL printouts; min (s).	15.0
DUO2	= diameter of the UO_2 in the original fuel pellet, normally the same as DF. Used only if a negative value is entered for FDCR. Enter zero for no UO_2 in debris particles in bottom head; ft (m).	None
ECROS	= fuel rod emissivity in radial direction. (See Section 7.2.)	0.70
ELONG	= fuel rod emissivity in axial direction. (See Section 7.2.)	0.214

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
ESTRU	= steel structure emissivity (emissivity of WBAR and CM(1)).	0.60
EWAT	= water emissivity.	0.95
F12	= radiation interchange factor between top of core and heat sink above the core.	0.445
FCOL	= fraction of core melted before total core collapses into bottom head.	0.75
FDCR	= control parameter on the in-vessel cladding reaction	None
	= 0.0, no reaction in the bottom head	
	= 0.X, reaction is forced to fraction 0.X by assuming complete reaction of cladding thickness 0.X*CLAD during core slumping	
	= -1.X, additional cladding reaction for slumped core nodes is calculated by subroutine MWDRP. All reaction is stopped when the fraction reacted exceeds 0.X for X ≠ .0. Enter values for DPART, DUO2, FZMCR, FZOCR, and FZOS1	
	= 1.0, reaction is forced to completion in slumped core nodes	
	= +1.X, no additional reaction in slumped core nodes. Reaction is stopped when the fraction exceeds 0.X.	
FDROP	= fraction of core melted before node-by-node slumping into bottom head starts.	1.0E-5
FLD	= Moody critical flow friction factor.	0.0
FM	= fraction of core material above axial node IMZ that has undergone prior melting. Fission product source is correspondingly reduced.	0.0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
FPV(I)	= fraction of decay heat of volatile fission products stored in-vessel which is absorbed in structure I, I ≤ ISTR. Note that energy is lost if the sum of FPV(I) < 1.	None
FR	= clad above axial node IMZ is assumed to be reacted to fraction FR at start of BOIL calculation.	0.0
FULSG	= mass of water in steam generator secondary under normal operating conditions; lb (kg).	0.0
FZ(I)	= ratio of axial node I power to average node power (sum FZ(I)), with I = 1 at the bottom of the core, I ≤ NDZ.	None
FZMCR	= fraction of Zr metal in the central core of debris particles in the bottom head; used only if a negative value is entered for FDCR.	1.0
FZOCR	= fraction of ZrO_2 in the central core of debris particles in the bottom head; used only if a negative value is entered for FDCR.	1.0
FZOS1	= fraction of ZrO_2 in the first outer shell of debris particles in the bottom head; used only if a negative value is entered for FDCR. Remaining ZrO_2 (1-FZOCR-FZOS1), is in second outer shell.	0.0
H	= active fuel height, ft (m).	None
HO	= effective unswollen initial liquid level above bottom of active core. BOIL calculates the initial primary system inventory of water from WMTOT = RHOL*ATOT*HO + WATBHX + WDED. Thus, the effective HO may be different from the true level, and may be negative for initial level below the bottom of the active core; ft (m).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
HW	= constant fuel to water (or water-steam mixture) heat transfer coefficient, used only for ITRAN (namelist NLMAR) = 0; Btu/hr/ft^2/F (W/m^2/K).	None
IAXC	= 0, no fuel rod axial conduction	None
	= 1, axial conduction modeled.	
IBEDC	= core quenching model for nodes which are or have been molten but have not slumped into bottom head.	None
	< 2, MARCH 1.1 model (original rod geometry)	
	= 2, Dhir-Catton debris bed (not recommended for DPART > 1 mm)	
	= 3, Lipinski debris bed	
	= 4, Ostensen-Lipinski debris bed.	
IBEDS	= quenching model used for debris in the bottom head.	None
	= -1, MARCH 1.1 model	
	= 0, particulate model with heat transfer coefficients calculated by subroutine SPHERE	
	= 1, flat-plate model with radiation plus Berenson film boiling	
	= 2, Dhir-Catton debris bed (not recommended for DPART > 1 mm)	
	= 3, Lipinski debris bed	
	= 4, Ostensen-Lipinski debris bed.	
ICON	= -1, steam generator directly cools water to reduce boiling, steam condensation in steam generator not modeled	1
	= 0, steam is condensed but condensate is not refluxed or included in primary water inventory (mass not conserved)	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
ICON (Cont'd)	= 1, steam is condensed and condensate is added to water in reactor vessel.	
ICONV	= 0, MARCH 1.1 gas properties and rod-to-gas heat transfer coefficients used	20
	= 1, complete Dittus-Boelter and forced laminar convection model used with gas properties from subroutine PROP	
	= 2, complete Dittus-Boelter and forced laminar convection model used with gas properties from subroutine STMH2P.	
	If ICONV > 10, ICONV = 2 modeling is also used for structures above the core.	
IDECAY	= 2 to 100, number of pairs of decay heat table entries	0
	= negative or zero, use ANS 5.1-1979 decay power.	
IFP	= 0, no fission product loss	2
	= 1, fission product loss in BOIL using WASH-1400 model	
	= 2, fission product loss by CORRAL group number.	
IHC	= 0, no convective heat transfer in molten regions	1
	= 1, convective heat transfer continues in molten regions unless IMWA = 2.	
IHR	= 0, neglect rod-to-steam radiation heat transfer	1
	= 1, calculate rod-to-steam radiation heat transfer.	
IMWA	= 0, no metal-water reaction; also see TMWOFF	3
	= 1, no metal-water reaction in melted nodes	
	= 2, no metal-water reaction or convective heat transfer above the lowest melted node in a given radial region	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
IMWA (Cont'd)	= 3, metal-water reaction not stopped by node melting.	
IMZ	= axial node above which cladding is assumed to be previously oxidized (FR) and fuel is assumed to be melted (FM).	100
IPRIMP	= 0, no diagnostic output from subroutine PRIMP	0
	= 1, diagnostic printout from subroutine PRIMP.	
IRAD	= 0, MARCH 1.1 core-to-water and core-to-upper grid plate radiation model, no in-core radiation	2
	= 1, in-core radiation heat transfer modeled using BOIL node temperatures	
	= 2, similar to IRAD = 1 except use effective radiating temperatures; input VIEW.	
ISAT	= 0, use input TT(I) for initial structure temperatures	0
	= 1, set initial temperatures of all structures except the steam generator and structures above an uncovered core equal to initial water temperature, TGOO.	
ISG	= 0, no steam generator	0
	= steam generator heat sink number $2 \leq ISG \leq ISTR$. For ITRAN > 0 in a PWR enter ISG = ISTR. Larger steam generator heat transfer is obtained for ISG > 0, and smaller for ISG < 0.	
ISTM	= 0, uniform steam generation in each radial region	0
	= 1, steam generation proportional to radial power PF(R).	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
ISTR	= number of structures including the steam generator (see ISG) which act as heat sinks in the exit gas stream above the core, ISTR ≤ 4. The input variables AH(I), ARSTR(I), DD(I), CM(I), and TT(I) must be specified for: I = 1, first upper grid plate I = 2,3,4; guide tubes, piping, steam generator, etc. For ITRAN (namelist NLMAR) > 0 must have ISG = ISTR I = ISTR+1, grid plate or structure immediately below core I = ISTR+2, next lower grid plate or structure I = ISTR+3, bottom head.	None
KRPSXX	= 0, subroutine ANSQ decay power is used = 1, power level decreases linearly from QZEROX to ANSK*QZEROX in time TRPS. At time TDK power level drops to subroutine ANSQ level. The BOIL time step is DTKXXX for time < TDK.	0
MELMOD	= 1, meltdown model A = 2, meltdown model B = 3, meltdown model C If a negative value is specified ECC continues after core melting starts. See Section 3.3.3.3 for discussion of models. Also, see namelist namelist NLBWR if IBWR = 1.	-1
MWORNL	= 1, Zr-steam oxidation rate is calculated using new model without output. Model features: (i) oxygen deprivation due to hydrogen blanketing and/or lack of steam, (ii) automatic time step reduction and iterative solution for solid-state oxidation rate, (iii) more representative geometric model for gaseous diffusion oxidation rate, (iv) laminar/turbulent flow conditions, (v) improved physical model (Urbanic-Heidrick) for solid-state oxidation rate	1

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
MWORNL (Cont'd)	= 2, Zr-steam oxidation rate is calculated as for MWORNL = 1, with output	
	= 3, Zr-steam oxidation rate is calculated using old model without output. Model features: (i) Cathcart solid-state oxidation rate, (ii) Baker-Just gaseous diffusion oxidation rate	
	= 4, Zr-steam oxidation rate is calculated as for MWORNL = 3, with output	
	= 5, Zr-steam oxidation rate is calculated using old model without output. Model features: (i) Baker-Just solid-state oxidation rate, (ii) Baker-Just gaseous diffusion oxidation rate	
	= 6, Zr-steam oxidation rate is calculated as for MWORNL = 5, with output	
	For IBWR = 1 in namelist NLBWR, MWORNL must be 3 or 5.	
NDTM	= maximum number of BOIL timesteps; stops execution.	100000
NDZ	= number of axial core nodes, $\|NDZ\| \leq 50$; reduced BOIL printout is obtained for negative values of NDZ.	None
NDZDRP	= melted nodes in a given radial region fall into the bottom head when the node at axial position NDZDRP melts and the fraction of core melted exceeds FDROP.	None
NR	= total number of fuel rods in core.	None
NRPLT(I)	= radial node number saved on plot file; $I \leq 7$.	7*0
NZPLT(I)	= axial node number saved on plot file; $I \leq 7$. If either NRPLT(I) or NZPLT(I) is zero, the following defaults apply:	7*0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
NRPLT(I) NZPLT(I) (Cont'd)	I ≤ 5: NRPLT(I) = center of core NZPLT(I) = equal steps from bottom to top of core I = 6: NRPLT(I) = halfway out from center of core NZPLT(I) = halfway between top and bottom of core I = 7: NRPLT(I) = perimeter of core NZPLT(I) = halfway between top and bottom of core	
PF(I)	= ratio of the radial zone I power to the average radial zone power; sum PF(I)*VF(I) = 1.0; I ≤ 10.	None
PITCH	= distance between fuel rod centers; ft (m).	None
PORB	= debris bed porosity used in BOIL.	0.4
PSETX	= primary system safety relief valve setpoint; psia (MPa).	None
PSG	= steam generator secondary relief valve setpoint; psia (MPa).	0.0
PSR(I)	= relief valve pressure setpoint for time greater than TB(I). If TB(I) > 0 and PSR(I) < 0 (but ≠ -1), the valve will cycle and use a full open flow area ASR(I) for vessel pressures above PSETX and reclose at PSETX - |PSR|; I ≤ 16; psia (MPa).	16*-1.0
PVSL	= initial primary system pressure; psia (MPa); used only if ITRAN > 0.	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
Q235U	= energy release per U235 fission; MeV.	200.0
QPUMP1	= primary coolant pump power for time < TPUMP1; Btu/hr (W). For nonzero primary coolant pump power the steam generator heat transfer defaults to ICON = -1 mode.	0.0
QPUMP2	= primary coolant pump power for TPUMP1 < time < TPUMP2; Btu/hr (W). For nonzero primary coolant pump power the steam generator heat transfer defaults to ICON = -1 mode.	0.0
QZEROX	= initial core thermal power; Btu/hr (W).	None
R1	= innermost radial region number (Integer); R1 $\geq$ 1.	None
R2	= outermost radial region number (Integer); R2 - R1 $\leq$ 10.	None
R239U	= atoms U239 produced per fission.	0.8
RHOCU	= volumetric core heat capacity, based on fuel rod volume (NR*π*D^2*H/4) in active core; Btu/ft^3/F (J/m^3/K).	None
TAFW	= temperature of steam generator secondary makeup water; F (K).	0.0
TALF1 TALF2	= between times TALF1 and TALF2, the void fraction in the level swell model is 1.	1.0E+10 1.0E+10
TB(I)	= if TB(I) > 0, time at which parameters ABR(I), ASR(I), PSR(I), YBR(I), and YSR(I) are changed if different from -1; I $\leq$ 16 ($\leq$ 15 if THKF > 0); min (s).	16*1.0E+10
TCAV	= average initial core temperature; F (K).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
TCORMB	= debris heat transfer mode switches from particulate to debris bed if debris temperature is less than TCORMB; F (K).	1.0E+10
TDK	= time at which power level drops to subroutine ANSQ decay power level; min (s). Used only if KRPSXX = 1.	0.0
TFAIL2	= failure temperature of 2nd lower grid plate; core falls into lower head.	1.0E+10
TFAILB	= core barrel failure temperature; core falls into lower head; F (K).	1.0E+10
TFAILX	= failure temperature for first lower grid plate (structure ISTR+1); debris falls to next grid plate position; F (K).	None
TFE00	= initial temperature of second heat sink above core, used after first structure melts and if input WFE2 is negative; F (K).	None
TFUS	= core melting temperature plus temperature equivalent of latent heat of fusion ($TMELT + \Delta H_{fus}/C_p$); F (K).	None
TG00	= average initial temperature of water (or water-steam mixture) in reactor coolant system; computed if ITRAN (namelist NLMAR) = 0; F (K).	None
TMAFW	= time at which steam generator secondary makeup is started; min (s).	1.0E+10
TMELT	= core melting temperature; F (K).	None
TMLEG(I)	= time at which YLEG changes; $I \leq 3$; min (s). For ISG < 0, the steam generator heat transfer is proportional to (YLIQ - YLEG)/HO. No effect if ISG $\geq$ 0	3*1.0E+10

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
TMLEG(I) (Cont'd)	YLEG = initial value for time < YMLEG(1) YLEG = YLEG2 for TMLEG(1) < time < TMLEG(3) YLEG = initial value for TMLEG(2) < time < TMLEG(3) YLEG = YLEG2 for time > TMLEG(3).	
TMSG1 TMSG2	= between times TMSG1 and TMSG2 the steam generator secondary pressure decreases from PSG to 100 psia; min (s).	1.0E+10 1.0E+10
TMUP1	= time at which makeup/letdown flow through letdown cooler changes from WMUP1 to WMUP2; min (s).	1.0E+10
TMUP2	= time at which makeup/letdown flow through letdown cooler changes from WMUP2 to zero; min (s).	1.0E+10
TMWOFF	= cladding-steam reaction is turned off after the node temperature reaches TMWOFF; F (K).	1.0E+10
TMYBK	= time at which break elevation changes from YBRK to YBRK2; min (s).	1.0E+10
TPM	= constant used to decrease the break flow when the break is below the collapsed liquid level, TPM $\geq$ 1.	1.0
TPN	= time at which BOIL printout interval is changed from DTPNTB to DTPN; min (s).	1.0E+10
TPUMP1	= time at which primary coolant pump power changes from QPUMP1 to QPUMP2; min (s).	1.0E+10
TPUMP2	= time at which primary coolant pump power changes from QPUMP2 to zero; min (s).	1.0E+10
TRPS	= time constant which determines linear (1-time/TRPS) rate of decrease in power level from QZEROX to ANSK*QZEROX for KRPSXX = 1; min (s).	0.0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
TSB(I)	= maximum BOIL timestep for times greater than or equal to TSCT(I); I ≤ 4; min (s). I = 1,2,3,4. For negative TSB timestep is changed at core uncovery; six timesteps after core collapse, timestep is TSB-100, if TSB > 100; if IRAD ≠ 0 or IBWR = 1 (NLBWR) timesteps after the core uncovers of about 0.1 minutes may be required for stability; metal-water reaction may be affected for time-steps over 0.25 minutes; after core collapse one minute timesteps (TSB = 101) are adequate.	4*1.0
TSCT(I)	= time to change BOIL timestep; I ≤ 4.	4*1.0E+10
TT(I)	= initial temperature of I-th structure in reactor coolant system if ISAT = 0. See ISAT; I ≤ 7; F (K).	None
VF(I)	= fraction of core volume in I-th radial region, R1 ≤ I ≤ R2.	None
VIEW	= interpolation factor used in IRAD = 2 in-core radiation heat transfer model.	2.0
VOLPX	= total volume of water and steam within reactor coolant system primary pressure boundary; recalculated in subroutine PRIMP from VOLSX and WMTOT for ITRAN (namelist NLMAR) > 0; ft^3 (m^3).	None
VOLSX	= initial volume of steam within reactor coolant system primary pressure boundary; ft^3 (m^3).	None
WAFW	= steam generator secondary makeup rate; lb/min (kg/s).	0.0
WATBHX	= mass of water, at initial density, which could be stored in bottom head; that is, volume of head * density; lb (kg).	None
WBAR	= mass times specific heat of core barrel used as heat sink in IRAD > 0 radiation heat transfer model in subroutines BOIL and HEAD; Btu/F (J/K).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
WCST	= mass of water available for makeup to the steam generator secondary; lb (kg).	0.0
WDED	= mass of water, at initial density, which could be trapped at low points in reactor coolant system and not boiled away during core uncovery; lb (kg).	None
WFE2	< 0, mass times specific heat of radiation heat sink used if upper grid plate melts; Btu/F (J/K). CM(1) is the corresponding heat capacity used prior to melting	None
	≥ 0, not used.	
WMUP1	= makeup/letdown flow rate for time < TMUP1; gpm (m^3/s). Note that this value is converted to ft^3/min (m^3/s) on output.	0.0
WMUP2	= makeup/letdown flow rate for TMUP1 < time < TMUP2; gpm (m^3/s). Note that this value is converted to ft^3/min (m^3/s) on output.	0.0
WSETX	= primary system relief valve rated capacity; lb/min (kg/s).	None
WTRSG	= initial mass of water in steam generator secondary; lb (kg).	0.0
XOO	= initial zirconium oxide thickness on CLAD; ft (m).	3.28E-6
YB	= for KRPSXX = 1 and unswollen water levels between YB and YT (YB < YT), a linear interpolation of the power level between the maximum of QZEROX*(1-time/TRPS) or ANSK*QZEROX and the decay power from subroutine ANSQ is performed; ft (m).	0.0
YBR(I)	= break elevation for times greater than TB(I); I ≤ 16; ft (m).	16*-1.0
YBR(16)	= hole elevation prior to head failure if THKF (namelist NLHEAD) > 0; ft (m).	

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBOIL (Continued)	
YBRK	= initial break elevation (measured from bottom of active core); ft (m). Break elevation is changed to YBRK2 at time TMYBK.	None
YBRK2	= break elevation after time TMYBK; ft (m).	1000.0
YLEG	= primary side water elevation to cut off steam generator heat transfer for ISG < 0; see TMLEG definition; measured from bottom of core; ft (m).	0.0
YLEG2	= alternative YLEG value for use with TMLEG values; ft (m).	1.0E+10
YSR(I)	= relief valve elevation for times greater than TB(I); I ≤ 16; ft (m).	16*-1.0
YSRV	= relief valve elevation; used to determine liquid versus steam blowdown; normally YSRV < HO + VOLPS/ATOT; ft (m).	
YT	= for KRPSXX = 1 and unswollen water levels between YB and YT (YB < YT), a linear interpolation of the power level between the maximum of QZEROX*(1-time/TRPS) or ANSK*QZEROX and the decay power from subroutine ANSQ is performed; ft (m).	0.0
	Namelist NLBWR	
	Namelist NLBWR contains BWR core parameters for explicit modeling of the channel boxes and control blades. These models are used only if IBWR = 1. The BWR core model features do not completely parallel those in namelist NLBOIL, and not all model options are available. Namelist NLBOIL parameters affected by IBWR = 1 are discussed below.	

TABLE A.1 (CONTINUED)

Variable	Description	Default

Namelist NLBWR (Continued)

Variable	Comment
ACOR	Flow area inside the boxes
IAXC	Axial conduction not modeled (IAXC = 0)
ICONV	Only option modeled is ICONV = 2 or greater than 10
IDBEDC	Not modeled (IDBEDC=0).
IRAD	IRAD may be 0, 1, or 2, but radiation from the boxes and blades to water and upper grid plate is neglected; see Equation E3.66 for ECROS.
MELMOD	Box and blade model A and B in-core slumping is suppressed unless input MELMOD = $\pm$ 10 (for A) or $\pm$ 20 (for B)
MWORNL	MWORNL must be 3 or 5
TMWOFF	Turns off both cladding and box reaction. The maximum box temperature will approach TMWOFF, and TMWOFF < TFUS is recommended.

In addition, a number of other variables must be input as fuel rod or cladding variables rather than lumped-core parameters. These include CLAD, FCOL, FDROP, FDCR, IMWA, RHOCU, TCAV, TFUS, and TMELT. Descriptions of the NLBWR input follows.

NLBWR Flags:

IBWR, IHRBOX, IMWBOX, IMWCB, NBOXS, NCBLAD

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBWR (Continued)	
	Box and Blade Variables:	
	DHBXCB, FBP, FBXCB, FRDBX PBOX, RHOCPZ, TMELBX, TFBOX, XBOX, XBOXZI, XBOXZO ALCBD, RHOCPC, TFCBD, TMELCB, XCBD, XCBDO, XCBDSS	
ALCBD	= length of one arm of control blade; ft (m).	None
DHBXCB	= hydraulic diameter box-to-control blade; ft (m).	None
FBP	= flow bypass fraction; i.e., fraction of steam flowing through box-blade region.	0.10
FBXCB	= radiation view factor between the box and a control blade, based on box area.	0.25
FRDBX	= radiation view factor between the fuel rod and the box, based on box area.	0.25
IBWR	= 1, use BWR core model = 0, do not use BWR core model.	None
IHRBOX	= 0, neglect box to steam radiation heat transfer = 1, calculate box to steam radiation heat transfer.	1
IMWBOX	= control for metal-water reaction in canister = 0, no metal-water reaction = 1, no metal-water reaction in a melted node = 2, no metal-water reaction above the lowest melted node in a given radial region = 3, metal-water reaction not stopped by node melting.	3

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBWR (Continued)	
IMWCB	= control for metal-water reaction in control blade = 0, no metal-water reaction = 1, no metal-water reaction in a melted node = 2, no metal-water reaction above the lowest melted node in a given radial region = 3, metal-water reaction not stopped by node melting.	3
NBOXS	= number of channel boxes in the core.	None
NCBLAD	= number of control blades in core.	None
PBOX	= inside wetted perimeter of one box; ft (m).	None
RHOCPC	= volumetric heat capacity of the control blade; Btu/ft^3/F (J/m^3/K).	None
RHOCPZ	= volumetric heat capacity of the box material; Btu/ft^3/F (J/m^3/K).	None
TFBOX	= melting temperature of the box plus the temperature equivalent of the heat of fusion; F (K).	4175.0
TFCBD	= melting temperature of the control blade plus the temperature equivalent of the heat of fusion; F (K).	3608.0
TMELBX	= box melting temperature; F (K).	3365.0
TMELCB	= control blade melting temperature; F (K).	2600.0
XBOX	= thickness of box; ft (m).	None
XBOXZI	= thickness of ZrO_2 on the inside of the box; ft (m).	3.28E-6

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLBWR (Continued)	
XBOXZO	= thickness of ZrO_2 on the outside of the box; ft (m).	3.28E-6
XCBD	= thickness of a control blade; ft (m).	None
XCBDO	= thickness of oxide layer on control blade stainless steel sheath; ft (m).	3.28E-6
XCBDSS	= thickness of control blade stainless steel sheath; ft (m).	None
	Namelist NLHEAD	
	NLHEAD contains input for the bottom head heatup and failure calculations. A number of the input variables (COND, THKF, TMLTXX, and WUO2XX) may also set model flags in addition to providing basic data.	
COND	= thermal conductivity of debris in the bottom head. Also sets flag for debris-to-head heat transfer coefficient; for negative COND, coefficient is based on Rayleigh number; for positive COND, decay-heat-based coefficients are used; Btu/hr/ft/F (W/m/K).	-8.0
DBH	= diameter of hemispherical bottom head; ft (m).	None
E1	= emissivity of core debris.	0.8
E2	= emissivity of mass WBAR (namelist NLBOIL).	0.5

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLHEAD (Continued)	
FHEAD	= fraction of the non-molten head to be included in the core debris after head failure. All of the liquid is included. The head mass is calculated from the debris-head interface area and the thickness of the bottom head.	None
FOPEN	= fraction of molten top surface area radiating at the internal debris temperature; the fraction 1-FOPEN radiates at the debris head (crust) interface temperature.	None
SIGF	= head ultimate (failure) strength at normal operating temperatures; psi (MPa).	50000.0
THICK	= thickness of bottom head; ft (m).	None
THKF	= head thickness at which a calculated temperature in excess of 1600 F will change the primary system break area to ABR(16) and the break elevation to YBR(16). May be used to model a small hole in the bottom head rather than gross head failure. For negative THKF, gross head failure is obtained; ft (m).	100.0
TMLTXX	= melting temperature of debris in bottom head. Normally TMLTXX defaults to TMELT in namelist NLBOIL. TMLTXX used if negative; F (K).	None
WFECXX	= mass of miscellaneous metal in core added to core debris when head fails; do not include the steel in control blade sheath (XCBDSS, namelist NLBWR) if IBWR (namelist NLBWR) = 1; lb (kg).	None
WGRIDX	= mass of grid plates and structures falling into bottom head; lb (kg).	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLHEAD (Continued)	
WUO2XX	= mass of UO_2 in core. Also sets temperature for calculating top surface molten area and solidus point for conduction limited debris heat transfer. For negative WUO2, liquidus temperature is oxide melting point. For positive WUO2, the steel melting point is used; lb (kg).	None
WZRCXX	= original mass of zirconium in core; lb (kg).	None
	Namelist NLHOT	
	NLHOT contains the input data for the subroutine HOTDRP models of debris-water interactions in the reactor cavity. Namelist NLMACE inputs NCAV, VCAV, VFLR, FPRA, namelist NLECC inputs ACMO and UHIO, and namelist NLMAR input IECCXX along with ECC function also affect reactor cavity modeling.	
	NLHOT Flags:	
	IDBED, IHOT, MWR, NSTOP	
	Cavity and Debris Parameters:	
	ACAV, FLRMC, TPOOLH, WTR CON, DP, PORO, TCORM, TMS, TQNCH	
ACAV	= heat transfer area of top of debris bed in reactor cavity; ft^2 (m^2).	None
CON	= thermal conductivity of debris in reactor cavity; Btu/hr/ft/F (W/m/K).	2.0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLHOT (Continued)	
DP	= diameter of debris particles in reactor cavity; ft (m).	None
FLRMC	= mass times heat capacity of structural metal below the reactor vessel; included in debris at start of INTER; Btu/F (J/K).	0.0
IDBED	= -1, MARCH 1.1 particulate quench model = 0, particulate model with heat transfer coefficients from subroutine SPHERE = 1 or 101, debris bed heat transfer from subroutine DBED using Berensen flat plate correlation = 2 or 102, debris bed heat transfer from subroutine DBED using Dhir-Catton correlation; not recommended for DP > 1.0 mm = 3 or 103, debris bed heat transfer from subroutine DBED using Lipinski correlation = 4 or 104, debris bed heat transfer from subroutine DBED using Ostensen-Lipinski flooding model If IDBED > 100 (that is, IDBED = 102 to 104), a model is employed to calculate the temperature of the gases at the top of the debris bed.	None
IHOT	= controls the logic for transfer to subroutine INTER and, along with input WTR, affects the initial reactor cavity water temperature. Normally the user chooses IHOT = 0 or 100 to model debris-water interactions, or IHOT = 2 to bypass the interaction. IHOT = 0, 2, or 100 with negative WTR or IHOT = 1 or 101 imposes artificial user-specified initial water temperatures, rather than using a code-calculated value.	None

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLHOT (Continued)	
IHOT	Debris-Water Interaction / Initial Water Temperature	
0, 100	interaction stops when debris is quenched (IHOT = 0) or all water is vaporized (IHOT = 100) / calculated or TPOOLH if WTR is negative	
1, 101	same as above / saturated at total containment pressure	
2	two 0.02 min timesteps; use large DP to minimize interaction / calculated or TPOOLH if WTR is negative	
	Transfer to INTER requires a minimum debris temperature of 2500 F. The quench temperature is based on a particulate model at thermal equilibrium.	
MWR	= 1 or 2, Zr-steam oxidation rate is calculated using (i) Urbanic-Heidrick solid-state, or (ii) Baker-Just gaseous diffusion = 3 or 4, Zr-steam oxidation rate is calculated using (i) Cathcart solid-state, or (ii) Baker-Just gaseous diffusion = 5 or 6, Zr-steam oxidation rate is calculated using (i) Baker-Just solid-state, or (ii) Baker-Just gaseous diffusion For MWR greater than 100, a model for the effect of hydrogen generation on debris bed flooding is employed. Steam limiting is based on the bed boiling rate.	1

