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

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ABSTRACT

The MARCH code,written at Battelle's Columbus Laboratories for the U. S. Nuclear Regulatory Commission,describes the response of the LWR systems to small or large pipe break and transient accidents which when combined with the failure of engineered safety features can result in core meltdown. The code performs the calculations from the time of the commencement of the accident through the stages of blowdown, core heat up, boiloff, core meltdown, pressure vessel bottom head melting and failure, debris-water interaction in the ractor cavity and the interaction of the molten debris with the concrete containment base pad. The mass and energy additions into the containment building during these stages are continuously evaluated and the pressure-temperature response of the containment with or without the engineered safety features is calculated. The containment can be divided into eight or less inter-connected compartment volumes. The engineered safety features which can be modeled included ECCS, containment sprays, containment building coolers, containment fans, PWR ice condensers, BWR pressure suppression pools, and ECC and containment spray recirculation heat exchangers. The analyses account for metal-water reactions, combustion of hydrogen, and heat losses to structures in the containment.

The MARCH code is written in FORTRAN EXTENDED. The code takes input and outputs data in either SI or British system of units. All input data are provided through the use of NAMELIST's. Many of the variables have default values. The amount of printed output is user controlled. A smaller program, MARPLT, is used to process and plot the data from the MARCH code on a Calcomp plotter. In this report, the models which are used in the MARCH code are described. Input requirements for the code are presented and output options are discussed.

ACKNOWLEDGEMENT

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A NOTE TO MARCH USERS

This MARCH code description and user's manual is the product of a
multi-year program at Battelle Columbus Laboratories, sponsored by the
Nuclear Regulatory Commission's Probabilistic Analysis Staff (now the
Division of Systems and Reliability Research). As the sponsor of this
effort, I believe a few comments are appropriate about Battelle's past
efforts and the future direction of NRC's research in this area.
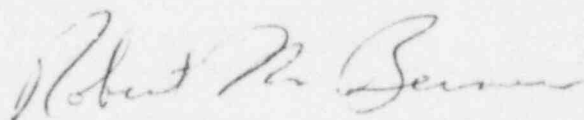
The origins of the MARCH code extend back to the time of the Reactor
Safety Study (RSS), published as WASH-1400, when Battelle was first
enlisted to assist NRC in the modeling of core meltdown accidents. With
the publication of the RSS in 1975, it was evident that the time and
need were ripe for a serious follow-up effort to extend and improve upon
the work done for the RSS. In the ensuing years, staff members at
Battelle have labored diligently to produce this code and its documenta-
tion. I believe it to be a commendable effort.

It is also important to note here what has been the intent in guiding
this code development. Our primary goal has always been the creation of
a computer code which can be used to analyze the entire, possibly prolonged,
course of a postulated core meltdown accident. In order to accomplish
this, it has been necessary to model particular phenomena on a somewhat
simplistic basis, sacrificing highly detailed modeling but achieving a
fast running, integral meltdown code. Within the (present) inherent
uncertainties associated with meltdown accident phenomenology and for
the purposes of risk assessment, this seems to be an entirely appropriate,
if not unavoidable, analytical approach. For this reason, it is essential
to emphasize the importance of a judicious use of the code, with recognition
of its limitations, uncertainties, and intended use.

The accident at Three Mile Island and subsequent events make it obvious
that both the analytical and experimental aspects of severe core damage
accident analysis will require intense efforts on the parts of many
people in the years to come. Within this context, further code development
will be necessary both to improve the modeling of important plant features
(e.g., the secondary heat removal system) and to incorporate the results
of ongoing experimental and analytical research. It is our intent to
vigorously pursue these needs, all the while keeping in mind the intent
of having a highly responsive, integral tool to assist us in both normal
regulatory matters and accident response situations.

Finally, a note about the logistics of obtaining the MARCH code. With the publication of this code description and user's manual, the code itself has been, for the moment, "frozen" in its development and made publicly available through the National Energy Software Center at Argonne National Laboratory. It is recommended that those readers who desire to use the code obtain it from this source to assure they have the most recent version. Also, for those who previously obtained preliminary versions of the code for particular applications, I strongly recommend that the code center version be obtained to avoid future problems with results from differing versions.

Robert M. Bernero, Director
Division of Systems and Reliability
    Research
Office of Nuclear Regulatory Research

MARCH
(Meltdown Accident Response CHaracteristics)
CODE DESCRIPTION AND USER'S MANUAL

by

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I. INTRODUCTION

The purposes of this manual are to describe the models used in
the MARCH computer code and to aid the user in the setup and operation
of the code. The MARCH/CORRAL code package has been written to describe
the phenomena associated with core meltdown accidents in light water power
reactors. The CORRAL[1,2] (Containment Of Radionuclides Released in A LOCA)
code describes the transport and deposition of released radionuclides within
containment and the airborne release of radioactivity to the environment.
The MARCH code predicts the thermal and hydraulic processes in a core
meltdown accident and provides the boundary conditions for the operation
of CORRAL.

The development of the MARCH code was undertaken by Battelle for
the U. S. Nuclear Regulatory Commission subsequent to the performance of
the Reactor Safety Study[3]. In that study, core meltdown accidents had
been found to be the dominant contributors to public risk from the operation
of light water reactors. The methods for analyzing core meltdown accidents
which had been developed for the Reactor Safety Study were recognized to
have a number of limitations. The development of the MARCH code was
undertaken in order to remove many of these limitations in subsequent
studies. The objectives of the development of MARCH were to:

- Generalize the existing analytical models to cover a broader
  range of LWR designs beyond those included in the Reactor
  Safety Study.

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(1) Appendix VII, in Reference (3).

(2) R. J. Burian and P. Cybulskis, "CORRAL 2 User's Manual", Battelle's
    Columbus Laboratories, Columbus, Ohio (January 1977).

(3) "Reactor Safety Study, An Assessment of Accident Risks in U. S. Commer-
    cial Nuclear Power Plants", WASH-1400 (October 1975).

- Extend the range of applicability of the models to include reactor transients and small break accidents as well as the large pipe break accidents that received the primary emphasis in the Reactor Safety Study.

- Provide a consistent and integrated treatment of the entire accident time period of interest.

- Incorporate relevant new experimental data that had been developed since the formulation of the previous models.

This document describes the structure and the models contained in MARCH together with a user's guide as they have evolved over a period of time, largely in conjunction with the Reactor Safety Study Methodology Applications Program. Section II provides a General Description of the MARCH code. In Section III, each of the major models is described. Sections IV and V cover input requirements and output options, respectively. Section VI is a brief outline of the MARCH code characteristics such as core memory size, execution time, etc. A smaller program, MARPLT, has been written to process the results of the MARCH code and plot them on a Calcomp plotter. The description of MARPLT and its input and output are in Section VII. Sample MARCH input and output, and sample plots from the MARPLT program are included in the Appendices A, B, and C, respectively. Appendix D gives a glossary of the acronyms used in the report.

The development of the MARCH code was undertaken for application to reactor risk studies and thus is primarily aimed at accident sequences involving gross core melting. With the increasing interest in degraded core behavior, MARCH is being applied to situations short of complete core melting as well as for the evaluation of core meltdown accident mitigation features. The existing code may not be completely suited for all such applications; however, it should provide a convenient framework in which changes and improvements can be made to suit particular applications.

The MARCH code models a wide variety of physical processes, consistent with the phenomena expected to be associated with meltdown accidents in light water power reactors. It should be recognized that limited bases exist for many of the models, though all are believed to be reasonable within the context in which the code was developed. In some areas, improvements

in MARCH can be made simply by the investment of the modeling effort. Other areas are limited by the state of knowledge on meltdown behavior and major experimental programs may be required to validate existing models or to provide the basis for the development of new ones. In view of the lack of a firmly established basis for some of the MARCH modeling, substantial care and judgement should be exercised in the selection of input parameters as well as the interpretation and application of the computational results. There are numerous user selected options that must be specified in implementing the MARCH code; the choice of options can clearly affect the results. Further, the MARCH code has incorporated in it default values for many of the required input variables. These have been provided to facilitate the initial implementation of the code and should not be construed in any way as being recommended values. The choice of a particular input parameter should be considered on a case-by-case basis.

II. GENERAL DESCRIPTION OF THE MARCH CODE

The MARCH code was developed to analyze the thermal-hydraulic response of the reactor core, the primary coolant system, and the containment system in light water reactors to core meltdown accidents. Depending on the accident sequence, the code can carry out the calculations through the stages of:

1) Initial blowdown of the primary system coolant into the containment,

2) Generation and transport of heat energy in the reactor core, the pressure and temperature response of the primary system, boiloff of water from the reactor vessel, melting and slumping of the core to the pressure vessel bottom head, and metal-water reactions in the vessel,

3) Interaction of the core debris with the pressure vessel bottom head and the melt-through of the vessel,

4) Interaction of the core debris with water in the reactor cavity following melt-through of the vessel, and

5) The interaction of the core debris with the concrete containment floor underneath the pressure vessel.

The mass and energy additions to the containment building during Stages 1 through 5 are continuously evaluated and the pressure-temperature response of the containment is calculated either with or without the operation of containment safety features. Models have been developed that also calculate the release of the volatile fission products from the melted fuel and follow the heat source associated with a number of groups of fission products into the containment or to the outside atmosphere if leakage occurs.

Figure II.1 shows schematically how the MARCH code treats the five stages of a meltdown accident sequence. In Figure II.1, INITIAL, BOIL, HEAD, HOTDROP, and INTER are the names of the subroutines that perform the analysis of Stages 1 through 5, respectively. If the accident is not a large pipe
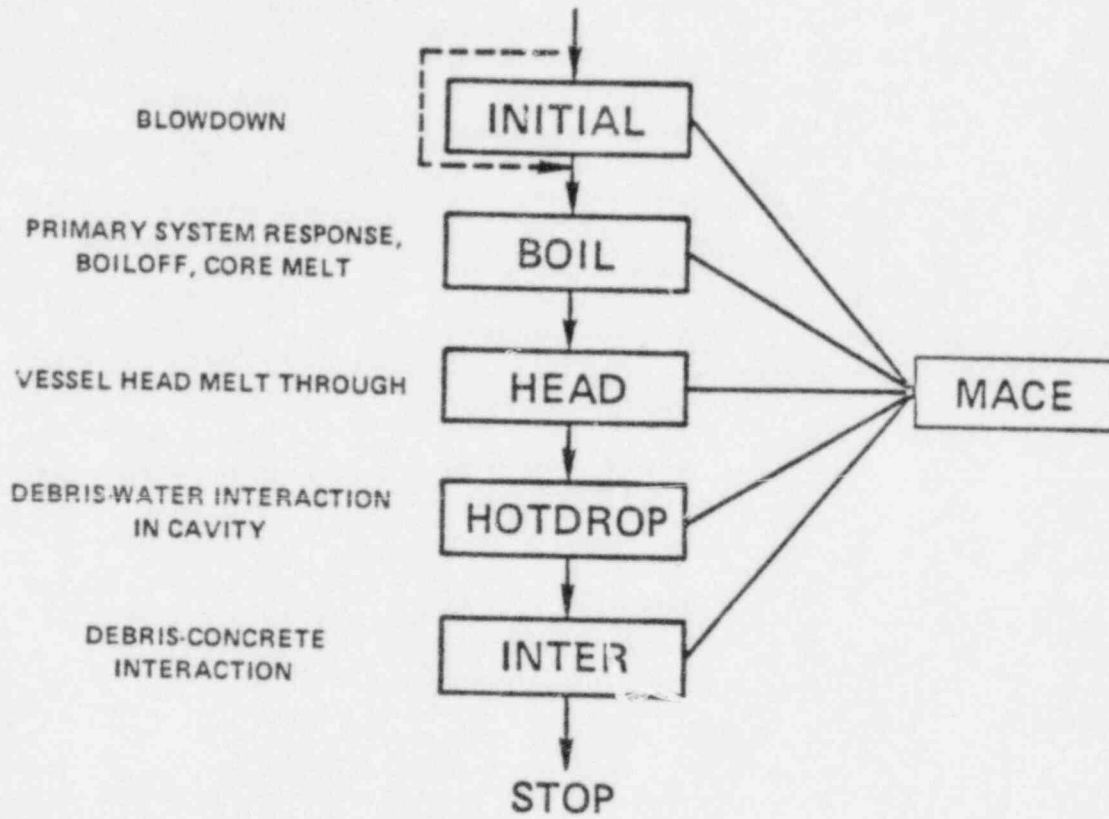
MARCH CODE TREATMENT OF A POSTULATED REACTOR ACCIDENT

FIGURE II.1

break accident, the subroutine INITIAL is bypassed and the BOIL calculations start immediately. In this case, the blowdown is calculated by subroutine PRIMP, which is called from BOIL. As shown in Figure II.1, all five subroutines are continuously and independently coupled to the containment analysis code MACE.

Figure II.2 is a simplified layout of the MARCH code. Subroutines INITIAL, BOIL, HEAD, HOTDROP, and INTER are all called from a main routine named MARCH. A call to the subroutine MACE is also made from MARCH after each call to one of the other subroutines. The subroutine INPUT is called only once at the very beginning of the calculations and is used to read all the card input data to the program. The data are read, edited, and echo-printed in tabular form by the subroutine INPUT. The input procedures used for the MARCH code are described in Section IV. In performing their tasks, the subroutines BOIL, HEAD, HOTDROP, INTER, and MACE are supported by a number of other subroutines or functions (see Figures II.3 - II.7).

The subroutine INTER and its associated subroutines shown in Figure II.6 were originally written as a separate code at Sandia Laboratories[4]. They have been adapted and integrated into the MARCH code by Battelle. Subroutine BOIL[5] was developed by Battelle for the Reactor Safety Study. The other portions of MARCH were developed by Battelle under a program sponsored by the Probabilistic Analysis Staff of the Nuclear Regulatory Commission.

Table II.1 lists in alphabetical order the names of the subroutines in the MARCH code (Figure II.1 - II.7) and gives a brief description of what each subroutine does. The function routines are listed in Table II.2.

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(4) Walter B. Murfin, "A Preliminary Model for Core/Concrete Interactions", Report SAND 77-0370, Sandia Laboratories, Albuquerque, New Mexico (August, 1977).

(5) Roger O. Wooton, "BOIL1, A Computer Program to Calculate Core Heatup and Meltdown in a Coolant Boiloff Accident", Battelle's Columbus Laboratories (March, 1975). Also see reference 2, Appendix VIII-A.
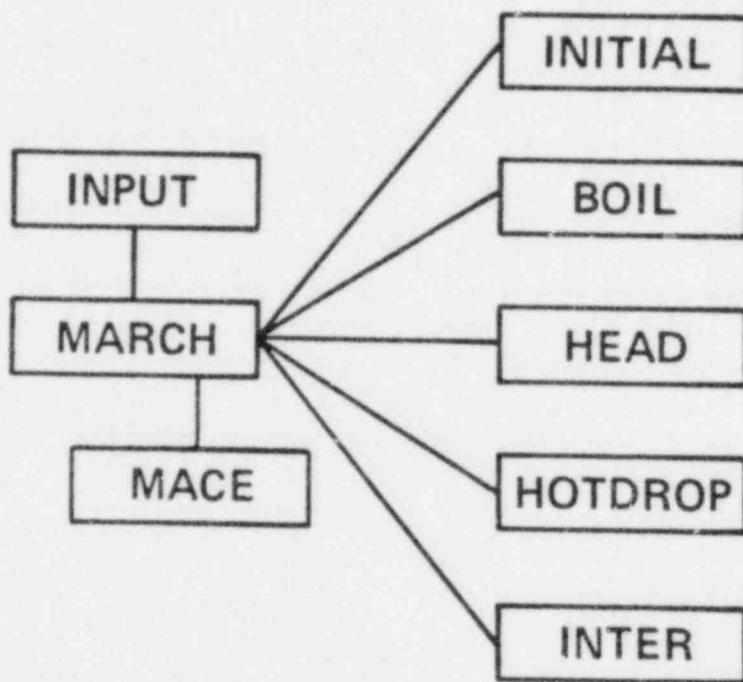
SIMPLIFIED LAYOUT OF MARCH CODE

FIGURE II.2
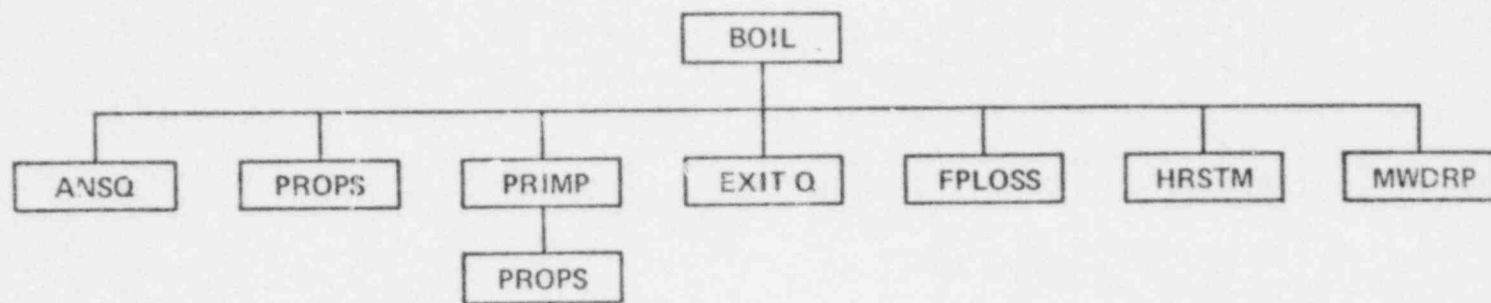
SUBROUTINES ASSOCIATED WITH BOIL

FIGURE II.3

```
        ┌──────────┐
        │   HEAD   │
        └──────────┘
      ┌──────┴──────┐
┌──────────┐   ┌──────────┐
│   ANSQ   │   │  FPLOSS  │
└──────────┘   └──────────┘
```
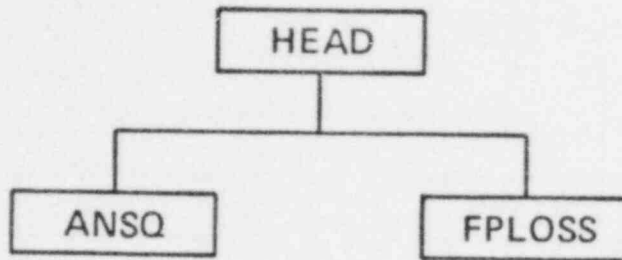
SUBROUTINES ASSOCIATED WITH HEAD

FIGURE II.4

```
          ┌──────────┐
          │ HOTDROP  │
          └──────────┘
     ┌─────────┼─────────┐
┌────────┐ ┌────────┐ ┌────────┐
│  ANSQ  │ │ PROPS  │ │ FPLOSS │
└────────┘ └────────┘ └────────┘
```
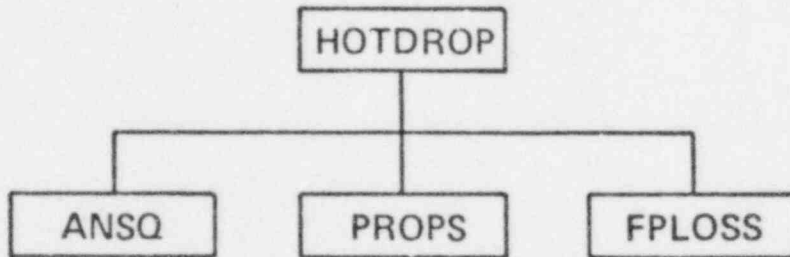
SUBROUTINES ASSOCIATED WITH HOTDROP

FIGURE II.5
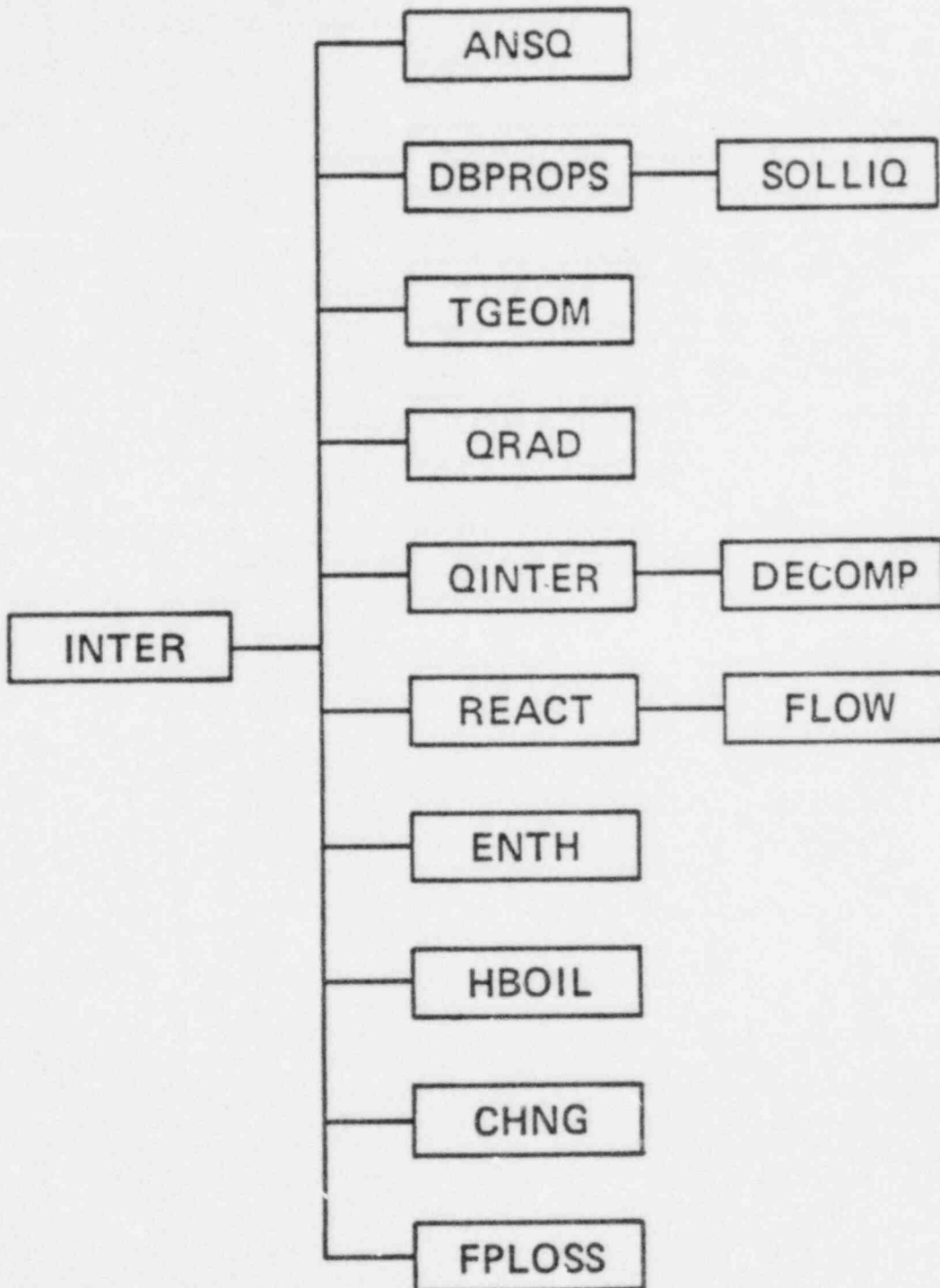
SUBROUTINES ASSOCIATED WITH INTER
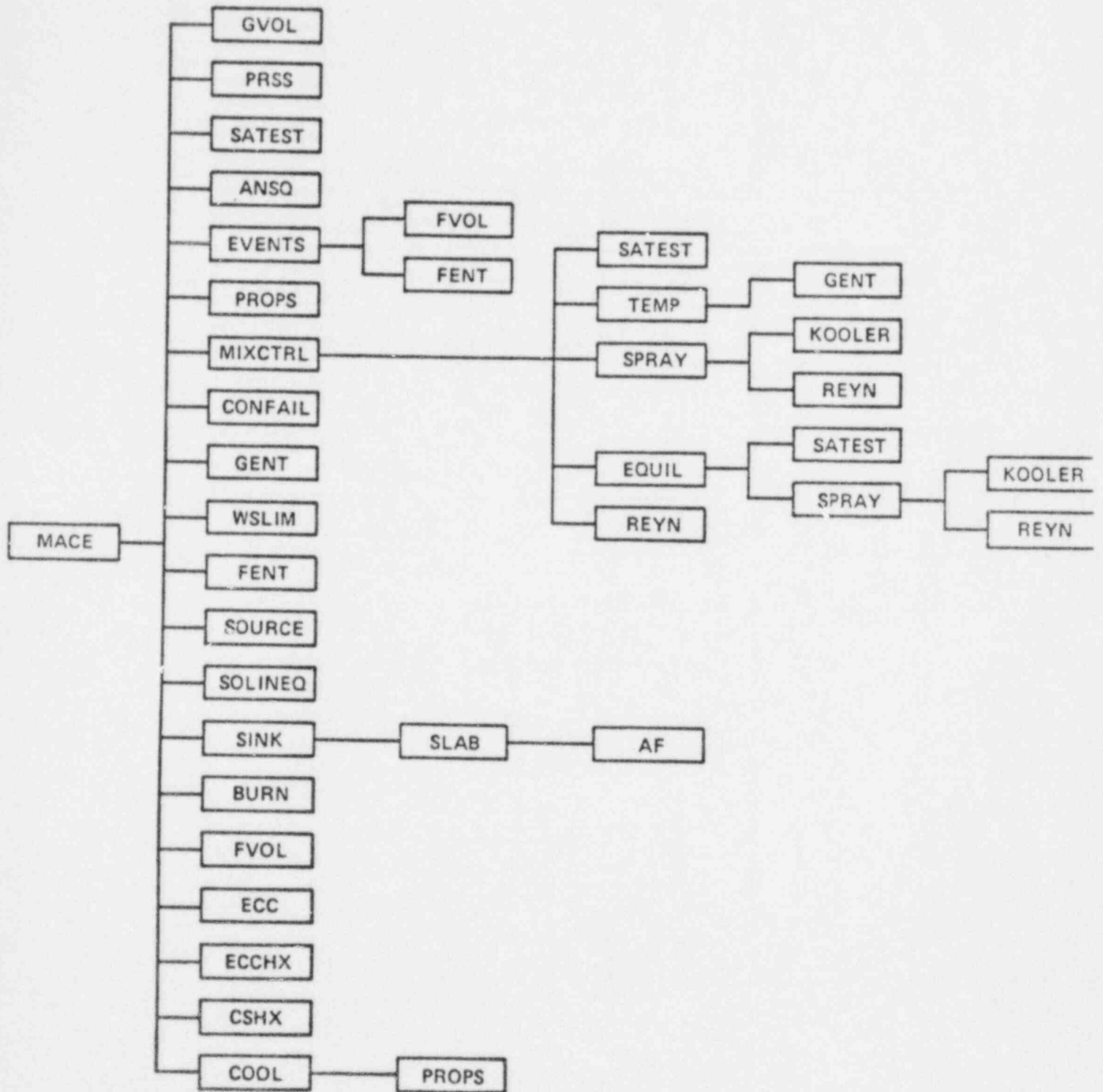
FIGURE II.6

SUBROUTINES ASSOCIATED WITH MACE

FIGURE II.7

TABLE II.1   SUBROUTINES IN THE MARCH CODE

Subroutine	Description
ANSQ	Calculates the American Nuclear Society standard decay heat fraction as a function of time after shutdown and time at power.
BOIL	Does the following: heat generation and transfer in the core, thermal-hydaulics of the primary system, boiloff of water from the reactor vessel, melting and slumping of the core material to the vessel bottom head, and Zr-H_2O reactions in the core and in the bottom head.
BURN	Burns hydrogen in containment volumes if its concentration exceeds flammability limits.
CHNG	Reduces the molten debris to single oxidic layer when all the metal has been used up by chemical reactions.
CONFAIL	Calculates the mass and energy leakage to outside atmosphere through the break area when the containment fails.
CONVENT	Calculates flow rates between compartments based on pressure difference when one compartment vents into another.
CONVERT	Converts input units from SI to British.
COOL	Calculates the rate at which the energy is extracted from the containment atmosphere by the coolers.
CSHX	Models the containment recirculation spray water heat exchanger.
DBPROPS	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.
DECOMP	Calculates the temperatures and energies associated with the decomposition of the constituents of concrete.
DEFINE	Lists definitions of variables printed in the output.
ECC	Regulates Emergency Core Cooling system water flow.
ECCHX	Models the Emergency Core Cooling recirculation flow heat exchanger.