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLHOT (Continued)	
NSTOP	= maximum number of HOTDRP timesteps; execution stopped without transfer to INTER.	200
PORO	= debris bed porosity.	0.4
TCORM	= debris melting temperature; also used as a logic flag to switch heat transfer from isolated-particle to debris bed mode. For debris temperatures above TCORM a particle model is used and a debris bed model below TCORM. For TCORM greater than 10,000 F (TCORM = TCORM - 10,000 F), the switch is based on a levitation model. For negative TCORM, multiple switching between bed and particulate heat transfer is permitted. For positive TCORM, subroutine INTER calculations begin if the debris temperatures exceeds TCORM (2500 F) after bed formation; F (K).	None
TMS	= maximum (debris) temperature used in steel-water solid-state diffusion rate law; TMS = 0 suppresses the steel reaction; F (K).	2600.0
TPOOLH	= sets the initial temperature of water in the reactor cavity if WTR is negative and IHOT = 0, 2, or 100; otherwise, the temperature is calculated; F (K).	100.0
TQNCH	= adiabatic debris heating starts if the debris temperature falls below TQNCH.	0.0
WTR	< 0, the mass of water in the reactor cavity is set equal to |WTR|; lb (kg) > 0, the reactor cavity water mass and temperature are calculated.	0.0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLINTR	
	Namelist NLINTR contains concrete properties and model data for use in the subroutine INTER calculations of concrete decomposition in the reactor cavity.	
	NLINTR Flags:	
	IGAS, IWRC, IZRFEO, NEPS	
	Concrete Properties:	
	CAYCXX, CPCXXX, DENSCX, RBRXXX, TIC FC1XXX, FC2XXX, FC3XXX, FC4XXX	
	Model Data:	
	EPSI, TEPS, FIOPEN, HIM, HIO FRCW, TDC, TAUL, TAUS RXXXXX, ROXXXX, WALL, ZF	
	Timestep and Output:	
	DTXXXX, DPRIN, TPRIN, TF	
CAYCXX	= thermal conductivity of wet concrete; W/cm/K.	None
CPCXX	= specific heat of wet concrete; J/g/K.	None
DENSCX	= density of wet concrete; g/cm^3.	None
DPRIN	= time interval between printouts; sec.	3600.0
DTXXXX	= initial timestep. Later timesteps can range from DT to 10 sec; sec.	0.5

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLINTR (Continued)	
EPSI(I)	= emissivity for TEPS(I) ≤ time < TEPS(I+1); I ≤ 10.	10*0.5
FC1XXX	= weight fraction of $CaCO_3$ in wet concrete. The Al_2O_3 weight fraction is 1-(FC1XXX + FC2XXX + FC3XXXX + FC4XXX).	None
FC2XXX	= weight fraction of $Ca(OH)_2$ in wet concrete.	None
FC3XXX	= weight fraction of SiO_2 in wet concrete.	None
FC4XXX	= weight fraction of free H_2O in wet concrete.	None
FIOPEN	= fraction (when molten) of the top layer surface area radiating to water in reactor cavity at the internal debris temperature.	None
FRCW	= fraction of the energy radiated to walls which decomposes or ablates concrete. Fraction 1-FRCW is lost from system.	1.0
HIM	= metal-concrete interface heat transfer coefficient. Negative HIM sets flag which suppresses radial heat transfer when both metal and oxide layers solidify; $W/cm^2/K$.	-0.01
HIO	= oxide-concrete interface heat transfer coefficient; $W/cm^2/K$.	0.01
IGAS	= 0, energy of concrete decomposition gases not added to reactor cavity water = 1, energy of concrete decomposition gases leaving the debris is added to reactor cavity water. IGAS greater than 100 sets flag which reduces both the vertical and radial heat transfer coefficients for layer temperatures less than 100 K above the melting temperatures.	1

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLINTR (Continued)	
IWRC	= 0, no heat transfer to reactor cavity water = 1, debris contacts water in reactor cavity.	1
IZRFEO	= 0, skip Zr-FeO reaction = 1, include Zr-FeO reaction during first 1000 sec. Calculations indicate subroutine INTER gives better agreement with the CORCON code if IZRFEO = 0.	0
NEPS	= number of time/emissivity points; $1 \leq$ NEPS ≤ 10; see EPSI(I) and TEPS(I).	2
ROXXXX	= radius of reactor cavity; cm.	None
RBRXXX	= mass of rebar per unit mass wet concrete.	None
RXXXXX	= initial radius of curvature of bottom of melt; cm.	6000.0
TAUL	= time constant for fission product loss from liquid debris; hrs.	0.5
TAUS	= time constant for fission loss from solid debris; hrs.	5.0
TDC	= concrete decomposition temperature in wall ablation model; TDC = 0 suppresses ablation; K.	1373.0
TEPS(I)	= time at which emissivity changes; $I \leq 10$; s.	0.0, 1.0E+10, 8*0.0
TF	= INTER time at which computation stops; s.	3.0
TIC	= initial temperature of wet concrete; K.	293.0

TABLE A.1 (CONTINUED)

Variable	Description	Default
	Namelist NLINTR (Continued)	
TPRIN	= INTER time for first printout; s.	0.0
WALL	= radial penetration of reactor cavity wall at which sump water enters cavity. Also see NCAV and NRPV2 in namelist NLMACE; cm.	1.0E+10
ZF	= vertical penetration of floor at which sump water enters reactor cavity.	1.0E+10

TABLE A.2 FORMAT OF ERROR MESSAGE FILE
(FORTRAN Unit "ERRMSG")

Variable	Meaning
SEVRTY	The severity of the error: 0 Informatory 1 Warning 2 Normal Exit (execution stops) 3 Fatal (execution stops) Other severity values are illegal and cause fatal error 65.
NUM	The error number
MSG	The text of the error message (80 characters)

The above variables are read in (I1, I5, 1X, A80) format, one record for each error number. The records in the file do not have to be sorted in any order.

APPENDIX B

OUTPUT GUIDE

APPENDIX B

OUTPUT GUIDE

Introduction

BOIL Output

The BOIL output includes the printed output, a plot file (Fortran unit "BOILPT"), two files for use in external fission product transport calculations (Fortran units "CORSOR" and "MERGE"), and the mass flow rates at the top of the core (Fortran unit "FLOWS"). The printed output variables obtained in a normal output are defined in Table B.1.

Additional output may be obtained if AB(I) > 0 in namelist NLBOIL. This latter output normally is printed only for diagnostic reasons, and requires familiarity on the part of the user with the names and function of the parameters printed. The variables printed are listed in Table B.2.

Output variables written on the BOIL plot file are listed in Table B.3. Tables B.4 and B.8 list the variables written on the fission product transport files. Table B.5 lists the variables written on the mass flow rate table. The output files on Fortran units "BOILPT", "CORSOR", "FLOWS", and "MERGE" must be saved by the user's control language.

MACE Output

The MACE output includes the printed output, a plot file (Fortran unit "MACEPT"), and a file (Fortran unit "CORRAL") for use in fission product transport calculations. Definitions of the printed output variables are given in Table B.1. The file written on Fortran units "CORSOR" and "MACEPT" must be saved by the user. The variables on the plot file are listed in Table B.6. Table B.7 lists the variables on the fission product file.

HEAD, HOTDRP, AND INTER Output

With two exceptions, only printed output is available from routines other than BOIL and MACE. The exceptions are the axial and radial concrete penetration variables calculated in subroutine INTER, which are included on the MACE plot file. Definitions are given in Table B.1.

TABLE B.1. DEFINITION OF OUTPUT VARIABLES

Output Variable	Description
	BOIL Output
ALF	Void fraction in level swell model at top of mixture.
BOXERR	Indicates negative box-blade space gas temperature calculated in AXIALC if BOXERR = 1.
CRF(I)	Fraction of Group I fission products released; $1 \leq I \leq 7$; (CORRAL group structure).
DMS	Mass times the heat capacity of the core material that slumped into the bottom head in the current timestep; Btu/F (J/K).
DTM	BOIL timestep; min.
DWTR	Water consumed by metal-water reaction in the bottom head in current timestep; lb (kg).
DX(I,R)/DT	Clad oxidation rate in core cladding node I,R; cm/sec.
EGAIN	Net error or imbalance in BOIL energy audit; Btu (J).
ERCSE	BOIL energy error (EGAIN) expressed as percent of the core stored energy.
ERDK	BOIL energy error (EGAIN) expressed as percent of the integrated core decay heat.
ERLK	BOIL energy error (EGAIN) expressed as percent of the total energy leakage from primary system blowdown.
FALLB	Mass times the heat capacity of the core material slumped into bottom head; Btu/F (J/K).
FBLDR(R)	Fraction of control blade sheath reaction in radial zone R.
FBOXM(R)	Fraction of channel box melted in radial zone R.
FBXIR(R)	Fraction of box reacted at rod-box surface in radial zone R.

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
FBXOR(R)	Fraction of box reacted at box-blade surface in radial zone R.
FBZM	Fraction of channel box melted.
FCBM(R)	Fraction of control blade melted in radial zone R.
FCBZM	Fraction of control blade melted.
FCM	Fraction of core melted.
FCR(R)	Fraction clad reacted in radial zone R.
FCRH	Fraction of the clad reacted in bottom head.
FCRO	Fraction of the clad reacted, not including that reacted in the bottom head in the current timestep.
FDMS	Fraction of core slumped into head in the current timestep.
FFALL	Fraction of core slumped into bottom head.
FMET	Fraction of decay heat associated with metal phase.
FNM(R)	Fraction node melted in radial zone R.
FOXB	Fraction of decay heat associated with oxide phase.
FPVSL	Fraction of core decay heat stored in primary system gas space.
FRM	Fraction of core which has ever been melted.
FZM	Fraction of core melted (same as FCM).
GAST(I)	Temperature of gas at the exit of structure I; F (K). GAST(1) is the core exit gas temperature. (Note: for ITRAN = 1, the steam generator is not treated as a structure in subroutine EXITQ, and GAST(ISG) is printed as zero.)

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
HYD	Hydrogen mass in vessel; lb (kg).
H2DRP	Hydrogen produced from metal-water reaction in bottom head; lb/min (kg/s).
H2ENI(I)	Hydrogen enthalpy corresponding to GAST; Btu/lb (J/kg).
H2EXC	Core exit hydrogen flow rate from metal-water reactions in core and bottom head; lb/min (kg/s).
H2GAN	Net error in BOIL hydrogen mass balance audit; lb (kg).
H2OGAN	Net BOIL water/steam mass balance error; lb (kg).
ISAVE	Axial node which contains the mixture level.
ISAVL	Axial node which contains the collapsed liquid level.
M	= 1 when water level in vessel drops below GRID1 elevation = 2 when GRID1 fails (TGRID1 > TFAIL) = 3 when GRID1 has failed and the fraction core melted exceeds FCOL.
MARCH	BOIL (MARCH) timestep number.
MIXEN(I)	Mixed gas enthalpy corresponding to GAST; Btu/lb (J/kg).
MM	= 0 initially = 3 when M = 3, TGRID2 > 800 F, and BOIL has advanced one timestep beyond first printout of M = 3.
NBOIL	Number of BOIL timesteps.
PRES	Primary system pressure; psia (MPa).
PHV	Partial pressure of hydrogen in pressure vessel; psia (MPa).

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
PSV	Partial pressure of steam in pressure vessel; psia (MPa).
PVSLO	Primary system pressure (next timestep); psia (MPa).
QBAR	Power radiated to core barrel; Btu/hr (W).
QCLAD	Power generated from Zr-H_2O reactions in the cladding corrected for enthalpy changes due to different temperatures of products and reactants; Btu/hr (W).
QCONV	Heat transfer from the fuel to the gas flowing through the core; Btu/hr (W).
QDK	Core decay power; Btu/hr (W).
QF(I)	Fraction of decay heat in Group I before fission product release; $1 \leq I \leq 7$; (CORRAL group structure).
QMWBLD	Power generated from Fe-H_2O reaction in the control blade sheath; Btu/hr (W).
QMWBOX	Power generated from Zr-H_2O reaction in the channel boxes; Btu/hr (W).
QMWDRP	Power produced from the metal-water reaction in the bottom head; Btu/hr (W).
QNCH	Power to water from core quenching; Btu/hr (W).
QRADT	Heat radiated from the top of the core to the first grid plate above core; Btu/hr (W).
QRADW	Heat radiated from the core to the water in the vessel; Btu/hr (W).
QSFP	Decay heat of fission products stored in the vessel gas space; Btu/hr (W).

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
QSG	Heat transfer to steam generator; Btu/hr (W).
QSLAB	Heat transfer from the metal structures below the core to the vessel water; Btu/hr (W).
QSTR	Heat transfer to the ISTR structures (not including the steam generator) from the gas stream leaving the core; Btu/hr ((W).
QWTRH	Heat transfer to the water from the core debris in the bottom head; Btu/hr.
RF(I)	Core melt fission product release fractions.
RFV(I)	Vaporization (concrete melt) fission product release fractions.
SGWS	Steam generation rate corresponding to heat transfer rate QSG (ICON $\geq$ 0); lb/min (kg/s).
STM	Steam mass in pressure vessel; lb (kg).
STMEN(I)	Steam enthalpy corresponding to GAST(I); Btu/lb (J/kg).
STMEXC	Core exit steam flow rate (production minus consumption in metal-water reaction); lb/min (kg/s).
STMV	Volume of steam and hydrogen in pressure vessel; ft^3 (m^3).
STRT	Temperature of structures; F (K).
TBAR	Temperature of core barrel; F (K).
TBLAD(R)	Control blade temperature in radial zone R; F (K).
TBOX(R)	Channel box temperature in radial zone R; F (K).
TCORE	Average temperature of the core nodes not slumped into the bottom head; F (K).

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
TDROP	Temperature (energy-equivalent) of the debris that fell into bottom head during current timestep; F (K).
TFALL	Equivalent temperature of core material in bottom head (actual temperature plus temperature equivalent of heat of fusion); F (K).
TFBOX2	Fraction of channel box reacted.
TFCBR	Fraction of control blade sheath reacted.
TFCRB	Fraction of clad reacted.
TFE	Temperature of the first grid plate above core; F (K).
TFPLB	Fraction of fission products retained in the core.
TG(I)	Fluid temperature in radial zone I; F (K).
TGERR	Indicates negative rod-box space gas temperature calculated in AXIALC if TGERR = 1.
TGEXC	Core exit gas temperature; F (K).
TGI(R)	Box-blade channel gas temperature in radial zone R; F (K).
TGLK	Temperature of gas leaked from the primary system; F (K).
TGRID1	Temperature of the first grid plate below the core; F (K).
TGRID2	Temperature of the second grid plate below the core; F (K).
THEAD	Temperature of the bottom head; F (K).
TIME	Accident time; min (sec).
TOTQSG	Total heat input to steam generator; Btu (J).

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
TPOOLB	Temperature of water in the reactor vessel; F (K).
TRO(R)	Fuel rod temperature in radial zone R; F (K).
TRMAX	Maximum core temperature; F (K).
TSATBB	Saturation temperature of water at system pressure (PRES); F (K).
VOLW	Volume of water in vessel; ft^3 (m^3).
WAFW	Feedwater flow rate to steam generator secondary; lb/min (kg/s).
WB	Boiling required to maintain a constant primary pressure; lb/min (kg/s).
WDED	Mass of water in "dead-end" volume; lb (kg).
WFLASH	Steam produced by boiling due to changes in the water saturation temperature; lb/min (kg/s).
WHBRK	Mass flow rate of hydrogen leaking through break; lb/min.
WHRV	Mass flow rate of hydrogen leaking through relief valve; lb/min.
WINJ	ECC flow rate into reactor vessel; lb/min (kg/s).
WLBRK	Mass flow rate of water leaking through the primary system break area; lb/min (kg/s).
WLRV	Mass flow rate of water leaking through relief valve; lb/min.
WMASS	Mass of water above the bottom of the core; lb (kg).
WMVSL	Mass of water in vessel excluding WDED (WMTOT-WDED); lb (kg).

TABLE B.1 (CONTINUED)

Output Variable	Description
	BOIL Output (Continued)
WMTOT	Total water mass in vessel; lb (kg).
WNT	Total steam generation rate; lb/min (kg/s).
WSBRK	Mass flow rate of steam leaking through the primary system break area; lb/min (kg/s).
WSGOUT	Steam generator secondary boiloff rate; lb/min (kg/s).
WSRV	Mass flow rate of steam leaking through relief valve; lb/min (kg/s).
WTRHD	Mass of water in the bottom head; lb (kg).
WTRSG	Mass of water in the steam generator secondary; lb (kg).
WTSGIN	Total mass of feedwater added to steam generator secondary; lb (kg).
XO(I,R)	Thickness of clad reacted in core node I,R; ft (m).
Y	Steam-water mixture level in vessel; ft (m).
YLIQ	Unswollen water level in vessel; ft (m).
YDOT	Rate of change of steam-water mixture level in reactor vessel; ft/min (m/s).
ZXXXXX	Distance from bottom of core; ft (m).
	HEAD Output
AW	Debris-head interface heat transfer area; ft^2 (m^2).
CASE	Indicates which debris-to-head heat transfer model is employed.

TABLE B.1 (CONTINUED)

Output Variable	Description
	HEAD Output (Continued)
DBMCHD	Mass times heat capacity of debris carried into HOTDRP; Btu/F (J/K).
DELD	Thermal penetration distance in debris; ft (m).
DELHED	Thermal penetration distance in vessel head; ft (m).
DELIQ	Equivalent debris-to-wall conduction thickness (DELIQ = COND/HI, where HI is the interface heat transfer coefficient); ft (m).
DPRES	Pressure difference between the pressure vessel and the containment; psi (MPa).
ENIT	Number of iterations in the current timestep.
FCMHD	Fraction of core material melted.
FDM	Fraction of debris melted.
FIM	Fraction of grid plates melted times weight fraction of grid plates in debris.
FOM	Fraction of core material melted times weight fraction of core material in the debris.
HTDBR	Debris depth in bottom head; ft (m).
QBAR	Heat radiated from top of debris to structure WBAR (see namelist NLBOIL); Btu/hr (W).
QDK1	Decay heat remaining in debris; Btu/hr (W).
QKD	Heat conducted into the vessel head; Btu/hr (W).
QMELTH	Heat that goes to melting the vessel head; Btu/hr (W).
QRAD	Heat radiated to upper reactor vessel internals; Btu/hr (W).

TABLE B.1 (CONTINUED)

Output Variable	Description
	HEAD Output (Continued)
QSTORH	Rate of increase in stored energy in vessel head; Btu/hr (W).
RBH	Radius of bottom head; ft (m).
RM	Radius of molten debris pool; ft (m).
SIG	Average tensile strength in the non-melted thickness of the bottom head; psi (MPa).
SIG1	Average tensile strength over the thermal penetration distance of the vessel head; psi (MPa).
SIG2	Tensile strength over the uniform temperature part of the vessel head; psi (MPa).
STRESS	Tensile stress in the bottom head; psi (MPa).
STRS1	Tensile stress where the bottom head meets the cylindrical part of the pressure vessel; psi (MPa).
TBAR	Temperature of structure WBAR (see namelist NLBOIL); F (K).
TD	Temperature of debris; F (K).
TDBRHD	Temperature of debris including portion of solid head carried into HOTDRP; F (K).
TED	Equivalent temperature of debris; F (K). (TED = TD + temperature equivalent of heat of fusion).
TFCRB	Fraction of clad reacted.
TH	Initial thickness of vessel head; ft (m).
THEAD	External head temperature; F (K).
TIME	Time after the initiation of accident; min (sec).
TW	Inside surface temperature of vessel head; F (K).

TABLE B.1 (CONTINUED)

Output Variable	Description
	HEAD Output (Continued)
T1	= (TW + THEAD)/2, average temperature in vessel head thermal peretration distance; F (K).
VDBRI	Initial volume of the debris; ft^3 (m^3).
VDBHD	Volume of debris carried into HOTDRP; ft^3 (cm^3).
WFI	Mass fraction of grid plates in debris.
WFO	Mass fraction of core material in debris.
WGT	Initial mass of the debris; lb (kg).
WGT2	Mass of debris carried into HOTDRP; lb (kg).
WHEAD	(first call) Head mass calculated in subroutine HEAD based on area AW and thickness THICK; lb (kg) (last call) Head mass carried into HOTDRP; lb (kg).
XMDOT	Rate of change of vessel head melt thickness; ft/min (m/s).
XM	Melted thickness of the vessel head; ft (m).
	HOTDRP Output
CLADDR	Initial Zr-metal layer thickness on debris particle; ft (m).
CLADS	Initial iron-metal particle radius; ft (m).
CLADMW	Power from metal-water reaction corrected for enthalpy changes due to different temperatures of products and reactants; Btu/hr (W).
CRF(I)	Fraction of group I fission products released $1 \leq I \leq 7$; (CORRAL group structure).

TABLE B.1 (CONTINUED)

Output Variable	Description
	HOTDRP Output (Continued)
DBMCHD	Mass times heat capacity of debris; Btu/F (J/K).
DP	Particle diameter; ft (m).
DPS	Particle diameter; ft (m).
DWS	Total steam used in metal-water reaction; lb/min (kg/s).
DWSS	Steam used by reaction with iron; lb/min (kg/s).
DWSZ	Steam used by reaction with zirconium; lb/min (kg/s).
ENP	Number of UO_2-Zr-ZrO_2 particles.
ENPS	Number of Fe particles.
FCMHD	Fraction of core which has ever been melted at start of HOTDRP.
FCMAX	Fraction of core material melted.
FDM	Fraction of debris melted.
FFE	Fraction of iron oxidized.
FMET	Fraction of decay heat associated with the metal phase of debris.
FOXHT	Fraction of decay heat associated with the oxide phase of debris.
FZRHOT	Fraction of zirconium reacted.
HCOF	Convection plus radiation heat transfer coefficient between the particle surface and water; Btu/hr/ft^2/F (W/m^2/K).
HDB	Height of porous debris; ft (m).

TABLE B.1 (CONTINUED)

Output Variable	Description
	HOTDRP Output (Continued)
HEFF	Effective heat transfer coefficient between the debris and water; includes effect of debris bed and conduction resistance inside particles; Btu/hr/ft^2/F (W/m^2/K).
HFE	Isothermal energy release in iron-steam reaction; Btu/lb (J/kg) of Fe reacted.
HWT	Height of water calculated assuming water fills the pores in the debris; ft (m).
HZR	Isothermal energy release in zirconium-steaam reaction; Btu/lb (J/kg) of Zr reacted.
H2S	Hydrogen generation rate in iron-steam reaction; lb/min (kg/s).
H2ST	Total mass of hydrogen produced in HOTDRP by iron-steam reaction; lb (kg).
H2Z	Hydrogen generation rate in zirconium-steam reaction; lb/min (kg/s).
H2ZT	Total mass of hydrogen produced in HOTDRP by zirconium-steam reaction; lb (kg).
H2ZST	Total mass of hydrogen generated in HOTDRP; lb (kg).
IIHOT	Input IHOT or IHOT-100 if IHOT is greater than 99.
QDK	Total decay heat, including released volatiles; Btu/hr (W).
QDRYB	Debris bed dryout heat transfer rate; Btu/hr (W).
QF(I)	Fraction of decay heat in group I before release; $1 \leq I \leq 7$; (CORRAL group structure).

TABLE B.1 (CONTINUED)

Output Variable	Description
	HOTDRP Output (Continued)
QMW	Heat generation rate from metal-water reaction; Btu/hr (W).
QMWS	Heat generation rate from iron-steam reaction; Btu/hr (W).
QMWZ	Heat generation rate from zirconium-steam reaction; Btu/hr (W).
QWTR	Total heat transferred to water (QWTRB + gas cooling); Btu/hr (W).
QWTRB	Direct heat transferred from debris to water; Btu/hr (W).
TDBHT	Temperature of the debris; F (K).
TE	Equivalent temperature of debris; TE = T + equivalent temperature rise due to heat of fusion; F (K).
TEMIN	Asymptotic temperature limit for the quenched particles; F (K).
TGAS	Temperature of the steam-hydrogen mixture added to containment atmosphere; F (K).
TFPLHT	Fraction of fission product decay heat remaining in debris.
TOTWS	Total mass of water vaporized in HOTDRP; lb (kg).
TPOOLA	Temperature of water in cavity; F (K).
TSAT	Water boiling temperature at the containment total pressure; F (K).
VDBHD	Volume of UO_2-Zr-ZrO_2 debris; ft^3 (m^3).
VOLFE	Volume of iron debris; ft^3 (m^3).

TABLE B.1 (CONTINUED)

Output Variable	Description
	HOTDRP Output (Continued)
WHBRK	Total hydrogen produced in metal-water reaction; lb/min (kg/s).
WLEV	Steam generation rate required to levitate particle; lb/min (kg/s).
WS	Total steam generation rate; lb/min (kg/s).
WSB	Steam generation rate corresponding to debris bed dry-out QDRYB; WSB is used to determine steam limiting in the metal-water reaction calculations; lb/min (kg/s).
WSBRK	Net steam flow (after metal-water reaction) to containment; lb/min (kg/s).
WSP	Boiling rate in saturated pool for isolated particles; lb/min (kg/s).
WTRHOT	Mass of water in cavity; lb (kg).
XDOT	Zirconium reaction rate; ft/min (m/s).
XDT	Iron reaction rate; ft/min (m/s).
XO	Thickness of Zr reacted, ft (m).
XS	Thickness of Fe reacted; ft (m).
	MACE Output
ABRKMM	Containment leak area; ft^2 (m^2).
ACM	Mass of water in accumulator; lb (kg).
ASWR	Air-to-steam weight ratio in compartment atmosphere.
CBRK	Containment leak orifice coefficient.

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
CHI	Compartment pressure difference; psia (MPa).
DTM	MARCH timestep; min (sec).
DTSUR	Average TSUR - TBULK, where TSUR is the wall surface temperature and TBULK is the temperature of the containment atmosphere (see Equation E6.29); F (K).
DTX	MACE timestep; min (sec).
DWI	Ice melting rate; lb/min (kg/s).
DWOVER	Overflow of water from reactor cavity onto floor of compartment NCAV (printed as a negative number); lb (kg).
EGRVTY	Rate of energy addition to sump from gravitational fallout of water droplets excluding spray; Btu/hr (W).
EP	Energy addition rate to compartment sump from water fallout, sprays, steam condensation in suppression pool, and melting ice; Btu/hr (W).
EPO	Compartment sump energy; Btu (J).
ERR	Energy balance error expressed as percent stored energy in containment atmosphere (100*GAIN/SEATM).
FCFM	Fan flow rate; ft^3/min (m^3/s).
FPA	Fraction of decay heat airborne in containment.
FPCOR	Fraction of the decay heat retained in the core debris.
FPLKD	Fraction of decay heat leaked from containment.
FPQ(I)	Fraction of fission product decay heat in containment compartment I.
FPSMP	Fraction of fission product decay heat in the sump.

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
FPVSL	Fraction of the decay heat stored in the primary system.
FTX(I)	Fraction of source volume transferred to receiver volume on path I.
GAIN	Net containment energy balance error (energy additions minus change in stored energy); Btu (J).
IBURN	Hydrogen burn control parameter = 0, hydrogen burn is not considered = -1, hydrogen burn parameters are calculated but not included in containment mass and energy balances, > 0, hydrogen burn is taken into account.
IBRNUN(I)	= -1, started by nonmechanistic propagation = 0, not burning = 1, started by downward propagation = 2, started by horizontal propagation = 3, started by upward propagation = 4, started by igniters = 5, started by mole fraction hydrogen = H2HI = 6, continuous burning.
I.E.	Internal energy of containment atmosphere; Btu (J).
JCOOL	Building cooler compartment number.
MARCH,MAR	Number of MARCH timesteps.
MGRVTY	Mass of water falling out of the containment atmosphere by gravity per unit time (excluding the spray water); lb/min (kg/s).

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
MLIQ	Mass of liquid water suspended in compartment atmosphere; lb (kg).
MP	Mass addition rate to compartment sump from water fallout, sprays, steam condensation in suppression pool, and ice melt; lb/min (kg/sec).
MPO	Mass of water on compartment floor (sump); lb (kg).
MVAP	Mass of vapor in compartment atmosphere; lb (kg).
MSCI	Mass of steam condensing on the ice per unit time; lb/min (kg/s).
MSCW	Mass of steam condensing on the walls per unit time; lb/min (kg/s).
NFAIL	Compartment number in which containment failure occurs.
NITF	Iteration counter in MACE (transfers too large).
NITU	Iteration counter in MACE (change transfer direction).
NITX	Iteration counter in MACE (zero coefficients in transfer matrix).
NRFLW	Fan receiver compartment.
NSFLW	Fan source compartment.
NSPRA	Spray compartment number.
NTSP	MACE timestep number.
NUPLAC	Indicates the source of mass and energy input to containment: = 1, from INITL = 2, from BOIL = 3, (not used)

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
NUPLAC (Cont'd)	= 4, from BOIL during head heatup = 5, from HOTDRP = 6, from INTER.
PADIAB	Equilibrium pressure in the containment volume in the event of an adiabatic hydrogen/CO burn; psia (MPa).
PCDO	Partial pressure of CO_2 in containment; psi (MPa).
PCMO	Partial pressure of CO in containment; psia (MPa).
PHOLD	Containment leak (vent) closing pressure; psia (MPa).
PHYD	Partial pressure of H_2 in containment; psia (MPa).
PLEAK	Containment leak opening pressure; psia (MPa).
PNCD	Partial pressure of noncondensables in containment atmosphere; psi (MPa).
PNTR	Partial pressure of N_2 in containment; psi (MPa).
POXY	Partial pressure of O_2 in containment; psi (MPa).
PSTM	Partial pressure of steam in containment; psi (MPa).
PTOT, PT	Total pressure in containment; psia (MPa).
QCOOL	Rate of energy removal from the containment by the building cooler; Btu/hr (W).
QSCHX	Rate of energy removal by the containment spray heat exchanger; Btu/hr (W).
QDLBWR	Sum of energy leaving the suppression pool and that directly added to wetwell atmosphere; Btu/hr (W).
QDLICE	Energy leaving the ice bed and entering atmosphere of compartment ICECUB; Btu/hr (W).