TABLE II.1 (Continued)

ENTH	Computes enthalpies of products passing into or out of melted debris which is in contact with the concrete containment floor.
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.
EVENTS	Initiates and controls the "events" used in the input to MACE.
EXITQ	Calculates the gas enthalpies and the heat transferred to structures in the gas flow path exiting the primary system.
FICH	Used to obtain the output from the code on microfiche.
FPLOSS	Models the loss of volatile fission products from the melted fuel.
HEAD	Performs the heat transfer analysis between the melted core debris and the pressure vessel bottom head, and calculates the bottom head failure.
HOTDROP	Analyzes the interaction of the core debris with water in the reactor cavity following the vessel bottom head melt-through including such effects as debris fragmentation, heat transfer, and chemical reactions.
HRSTM	Calculates the rod-to-steam radiation heat transfer coefficients in the core.
INITIAL	Inputs initial blowdown coolant into containment for large pipe break loss of coolant accidents.
INPUT	Reads the card input data into the code, edits, and echo-prints the same data in tabular form.
INTER	Analyzes the interaction between the molten core debris and the concrete containment floor, and the penetration of the molten debris into concrete.
KOOLER	Does the spray water droplet – containment atmosphere heat transfer analysis if the initial spray water temperature is greater than the containment temperature.

TABLE II.1 (Continued)

MACE	Computes the containment response to mass and energy inputs from subroutines INITIAL, BOIL, HEAD, HOTDROP, and INTER.
MARCH	The main program. It calls various subroutines for performing appropriate tasks during an accident sequence and regulates program flow.
MIXCTRL	MIXCTRL 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.
MWDRP	Analyzes the metal-water reactions taking place in the pressure vessel bottom head after the core slumps.
PRIMP	Evaluates the pressure in the primary coolant system for small pipe break and transient accidents. It also calculates the amount of water/steam leakage into containment through a small pipe break and/or safety/relief valve.
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 values in the table. The properties included in the table are pressure, temperature, specific volumes, specific enthalpies, and specific heat of water.
QINTER	Performs heat transfer analysis at the molten debris-concrete interface, and calculates the rate of penetration of the melt into concrete.
QRAD	Calculates the heat radiated from the top surface of the molten debris to the walls of the cavity.
REACT	Performs mass and energy balances in chemical reactions $Fe + H_2O$, $Fe + CO_2$, $Zr + H_2O$, $Zr + FeO$, $Cr + H_2O$, and $Ni + H_2O$ during the time when the debris is melting the concrete floor of the containment. The reactions take place in the metallic layer of the debris.

TABLE II.1 (Continued)

REYN	Calculates the Reynold's number and the fall velocity associated with the spray water droplets in containment atmosphere.
RSTART	Catalogs the files created by the code and stops the problem. It can be used to restart the same problem from the beginning or from where it left off. When the problem is restarted, some of the input numbers can be changed if desired. RSTART is the last subroutine called from the main program MARCH.
SATEST	Determines whether or not the steam in the containment atmosphere is superheated.
SINK	Subroutines SINK and SLAB do heat transfer analysis between the containment atmosphere and the walls and the structures in the containment. They calculate the amount of heat lost to the walls and the structures and an average wall surface temperature in each containment volume.
SLAB	See SINK above.
SOLINEQ	Solves for the mass transfer between containment volumes which equilibrate the pressures in all volumes at the end of a timestep.
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 the oxide layer due to melting or freezing of its constituents.
SOURCE	Arranges the containment volumes in the order of decreasing pressure before inter-compartmental transfers take place.
SPRAY	Performs mass and heat transfer calculations between the spray water droplets and the containment atmosphere. It also calculates how much water and energy is added to the containment sump as a result of spray action.

TABLE II.1 (Continued)

TEMP	Calculates the equilibrium thermodynamic properties such as partial pressure of steam, air, and its constituents, specific enthalpy, specific volume, and mass of steam and water droplets in containment atmosphere after uniformly distributing the net effect of any mass/energy additions or deletions in containment volumes.
TGEOM	Calculates the thermal boundary layer thicknesses in the debris and the concrete.
UNITS	Lists units used in the output from the code.
WSLIM	Limits the steam mass in the containment atmosphere to that minimum value which would be present if the containment volume were filled with 40°F saturated steam.

TABLE II.2 FUNCTION ROUTINES IN THE MARCH CODE

Function	Description
AF(X)	Wall condensing heat transfer coefficient correlation where X is the air-to-steam weight ratio.
FENT(T)	Enthalpy of saturated water at T°F.
FLOW(G)	The gas fraction which is available for reactions with the constituents of the metallic layer of the debris. $G = \dfrac{\dot{m}}{V_m}$, where $\dot{m}$ is the mass rate of production of gases (CO_2 and H_2O) and V_m is the volume of the metallic phase of the molten debris.
FVOL(T)	Specific volume of saturated water at T°F.
GENT(T)	Enthalpy of saturated steam at T°F.
GVOL(T)	Specific volume of saturated steam at T°F.
HBOIL (X1, X2, X3, X4)	Boiling heat transfer correlation for water which is in contact with the molten debris.
PRSS(T)	Saturation pressure of steam at T°F.

III.   DESCRIPTION OF MODELS

In this chapter, the calculational procedures in the MARCH code
which model the various physical processes that would take place during
a postulated LWR accident are described. To the extent possible, the ra-
tionale behind the calculations, the assumptions used, as well as the
mathematical equations programmed in the code are provided. However,
because of the large diversity and size of the subject matter treated
in the MARCH code, it was not possible to give a comprehensive review
of literature in all areas discussed.

Some models are treated in single subroutines and others spread
over more than one routine. A brief description of all subroutines in the
code was given previously in Chapter II. In the sections below, the sub-
routines in which the models are contained are identified. This provides
a cross reference between Chapters II and III as an aid to the user who
would like to study some of the models in more detail by looking at the
programmed algorithms.

III.A.   PRIMARY SYSTEM MODELS (BOIL)

The subroutine BOIL and its associated subroutines (Figure II.3)
in the MARCH code analyze the events and conditions in the primary system
during the core heatup and meltdown stage of the accident. After core
slumping into the bottom head and bottom head dryout, conditions are cal-
culated in HEAD.

The subroutine BOIL was originally developed by Battelle[5] as
a separate code for the Reactor Safety Study[2]. Recently, it has been
incorporated in the MARCH code as a module. The capabilities of the BOIL
package have been extended over the original version and some of the original
models have been modified. This section will explain the current methodology
and document the models used in the BOIL routine at the present time.

Figure III.A.1 is a diagram showing the sequential flow of the calculations in the BOIL subroutine. Briefly the major steps include:

1) initializing the conditions in the primary system from input values and doing some preliminary calculations,

2) changing some parameters as required by input, such as timestep size, break elevation and area, restart parameters, etc.,

3) determining the decay power level (Section III.G),

4) analyzing heat transfer between the primary coolant and lower pressure vessel internals (Section III.A.8),

5) modeling the steam generator (Section III.A.4),

6) calculating the void fraction and steam-water mixture level in the core (Section III.A.3),

7) analyzing the heat transfer mechanisms in core (Section III.A.1),

8) calculating the mass and energy balances from metal-water reactions (Section III.A.6),

9) calculating core melt fractions (Section III.A.5),

10) finding the fission product release fractions from fuel (actually these calculations are done in sub-routine FPLOSS) (Section III.F),

11) checking to see if bottom grid plates have failed (Section III.A.8),

12) calculating leakage rates from the primary system (Calculations are done in subroutine PRIMP for transients and small pipe break accidents (Section III.A.9.a-c),

13) calculating the primary system pressure (Section III.10)

14) analyzing the heat transfer between the gases exiting from the top of the core and the structures above the core (Section III.A.7),

15) printing the BOIL output parameters describing the present conditions in the primary system.
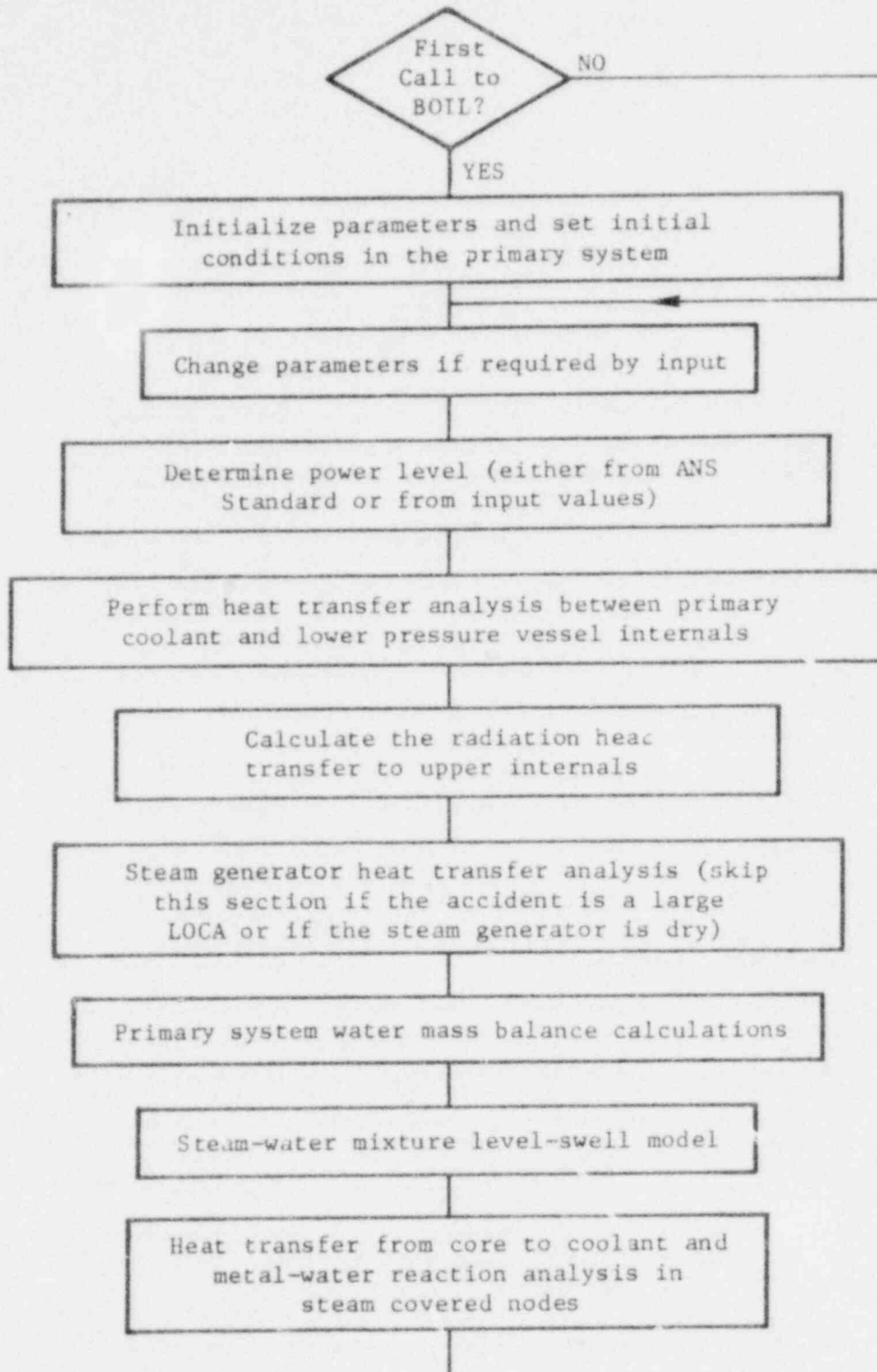
FIGURE III.A.1 FLOW DIAGRAM FOR CALCULATIONS IN SUBROUTINE BOIL

```
                        │
          ┌─────────────────────────────┐
          │    Core meltdown analysis    │
          └─────────────────────────────┘
                        │
      ┌───────────────────────────────────────┐
      │ Metal-water reactions in the bottom head │
      └───────────────────────────────────────┘
                        │
        ┌─────────────────────────────────┐
        │  Fission product loss calculation │
        └─────────────────────────────────┘
                        │
        ┌─────────────────────────────────┐
        │  Grid plate failure calculation  │
        └─────────────────────────────────┘
                        │
     ┌──────────────────────────────────────┐
     │  Calculate mass and enthalpy leakage   │
     │   rates into containment building      │
     └──────────────────────────────────────┘
                        │
   ┌──────────────────────────────────────────┐
   │ Calculate the present thermodynamic and thermal │
   │   hydraulic conditions in the primary system    │
   └──────────────────────────────────────────┘
                        │
   ┌──────────────────────────────────────────┐
   │ Heat transfer analysis between the gas exiting the │
   │  primary system and the structures above core      │
   └──────────────────────────────────────────┘
                        │
              ┌───────────────┐
              │    Output     │
              └───────────────┘
                        │
                   RETURN
```

FIGURE III.A.1 (CONTINUED)

The individual models in the subroutine BOIL are explained below in subsections III.A.1 through III.A.10. However, some general remarks regarding the BOIL code and the calculations in it are given here.

The calculational approach used in BOIL is to divide the core into small volumes or nodes and (1) calculate the heat produced in each node and perform heat balances between the fuel and coolant nodes, (2) calculate the water-steam mixture level in the core and the steam-boiloff rate and, (3) perform a meltdown calculation when the temperature of a node exceeds the melting point of the core.

The core is divided into a maximum of 10 radial zones composed of fuel rods and their associated flow channels. The radial zones are sectioned into a maximum of 50 equi-dimensioned axial nodes. The sizes of the radial zones are arbitrary, and are normally chosen in a manner which conveniently describes the radial power distribution of the core. In the heat-transfer calculations, the only coupling between radial zones before core melting occurs is by a uniform steam mass flow velocity at the inlet to the steam-covered region. At the channel exit, the steam concentration depends on the amount of metal-water reaction in that particular channel. There is normally no coupling of radial zones by conduction, convection, or radiation heat transfer. After core melting occurs, radial zones may (program options) be coupled by steam cross flow and mixing within the pool of molten fuel in the core. The axial fuel-rod nodes within a given radial zone are normally coupled in the heat-transfer calculations only through their connection to a common steam channel. During core meltdown, the axial nodes are assumed to be coupled within the molten region by convective mixing. The axial nodes are not coupled by conduction heat transfer, but are connected by the axial flow of steam in the flow channel.

III.A.1 CORE HEAT TRANSFER ⌐ . ⌐⌐

The core heat transfer models in the subroutine BOIL account
for (1) convection heat transfer between the fuel rods and steam or water
coolant, (2) radiation heat transfer from fuel rods to steam and from the
uncovered nodes to structures above the core or to water below the nodes
and (3) heat transfer resulting from the quenching of the slumped molten
core material and recovered nodes. The overall primary system heat balance
equations include the heat energy transferred to and from the fuel, coolant,
structures above and below the core, and the steam generator if there is
one. The models employed in the MARCH code in the analysis of the heat
transfer mechanisms involving the structures above and below the core and
the steam generator are outlined in section III.A.7, III.A.8, and III.A.4,
respectively. The heat transfer mechanisms inside the core are explained
in this section.

The core is divided into two heat transfer regions, a gas (steam
and hydrogen) covered region and a region covered with a water-steam mix-
ture. In the gas covered region, the heat transfer from the fuel rods to
the gas is calculated using an effective heat transfer coefficient, h, as

$$Q_c = h(T_R - T_G)$$ (III.A.1)

where T_R and T_G are the fuel rod and gas temperatures respectively. h is
given by

$$h = h_c + h_{rad}$$ (III.A.2)

where h_c = convection heat transfer coefficient and h_{rad} = radiation heat
transfer coefficient. h_c used in Equation (III.A.2) is taken as the maximum
of h_{cD} and h_{nat} where h_{cD} is calculated from a simplified Dittus-Boelter cor-
relation[6] and h_{nat} is the natural convection heat transfer coefficient.
h_{cD} is given by

$$h_{cD} = 0.0144C_p G^{0.8}/D^{0.2}$$ (III.A.3)

_____

(6) W. H. McAdams, Heat Transmission, 3rd ed., McGraw-Hill Book Co. (1954).

where C_{p} = specific heat of gas, Btu/lb/F; G = gas mass flow velocity, lb/hr/ft^2; D = equivalent diameter of channel, ft; and

$$C_p = \frac{\dot{M}_s C_{ps} + \dot{M}_H C_{pH}}{\dot{M}_s + \dot{M}_H} \qquad \text{(III.A.4)}$$

$\dot{M}_s$, $\dot{M}_H$ = generation rate of steam and hydrogen in the core, respectively.
C_{ps}, C_{pH} = specific heats of steam and hydrogen in the core, respectively.
C_{ps} and C_{pH} depend on the gas temperature and are given by

$$C_{ps} = 0.43 + 0.8 \times \frac{T_G}{10,000} \qquad \text{(III.A.5)}$$

$$C_{pH} = 3.4 + 11 \times \frac{T_G}{1,000} \qquad \text{for } T_G \leq 1,000$$

$$= 3.26 + 2.48 \times \frac{T_G}{10,000} \qquad \text{for } T_G > 1,000 \qquad \text{(III.A.6)}$$

G is given by

$$G = \frac{\dot{M}_H + \dot{M}_s}{A_{core}} \qquad \text{(III.A.7)}$$

where A_{core} = flow area of core (input number).

h_{nat} is calculated as:

$$h_{nat} = 0.095 \times (T_R - T_G)^{1/3} \qquad \text{(III.A.8)}$$

The radiation heat transfer coefficient, h_{rad} is calculated assuming the fuel rod radiates only to steam and is given by:

$$h_{rad} = 17.3 \times 10^{-10} (\varepsilon_{SR} T_R^{'4} - \varepsilon_{SG} T_G^{'4})/(T_R^{'} - T_G^{'}) \times (1 + \varepsilon_R)/2 \qquad \text{(III.A.9)}$$

$$Btu/hr/ft^2/F$$

where

ϵ_{SR} = steam emissivity at temperature T_R'

ϵ_{SG} = steam emissivity at temperature T_G'

ϵ_r = fuel rod emissivity

T_R' = rod temperature, $^\circ R$

T_G' = steam temperature, $^\circ R$

The steam emissivities in the BOIL model are evaluated at an optical thickness, PD_H, where P is the local partial pressure of steam in the flow channel and D_H is the hydraulic diameter. At low pressures, such as would occur in a large pipe break LOCA, the results of McAdams[6] indicate the optical thickness and the steam emissivities are small, and radiation heat transfer to steam can be neglected. Likewise, if the gas in the flow channel is all hydrogen, radiation heat transfer is negligible. For high system pressures, such as those prevailing in transient accidents, there are no experimental data on steam emissivities. However, if the low pressure data of McAdams are extrapolated to high pressures, large steam emissivities are predicted. In some cases, the radiation heat transfer coefficients may be an order of magnitude larger than the convection coefficients.

In the water or water-steam mixture covered nodes of the core, a constant heat transfer coefficient is used in conjunction with Equation (III.A.2). This coefficient is supplied to the code by the user in cases of large pipe break accidents. In other types of accidents, it is calculated in the code at the start of calculations from:

$$h_B = \frac{Q_D}{(T_{ci} - T_{wi}) A_f} \qquad \text{(III.A.10)}$$

where

h_B = heat transfer coefficient

Q_D = core power

T_{ci} = average core temperature

T_{wi} = water temperature

A_f = total wetted fuel rod area   .

Heat can also be radiated from the uncovered part of the core
to (1) the pressure vessel internal structure immediately above the core,
(2) the water inside or below the core. The heat transferred by radiation
from a node with emitting area A_R is:

$$Q_{rad} = 0.173FA_R \left[(T_{RO}/100)^4 - (T_0/100)^4\right] \qquad \text{(III.A.11)}$$

where

Q_{rad} = radiation heat transfer, Btu/hr

A_R = radiating area, ft^2

T_{RO} = temperature of radiating node, R

T_0 = temperature of receiver node, R

F = radiation interchange factor.

The interchange factor used for heat transfer to the structure
above the core is user supplied. For radiation heat transfer to water
below the uncovered nodes, a constant value of 0.5 is used. The area,
A_R, is the part of the cross sectional area of the core in a given radial
zone. The total heat radiated is calculated by summing the Q_{rad} over the
total cross section of the core. For radiation heat transfer from the core
to the water, the T_{RO}'s are evaluated in the plane of the first uncovered
node above the water. For heat transfer to the internal structure above the
core, the T_{RO}'s are evaluated for nodes in a plane at the top of the core.

BOIL contains models for the quenching of molten core debris fall-
ing into the water and quenching of solid fuel rods which have been recovered
with water due to ECCS injection or mixture level swelling in the core. The
quenching rate in BOIL is calculated from the minimum obtained using either
a boiling heat transfer coefficient or rates characterized by a time constant
τ. Three terms are evaluated:

$$QB1 = h_B A(TROD - TPOOL)\Delta t \qquad\qquad \text{(III.A.12)}$$

$$QB2 = MC(TROD - T_R)\Delta t/\tau \qquad , \text{ and} \qquad \text{(III.A.13)}$$

$$QB3 = \rho_L V_L h_{fg}(1 - \alpha)\Delta t/\tau \qquad , \qquad\qquad \text{(III.A.14)}$$

where

h_B = boiling heat transfer coefficient, $Btu/hr/ft^2$ F
(Equation III.A.10 or in input)

A = node heat transfer area, ft^2

MC = node heat capacity, Btu/F

ρ_L = water density, lb/ft^3

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

V_L = node water volume, ft^3

$TROD$ = fuel node temperature, F (from previous timestep)

T_R = equilibrium temperature, F (obtained from Eq. III.A.2
with Q_c = decay power in the node)

Δt = timestep, min

τ = time constant, min, and

α = local void fraction.

QB2 is the change in stored heat obtained in quenching to decay heat or
equilibrium levels. QB3 is the heat required to vaporize the water in the
coolant channel next to the fuel node. For a 1.0 minute time constant τ,
the QB2 and QB3 terms are generally found to control the quenching rate in
BOIL.

For a fuel-rod node in the gas-covered region, the node tempera-
ture generally increases because the gas flow is insufficient to carry off
the decay heat. The generalized fuel-rod-node heat balance in this region
is

$$RHOCU \times V_R \frac{\partial T_R}{\partial t} + \dot{F}_{melt} \lambda\rho V_R =$$
$$Q_{D,R} + Q_{MW} + Q_{melt} - Q_{rad} - hA(T_R - T_G) \qquad , \qquad \text{(III.A.15)}$$

where

V_R = volume of node, ft^3

$RHOCU$ = heat capacity of core material per unit volume, Btu/ft^3 °F

$\dot{F}_{melt}$ = fraction of node melted per unit time

λ = heat of fusion of core material in the node, Btu/lb

ρV_R = mass of core material in the node, lb

$Q_{D,R}$ = decay power in the node, Btu/hr

Q_{MW} = heat from metal-water reaction, Btu/hr

Q_{melt} = heat added to node from slumping during meltdown, Btu/hr

Q_{rad} = radiation heat-transfer losses, Btu/hr

h = from Equation (III.A.2)

T_G = gas temperature in the node, F .

The increase in the gas temperature along the length of the channel is given by

$$\dot{m}C_p\frac{\partial T_G}{\partial Z} = hp(T_R - T_G) \quad , \qquad \text{(III.A.16)}$$

where

$\dot{m}$ = total gas flow rate, lb/hr

Z = distance measured up the channel, ft

p = fuel rod circumference, ft

In the water or mixture covered regions of the core the generalized fuel-rod-node heat balance equation is

$$Q_{D,R} + Q_{melt} = h_B A(T_R - T_W) \qquad \text{(III.A.17)}$$

where h_B is either an input number or calculated from Equation (III.A.10).

If an uncovered node is recovered due to ECCS water injection or level swelling, the fuel node temperature is the maximum of that calculated from Equation (17) or that obtained from quenching (Equations (III.A.12-14).

III.A.2 PRIMARY SYSTEM MASS AND ENERGY BALANCES

The amount of water in the primary system at the beginning of the accident is supplied to the code as input by the user. During the accident, water may enter the primary system by ECCS injection and leave it through breaks or safety valves either in the form of steam or liquid. Steam may also be lost from the primary system when it reacts with cladding to form ZrO_2 and H_2.

The mass balance equation on the amount of water and steam in the primary system at any time during the accident is

$$WM = WMO + (WECC - WLBRK - WSBRK - DWS + SGDWS)*\Delta t \qquad (III.A.18)$$

where

WM = mass of water + steam in the primary system

WMO = mass of water + steam in the primary system at the end of previous timestep

$WECC$ = ECC injection rate

$WLBRK$ = loss rate of liquid water through breaks and/or valves

$WSBRK$ = loss rate of steam through breaks and/or valves

DWS = consumption of steam by metal-water reactions (See Section III.A.6)

$SGDWS$ = condensate from steam generator

Δt = timestep

WM in this timestep is used as WMO in the next timestep.

WLBRK and WSBRK are calculated in subroutine PRIMP for transient and small pipe break accidents (See Section III.A.9.a). For a large pipe break accident, the BOIL calculations start after the end of blowdown, and WLBRK and WSBRK are calculated in subroutine BOIL. (See Section III.A.9.c for the calculation of primary system leakage rates during a large pipe break accident.)

Water may change phase and turn into steam in the primary system as a result of boiling or flashing. The phase change can also reverse by condensation in the steam generator.

Boiling of water in the primary system takes place in the core as a result of the heat transfer mechanisms discussed in Section II.A.1., and the mass rate of steam generation from these causes, $\dot{M}_S$ is given by Eq. III.A.20.

Flashing of water into steam in the primary system takes place if there is a sudden depressurization in the primary system when the water in the primary system is at the saturation point. The mass rate of steam generation from flashing is calculated as

$$WFLASH = \frac{WM*C_p*(T_{sold} - T_{snew})}{h_{fg} \cdot \Delta t}$$

where

C_p = specific heat of water

T_{sold} = saturation temperature of water before depressurazation

T_{snew} = saturation temperature of water after depressurization

h_{fg} = heat of vaporization of water at T_{snew}

For computational reasons, the flashing rate is limited so that the amount of steam in the primary system does not increase by more than 5% in a timestep.

The condensation of steam in the steam generator primary side is permitted as an input option. The mass rate of steam condensed SGDWS, is calculated in Section III.A.4 using Equation (III.A.30). As an input option, the condensate SGDWS can either be returned to the water in the reactor vessel or assumed to be lost.