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
QECCHX	Rate of energy removal from the ECC recirculation flow by the ECC heat exchanger; Btu/hr (W).
QPOOL	Energy addition rate to the suppression pool; Btu/hr (W).
QQRS	Energy absorbed by containment walls per unit time; Btu/hr (W).
QS[illegible]	Total energy dissipated to the atmosphere in cooling the steam plus air mixture leaked from the containment to 100 F with no phase change (CRAC code input); Btu (J).
RSPRAY	Spray flow rate; lb/min (kg/s).
RWSTM	Mass of water in refueling water storage tank; lb (kg).
SEATM	Total stored energy in the containment atmosphere; Btu (J).
SEWTR	Total stored energy in the containment sump or floor water; Btu (J).
SUMPM	Mass of water in containment sump; lb (kg).
SUMPT	Temperature of water in containment sump; F (K).
SUMPU	Internal energy of water in containment sump; Btu (J).
TAD[illegible]	Equilibrium temperature in the containment volume in the event of an adiabatic hydrogen burn; F (K).
TECC	ECC water temperature; F (K).
TEMP, TEM	Compartment temperature; F (K).
TIMEMM	MACE time; min (sec).

TABLF B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
TINJ	Actual ECC injection water temperature. (Saturation temperature of water at primary system pressure if IECCXX = 2, otherwise TINJ = TECC); F (K).
TNOD(I)	Temperature of containment heat sink wall nodes (input) NOD(I); F(K). TNOD(5) is a heat flux (Btu/hr/ft^2, W/m^2) if input NOD(5) < 0.
TOTALK	Total mass of non-condensable gases leaked from containment; lb (kg).
TOTH2B	Total hydrogen burned; lb (kg).
TOTH2O	Total water plus steam mass in containment; lb (kg).
TOTCOB	Total carbon monoxide burned; lb (kg).
TOTQBN, TQBN	Total energy addition to the containment from hydrogen and carbon monoxide burns; Btu (J).
TOTSLK	Total mass of steam leaked from the containment building since the beginning of the accident; lb (kg).
TOTUAR	Total enthalpy of leaked non-condensables at a temperature of 100 F; Btu (J).
TOTULK	Total integrated steam plus hydrogen enthalpy leaked from the containment; Btu (J).
TOTUSR	Total enthalpy of leaked steam at a temperature of 100 F; Btu (J).
TPO	Temperature of water on compartment floor (sump); F (K).
TQDKMM	Total energy added to the containment by fission product decay heating; Btu (J).
TQHX	Total energy added to the containment by spray heat exchangers and building coolers; Btu (J).

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
TQICE	Total energy added to the containment from the ice bed; Btu (J).
TQRU	Total energy added to the containment by the water and gases from table inputs (MACE events and INITL), from BOIL, HOTDRP, and INTER; Btu (J).
TQWALL	Total energy added to the containment from containment walls; Btu (J).
TRC	Temperature of water in the reactor cavity; F (K).
TS(MVL/VC)	Saturation temperature corresponding to vapor density (MVAP + MLIQ)/VC; F (K).
TSPECH	Total energy added to the containment by direct heating of water (HOTDRP), injection spray, ECC spill-over, and ECC recirculation; Btu (J).
TSPRA	Average temperature of injection and recirculation spray water; F (K).
TSPRAI	Injection spray water temperature; F (K).
TSPRAR	Recirculation spray water temperature; F (K)
TULK	Total energy added to the containment by gas flow through containment holes; Btu (J).
UHI	Mass of water in upper head injection tank; lb (kg).
URC	Reactor cavity water energy; Btu (J).
WCBRK	Containment mass leak rate; lb/min (kg/s).
WCDO	Mass of CO_2 in containment atmosphere; lb (kg).
WCMO	Mass of CO in containment atmosphere; lb (kg).

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
WCOOL	Steam condensation rate in containment building cooler; lb/min (kg/s).
WECC	ECC water flow rate including pumps and accumulator; lb/min (kg/s).
WHYD	Mass of H_2 in containment atmosphere; lb (kg).
WICELL	Mass of ice in ice compartment; lb (kg).
WINJ	Actual injection rate of ECC water into the pressure vessel (WECC-WINJ overflows into containment); lb/min (kg/s).
WNTR	Mass of N_2 in containment atmosphere; lb (kg).
WOXY	Mass of O_2 in containment atmosphere; lb (kg).
WPUMP	ECC pump flow rate; lb/min (kg/s).
WRC	Mass of water in reactor cavity; lb (kg).
WSCWW	Steam condensation or addition rate to the suppression pool; lb/min (kg/s).
WSMP	Sump vaporization rate; lb/min (kg/sec).
WSPRA	Total spray water flow rate; lb/min (kg/s).
WSPRAI	Injection spray water flow rate; lb/min (kg/s).
WSPRAR	Recirculation spray water flow rate; lb/min (kg/s).
WVRC	Vaporization rate of water in the reactor cavity; lb/min (kg/s).
XDSUM	Total carbon dioxide leakage; lb (kg).
XHSUM	Total hydrogen leakage; lb (kg).

TABLE B.1 (CONTINUED)

Output Variable	Description
	MACE Output (Continued)
XMSUM	Total carbon monoxide leakage; lb (kg).
XNSUM	Total nitrogen leakage; lb (kg).
XOSUM	Total oxygen leakage; lb (kg).
	INTER Output
DHQCD	Energy required to heat concrete to the decomposition temperature (input TDC) and decompose it; J/gm.
FCO2	CO_2 released per gram of concrete decomposed; gm Co_2/gm concrete.
FH2O	Steam released per gram of concrete decomposed; gm H_2O/gm concrete.
PATM	Containment pressure; atm.
TAUM	Metal layer fission product vaporization time constant; hr.
TAUOX	Oxide layer fission product vaporization time constant; hr.
TFCR	Fraction zirconium reacted.
TWRC	Temperature of water in reactor cavity; K.
WRCO2	CO_2 released from wall decomposition; gm/s.
WRH2O	Steam released from wall decomposition; gm/s.

TABLE B.2 BOIL DIAGNOSTIC OUTPUT

Condition	Subroutine	Variables
AB(7) > 0 and RBBBBB = 1	BOIL	ATIME, HDB, QBEDC, QDB2, QB2.
AB(8) ≠ 0 and AB(9) ≠ 0	BOIL	NBBBBB, ATIME, SH2O, H2OIN, CMH2O, H2OGAN, SH2, H2IN, CMH2, H2GAN.
AB(9) ≠ 0	BOIL	NBBBBB, ATIME, TQDK, TQMW, TQIN, TQLK, TQMP, DSEWTR, DSEG, DSEC, DSEVE, DSE, DSEB, TBOIL, THLK, DTP, CWC, CH, CW, CMC, TQ, TDSE, EGAIN, TERR, TGX, STM, TPOOLB, WMTOT, ENL2, ENL1, ENS1, ENH1, SEWTR, SEWTR1, SEG, SEG1, ERDK, ERCSE, ERLK.
AB(10) > 0	BOIL	NBBBBB, QBX, QBOIL, QDK, FF(ISAVE), FY, Y, ZXXXXX(ISAVE).
AB(10) > 0 and I = SAVE	BOIL	NBBBBB, RBBBBB, I, QKR, QK(RBBBBB).
AB(11) > 0	BOIL	NBBBBB, DTM, ATIME, WXXXXX, WB, WBMX, WFLASH, SGDWS, FL1, FL2, PRES, TPOOLB, TSATBB, DTOT, RS, F1.
AB(12) > 0 and M > 0	BOIL	NBBBBB, RBBBBB, ISAVE, QVRAD(RBBBBB), QV1, QV2, QV3, SQRAD, VNODE, FY.
AB(13) > 0	BOIL	NBBBBB, RBBBBB, ISAVE, QVRAD(RBBBBB), QV1, QV2, QV3, SQRAD, VNODE, FY.
AB(14) > 0 and RBBBBB = R1 and I = NDZ	BOIL	NBBBBB, QKHC, QKHC2, HTOR (every other node from 2 to NDZ).
AB(15) ≠ 0 and Y ≤ H	BOILP2	SQRAD, STOP, SBAR, TBAR, TFEO.
AB(15) ≥ 2 and Y ≤ H	BOILP2	SHC, SHR, SRE, SPR, SDEN, SCP, SVIS, SCOND.

TABLE B.2 (CONTINUED)

Condition	Subroutine	Variables
AB(16) > 0	BOILEX	NBBBBB, ATIME, GG (elements 1 through IST), TT (elements 1 through ISTR).
IPRIMP > 0	PRIMP	DTM, TIMM, WLBK1, WSBK1, WHBK1, WLRV1, WSRV1, WHRV1, WGBRK1, WVENT1, WVENT2, PVSL, POLDLL, TGX, WS.
IPRIMP > 0 and K > 2	PRIMP	K, TIMM, PK, PVSL, CF, WVENT.
IPRIMP > 0 and WTO > 0	PRIMP	DTM, TIMM, WPLIM, WG, WG1, WG2, WG3, WG4, WGO.

where

ATIME	=	Accident time; min (sec).
CF	=	Critical flow rate of steam in subroutine PRIMP; lb/min/ft^2 (kg/s/m^2).
CH	=	Previous BOIL timestep water specific heat; Btu/lb/F (J/kg/K).
CMC	=	Core heat capacity; Btu/lb/F (J/kg/K).
CMH2	=	Change in mass of hydrogen in vessel; lb (kg).
CMH2O	=	Change in mass of H_2O in vessel; lb (kg).
CW	=	Current specific heat of water in BOIL; Btu/lb/F (J/kg/K).
CWC	=	Ratio CP/(ΔHL/ΔT) from PROPS data.
DSE	=	Change in stored energy in BOIL structure I; Btu (J).
DSEC	=	Change in core stored energy; Btu (J).

TABLE B.2 (CONTINUED)

Condition		Subroutine Variables
DSEFE	=	Change in stored energy of all non-core structures including core barrel; Btu (J).
DSEG	=	Change in stored energy in gas in BOIL; Btu (J).
DSEWTR	=	Change in stored energy in water in BOIL; Btu (J).
DTM	=	BOIL timestep; min (s).
DTOT	=	Water temperature change in BOIL timestep; F° (K).
DTP	=	Water temperature change in BOIL timestep without boiling; F° (K).
EGAIN	=	Net error or imbalance in BOIL energy audit; Btu (J).
ENH1	=	Hydrogen gas space enthalpy in BOIL; Btu/lb (J/kg).
ENL1	=	Water enthalpy in BOIL; Btu/lb (J/kg).
ENL2	=	BOIL water enthalpy at end of timestep; Btu/lb (J/kg).
ENS1	=	Steam gas space enthalpy in BOIL; Btu/lb (J/kg).
ERCSE	=	EGAIN as percent core store energy.
ERDK	=	EGAIN as percent integrated decay heat.
ERLK	=	EGAIN as percent energy leaked to containment.
F1	=	Flag in BOIL; F1 = -1 for YLIQ < H; F1 = 1 for YLIQ > H; F1 = 2 during core slump.
FF	=	Axial peaking factor.
FL1	=	Steam + 9 times hydrogen leakage; lb/min (kg/s).
FL2	=	Water leakage * RHOS/RHOL; lb/min (kg/s).

TABLE B.2 (CONTINUED)

Condition		Subroutine Variables
FY	=	Fraction of axial node covered by mixture.
GG	=	Gas temperature in structures above core; F (K).
H2GAN	=	Net error in BOIL hydrogen mass balance audit; lb (kg).
H2IN	=	(-) hydrogen leaked + hydrogen added from metal-water reaction; lb (kg).
H2OGAN	=	Net BOIL water/steam mass balance error; lb (kg).
H2OIN	=	Net water added (input - leakage) less water reacted; lb (kg).
HDB	=	Depth of in-core debris bed in radial region 1; ft (m).
HTOR	=	Rod temperature correction (DELTF); F° (K).
I	=	Axial node number.
ISAVE	=	Axial node which contains the mixture level.
K	=	Pressure iteration counter in subroutine PRIMP.
NBBBBB	=	BOIL timestep number.
PK	=	Previous iteration vessel pressure; psi (MPa).
POLDLL	=	Previous timestep vessel pressure; psi (MPa).
PRES	=	Primary system pressure; psia (MPa).
PVSL	=	New vessel pressure; psi (MPa).
QB2	=	Core node quench term Q = hAΔT in radial zone 1; Btu (J).
QBEDC	=	Debris bed core quench term; Btu/hr (W).
QBOIL	=	Decay heat of mixture-covered core; Btu/hr (W).

TABLE B.2 (CONTINUED)

Condition		Subroutine Variables
QBX	=	Fraction of core decay heat below mixture level.
QDB2	=	Debris bed core node quench term; Btu/hr (W).
QDK	=	Core decay power; Btu/hr (W).
QK	=	Node decay heat less convective loss times uncovered fraction; Btu/hr/ft (W/m).
QKHC	=	Node convective heat loss; Btu/hr/ft (W/m).
QKHC2	=	Node convective loss by cooling halfway to gas temperature; Btu/hr/ft (W/m).
QKR	=	Node decay heat less convective loss; Btu/hr/ft (W/m).
QV1	=	Node radiation heat loss to water from T^4 law; Btu/hr/ft^3 (W/m^3).
QV2	=	Node radiation loss limited by cooling halfway to water temperature; Btu/hr/ft^3 (W/m^3).
QV3	=	Node radiation loss limited by amount of water above grid number 2; Btu/hr/ft^3 (W/m^3).
QVRAD	=	Node radiation heat loss; Btu/hr/ft^3 (W/m^3).
RBRBBB	=	Radial zone number.
RS	=	Steam gas constant; psi-ft^3/lb/F ($1/s^2$/K).
SBAR	=	Power radiated to core barrel; Btu/hr (W).
SCOND	=	Gas thermal conductivity from subroutine PROP; Btu/hr/ft/F (W/ft/K).
SCP	=	Gas specific heat from subroutine PROP; Btu/lb/F (J/kg/K).
SDEN	=	Gas density from subroutine PROP; lb/ft^3 (kg/m^3).

TABLE B.2 (CONTINUED)

Condition		Subroutine	Variables
SEG	=		Stored energy in the gas; Btu (J).
SEG1	=		Original stored energy in the gas; Btu (J).
SEWTR	=		Stored energy in the water; Btu (J).
SEWTR1	=		Original stored energy in the water; Btu (J).
SGDWS	=		Steam generation rate corresponding to heat transfer rate QSG (ICON $\geq$ 0); lb/min (kg/s).
SH2	=		Hydrogen leakage; lb (kg).
SH2O	=		Water injection minus leakage; lb (kg).
SHC	=		Convection heat transfer coefficient; Btu/hr/ft^2/F (W/m^2/K).
SHR	=		Radiation (to gas) heat transfer coefficient; Btu/hr/ft^2/F (W/m^2/K).
SPR	=		Prandtl number from subroutine PROP.
SQRAD	=		Total heat radiated to water; Btu/hr (W).
SRE	=		Reynolds number from subroutine PROP.
STM	=		Steam mass in primary system; lb (kg).
STOP	=		Radiation from top of core; Btu/hr (W).
SVIS	=		Gas viscosity from subroutine PROP; lb/min/ft (kg/s/m).
TBAR	=		Temperature of core barrel; F (K).
TBOIL	=		Integrated decay heat below mixture level; Btu (J).
TDSE	=		Change in primary system stored energy; Btu (J).
TERR	=		Core temperature equivalent of EGAIN error; F° (K).
TFEO	=		Temperature of grid above core; F (K).

TABLE B.2 (CONTINUED)

Condition		Subroutine Variables
TGX	=	Temperature of gases in upper plenum (leaked to containment); F (K).
THLK	=	Water enthalpy leaked; Btu (J).
TIMM	=	Accident time; min (s).
TPOOLB	=	Temperature of water in pressure vessel; F (K).
TQ	=	Total energy input; Btu (J).
TQDK	=	Total decay heat energy; Btu (J).
TQIN	=	Total energy added by ECC injection; Btu (J).
TQLK	=	Total energy leaked; Btu (J).
TQMP	=	Total energy added by pumps (QPUMP); Btu (J).
TQMW	=	Total metal-water reaction energy; Btu (J).
TSATBB	=	Primary system saturation temperature; F (K).
TT	=	Temperatures of structures above core; F (K).
VNODE	=	Core volume per axial node; ft^3 (m^3).
WB	=	Boiling required to maintain a constant primary pressure; lb/min (kg/s).
WBMX	=	Boiling rate corresponding to TPOOLB-TSATBB; lb/min (kg/s).
WFLASH	=	Steam produced by boiling due to changes in the water saturation temperature; lb/min (kg/s).
WG	=	Minimum of WPLIM or 0.9 * WVENT1; lb/min (kg/s).
WG1	=	Minimum WPLIM or 0.9 * WGBRK1; lb/min (kg/s).
WG2	=	WG - WGBRK1; lb/min (kg/s).

TABLE B.2 (CONTINUED)

Condition		Subroutine Variables
WG3	=	Estimate of gas leakage based on PVSL minus limiting vessel pressure; lb/min (kg/s).
WG4	=	Leakage of 0.025 of stored gas; lb/min (kg/s).
WGBRK1	=	Steam break flow based on minimum of orifice and critical flow; lb/min (kg/s).
WGO	=	Final gas leakage; lb/min (kg/s).
WHBK1	=	Hydrogen break flow; lb/min (kg/s).
WHRV1	=	Hydrogen valve flow; lb/min (kg/s).
WLBK1	=	Water leakage through primary system break area; lb/min (kg/s).
WLRV1	=	Water leakage through relief valve; lb/min (kg/s).
WMTOT	=	Total water mass in vessel; lb (kg).
WPLIM	=	Limiting gas flow based on limiting final pressure (containment or valve setpoint); lb/min (kg/s).
WS	=	Steam input to gas space; lb/min (kg/s).
WSBK1	=	Steam leakage through primary system break area; lb/min (kg/s).
WSRV1	=	Steam leakage through relief valve; lb/min (kg/s).
WVENT	=	Valve gas flow, minimum of WG2 or (WVENT1 + WVENT2); lb/min (kg/s).
WVENT1	=	Flow through full-open part of valve area; lb/min (kg/s).
WVENT2	=	Gas flow through "closed" part of valve area; lb/min (kg/s).
WXXXXX	=	Primary system boiling rate; lb/min (kg/s).
Y	=	Steam-water mixture level in vessel; ft (m).
ZXXXXX	=	Distance from bottom of core; ft (m).

TABLE B.3 BOIL PLOT FILE (FORTRAN UNIT "BOILPT")

This unformatted file contains a single initial record followed by a pair of records for each timestep.

Record	Variables
1	MAR, IU
2n	NBBBBB, ATIME
2n+1	TRMAX, TCORE, TPOOLB, TSATBB, PRES, Y, WINJ, WLBK1, WSBK1, WSOUT, WHOUT, STM, HYD, TGX, QDK, QCLAD, TFCRB, WNT, TGEX, QSG, WTRSG, FCM, WLK, WMTOT, WLRV1, WSRV1, TT (7 elements), TBAR, EGAIN, ERDK, ERSCE, ERLK, QCORE, STMEXC, H2EXC, TH2, ROD (7 elements), SBAR.

where

n	=	1 to total number of BOIL timesteps.
ATIME^{R}	=	Accident time; min (s).
EGAIN^{R}	=	Net error or imbalance in BOIL energy audit, Btu (J).
ERCSE^{R}	=	EGAIN as percent core stored energy.
ERDK^{R}	=	EGAIN as percent integrated decay heat.
ERLK^{R}	=	EGAIN as percent energy leaked to containment.
FCM^{R}	=	Fraction core melted.
H2EXC^{R}	=	Core exit hydrogen flow; lb/min (kg/s).
HYD^{R}	=	Hydrogen mass in primary system; lb (kg).
IU^{I}	=	0, 1. This file is in American Engineering units
	=	2, 3. This file is in SI units.
MAR^{I}	=	MARCH timestep number.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.3 (CONTINUED)

Record		Variables
NBBBBB^I	=	BOIL timestep number.
PRES^R	=	Primary system pressure; psia (MPa).
QCLAD^R	=	Power generated from Zr-H_2O reactions; Btu/hr (W).
QCORE^R	=	Heat transfer to gas in core; BTU/hr (W).
QDK^R	=	Core decay power; BTU/hr (W).
QSG^R	=	Rate of energy loss to steam generator; BTU/hr (W).
ROD^R(NZ, NR)	=	Core node temperature, where NZ = NZPLT(I) and NR = NRPLT(I), $1 \leq I \leq 7$; F (K).
SBAR^R	=	Power radiated to core barrel; Btu/hr (W).
STM^R	=	Steam mass in primary system; lb (kg).
STMEXC^R	=	Core exit steam flow; lb/min (kg/s).
TBAR^R	=	Temperature of core barrel; F (K).
TCORE^R	=	Average core temperature; F (K).
TFCRB^R	=	Fraction clad reacted.
TGEX^R	=	Core exit gas temperature; F (K).
TGX^R	=	Temperature of gases in upper plenum (leaked to containment); F (K).
TH2^R	=	Total H_2 produced; lb (kg).
TPOOLB^R	=	Temperature of water in pressure vesel; F (K).
TRMAX^R	=	Maximum core temperature; F (K).
TSATBB^R	=	Primary system saturation temperature; F (K).
TT^R	=	Temperatures of structures above core (7 elements); F (K).

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.3 (CONTINUED)

Record		Variables
$WHOUT^R$	=	Hydrogen leakage rate from primary system; lb/min (kg/s).
$WINJ^R$	=	ECC flow rate into pressure vessel; lb/min (kg/s).
$WLBK1^R$	=	Water leakage through primary system break area, lb/min (kg/s).
WLK^R	=	Total water and steam leak rate; lb/min (kg/s).
$WLRV1^R$	=	Water leakage through relief valve; lb/min (kg/s).
$WMTOT^R$	=	Total water mass in vessel; lb (kg).
WNT^R	=	Primary system boiling rate; lb/min (kg/s).
$WSBK1^R$	=	Steam leakage through primary system break area; lb/min (kg/s).
$WSOUT^R$	=	Steam leakage rate from primary system; lb/min (kg/s).
$WSRV1^R$	=	Steam leakage through relief valve; lb/min (kg/s).
$WTRSG^R$	=	Mass of water in steam generator secondary; lb (kg).
y^R	=	Steam-water mixture level in vessel; ft (m).

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.4 BOIL FISSION PRODUCT TRANSPORT FILE (FORTRAN UNIT "MERGE")

This unformatted file has a pair of records for each BOIL timestep.

Record	Variables
1	NBBBBB, ATIME
2	TRMAX, TCORE, TSATBB, TGEX, PRES, STMEXC, H2EXC, DTM, FCM, HSAT, TMAXSG, HFGSG, WTRSG, RADT

where

ATIME^R	=	Accident time; min.
DTM^R	=	BOIL timestep; min.
FCM^R	=	Fraction core melted.
H2EXC^R	=	Core exit hydrogen flow rate; lb/min.
HFGSG^R	=	Steam generator secondary heat of vaporization; Btu/lb.
HSAT^R	=	Saturated steam enthalpy; Btu/lb.
NBBBBB^I	=	BOIL timestep number.
PRES^R	=	Primary system pressure; psia.
RADT^R	=	Heat radiated from top of core; Btu/hr.
STMEXC^R	=	Core exit steam flow rate; lb/min.
TCORE^R	=	Average temperature of (non-slumped) core; F.
TGEX^R	=	Core exit gas temperature; F.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.4 (CONTINUED)

Record		Variables
TMAXSG^{R}	=	Steam generator secondary boil-off saturation temperature; F.
TRMAX^{R}	=	Maximum core temperature; F.
TSATBB^{R}	=	Saturation temperature; F.
WTRSG^{R}	=	Steam generator secondary water inventory; lb.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.5 MASS FLOW RATE FILE (FORTRAN UNIT "FLOWS")

The flow rate file is written with format (4 (G10.4, 5X), I3, 5X, G10.4, 5X, G10.4), a group of records each timestep. Each group of records has one record for each core region.

Variable	Format
TIME	G10.4, 5X
DELTAT	G10.4, 5X
TEMP	G10.4, 5X
PRSURE	G10.4, 5X
NREGON	I3, 5X
STMFLW	G10.4, 5X
H2FLW	G10.4

where

$DELTAT^R$	=	Current BOIL timestep; min (s).
$H2FLW^R$	=	Hydrogen mass flow rate; lb/min (kg/s).
$NREGON^I$	=	Core region number.
$PRSURE^R$	=	Core pressure; psia (MPa).
$STMFLW^R$	=	Steam mass flow rate; lb/min (kg/s).
$TEMP^R$	=	Temperature at the top of the core; F (K).
$TIME^R$	=	Accident time; min (s).

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.6 MACE PLOT FILE (FORTRAN UNIT "MACEPT")

This unformatted file contains a single initial record followed by three records for each MACE timestep.

Record	Variables
1	NCUB, IU
3n-1	NTSP, TIMEMM
3n	PT(I), PG(I), PHYD(I), PADIAB(I), TEMMMM(I), WS(I), WHMMMM(I), FPMMMM(I), SMF(I), HMF(I), OXMF(I), PA(I), XMF(I) , elements 1 through NCUB.
3n+1	DZINTR, DRINTR, RWSTMM, TECC, WECC, WINJ, TSPRA, WSPRA, WICELL, TOTULK, QSENS, TOTSLK, TOTRC, RC(NAD), FPMMMM(NCUB+1), FPMMMM(NCUB+2), SUMPM, SUMPT, WRC, TRC, TRMFS, TRWHYD, TNOD (5 elements), TOTVNT, RCVNT.

where

n	=	1 to total number of MACE timesteps.
$DRINTR^R$	=	Radial concrete penetration; cm.
$DZINTR^R$	=	Vertical concrete penetration; cm.
$FPMMMM^R(I)$	=	Fraction of fission product decay heat in containment compartment I; $I \leq NCUB$
	=	Fraction of decay heat leaked; I = NCUB + 1
	=	Fraction of decay heat in sump; I = NCUB + 2.
HMF^R	=	Mole fraction, hydrogen.
IU^I	=	0, 1. This file is in American Engineering units
	=	2, 3. This file is in SI units.
$NCUB^I$	=	Number of compartments in containment.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.6 (CONTINUED)

Record		Variables
NTSP^I	=	MACE timestep number.
OXMF^R	=	Mole fraction, oxygen.
PA^R	=	Non-condensibles partial pressure; psia (MPa).
PADIAB^R	=	Adiabatic hydrogen burn pressure; psia (MPa).
PG^R	=	Steam partial pressure; psi (MPa).
PHYD^R	=	Hydrogen partial pressure; psi (MPa).
PT^R	=	Total compartment pressure; psia (MPa).
QSENS^R	=	Total sensible energy release; Btu (J).
RC^R	=	Containment volumetric leak rate; ft^3/min (m^3/s).
RCVNT^R	=	Volumetric vent rate; ft^3/min (m^3/s).
RWSTMM^R	=	Mass of water in ECC storage tank; lb (kg).
SMF^R	=	Mole fraction, steam.
SUMPM^R	=	Mass of water in sump; lb (kg).
SUMPT^R	=	Temperature of water in sump; F (K).
TECC^R	=	ECC water temperature; F (K).
TEMMMM^R	=	Compartment temperature; F (K).
TIMEMM^R	=	Accident time; min (s).
TNOD^R(I)	=	Containment wall temperature of node NOD(I); F (K).
TNOD^R(5)	=	Wall heat flux through surface NOD(5) if NOD(5) < 0; Btu/hr/ft^2 (W/m^2).
TOTRC^R	=	Total volume of gases leaked; ft^3 (m^3).

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.6 (CONTINUED)

Record		Variables
TOTSLK^R	=	Total mass of steam leaked; lb (kg).
TOTULK^R	=	Total energy leaked from containment; Btu (J).
TOTVNT^R	=	Total volume of gases vented; ft^3/min (m^3/s).
TRC^R	=	Temperature of water in reactor cavity; F (K).
TRMFS^R	=	Water and steam input to containment; lb/min (kg/s).
TRWHYD^R	=	Hydrogen input to containment; lb/min (kg/s).
TSPRA^R	=	Containment spray temperature; F (K).
WECC^R	=	Total ECC pump and accumulator flow; lb/min (kg/s).
WHMMMM^R	=	Mass of hydrogen; lb (kg).
WICELL^R	=	Mass of ice in ice bed; lb (kg).
WINJ^R	=	ECC injection rate to vessel; lb/min (kg/s).
WRC^R	=	Mass of water in reactor cavity; lb (kg).
WS^R	=	Mass of steam plus suspended liquid; lb (kg).
WSPRA^R	=	Spray flow rate; lb/min (kg/s).
XMF^R	=	Mole fraction, others.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.7 MACE FISSION PRODUCT DATA FILE (FORTRAN UNIT "CORRAL")

This unformatted file consists of three initial records followed by a series of records for each MACE timestep.

Record	Variables
1	TITLE
2	ICECUB, NCUB
3	I, VC(I), AREA(I), HCMMMM(I) , elements 1 through NCUB
NCUB records, for I = 1 through NCUB:	NTSP, TIMEMM, DTX, PT(I), PG(I), TEMMMM(I), DTSUR(I), DENG(I), MSCW(I), DML, DMC, B1TEMP, RWHYD(I)
If NBWR > 0:	NTSP, WSRV, WHRV, TUP, PVSLMM, WS30, WA30, WH30, WM30, WD30, SUMPT, QDKP, WSMP, WVRC
If ICECUB > 0:	NTSP, WS30, WH30, WO30, WN30, WM30, WD30, MSCI(ICECUB), DMI, WICELL, TWTR, TWALL(NOD (4)).
	NTSP, NU, [NS(I), NRMMMM(I), RC(I)], elements 1 through NU

where

$AREA^R$	=	Compartment floor area; ft^2.
$B1TEMP^R$	=	Compartment H_2O input rate; lb/min.
$DENG^R$	=	Compartment atmosphere gas density; lb/ft^3.
DMC^R	=	Compartment condensation rate on spray; lb/min.
DMI^R	=	Water drain rate from ice bed; lb/min.
DML^R	=	Compartment time d/dt (MLIQ); lb/min.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.7 (CONTINUED)

Record		Variables
DTSUR^{R}	=	Compartment atmosphere minus wall temperature; F°.
DTX^{R}	=	MACE timestep size; min.
HCMMMM^{R}	=	Height of compartment; ft.
I^{I}	=	Loop index.
ICECUB^{I}	=	If ICECUB > 0, ICECUB is the compartment number which contains the ice bed.
MSCI^{R}	=	Steam condensation rate in ice bed; lb/min.
MSCW^{R}	=	Compartment wall condensation rate; lb/min.
NCUB^{I}	=	Number of compartments.
NRMMMM^{I}	=	Receiver compartment for path.
NS^{I}	=	Source compartment for path.
NTSP^{I}	=	MACE timestep number.
NU^{I}	=	Number of intercompartment flow paths.
PG^{R}	=	Compartment vapor pressure; psia.
PT^{R}	=	Compartment pressure; psia.
PVSLMM^{R}	=	Primary system pressure; psia.
QDKP^{R}	=	Decay heat in suppression pool; Btu/hr.
RC^{R}	=	Inter-compartment flow rate; ft^3/min.
RWHYD^{R}	=	Compartment hydrogen input rate; lb/min.
SUMPT^{R}	=	Suppression pool temperature; F.
TEMMMM^{R}	=	Compartment temperature; F.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.7 (CONTINUED)

Record		Variables
TIMEMM^R	=	Accident time; min.
TITLE	=	Title of problem. A CHARACTER*80 variable.
TUP^R	=	Primary system leaked gas temperature; F.
TWALL^R(NOD(4))	=	Ice bed structure temperature; F.
TWTR^R	=	Temperature of water draining from ice bed; F.
VC^R	=	Compartment volume; ft^3.
WA3O^R	=	O_2 + N_2 flow from drywell into pool or lower compartment into ice bed; lb/min.
WD3O^R	=	CO_2 flow from drywell into pool or lower compartment into ice bed; lb/min.
WH3O^R	=	H_2 flow from drywell into pool or lower compartment into ice bed; lb/min.
WHRV^R	=	Relief valve hydrogen flow; lb/min.
WICELL^R	=	Mass of ice bed; lb.
WM3O^R	=	CO flow from drywell into pool or lower compartment into ice bed; lb/min.
WN3O^R	=	N_2 flow from drywell into pool or lower compartment into ice bed; lb/min.
WO3O^R	=	O_2 flow from drywell into pool or lower compartment into ice bed; lb/min.
WS3O^R	=	H_2O flow from drywell into pool or lower compartment into ice bed; lb/min.
WSMP^R	=	Sump vaporization rate; lb/min.
WSRV^R	=	Relief valve H_2O flow; lb/min.
WVRC^R	=	Reactor cavity vaporization rate; lb/min.

R superscript = REAL variable.

I superscript = INTEGER variable.

TABLE B.8 BOIL FISSION PRODUCT TRANSPORT FILE
(FORTRAN UNIT "CORSOR")

This unformatted file has a series of |NDZ| + 1 records for each BOIL timestep when M1 ≠ 1 and NFPS ≠ 0.

Record	Variables
1	NBBBBB, ATIME, FCM
2	ROD(1,J), S(1,J), FZRN(1,J), for R1 ≤ J ≤ R2
3	ROD(2,J), S(2,J), FZRN(2,J), for R1 ≤ J ≤ R2
...	
|NDZ| + 1	ROD (|NDZ|,J), S(|NDZ|,J), FZRN(|NDZ|,J), for R1 ≤ J ≤ R2

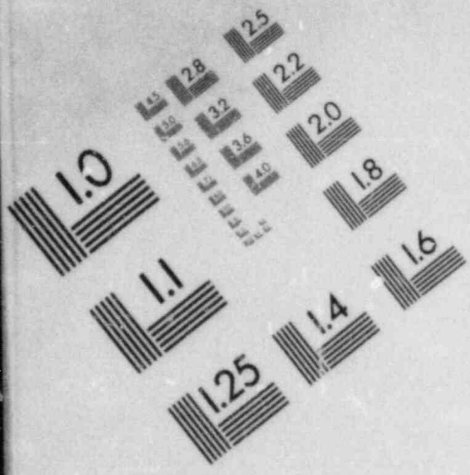
where

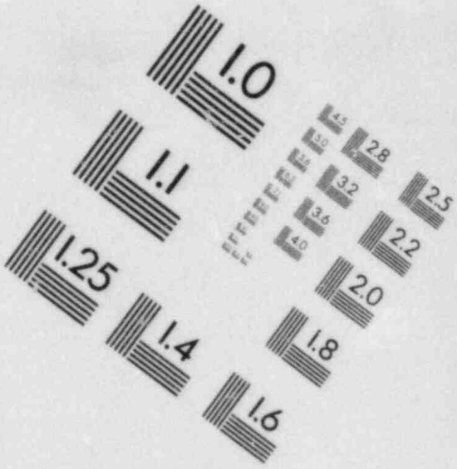
$ATIME^R$	=	Accident time; min.
FCM^R	=	Fraction of core melted.
$FZRN^R(I,J)$	=	Fraction of core node (I,J) cladding reacted.
$NBBBBB^I$	=	BOIL timestep number.
NDZ^I	=	Number of axial core nodes.
$R1^I$	=	Innermost radial region number.
$R2^I$	=	Outermost radial region number.
$ROD^R(I,J)$	=	Core node (I,J) temperature; F.
$S^R(I,J)$	=	ROD(I,J) until core slump, 0 afterward.

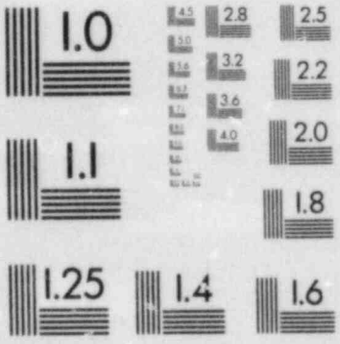
R superscript = REAL variable.

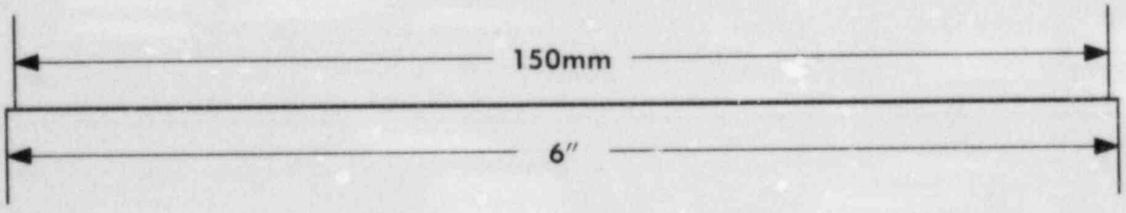
I superscript = INTEGER variable.

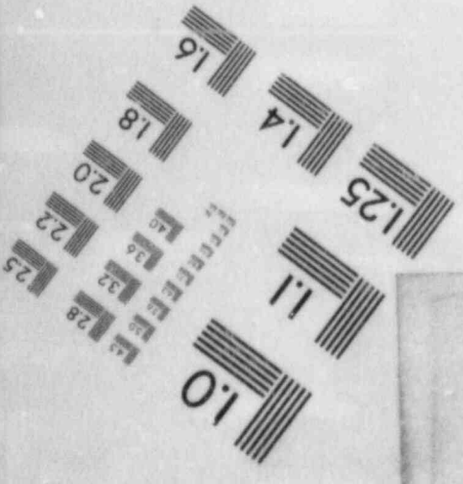
IMAGE EVALUATION TEST TARGET (MT-3)

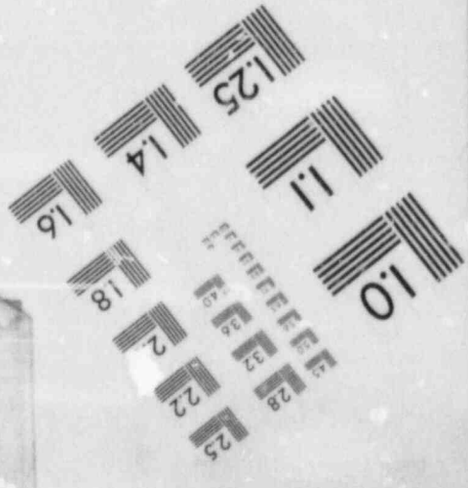












APPENDIX C

ERROR MESSAGES

APPENDIX C

ERROR MESSAGES

Introduction

Table C.1 lists all of the error messages that may be printed by subroutine PERROR, with a brief description of each. The text of each message is held in a file, so the user may choose to change the message texts or add other messages.

Refer to Table A.2 for the format of the error message file.

TABLE C.1. ERROR MESSAGES

Number	Text
1 Normal Exit	MARCH: PTNBR >= PRST The containment pressure has reached the user-specified pressure.
2 Normal Exit	MARCH: CPU TIME >= CPSTP The central processor time has reached the user-specified central processor time limit.
3 Normal Exit	MARCH: TOLD >= TRST The accident time has reached the user-specified accident time.
4 Normal Exit	MARCH: WHERE > IS The problem has reached the subroutine where the user has told it to stop.
5 Normal Exit	MARCH: NUPLAC = 7 The problem has finished executing subroutine INTER. The problem has reached its conclusion.
6 FATAL	MARCH: COMPUTED GOTO ERROR (WHERE) The value of variable "WHERE" in routine MARCH is not in the range of 1 through 6. Indicates an error in the code.
7 FATAL	BOIL: NEGATIVE CP Ratio of water specific heat from subroutine PROPS specific heat data and calculated from enthalpy data is negative.

TABLE C.1 CONTINUED

Number	Text
8 FATAL	BOIL: NEGATIVE CORE TEMPERATURE Negative rod or gas temperature with IBWR = 0, probably associated with use of IRAD ≠ 0. Try smaller BOIL timesteps, or re-node core to eliminate very small radial regions next to large regions.
9 FATAL	BOILP2: MWORNL OUT OF RANGE The value of variable "MWORNL" in subroutine BOILP2 is not in the range of 1 through 6. Indicates an error in the code.
10 Normal Exit	BOILPR: N > NDTM Subroutine BOIL has executed the user-specified number of BOIL timesteps.
11 FATAL	BOILLP: MODEL(I,J) OUT OF RANGE The value of variable "MODEL (I, J)" in subroutine BOILLP is not in the range of 1 through 18. Indicates an error in the code.
12 FATAL	CNVERT: NT(J) OUT OF RANGE The value of input value "NT (J)" is not in the range of 1 through 8. Indicates an error in the code.
13 FATAL	CSHX: BAD INPUT DATA Heat exchanger input data give primary outlet temperature greater than secondary input. Check the input.

TABLE C.1 CONTINUED

Number	Text
14 FATAL	CSHX: MORE THAN 2000 ITERATIONS Subroutine CSHX did not converge while solving for heat exchanger outlet temperatures. May indicate bad heat exchanger input data.
15 FATAL	CSHX: HIGH SECONDARY EXIT TEMP Heat exchanger secondary outlet temperature is greater than 358 F. May be due to bad input data, or could indicate a problem with the code.
16 FATAL	DBED: COMPUTED GOTO ERROR (IDBED) The value of variable "IDBED" in subroutine DBED is not in the range of 1 through 4. Indicates an error in the code.
17 FATAL	ECCHX: BAD INPUT DATA Heat exchanger input data give primary outlet temperature greater than secondary input. Check the input.
18 FATAL	ECCHX: MORE THAN 2000 ITERATIONS Subroutine ECCHX did not converge while solving for heat exchanger outlet temperatures. May indicate bad head exchanger input data.
19 FATAL	ECCHX: HIGH SECONDARY EXIT TEMPERATURE Heat exchanger secondary outlet temperature is greater then 358 F. May be due to bad input data, or could indicate a problem with the code.

TABLE C.1 CONTINUED

Number	Text
20 FATAL	EVENTS: NEGATIVE FLAG Negative time, containment pressure, containment temperature, or spray flow rate encountered during start of containment "event" in subroutine EVENTS. Check input spray. If not due to input, indicates a problem with the code.
21 FATAL	EVENTS: I OUT OF RANGE The value of variable "I" in subroutine EVENTS is not in the range of 1 through 4. Indicates an error in the code.
22 FATAL	EVENTS: COMPUTED GOTO ERROR (NTY) The value of variable "NTY (I, J)" in subroutine EVENTS is not in the range of 1 through 9. One of the values of input NT, namelist NLMACE, is invalid.
23 FATAL	FENT: TEMPERATURE OUT OF RANGE The argument to function FENT is less than 40 or greater than 400 F.
24 FATAL	FVOL: TEMPERATURE OUT OF RANGE The argument to function FVOL is less than 40 F or greater than 400 F.
25 FATAL	GENT: TEMPERATURE OUT OF RANGE The argument to function GENT is less than 40 F or greater than 400 F.

TABLE C.1 CONTINUED

Number	Text
26 FATAL	GVOL: TEMPERATURE OUT OF RANGE The argument to function GVOL is less than 40 F or greater than 400 F.
27 Normal Exit	HOTDRP: N > NSTOP Subroutine HOTDRP has executed the number of user-specified HOTDRP timesteps.
28 FATAL	HOTDRP: MWR OUT OF RANGE The value of variable "MWR" in subroutine HOTDRP is not in the range of 1 through 6. Indicates an error in the code.
29 FATAL	CONVERT: DECAY HEAT TABLE MISSION The input for namelist NLBOIL specified that the user input a decay heat table (IDECAY > 0), but one or more entries for the power level (DHEAT) was less than zero. Fix input.
30 Normal Exit	ECHO: END OF MARCH INPUT CHECK The user had requested a printout of the input read by the program, followed by an exit (ICHECK ≠ 0). To run the problem, set ICHECK to zero.
31 FATAL	INP: END OF INPUT FILE The end of file was encountered on the input file before all the data was read. Fix the input so that all namelists are present, even if empty, and ensure that all namelists end with a "$END" record.

TABLE C.1 CONTINUED

Number		Text
32	FATAL	INTER: NEGATIVE WT Negative mass calculated for component of debris in subroutine INTER. Check input mass fractions. If error is small and not due to input, try changing the tolerance.
33	FATAL	INTER: IFLOP OUT OF RANGE #1 The value of "IFLOP", which indicates the order of the oxide and metal layers, is not in the range of 1 to 3. Indicates an error in the code.
34	FATAL	INTER: IFLOP OUT OF RANGE #2 The value of "IFLOP", which indicates the order of the oxide and metal layers, is not in the range of 1 to 3. Indicate an error in the code.
35	FATAL	INTER: IGC OUT OF RANGE The value of "IGO" in subroutine INTER is not in the range of 1 to 6. Indicates an error in the code.
36	Normal Exit	INTER: TIME > TF The accident time has reached the user-specified accident time.
37	FATAL	MACE: MACE ITERATION FAILURE, NIT Subroutine MACE could not calculate inter-compartment transfers in 10 tries. If failure occurs during an "event", try changing events. Increasing the number of iterations will probably not help.

TABLE C.1 CONTINUED

Number	Text
38 FATAL	MACE: MACE ITERATION FAILURE, NITU Subroutine MACE could not find the proper transfer direction in 10 tries. Increasing the number of iterations will probably not help. If failure occurs during an "event", try changing the event.
39 FATAL	MACE: MACE ITERATION FAILURE, NITF Inter-compartment transfer is too large. Increasing number of iterations will probably not help. Try modifying the problem to reduce the size of the event.
40 FATAL	NO MESSAGE ASSIGNED--SHOULD NEVER OCCUR The call to PERROR that originally printed this error message no longer exists. Indicates an error in the code.
41 FATAL	MACE: NTIME > 20 Failure to converge on burn temperature in subroutine BURN in 20 tries.
42 Normal Exit	MACEND: TIME >= DTS The accident time has reached the user-specified accident time.
43 FATAL	MACENT: NS (I) OUT OF RANGE The value of "NS(I)" is not in the range of 1 to 4. One of the values of input NS, namelist NLMACE, is invalid.

TABLE C.1 CONTINUED

Number		Text
44	FATAL	MELT: COMPUTED GOTO ERROR (MELMOD) The value of "MELMOD", the meltdown model number, is not in the range of 1 to 3. Indicates an error in the code.
45	FATAL	MWDRP: MWR OUT OF RANGE The value of "MWR" is not in the range of 1 to 6. Indicates an error in the code.
46	FATAL	MWDRP: COMPUTED GOTO ERROR (ICASE) The value of "ICASE" is not in the range of 1 to 3. Indicates an error in the code.
47	FATAL	PRIMP: STMV <= 0 Negative gas volume calculated in subroutine PRIMP. Sometimes occurs for large breaks or initially low system pressure accompanied by a large steam spike due to core collapse. Try changing BOIL timestep or break size.
48	FATAL	NO MESSAGE ASSIGNED--SHOULD NEVER OCCUR The call to PERROR that originally printed this error message no longer exists. Indicates an error in the code.
49	FATAL	PROP: COMPUTED GOTO ERROR (N) The value of "N", passed to subroutine PROP, is not in the range of 1 to 16. Indicates an error in the code.

TABLE C.1 CONTINUED

Number	Text
50 FATAL	PRSS: TEMPERATURE OUT OF RANGE The argument to function PRSS was less than 40 F or greater than 400 F. Indicates an error in the code.
51 FATAL	SATEST: TSAT > 400 F Steam saturation temperature out of range of subroutine MACE correlations.
52 FATAL	TGEOM: COMPUTED GOTO ERROR (IFLOP) The value of "IFLOP", which indicates the order of the metal and oxide layers, was not in the range of 1 to 3. Indicates an error in the code.
53 FATAL	TGEOM: IFLOP OUT OF RANGE The value of "IFLOP", which indicates the order of the metal and oxide layers, was not in the range 1 to 3. Indicates an error in the code.
54 FATAL	ZRWATR: MWORNL OUT OF RANGE The value of "MWORNL" was not in the range 1 to 6. Indicates an error in the code.
55 FATAL	MACE: NRPV = 0 Input error. Check NRPV1 and NRPV2.
56 FATAL	PRIMP: STM < 0 Subroutine PRIMP calculated a negative steam mass. May occur at low system pressure with large break. Try changing the problem by closing valve or decreasing break area.

TABLE C.1 CONTINUED

Number	Text
57 FATAL	PRIMP: HYD < 0 Subroutine PRIMP calculated a negative hydrogen mass. May occur at low system pressure with large break. Try changing the problem by closing valve or decreasing break area.
58 FATAL	MACEDT: NEGATIVE "UT" Negative containment enthalpy calculated by subroutine MACE. Check containment energy losses by constant capacity cooler, bad (large) containment wall mesh size, large area containment leak, etc.
59 FATAL	CNVERT: SLAB MESH INTERVAL <= 0 Check the namelist NLSLAB input for X (I).
60 Normal Exit	PAGE: CPU TIME >= CPSTP The central processor time has reached the user-specified limit.
61 FATAL	INP: END OF DEFAULT FILE An end-of-file condition occurred on the default values file unexpectedly. This usually indicates that the namelist input was improperly formatted.
62 Informatory	INP: NO DEFAULT FILE AVAILABLE The program attempted to open a user default values file. No file was found. Execution continues without using any defaults other than those in the code.

TABLE C.1 CONTINUED

Number	Text
63 FATAL	PERROR: INVALID ERROR NUMBER The value passed to subroutine PERROR was not found in the error message file. The error message file may be damaged or defective. If the error message file is correct, there could be an error in the code.
64 FATAL	PERROR: ERROR READING ERROR TEXT FILE An error occurred while reading the error message file. This usually indicates trouble with the error message file or the operating system.
65 FATAL	PERROR: ILLEGAL SEVERITY VALUE READ IN ERROR TEXT FILE The error message that PERROR is printing has an invalid severity value. Severity codes run from 0 to 3 (see Table A.2). The text of the message is printed as read. This usually is caused by a damaged or defective error message file.
66 FATAL	THTRPS: SPECIFIC HEAT <= 0 Bad specific heat calculated in subroutine THTRPS. Try ICONV < 2.
67 FATAL	SPHERE: TW OUT OF RANGE Debris temperature out of range.
68 FATAL	THTRPS: PRESSURE > 3208.2 PSI Pressure outside range of correlation in subroutine THTRPS. Change problem or try ICONV < 2.

TABLE C.1 CONTINUED

Number		Text
69	FATAL	THTRPS: CANNOT COMPUTE PRANDTL NUMBER Negative properties used in Prandtl number calculation. Try ICONV < 2 or change problem.
70	FATAL	SPEEDY: REFERENCE OUTSIDE PHYSICAL PROPERTIES TABLE Change problem or try ICONV < 2.
71	FATAL	SOLINQ: EQUATIONS ARE INCONSISTENT Subroutine SOLINQ thinks the compartment connections in namelist NLMACE are inconsistent.
72	FATAL	HOTDRP: HEFF < 0 OR H < 0 Negative heat transfer coefficient calculated in subroutine HOTDRP.
73	FATAL	HOTDRP: TEMIN < TSAT Implies negative heat transfer coefficient in subroutine HOTDRP.
74	FATAL	HOTDRP: QWTR < 0 Implies negative mass of water in reactor cavity or negative heat flux from debris to water subroutine HOTDRP.
75	FATAL	SPHERE: H < 0 Negative heat transfer coefficient calculated in subroutine SPHERE.

TABLE C.1 CONTINUED

Number		Text
76	FATAL	DBED: QDRYOT < 0 Negative debris bed dryout heat flux calculated in subroutine DBED.
77	FATAL	HOTDRP: TCORM < 2500 F Input TCORM in namelist NLHOT must be over 2500 F.
78	FATAL	CNVERT: NCAV = 0 A value of zero as input for variable "NCAV" is not legal. Consult Table A.1., namelist NLMACE, for guidance.
79	FATAL	MACENT: NCAV > NCUB Input NCAV must be less than NCUB in namelist NLMACE.
80	FATAL	AXIALC: TG (I, R) < 0 Negative gas temperature in rod-box space if TGERR = 1, or negative gas temperature in box-blade space if BOXERR = 1. Failure in BWR core model (IBWR = 1 in namelist NLBWR) convective heat transfer model. Try a smaller BOIL timestep.
81	FATAL	EXPFUN: ARGUEMENT TO EXPONENTIATION TOO LARGE An attempt was made to take the exponential of too large a number.

TABLE C.1 CONTINUED

Number		Text
82	Warning	INTRNT: NEGATIVE INPUT FLRMC Code adds mass (in grams) of FeO equal to (-) FLRMC*10^6 to initial subroutine INTER debris.
83	FATAL	CONVERT: MWORNL MUST BE 3 OR 5 WHEN IBWR = 1 The BWR core model uses MWORNL = 3 or 5 only.
84	Warning	BOIL: BOIL TIMESTEP MAY BE TOO LONG FOR SUBROUTINE ZRWATR Subroutine ZRWATR has reduced its internal timestep to as small as possible, but the oxide produced in at least one node is greater than 0.1 percent of the unreacted cladding. This message is printed only once for each series of BOIL timesteps that meet this condition.
85	FATAL	STMH2P: NEGATIVE PROPERTIES One or more of the properties calculated in subroutine STMH2P are less than zero.

APPENDIX D

SAMPLE PROBLEMS

APPENDIX D

SAMPLE PROBLEMS

Introduction

As an aid to the MARCH 2 user, a series of sample problems have been included with the distribution package for the code. The rationale for the selection of the specific sample problems, the specific input parameters selected, and the results obtained are discussed in this section. The approach utilized in the selection of these sample problems for MARCH 2 involved consideration of a representative selection of reactor and containment system design, a variety of accident sequences, and also consideration of physical phenomena modeling options that would exercise a variety of the features available in MARCH 2. Although the input parameters are believed to be generally representative of actual reactor systems, the specific values have been chosen for illustration and should not be taken as recommended parameters for any actual plant design. Similarly, the modeling options utilized in these sample problems are plausible choices, but should not be construed as being recommended or best estimate value. The individual user is responsible for the selection and justification of the particular choices for the application at hand.

The specific reactor designs and accident sequences considered in the sample problem set include:

PWR Large Dry Containment Transient
PWR Ice Condenser Containment Small Break LOCA
BWR Mark III Transient
BWR Mark II Large LOCA

As can be seen, the above sequences encompass both PWR and BWR designs, several of the principal containment system concepts, and a variety of initiating accident events.

The PWR Large Dry Containment Transient represents a transient-initiated accident event accompanied by the loss of the normal power conversion system, loss of the auxiliary feedwater system, and loss of all electric power for a significant period of time, e.g., more than three hours. This is

the TMLB sequence in the WASH-1400 nomenclature. The lack of electric power prevents the operation of the primary and secondary coolant makeup systems as well as preventing the operation of the containment safety systems. In this sequence the primary coolant inventory is boiled off through the pressurizer relief valve, with eventual core uncovering and melting; the absence of containment heat removal may lead to pressure rises that may challenge containment integrity. A sequence of this type was one of the dominant accidents in the WASH-1400 analyses for this type of design and has been found to be among the important sequences in the risk assessments of other PWR's. It is one of the most widely analyzed accident sequences since the advent of probabilistic risk assessments and consideration of severe accident issues.

The PWR Ice Condenser Small Break LOCA represents an accident initiated by a small break in the primary piping system accompanied by the failure of the emergency core cooling system. The containment engineered safety features are assumed to be available in this sequence. The small pipe break is believed to be among the more likely initiating accident events, though the combination of the pipe break and failure of the core cooling system may not be of very high probability.

The BWR Mark III Transient represents a transient-initiated event with loss of normal power conversion together with failure of the high pressure and low pressure emergency core cooling systems. In order to illustrate a number of code features,delayed scram, a small leak in the vessel bottom head, and restoration of some of the core cooling injection system have been included in the sample problem. In the latter respects this problem is not typical of a standard severe accident sequence.

The BWR Mark II Large LOCA represents a large break loss-of-coolant accident with simultaneous failure of the emergency core cooling injection system.

The input for each of these sequences as well as the results obtained are discussed below. The sample problem input decks together with the MARCH 2 calculated results are included with the code distribution package.

IT IS IMPORTANT TO NOTE THAT THE SAMPLE PROBLEMS TRANSMITTED WITH THE CODE AND DISCUSSED HERE HAVE BEEN PREPARED SOLELY TO ILLUSTRATE PREPARATION OF THE INPUT FOR THE CODE AND TO ENABLE THE POTENTIAL MARCH 2 USER

TO VERIFY OPERABILITY OF THE CODE AT HIS INSTALLATION. NO REPRESENTATION IS MADE AS TO THE APPLICABILITY OF THESE INPUT DECKS TO ANY PARTICULAR SYSTEM DESIGN, OR THAT THE PARTICULAR MODELING OPTIONS SELECTED HERE ARE IN ANY WAY RECOMMENDED CHOICES. IT IS OBVIOUSLY THE RESPONSIBILITY OF THE INDIVIDUAL MARCH CODE USER TO ASSESS THE SUITABILITY OF INPUT AND MODELING PARAMETERS TO HIS PARTICULAR DESIGN AND INTENDED APPLICATION.