The amount of heat transferred to the water in the covered regions of the core (1) may increase the water temperature to saturation temperature, and (2) boil the water, i.e.,

$$Q_{cT} = \frac{m_W C_{pW}(T_{sat} - T_W) + \dot{m}_s h_{fg}}{\Delta t} \qquad (III.A.\angle 0)$$

where

Q_{cT} = total heat transferred to water

m_W = total mass of water in the core

C_{pW} = specific heat of water

T_{sat} = saturation temperature of water

T_W = water temperature from previous timestep, $T_W \leq T_{sat}$

$\dot{m}_s$ = steam generation rate in the core

h_{fg} = heat of vaporization of water at T_{sat}

If the first term on the right hand side of Equation (III.A.20) is greater than or equal to Q_{cT}, $\dot{m}_s = 0$ and Equation (III.A.20) is used to find the new temperature of water T_{Wnew}, with T_{Wnew} substituting for T_{sat}.

The saturation temperature T_{sat} in Equation (III.A.20) is the water saturation temperature at the total primary system pressure (See Sections III.A.10 and III.H.)

The total heat input to the water in the primary system is composed of that from the core, structure in the bottom head, and the steam generator. Coolant leakage and ECC injection also produce energy changes in the total enthalpy of the water. The energy balance equation for the water is:

$$Q_{cT} = Q_{DK} + QB + QRAD + QSLAB - QSG - WECC(HL'-HECC) - \\ WLBRK(HL'-HL) + SGDWS(HCON-HL) \qquad (III.A.21)$$

where

Q_{DK} = decay heat of mixture covered core nodes

QB = Equations III.A.12-III.A.14

QRAD = Equation III.A.11

QSLAB = Equation III.A.48

QSG = Equation III.A.30

HL' = new specific water enthalpy

HL = old specific water enthalpy

HECC = ECC water enthalpy

HCON = enthalpy of condensate from steam generator

III.A.3 STEAM-WATER MIXTURE LEVEL CALCULATION MODEL

The liquid level calculated in BOIL is defined as

$$YLIQ = WMASS/(RHOL \times ATOT) \quad , \tag{III.A.22}$$

where ATOT is the total connected water cross sectional area of the re-
actor vessel in the active core region. WMASS is the portion of the
primary system water inventory located above the bottom of the core.
When the calculated YLIQ is within the core region, YLIQ is the collapsed
liquid level with a reference level of zero at the bottom of the core.
When YLIQ is outside the core region, YLIQ is an artificial parameter
since, in an actual reactor, ATOT changes with elevation. As discussed
in Section III.A.1, the modeling of the liquid level also assumes the
liquid node is at the bottom of the primary system.

When boiling occurs within the core region, level swell is cal-
culated assuming a linear variation of void fraction with elevation. Thus,
the steam generation rate, $\dot{M}_s$, is related to the separation velocity, V,
and core average void fraction, ALF, by

$$\dot{M}_s = RHOS \times ACOR \times V \times (2 \times ALF) \quad . \tag{III.A.23}$$

Note that 2 x ALF is the void fraction at the top of the mixture. The
Wilson[7] correlations for separation velocity and void fraction are used
in BOIL. As recommended by Slifer and Hench[8], a minimum velocity of
1 ft/sec is specified. The Wilson correlation is

$$V = [\frac{ALF}{0.75 \times H \times F}]^{\frac{1}{0.78}}[DH \times F^{\frac{1}{0.19}} \times 33.2]^{0.5} \quad , \text{ ft/sec} \tag{III.A.24}$$

(7) J. F. Wilson, et al, "The Velocity of Rising Steam in a Bubbling
     Two Phase Mixture", ANS Transactions, 5, (1), p 151 (June, 1962).

(8) B. C. Slifer and J. E. Hench, "Loss-of-Coolant Accident and Emergency
     Core Cooling Models for General Electric Boiling Water Reactor", NEDO-
     10329 (April, 1971).

where

$$H = \left[\frac{RHOS}{RHOL - RHOS} \right]^{0.32} \tag{III.A.25}$$

$$F = \left[\frac{1}{DH} \left(\frac{SIG/32.2}{RHOL - RHOS} \right)^{0.5} \right]^{0.19} \tag{III.A.26}$$

$$SIG = 8.33 \times 10^{-6} (705 - TSAT) \tag{III.A.27}$$

DH = hydraulic diameter, ft

TSAT = saturation temperature, F

The swollen mixture level is

$$YM = YLIQ/(1.0 - ALF) \quad , \tag{III.A.28}$$

for mixture levels below the top of the core (YM < H). If the mixture level is above the top of the core, only level swell within the core region is modeled. Thus,

$$YM = YLIQ + H \times ALF \tag{III.A.29}$$

for YM > H, where H is the core height.

As discussed in Section III.A.1, core nodes within the mixture region are assumed to transfer heat to the water, and are consequently well-cooled. Core nodes above the mixture level are assumed to be in the steam region. 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.

III.A.4 STEAM GENERATOR HEAT TRANSFER MODEL

The steam generator model in BOIL permits (input option) cooling of either the water space or condensation of steam from the steam space. For cooling of the water space, the model first defines a heat transfer coefficient, H_1, based on the initial operating conditions,

$$H_1 = QZERO/(A\Delta T_1)$$,

where

QZERO = initial core power, Btu/min

A = steam generator heat transfer area, ft^2

ΔT_1 = initial primary-to-secondary temperature difference, F

The steam generator heat transfer rate, QSG, is extrapolated to other conditions using the relation

$$QSG = FSG \times H_1 \times (\Delta T/\Delta T_1)^{1/3} \times A \times \Delta T$$,   (III.A.30)

where ΔT is the temperature difference for the current timestep. The factor FSG is incorporated in the model to account for changes in the effective heat transfer area due to changes in the primary or secondary side water levels. FGS is defined as the minimum of (WTRSG/FULSG) or a term proportional to (YLIQ - YLEG). FULSG is the initial steam generator secondary side water inventory and WTRSG is the current value. YLIQ is the primary side liquid level and YLEG is an input controlled number. The (YLIQ - YLEG) term is used to simulate draining of primary side water out of the steam generator.

The secondary side heat and mass balance considers both boiloff and feedwater addition. Secondary side pressure is input. The secondary safety relief valves are not explicitly modeled and are assumed to be large enough to accommodate the calculated boiloff rate.

At (input specified) times, the steam generator may condense steam out of the primary side steam space. For example, steam condensation may occur when cold auxiliary feedwater is being poured over the tops of the steam generator tubes. The condensation rate is modeled as

$$SGDWS = FS \times STM/DTM \times [1 - (PSG + PRES)/(2PRES)] \quad (III.A.31)$$

where

        DTM = time step, min

        FS = mole fraction steam

        STM = steam mass in the primary, lb

        PSG = (input specified) secondary pressure, psia

        $PRES$ = primary side pressure, psia.

The model condenses steam from the primary until the primary and secondary side steam partial pressures equilibrate. The condensed steam may (input option) be returned to the water in the reactor vessel or be assumed to remain in the bottom of the steam generacor.

The BOIL steam generator model generally predicts a large heat trans er coefficient. Thus, the primary water temperature will generally closely follow the secondary side water temperature provided the primary and secondary water levels remain sufficiently high (i.e., the factor FSG is not small). The BOIL steam generator model is quite simple. However, it is believed significant improvement in the model would require addition of a primary side loop flow capability and more detailed modeling of the secondary.

III.A.5 CORE MELTDOWN MODEL

To scope the effects of core meltdown on core heatup, three core meltdown models were developed for incorporation in BOIL. 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 slumping is triggered when a fuel node reaches the melting point of the core and absorbs additional energy equal   the latent heat of fusion. Two of the meltdown models (Model A and B) assume the molten fuel is retained in the core as a continuous region, and one model (Model C) assumes the molten fuel falls into the bottom head. Calculations indicate that the

different model assumptions can significantly affect the course of the core heatup, primarily because of the influence of the meltdown model on the boil-off rate and the cladding-water reaction. This section of the report describes the meltdown models developed for BOIL.

Because the core power tends to peak at the center of the core and because the cladding-steam reaction increases the heat-up rate of the hotter regions, core melting usually starts at or above the center of the core in a coolant boiloff accident. 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 are 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. 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 down-ward. If the molten pool moves downward fast enough, it will intercept the water that is boiling out of the bottom of the core. When this happens, either (1) steam explosions will occur or (2) the boiloff rate, and therefore, the cladding-steam reaction rate will increase. When the molten region grows to include 50 to 80 percent of the core, it becomes intuitively questionable whether or not 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 4 ft thick, and will presumably be held up by a layer of rubble. When large fractions of the core are molten, the core-support plates and shrouds are also exposed to high thermal loadings. Failure of these major structural members would release the molten poool and either (1) the rest of the water boils out of the pressure vessel, or (2) a steam explosion results.

Meltdown Model A. In meltdown Model A, it is assumed that the excess heat in the molten pool above that required to just keep the pool molten is transferred downward. There is no convection of heat to the

top and sides of the pool. For Model A to be physically consistent, it is necessary for the molten region to actually penetrate the solid regions below the molten pool. Thus, Model A is physically consistent with a meltdown situation in which the molten region tends to cover and mix (downward) with the solid region at such a rate that the homogenized molten 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. It is assumed that no solid core material falls into the molten pool from above.

Meltdown Model B. In meltdown Model B, it is assumed that the excess heat in the molten pool is transferred upward, and none is transferred down. Within the molten region, heat may be transferred radially if the average temperature of a radial power region exceeds the melting temperature. The heat transferred upward is used in the BOIL calculations to melt solid core material, which is assumed to fall into the molten pool. 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. When the top nodes in the core are melted, it is assumed the decay heat in the pool may be radiated to the support structures above the core. Whether Model A or Model B is a better description of an actual core meltdown cannot be stated definitely. The two models yield very similar results for core-meltdown fractions of up to about 50 percent. However, for larger meltdown fractions, Model A results in faster core heatup. In Model A, the more rapid downward progression of the molten region results in increased metal-water reaction when the molten region intercepts the water level. If it is assumed that during the melting period, a small part of the molten core ($\sim$1 percent per timestep) continually falls into the water, the results for the two models are similar.

Meltdown Model C. In Model C, it is assumed that when a fuel node melts, it immediately falls to the bottom of the pressure vessel. The fuel node is quenched in one timestep, and the decay heat of the node is added to

the water. The large boiloff rates obtained under these assumptions result in very high heatup rates, due to the cladding-steam reaction, between the times when core melting first starts and all of the water in the pressure vessel is boiled off. Model C is not believed to give a realistic picture of core meltdown. It was developed to illustrate the effect of molten fuel dropping out of the core rather than being retained in a molten zone within the core region.

III.A.6 METAL WATER REACTION MODEL

III.A.6.a In Core

If the zirconium cladding is over-heated ($\stackrel{\sim}{>}$1800 F) in the presence of steam, an exothermic metal-water reaction can occur.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 \qquad (III.A.32)$$
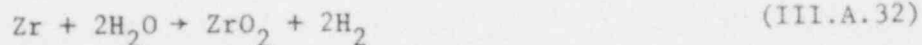
As already explained, the core is divided into a number of radial zones which are subdivided into axial regions, resulting in volumes of core called nodes. Each node is assumed to be small enough that average values of temperature, reaction rate, etc., apply.

In each of the nodes, the metal-water reaction is generally a two-step process which is initially controlled by the gaseous diffusion of water vapor toward the hot fuel rod and by the gaseous diffusion of the hydrogen away from the fuel rod. At a later time, determined by the diameter of the fuel rod, the thickness of the oxidized layer, and the temperature of the steam and fuel rod, the reaction rate becomes controlled by the solid-state diffusion of oxygen into the cladding.

The rate at which the thickness of the oxidized layer increases when gaseous diffusion controls is given by

$$\dot{X}_1 = \frac{1.849E\text{-}7 \cdot RP \cdot (TFILM)^{0.68}}{(RP - XO/3C.48)^{2.0}} \qquad (III.A.33)$$

This is the Baker-Just gaseous diffusion formulation.[9]

The rate at which the thickness of the oxidized layer increases when solid-state diffusion controls is given by

$$\dot{X}_2 = \frac{0.394}{XO} \cdot \exp\left(-\frac{41220.0}{ROD + 460.0}\right) \quad , \quad \text{(III.A.34)}$$

which is the Baker-Just solid-state diffusion formulation; or is given by

$$\dot{X}_2 = \frac{0.03732}{XO} \cdot \exp\left(-\frac{36181.0}{ROD + 460.0}\right) \quad , \quad \text{(III.A.35)}$$

which is the Cathcart solid-state diffusion formulation.[10] An input parameter controls which formulation is used. The variables used in these equations are:

$\dot{X}_{1,2}$ = the advancement rate of the oxidized layer in cm/sec

RP = the fuel rod radius in feet

XO = the thickness of the oxidized layer in cm

TFILM = the average of rod temperature and steam temperature, in K

ROD = the fuel rod temperature in F.

In the BOIL calculations, $\dot{X}_1$ and the appropriate $\dot{X}_2$ are both calculated and the smaller of these is used for $\dot{X}$. The rate of zirconium reaction is then given by

$$\dot{Z}r = \Pi D \dot{X} \ell / (\Pi D^2 \ell / 4) \quad \text{(III.A.36)}$$

$$= 4\dot{X}'D \quad cm^3 \text{ reacted/sec/cm}^3 \text{ of fuel rod}$$

where D = the fuel rod diameter in cm. Using 140,000 cal of heat release per gram mole of zirconium oxidized results in a rate of heat release given by

(9) L. Baker and L. C. Just, "Studies of Metal-Water Reactions at High Temperatures III. Experimental and Theoretical Studies of the Zirconium-Water Reaction", Argonne National Laboratory, ANL-6548 (May, 1962).

(10) J. V. Cathcart, "Quarterly Progress Report on the Zirconium Metal-Water Oxidation Kinetics Program Sponsored by the NRC Division of Reactor Safety Research for Oct-Dec 1976", Oak Ridge National Laboratory, ORNL-NUREG-TM-87.

$$QMWV = 8.843E6 \cdot \frac{\dot{X}}{D} \text{ Btu/min/ft}^3 \text{ of fuel rod.} \qquad \text{(III.A.37)}$$

In cases where the supply of steam is limited by consumption at lower levels or because the water covering the core is nearing depletion, the rate of heat release by a node may be limited by the steam available to react. Therefore, the rate of steam formation per fuel rod is calculated initially. The amount used at each of the axial nodes is calculated as

$$DWS = \frac{QMWV \cdot AR \cdot DZ}{7000} \quad \text{pound/min} \qquad \text{(III.A.38)}$$

where

AR = the fuel rod cross sectional area in ft^2

DZ = the axial node length in ft

and   7000 = the BTU released per pound of steam reacted.

This amount of steam is subtracted from the available supply to find the amount available to be reacted at the next higher node.

III.A.6.b In Bottom Head

At some stage of core meltdown, molten core material would begin to fall into the bottom head of the pressure vessel. A number of input variables control when dropping of nodes from the core begins and ends. These include:

TFUS = the temperature of the fuel rods must equal TFUS (Melting) before the node can drop

FDROP = the fraction of the core which must be melted before dropping of any node occurs

NZDRP = the number of the node, counting axially upward with 1 at the bottom, which must be melted before the melted nodes in this radial region drop

FCOL = fraction core melted when total collapse of the remaining core into the head occurs.

When a node drops into the bottom head, the zirconium cladding in this node, which is generally partially oxidized, may react further with the water in the bottom head. Calculation of the extent of this reaction is done in subroutine MWDRP which is called by BOIL each time a node is dropped. 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 DCR, 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, the axial node length, the volume fraction of the core in this 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. Shell 1 may contain zirconium and/or zirconium oxide. Shell 2 may contain only zirconium oxide. The placement of the zirconium and the zirconium oxide is specified by several input variables:

FZRCOR = the fraction of the zirconium to be put into the
particle core (the remainder goes into the shell 1)

FZOCOR = the fraction of the zirconium oxide to be put into
the particle core (the remainder is shared by
shells 1 and 2)

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

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 $\dot{X}_2$ which are given in Section III.A.6.a. The quantity XO used is the shell 2 thickness. The steam temperature is replaced

by TPOOL in the present calculations where TPOOL is the temperature of the water in the bottom head. The heat released during the present reaction is like that calculated in III.A.6.a but when the material being oxidized is not pure zirconium that heat release is multiplied by the volume fraction of zirconium that exists in the alloy being oxidized.

The oxidation reaction is calculated in a "DO" loop using a timestep of:

$$dt = 0.4 \cdot DCR \cdot 30.48 \quad \text{seconds} \quad , \quad \text{(III.A.30)}$$

finding the reaction rate, the heat release rate, and heat transfer rate to the water at the conditions existing, calculating new conditions at the end of the timestep, and repeating. 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.

III.A.7. UPPER HEAD STRUCTURES HEAT TRANSFER MODEL (EXITQ)

The structures in the exit gas stream between the top of the core and the primary system break can be modeled in the MARCH code as passive heat sinks. Up to four structures are permitted. For a large LOCA, one of the structures may be a steam generator. The required input data for each structure include the initial temperature, mass times heat capacity, heat transfer area, flow equivalent diameter, and flow area.

The heat is transferred from the steam and hydrogen gas mixture exiting the top of the core to each structure through an internally calculated heat transfer coefficient. The first structure above the core 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:

$$Q = \dot{m}C_{pm}(T_2 - T_1)\Delta t = hA_h \left(\frac{T_2 + T_1}{2} - \frac{T_s + T_s'}{2} \right) = MC_{ps}(T_s' - T_s) \quad \text{(III.A.40)}$$

where

Q = energy transferred between the flowing gas mixture and the structure over 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 tranfer area

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

MC_{ps} = mass times the heat capacity of the structure.

If the structure modeled is a steam generator, T_s' is reduced to the saturation temperature of the steam generator secondary by boiloff of the appropriate amount of secondary water. The specific heat of the gas mixture, C_{pm}, is

$$C_{pm} = \frac{C_{pst}\dot{m}_{st} + C_{pH}\dot{m}_H}{\dot{m}} \qquad (III.A.41)$$

where

C_{pst}, C_{pH} = specific heats of steam and hydrogen

$\dot{m}_{st}, \dot{m}_H$ = mass flow rates of steam and hydrogen

$\dot{m} = \dot{m}_{st} + \dot{m}_H$

and

$$C_{pst} = 0.43 + 0.8 \frac{T_1}{10,000} \quad \text{Btu/lb/F} \qquad (III.A.42)$$

$$C_{pH} = 3.4 + 0.11 \frac{T_1}{1000} \quad \text{Btu/lb/F} \quad \text{for } T_1 \leq 1000 \text{ F}$$

$$\qquad (III.A.43)$$

$$= 3.26 + 2.48 \frac{T_1}{10,000} \quad \text{Btu/lb/F} \quad \text{for } T_1 > 1000 \text{ F}$$

and the heat transfer coeff..._.nt is taken as the maximum of h_1, and h_2

where

$$h_1 = 0.0144 \ C_{pm} \ \frac{G^{0.8}}{d^{0.2}} \quad Btu/hr/ft^2/F \tag{III.A.44}$$

$$h_2 = 0.2 \left| T_1 - T_s \right|^{1/3} \quad Btu/hr/ft^2/F \tag{III.A.45}$$

with

G = mass velocity, $lb/hr/ft^2$

A = flow area, ft^2

d = flow equivalent diameter, ft

T_1 for the first structure is the same as the gas temperature at top of the core. For the other structures T_1 is the gas temperature at the outlet of the previous structure.

In addition to the energy, Q, calculated in Equation (III.A.40), the first structure above the core also receives energy, QR, radiated from the top of the core. If the top of the core is solid (not melted), QR is limited to the decay heat of the top layer of core nodes. In meltdown model B, QR may approach the decay heat of all melted nodes within the molten pool. QR is calculated in subroutine BOIL as follows:

$$QR = \sum_{\substack{top \\ axial \\ nodes}} 0.173 \ FA_R \left[\left(\frac{T_{rad}}{100} \right)^4 - \left(\frac{T_{SR}}{100} \right)^4 \right] \tag{III.A.46}$$

where

QR = radiation heat transfer, Btu/hr

F = radiation interchange factor (input value)

A_R = radiating area of the node, ft^2

T_{rad} = fuel rod temperature in the node, R

T_{SR} = structure temperature, R

The temperature of the first structure at the end of a timestep is calculated from

$$T'_{s1} = T_{s1} + \frac{Q_R \Delta t + Q}{(MCp)_{s1}} \tag{III.A.47}$$

where T_{s1} is the temperature of the structure at the beginning of the timestep.

III.A.8. HEAT TRANSFER TO THE LOWER REACTOR PRESSURE VESSEL INTERNALS

The reactor pressure vessel internals below the core and the bottom head are modeled as three heat absorbing structures. The first structure is usually taken as the first grid plate underneath the core, the second structure as the second grid plate, and the rest of the piping, baffles, etc. The bottom head makes up the third structure. When the bottom head is full, these structures transfer heat to the water in the primary system.

The intial temperature, mass times the heat capacity, heat transfer area, thickness and distance from the bottom of core are the required input parameters for each of the three structures.

The temperature and the amount of heat energy stored in each structure when the bottom head is still full of water is calculated by a simple convection equation

$$Q = hA(T_{sold} - T_W) \Delta t \qquad \text{(III.A.48)}$$

where

- Q = total heat transferred from structure to water
- h = heat transfer coefficient
- A = heat transfer area
- T_{sold} = temperature of structure at the end of previous timestep
- T_W = temperature of water
- Δt = timestep

The heat transfer coefficient is given as

$$h = \frac{1}{\dfrac{1}{HC} + \dfrac{D}{2k}} \qquad \text{(III.A.49)}$$

where

$$HC = 2.02 \times 10^8 (T_{sold} - T_W)^{-2.575} \times (\frac{P}{15})^{0.25} \quad \text{for } T_{sold} - T_W \geq 42 \quad \text{(III.A.50)}$$

or

$$HC = 44.5 (T_{sold} - T_W)^{1.523} \times (\frac{P}{15})^{0.25} \quad \text{for } T_{sold} - T_W < 42 \quad . \quad \text{(III.A.51)}$$

where

P = primary system pressure in psia

T_{sold}, T_W are in F

HC = convection heat transfer coefficient in units of $Btu/hr/ft^2/F$

k = thermal conductivity of the structure

D = thickness of structure

and the new temperature of the structure is found from

$$T_{snew} = T_{sold} - \frac{Q}{CM} \tag{III.A.52}$$

where

CM = mass times the heat capacity of the structure.

After the core has uncovered and the water level in the pressure vessel has dropped below the first grid plate elevation, the temperature of the grid plate is calculated on the basis of how much of the core material has slumped to the bottom head or is retained on the grid plate. It is assumed that the first grid plate and the core material on top of it are at the same uniform temperature. This grid plate is assumed to support the core (input option). When the grid plate temperature exceeds the failure temperature (user supplied) the grid plate is assumed to fail. When the grid plate fails, all the debris is assumed to fall to the bottom head and be quenched. The heat from quenching, the decay heat, and the heat from metal-water reactions in the bottom head are used to boil off the remaining water in the bottom head. When all the water has evaporated, the control is transferred to the debris-vessel interaction code, HEAD.

III.A.9 PRIMARY SYSTEM LEAKAGE MODEL

III.A.9.a Small LOCA's and Transients (PRIMP)

The primary system pressure and coolant leakage rates are calculated in subroutine PRIMP for small LOCA's and transients. The pressure calculation is discussed in Section III.A.10. For large LOCA's, the primary system pressure is assumed to be the same as the containment pressure. Coolant blowdown for large LOCA's is provided by tabulated data input to subroutine INITIAL. During the boiloff phase of a large LOCA accident, BOIL assumes the leakage rate is that required to equalize the primary system and containment pressures.

PRIMP assumes the primary system is divided into a steam node at the top of the primary and a water node at the bottom. PRIMP leaks steam from the primary system steam space if the primary system liquid level is below the (user specified) break elevation. Water leaks from the water region if the break is below the liquid level. MARCH has no models which would permit leakage of a two-phase steam-water mixture. The user may specify that a constant two-phase flow multiplier be applied to the water leakage when the calculated water temperature is less than 20 F subcooled. However, as modeled, the multiplier affects only the water leakage rate and not the steam content of the leakage.

The steam and water leakage rates are the minimum of either an orifice flow (G) or a critical flow rate (G_c). The PRIMP flow rates for steam are

$$G = 5778 \ CBRK(\rho \times DP)^{0.5} \ , \quad lb/min/ft^2 \quad (III.A.53)$$

and

$$G_c = 1642(\rho \times P)^{0.5} \ , \quad lb/min/ft^2 \quad (III.A.54)$$

where

    CBRK = orifice coefficient (0.583 used)

      DP = pressure differential between vessel and containment

       P = vessel pressure, psia

and ρ = gas density.

For mixtures of steam and hydrogen, the gas density is defined as $(STM + H_2)/VOL$, and the steam and hydrogen leakage rates are assumed proportional to their mass fractions in the gas space. The water leakage is calculated from

$$G = 5778 \ CBRK(\rho_L \times DP/TPM)^{0.5} \ , \quad lb/min/ft^2 \qquad (III.A.55)$$

and

$$G_c = 1570.2(P/TPM)^{0.813} \ , \quad lb/min/ft^2 \qquad (III.A.56)$$

where

ρ_L = water density, lb/ft^3,

and

TPM = (input) two-phase multiplier.

The mass leak rate is WLK = ABRK x GMIN, lb/min, where ABRK is the break area and GMIN is the minimum of G and G_c above. Steam leakage through the safety relief valves is calculated from

$$WVENT = CSRV \times (\rho \times P)^{0.5} \ , \quad lb/min \ (P \geq PSET) \qquad (III.A.57)$$

where CSRV is an input coefficient calculated to reproduce the rated venting rate. For water leakage through the safety valves, an effective break area, ASRV, for steam flow is calculated from the relation

$$ASRV \times 1642(\rho \times P)^{0.5} = CSRV \times (\rho \times P)^{0.5} \ . \qquad (III.A.58)$$

The calculated area is also assumed to be valid for water leakage. The water leakage equations above with ABRK = ASRV are applied to vent valve leakage.

The PRIMP models will reduce the vent valve leakage so that the system pressure does not fall below the relief valve setpoint, PSET. Thus, if the leak rated does not exceed the valve capacity, a constant leak rate is calculated, which is the leakage required to maintain the system pressure at PSET. Opening and closing cycles for the vent valves are not explicitly modeled.

PRIMP also calculates the MARCH (or BOIL) timestep size and places an upper limit on the coolant flashing rate for small LOCA transients. The timestep criterion limits the pressure change to 2 percent per timestep. The flashing rate criterion limits the pressure change due to flashing to 1 percent per timestep.

III.A.9.b   Controlled Primary System Venti g

MARCH contains two types of controlled primary system venting options. In one option, an array of times and break areas (variables TB(I) and AB(I)) are input to BOIL in NLBOIL. Thus, at specified times the break area can be changed simulating opening and closing of a power operated relief valve or an automatic depressurization system.

The second option requires entries on the IVENT card in NLMACE, in which case both primary system and containment venting may be initiated. When the average gas temperature exiting the top of the core (TGEX in BOIL) exceeds TVNT2, all of the primary system safety relief valves are opened. Simultaneously, the blowdown flow from the primary system is directed to containment compartment NRPV2 (NLMACE input).