PWR Large Dry Containment Transient

Input Description

In this sequence, as has been noted previously, the active engineered safety features are not available, so little will be said about their modeling in this discussion. The principal attention will be given to the code modeling options utilized.

The first data entry is the title card. The remaining input data are entered in twelve namelists which are discussed below in order. In general, all namelist variables which do not have default values must be entered. Failure to do so will cause the code to stop execution during the units conversion check.

Namelist NLMAR primarily provides control information on problem execution and sets accident sequence flags. The ICHECK parameter allows the user to have MARCH process and print out the input data without execution, and is particularly useful during the initial data preparation stage. NLMAR defines this sequence as being a transient (ITRAN = 1 and IBRK = 0) with no containment sprays (ISPRA = 0). While there is no active emergency core cooling, IECC is set to 2 in order to permit the discharge of the accumulators after vessel failure. The containment does not contain an ice condenser (ICE = 0). There is no input blowdown table (NPAIR = 0). Steam explosions and check valve failures are not considered (IXPL = 0 and ICKV = 0), and reference fission product releases are assumed (IFPSM and IFPSV = 2). Plot files are written (BOILPT = 9 and MACEPT = 11); the other files are not saved in order to save disc file space during execution (CORRAL, CORSOR, FLOWS, and MERGE = 0). Since the input blowdown table option is not utilized, there is no NLINIT input.

NSLAB is used to describe the containment structural heat sinks. In the problem at hand there are five slabs composed of two materials (NSLAB = 5 and NMAT = 2); the materials are steel and concrete and the density, heat capacity, and thermal conductivity for each must be provided. Slab and material names are entered as ISLAB and IMAT. The specification of the slab properties includes the compartment number in which the left and right faces of the slab are located (IVL and IVR), the number of nodes in each region of the slab (NNO1 and NNO2), the material number of each region (MAT1 and MAT2), the surface area of each slab (SAREA), the interface heat transfer coefficient between different materials in a composite slab (HIF), and a flag for the symmetry of the temperature distribution within a slab (DTDX). For symmetrical slabs entirely in one compartment the heat transfer area may be doubled and only half of the slab considered in the heat conduction analysis. In this sample problem, the dome and the shell of the containment structure are characterized as two-material slabs consisting of a steel liner and a concrete shell; the other slabs are single material of either steel or concrete. The node coordinates measured from the left boundary must be provided for each slab. Small node distances are required near the faces of low conductivity materials such as concrete, but they can be successively doubled with distance into the slab. Near the interface of two different materials the node spacing should be comparable. The one-hundredth of a foot node spacings between the first two nodes in the concrete slab used in this problem has been found to give satisfactory agreement with analytic solutions. The initial temperature for each node must be provided as input; for uniform temperature distribution within each slab this can easily be accomplished by means of the namelist input format. If the temperatures within the slabs are not uniform at the start of the problem, and/or the slab temperatures in a compartment are different from that of the atmosphere, an initial conduction transient may be induced. The input array NOD(I) permits the specification of up to five nodes whose temperatures are saved on the containment plot files. Negative NOD(5) will save a heat flux value on the MACE plot file, and NOD(4) is saved on the ice condenser fission product file. The choice of the nodes to be saved is left to the user.

NLECC provides for the description of the emergency core cooling system characteristics. In this sample problem only the accumulator is

pertinent; the latter is characterized in American engineering units by a pressure setpoint (PACMO = 600), initial mass of water (WACM = 124,800), and initial water temperature (TACMO = 110). The other ECC system variables do not enter into this problem, but will be discussed in the context of other sample problems. The namelists used to describe the emergency core cooling recirculation heat exchanger and the containment spray recirculation heat exchanger (NLHX) and building coolers (NLCOOL) will be discussed in connection with sample problems in which they are considered. In this sample problem the ECC heat exchanger will not work because the ECC pumps are not on, although performance data are entered for it. Likewise, the cooler will not work since it is placed in compartment JCOOL = 0 with a start time of 1,000,000 minutes.

The physical description of the containment, its performance characteristics, as well as the performance of certain engineered safety features are described in NLMACE. In the present problem the containment is modeled as a single compartment (NCUB = 1) at an initial pressure of 14.7 psia (PO = 14.7). There is no ice condenser or suppression pool; thus a number of the variables associated with these containment types are not used, although default data are entered. Since the containment has only a single compartment, the location of the break flows before vessel failure (NRPV1), the location of the break flow after vessel failure (NRPV2), and the location of the relief/safety valve flow (JRPV1) are all set equal to one. After head failure the sources generated by HOTDRP and INTER are interpreted as break flows, thus NRPV2 must be specified. NSMP and NSMP2 are both equal to one in this problem; in multi-compartment representations these variables may be used to specify more than on sump, identify the relationship among them, and specify which is the recirculation sump. NCAV specifies the compartment in which the reactor cavity is located; positive NCAV allows the reactor cavity to refill due to overflow from the sump during the (HOTDRP) interaction of the core debris with water in the reactor cavity when the sump water volume exceeds VFLR (a value of 4000 cubic feet has been selected for the present problem). VCAV is used to define the maximum volume of water in the reactor cavity. The variables WVMAX and WVMAKS may be used to specify the disposition of excess emergency core cooling water if the latter system is operable; they do not enter into the present problem and are set equal to zero. FALL specifies the fraction of the liquid in the flashed coolant blowdown that falls directly to

the containment sump; FSPRA defines the fraction of the containment spray water that falls directly into the reactor cavity. IXPL = 0 indicates that containment steam explosions are not included in this problem; IVENT = 0 indicates that containment venting or orifice flow connections are not considered and a number of related variables are defaulted. STPECC defines the time when all ECC pumps and accumulator flows are stopped, and STPSPR does the same for containment sprays and coolers; both are set to large numbers since they do not enter into the present problem. DTPNT specifies the time interval between printed MACE outputs, and DTS may be used to specify a time for stopping the calculation. The containment initial conditions are characterized by the compartment volume, VC(I), floor area, AREA(I), initial relative humidity, HUM(I), and initial temperature, TEMPO(I). The arrays WCDO(I), WCMO(I), WHYD(I), WNTR(I), and WOXY(I) are used to specify the initial composition of the atmosphere in each compartment in terms of mole fractions (negative values) or mass fractions (positive values) of carbon dioxide, carbon monoxide, hydrogen, nitrogen, and oxygen, respectively. If no entries are made, these variables default to "standard" air of 79 percent nitrogen and 21 percent oxygen. The containment events table in NLMACE may be used to specify containment performance and to activate a variety of containment safety systems. In the present case there are two events (N = 2). NS(1) = 2 indicates that the first event is initiated when the compartment pressure reaches the input value C1(1). NC(1) = 1 indicates that the first event takes place in compartment number one. NT(1) = 1 indicates that the event is spray injection initiation, and C1(1) = 500 gives the value of the containment pressure at which the spray is initiated (since NS(1) = 2); in this case the high initiation pressure is used to prevent spray operation even though the other input data has been provided. C2(1) = 2000 is the spray flow rate, C3(1) = 100 specifies the spray temperature, and C4(1) = 0.0013 is the spray droplet diameter in feet. NS(2) = 2 indicates that the second event is also initiated on the compartment pressure reaching the input value C1(2). NC(2) = 1 indicates that the second event also occurs in compartment number one. NT(2) = 7 specifies that the event is containment failure or venting. C1(2) = 500 defines the containment failure pressure (since NS(2) = 2). The use of a high failure pressure is in this case used to maintain containment integrity, though just a single input change can be used to investigate the

effect of failure in subsequent runs. C2(2) = .583 defines the containment break orifice coefficient, and C3(2) = 7.0 is the containment break area (since NT(2) = 7). C4(2) is not used in this case and thus is set to zero. The various other events that can be specified by means of the events table are described in the definition of input variables.

Compartment connections are specified by either the KT(I,J) or BK(I,J) arrays. If the BK(I,J) are non-zero, the compartment connections are specified in the code by the BK rather than by the KT array. In this sample problem the inputs controlling the hydrogen and carbon monoxide combustion are all code default with the exception of IBURN, IBURNJ, IBURNL, and IBURNM. The default values represent a convenient point of departure for accident analyses, although the user should be aware of the significant uncertainty in the specification of ignition and burn propagation criteria.

NLBOIL contains a large number of variables that define the physical characteristics of the core and primary systems; these are individually described in the definition of input variables and will not be discussed in detail here except where the meaning may not be straightforward. The present discussion will concentrate on the modeling options selected for this sample problem and the rationale behind this selection. The variables R1 = 1 and R2 = 10 indicate that the core will be described using ten radial regions; NDZ = 24 denotes the use of twenty four axial nodes. The axial and radial power peaking factors in the various core regions are input by means of the arrays FZ(I) and PF(I), respectively; the fraction of the core volume in each radial region is input as VF(I). The use of a negative value for NDZ will reduce by half the core temperature printout; a positive value will result in all the node temperatures being printed. ISTR = 3 and ISG = 3 indicate that there are three structures in the gas stream above the core and that the third structure represents the steam generator. HO is the initial elevation of the liquid level in the primary system relative to the bottom of the core. This is an artificial level that is used by the code to keep track of the coolant inventory; it does not correspond to the actual level of liquid in the primary system except when the level is in the core region. VOLSX is the initial volume of steam in the primary system; it would typically correspond to the steam volume in the pressurizer of a PWR at the start of the accident event. It should be noted that the calculation of the primary system pressure

requires the existence of a steam bubble; if the calculated gas space volume falls below a minimum value, the code will assume the minimum value. ICON and the sign on the variable ISG are used to select the steam generator heat transfer options. ABRK and YBRK denote the area and elevation, respectively, of primary system breaks; since the present case is not a loss of coolant accident, these parameters are not used. The relief valve is located at the elevation YSRV; the value of 26.7 feet used in the sample problem is intended to represent to the elevation in terms of coolant inventory of the pressurizer surge line. IHR specifies that the fuel rod to steam radiation heat transfer will be calculated. MWORNL is used to select the metal-water reaction models for the analysis. MELMOD = -1 denotes the use of meltdown model "A", with the negative sign indicating that emergency coolant injection will not be automatically stopped with the onset of core melting; IMWA = 3 is used to specify that the metal-water reactions are allowed to continue in the melted nodes. ISTM = 0 and IHC = 1 specify that uniform steam flow distribution across the core is assumed and that convective heat transfer to the steam from melted nodes will be calculated. The parameters FDRP and FCOL represent the core fraction that must be melted before initial slumping of the fuel and total collapse of the core into the bottom head are allowed to take place. NDZDRP is an additional variable used to control fuel movement and represents the axial node number which must be molten before slumping is allowed. The choices of NDZDRP = 1, FDRP = .02, and FCOL = .75, selected for this problem will allow the fuel to fall region by region whenever the lowest node in a radial region is fully molten; when the fraction of the core molten reaches 0.75 the entire core will be allowed to fall onto the structures in the lower head. TFAILX is the failure temperature of the first support structure below the core, and TFAIL2 that of the second. Since TFAIL2 is set to a large value, failure of the core support structures will not be used to control collapse of the core. Similarly, the input value for TFAILB may permit core collapse to be triggered by high core barrel temperature. FDCR is the control parameter for treating metal-water reaction during the slumping of the core into the bottom head; a negative value in this case specifies that the extent of reaction is to be calculated by the subroutine MWDRP. The latter requires the specification of the input variables DPART, DUO2, FZMCR, FZOCR, and FZOS1 to describe the size and configuration of the assumed debris particles. The

input values used describe a particle in which the oxide and metal are mixed. A debris bed model is used to calculate the evaporation of the water in the bottom head as specified by IBEDS = 3. The arrays TCST(I) and TSB(I) specify the times and values to be used for the BOIL time steps in the calculations; the negative value for time step is a flag which triggers a change in time step size upon core uncovery. The new MARCH 2 models for core radiation (IRAD = 2), axial conduction (IAXC = 1), and gas convection (ICONV = 20) heat transfer are used. The NLBWR namelist contains the default input values for the parameters used in the BWR core model which is not used in this problem.

NLHEAD provides the input required for the analysis of the heatup and failure of the vessel bottom head by the core and structural debris; required inputs include: WFECXX, the mass of miscellaneous metal in the core included in the core debris, WGRIDX, mass of core support structures falling into the bottom head, WUO2XX, mass of UO2 in the core, and WZRCXX, mass of Zircaloy cladding in the core. Additional inputs include DBH, the diameter of the hemispherical head, THICK, the thickness of the bottom head, TMLT, the melting temperature of the debris in the bottom head, and COND, the thermal conductivity of the debris. In this sample problem head failure is assumed to result when the temperature at a depth THKF = -0.0833 feet reaches 1600 F; this is a simulation of a small failure in the vessel bottom head. The negative sign here signals failure of the head when the criteria are satisfied; a positive input for THKF would allow only leakage of water, steam, and hydrogen with release of core debris delayed until gross head failure. FHEAD = 0.0 means that none of the still solid portion of the vessel head at the time of failure will be included in the core debris in subsequent analyses in the reactor cavity.

NLHOT provides the input to the subroutine HOTDRP for calculating the interaction of the core debris with water in the reactor cavity. The input includes DP, the diameter of the debris particles, CON, the conductivity of the debris, FLRMC, mass times the heat capacity of any structural material in the reactor cavity to be added to the core debris. Other parameters include MWR, specifying the metal-water reaction model to be used, IHOT, which specifies the reactor cavity water temperature and logic for transfer to the INTER subroutine, and NSTOP, which defines the maximum number of HOTDRP timesteps to be computed. In this problem a debris bed model (IDBED = 103)

has been selected, but the formation of the debris bed is delayed until permitted by the levitation model by setting TCORM, the debris melting temperature greater than 10,000. The high value is used as a flag, with the 10,000 being subtracted from the input value in the code.

NLINTR provides the input to the subroutine INTER for evaluating the interaction of the core debris with the concrete basemat. The required inputs include: FC1XXX through FC4XXX for specifying the initial composition of the concrete, CAYCXX and CPCXXX representing the thermal conductivity and heat capacity of the concrete, DENSCX, the density of the concrete, RBRXXX, the mass of rebar per unit mass of concrete, ROXXXX, the effective radius of the reactor cavity, and RXXXXX, the initial radius of curvature of the bottom of the melt. Modeling parameters include HIM and HIO, the heat transfer coefficients between the concrete and the metal and oxide phases of the debris, respectively; FIOPEN, fraction of the debris top surface radiating to water at the debris internal temperature; IGAS, which controls the interaction of the concrete decomposition gases with overlaying water; IWRC, a parameter which permits ingression of the sump water into the reactor cavity after the debris have penetrated a radial distance WALL, or vertical distance ZF. The negative sign with HIM specifies that the geometry of the debris will be held fixed after both layers have solidified. The potential reaction between the metallic zirconium and iron oxide in the debris is not considered by setting IZRFEO = 0. All the energy radiated from the debris surface after the cover water is vaporized is assumed to decompose concrete (FRCW = 1.0).

In addition to the principal modeling parameters discussed above, each of the subroutines may have one or more input parameters that control the level and frequency of printed output from the calculations. These are described for each subroutine in the definition of the input variables.

PWR Transient Results

Table D-1 is a reproduction of the summary of results as calculated by MARCH 2 for the PWR Large Dry Containment Transient sample problem. The summary sheet gives the timing of key events as well as the values of selected key parameters at each time. The entry under the heading for the mass of debris at the time of initial core slump is actually the fraction of the core

TABLE D.1 SUMMARY OF PWR TRANSIENT RESULTS

SUMMARY OF RESULTS MARCH 2 VERSION 151 MARCH 2 SAMPLE PROBLEM--PWR TRANSIENT

THE REACTOR IS A PWR

THE ACCIDENT IS A NORMAL TRANSIENT

CONTAINMENT SPRAY DOES NOT WORK

ECC SYSTEM WORKS

HYDROGEN BURNS ARE NOT ACCOUNTED FOR

OUTPUT IS IN AMERICAN ENGINEERING UNITS

EVENT	TIME (MIN)	PRIMARY PRESSURE	CONTMNT PRESSURE	DEBRIS MASS	DEBRIS TEMP	FRACTION OF ZIRC REACTED	SUMP MASS	SUMP TEMP	REACTOR CAVITY MASS	REACTOR CAVITY TEMP
STM GEN DRY	17.00	1687.485	15.771				6.24768E+03	111.6	.0000L+00	100.0
CORE UNCOVER	60.50	2544.762	39.752				2.18058E+05	206.8	.0000E+00	100.0
START MELT	88.50	2542.371	38.771		4130.0	.0626	2.39332E+05	212.2	2.83048E+04	211.2
CORE SLUMP FRACTION CORE MELTED	113.25	2528.519	31.519	4.28582-01	4016.0	.1832	2.39288E+05	213.3	4.84858E+04	211.9
START HEAD HEATUP	116.75	2544.341	40.187	2.61308E+05	3554.3	.4510	2.39258E+05	213.4	4.60558E+04	211.8
BOTTOM HEAD FAIL	134.75		88.450	3.61308E+05	3613.4	.4510	2.50588E+05	217.8	1.64848E+05	143.2
HOTDRP, WRC = 0	469.27		129.659	3.62318E+05	370.0	.4580	2.23178E+05	283.8	.0000E+00	347.1
HOTDRP, WRC = 0	471.27		129.481	3.62318E+05	392.0	.4580	2.22758E+05	283.9	.0000E+00	347.0
HOTDRP, WRC = 0	484.27		129.201	3.62318E+05	610.8	.4580	2.24658E+05	285.2	.0000E+00	346.8
HOTDRP, WRC = 0	493.27		129.026	3.62318E+05	705.6	.4580	2.24188E+05	288.2	.0000E+00	346.7
HOTDRP, WRC = 0	503.27		129.117	3.62318E+05	835.9	.4580	2.24258E+05	287.3	.0000E+00	346.8
HOTDRP, WRC = 0	513.27		129.142	3.62318E+05	956.2	.4580	2.24858E+05	288.2	.0000E+00	346.8
HOTDRP, WRC = 0	523.27		129.188	3.62318E+05	1082.2	.4580	2.24778E+05	289.1	.0000E+00	346.8
HOTDRP, WRC = 0	533.27		129.184	3.62318E+05	1206.7	.4580	2.24738E+05	289.9	.0000E+00	346.8
HOTDRP, WRC = 0	543.27		129.198	3.62318E+05	1336.5	.4580	2.24708E+05	290.7	.0000E+00	346.8
HOTDRP, WRC = 0	548.27		129.882	3.62318E+05	1373.5	.4581	2.22808E+05	291.1	.0000E+00	346.8
HOTDRP, WRC = 0	583.27		130.682	3.62398E+05	1824.7	.4622	2.23928E+05	293.3	.0000E+00	346.6
HOTDRP, WRC = 0	580.27		129.035	3.62482E+05	1843.8	.4649	2.22868E+05	293.6	.0000E+00	346.8
HOTDRP, WRC = 0	617.27		129.569	3.65918E+05	2525.4	.5112	2.22778E+05	294.7	.0000E+00	347.1
END HOTDRP	626.27		128.280	3.80578E+05	2871.8	.5113	2.26078E+05	295.8	2.13038E+03	295.1
INTER	626.28		129.260	3.82768E+05	2871.7	.5113	2.26078E+05	295.6	2.12928E+03	295.1
METAL IS FROZEN	650.21		129.581	3.98048E+05	2839.1	.5125	2.23018E+05	296.8	1.82028E+03	347.1
INTER	746.35		129.046	4.07888E+05	3952.3	.5125	2.22768E+05	301.2	6.83008E+03	339.6
LAYERS INVERT	830.30		128.450	4.17288E+05	3894.4	.5125	2.22828E+05	303.7	1.16728E+04	343.2
INTER	886.41		132.007	4.20888E+05	3929.8	.5125	2.22528E+05	304.8	.0000E+00	348.4
METAL IS MOLTEN	936.68		132.075	4.29538E+05	4879.0	.5125	2.22448E+05	305.5	.0000E+00	348.9
INTER	988.29		136.436	4.87638E+05	3440.9	.5455	2.21988E+05	306.6	.0000E+00	352.1
INTER	1104.35		146.391	5.65508E+05	2786.9	.6724	2.21368E+05	306.5	.0000E+00	355.8
INTER	1224.32		161.084	6.44688E+05	2545.5	.8433	2.21368E+05	306.6	.0000E+00	355.8

36 NORMAL EXIT INTER TIME = TF

NUMBER BOIL TIMESTEPS = 286 NUMBER OF MACE TIMESTEPS = 1369

that is melted at that time. The start of head heatup is essentially equivalent to the collapse of the core into the vessel head. In this sequence the primary system is maintained at a high pressure during core heatup and melting; thus the failure of the vessel bottom head takes place due to the combination of overheating and pressure stresses. The time between core collapse and vessel failure is relatively short. The interaction of the core debris with water in the reactor cavity starts immediately following head failure. The multiple printouts "HOTDRP, WRC = 0" relate to the dryout of the reactor cavity; in this case some refluxing of water condensate from containment structures is predicted to take place; hence, the multiple dryout messages. Since attack of the concrete is not allowed until the debris reach a temperature of 2500 F, the calculation stays in HOTDRP for some time. It is interesting to note that during the attack of the concrete some additional water is refluxed back into the reactor cavity, but this too is eventually evaporated. During the attack of the concrete the debris is partitioned into an oxide layer and a metal layer; the debris temperature given in the summary sheet if a weighted average temperature. The calculation of this sample problem was terminated by input after 10 hours of concrete attack.

Figure D-1 illustrates the primary coolant leak rate for this sequence. After the initial transient which results in some expulsion of primary coolant from the system, all the decay heat goes into the boiloff of the steam generator secondary side inventory. The dryout of the steam generators is followed by the lifting of the pressurizer safety/relief valve and loss of primary coolant inventory. The change from water plus steam leak to a purely steam leak takes place when the water level reaches the elevation of the pressurizer surge line. The decrease in the steam leakage rate corresponds to core uncovery. The rapid short term rise in steam leakage near the end of the in-vessel phase is associated with the slumping of the core into the bottom head of the reactor vessel.

Figure D-2 illustrates the maximum and average core temperatures for this sample problem. In this plot the maximum temperature plotted is the peak value anywhere in the core. The peak temperature is seen to be arrested at the input melting temperature for the core material, with a slight excursion above it during the core slumping process. This is typical of the type of results obtained for the core meltdown and slumping models selected for this

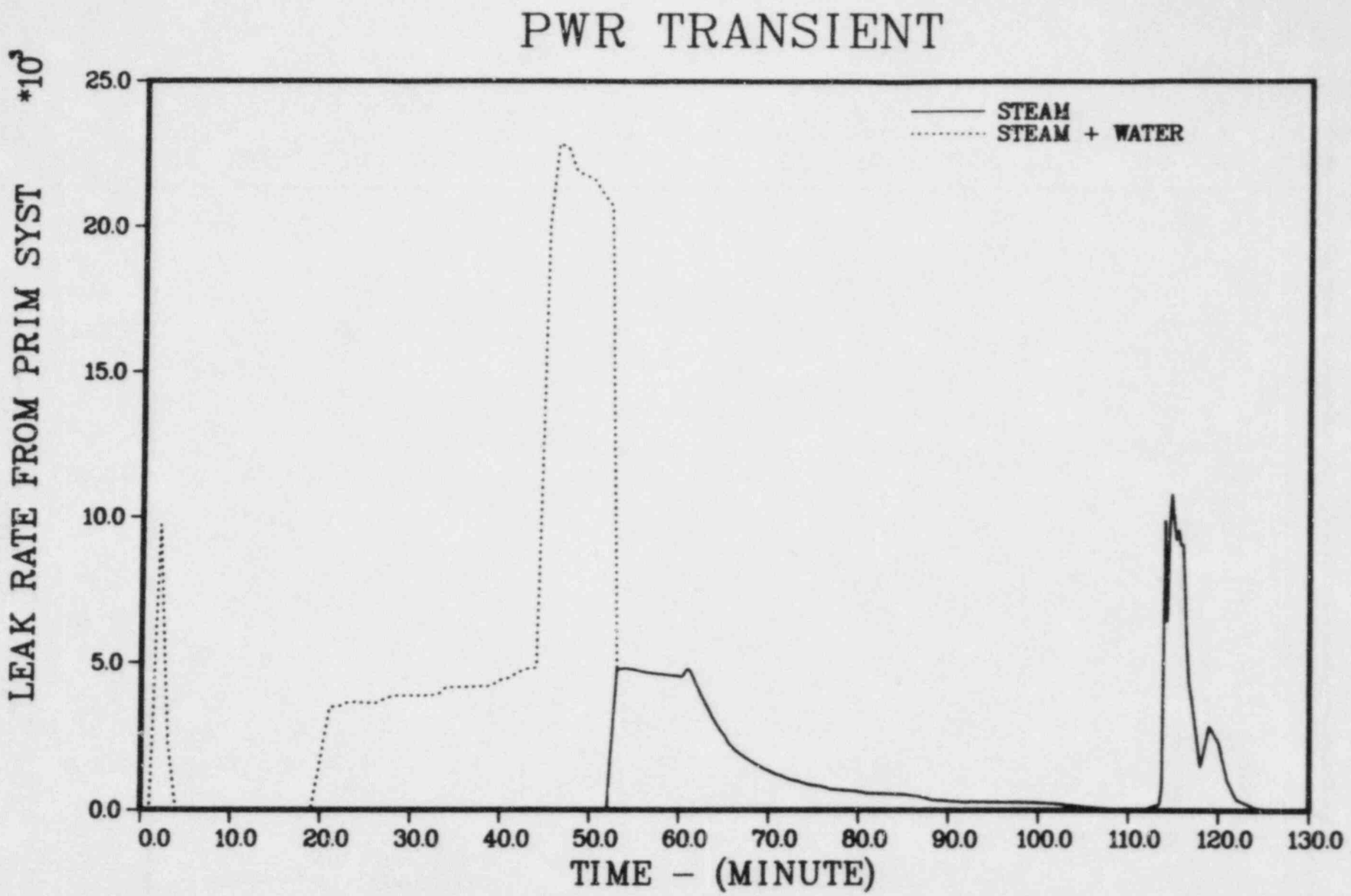


FIGURE D.1 PRIMARY SYSTEM LEAKAGE FOR PWR TRANSIENT

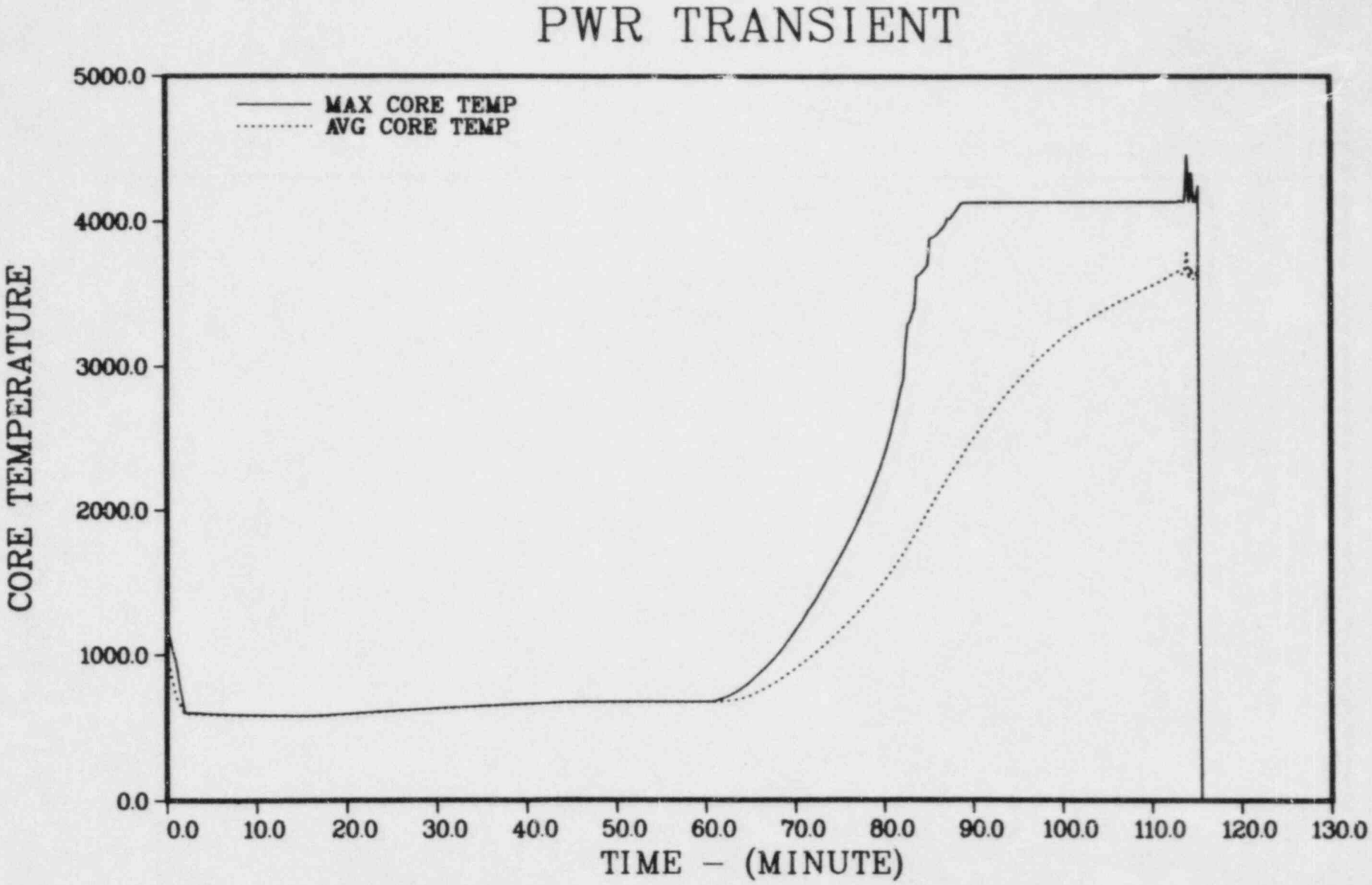


FIGURE D.2 MAXIMUM AND AVERAGE CORE TEMPERATURES FOR PWR TRANSIENT

sample problem. The abrupt drop of the temperature traces corresponds to the collapse of the core into the bottom head. Figure D-3 illustrates the fraction of core molten and fraction of the cladding reacted for this problem. The results are again quite typical for the choice of modeling options. As the steam boiloff rate decreases, the rate of metal-water reaction becomes steam limited until the slumping of the fuel into the bottom head; at that time both the extent of cladding reaction and fraction core melted increase rapidly due to the energy release associated with cladding oxidation. The collapse of the entire core into the bottom head is reflected by the leveling off of both traces.