III.A.9.c   Large LOCA's

The leakage of the primary system water from the primary system into the containment during a large LOCA takes place in two stages: (1) blowdown stage, and (2) post-blowdown stage. During the blowdown stage, the mass and enthalpy transfers from the primary system to the containment are supplied to the code by the user. The data are input to the code in the NAMELIST NLINTL. The data may be obtained from the results of codes such as RELAP or TRAC. The response of the containment to the mass and enthalpy additions during the blowdown stage are calculated in subroutine MACE.

After the blowdown stage is over, the water remaining in the core is boiled off due to normal core heat transfer mechanisms outlined in section III.A.1. The water in the bottom head boils off as the result of quenching of falling molten core debris, fission product decay power in previously fallen material, and metal-water reactions taking place in the bottom head. For a large pipe beak accident flow from the primary system is determined such that the primary system and containment building pressures are the same for every timestep.

III.A.10 PRIMARY SYSTEM PRESSURE CALCULATION MODEL (PRIMP)

As discussed in Section III.A.9.c, during the post-blowdown stage of a large pipe break accident, the primary system is assumed to have the same pressure as the containment. The containment pressure is calculated in the MACE package (See Section III.B.9).

For transients and small pipe break accidents, the primary system pressure is calculated in subroutine PRIMP as follows: First the masses of steam and hydrogen in the gas-filled part of the primary volume are calculated from mass balance considerations, i.e.,

$$STM = STM_B + (\dot{M}_S - WSBRK) \times \Delta t \qquad (III.A.59)$$

$$H2 = H2_B + (\dot{M}_H - WHBRK) \times \Delta t \qquad (III.A.60)$$

where

$\quad$ STM, H2 = masses of steam and hydrogen in the primary system, respectively

$\quad STM_B, H2_B$ = masses of steam and hydrogen in the primary system at the end of the previous timestep

$\quad \dot{M}_S, \dot{M}_H$ = masses of steam and hydrogen leaving the core per unit of time

and

$\quad$ WSBRK, WHBRK = masses of steam and hydrogen leaking from the primary system per unit of time (See Section III.A.9.a)

$\quad \Delta t$ = timestep $\qquad$.

The volume occupied by the gas in the primary system, V_g, is

$$V_g = V_p - V_w \qquad (III.A.61)$$

where

$\quad V_p$ = total primary volume (input number)

$\quad V_w$ = volume occupied by water in the primary system

$$V_w = \frac{M_w}{\rho_w} \qquad \text{(III.A.62)}$$

where

M_w = the mass of water in the primary system, which is found from mass balance calculations in subroutine BOIL, and

ρ_w = the density of water in the primary system

The temperature of the gas in the primary system, TGX is

$$TGX = \frac{M_{gB} TGX_B + (\dot{M}_S + \dot{M}_H) \times \Delta t \times TGEX}{M_{gB} + (\dot{M}_S + \dot{M}_H) \times \Delta t} \qquad \text{(III.A.63)}$$

where

M_{gB}, TGX_B = mass and temperature of gas in the primary system at the end of the previous time step, respectively

TGEX = temperature of gas coming out of the core

Knowing the masses, volume, and the temperature of gases in the primary system, their partial pressures are calculated from the equation of state for ideal gases as:

$$PSV = \frac{STM}{V_g} \times RS \times (TGX + 460) \qquad \text{(III.A.64)}$$

$$PH2 = \frac{H2}{V_g} \times RH \times (TGX + 460) \qquad \text{(III.A.65)}$$

where

PSV, PH2 = partial pressures of steam and hydrogen in the primary system, respectively

RS, RH = gas constants for steam and hydrogen. RH is assumed constant at 767/144 but RS is calculated from saturated steam properties as

$$RS = \frac{PR}{\rho_s} (T_w + 460)$$ (III.A.66)

where

T_w = temperature of water in the primary system

PR = saturation pressure of water at T_w

ρ_s = saturation density of steam at T_w and PR.

The total pressure, PVSL in the primary system is

PVSL = PSV + PH2 (III.A.67)

and the saturation properties of steam and water in the primary system for the next time step are those corresponding to PVSL. The properties are obtained in subroutine PROPS (See Section III.H)

III.B. CONTAINMENT ANALYSIS MODELS (MACE)

In the MARCH code, the subroutine MACE and its associated sub-routines (Figure II.7) anayze the thermal-hydraulic processes in the re-actor containment building. MACE is the main subroutine for the contain-ment analysis and is the largest subroutine in the code.

As shown in Figure II.1, one of the subroutines INITIAL, BOIL, HEAD, HOTDROP, or INTER is always coupled to MACE and provides the input masses and enthalpies to the containment. The user can also specify other sources of mass and enthalpy to the containment, such as containment sprays taking suction from outside the containment.

The MACE subroutine can accomodate a variety of containment con-figurations. It can handle both PWR and BWR systems. The containment building can be modeled with up to 8 compartments. Transfer of material between compartments takes place in a step-wise fashion by one of several mechanisms. Only series-type compartment connections are allowed.

For compartments that are freely interconnected, transfers are driven by pressure differences that result from enthalpy inputs and heat losses. Transfers of this type are such that they establish pressure equilibrium among all compartments in each timestep (See Section III.B.10). Leakage type transfers occur between compartments and outside air when the containment fails (Section III.B.11). These transfers are driven by pres-sure differences across specified orifices, and do not necessarily establish pressure equilibrium. The third type of transfer is driven by intercompart-ment fans according to a specified volume flow rate (Section III.B.8). In all cases, quantities of mass and enthalpy transferred in one timestep are limited by control of the timestep length (Section III.K) to certain frac-tons of the initial mass and enthalpy in compartments.

The calculations performed in MACE follow the general flow shown in Figure III.B.1. Briefly the steps include:

(1) Setting the initial conditions in containment compartments.
    This is done using the input values to the code the first
    time the subroutine MACE is called.

(2) Estimating the final conditions in all compartments at the
    end of the current MARCH timestep, by using the mass and
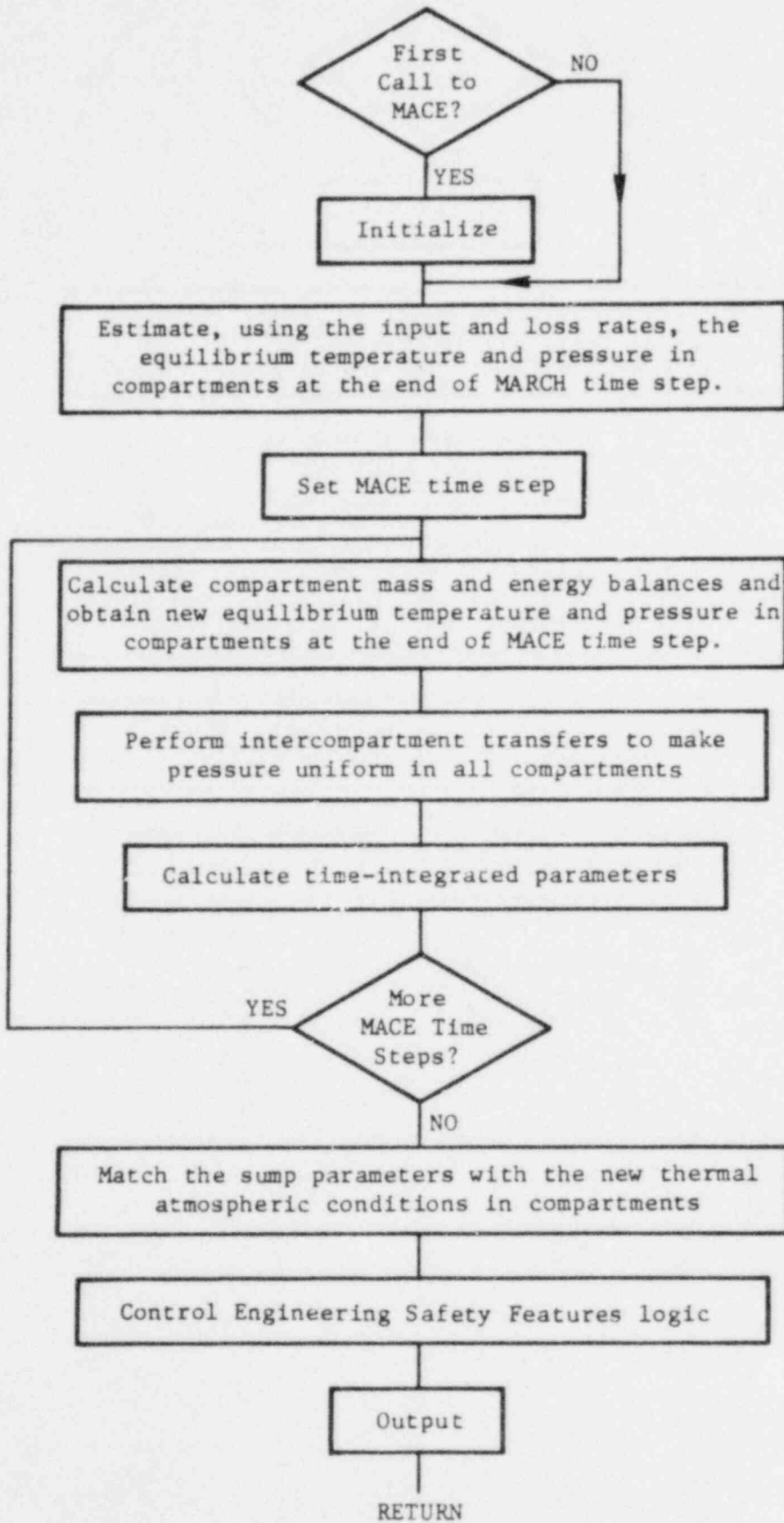
FIGURE III.B.1   SIMPLE FLOW CHART FOR THE MACE SUBROUTINE

enthalpy input rates provided by the source programs
and loss rates of the previous timestep.

(3) Setting the MACE timestep. The MARCH timestep, which
is set either in the main program or in one of the
source programs, is broken down to smaller timesteps
in MACE for the purpose of calculating the containment
response so that in one MACE timestep:

(a) the total enthalpy in any compartment does not
change by more than 20%,

(b) the pressure in any compartment does not change
by more than 20%,

(c) the change in the total enthalpy in any compartment
due to hydrogen burns is not more than 10%,

(d) the change in the total enthalpy in any compartment
due to heat losses to walls and structures is not
more than 10%.

(4) Calculating the equilibrium temperature, pressure, and other
thermo-dynamic parameters, and masses of gases, steam, and
air-borne water droplets in compartments by taking into
account:

(a) inputs from source routines (e.g. BOIL)

(b) inputs due to events (e.g. sprays)

(c) PV term for gases

(d) heat transfer to walls and structures (Section III.B.4)

(e) hydrogen burns (Section III.B.7)

(f) fan flow (Section III.B.8)

(g) building coolers (Section III.B.2)

(h) ice condensers (Section III.B.3)

(i) gravitational settling of water droplets in
atmosphere (Section III.B.5)

(j) pressure suppression pools (Section III.B.6).

(5) Based on the pressures calculated in step 4, transferring
enough material between compartments over the allowed paths
to obtain a uniform pressure in the whole containment
(Section III.B.10).

(6) Calculating the time integrated parameters such as total heat losses to the walls and structures, mass and enthalpy additions to sumps, leakage parameters to outside air, etc.

(7) Repeating steps 4, 5, and 6 until the sum of MACE timesteps equals the MARCH timestep.

(8) Adjusting the sump parameters so that they are in thermal equilibrium with the atmosphere conditions in the compartment in which the sump is located, e.g., flashing due to containment depressurization, boiling due to fission product heating, evaporation due to undersaturation in atmosphere (the compartment atmosphere is assumed to have enough steam at all times to make it saturated at sump temperature).

(9) Controlling the Engineered Safety Features, such as ECC flow rates; switching the ECCS and Containment Sprays from injection to recirculation mode; and turning off the ECC flow, sprays or building coolers.

(10) Printing the output parameters which describe the current conditions in the containment.

(11) Returning control to the main program.

The major containment response analysis models are expained in Sections III.B.1 - III.B.14 below.

III.B.1 SPRAY DROPLET HEAT TRANSFER MODEL

The mechanisms for heat and mass transfer between the containment sprays and the containment atmosphere are modeled in subroutine SPRAY in the MARCH code. Heat transfer mechanisms are discussed in this section; the mass transfer will be explained in Section III.B.5 under the gravitational fall-out 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 supplied to the code by the user as input. The characteristics of

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the initial spray droplets as they come out of the spray headers (mass, volume, surface area, and number of droplets per unit time) are calculated from values given in input.

In analyzing the spray droplet heat and mass transfer mechanisms, it is assumed that:

- spray droplets are rigid,
- spray droplets are at uniform temperature, i.e., there is no temperature variation within 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[11] (all units in the following are British units):

$$h = \frac{k}{D} (2.0 + 0.54 \ Re^{1/2}) \tag{III.B.1}$$

where

k = thermal conductivity in droplets

D = diameter of droplets

Re = Reynolds number.

The Reynolds number is calculated in subroutine REYN as follows:

$$Re = (\frac{f}{15.71})^{0.7057} \qquad \text{for } f < 10700. \tag{III.B.2}$$

$$Re = (\frac{f}{6.477})^{0.6215} \qquad \text{for } f \geq 10700. \tag{III.B.3}$$

where

$$f = \frac{4}{3} \rho_D \rho_m D^3 \ \frac{4.17 \times 10^8}{\mu_m^2} \tag{III.B.4}$$

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(11) W. E. Ranz and W. R. Marshall, Jr., "Evaporation from Drops", Chem. Eng. Prog., 48, No. 3, p. 141 (1952) and 48, No. 4, p. 173 (1952).

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:

$$\mu_m = \frac{\mu_{air}}{1 + \frac{VAP}{1 - VAP}\left(\frac{1 + \sqrt{\frac{\mu_{air}}{\mu_s} \cdot \frac{18}{29}}\,}{4.5704}\right)^2} + \frac{\mu_s}{1 + \frac{\left(1 + \sqrt{\frac{\mu_s}{\mu_{air}} \cdot \frac{29}{18}}\,\right)^2}{\frac{VAP}{1 - VAP}}} \qquad (III.B.5)$$

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

$$TA = T_o + 460$$

and

T_o = compartment temperature .

The droplet fall velocity, v_D, is calculated from the Reynolds number,

$$v_D = \frac{Re\,\mu_m}{\rho_D D} \qquad (III.B.6)$$

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.,

$$mC_p \dot{T} = hA(T_o - T) \quad . \quad (III.B.7)$$

where

m = droplet mass,

C_p = specific heat of droplet,

T = T(t), temperature as a function of time,

and

A = droplet surface area.

The equation above can be put into the form

$$\dot{T} + \lambda T - \lambda T_o = 0 \quad , \quad \lambda = \frac{hA}{mC_p} \quad (III.B.8)$$

The solution to this equation with the initial condition $T(o) = T_i$ is:

$$T = T_i + (T_o - T_i)(1 - e^{-\lambda t}) \quad . \quad (III.B.9)$$

The final temperature of the droplet is found by substituting 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.

$$T_f = T_i + (T_o - T_i)(1 - e^{-\lambda t_f}) \quad . \quad (III.B.10)$$

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:

$$DEW = mC_p(T_f - T_i) \quad \text{for } T_f \leq T_o < T_{sat} \quad \text{or} \quad T_f \leq T_{sat} \leq T_o \quad (III.B.11)$$

or

$$DEW = mC_p(T_{sat} - T_i) - |DMW| \cdot h_\ell \quad \text{for} \quad T_{sat} < T_f \leq T_o \quad , \quad (III.B.12)$$

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 III.B.5)

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:

$$DEW = \frac{mC_p(T_i - T_{sat})}{h_g' - h_\ell'} \cdot h_g' \qquad \text{for } T_f \geq T_{sat} \qquad \text{(III.B.13)}$$

$$DEW = \frac{mC_p(T_i - T_{sat})}{h_g' - h_\ell'} \cdot h_g' + (m - \frac{mC_p(T_i - T_{sat})}{h_g' - h_\ell'})C_p(T_{sat} - T_f)$$

$$\text{(III.B.14)}$$

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:

$$EC = DEW \times N \qquad \text{(III.B.15)}$$

where N is the total number of spray droplets flowing out of the spray headers per unit time.

III.B.2 CONTAINMENT BUILDING COOLER MODEL

The required input for the containment building cooler model calculations in the MARCH code consists of:

QR = rated capacity, Btu/hr

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

and

TCOOL = time to start cooler, min.

The heat transfer coefficient correlation information is taken from the OCONEE Power Reactor Final Safety Analysis Report[12] and is as follows:

$$h = 269 + 4.095 \ (VAP - 0.26) \times 100 \qquad \text{for } VAP \geq 0.26 \qquad , (III.B.16)$$

$$h = 104 + 6.346 \times VAP \times 100 \qquad \text{for } VAP < 0.26 \qquad , (III.B.17)$$

where VAP is the vapor mole fraction in the containment, and h is in units of $Btu/hr/ft^2/F$.

The heat transfer area of the cooler is found from the rated input conditions and h correlation as:

$$AREA = \frac{QR}{h(TP1R - TS1R) - \frac{QR \cdot h}{WSR \times 120}} \qquad (III.B.18)$$

where h is calculated using VAP under normal operating conditions.

In accident situations, the amount of heat taken out of the containment atmosphere by the containment building cooler per unit time is given as:

$$QRH = h \times AREA \times \frac{TEM - TS1R}{(1 + \frac{h \times AREA}{WSR \times 120}) \times 60} \qquad (III.B.19)$$

---

(12) Duke Power Company, Oconee Nuclear Station Units 1, 2, and 3, Final Safety Analysis Report.

where $\dot{n}$ 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 in the MARCH code.

MACE contains a second type of building cooler (input option). The cooler may be turned on and off automatically at preset containment building pressures. The cooler operates at a constant capacity. The set-point pressure at which the cooler is turned on and off and the cooler capacity (QRCOOL) are supplied as input by the user. The two types of coolers must be in different containment volumes.

III.B.3   ICE CONDENSER MODEL

Ice condensers are used in some PWR's to provide pressure suppression during the initial stages of an accident. A schematic for an ice condenser building is given in Figure III.B.3.1. In the MARCH code, an ice condenser containment is modeled as two subvolumes connected through an ice condenser module as shown in Figure III.B.3.1. The reactor vessel is located in the lower compartment and any direct leakage into the containment from the primary system is assumed to go into this lower compartment. The required input parameters for the modeling of an ice condenser cooler in the MARCH code are given below:

> WICE = mass of ice in icebed
>
> TICE = initial temperature of ice
>
> TWTR = temperature of water draining from icebed
>   during blowdown
>
> TWTR2 = temperature of water draining from icebed
>   during boiloff
>
> TSTM = temperature of air-steam mixture exiting
>   top of icebed
>
> DCFICE = decontamination factor for condensable
>   fission products flowing through icebed.
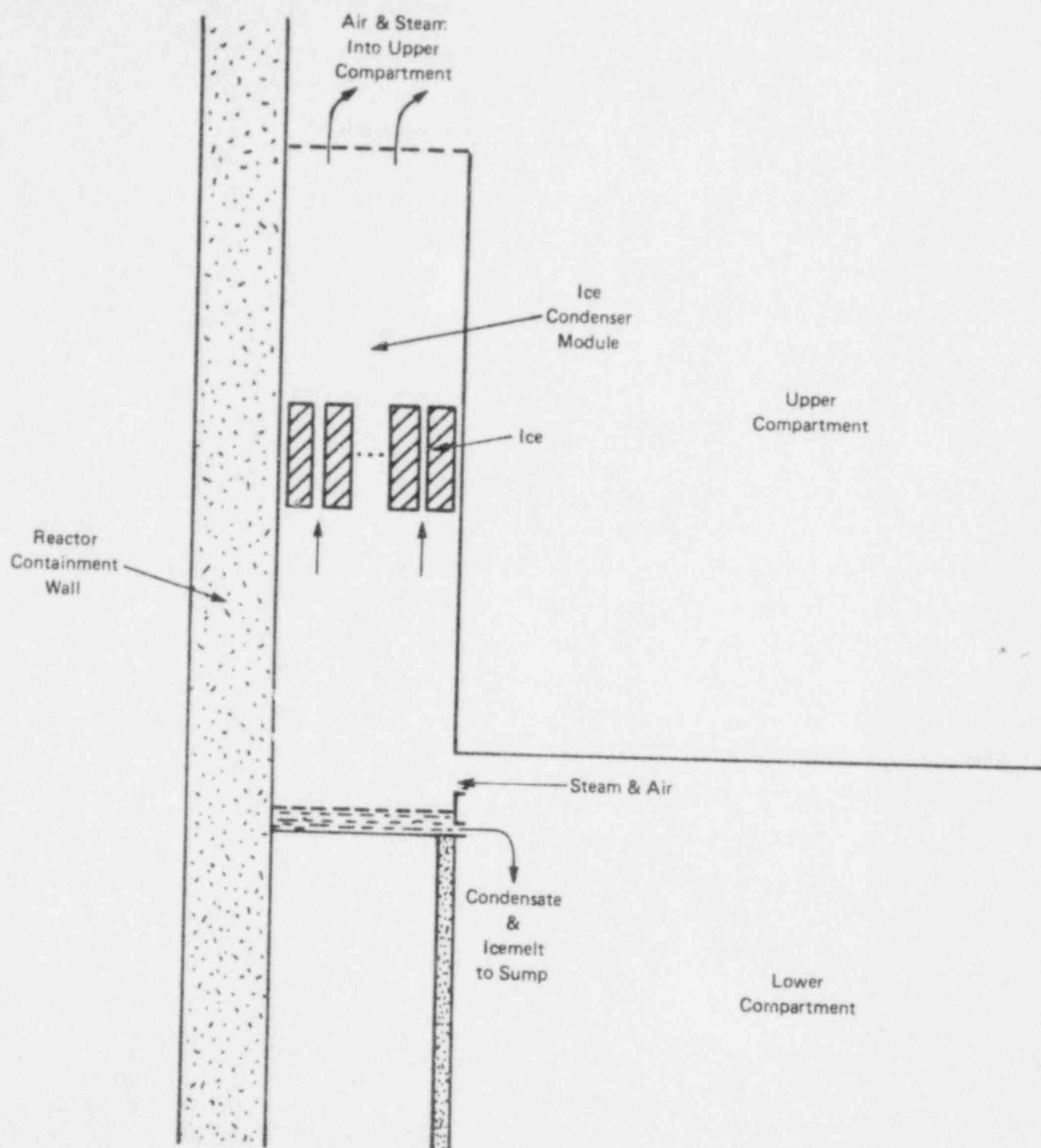
SCHEMATIC FOR AN ICE CONDENSER CONTAINMENT

FIGURE III.B.3.1

The default values used by the code for TICE, TWTR, TWTR2, TSTM
are 20 F, 190 F, 130 F, and 105 F, respectively. These numbers are based
on experiments conducted by Westinghouse.[13]

In the MARCH code, the ice condenser modeling calculations are
done in the subroutine MACE. The assumptions regarding these calcula-
tions are given below:

- Ice condenser doors do not interfere with the flow of
  steam and air mixture from one compartment to the other,
- 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 assumed constant and they are supplied by the user,
- During ice melt, the steam partial pressure and density
  in the upper compartment are constant and are equal to
  saturated steam pressure and density at T_{sat} = TSTM ,
- The maximum amount of steam that can be present in the
  upper compartment during the ice melt is that which would
  be present if that compartment were saturated with steam
  at T_{sat} = TSTM.

The mass of steam condensed on the ice cooler per unit time, MSCI,
is given by

$$MSCI = \frac{WSX - (\rho(TSTM)*VC - WS)}{DTX} \qquad (III.B.20)$$

where

WSX = mass of steam that would have been transferred from the
lower compartment to the upper compartment if the ice
cooler were not there,

VC = upper compartment volume,

WS = mass of steam in upper compartment,

(13) "Test Plans and Results for the Ice Condenser System", Westinghouse
Report WCAP-8110, Sup 6 (1973).

ρ(TSTM) = steam density at TSAT = TSTM,

DTX = timestep size.

Fission product decay heat fraction taken out of the atmosphere by the ice cooler, DFP, is:

$$DFP = FP \times FTX \times (1 - \frac{1}{DCFICE}) \times CGF \qquad (III.B.21)$$

where

FTX = fraction of lower compartment volume transfered

FP = fraction of fission product decay heat in the lower compartment before transfer

DCFICE = decontamination factor for condensable gaseous fission products (input parameter)

CGF = the condensable fraction of fission products released from the fuel (from subroutine FPLOSS).

Enthalpy taken out of the containment atmosphere by the ice cooler per unit time is

$$QICE = \frac{UTX}{DTX} - [\frac{CA \times (TSTM - 32.0) \times FTX}{DTX} + (\frac{WSX}{DTX} - MSCI) \times HTSTM] \qquad (III.B.22)$$

where

UTX = enthalpy that would have been transferred from the lower to the upper compartment if the ice cooler were not present,

CA = mass x specific heat of non-condensables in the lower compartment before transfer,

HTSTM = specific enthalpy of steam at T = TSTM,

And the mass of ice melted over the time DTX is given by:

$$DWI = \frac{QICE}{HICE} \times DTX \qquad (III.B.23)$$

whe..

HICE is the amount of enthalpy 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 depending on whether the accident is in the blowdown or boiloff stage.

The masses DWI and MSCI x DTX are added to the sump at the end of the timestep.

The grid and the structures used to hold up the ice blocks in the ice condenser can be treated as passive heat sinks with an initial temperature of TICE after all the ice has melted. Heat transfer to sprays in the upper volume is suppressed until icebed melt is complete.

III.B.4 CONTAINMENT STRUCTURE HEAT TRANSFER AND CONDENSATION MODELS

The containment walls and the structures are modeled in the MARCH code as passive one-dimensional, slab geometry heat sinks. The code allows up to 15 heat sinks and up to 5 materials to make up the sinks. Material densities, heat capacities, thermal conductivities, as well as the physical location, composition, 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.* Therefore, it is also necessary for the user to input the node coordinates and initial temperatures. Two adjacent slabs made up of two different materials can be modeled as one heat sink, with a constant interface heat transfer coefficient. The heat transfer coefficients at the boundaries in contact with the containment atmosphere are calculated in the code. The boundary in contact with the outside air is assumed insulated.

The heat transfer coefficient at the boundary between the containment atmosphere and the surface of the heat sink is calculated as:

$$h_T(T_b - T_w) = h_c(T_{sat} - T_w) + h_N(T_b - T_w) \quad , \quad \text{(III.B.24)}$$

where the term on the left side is the total heat transfer at the boundary per unit area per unit time. The first term on the right side is due to steam condensation on the surface and the second is the natural convection term. Rearranging this equation, the total heat transfer coefficient at the boundary, h_T is obtained:

$$h_T = h_c \frac{T_{sat} - T_w}{T_b - T_w} + h_N \quad , \quad \text{(III.B.25)}$$

---

* The method used to solve the conduction equation is the same as that described in the CONTEMPT-LT manual, ANCR-1219 (June 1975), Appendix E.

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,

and

h_N = natural convection heat transfer coefficient,

h_c and h_N are calculated from

$$h_c = 66.75*ASWR^{-0.707} \qquad \text{for ASWR} \leq 20 \qquad ,$$

or

$$h_c = 12 - \frac{ASWR}{50} \qquad \text{for ASWR} > 20 \qquad , \qquad \text{(III.B.26)}$$

where ASWR = air-to-steam weight ratio in the containment atmosphere, and

$$h_N = 0.19*|T_b - T_w|^{1/3} \qquad , \qquad \text{(III.B.27)}$$

h_c and h_N are in units of $Btu/hr/ft^2/F$, and in the code h_c is bounded between 2.0 and HMAX, where HMAX is an input number.

The boundary condition at the surface of the slab heat sink is

$$-k \frac{dT}{dX} = h_T(T_b - T_w) \qquad , \qquad \text{(III.B.28)}$$

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

$$k \frac{dT}{dX} = 0.0 \quad \text{or} \quad h_T = 0.0 \qquad \text{(III.B.29)}$$

At the same interface between two adjacent slabs, the boundary condition is

$$-k_1 \frac{dT}{dX}\bigg|_{1R} = h_i(T_{1R} - T_{2L}) = -k_2 \frac{dT}{dX}\bigg|_{2R} \qquad , \qquad \text{(III.B.30)}$$

where

k_1, k_2 = thermal conductivities of materials in slabs 1 and 2, respectively

$\frac{dT}{dX}\bigg|_{1R}, \frac{dT}{dX}\bigg|_{2L}$ = slopes of temperature profiles in slabs 1 and 2 at the interface, respectively

$$h_i = \text{interface heat transfer coefficient (input value)} \quad,$$

$$T_{1R} = \text{temperature of last node in slab 1} \quad,$$

and

$$T_{2L} = \text{temperature of first node in slab 2} \quad.$$

The subroutine SLAB in the MARCH code calculates the node temperatures in all heat sinks at the end of each timestep. It also calculates the heat fluxes into and out of each slab and the total amounts of heat input, output, and absorption in each slab during the timestep. Using these parameters calculated in the subroutine SLAB, the SINK subroutine finds

$$DTEM(J) = \left(\frac{\sum\limits_{i=1}^{NSLAB} \Delta T_i^{1/3} \cdot AREA_i}{\sum\limits_{i=1}^{NSLAB} AREA_i} \right)^3 \quad, \qquad \text{(III.B.31)}$$

where

$DTEM(J)$ = average bulk to heat sink surface temperature difference in compartment J in the containment,

$\Delta T_i = T_b - T_w$ 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 part of the CORRAL code input.[2] The total heat absorption rate in all slabs in compartment J, QRS(J) is

$$QRS(J) = \sum\limits_{i=1}^{NSLAB} (QL_i - QR_i) \quad, \qquad \text{(III.B.32)}$$

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.

Rate of steam condensation on the walls of the containment heat sinks is calculated in the subroutine MACE. MACE calls the subroutine MIXCTRL, which along with its own associated subroutines, calculates the equilibrium temperature, pressure, atmospheric quality, and steam concentration of each compartment atmosphere, with and without QRS(J)*DTX of enthalpy taken out of the

atmosphere. (See Section III.B.9 on compartment pressure and temperature equilibrium models.) Then the rate of steam condensing on the structures in compartment J, MSCW(J), is

$$MSCW(J) = \frac{WL_2 - WL_1}{DTX} \quad , \qquad (III.B.33)$$

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 enthalpy is taken out.

III.B.5 GRAVITATIONAL FALLOUT MODEL

There are two components to the amount of water that falls out of the containment atmosphere due to gravity. One is associated with the containment sprays and the other is simple settling of the water droplets suspended in the atmosphere. Water from both sources is added to the containment sump at the end of the timestep.

The amount of water falling out of the containment atmosphere during a timestep is calculated separately for each compartment and then summed over all compartments to give the total amount.

The amount, CFALL, falling out of the atmosphere in a single compartment over a timestep is given as

$$CFALL = DMP + DMF \quad . \qquad (III.B.34)$$

Where DMP is the component associated with sprays and is present only if there are sprays in the compartment. It is given by

$$DMP = N(M + DMW)*DTX \quad .$$

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 spray droplets is less than the saturation temperature of steam in the compartment atmosphere, and if the compartment is not superheated, DMW is the mass of steam condensed on a droplet and is given by

$$DMW = \frac{QC*STHR}{h_g - h_f} \qquad (III.B.35)$$

where

$$QC = M \cdot C_p \cdot (T_f - T_i) \qquad (III.B.36)$$

C_p = specific heat of spray water

T_f = final temperature of spray droplets (See Section III.B.1 to find out how T_f is calculated)

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,

$$DMW = \frac{-QC}{h_g - h_f} \qquad (III.B.37)$$

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

$$DMF = XMF \left(1 - e^{-\frac{v_D \, DTX}{HC}} \right) \qquad \text{(III.B.38)}$$

where

XMF = mass of water droplets suspended in the atmosphere,

v_D = droplet fall velocity,

HC = compartment height,

v_D is given by

$$v_D = \frac{Re \cdot \mu_m}{\rho_m \cdot D} \qquad \text{(III.B.39)}$$

where

Re = Reynold's 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 normally use a droplet diameter of 4 microns[14]. However, if excess liquid accumulates in the atomphere, the drop size is increased to 400 microns. The calculations of Re and μ_m are shown in Section III.B.1.

III.B.6 BWR WET-WELL PRESSURE SUPPRESSION MODEL

A typical BWR wet-well pressure suppression system is shown in Figure III.B.6.1. When the pressure in the dry-well increases due to the accumulation of steam which has leaked from the primary system, a part of the dry-well volume is driven into the wet-well through the vent pipes and the pressure suppression pool. In the process, the steam that was in the dry-well atmosphere condenses in the pool. This keeps the pressure in the dry-well from rising too high.

The required input data for the BWR pressure suppression system modeling calculations in the MARCH code are:

WPOOL = initial mass of water in the pressure suppression pool;

TPOOL = initial temperature of water in the pressure suppression pool;

---

(14) R. K. Hilliard and L. F. Coleman, "Natural Transport Effects on Fission Product Behavior in the Containment Systems Experiment", BNWL-1457 (December, 1970).
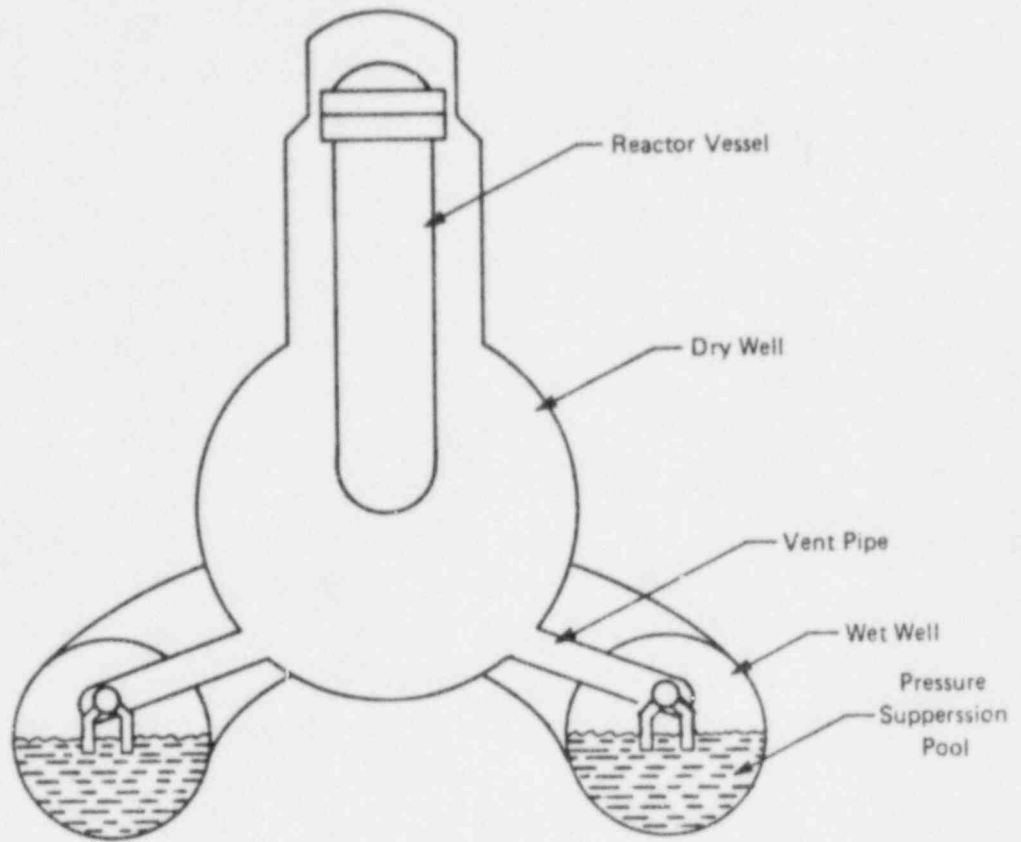
TYPICAL BWR PRESSURE SUPPRESSION SYSTEM

FIGURE III.B.6.1

VTORUS = total volume of the wet-well;

DCF = decontamination factor for condensable
fission products in the pool

PRESS = (optional) minimum pressure difference
between the dry-well and wet-well before the
dry-well and wet-well are connected.

The assumptions made and the procedures used in the BWR wet-well
pressure suppression system modeling in the MARCH code are given below:

- Steam entering the pressure suppression pool
  in excess of that required to keep the partial
  pressure of stea in the wet-well at the pool
  saturation pressure is condensed;

- All noncondensables leaving the pressure suppression
  pool leave at pool temperature;

- Heat input due to condensing steam and to lowering the
  temperature of noncondensables increases the suppres-
  sion pool temperature, TPOOL;

- Steam leaking from the primary system can be sent
  directly into the pressure suppression pool (input option);

- For transfers from the dry-well to the wet-well to take
  place a minimum pressure difference can be required as an
  input option;

- Condensable airborne fission products flowing through the
  pressure suppression chamber as a result of inter-compartment
  transfers are retained in the pool according to:

$$DFP = FP*FTX*(1 - \frac{1}{DCF})*CGF \qquad\qquad (III.B.40)$$

where

DFP = fraction of fission product decay heat retained in the
pressure suppression pool,

FP = fraction of fission product decay heat in the dry-well
before transfer,

FTX = fraction of dry-well 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.

III.B.7 HYDROGEN BURNING MODEL (BURN)

The hydrogen burning model employed in the MARCH code consists
of

- Checking at every timestep whether the hydrogen and
  oxygen concentrations in any compartment exceed the
  assumed flammability limits for H_2 and O_2. (6.5 m/o O_2,
  input for H_2)

- If the flammability limit has been exceeded, burning down to
  a lower H_2 limit (or part of it if there is not enough O_2) in
  either (input options) (1) all compartments, or (2)
  only those compartments in which the flammability
  limit has been exceeded.

The equation for the chemical reaction is

$$2H_2 + O_2 \rightarrow 2H_2O + Q \qquad\qquad\qquad \text{(III.B.41)}$$

and the enthalpy of reaction, Q, is equal to 1.03×10^5 Btu per lb-mole of
H_2 burned.[15] (4.94×10^4 Joules per gr-mole of H_2 burned).

The energy generated by the hydrogen burns, the amounts of H_2
and O_2 consumed and the amount of H_2O produced by the reaction are calculated
in the subroutine BURN. These are included in the containment mass and energy
balance calculations in subroutine MACE. The burn time (length of burn) is an
input parameter.

The input options allow for the hydrogen burning calculations to
start either when the flammability limit is first attained in one of the
compartments or to wait until a certain stage in the accident seqeunce has

(15) Mark's Standard Handbook for Mechanical Engineers, T. Baumeister, ed.,
7th ed., McGraw-Hill Book Co., pp. 4-72 (1967).

been reached and then to burn subject to the flammability limit condition. It is also possible in the code to skip over the H_2 burning calculations entirely. If desired, the code will calculate the masses of reactants and products, and the enthalpy generated from the reactions and print them in the output from the code but not actually include them in the containment mass and energy balance calculations in subroutine MACE. Thus, the adiabatic burn pressure can be calculated at any time without actually burning the hydrogen.

III.B.8 INTER-COMPARTMENT FAN MODEL

A fan that transfers containment gases from one compartment to the other can be incorporated in the MARCH containment analysis calculations. The fan can be turned on at an input 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 m^3 (ft^3) of volume (FCFM is the fan flow rate specified by the user and DTX is the timestep) is transferred from the fan source compartment to the receiver compartment per timestep. Transfers due to fan flow precede those that are driven by pressure gradients.

The fan is automatically turned off when the containment fails.

III.B.9 COMPARTMENT THERMODYNAMIC
EQUILIBRIUM MODEL

The amounts of mass and enthalpy added to a containment compart-
ment from various sources are assumed to be uniformly distributed over the
total volume of the compartment. Based on this assumption, the equilibrium
thermodynamic properties of the compartment, such as temperature, pressure,
atmospheric quality, etc., are calculated in subroutines MIXCTRL, EQUIL,
TEMP, SATEST, and MACE.

The total inventory of the masses of the materials that make up
the compartment atmosphere and the total enthalpy in those compartments
are continuously updated in the subroutine MACE. The temperature, pres-
sure and other thermodynamic properties of the compartment .tmosphere are
calculated as follows.

First, it is checked in subroutine SATEST to see if the compart-
ment atmosphere is superheated. If it is not superheated, the compartment
temperature, T_o is calculated by a trial and error method from the following
equation:

$$\text{UTOT} = (MC_p)_{air}(T_o - 32.0) + (WS - \frac{VC}{V_g(T_o)})\, h_f(T_o) + \frac{VC}{V_g(T_o)}\, h_g(T_o) \qquad \text{(III.B.42)}$$

where

$\qquad$ UTOT = total enthalpy in the compartment;

$\qquad (MC_p)$ = sum of the mass times the specific heat of the
$\qquad\qquad\qquad$ constituents of air, i.e., $(MC_p)_{air} = (MC_p)_{N_2} +$
$\qquad\qquad\qquad (MC_p)_{O_2} + (MC_p)_{H_2} + (MC_p)_{CO}$;

$\qquad\quad T_o$ = compartment temperature;

$\qquad\quad$ WS = mass of steam plus suspended water droplets in
$\qquad\qquad\qquad$ the atmosphere;

$\qquad\quad$ VC = compartment volume;

$\qquad V_g(T_o)$ = specific volume of steam at saturation temperature
$\qquad\qquad\qquad$ of T_o;

$\qquad h_f(T_o)$ = specific enthalpy of water at saturation temperature
$\qquad\qquad\qquad$ of T_o;

$h_g(T_o)$ = specific enthalpy of steam 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 III.H).

Once T_o is known, the partial pressure of steam, specific volumes, and enthalpies of steam and water at saturation temperature of T_o are found from the polynomial functions as given in Section III.H.

If, however, the compartment atmosphere is superheated, the temperature is found from

$$UTOT = (MC_p)_{air} (T_o - 23.0) + WS\ h_g (T_o) \qquad (III.B.43)$$

$h_g(T_o)$ is derived from two equations of state that have been obtained by fitting to steam tables data for saturated steam conditions. These equations are

$$P*V_g = 1.34863\ H - 1157.716 \qquad (III.B.44)$$

$$P*V_g = 0.50662\ T_o + 282.4364 \qquad (III.B.45)$$

where

P = pressure, psia

V_g = specific volume, ft_3/lb

H = specific enthalpy, Btu/lb

From equations (III.B.44) and (III.B.45),

$$H = h_g(T_o) = (0.50662\ T_o + 1440.15)/1.3486 \qquad (III.B.46)$$

Substituting $H_g(T_o)$ in equations (III.B.43) and solving for T_o gives the temperature of compartment atmosphere.

Then the partial pressure of steam in the compartment atmosphere, P_s, is found from equation (III.B.45) with $V_g = \frac{VC}{WS}$. The specific enthalpy of steam is given by equation (III.B.46).

The partial pressures of gases in the atmosphere are found by using the ideal gas law, i.e.,

$$P_i = \frac{W_i R_i (T_o + 460)}{144 \ VC} \qquad \text{(III.B.47)}$$

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.,

$$P_{tot} = P_s + \sum_i P_i \qquad \text{(III.B.48)}$$

where P_s is the partial pressure of steam and i goes over N_2, O_2, H_2, CO_2, and CO.

The enthalpy associated with the non-condensables in the atmosphere is

$$UAIR = (MC_p)_{air} (T_o - 32.0) \qquad . \qquad \text{(III.B.49)}$$

The enthalpy of steam plus water droplets in atmosphere is

$$ENSX = UTOT - UAIR \qquad .$$

Then the fraction of steam in the steam-water mixture in the atmosphere is given by

$$X = \frac{\frac{ENSX}{WS} - h_f(T_o)}{h_g(T_o) - h_f(T_o)} \qquad \text{(III.B.50)}$$

and the masses of steam and water droplets in atmosphere are

$$M_f = (1 - X) \ WS \qquad \text{(III.B.51)}$$

$$M_g = WS - M_f \qquad . \qquad \text{(III.B.52)}$$

III.B.10 INTER-COMPARTMENT TRANSFERS MODEL

At the end of a MACE timestep, those compartments in the containment that have been specified in the input as connected are allowed to transfer enough material among themselves so that they all have the same pressure. The use of this approximation, rather than requiring conservation of mementum, permits MACE to use large timesteps. The MACE timestep is adjusted to limit the amount of enthalpy transferred from any one compartment to another to within 20% of the enthalpy in the compartment that is doing the transfer.

As explained in Section III.B.9, the effect of any mass or enthalpy addition or removal from a compartment is assumed to be uniformly distributed over the total volume of the compartment. Since enthalpy is not added to or taken out of all compartments at the same rate, transfers between compartments must take place to attain a uniform containment pressure at the end of a MACE timestep.

The way the inter-compartment transfer models in the MARCH code are set up is

    (1) On the first iteration, assume each transfer path carries 20% of the enthalpy in its source volume,

    (2) Find the pressure, temperature, and other thermodynamic properties in each compartment,

    (3) Find the pressure change in each compartment per unit of enthalpy transferred over each path connected to that compartment,

    (4) From a set of linear algebraic equations, find the amount of enthalpy that would be required to be transferred over each path in order to bring all compartments to a uniform pressure, P_o,

    (5) Iterate on the transfers until the calculated pressure P_o does not change by more than 0.01 psia.

The algebraic equations used in step 4 are as follows (these equations are solved in subroutine SOLINEQ)

$$K_{11}\Delta U_1 + K_{12}\Delta U_2 + \ldots + K_{1NU}\Delta U_{NU} - 1.0\, P_o = -P_1$$

$$K_{21}\Delta U_1 + K_{22}\Delta U_2 + \ldots + K_{2NU}\Delta U_{NU} - 1.0\, P_o = -P_2$$

$$\vdots$$

$$K_{N1}\Delta U_1 + K_N 2\Delta U_2 + \ldots + K_{N.NU}\Delta U_{NU} - 1.0\, P_o = -P_N$$

(III.B.53)

where

N = the number of compartments;

NU = the number of transfer paths;

$\Delta U_1, \Delta U_2 \ldots \Delta U_{NU}$ = (unknowns) enthalpy transferred over paths 1, 2, ... NU;

P_o = (unknown) uniform pressure in all compartments after transfers;

$P_1, P_2, \ldots P_N$ = pressures in compartments 1, 2, ... N, respectively, found in step 2.

Since only series paths (no parallel paths) are allowed in the MARCH code, $NU = N -1$, and there are the same number of equations as the number of unknowns.

The K's in the above equation are:

$$K_{ij} = \frac{\Delta P_{ij}}{\Delta U_j}$$

(III.B.54)

where ΔP_{ij} = change in pressure in compartment i as a result of ΔU_j. ΔU_j = the amount of enthalpy transferred over path j in the previous interation.

If path j is not connected to compartment i,

$$K_{ij} = 0.0 \quad .$$

There are two other types of mass and enthalpy transfers between compartments. One is the leakage type transfer which takes place between a compartment and the outside air after the containment has failed. These

transfers are pressure-driven across specified orifices and do not necessarily establish pressure equilibrium. They are explained in Section III.B.11. The transfers of the third type do not depend on pressures in compartments but are driven by inter-compartment fans according to a specified volume flow rate. They are given in Section III.B.8.

III.B.11 CONTAINMENT FAILURE AND LEAKAGE MODELS

In the MARCH code, the containment is assumed to fail when an input specified containment pressure, containment temperature, or accident time is reached. In addition to the numerical values of the pressure, temperature, or time that initiates the containment failure, the number of the compartment in which the failure occurs, the containment break area, and the orifice coefficient for the break are also input to the code.

Once the containment has failed the leakage to outside is calculated as follows:

$$WBRK = ABRK*G \qquad (III.B.55)$$

where WBRK = mass rate of leakage of the air-steam mixture in the containment (calculated in subroutine CONFAIL in the MARCH code), ABRK = break area, G = mass flow velocity. G is taken as the minimum of G1 and G2, where

$$G1 = CBRK*60. \quad (2 \cdot g \cdot \rho_c \cdot \Delta P \cdot 144)^{1/2} \qquad (III.B.56)$$

$$G2 = 1642. \quad (P_c \cdot \rho_c)^{1/2} \qquad (III.B.57)$$

CBRK = orifice coefficient for the containment break; g = gravitational acceleration, 32.2 ft/sec^2; ρ_c = density of the air-steam mixture in the compartment where the containment fails; $\Delta P = P_c - 14.7$; P_c = pressure in the compartment, psia; G1 and G2 are expressed in units of lb/ft^2/min.

The escaped fraction, FTX, of the air-steam mixture in the compartment where the failure occurred over the timestep of DTX is

$$FTX = \frac{WBRK*DTX}{WAIR+WST}$$

where WAIR and WST are the masses of air and steam, respectively, in the compartment at the beginning of the timestep. The masses of steam and air, the fission product decay heat, and the total enthalpy that escaped to the outside atmosphere are calculated by multiplying the amount present in the compartment by FTX.

If the pressure in the compartment is less than the atmospheric pressure, the leakage is assumed to be inwards with net addition of air mass and enthalpy into the compartment. For the amount of enthalpy added to the compartment atmosphere, the outside air is assumed to be 79% N_2, 21% O_2, and at 70 F temperature.

III.B.12 CONTAINMENT SUMP MODEL

For a BWR, the dry-well and the wet-well are usually modeled as two separate compartments, each having its own sump. In the wet-well, the pressure suppression pool serves as the sump. In the dry-well, water collects on the floor and when its volume exceeds an input specified value, it is assumed to overflow into the wet-well through the vent pipes.

For a PWR, the containment usually has only one sump and water from all compartments drains into that sump. However, for a PWR with an ice condenser containment, if the upper and lower compartments are assumed unconnected, except through the ice condensers, there are two sumps; one for each compartment. 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 only.

Water may leave a sump by:

- flashing during containment depressurization,
- boiling due to fission product heating,
- ECC recirculation intake,
- containment spray recirculation intake,
- vaporization,
- boiling if it comes into contact with fragmented core debris after reactor pressure vessel melt-through (in subroutine HOTDROP),
- boiling if sump water contacts debris in subroutine INTER.

Fission products that are scrubbed by the ice beds in a PWR are assumed to enter the lower compartment sump, and the ones that are scrubbed by the pressure suppression pool in a BWR are assumed to remain in the pressure suppression pool.

III.B.13 REACTOR CAVITY MODEL

In addition to the modeling of the regular sumps as explained in Section III.B.12, it is also possible to model in the MARCH code (NCAV data in NLMACE) a reactor cavity that is located immediately under the reactor pressure vessel. For a BWR, this is shown in Figure III.B.13.1. Water from all sources (except if there are sprays in the dry-well, part of that water may be sent directly into the reactor cavity) first falls on the dry-well floor. After the volume of the water on the floor exceeds an input specified value, the water is assumed to overflow into the cavity. If the cavity also fills up, the extra water drains into the wet-well.

The reactor cavity arrangement for a PWR is shown in Figure III.B.13.2. Water from all sources except a fraction of spray water (input controlled) collects on the containment floor. When the volume of the water exceeds an input
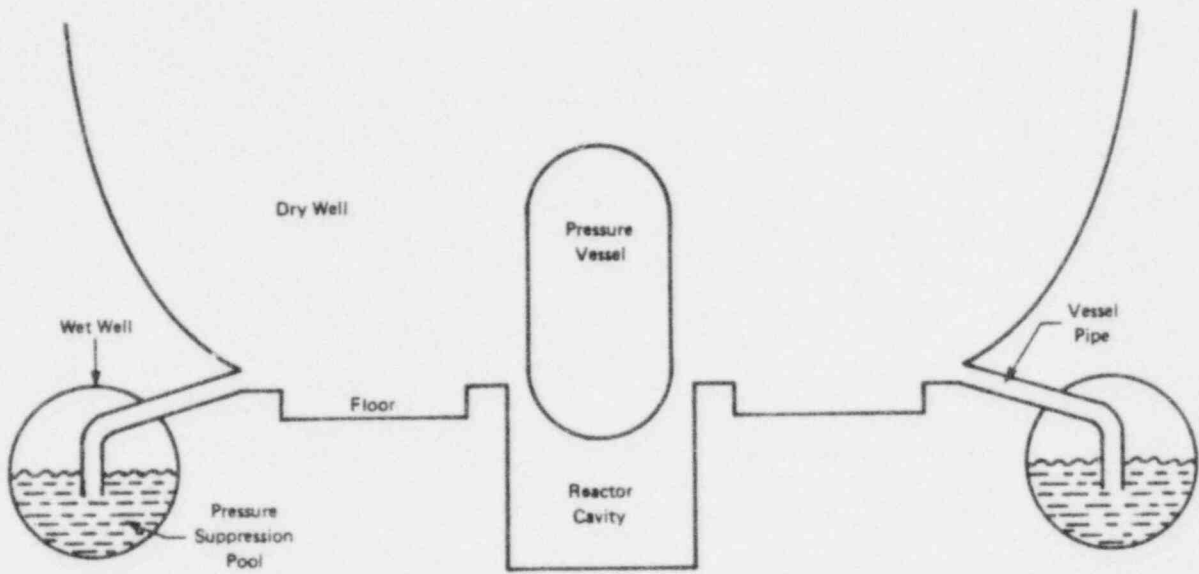
REACTOR CAVITY ARRANGEMENT FOR A BWR

FIGURE III.B.13.1
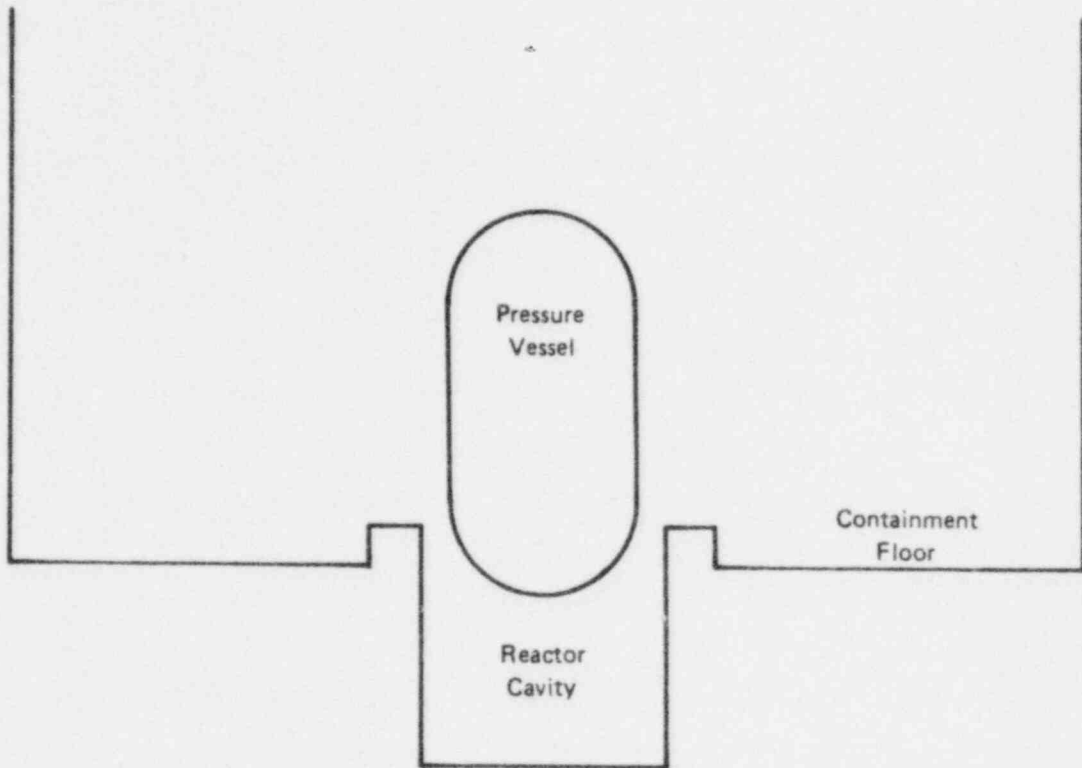
REACTOR CAVITY ARRANGEMENT FOR A PWR

FIGURE III.B.13.2

specifid value, it overflows into the cavity. In this case, there is not a separate sump but the containment floor serves as the sump.