Figures D-4 and D-5 illustrate the containment pressure and temperature histories for this problem.

PWR Ice Condenser Containment Small Break LOCA

Input Description

The primary differences between the MARCH input for the ice condenser small break LOCA sequence and the transient discussed above, other than detailed plant specific parameters, are related to the modeling of the ice condenser, the operation of the sprays, and the use of somewhat different meltdown and debris interaction models. In NLMAR, ICE = 1 is used to specify an ice condenser. A small LOCA is specified by ITRAN = 1 and IBRK = 1. The containment is modeled as a two compartment system, with heat sinks in both the upper and lower compartments described in NLSLAB. Note that the temperature of the metal baskets in the ice bed is initialized at 20 F. MACE contains coding which requires ice bed structures to be initialized at 20 F and to be the last structure in the input data. The operational ECC systems described in NLECC include the accumulators and the upper head injection tank. The containment spray is operational, and the spray heat exchanger is described by NLHX input data. Spray recirculation starts when the quantity of water in the refueling water storage tank (RWSTMA = 2,900,000) is less than the fractional value CSPRC in NLECC. The ice bed in NLMACE is assumed to be located in the flow path between compartment 1 and 2 (ICECUB = 2); the ice bed will remove energy only for gases flowing from compartment 1 into

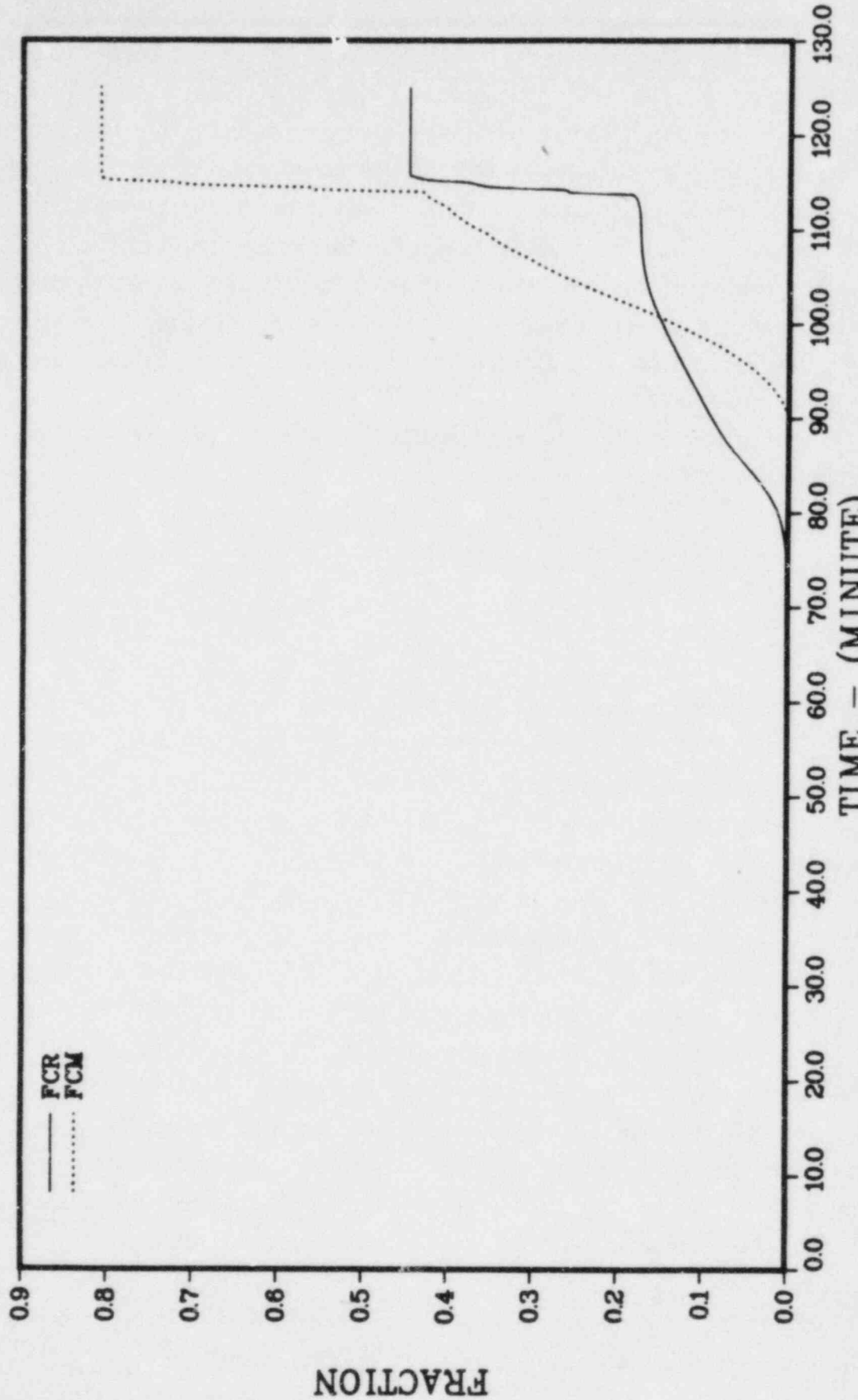


FIGURE D.3 EXTENT OF CORE MELTING AND CLADDING OXIDATION FOR PWR TRANSIENT

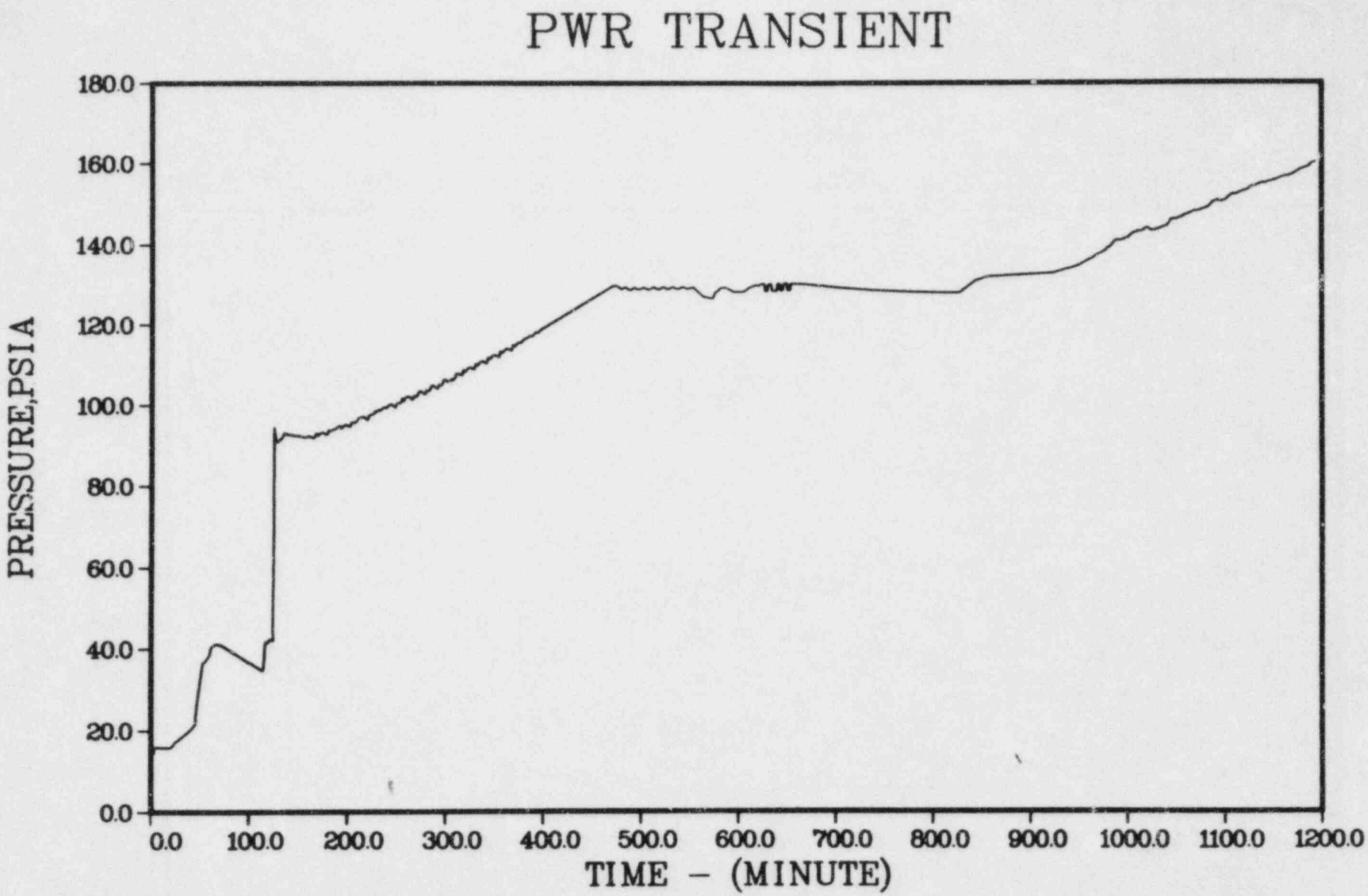


FIGURE D.4 CONTAINMENT PRESSURE RESPONSE FOR PWR TRANSIENT

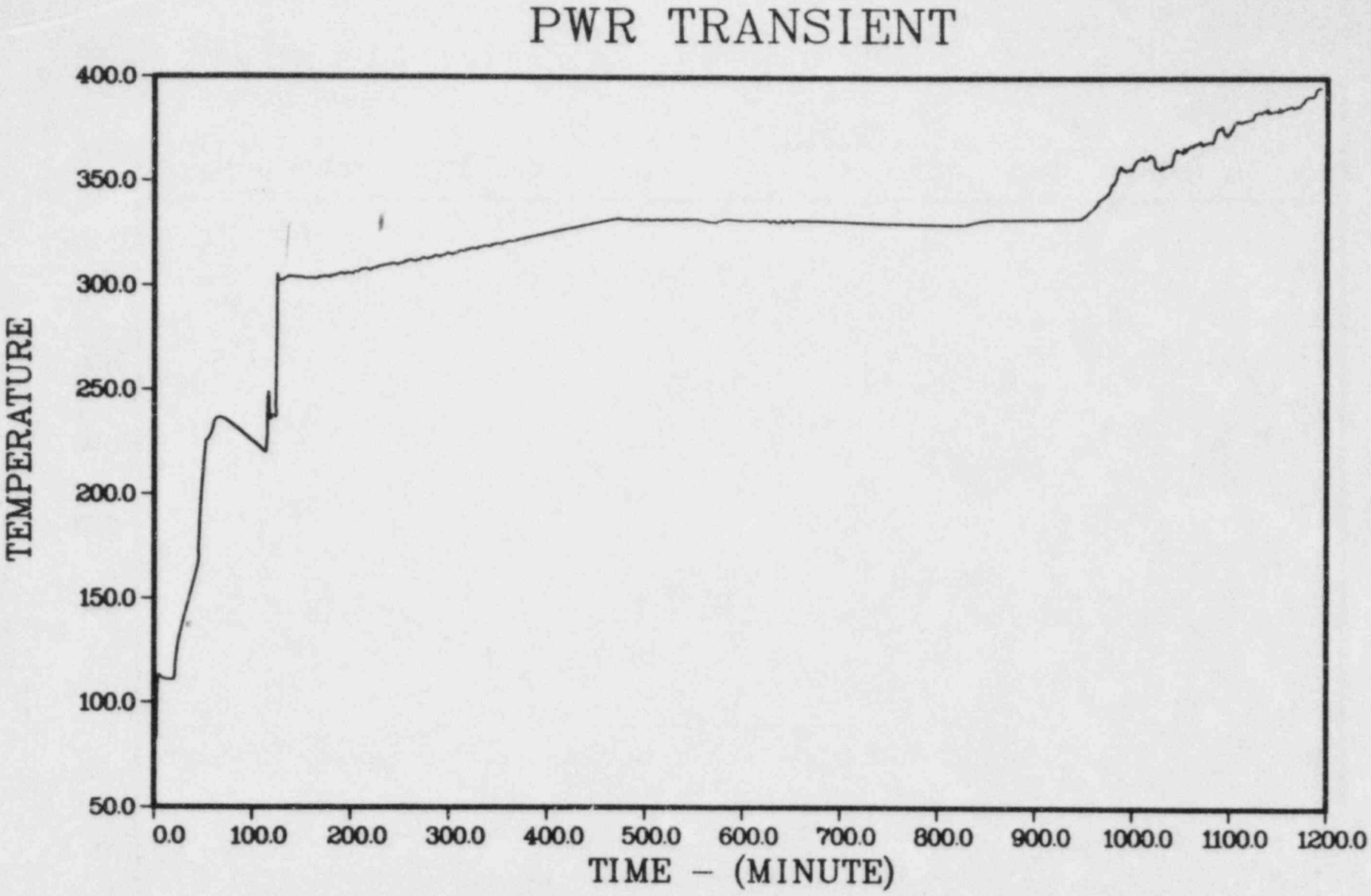


FIGURE D.5 CONTAINMENT TEMPERATURE RESPONSE FOR PWR TRANSIENT

compartment 2 for this compartmentalization. The blowdown is directed into the lower compartment, ICECUB - 1 = NRPV1 = NRPV2 = JRPV1 = 1. With the exception of the mass of ice (WICE) and the decontamination factor (DFICE), the ice bed parameters (TICE, TWTR, TWTR2, and TSTM) are set at default values. The input of NCAV = 1 allows the cavity to refill during the debris-water interaction phase of the accident. The operational events include a containment spray (4750 gpm in volume 2) and a fan returning air from compartment 2 back to compartment 1. (Note that the MARCH echo print of the input spray flow rate has units of cubic feet per minute rather than the input units of gallons per minute.) IBURN = 1 allows hydrogen and carbon monoxide burning when the flammability criteria are satisfied, and hydrogen igniters are assumed in both compartments (IGNITE(1) = IGNITE(2) = 1). The flow path and combustion propagation criteria are specified by the BK array; H2DIST(1) entries represent the characteristic dimensions in each compartment. The other combustion model inputs are default values. A 3-inch diameter break (ABRK = 0.0491 square feet) is located at an elevation YBRK = 16.0 feet above the bottom of the core. The steam generator secondary inventory is maintained by starting the feedwater system (WAFW = 3643 lb/min) at time TMAFW = 0.5 min. A gradual initial core slumping model is prescribed in NLBOIL by FDROP = 0.05, NDZDRP = 12, and FCOL = 0.75. In-core metal-water reactions are turned off at a node temperature TMWOFF = 3370. The core barrel failure temperature is set at TFAILB = 2600. Head leakage prior to gross failure is precluded by THKF = 10.0 feet in NLHEAD. In NLHOT the debris is allowed to quench to the solidification point of steel (TQNCH = 2800) before switching to INTER. The remaining input data are similar to that discussed previously.

Ice Condenser Results

The summary of the MARCH 2 calculated results for the Ice Condenser PWR Small Break LOCA sample problem is given in Table D-2. Due to the break in the piping, the primary system is seen to depressurize quite rapidly. The particular choice of meltdown model and core slumping options selected lead to relatively early start of initial core slumping, but the collapse of the entire core into the bottom head is seen to require considerable time. Also

TABLE D.2 SUMMARY OF ICE CONDENSER PWR RESULTS

SUMMARY OF RESULTS MARCH 2 VERSION 181 MARCH 2 SAMPLE PROBLEM--ICE CONDENSER PWR 3.0 INCH LOCA (S2D)

THE REACTOR IS A PWR WITH ICE CONDENSER CONTAINMENT

THE ACCIDENT IS A SMALL LOCA

CONTAINMENT SPRAY WORKS

ECC SYSTEM WORKS

HYDROGEN BURNS ARE ACCOUNTED FOR STARTING WITH START OF PROBLEM

OUTPUT IS IN AMERICAN ENGINEERING UNITS

EVENT	TIME (MIN)	PRIMARY PRESSURE	CONTMNT PRESSURE	DEBRIS MASS	DEBRIS TEMP	FRACTION OF ZIRC REACTED	SUMP MASS	SUMP TEMP	REACTOR CAVITY MASS	REACTOR CAVITY TEMP
SPRAY ON	.75		18.465				2.0108E+04	188.2	.0000E+00	100.0
FAN ON	10.01		21.409				9.4818E+05	140.5	.0000E+00	100.0
CORE UNCOVER	17.86	1072.311	19.685				1.5989E+06	132.6	.0000E+00	100.0
SPRAY RECIRC ON	84.46		18.858				3.4726E+06	121.3	9.8486E+05	130.2
START MELT	72.96	167.385	18.404		4130.0	.0820	3.5495E+06	119.7	9.8488E+05	130.2
CORE SLUMP FRACTION CORE MELTED	84.06	84.550	18.459	1.4585E-01	1886.8	.1524	3.5888E+06	117.7	9.8488E+05	170.2
START HEAD HEATUP	188.22	18.819	17.852	2.9582E+05	2513.4	.2673	4.0078E+06	112.4	9.8854E+05	126.8
BOTTOM HEAD FAIL	202.36		17.703	4.8188E+05	3780.3	.2673	4.0236E+06	109.0	9.8889E+05	121.6
END HOTDRP	206.42		17.869	4.8419E+05	2541.5	.2673	4.0448E+06	109.1	9.8738E+05	184.8
INTER	206.43		17.859	4.8419E+05	2541.3	.2673	4.0449E+06	109.1	9.8736E+05	184.8
OXIDE IS MOLTEN	256.11		17.610	4.9182E+05	3382.4	.2673	4.0849E+06	106.0	9.5784E+05	209.9
INTER	326.42		19.480	5.2830E+05	2858.2	.3202	4.2818E+06	110.8	9.5108E+05	226.0
LAYERS INVERT	339.29		19.815	5.3230E+05	2835.1	.3288	4.3418E+06	111.4	9.5057E+05	227.1
CONTMNT FAIL	388.34	70.209	70.000				4.4630E+06	111.9	9.5017E+05	228.1
INTER	446.42		16.709	5.7850E+05	2848.0	.3820	4.7182E+06	116.2	9.5430E+05	218.4
ICE MELT COMPLETE	456.37		16.823				4.8082E+06	117.9	9.5408E+05	218.9
INTER	586.51		15.313	8.2548E+05	2726.5	.4872	4.7905E+06	121.7	9.5598E+05	214.5
INTER	686.48		17.398	8.7854E+05	2637.4	.5480	4.7880E+06	125.1	9.5269E+05	222.4
OXIDE IS FROZEN	723.67		16.854	8.9468E+05	2363.5	.5766	4.7857E+06	131.2	9.5337E+05	220.6
INTER	806.51		15.528	7.2640E+05	2347.1	.6346	4.7850E+06	133.8	9.5832E+05	213.7

36 NORMAL EXIT INTER: TIME > TF

NUMBER OF BOIL TIMESTEPS = 1785 NUMBER OF MACE TIMESTEPS = 3950

due to the input options selected, the extent of in-vessel metal-water reaction in this case if relatively limited. Since the primary system is at a low pressure during the vessel head heatup, some time is required to reach predicted head failure. In this problem there is a considerable quantity of water in the reactor cavity through most of the accident sequence from the overflow of spray water as well as the water due to the melting ice. The presence of this water in the reactor cavity may offer the potential for the formation of a coolable debris bed and the termination of the accident sequence. The particular choice of input parameters utilized allowed for only partial quenching of the core debris prior to the onset of concrete attack.

The combination of the ice condenser and the containment sprays keep the containment pressure at low levels, except for those due to hydrogen burns. Figures D-6 and D-7 illustrate the predicted containment pressure and temperature histories for this sequence. The several large pressure excursions are associated with hydrogen burning, predicted to take place in the upper compartment of the containment. The last burn is calculated to exceed the input failure pressure. The containment leak rate and total volume of gases leaked are illustrated in Figures D-8 and D-9. It should be noted that the combustion model parameters for this sample problem were the default values in the code, which may or may not be suitable for any particular application. The prediction of peak containment loadings due to combustion events is known to be sensitive to ignition criteria, flame propagation criteria, and containment compartmentalization.

As indicated in the summary table, the ice is calculated to be completely melted shortly after the predicted time of containment failure for this particular calculation. This calculation was again terminated by input after 10 hours of concrete attack.

BWR Mark III Transient

Input Description

The transient accident sequence for the Mark III pressure suppression containment described here does not represent a typical accident sequence but has been selected to illustrate a variety of modeling features available in