When the pressure vessel bottom head melts through, the debris is assumed to fall directly into the water in the cavity.

III.B.14 CONTAINMENT VENTING MODELS

The input parameter IVENT controls "venting" between compartments. The IVENT parameter permits two compartments to be connected at some point in the accident. Thus, one compartment "vents" into the other. The "venting" occurs through a pool of water. When IVENT is zero, no venting occurs. When venting is to occur, IVENT is set equal to the sum of 10 times the compartment number vented from initially plus 1 times the compartment number vented to initially. If IVENT is negative, the flow between compartments is calculated in subroutine CONVENT and depends always on the pressure difference between the compartments. If IVENT is positive, the inter-compartment flow is initially calculated by CONVENT and then switches to the MACE transfer method (Section III.B.10) after compartment pressures equilibrate.

Initially, the vent between the compartments is assumed to be closed. Vent opening is controlled by the input parameter TVNT1. If TVNT1 is positive, the vent is opened when the average temperature of the gas exiting the core (TGEX as calculated in BOIL) excceds TVNT1. If TVNT1 is negative, the vent is opened when the pressure in the vented compartment initially exceeds TVNT1.

The rate of gas flow between compartments is calculated in subroutine CONVENT as the minimum of the orifice flow rate as given by

$$G1 = 5778 \cdot AVBRK \cdot CVBRK \cdot (RHO \cdot \Delta P)^{1/2} \qquad \text{(III.B.59)}$$

and the critical flow rate given by

$$G2 = 1642 \cdot AVBRK \cdot (RHO \cdot P)^{1/2} \qquad \text{(III.B.60)}$$

where

AVBRK = vent area,

CVBRK = orifice coefficient,

RHO = density of gas being vented,

ΔP = pressure difference between compartments,

and

P = pressure in the compartment being vented.

The steam flow rate is the gas flow rate multiplied by the steam fraction. This is given by

$$FSTM = 1/(1 + ASWR) \tag{III.B.61}$$

where ASWR is the air to steam weight ratio and is calculated in MACE. The difference between gas flow rate and steam flow rate is the flow rate of the other constituents in the atmosphere of the vented compartment. Individual flow rates of the constituents are based on weight ratios of these constitutents.

Gas flow from the vented compartment to the receiver compartment is through a pool of water. The modeling of the receiver compartment is the same as for a BWR pressure suppression containment. It is assumed that the gas portion of the flow emerges from the pool at the pool temperature. Gas flow in the reverse direction travels through a "vacuum breaker" as in a BWR.

III.C. DEBRIS-PRESSURE VESSEL BOTTOM HEAD INTERACTION MODELS (HEAD)

After the core has melted and all water in the bottom head has evaporated, the control is transferred from subroutine BOIL to subroutine HEAD. The HEAD routine analyzes the conduction-limited progress of the thermal front where the molten debris contacts the bottom head. The bottom head failure criteria include stresses due to pressure differential between the vessel and containment, hydrostatic pressure, and discontinuity stresses in the vessel. Figure III.C.1 is a flow diagram for the calculations in subroutine HEAD.

The procedures and reasoning employed in the calculations for the debris-bottom head heat transfer analysis and the bottom head failure mechanisms are explained in Sections III.C.1 and III.C.2, below.

III.C.1. DEBRIS-TO-HEAD HEAT TRANSFER MODEL

Heat transfer from the core debris to the bottom head is calculated in subroutine HEAD. Subroutine HEAD calculations do not start until the core has collapsed into the bottom head, and all of the water in the bottom head has been boiled away. MARCH models core heatup and bottom head melting as distinct, sequential phases. Although certainly credible, MARCH does not model a scenario in which core melting and bottom head melting occur simultaneously.

The development of the bottom head heat transfer model assumes an initially dry bottom head with a uniform wall temperature, TB. The outside of the head is assumed to be insulated. The core debris at temperature TD, is dropped into the head. The debris may be either liquid or solid. The head melting model assumes one dimensional heat transfer with a uniform wall heat flux.

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
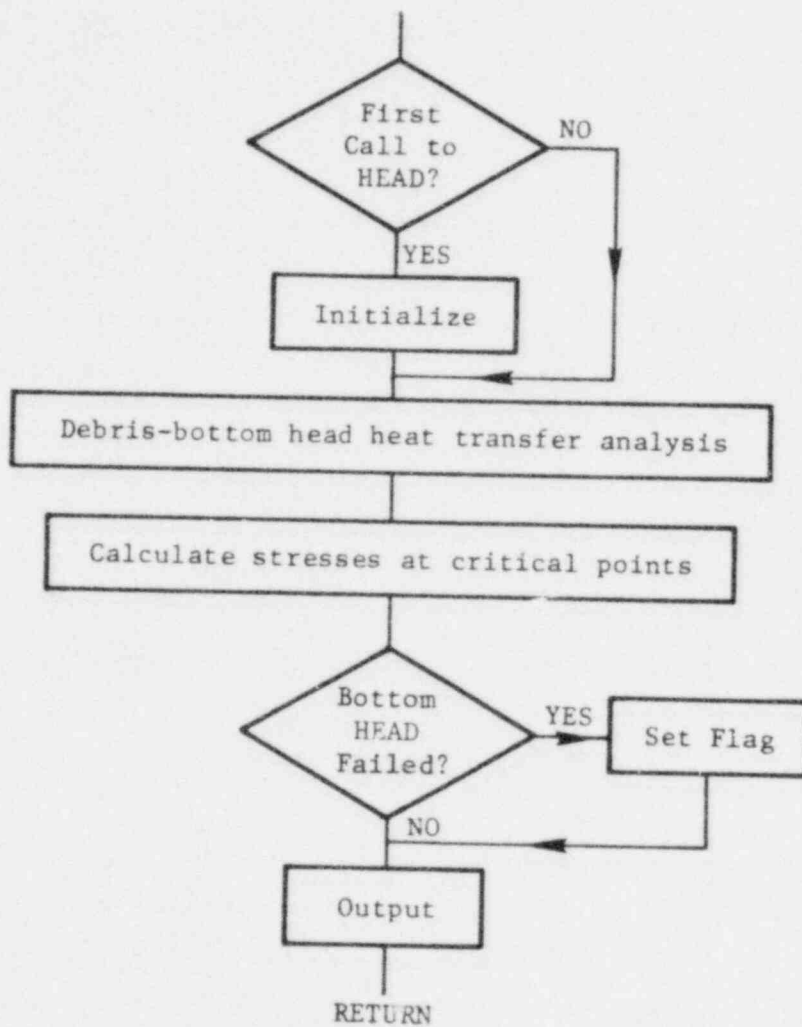
FIGURE III.C.1 SUBROUTINE HEAD FLOW DIAGRAM

$$Q = k_H \frac{(TW - TB)}{\delta_H} \qquad (III.C.1)$$

where $\delta_H = \sqrt{\alpha \pi t} \equiv$ thermal penetration distance

$\quad k_H =$ head thermal conductivity

$\quad \alpha_h = k_H/(\rho c) =$ head thermal diffusivity

$\quad \rho =$ density of head

$\quad c =$ specific heat of head

$\quad t =$ time.

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

$$\frac{d\delta_H}{dt} = \frac{\pi}{2} \frac{\alpha_H}{\delta_H} \qquad (III.C.2)$$

The initial contact temperature, TW, at the debris-head interface is obtained by equating the heat fluxes. Thus,

$$k_D \left(\frac{TD - TW}{\delta_D}\right) = k_H \left(\frac{TW - TB}{\delta_H}\right) , \qquad (III.C.3)$$

and

$$TW = \left(\frac{TD + A_o TB}{1 + A_o}\right)$$

where

$$A_o = \sqrt{\frac{(k\rho C)_H}{(k\rho C)_D}} . \qquad (III.C.4)$$

Figure III.C.1.1 illustrates a case in which the head is melting. With melting, the thermal penetration distance increases at a rate

$$\frac{d\delta_H}{dt} = \frac{\pi}{2} \frac{\alpha_H}{\delta_H} - \frac{dX_m}{dt} , \qquad (III.C.5)$$

where X_m is the thickness of head melted. The head heat balance is

$$QDB = (\rho C)_H A_H \frac{d}{dt} \left\{ \int_{X_m}^{L} T(x)\,dx \right\} + (\rho \lambda)_H A_H \frac{dX_m}{dt} \qquad (III.C.6)$$

where
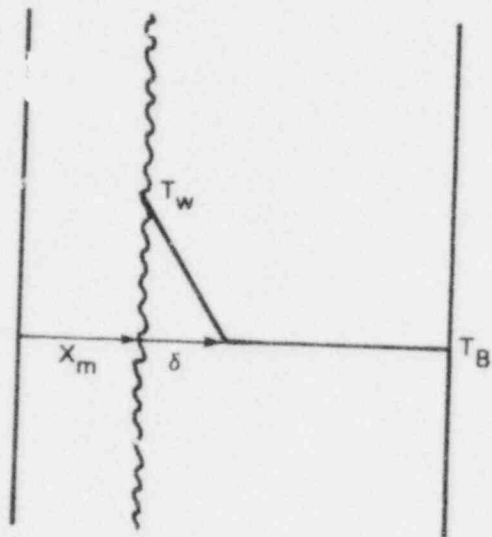
FIGURE III.C.1.1.   HEAD HEATUP WITH MELTING

λ_H = head heat of fusion

A_H = debris-head interface area

$T(x)$ = head temperature

QDB = heat from debris.

The debris heat balance is

$$(MC)_D \frac{dTD}{dt} = QDK - QRAD - QDB - (\rho C)_H A_H \frac{dX_m}{dt} (TD - TMH) \qquad (III.C.7)$$

where

$(MC)_D$ = debris heat capacity

QDK = debris decay heat

TMH = head melting point

$QRAD$ = heat loss from top surface of debris.

The advancement of the thermal front into the debris is modeled in a manner similar to that for the head;

$$QDB = k_D A_w \frac{(TD - TW)}{\delta_D} \qquad (III.C.8)$$

and

$$\frac{d\delta_D}{dt} = \frac{\pi}{2} \frac{\alpha_D}{\delta_D} - \frac{R_m}{dt} \qquad (III.C.9)$$

where

$R_m = R(FM)^{1/3}$ = debris melt radius

R = radius of bottom head

FM = fraction debris molten based on either iron or debris liquidus temperature.

When the debris is completely molten, there is no solid material, and δ_D becomes small. For small δ_D with the debris molten, the heat flux from the debris would become controlled by a molten debris heat transfer coefficient. However, the heat transfer coefficients for this situation are not well defined. Thus, in the HEAD calculations δ_D is given a

minimum value which restricts the heat transfer from the debris to the head to the debris decay heat; that is,

$$\delta_D > k_D A_W (TD - TW)/QDK \quad . \qquad (III.C.10)$$

Subroutine HEAD contains a radiation heat transfer model for the heat losses from the top surface of the molten debris. However, the modeling of the heat sink for the radiated heat is not complete and contains artificial assumptions. For example, a constant temperature heat sink is assumed. Thus, QRAD is normally defaulted to zero by MARCH.

III.C.2 BOTTOM HEAD FAILURE MODEL

The failure criterion for the pressure vessel bottom head in contact with the molten core debris is that the bottom head has failed if the total tensile stress exceeds the tensile strength at any location. The critical locations considered in subroutine HEAD are the circular line where the cylindrical vessel joins the hemispherical bottom head 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, σ, is calculated as follows.

$$\sigma = \frac{\sigma_1 X_1 + \sigma_2 X_2}{X_1 + X_2} \quad . \qquad (III.C.11)$$

Using the schematic of Figure III.C.2.1,

X_1 = thermal penetration distance in the bottom head

$X_2 = t - X_m - X_1$

t = initial thickness of the bottom head

X_m = the thickness of the melted portion of the bottom head

σ_1 = average tensile strength over the thermal penetration distance part of the bottom head

σ_2 = tensile strength over the uniform temperature part of the bottom head.
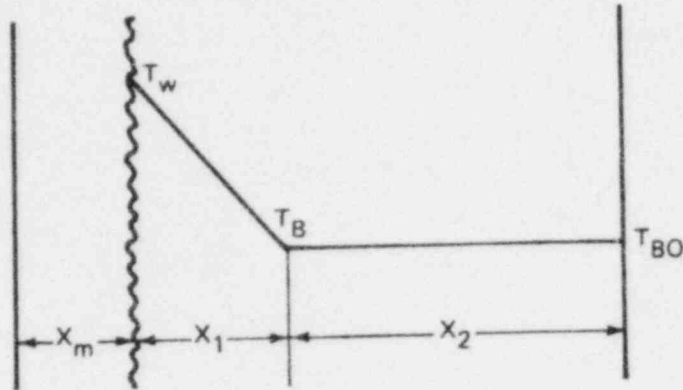
FIGURE III.C.2.1. POSSIBLE TEMPERATURE PROFILE IN
THE PARTIALLY MELTED BOTTOM HEAD

σ_1 and σ_2 are calculated from

$$\sigma_1 = 1.49 \times 10^{16} \, T_{ave}^{-3.91} \quad \text{for } T_{ave} \leq 1500 \text{ F} \qquad \text{(III.C.12)}$$

$$\sigma_1 = 1.49 \times 10^{16} \, T_{ave}^{-3.91} \left(\frac{T_m - T_{ave}}{T_m - 1500}\right) \quad \text{for } T_{ave} > 1500 \text{ F} \; .$$

$$\sigma_2 = 1.49 \times 10^{16} \, T_{BO}^{-3.91} \qquad . \qquad \text{(III.C.13)}$$

where

σ_1, σ_2 are in units of psi

$$T_{ave} = \frac{T_W + T_B}{2}$$

T_W = temperature at the debris-head boundary

T_B = temperature behind the thermal penetration distance

T_m = melting point of the bottom head

T_{BO} = temperature on the outside surface of the bottom head.

In parts of the vessel where there is no heating, $\sigma = \sigma_2$ and if the thermal penetration distance extends over the remaining thickness of the vessel $\sigma = \sigma_1$.

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 bottom head

    b) the volume of the debris is greater than the volume of the bottom head.

Cases (a) and (b) are shown schematically in Figure III.C.2.2.

a. $V_D < V_{BH}$ b. $V_D > V_{BH}$
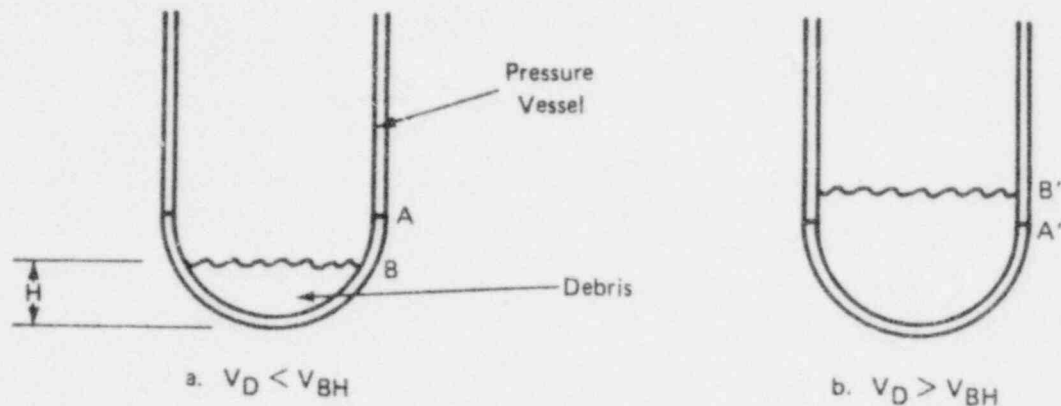
FIGURE III.C.2.2.   MOLTEN DEBRIS IN PRESSURE VESSEL BOTTOM HEAD (V_D = VOLUME OF DEBRIS, V_{BH} = VOLUME OF BOTTOM HEAD)

The stresses in case (a) at point A are calculated as[16]

$$\sigma_L = \frac{\Delta P \cdot D}{4t} + \frac{3.0 \times \Delta P \times 0.3224}{4.0 t^2 \beta^2} + W \qquad (III.C.14)$$

$$\sigma_c = \frac{\Delta P \cdot D}{2t} + \frac{3.0 \times 0.3 \times \Delta P \times 0.2709}{4.0 t^2 \beta^2} - 0.3W \qquad (III.C.15)$$

(16) John F. Harvey, "Pressure Vessel Design", D. Van Nostrand Co. (1963) p 126-130.

where

σ_L, σ_c = the longitudinal and circumferential tensile stresses at point A, respectively,

ΔP = pressure difference between the vessel and the containment

D = diameter of the bottom head.

$$\beta = \frac{1.285}{(\frac{D}{2} \times t)^{0.5}} \qquad (III.C.16)$$

$$W = \frac{(M_D + M_{BH})}{\pi \left[(\frac{D}{2} + t)^2 - (\frac{D}{2})^2 \right] \times 144} \qquad (III.C.17)$$

M_D = mass of debris

M_{BH} = mass of bottom head.

The maximum stress at point A is the maximum of σ_L and σ_c. It is compared with the tensile strength calculated using Equation (III.C.13), i.e.,

$$S_A = AMAX1 \, (\sigma_L, \sigma_c) \qquad (III.C.18)$$

If $S_A > \sigma$, the bottom head is assumed to fail.

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

$$S_B = \frac{\Delta P \cdot D}{4(t - X_m)} + \frac{(M_D + M_{BH})}{\pi \left[(\frac{D}{2} + t)^2 - (\frac{D}{2} + X_m)^2 \right] \times 144} . \qquad (III.C.19)$$

If $S_B > \sigma$, where σ is calculated using Equation (III.C.11), the bottom head is also assumed to fail.

The criteria at both locations A and B are checked every time step. 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 location A' are more strict than at location B'. Therefore only the conditions at A' are checked. The stresses at A' are [16]

$$\sigma'_L = \frac{\Delta \Gamma \cdot D_h}{4t_h} + \frac{3.0 \times \Delta P \times 0.3224}{4.0 t_h^2 \beta_h^2} + W_h \qquad \text{(III.C.20)}$$

$$\sigma'_c = \frac{\Delta P_h \cdot D_h}{2t_h} + \frac{3.0 \times 0.3 \times \Delta P \times 0.2709}{4.0 t_h^2 \beta_h^2} - 0.3 W_h \qquad \text{(III.C.21)}$$

where

$$D_h = D + 2.0 \times X_m$$
$$t_h = t - X_m$$

$$W_h = \frac{(M_D + M_{BH})}{\pi \left[(\frac{D}{2} + t)^2 - (\frac{D_h}{2})^2 \right] \times 144} \qquad \text{(III.C.22)}$$

$$S_{A'} = \text{AMAX1} \, (\sigma'_L, \sigma'_c) \qquad \text{(III.C.23)}$$

and if $S_{A'} > \sigma$, where σ is from Equation (III.C.11), the bottom head is assumed to fail.

III.D. EX-VESSEL DEBRIS-WATER INTERACTION MODELS (HOTDROP)

After the reactor pressure vessel fails, the core debris is assumed to fall onto the containment floor (or into the reactor cavity) under the vessel, and to react with any water that may be present there. The core debris may be assumed to particulate. The calculations regarding the heat transfer between the water and the core debris particles and the chemical reactions between the metallic part of the debris and water are carried out in subroutine HOTDROP in the MARCH code. Figure III.D.1 is a flow diagram of the subroutine HOTDROP. Sections III.D.1 and III.D.2 below explain the models used in subroutine HOTDROP for the analysis for the debris-water heat transfer and the metal-water reactions, respectively.

III.D.1 DEBRIS-WATER HEAT TRANSFER MODEL

The number of spherical core debris particles, Np, is

$$Np = \frac{V_D}{\frac{4}{3} \pi R_p^3} \qquad \text{(III.D.1)}$$

where

V_D = volume of debris (from subroutine HEAD)

R_p = radius of each particle (from input)

The rate of heat transfer from each particle to water, Q_W, is

$$Q_W = h_{eff} A_p (T_E - T_W) \qquad \text{(III.D.2)}$$

where

h_{eff} = effective heat transfer coefficient

$A_p = 4 \pi R_p^2$, particle surface area

T_E = average particle temperature

T_W = water temperature
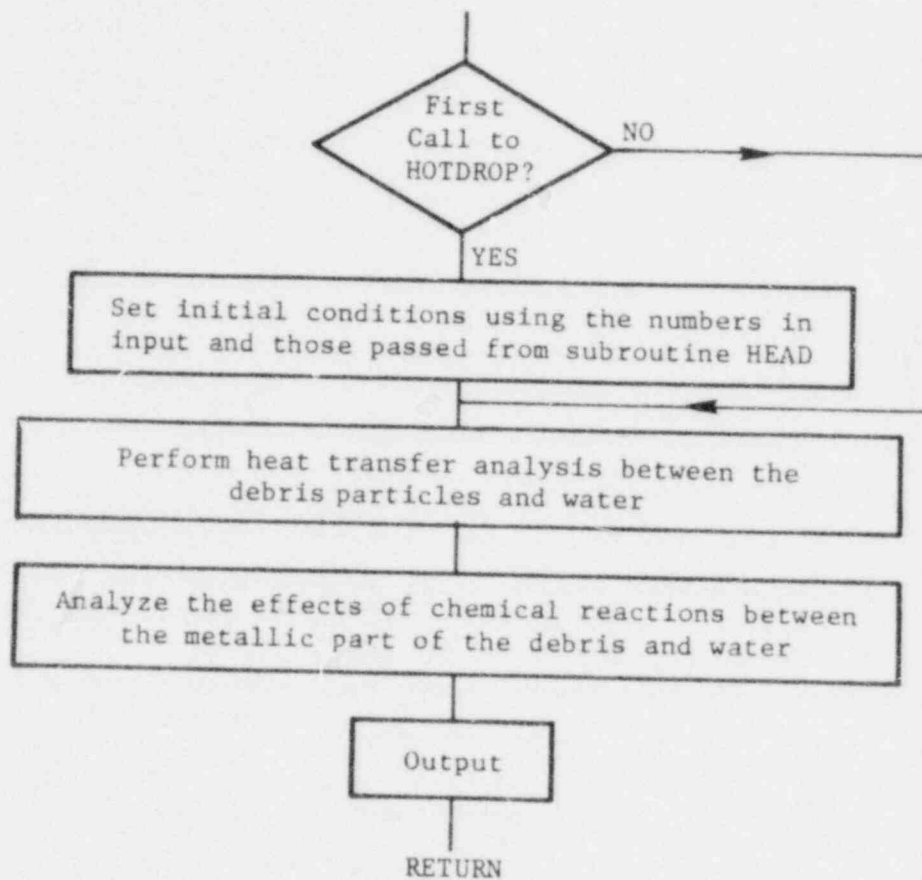
FIGURE III.D.1   FLOW DIAGRAM OF THE SUBROUTINE HOTDROP
IN THE MARCH CODE

The particle heat balance equation is

$$M_p C_p \frac{dT_E}{dt} = Q_D + Q_{MW} - Q_W \qquad \text{(III.D.3)}$$

where

M_T mass of each particle

C_p = specific heat of particle

Q_D = fission product decay power in each particle

Q_{MW} = rate of heat generated from metal-water reactions per particle. The way Q_{MW} is calculated is explained in the next section.

Q_W = equation III.D.2

The effective heat transfer coefficient h_{eff} is defined as follows. The temperature distribution inside a particle with uniform heat generation is parabolic with the maximum at the center, and is given by

$$T = T_s + \frac{Q}{V_p} \left(\frac{R_p^2 - R^2}{6k} \right) \qquad \text{(III.D.4)}$$

V_p = volume of one particle

T_s = surface temperature

The volume average particle temperature, T_E, is

$$T_E = T_s + \frac{1}{5} \frac{Q \, R_p}{A_p k} \qquad \text{(III.D.5)}$$

The surface temperature of the debris particle is

$$T_s = T_W + \frac{Q}{A_p h} \qquad \text{(III.D.6)}$$

where

h = surface heat transfer coefficient.

It is assumed that Equations III.D.4, 5, and 6 are applicable to the transient situations. Thus, replacing Q by QW in Equation III.D.2 and eliminating T_s in Equations III.D.5 and 6, h_{eff} becomes

$$h_{eff} = \frac{1}{\frac{0.2R_p}{k} + \frac{1}{h}}$$ (III.D.7)

where

k = thermal conductivity in particles (from input)

$h = h_c + h_{rad}$, pool boiling + radiation heat transfer coefficient

$$h_c = h_T (\frac{P}{15})^{0.25}$$ (III.D.8)

where

P = containment pressure in psia.

$$h_T = 44.5 \times \Delta T^{1.523} \text{ for } \Delta T < 42 \text{ F}$$

or

$$h_T = 2.02 \times 10^8 \times \Delta T^{-2.575} \text{ for } \Delta T \geq 42 \text{ F}$$ (III.D.9)

$$\Delta T = T_E - T_W$$

$$h_{rad} = \frac{0.173 \times 0.4 \times [(\frac{T_E}{100} + 4.6)^4 - (\frac{T_W}{100} + 4.6)^4]}{\Delta T}$$ (III.D.10)

In the calculations, h_c has an upper bound of 10,000 and h has a lower bound of 10. The conduction approximation implicit in Equation III.D.7 restricts the use of HOTDROP to small particles where h_{eff} is dominated by the surface coefficient, h. For reasonable debris thermal conductivities, the particle diameter should generally be less than a few inches.

III.D.2 DEBRIS-WATER REACTION MODEL

Subroutine HOTDROP does the calculation of the debris-water
interaction when the bottom head of the reactor vessel fails and drops
a mixture of uranium oxide, iron, zirconium, and zirconium oxide into
the water in the reactor cavity. The debris is assumed to drop in the
form of spheres with diameter DP, an input variable. The spheres
contain a core of uranium fuel and iron, an inner shell of zirconium,
and an outer shell of zirconium dioxide. The oxidation rate and heat
release rate equations used in HOTDROP are like those used in section
III.A.6. (The rod temperature, ROD, used there is replaced by the debris
temperature, T_E. The steam temperature is replaced by the water temperature,
T_W.)

HOTDROP is called once each MARCH timestep until the debris is
quenched or the water is vaporized. The number of HOTDROP timesteps may
also be controlled by the input variable IHOT. Thus, HOTDROP can be effec-
tively bypassed. IHOT also controls the temperature used for TPOOL.

III.E.   THE DEBRIS-CONCRETE INTERACTION MODEL

The interaction of the core debris with the concrete containment base pad is modeled in the subroutine INTER and its associated subroutines (Figure II.6). The INTER package was originally written by the Sandia Laboratories as a separate code. It has been incorporated in the MARCH code as a module by Battelle with a few modifications in the areas of debris decay heat calculation, debris to water heat transfer, and the input initialization.

The INTER package will not be documented in detail here. Important modeling considerations and the changes incorporated into the original INTER code will be highlighted. For more information on INTER, the reader is referred to Sandia publications.[4]

The major thrust of the INTER code is to model the heat and mass transfer mechanisms between the molten core debris and a concave concrete pad. Depending on the curvature of the floor, and the volume of the molten debris, the melt can be geometrically described as a hemispherical segment or a hemispherical segment intersected by a cylindrical segment. The melt is assumed to be separated into an oxidic and a metallic phase with the denser of the two phases being on the bottom layer.

The heat exchange takes place between the debris and the concrete, debris and the medium above the debris and between the two phases of the debris. A schematic of the concept is shown in Figure III.E.1.* Each layer (metal or oxide) 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 acrss a boundary layer or film whose thickness varies with the violence of mixing.

The conservation of energy principle is used to find the temperature of each debris layer,

$$\frac{d}{dt} (M_i C_{pi} T_i) = \frac{d}{dt} Q_i = \dot{q}_i \qquad (III.E.1)$$

---

* Figures III.E.1, 2, and 3 are reproduced from Reference 4.
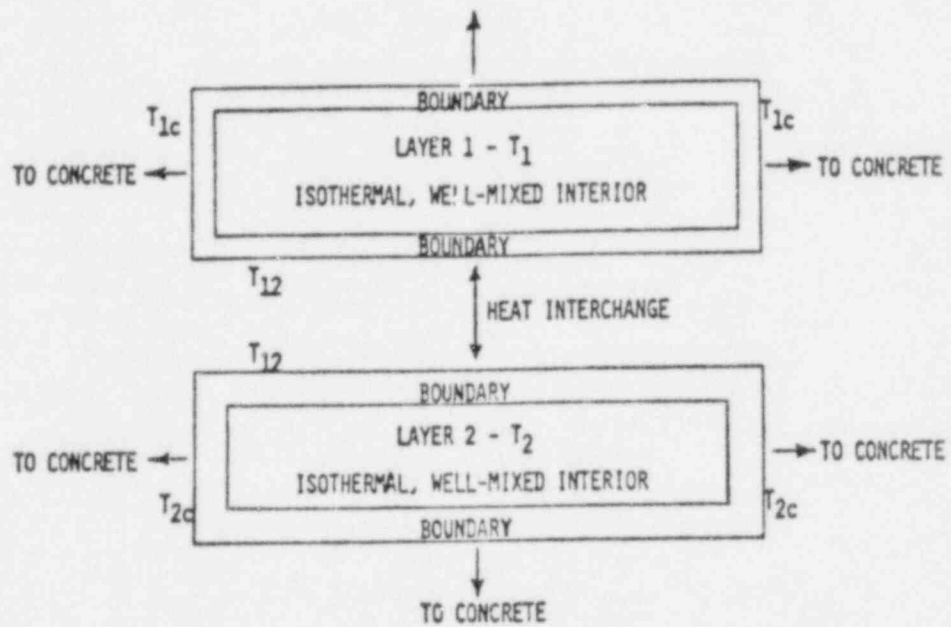
FIGURE III.E.1. SCHEMATIC CONCEPTUALIZATION OF HEAT
EXCHANGE IN DEBRIS-CONCRETE SYSTEM[4]

where

$i = 1, 2$ (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

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

t = time

$\dot{q}_i$ is found from

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

where

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

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

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

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

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

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

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

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

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

Mass balances on each layer include effects due to melting and decomposition of concrete, and chemical reactions. Figure III.E.2 shows schematically the flow paths of materials going in and out of debris layers. A few simplifying assumptions are made.

It is assumed that:

• All oxides and metals are promptly transmitted to the 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 III.E.3 shows the expansion of the debris-concrete melt front in both the hemispherical segment, and the hemispherical plus cylindrical segments geometries.

Modifications made in the original INTER code to incorporate it into the MARCH code affect fission product decay heat in debris, debris-water heat transfer and the initial conditions in INTER. Previously, the decay heat was calculated by the user and supplied to the code as input. At present, it is calculated in the MARCH code in subroutines ANSQ and FPLOSS using the ANS standard decay heat curve (See Section III.G). The heat transfer between the debris and any water that may be present on top of the debris used to be by convection only. It was assumed that the water was in contact with a cold crust whose temperature was lower than the internal temperature of the debris. This has been modified so that it is now possible for the debris to also radiate some of its heat to the water. The radiation area is specified in the input as a fraction of the debris surface area and the temperature the debris radiates at is the internal debris temperature. The mass of water on top of the debris is calculated in Section III.B.13. The initial conditions in INTER, such as initial masses and temperatures, used to be input parameters. In the MARCH code, they are calculated in the earlier parts of the code and are passed to INTER through COMMON blocks.
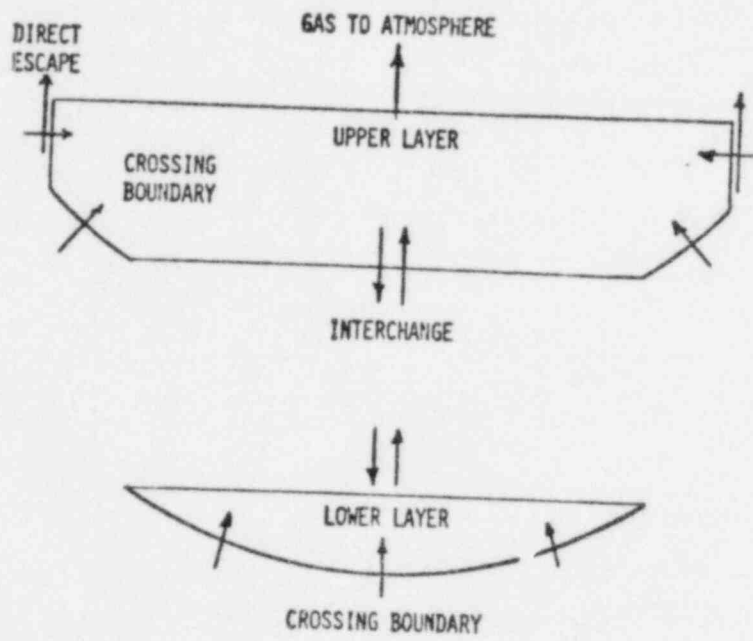
FIGURE III.E.2. FLOW OF MATERIAL IN DEBRIS-CONCRETE SYSTEM[4]
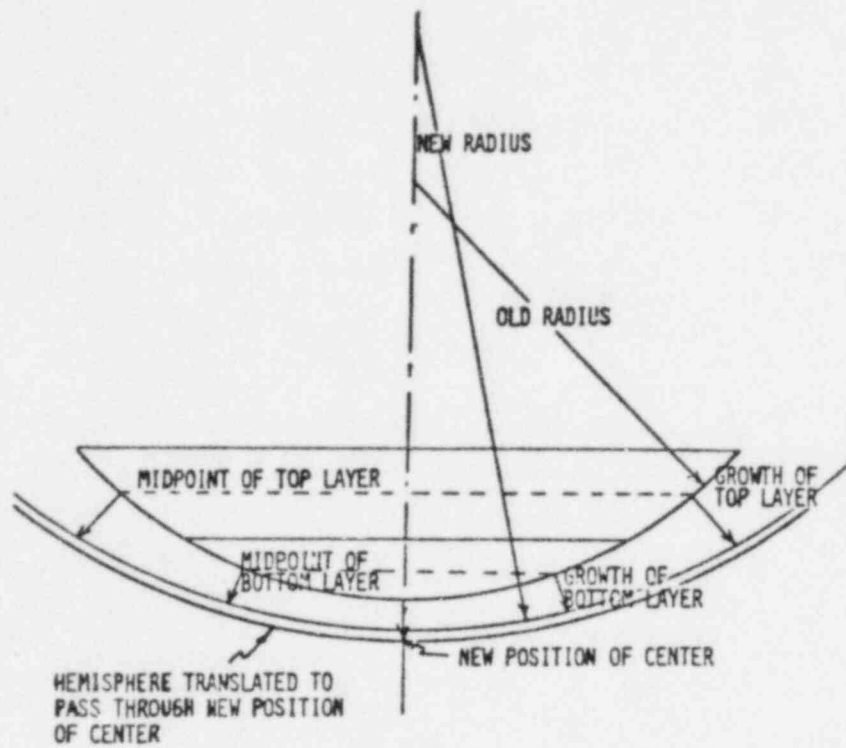
a. Hemispherical Segment
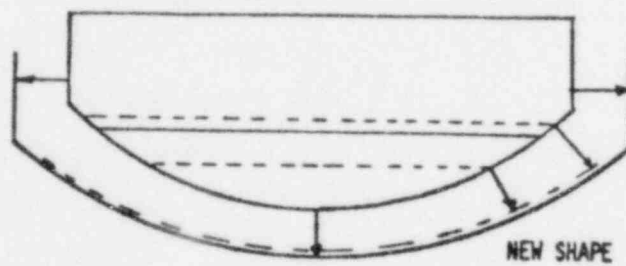
b. Hemispherical/cylindrical segments

FIGURE III.E.3. CHANGING SHAPE OF CAVITY IN CONCRETE MELTING[4]

III.F. FISSION PRODUCT LOSS MODEL

During core meltdown, fission products are released from the fuel. The release of fission products reduces the fission product heat source for the core. The released fission products may, in general, be redeposited on cooler primary system surfaces or in water remaining in the primary system or be released to the containment building. The MARCH thermal-hydraulic models assume fission products released from the core are immediately released to the containment building. Fission product holdup in the primary system is not modeled. 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.

Fission product losses are calculated in subroutine FPLOSS. FPLOSS divides the fission products into the 7 groups listed in Table III.F.1, according primarily to their volatilities. Each group is further subdivided into metal- (FMET) and oxide-associated (FOX) phases. The total releases during the core meltdown (RF) and concrete interaction or vaporization (RFV) phases are programmed as FPLOSS data. The total releases and oxide/metal phase partition are the WASH-1400 best-estimate values.[3] The WASH-1400 gap release is included in the melt release in FPLOSS. Table III.F.1 also lists the percent of the total decay heat which is associated with each of the 7 fission product groups for three different decay times.

The fission products are initially assumed to be distributed throughout the core with the same distribution as the power peaking factors and noding input to subroutine BOIL. The melt release is assumed proportional to the fraction of the BOIL node melted. Thus, the fractional release, DRF, of a given fission product group is

$$DRF = FF \times PF \times VF/NDZ \times RF \times FNM \qquad (III.F.1)$$

where

      FF = axial peaking factor

      PF = radial peaking factor

      VF = radial volume fraction

    NDZ = number of axial nodes

      RF = total melt release

    FNM = fraction node melted.

The total release, CRF, is obtained by summing over all melted core nodes.

The fraction of the decay heat in each fission product group before accounting for losses is

$$QF = Ce^{-\lambda t} \tag{III.F.2}$$

where C and λ are obtained by interpolating between the appropriate decay times in Table III.F.1. For decay times greater than 10^6 sec, the table values at 10^6 sec are used. The fraction of the decay heat released per node and group is DFPL = QF x DRF. The INTER code divides the core-concrete melt into oxide and metal layers. The vaporization release is assumed in FPLOSS to be characterized by an exponential release with time constants TAUOX and TAUM for the oxide and metal layers, respectively. TAUOX and TAUM are assumed to be equal unless one layer is solid and the other liquid. The liquid and solid time constants are input to subroutine INTER. The fractional vaporization release per group is:

$$DRFV = 0.693 DT \ (RF + RFV - CRF)(FOX/TAUOX + FMET/TAUM) \tag{III.F.3}$$

where FOX = 1 - FMET is listed in TAble III.F.1 as the oxide associated portion of the fission product decay heat. The release is stopped when the total release is the sum of the melt and vaporiztion releases in Table III.F.1. The fraction of the decay heat remaining in the oxide layer for each group is

$$DFOX = (1 - CRF) \ x \ FOX \ x \ QF \ , \tag{III.F.4}$$

and a similar expression applies to the metal layer.

Note that FPLOSS merely partitions the decay heat between the core debris and that which has been released. The absolute value of the decay heat is calculated in subroutine ANSQ.

TABLE III.F.1. FPLOSS FISSION PRODUCT DATA

Group	Melt Release, RF	Vaporization Release, RFV	Fraction Oxide, FOX	Percent Heat Per Group 10^2 sec	10^4 sec	10^6 sec
1, Xe	0.9	0.1	0.5	5.5	4.3	0.85
2, I	0.9	0.1	0.5	9.3	16.0	4.3
3, Cs	0.81	0.19	0.5	9.9	3.3	5.7
4, Te	0.1501	0.85	(a)	6.1	2.9	0.93
5, Sr	0.1	0.01	1.0	7.2	5.3	6.0
6, Ru	0.03	0.05	0.0	16.3	8.9	16.5
7, La	0.003	0.01	(b)	44.0	58.0	65.0

(a) FOX(4) = FZR, fraction cladding reacted

(b) FOX(7) = 0.87 + 0.13 x FZR

III.G. CORE DECAY POWER CALCULATION MODEL

In the MARCH code, the fission product decay heat source term can be either supplied by the user in the form of a power trace giving the fractional power level as a function of time after shutdown or the code calculates it automatically from the American Nuclear Society (ANS) Standard decay power curve. The input option can be exercised by setting the appropriate parameters in the NAMELIST NLBOIL in the MARCH input. The ANS standard is calculated in subroutine ANSQ as follows:

$$\frac{P}{P_o} = ANS(t) - ANS(t + t_o)$$

where

P = current power level

P_o = reactor operating power level

t = time after shutdown, sec

t_o = time at power, sec

$ANS = \dfrac{0.0603}{t^{0.0639}}$ for 5 sec $\leq$ t $<$ 10 sec.

$ANS = \dfrac{0.0766}{t^{0.181}}$ for 10 sec $<$ t $\leq$ 150 sec.

$ANS = \dfrac{0.130}{t^{0.283}}$ for 150 sec $<$ t $\leq$ 4 x 10^6 sec.

$ANS = \dfrac{0.266}{t^{0.335}}$ for t $>$ 4 x 10^6 sec.

For t < 5 sec, P/P_o = 1.0 is used. Decay of U239 and NP239 are not accounted for.

III.H.   STEAM-WATER THERMODYNAMIC PROPERTY DATA MODEL

III.H.1.   SUBROUTINE PROPS

The subroutine PROPS in the MARCH code contains a table of saturated steam-water thermodynamic properties. The properties listed are pressure, temperature, specific volumes and enthalpies of steam and water, and the specific heat of water. If pressure, temperature, or the specific volume of steam is given, the other corresponding properties can be found by interpolating between the values in the table. The interpolation schemes vary from linear-linear, to log-linear, and to log-log to give the best fit to the actual values in steam tables in literature.[17]

III.H.2.   POLYNOMIAL FUNCTIONS

In subroutines SATEST, TEMP, EQUIL, and function routines FENT, FVOL, PRSS, GVOL, and GE.T, there is a set of 4th degree polynomial equations that describe saturation properties of the steam-water system. These equations were obtained by fitting the data in steam tables[17] by use of regression analysis. Their range of validity is between 40 F and 400 F. These equations are given below.

$$V = \ell n V_g$$

$$\ell n T = 6.11067 - 0.180564V - 0.0292964V^2 + 0.00629137V^3 - 0.59749 \times 10^{-3}V^4$$

$$X = \ell n T$$

$$\ell n P = -27.7630 + 23.7433X - 8.69638X^2 + 1.41067X^3 - 0.0777638X^4$$

$$VF = 0.0903737 - 0.0694378X + 0.0242644X^2 - 0.00376979X^3 + 0.000220413X^4$$

$$\ell n VG = 25.9245 - 16.8828X + 6.35612X^2 - 1.06006X^3 + 0.0587298X^4$$

$$HF = 2068.48 - 2011.26X + 726.624X^2 - 117.646X^3 + 7.43066X^4$$

$$HG = -1043.94 + 1910.76X - 640.327X^2 + 93.7205X^3 - 4.94574X^4$$

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(17)   J. H. Keenan and F. G. Keyes, Thermodynamic Properties of Steam, John Wiley and Sons, Inc., New York (1937).

where

V_g = specific volume of steam ft^3/lb

T = temperature, $°F$

P = pressure, psia

VF = specific volume of water, ft^3/lb

VG = specific volume of steam, ft^3/lb

HF = specific enthalpy of water, Btu/lb

HG = specific enthalpy of steam, Btu/lb

Also used in subroutine TEMP are two equations of state that describe the properties of saturated steam. These equations were also obtained by fitting to data in steam tables. They are:

$$P \cdot VG = 1.34863HG - 1157.716$$

$$P \cdot VG = 0.50662T + 282.4364$$

where the definitions of variables are the same as before.

III.I. EMERGENCY CORE COOLING SYSTEM (ECCS) MODEL

In the MARCH modeling, 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. It is possible to have up to 9 different injection rates and starting and stopping times for the pumps.

The input from cards for the ECCS operation include the mass, temperature, and the pressure of water in the three tanks, nominal flow rates, pressure set points, and starting and stopping times for each set of pumps. The fraction, ECCRC, of RWST mass at which the ECCS pump suction switches from the RWST to the sump is also input. After this time, the ECCS water is chilled by an ECCS heat exchanger (see Section III.j), 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:

$$W = A \sqrt{P - PVSL} \qquad (III.I.1)$$

where

$\quad$ W = water injection rate

$\quad$ A = empirical constant

$\quad$ P = pressure in the tank

$\quad$ PVSL = pressure in the reactor pressure vessel

and

$\quad$ P is given by

$$P = \frac{PO}{2.0} \left(1.0 + \frac{WM}{WMO}\right) \qquad (III.I.2)$$

where

$\quad$ PO = initial pressure in the tank

$\quad$ WM = mass of water in the tank

$\quad$ WMO = initial mass of water in the tank.

For transients and small pipe break accidents, when PVSL > P, W = 0. Any remaining water in the accumulator and 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 in the input. The pump flow can be either constant as specified in the input or it can be calculated using a quadratic pump performance curve. The form of the equations used to calculate the pump flow rate is

$$WPUMP_i = WPUMPO_i \sqrt{1 - \frac{\Delta P}{PH_i}}$$

when

$WPUMP_i$ = flow rate for i-th set of pumps

$WPUMPO_i$ = rated flow for a head of $\Delta P = 0$ (input)

PH_i = pressure set point or shutoff head for i-th set of pumps

ΔP = PVSL - PCON

PCON = containment pressure and PVSL is given above.

If the amount of water in the primary system exceeds a certain input specified value, part of the ECC flow is diverted (input option) and is assumed to go directly to the sump.

III.J. RECIRCULATION EMERGENCY CORE COOLING AND RECIRCULATION CONTAINMENT SPRAY HEAT EXCHANGER MODEL

When the Emergency Core Cooling System (ECCS) and the Containment Spray System (CSS) are in the recirculation mode, the ECCS or the CSS pumps take suction from the sump. The pumped water goes through the ECCS or CSS Recirculation Heat Exchanger (RHX), is cooled, and is sent to ECCS or CSS headers. Both ECCS and CSS RHX's are modeled the same way except in different subroutines. The ECCS RHX is modeled in subroutine ECCHX and the CSS RHX is modeled in subroutine CSHX.

Figure III.J.1 is a flow chart of subroutine ECCHX. When the subroutine ECCHX is first called from subroutine MACE, the following input parameters are available to it in a COMMON from the subroutine INPUT:

QR = rated heat exchanger capacity
WPR = rated primary side flow rate
WSR = rated secondary side flow rate
$TP1R$ = rated primary side inlet temperature
$TS1R$ = rated secondary side inlet temperature.

From these input parameters, the rated primary and secondary side outlet temperature, TP2R and TS2R, respectively, are calculated by

$$TP2R = TP1R - QR/WPR/C_p \tag{III.J.1}$$
$$TS2R = TS1R + QR/WSR/C_p \tag{III.J.2}$$

where C_p is the heat capacity of water at constant pressure.

The effective heat transfer coefficient times the heat transfer area between the primary and the secondary at rated conditions, $(h \cdot A)_{effR}$ is given by

$$(h \cdot A)_{effR} = \frac{QR}{DTLN} \tag{III.J.3}$$

where DTLN is the log-mean temperature difference and is given by

$$DTLN = \frac{(TP1R - TS2R) - (TP2R - TS1R)}{ALOG \left(\frac{TP1R - TS2R}{TP2R - TS1R} \right)} \tag{III.J.4}$$

assuming once-through counter-current heat exchanger.

During the subsequent calls to subroutine ECCHX, the effective h·A is calculated from

$$(h \cdot A)_{eff} = (h \cdot A)_{effR} \left(\frac{WP}{WPR}\right)^{0.8} \qquad (III.J.5)$$

where WP is the primary flow rate at present conditions.

Knowing the $(h \cdot A)_{eff}$, the primary and the secondary inlet temperatures and flow rates, the primary outlet temperature is calculated in an iterative manner by matching up the primary to secondary heat transfer with the sensible heat changes in the primary and the secondary flow.
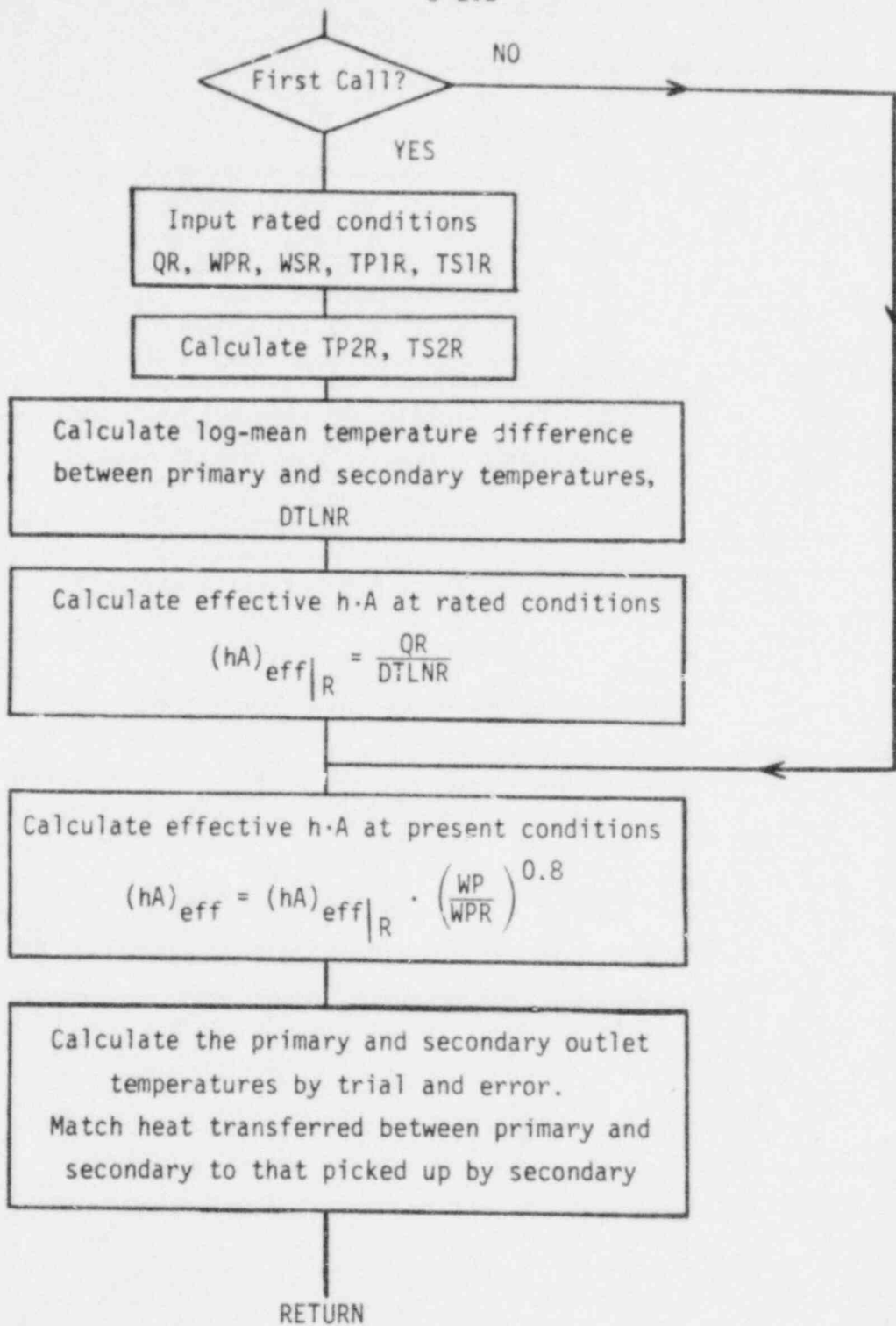
FIGURE III.J.1. RECIRCULATION EMERGENCY CORE COOLING SYSTEM
HEAT EXCHANGER MODEL FLOW CHART

III.K. TIME-STEP CONTROL MODEL

In the MARCH code, the calculations are done in a step-wise
fashion over finite timesteps. There are usually two concurrent time-
steps. One is used by the source routines INITIAL, BOIL, HEAD, HOTDROP,
and INTER in calculating the mass and enthalpy input rates to the con-
tainment. This timestep is also called the MARCH timestep. The other
timestep is used in subroutine MACE and its associated subroutines in
calculating the containment's response to source terms provided by the
source routines. The MACE timestep is either less than or equal to the
MARCH timestep and there are always an integral number of MACE timesteps
in a MARCH timestep. the MACE timestep is automatically set by the code.
The user can control the MARCH timestep during some stages of the accident.

During the blowdown stage of a large LOCA, the MARCH timestep
is supplied by the user as parameter DTINIT in NAMELIST NLMAR.

The MARCH timestep when the subroutine BOIL is the source routine
is set in the MARCH main program before every call to BOIL. At the first
call, the timestep is always 0.001. At subsequent calls, it is set to a
value between 0.001 minutes and 10.0 minutes depending on the type of
the reactor, the type of the accident, and whether the containment has failed,
or the hydrogen is burning in the containment. For most cases, this timestep
is 1.0 minute. It can, however, be changed in subroutine BOIL if (1) it exceeds
a maximum timestep specified by the user (input arrays TSCT(4) and TSB(4) in
NAMELIST NLBOIL), (2) the break area changes (in which case it is set equal
to 0.001 minute for the next timestep), and (3) the power level is read in
from card input (in which case the timestep has to be less than the input
parameter DTK which is read in NAMELIST NLBOIL). For small pipe break LOCA's
the timestep is calculated in PRIMP.