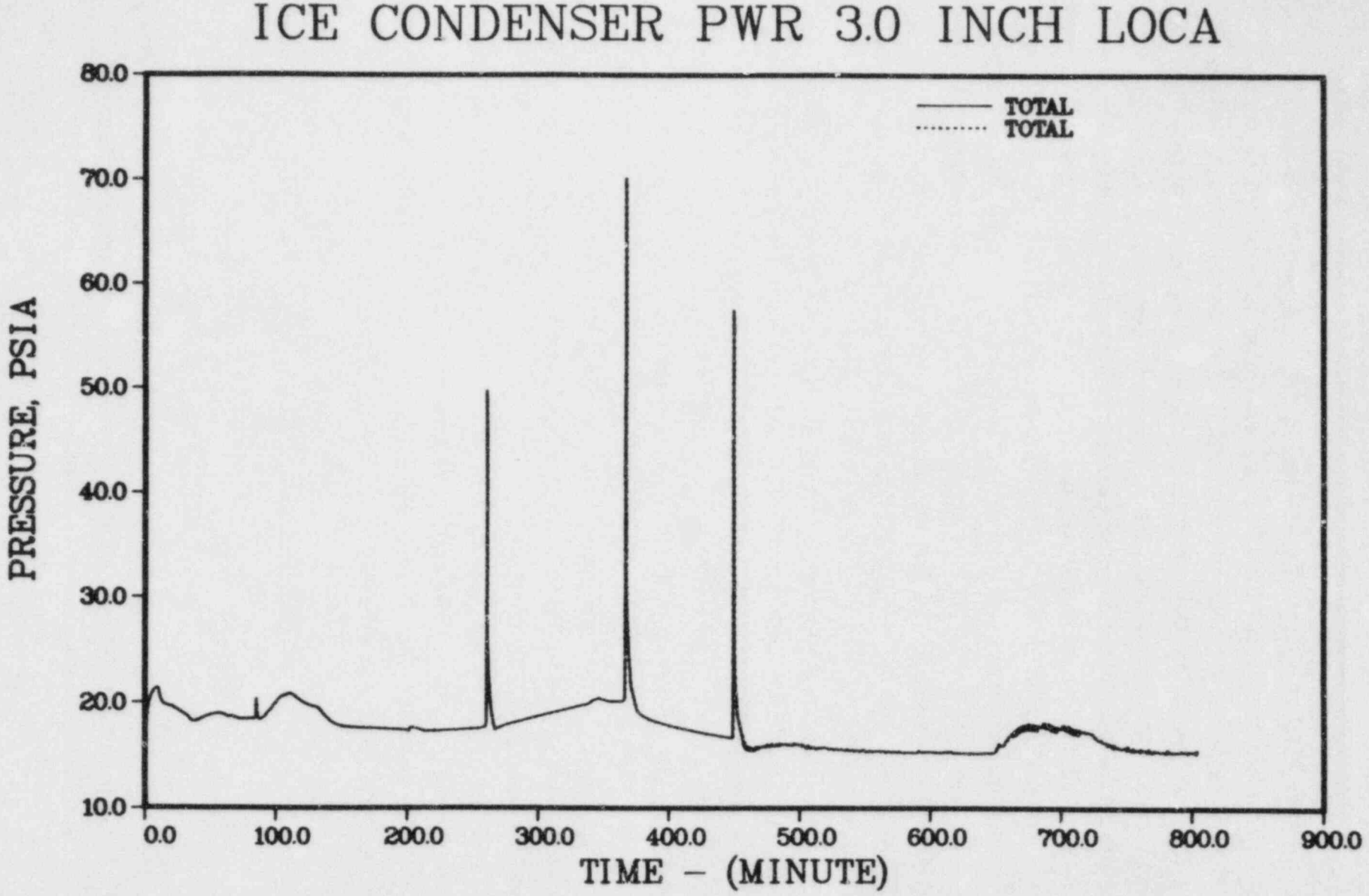


FIGURE D.6 CONTAINMENT RESPONSE FOR ICE CONDENSER PWR LOCA

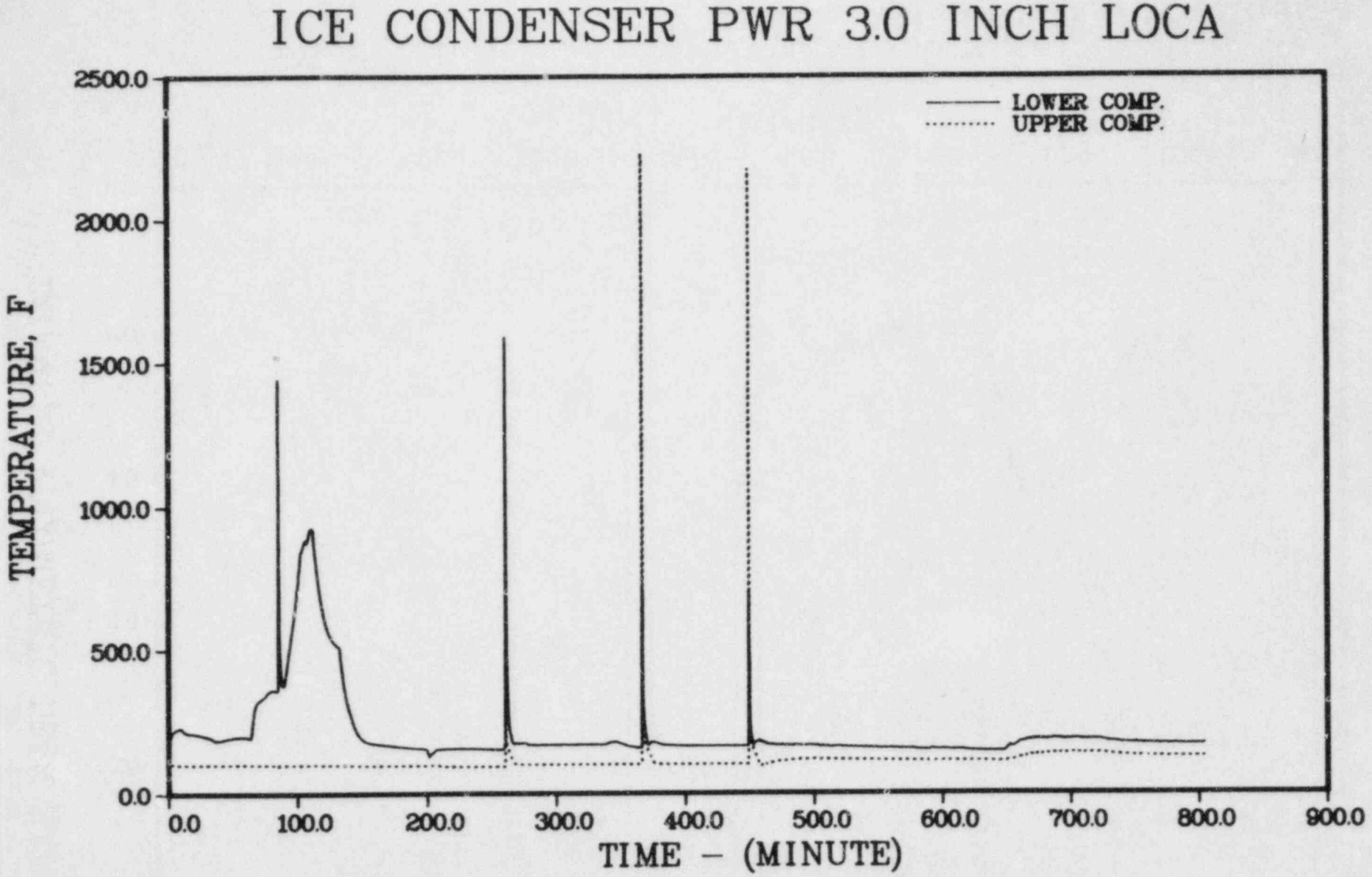


FIGURE D.7 CONTAINMENT TEMPERATURE RESPONSE FOR ICE CONDENSER PWR LOCA

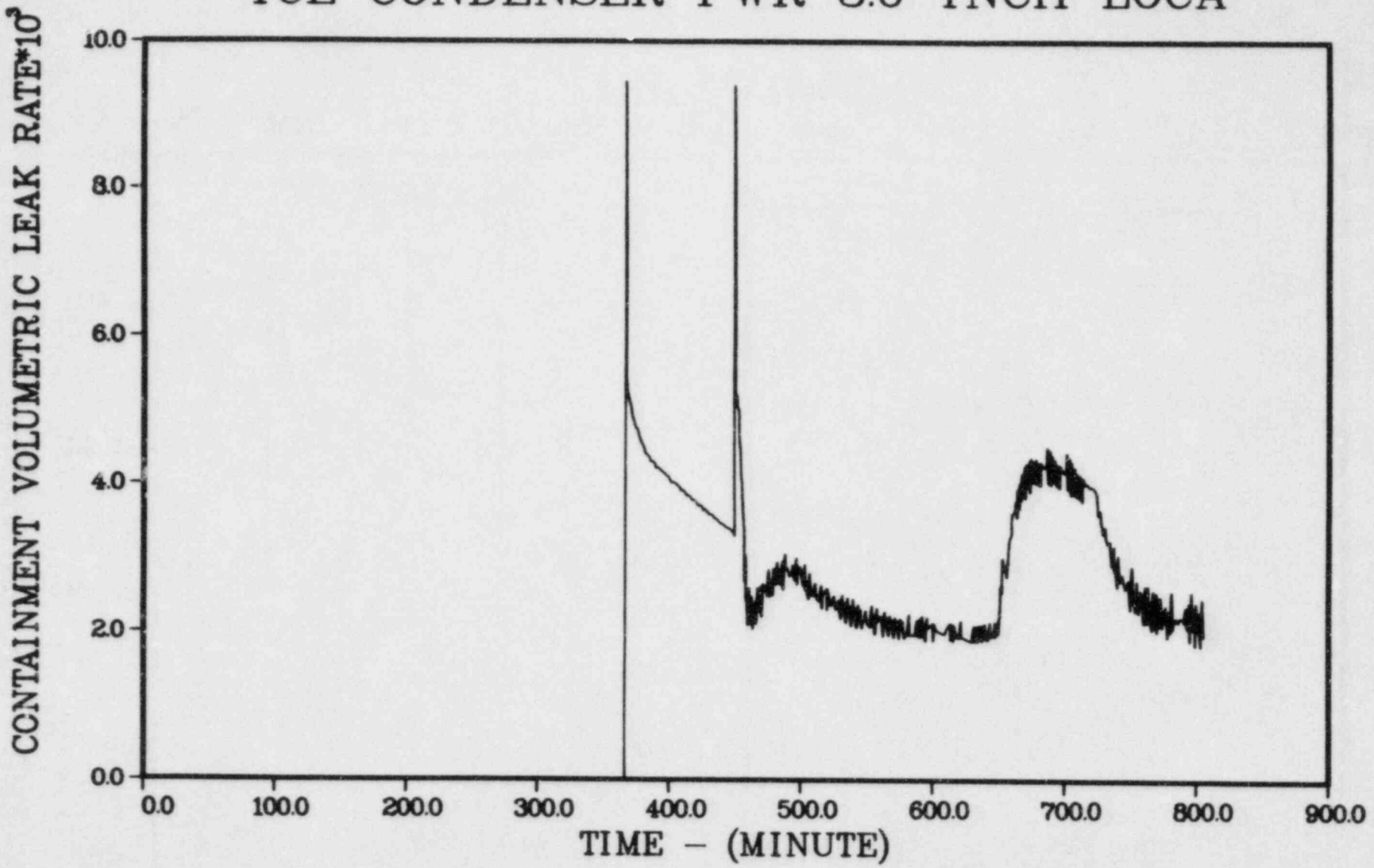


FIGURE D.8 CONTAINMENT LEAK RATE FOR ICE CONDENSER PWR LOCA

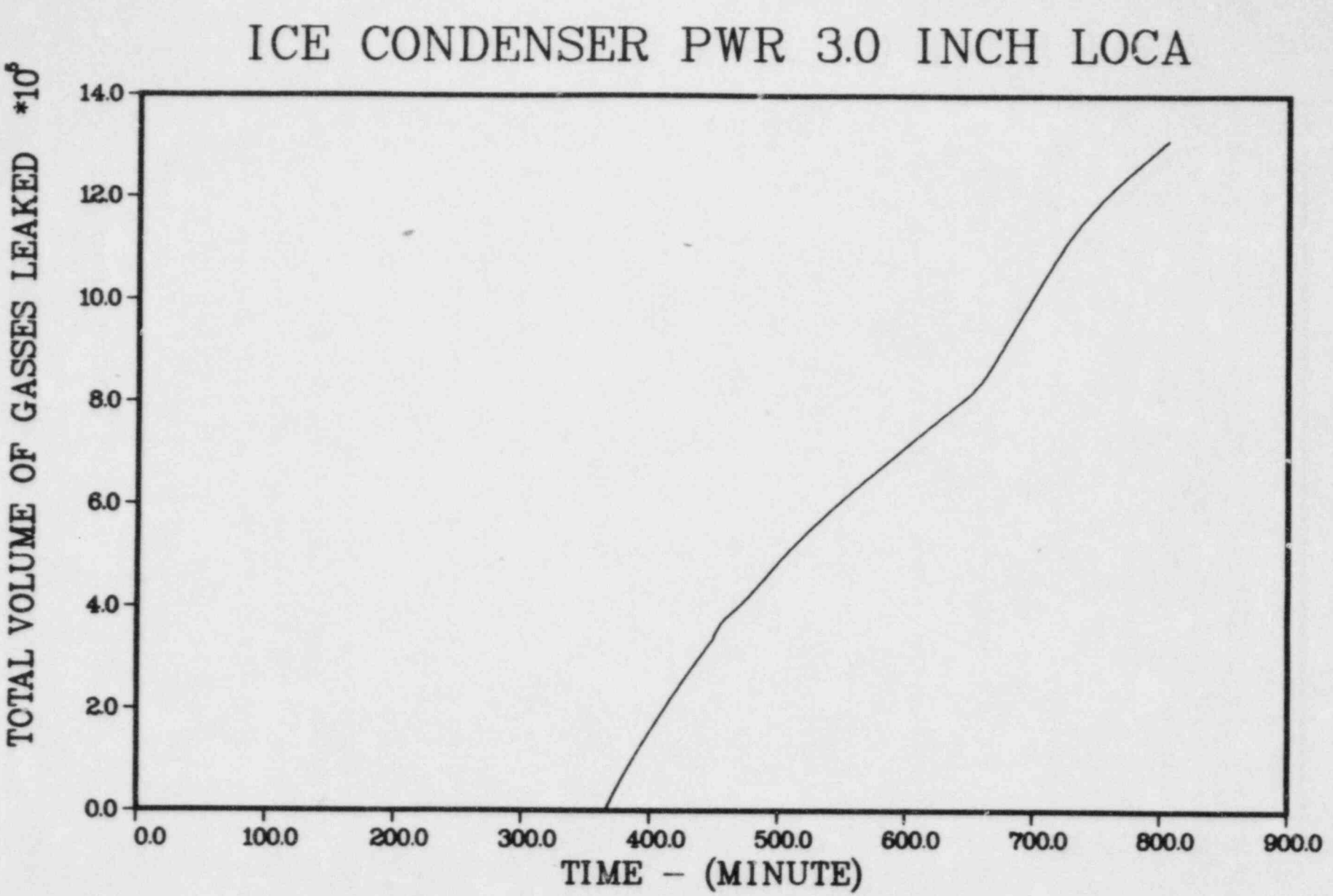


FIGURE D.9 TOTAL LEAKAGE FOR ICE CONDENSER PWR LOCA

MARCH 2. The input data models a small break in the primary system with delayed emergency coolant injection; thus ITRAN = 1, IBRK = 1, and IECCXX = -3. The delayed operation of the ECC system is permitted until failure upon switchover to recirculation, as denoted by the negative sign on IECCXX. The available ECC pump parameters are given in NLECC. The containment is modeled as a two compartment system; suppression pool data in NLMACE include identification of the drywell (IDRY), the wetwell (IWET), quantity of water in the suppression pool (WPOOL), initial temperature of the pool (TPOOL), the decontamination factor for fission products flowing through the pool (DCF), and the total volume of the wetwell compartment (VTORUS). All water on the drywell floor is assumed to enter the reactor cavity since VCAV is set to a large value. The safety valve flow is directed into the suppression pool since JRPV1 = IWET = 2. Flows from head failure, HOTDRP, and INTER are directed into the drywell since NRPV1 = NRPV2 = IDRY = 1. Compartment connections are specified by the KT array.

The residual heat removal system uses features of the MACE spray system. Thus, ISPRA = 1 in NLMAR, spray heat exchanger data are entered in NLHX, and a spray event is included in NLMACE. Spray recirculation from the suppression pool to the heat exchanger is started immediately by setting CSPRC = 2.0 in NLECC. A spray event in the wetwell of a BWR (with NT = +1, NC = IWET, ICECUB = -1 in NLMACE) sets flags which allow the spray water to return to the pool without interacting with the atmosphere. A real spray would be obtained if NT = -1 or if NC were not the same as IWET. The second MACE event allows controlled leakage or venting of the containment between pressures C1 = 35 and C4 = 25 psia. In this sample problem the adiabatic burn pressures will be calculated throughout the sequence as specified by IBURN = -1; for this option the burning is not included in the containment energy balance, but is calculated in order to give an indication of the potential impact of burning on the containment response. If actual hydrogen and CO burns were being calculated, the BK array would require definition. For the adiabatic burn calculation default combustion modeling parameters have been utilized.

For this sample problem, delayed shutdown of the core is modeled. For the NLBOIL input parameter KRPSXX = 1, the power level decreases linearly from QZERO, the normal operating level, to the fractional power ANSK = 0.1 in

the time TRPS = 0. At time TDK = 10.0 minutes the power drops to the level calculated by the ANSQ decay heat model. Should the core become uncovered prior to the input shutdown time, the power will decrease from fractional level ANSK to the decay heat level as the collapsed liquid level in the core decreases from YT = 9.0 to YB = 3.0 feet in the core.

The core meltdown models in this problem as defined in NLBOIL are similar to those previously discussed for the PWR transient, except that the original MARCH 1.1 heat transfer models have been selected (IAXC = ICONV = IRAD = 0). The primary system relief valve is allowed to cycle between PSETX and PSETX-/PSR/ by the entries TB(1) = 0.1, ABR(1) = 0.199, and PSR(1) = -100. The negative sign on the PSR entry triggers the use of the valve cycling model, with the absolute value being the pressure range; a positive entry would just redefine the value setpoint. A small break in the lower head region is also included (ABRK = 0.001 and YBRK = -10.0). The explicit modeling of BWR control blades and channel boxes is not utilized in this problem, the cladding thickness (CLAD) has been increased to include the mass of Zircaloy in the channel boxes. Head failure is allowed to take place due to overheating at a depth THKF = -0.0833 feet. The remaining NLHEAD, NLHOT, and NLINTR input selections are similar to those discussed previously.

Mark III BWR Transient Results

The summary table of MARCH 2 results for the Mark III BWR accident sequence considered is shown in Table D-3. It will be recalled that for this problem reactor shutdown was delayed for 10 minutes, with the power remaining at 10 percent of full power. In the absence of primary coolant makeup this leads to the rapid uncovery of the core. The primary system stays at an elevated pressure even though a small leak is assumed in the bottom head. For the choice of meltdown model and core slumping model options selected, collapse of the entire core into the bottom head is predicted to take place shortly after the onset of initial core slumping. The generation of steam by the quenching of the debris in the bottom head raises the primary system pressure to the point where the relief valves are actuated. The vessel head analysis options selected lead to the prediction of head failure soon after core collapse. Delayed emergency coolant injection is started at 100 minutes

TABLE D.3 SUMMARY OF MARK III BWR RESULTS

SUMMARY OF RESULTS MARCH 2 VERSION 151 MARCH 2 SAMPLE PROBLEM--MARK III BWR TRANSIENT

THE REACTOR IS A BWR

THE ACCIDENT IS A SMALL LOCA

ECC SYSTEM WORKS AFTER HEAD FAILURE

CONTAINMENT SPRAY WORKS

ECC SYSTEM WORKS UNTIL SWITCHOVER TO RECIRCULATION

HYDROGEN BURNS ARE ACCOUNTED FOR STARTING WITH START OF PROBLEM
HYDROGEN BURNS ARE ADIABATIC ONLY

OUTPUT IS IN AMERICAN ENGINEERING UNITS

				DEBRIS		FRACTION OF ZIRC	SUMP		REACTOR CAVITY	
EVENT	TIME (MIN)	PRIMARY PRESSURE	CONTMNT PRESSURE	MASS	TEMP	REACTED	MASS	TEMP	MASS	TEMP
SPRAY ON	10.01		18.191				9.9993E+06	135.6	3.4273E+03	158.1
SPRAY RECIRC ON	10.05		18.206				1.0003E+07	135.7	3.4447E+03	158.1
CORE UNCOVER	10.58	1086.826	18.340				1.0017E+07	137.0	3.5348E+03	159.1
START MELT	45.38	1050.767	19.048		4130.0	.0082	1.0068E+07	135.2	1.8897E+04	187.9
CORE SLUMP FRACTION CORE MELTED	66.13	1058.989	19.113	4.4300E-01	3398.1	.0158	1.0088E+07	132.0	2.7987E+04	196.2
START HEAD HEATUP	87.84	1163.549	21.895	5.8729E+05	4441.2	.2577	1.0101E+07	138.9	2.8834E+04	196.9
BOTTOM HEAD FAIL	75.19		27.894	7.1013E+05	3728.8	.2577	1.0288E+07	154.0	3.0878E+04	196.9
END MOTORP	75.21		29.474	8.1039E+05	3342.8	.2620	1.0325E+07	157.1	3.7848E+02	249.3
INTER	75.22		29.474	8.1059E+05	3341.8	.2620	1.0325E+07	157.1	3.7849E+02	249.3
OXIDE IS MOLTEN	116.68		27.934	8.2457E+05	3788.1	.2620	1.0340E+07	151.1	1.3313E+05	212.2
OXIDE IS FROZEN	131.31		28.527	8.3787E+05	3517.2	.2698	1.0350E+07	148.8	2.4823E+05	241.0
INTER	185.33		28.687	8.7418E+05	3014.7	.2721	1.0359E+07	142.2	7.7773E+05	241.5
LAYERS INVERT	241.89		30.898	9.0973E+05	3096.2	.2868	1.0370E+07	138.1	1.1588E+06	250.8
ECC RECIRC ON	271.75	14.700	33.375				1.0440E+07	138.4	1.3611E+06	256.4
ECC OFF	272.31	33.384	33.384				1.0439E+07	138.5	1.3655E+06	256.4
CONTMNT LEAK	301.73	35.028	35.028				1.0470E+07	141.9	1.2978E+06	259.2
METAL IS FROZEN	307.81		34.743	9.5832E+05	2211.4	.3172	1.0482E+07	143.4	1.2858E+06	256.8
INTER	315.26		34.077	9.5903E+05	2206.1	.3172	1.0490E+07	144.5	1.2772E+06	257.5
INTER	435.27		25.333	9.8735E+05	2873.6	.3172	1.0588E+07	155.9	1.1955E+06	240.8
INTER	555.24		27.845	1.0171E+06	2686.7	.3172	1.0640E+07	165.8	1.1211E+06	245.8
INTER	675.37		31.383	1.0488E+06	2671.8	.3172	1.0718E+07	175.7	1.0395E+06	252.7

36 NORMAL EXIT INTER TIME > TF

NUMBER OF BOIL TIMESTEPS = 913 NUMBER OF MACE TIMESTEPS = 2280

per input, and enters the reactor cavity, since the vessel is failed at that time. The coolant injection fails upon switchover to the recirculation mode, after having delivered a substantial quantity of water to the reactor cavity.

The containment pressure in the absence of hydrogen burning stays at relatively low levels, as illustrated in Figure D-10; the corresponding temperature responses are shown in Figure D-11. The input venting pressure is reached after some time of concrete attack and recloses later in time; this is illustrated by the containment leak rate in Figure D-12. The calculation of the adiabatic hydrogen burn pressures, illustrated in Figure D-13, indicates that the atmosphere in compartment 2, the main containment volume, would reach flammable conditions during the core slumping process and remain flammable for the duration of the sequence. It should again be noted that for purposes of this sample problem the default combustion modeling parameters were utilized; these may not necessarily be the most appropriate parameters to use. The possible effects of hydrogen igniters were not considered in this sample problem.

BWR Mark II Large LOCA

Input Description

The BWR Mark II Large LOCA sample problem illustrates the analysis of an accident sequence initiated by a large break in the primary system accompanied by the failure of the emergency core cooling system. Such a sequence was designated as AE in the WASH-1400 terminology for the boiling water reactor design. For the modeling of a large break accident, the blowdown of the primary system inventory is input via NLINTL. For a large break ITRAN = 0 and NPAIR in NLMAR specifies the number of entries in the blowdown table. The blowdown table data entries in NLINTL correspond to the release of 555,000 lb of primary coolant in 0.5 minutes, with an average enthalpy of 633.0 Btu/lb. Two calls are made to the subroutine INITL during the 0.5 minute blowdown (DTINTL = 0.25), and one MACE printout is made per call (IBLDP = 1). The blowdown is directed to the drywell by NRPV1 = NRPV2 = IDRY = 1 in NLMACE. The sumps in the two compartments are connected by

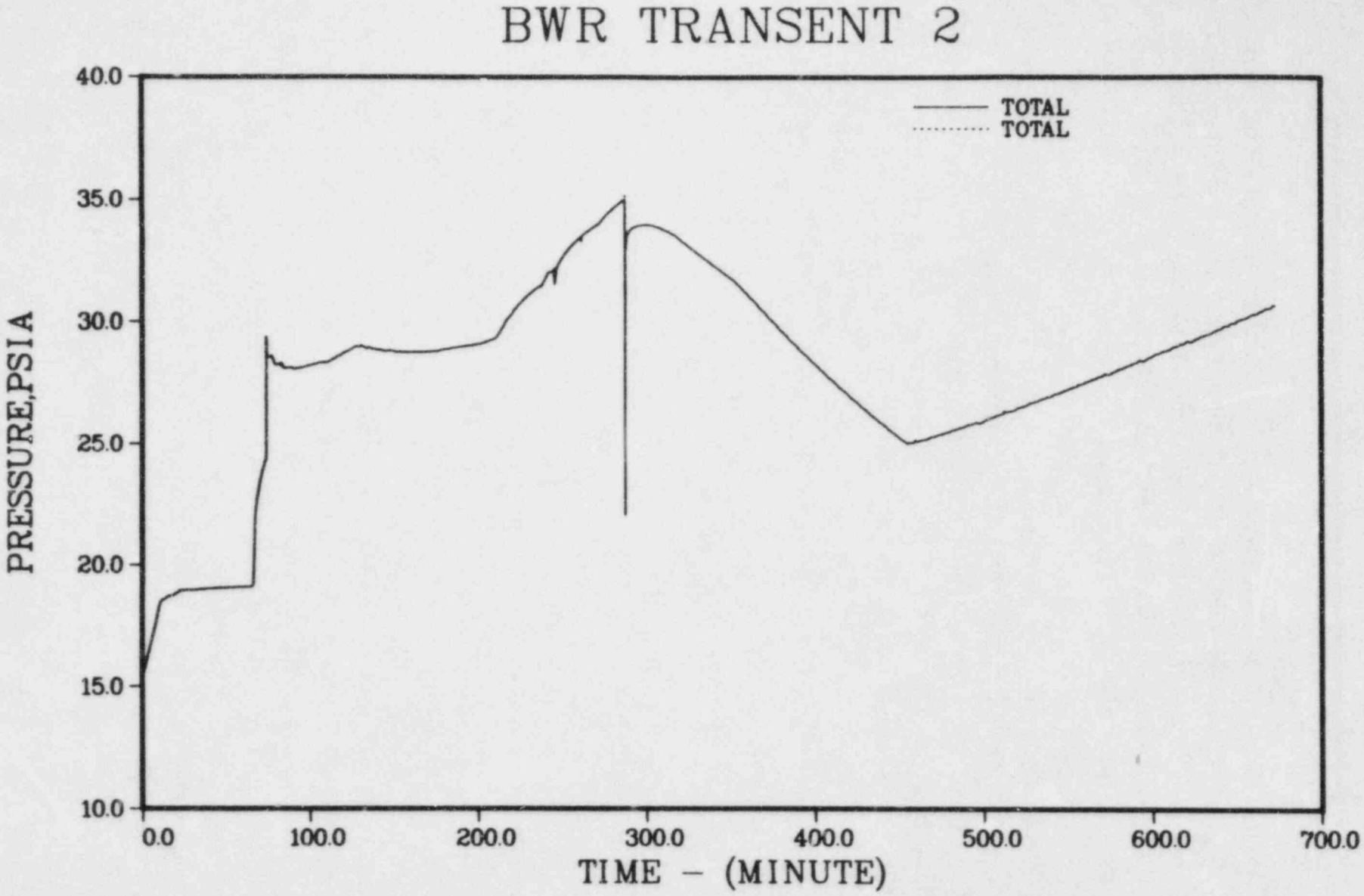


FIGURE D.10 CONTAINMENT PRESSURE RESPONSE FOR MARK III BWR TRANSIENT

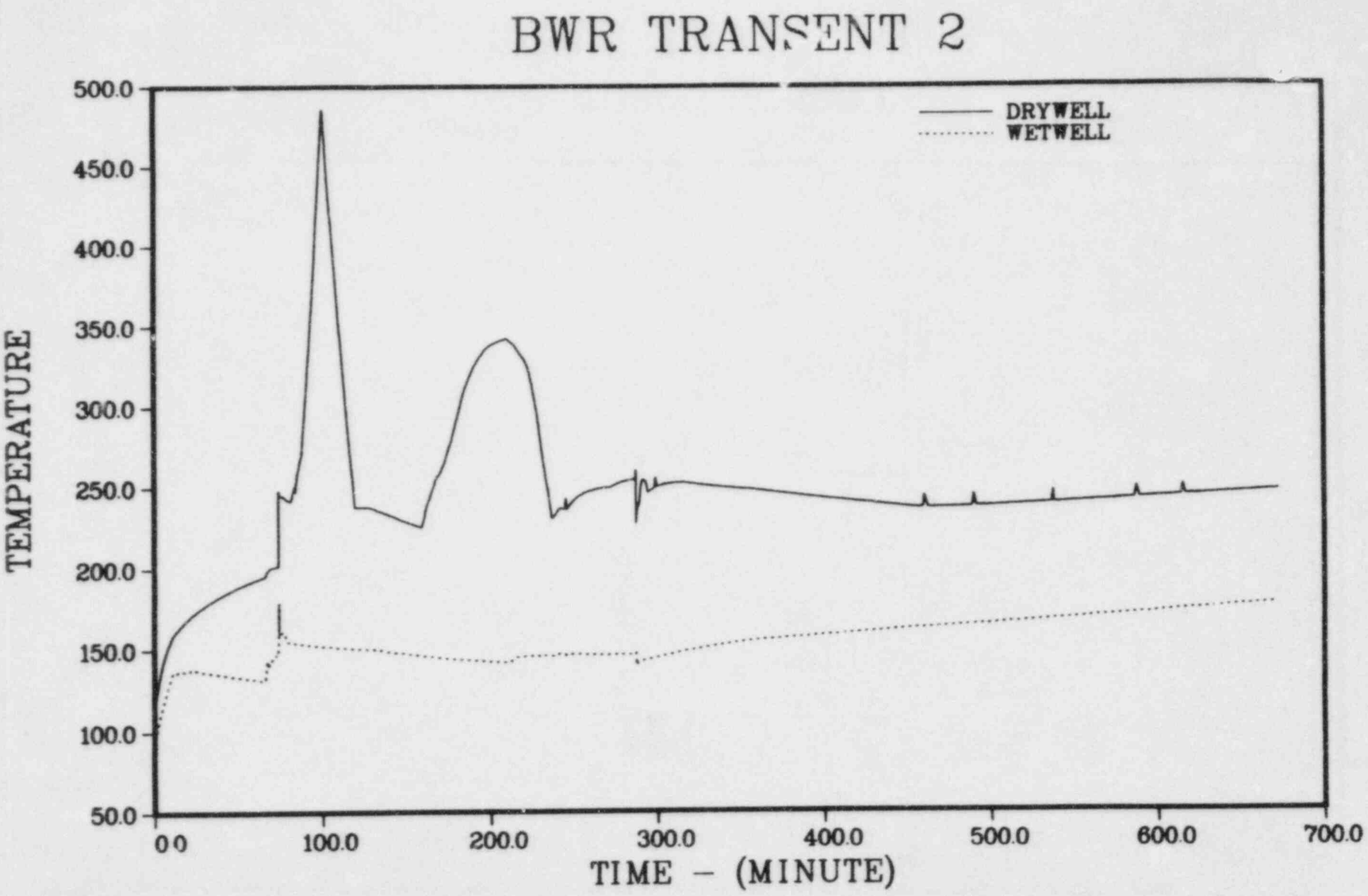


FIGURE D.11 CONTAINMENT TEMPERATURE RESPONSE FOR MARK III BWR TRANSIENT

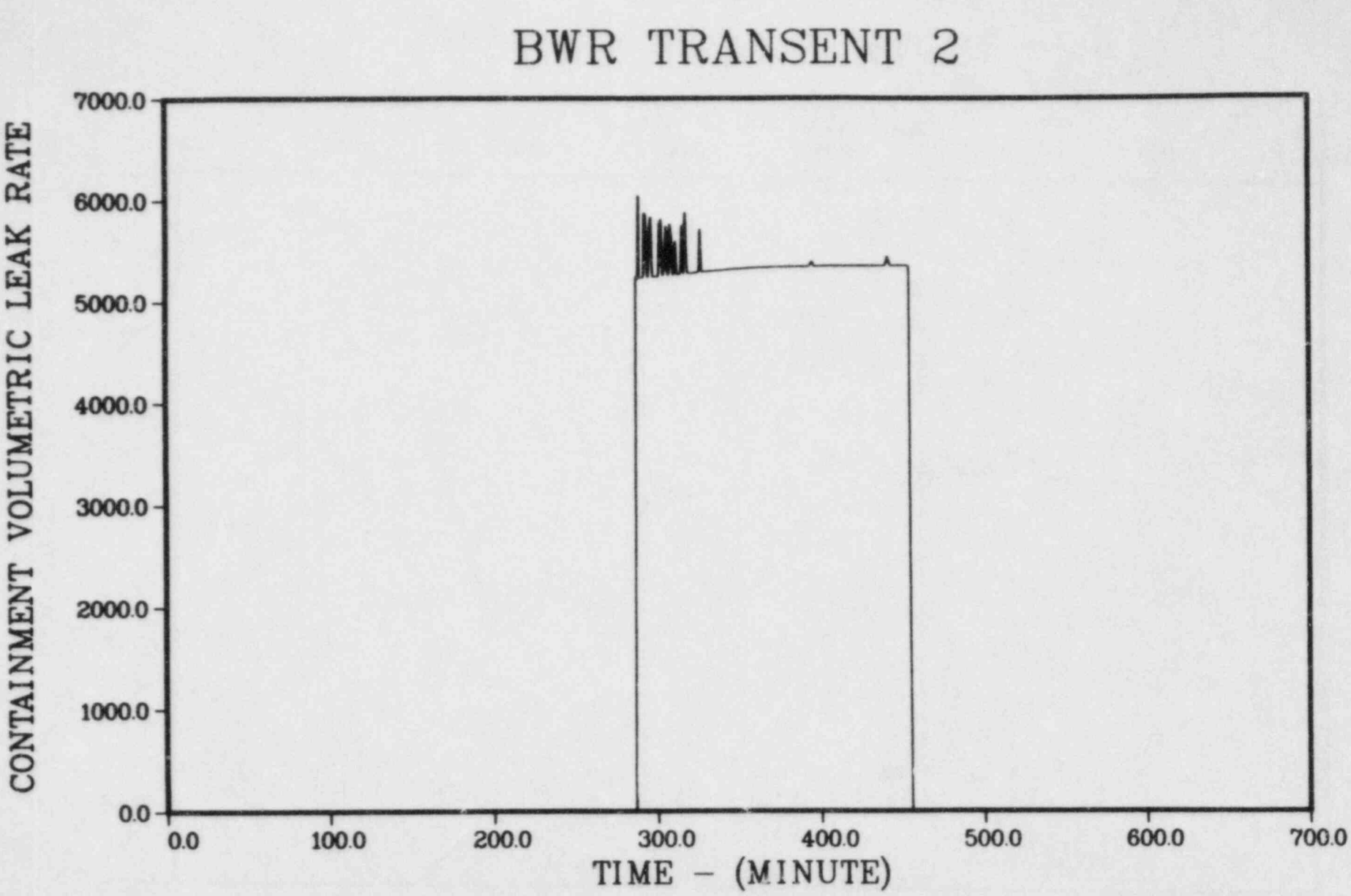


FIGURE D.12 CONTAINMENT LEAK RATE FOR MARK III BWR TRANSIENT

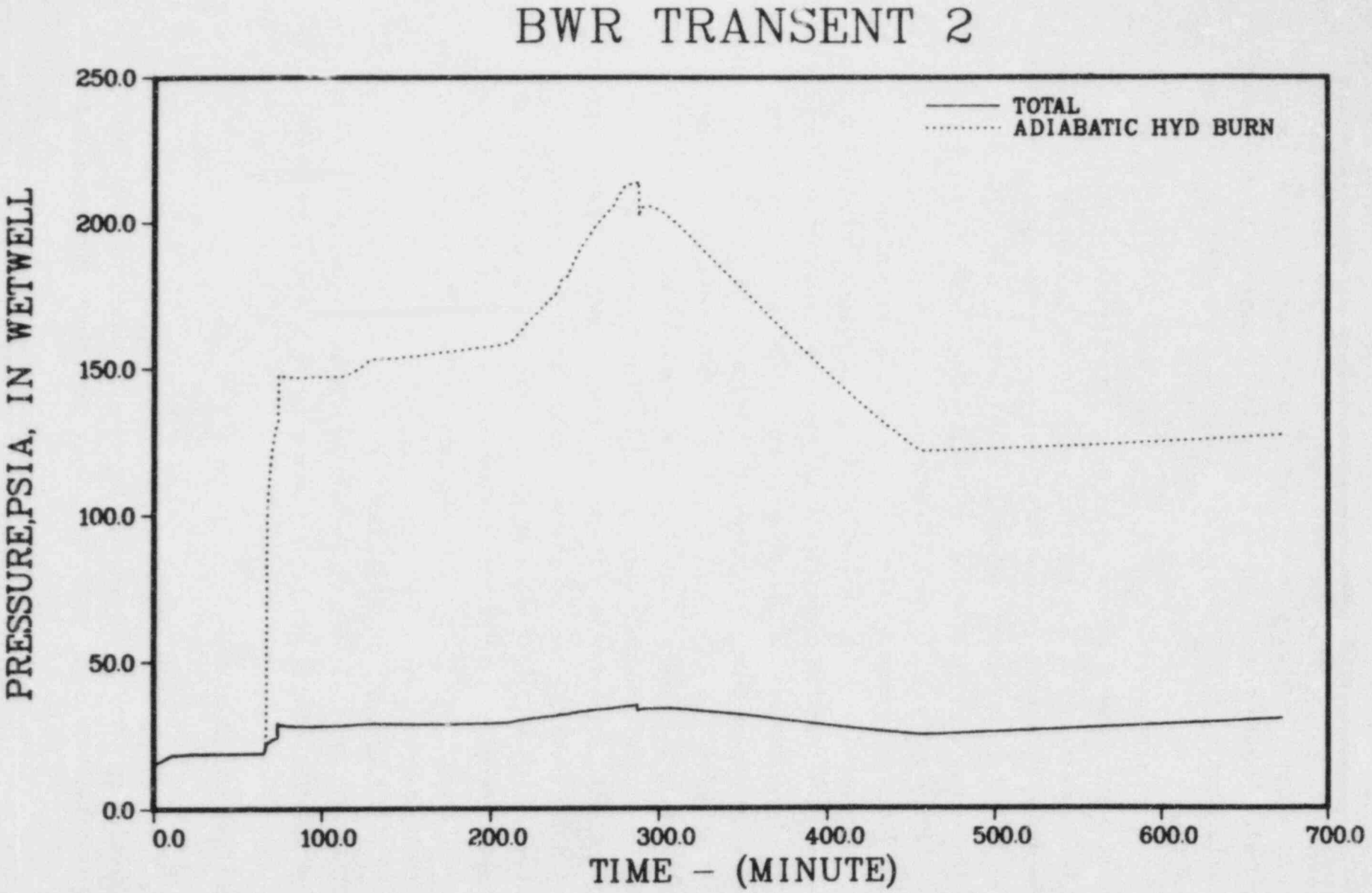


FIGURE D.13 CALCULATED ADIABATIC BURN PRESSURE IN MARK III BWR TRANSIENT

specifying NSMP = +2. The containment spray in the drywell is started at 10 minutes by the first entry in the events table. Containment failure at 145 psia with leakage from the drywell (NC = 1) is specified by the second MACE event. Combustion of hydrogen is not considered in this calculation (IBURN = 0).

There are several input variables in NLMACE and NLINTR that are interrelated and somewhat unique to the Mark II containment. When the core debris have penetrated through the concrete diaphragm separating the drywell from the wetwell (ZF = 100 cm in NLINTR), the pressure suppression function will fail and the suppression pool water will come into contact with the core debris (NRPV2 = 101 and NCAV = -12 in NLMACE). These modeling assumptions may not necessarily apply to all Mark II containment designs.

The core is modeled using the explicit modeling of BWR control blades and channel boxes by specifying IBWR = 1 in NLBWR. This core model always uses heat transfer coefficients and gas properties corresponding the ICONV = 2, i.e., improved property correlations. Use of ICONV = 20 results in the use of the improved property correlations also for the above-core structure heat transfer in EXITQ. Radiation heat transfer between core nodes is calculated using the IRAD = 2 models, with a reduced ECROS = 0.237 to compensate for the channel boxes and control blades. Metal-water reactions are permitted to take place in the melted nodes (IMWA = IMWBOX = IMWCB = 3, TMWOFF = 5,000), and the channel box and control blade in-core slumping is suppressed (MELMOD = -1). A value of +/-10 for the latter parameter would permit axial energy redistribution when the control blades and channel boxes melt. The Cathcart-Powell constants are used in the zirconium-steam reaction calculations (NWORNL = 3).

In the analysis of debris behavior in the reactor cavity the debris interaction with water is effectively bypassed by specifying IHOT = 2 in NLHOT. A basaltic type of concrete is specified by the input in NLINTR.

Mark II Large LOCA Results

The summary of the MARCH 2 results for the BWR Mark II Large LOCA sample problem is given in Table D-4. The core is uncovered during the primary system blowdown for this case. Since the core is uncovered, initial

TABLE D.4 SUMMARY OF MARK II BWR LOCA RESULTS

SUMMARY OF RESULTS MARCH 2 VERSION 151 MARCH 2 SAMPLE PROBLEM-- MARK II BWR LARGE BREAK LOCA

THE REACTOR IS A BWR

THE ACCIDENT IS A LARGE LOCA

CONTAINMENT SPRAY WORKS

ECC SYSTEM DOES NOT WORK

HYDROGEN BURNS ARE NOT ACCOUNTED FOR

OUTPUT IS IN AMERICAN ENGINEERING UNITS

EVENT	TIME (MIN)	PRIMARY PRESSURE	CONTMNT PRESSURE	DEBRIS MASS	DEBRIS TEMP	FRACTION OF ZIRC REACTED	SUMP MASS	SUMP TEMP	REACTOR CAVITY MASS	REACTOR CAVITY TEMP
CORE UNCOVER	.80	49.571	49.571				7.8869E+06	129.1	.0000E+00	100.0
SPRAY ON	10.00		40.074				7.9858E+06	129.7	.0000E+00	100.0
SPRAY RECIRC ON	10.10		40.059				7.9820E+06	129.8	.0000E+00	100.0
START MELT	17.50	38.178	38.178		4130.0	.0365	7.9837E+06	128.5	.0000E+00	100.0
CORE SLUMP FRACTION CORE MELTED	36.00	38.787	38.787	3.9191E-01	1949.8	.0844	7.9864E+06	125.8	.0000E+00	100.0
START HEAD HEATUP	36.90	51.152	51.687	5.4439E+05	3789.0	.1976	8.0046E+06	126.6	.0000E+00	100.0
BOTTOM HEAD FAIL	186.30		73.836	5.9728E+05	5840.3	.1976	8.1001E+06	118.7	.0000E+00	100.0
END HOTDRP	186.34		73.734	7.7581E+05	4130.0	.1976	8.1008E+06	118.7	.0000E+00	100.0
INTER	186.35		73.734	7.6346E+05	4129.4	.1976	8.1008E+06	118.7	.0000E+00	100.0
OXIDE IS MOLTEN	213.80		81.840	7.8770E+05	4026.0	.1976	8.1127E+06	118.8	.0000E+00	100.0
LAYERS INVERT	240.82		97.878	8.5362E+05	3585.3	.2200	8.1234E+06	118.4	.0000E+00	100.0
CONTMNT FAIL	312.17	146.201	145.000				8.2237E+06	115.7	.0000E+00	100.0
INTER	318.40		17.049	1.0860E+06	2838.3	.3127	8.2228E+06	115.7	.0000E+00	100.0
R.C. WALL MELT	362.13		15.393				7.7329E+06	117.6	4.8974E+05	117.6
INTER	436.43		15.206	1.2261E+06	2480.0	.3869	7.6484E+06	121.1	4.7143E+05	217.2
OXIDE IS FROZEN	471.18		15.045	1.2717E+06	2398.8	.4101	7.5905E+06	122.7	4.7225E+05	213.4
INTER	556.38		15.033	1.3743E+06	2292.8	.4874	7.5288E+06	126.4	4.7208E+05	214.3
INTER	676.50		15.207	1.5252E+06	2325.7	.5545	7.4624E+06	131.3	4.7233E+05	212.9
INTER	796.45		14.955	1.6761E+06	2276.4	.6377	7.3857E+06	135.9	4.7212E+05	214.0

36 NORMAL EXIT INTER TIME > TF

NUMBER OF BOIL TIMESTEPS = 545 NUMBER OF MACE TIMESTEPS = 3212

core heatup and melting are largely driven by fission product decay heating; this is reflected in the very low extent of cladding oxidation up to the point of core slumping. The interaction of the core debris with water in the lower head of the vessel leads to rapid steam production which in turn results in significant reaction with the cladding as this steam flows past the still standing fuel rods. The collapse of the entire core onto the support structures takes place shortly after the onset of core slumping. The time to predicted bottom head failure is quite long in this case due to the heat capacity of the support structures in the vessel bottom head as well as the absence of high internal pressure in the vessel. Attack of the concrete starts immediately after head failure since there is no water in the reactor cavity. The message that the layers invert indicates that enough concrete has been absorbed by the debris to decrease the density of the oxide phase below that of the metal, and the latter is assumed to sink to the bottom. The ensuing increased concrete attack rate leads to the prediction of containment failure in about an hour after the layers invert. In this case containment overpressurization is due to the buildup of noncondensables; the suppression pool is seen to remain subcooled throughout the sequence.

The reactor cavity melt message corresponds to the predicted penetration by the debris of the concrete diaphragm separating the drywell from the wetwell in this design. At this time the sump water is assumed to come into contact with the debris, hence the appearance of the water in the reactor cavity. Due to constraints in the code logic, the debris do not literally fall to the bottom of the suppression pool, but the pool is assumed to be able to communicate with the reactor cavity. In the summary page output the total water inventory in the pool is divided between the pool and the cavity. Repeated messages regarding the melting and freezing of the oxide indicate that the oxide phase is near its solidification temperature, but cannot fully dissipate its heat sources by conduction. The calculation was terminated by input after 10 hours of concrete attack.

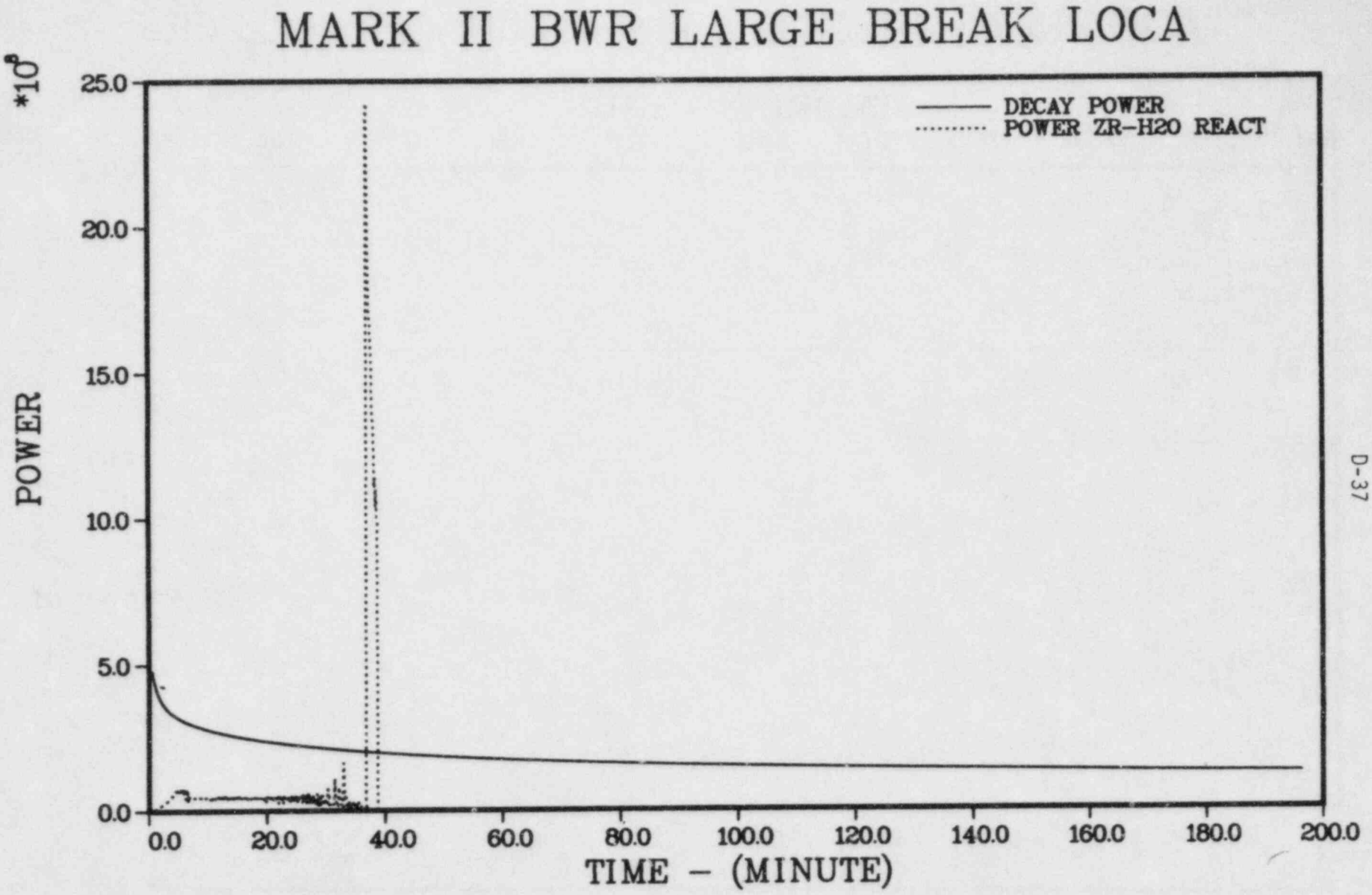


FIGURE D.14 DECAY POWER AND ENERGY FROM ZIRCALOY OXIDATION FOR MARK II LARGE LOCA

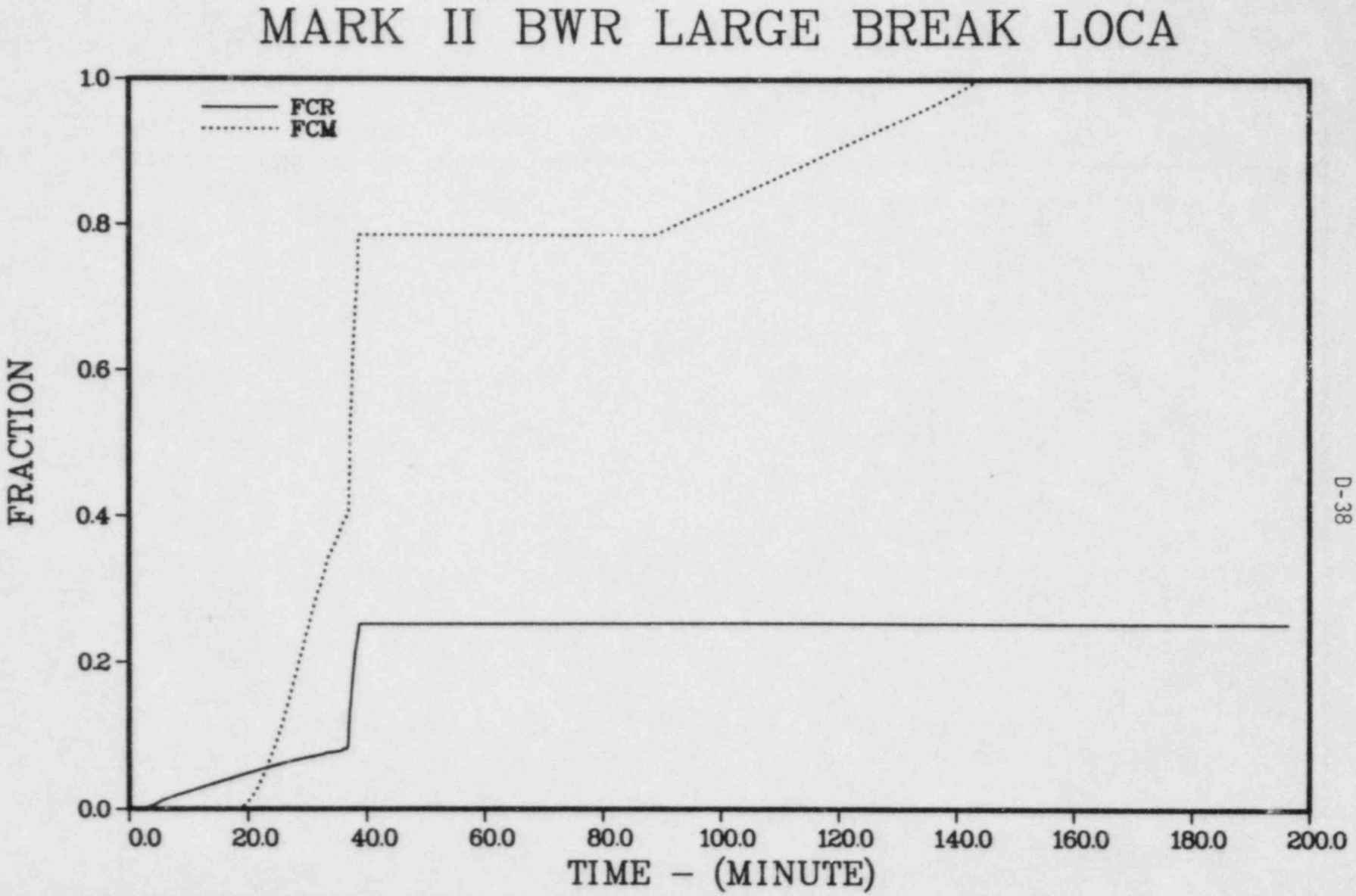


FIGURE D.15 EXTENT OF CORE MELTING AND CLADDING OXIDATION FOR MARK II BWR LARGE LOCA

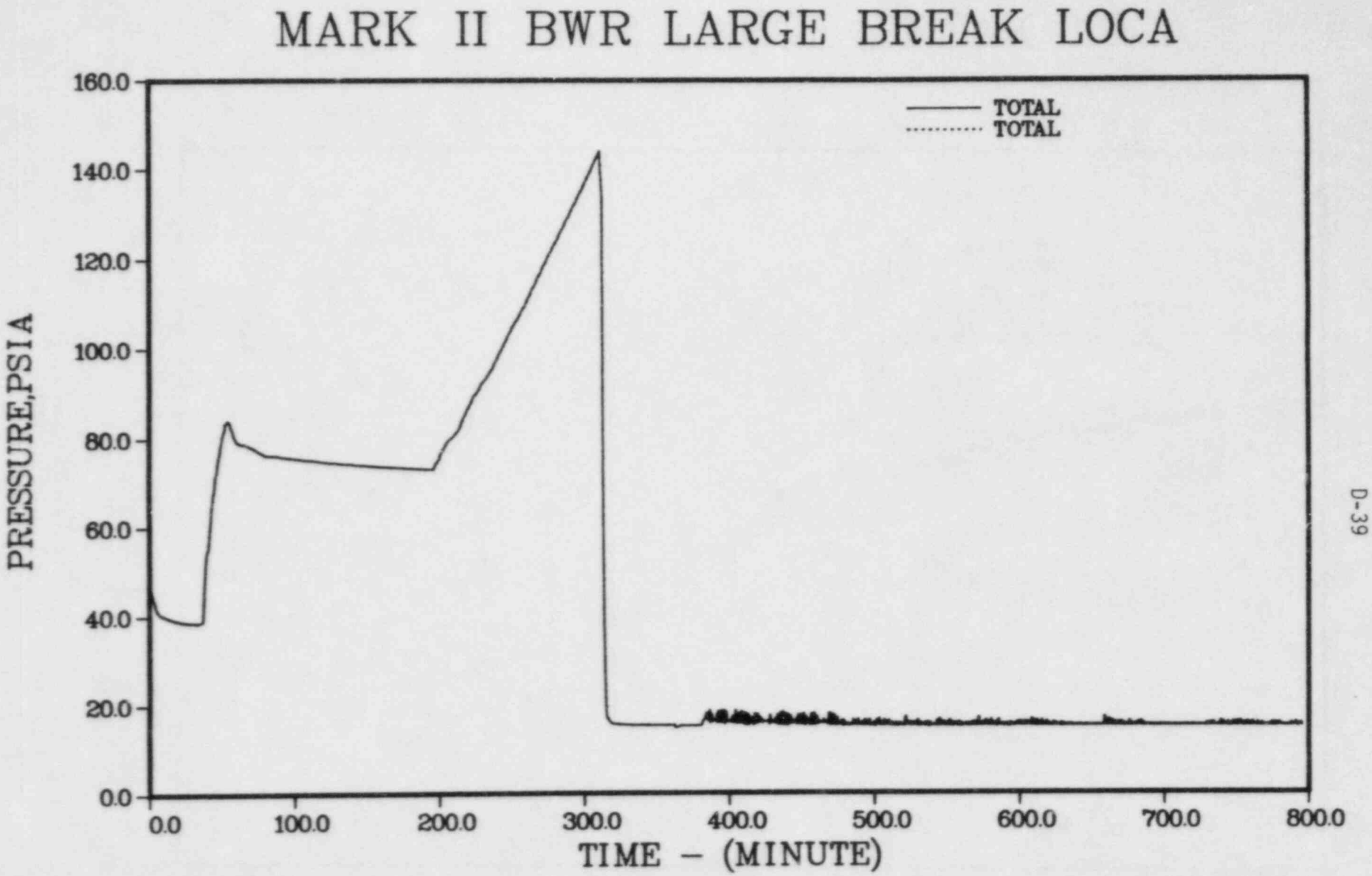


FIGURE D.16 CONTAINMENT PRESSURE RESPONSE FOR MARK II BWR LARGE LOCA

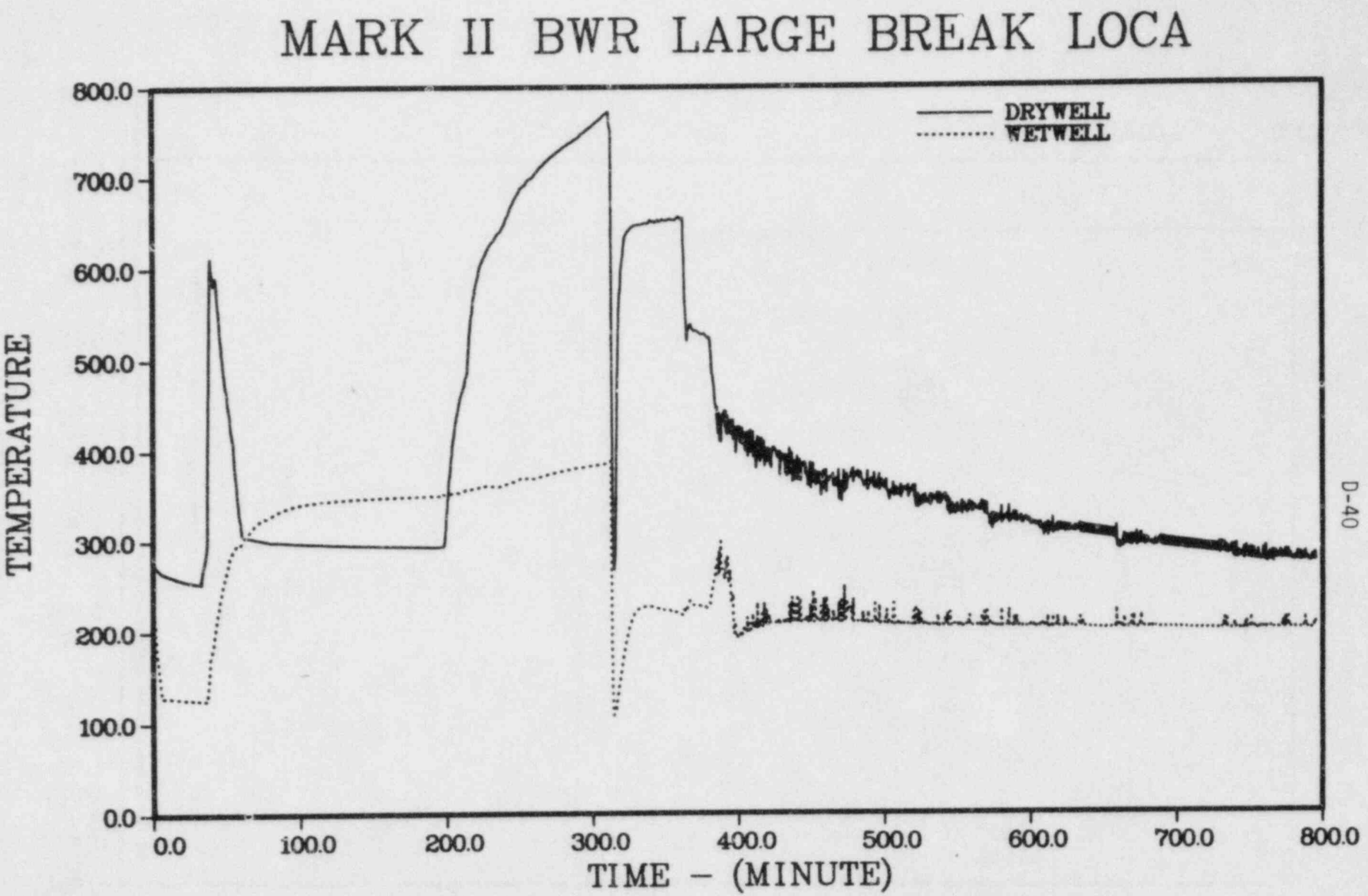


FIGURE D.17 CONTAINMENT TEMPERATURE RESPONSE FOR MARK II BWR LARGE LOCA

NRC FORM 335 (2-84) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

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5. AUTHOR(S)

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13. ABSTRACT (200 words or less)

MARCH 2 describes the response of water-cooled reactor systems to severe accidents, particularly those leading to core meltdown. The code performs the calculations from the time of accident initiation through the stages of coolant blowdown and boiloff, core heat up and meltdown, pressure vessel bottom head melting and failure, and debris-water and debris-concrete interactions in the reactor cavity. Both the primary system and the containment building are modeled. Mass and energy additions to the containment building are evaluated and the pressure-temperature response of the containment with or without engineered safety features is calculated. A maximum of eight containment sub-volumes may be modeled. Engineered safety features modeled include emergency core cooling systems, containment sprays, building coolers and fans, suppression pool and ice condenser containments, and emergency core cooling and spray heat exchangers. Effects of of metal-water reactions, combustion of hydrogen and carbon monoxide, heat losses to containment structures, and redistribution of the decay heat due to loss of volatile fission products from the core are considered. MARCH 2 is intended to replace the earlier MARCH1.1 code. It is written in FORTRAN 77 to improve transportability.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS

accidents
severe accidents
core melt
containment response
accident analysis
metal-water reactions
fuel-coolant interactions
hydrogen generation
hydrogen burning
conium-concrete interactions

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