During the time when subroutine HEAD is the source routine, the
MARCH timestep is reset before every call to HEAD in the main program MARCH.
The timestep is usually 2.0 minutes, however, it could be smaller if the
accident is a small LOCA, or the containment has failed and the sump is
boiling, or if there has been hydrogen burning in containment.

During HOTDROP calculations, the MARCH timestep is again set in the main program before every call to HOTDROP. It could be between 0.02 min and 10. min, however, for most conditions, it is 0.02 min.

The first INTER timestep is user specified (usually 0.5 sec). The rest of the time it is calculated in INTER depending on how fast things are advancing and it is in the range of 0.5 sec to 10.0 sec. The number of INTER timesteps per MARCH timestep is user controlled.

Using the mass and enthalpy input rates provided by the current source code and the mass and enthalpy loss rates calculated in the previous timestep, the MACE subroutine estimates what the thermal and hydraulic conditions in all compartments in the containment would be at the end of a small timestep DTO. A new MACE timestep DTX is then determined such that in one timestep:

     (1)   the total enthalpy in any compartment does not change by more than 20%,

     (2)   the pressure in any compartment does not change by more than 20%,

     (3)   the change in the total enthalpy in any compartment due to hydrogen burns is not more than 10%,

     (4)   the change in the total enthalpy in any compartment due to heat losses to walls and structures is not by more than 10%.

The calculations in the MACE package are repeated until the sum of MACE timesteps is equal to the current MARCH timestep.

IV.   INPUT GUIDE

All card input to the MARCH code is read in one subroutine
named INPUT, edited and printed back by formated print statements be-
fore the start of calculations.

Except for a couple of title and name cards containing hollerith
character information, all input is in namelists. There are 13 namelists.
Each namelist is associated with one subroutine. The titles of the name-
lists and the subroutines to which they relay information are given in
Table IV.1.

Namelists NLMAR through NLINTR are read from Unit No. 5 in the
same order as they are listed in Table IV.1.   Namelist CHANGE and the
one data card preceding the namelist CHANGE are read from Unit No. 4.   One
data card precedes namelist NLMAR and contains the title information to be
used in the output. There are also three data cards between namelists
NLINTL and NLSLAB. The first of these cards contains the names of the
materials in the slab heat sinks in the containment and the other two
contain the names of the slabs. These names are used in the output to
label data for easy identification.

Table IV.2 gives a detailed description of the input to the
MARCH code. It lists the names and the descriptions of the variables
in each namelist and shows the values that are assigned to those vari-
ables by default if they are omitted from namelist input.

The code accepts input either in British or SI units. The IU
parameter in the namelist NLMAR indicates which set of units is being
used. The list in Table IV.2 also gives the units that are assigned to
each variable in the input. The first of the two units given is used if
the input is in British units and the second one is used if the input is
in SI units.

A sample input for the case of a large LOCA in a BWR with no
ECC injection is given in Appendix A. The units used are SI units.

TABLE IV.1 THE NAMELISTS IN MARCH INPUT AND THE SUBROUTINES
THAT THEY SUPPORT

Namelist	Subroutine	Short Description of Subroutine
NLMAR	MARCH (Main routine)	Main program
NLINTL	INITIAL	Initial blowdown input to MACE
NLSLAB	SLAB	Slab heat sinks in containment
NLECC	ECC	Emergency core cooling (ECC) system
NLECX	ECCHX	ECC heat exchanger
NLCSX	CSHX	Containment spray heat exchanger
NLCOOL	COOL	Building cooler
NLMACE	MACE	Containment response
NLBOIL	BOIL	Primary system response
NLHEAD	HEAD	Vessel bottom head meltthrough
NLHOT	HOTDROP	Debris-water interaction in the reactor cavity
NLINTR	INTER	Concrete floor meltthrough
CHANGE	RSTART	Stopping and restarting the problem, cataloging files

TABLE IV.2   DESCRIPTION OF INPUT TO MARCH

Title Card (8A10)				Default
Namelist NLMAR Variables				Value

ITRAN   = 0   large pipe LOCA   0

           = 1   transients* and small pipe LOCA

           = 2   transients (ECCS recirculation is operable in subroutines HOTDROP and INTER)

IBRK   = 1   small pipe LOCA (ABRK > 0 in namelist NLBOIL)   0

          = 0   otherwise

ICBRK   = 0   ECR, CSR and cooler fail when containment fails   0

          = 1   ECR, CSR and cooler do not fail when containment fails

**ISPRA   = 1   containment spray works   1

          = 0   containment spray does not work

**IECC   = 0   no ECC   2

          = 1   injection of saturated water (at vessel pressure)

          = 2   injection of water at actual ECC temperature

ICE   = 1   ice condenser containment   0

          = 0   otherwise

NPAIR   =   Number of time entries of data in subroutine INITIAL   0
for initial blowdown to containment 2<NPAIR≤20

          = 0   no blowdown - subroutine BOIL calculations start immediately

NINTER   =   number of INTER time steps per MACE calculation   60

IXPL   = 0   no in-vessel steam explosion   0

          = 1   in-vessel steam explosion fails containment and vessel when FCM ≥ FDROP (See namelist NLBOIL for definition of FDROP, and FCM is fraction of core melted)

IBURN   = 0   no hydrogen burn calculation   -1

          = -1   call subroutine BURN but do not actually burn the hydrogen, calculate adiabatic burn pressure

          = 1 to 6 (or 11 to 16) selects NUPLACE at which hydrogen burns start to occur as follows:

NUPLACE	Subroutine
1	INITIAL
2	BOIL
3	--------
4	HEAD
5	HOTDROP
6	INTER

For IBURN = 1-6, all hydrogen is burned, for 11-16, hydrogen burns only in flammable compartments

---

*   For transients with ITRAN = 1, ECCS is assumed to fail when the bottom head dry-out first occurs.

**   Negative values trigger failure when recirculation starts.

Default
Value

TBURN =   length of hydrogen burn, min (sec)   .01

H2HI   =   ignition point for hydrogen burning, volume fraction   .04

H2LO   =   lower limit for hydrogen burning, volume fraction   0

IPDTL   Print control parameter   0

        = 0 Regular printout

        = 1 Detailed printout from MACE

        = 2 Detailed printout from BOIL

        = 3 not used

        = 4 Detailed printout from HEAD

        = 5 Detailed printout from HOTDROP

        = 6 Detailed printout from INTER

        = 7 Detailed printout

Note: Regular printout is automatically included in options 1-7.

IPDEF   Print control parameter   0

        = 0 Definitions of output variables are not given

        = 1 Definitions of output variables from MACE are given

        = 2 Definitions of output variables from BOIL are given

        = 3 not used

        = 4 Definitions of output variables from HEAD are given

        = 5 Definitions of output variables from HOTDROP are given

        = 6 Definitions of output variables from INTER are given

        = 7 Definitions of all output variables are given

IPLOT   is used to catalog data later to be plotted by plot routine   0

        = 0 No plot data is cataloged

        = 1 BOIL data is cataloged

        = 2 MACE data is cataloged

        = 3 Both BOIL and MACE data are cataloged

IU   Designates units to be used in input and output from the
the following table: 0

IU	Input Units	Output Units
0	British	British
1	SI	British
2	SI	SI
3	British	SI

For negative IU, the TAPE7 output is British (for compatability
with CORRAL)

			Default Value

ICKV   = 0   the check valve does not fail*   0

       = 1   check valve failure, direct leakage to outside

       = -1   check valve failure, leakage to an auxilliary building

IFPSM   = 1   small melt release   2

       = 2   best estimate melt release

       = 3   large melt release

IFPSV   = 1   small vaporization release   2

       = 2   best estimate vaporization release

       = 3   large vaporization release

VOLC   total containment volume, ft^3 (M^3) 2×10^6

DTINIT   time step size used in subroutine INITIAL, min (sec)   0.02

TIME   time at start of problem in MARCH, min (sec)   0.0

TAP   time at power, min (sec) 1.0512×10^6

Namelist NLINTL Variables

Initial blowdown input to containment. Note: BOIL calculations start immediately for NPAIR = 0. The blowdown fluid may be either "steam" or "water", or a mixture of steam and water.

For the following arrays

I = 1, NPAIR where NPAIR $\leq$ 20

T(I)   =   time, min (sec) (T(1) must be 0.0)   20 * 0.0

W(I)   =   mass flow rate, lb/min (kg/sec)   20 * 0.0

EW(I)   =   specific enthalpy, Btu/lb (J/kg)   20 * 0.0

Before reading next NAMELIST, insert three name cards for materials and slabs

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* The check valve separates the high pressure primary system from the low pressure ECCS.

Card 1 Material Names (8A10)
  IMAT(I), I = 1,5

Card 2 Slab Names, Slabs 1 to 8 (8A10)
  ISLAB(I), I = 1,8

Card 3 Slab Names, Slabs 9 to 15 (8A10)
  ISLAB(I), I = 9,15

Card 3 must be present even if less than 9 slabs
used, in which case leave blank.

Namelist NLSLAB Variables*

Data for Containment Slab Heat Sinks

NMAT	=	number of materials in the slabs (≤ 5)	0
NSLAB	=	number of slabs (≤ 15)	0

For following three data input, NM is the material
number, $1 \leq NM \leq NMAT$

DEN(NM)	=	density of material, lb/ft^3 (kg/M^3)	0.0
HC(NM)	=	heat capacity, Btu/lb/F (J/kg/K)	0.0
TC(NM)	=	thermal conductivity, Btu/hr/ft/F (W/M/K)	0.0

For the following ten data input NS is slab number,
$1 \leq NS \leq 15$ (See also Footnote on slab data)

NOD(I)	=	node numbers for temperature output to TAPE11, I=1,5; NOD(I) $\leq$ NN

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* Footnotes on slab data:
  1. Total number of nodes, NN $\leq$ 200
  2. SAREA(NS) is the area of one face of a slab. Slabs with temperature distributions having midplane symmetry may be modeled with DTDX = 0, SAREA = twice area of one face, and X(NN) are just half of actual nodes.
  3. Heat transfer to material in the ice baskets of an ice condenser containment is neglected until all the ice is melted. Ice basket material must be the last slab data entered with TEM(NN) = 20 F.(266.5 k)
  4. Materials are numbered (MAT1 and MAT2) according to the order in which their properties are given by DEN(NM), HC(NM) and TC(NM).
  5. The coordinate of the first node in each slab is 0.0.
  6. For one-region slabs, enter IVR = IVL, NNO2 = 0, MAT2 = MAT1.

			Default Value
IVL(NS)	=	Containment volume number for slab left boundary	0
IVR(NS)	=	Containment volume number for right boundary	0
NNO1(NS)	=	number of nodes in left material region	0
NNO2(NS)	=	number of nodes in right material region	0
MAT1(NS)	=	material number in left region	0
MAT2(NS)	=	material number in right region	0
SAREA(NS)	=	slab heat transfer area, ft^2 (m^2)	0.0
HIF(NS)	=	interface heat transfer coefficient for 2-material slab, $Btu/hr/ft^2/F(W/M^2/K)$, HIF = 0, for 1-material slab	0.0
DTDX(NS)	=	0.0 for an insulated right hand boundary	0.0
	=	1.0 otherwise	
*X(NN)	=	node coordinates measured from left boundary of each slab, ft. (m)	0.0
*TEMP(NN)	=	initial node temperatures, F(K)	0.0

Namelist NLECC Variables

PUHIO	=	initial pressure of upper head injection (UHI) tank, psia(Pa)	0.0
**UHIO	=	initial mass of water in UHI, lb (kg)	0.0
PACMO	=	initial accumulator pressure, psia (Pa)	0.0
**ACMO	=	initial mass of water in accumulator, lb (kg)	0.0
TMHH	=	time for start of high head pumps, min (sec)	0.0
***PHH	=	pressure set point for high head pumps, psia (Pa)	0.0
***WHH1	=	nominal flow rate of high head pumps, gpm (m^3/sec)	0.0
TMSIS	=	time for start of safety injection pumps, min (sec)	0.0
PSIS	=	pressure set point for safety injection pumps, psia (Pa)	0.0
***WSIS1	=	nominal flow rate of safety injection pumps, gpm (m^3/sec)	0.0
TMLH	=	time for start of low head pumps, min (sec)	0.0
PLH	=	pressure set point for low head pumps, psia (Pa)	0.0
***WLH1	=	nominal flow rate of low head pumps, gpm (m^3/sec)	0.0

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* The nodes are stacked; e.g., X(1)...X(NNO1(1) + NNO2(1)) for slab 1, X(NNO1(1) + NNO2(1) + 1)...X(NNO1(1) + NNO2(1) + NNO1(2) + NNO2(2)) for slab 2, etc.

** The remaining accumulator water (ACM + UHI) is added to the reactor cavity when the head fails.

*** Negative WHH1 triggers use of pump performance curve with WHH1 = (-) maximum flow, PHH = shutoff pressure. Likewise for WSIS1 and WLH1.

			Default Value
NP	=	number of additional ECC pumps beyond High Head (HH), Safety Injection System (SIS), and Low Head (LH) pumps, $0 \leq NP \leq 6$.	0
TM(I)	=	start time for extra ECC pumps, min(sec)	10^6
STP(I)	=	stop time for extra ECC pumps, min (sec)	10^6
P(I)	=	shutoff head for extra ECC pumps, psia (Pa)	0.0
WEC(I)	=	injection rate for extra ECC pumps, gpm (m^3/sec)	0.0
STPHH	=	stop time for HH pumps, min (sec)	10^6
STPSIS	=	stop time for SIS pumps, min (sec)	10^6
STPLH	=	stop time for LH pumps, min (sec)	10^6
RWSTM	=	mass of water in refueling water storage tank, lb(kg)	3.0×10^6
ECCRC	=	fractional value of RWSTM to start ECC recirculation	0.0
CSPRC	=	fractional value of RWSTM to start spray recirculation (and stop spray injection from RWST)	0.0
DTSUB	=	subcooling (DTSUB = TSAT - TSUMP) at which recirculation pump cavitation occurs, F(K)	100.0
WTCAV	=	minimum sump mass to avoid pump cavitation, lb(kg)	100.0
TUHI	=	upper head injection water temperature, F (K)	100.0
TACM	=	accumulator water temperature, F (K)	100.0
TRWST	=	refueling water storage tank temperature, F (K)	100.0

Default
Value

Namelist NLECX Variables

EQR	=	rated ECC heat exchanger capacity, Btu/hr (W)	0.0
EWPR	=	rated ECC primary side flow rate, lb/min (kg/sec)	0.0
EWSR	=	rated ECC secondary side flow rate, lb/min (kg/sec)	0.0
ETP1R	=	rated ECC primary side inlet (hot) temperature, F(K)	0.0
ETS1R	=	rated ECC secondary side inlet (cold) temperature, F(K)	0.0

Namelist NLCSX Variables

SQR	=	rated containment spray heat exchanger (CSHX) capacity, Btu/hr (W)	0.0
SWPR	=	rated CSHX primary side flow rate, lb/min (kg/sec)	0.0
SWSR	-	rated CSHX secondary side flow rate, lb/min (kg/sec)	0.0
STP1R	=	rated CSHX primary side inlet (hot) temperature, F (K)	0.0
STS1R	=	rated CSHX secondary side inlet (cold) temperature, F(K)	0.0

Namelist NLCOOL Variables

JCOOL	=	number of the containment volume which contains the cooler	0
	=	0, no cooler	
CQR	=	rated capacity, Btu/hr (W)	0.0
CWPR	=	rated fan flow rate, cu ft/min (m^3/sec)	0.0
CTPR	=	rated cooler inlet air temperature, F (K)	0.0
CWSR	=	secondary flow rate, lb/min (kg/sec)	0.0
CTSR	=	secondary water temperature, F (K)	0.0
TCOOL	=	time to start cooler, min (sec)	0.0

Note: The following four entries are for an additional containment cooler that turns on and off automatically on containment pressure.

NCOOL	=	number of the containment volume which contains the cooler	0
QRCOOL	=	capacity (constant), Btu/hr (W)	0.0
PCOOL	=	cooler on for P > PCOOL, psi (Pa)	0.0
POFF	=	cooler off for P < POFF, psi (Pa)	0.0

Default
Value

Namelist NLMACE Variables

NCUB	=	number of containment volumes, (NCUB $\le$ 8)	1
NRPV1	=	containment volume which receives initial primary system boiloff	1
NRPV2	=	receiver volume after bottom head failure; negative bypasses BWR pressure suppression after head failure; if over 100, bypassed in INTER	1
*ICECUB	=	volume number of ice bed	0
	=	0 no ice bed	
	=	-1 for a BWR	
PO	=	initial containment pressure, psia (Pa)	14.7
FALL	=	fraction of non-flashed blowdown water falling directly to floor	0.7
HMAX	=	maximum atmosphere-wall condensing heat transfer coefficient, $Btu/hr/ft^2/F$ ($W/m^2/K$)	280.0
DTO	=	initial MACE time step size, min (sec)	0.05
DTS	=	stop time for calculation, min (sec)	5000.0
DTPNT	=	MACE output data is printed every DTPNT minutes(sec)	10.0

Note: Variables IDRY thru WVMAX are for a BWR only

IDRY	=	dry well volume number, negative vaporizes sump into both wet well and dry well	1
IWET	=	wet well volume number	2
IBETA	=	1 for a steam explosion in the reactor cavity	0
	=	0 no explosion	
WPOOL	=	mass of water in pressure suppression pool, lb (kg)	0.0
TPOOL	=	temperature of pool, F (K)	0.0
DCF	=	pool decontamination factor, DCF $\ge$ 1	100.0
VDRY	=	maximum water volume in dry well before overflow to wetwell, $ft^3 (m^3)$	0.0
VTORUS	=	total (water + air) wet well volume, $ft^3 (m^3)$	0.0
WVMAX	=	when the primary water inventory (WMTOT) exceeds WVMAX, the ECC pump flow is reduced to maintain WMTOT = WVMAX; skipped if WVMAX = 0, lb (kg)	0.0
WICE	=	mass of ice in ice bed, lb (kg)	0.0
TICE	=	temperature of ice [20 F (266.5 K) required]	20.0
TWTR	=	temperature of water draining from ice bed during blowdown, F (K)	190.0

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* For an ice condenser containment, use NCUB=ICECUB=2 and NRPV1=1.

			Default Value
TWTR2	=	temperature of water draining from ice bed during boiloff phase, F (K)	130.0
TSTM	=	temperature of air-steam mixture exiting top of ice bed, F (K)	105.0
DCFICE	=	decontamination factor for halogens and particulates flowing through ice bed, DCFICE $\geq$ 1	100.0
NSMP	=	initial containment sump volume number. (For negative NSMP, water does not drain into a common sump)	1
NSMP2	=	containment sump volume number after bottom head failure	1
WVMAKS	=	when the primary water inventory (WMTOT) exceeds WVMAKS, the ECC injection to the vessel is reduced and the overflow to the sump increased so that WMTOT is held constant at WVMAKS; skipped if WVMAKS = 0 or the accumulators are not empty, lb (kg)	0.0
NCAV	=	0, reactor cavity does not fill.	0.0
	=	containment volume which contains reactor cavity, NCAV = NSMP for PWR; read values for next three variables	
	=	negative, cavity does not refill during HOTDROP.	
VCAV	=	maximum water volume of reactor cavity, ft^3 (m^3)	0.0
VFLR	=	maximum water volume on floor before overflow to reactor cavity, ft^3 (m^3)	0.0
FSPRA	=	fraction of spray falling into reactor cavity	0.0
IVENT	=	0, skip containment venting	0.0
	=	integer JK, volume J will vent into a suppression pool in initially isolated volume K. (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.	
TVNT1	=	core exit temperature flag initiating transfers from volume J to volume K. Negative TVNT1 initiates transfers from J to K when the pressure in J exceeds $|TVNT1|$.	0.0
TVNT2	=	core exit temperature flag initiating primary system depressurization directly into th suppression pool (if present) in volume NRPV2, F (K).	0.0
AVBRK	=	flow area for vent, ft^2 (m^2)	0.0
CVBRK	=	vent orifice coefficient	0.0
VC(I)	=	compartment volume, ft^3 (m^3), (I = 1, NCUB)	0.0
AREA(I)	=	compartment floor area, ft^2 (m^2), (I = 1, NCUB)	0.0
HUM(I)	=	initial relative humidity in compartment (I = 1, NCUB)	0.5
TEMPO(I)	=	initial compartment temperature, F(K), (I = 1,NCUB)	100.0

Default
Value

The following 8 sets of data entries are "Event" data, used to turn on sprays, fans, set containment failure pressure, etc.

N = number of "events" $0 < N < 10$ 0

In the following entries L goes from 1 to N

NS(L) = event initiating parameter index   0

= 1, time,

= 2, pressure,

= 3, temperature,

(NOTE: negative 2 or 3 initiates on declining pressure or temperature)

NC(L) = volume number in which event occurs. (For an inter-compartment fan, NC is the receiver volume)   0

NT(L) = event type index   0

= 1, spray (NT(L) = -1 if the recirculation spray is a separate "event" or system)

= 2, heat removal system

= 3, steam source

= 4, hydrogen source

= 5, carbon dioxide source

= 6, carbon monoxide source

= 7, containment failure or containment venting (-7 holds pressure at 14.7 psia after initial depressurization for a containment failure)

= 8, inter-compartment fan

C1(L) = event initiating parameter switch value   0.0

NS(L) = 1, C1(L) = time, min (sec)

NS(L) = 2, C1(L) = pressure, psia(Pa), (negative for decreasing switch) (For a containment vent event, C1(L) is the opening pressure for the vent)

NS(L) = 3, C1(L) = temperature, F (K), (negative for decreasing switch)

C2(L) = event constant   0.0

NT(L) = 1, C2(L) = spray flow rate, gpm (m^3/sec)

NT(L) = 2, C2(L) = heat removal rate, Btu/min (W)

NT(L) = 3, C2(L) = steam input rate, lb/min (kg/sec)

Default
Value

NT(L) = 4, C2(L) = hydrogen input rate, lb/min (kg/sec)

NT(L) = 5, C2(L) = CO_2 input rate, lb/min (kg/sec)

NT(L) = 6, C2(L) = CO input rate, lb/min (kg/sec)

NT(L) = 7, C2(L) = orifice coefficient to containment break

NT(L) = 8, C2(L) = fan flow rate, ft^3/min (m^3/sec)

C3(L)   = event constant   0.0

NT(L) = 1, C3(L) = spray temperature, F (K)

NT(L) = 2, C3(L) = 0.0

NT(L) = 3, C3(L) = steam enthalpy, Btu/lb (J/kg)

NT(L) = 4, C3(L) = hydrogen temperature, F (K)

NT(L) = 5, C3(L) = CO_2 temperature, F (K)

NT(L) = 6, C3(L) = CO temperature, F (K)

NT(L) = 7, C3(L) = containment break area, ft^2 (m^2)

NT(L) = 8, C3(L) = fan source volume number

C4(L)   = event constant   0.0

NT(L) = 1, C4(L) = spray drop diameter, microns (m)

NT(L) = 2, C4(L) = 0.0

NT(L) = 3, C4(L) = 0.0

NT(L) = 4, C4(L) = 0.0

NT(L) = 5, C4(L) = 0.0

NT(L) = 6, C4(L) = 0.0

NT(L) = 7, C4(L) = 0.0 or >0.0 [C4(L) > 0 is the closing pressure for the containment vent, psia (Pa)]

NT(L) = 8, C4(L) = 0.0

KT(I,J)   = matrix of allowed intercompartment transfer   0
paths where I = source and J = receiver
volumes. (= 0, no transfer permitted; = 1, transfers
allowed)

STPECC   = stop time for all ECC pumps, min (sec) 10^6

STPSPR   = stop time for all containment sprays and building
coolers, min. (sec) 10^6

Default
                                                                    Value

Namelist NLBOIL Variables

NDTM   = number of BOIL time steps to stop problem   100,000

R1   = zone number of innermost radial region, R1 $\geq$ 1   1

R2   = zon‘ number of outermost radial region, R2-R1 $\leq$ 10   10

NNT   = total number of lattice positions in core   0

NR   = total number of fueled rods in core   0

NDZ   = number of axial nodes, NDZ $\leq$ 50 (reduced printout   -24
           for NDZ $<$ 0)

ISTR   = number of heat sinks in exit gas flow   3
           (1 $\leq$ ISTR $\leq$ 4).

ISG   = steam generator heat sink number (2 $\leq$ ISG $\leq$ ISTR)   3

         = 0, no steam generator

           Also, for ITRAN = 1 in PWR, enter ISG = ISTR.
           For a BWR, ISG = 0.

*MELMOD   = 1 for meltdown Model A
                                                                     1
         = 2, meltdown Model B

         = 3, meltdown Model C

IMWA   = 0, no metal-water reaction
                                                                     1
         = 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

ISTM   = 0, steam remains in initial channel   0

         = 1, steam bypasses plugged channels and reacts in
           unplugged channels

           Note: ISTM $\neq$ 0 only for IMWA = 2

IHC   = Zero for no convective heat transfer in molten regions   0

IHR   = 0, neglect rod-to-steam radiation heat transfer   0

         = 1, calculate rod-to-steam radiation heat transfer

NDZDRP   = melted nodes fall from core when node NDZDRP melts   2
           and fraction core melted is greater than FDROP

IMZ   = nodes above node # IMZ are assumed to be partly   100
           preoxidized and melted according to FR and FM
           below

FR   = Fraction of clad above node IMZ that has pre-reacted   0.0

---

* Negative MELMOD continues ECC after core melt starts; if negative,
  it must be input in NAMELIST/CHANGE/as parameter MEL.

Default
Value

FM = Fraction of core material above node IMZ that has   0.0
pre-melted (Fission product source is correspondingly
reduced)

MWORNL = 1, zirconium-water reaction model from ORNL-TM-41   1

= 0, zirconium-water reaction model from BMI-1779

IFP = 0, no fission product loss   2

= 1, original WASH-1400 BOIL fission product loss
model (available in BOIL only)

= 2, fission product loss by CORRAL group number

ISAT = 1, temperature of grid plates in water set equal to   0
initial water temperature in pressure vessel,
(see TGOO below)

= 0, input gridplate temperatures used

IGRID1 = 0, IRGID2 = 0, Grid plate masses not added to   0,1
core debris

IGRID1 = 1, IGRID2 = 0, intermediate debris holdup on
grid number 1.

IGRID1 = 0, IGRID2 = 1, no debris holdup on grid plates

KRPS = 1, power level read from following six variables.   0
= 0, ANS standard decay power is used.

TRPS = for time < TRPS the power level is (1.0 - time/TRPS),   0.0
min (sec)

ANSK = minimum fractional power level used for time < TDK.   0.0
ANSK > ANS decay power

TDK = time at which power level drops to ANS decay power,   0.0
min (sec)

YT, YB = for(unswollen) water levels between YT and YB (YT >   0.0, 0.0
YB), a linear interpolation of the power level
between the maximum of (1 - time/TRPS) and ANSK,
and the ANS decay power is performed, ft (m)

DTK = maximum BOIL time step size, for time <TDK, min(sec)1000.0

ICON = 1, steam condensed in steam generator is added to   0
water in reactor vessel; = 0, condensate is not
refluxed or included in primary water inventory;
= -1, no steam condensation in steam generator.

TMSG1, = Between TMSG1 and TMSG2 the steam generator secondary 10^6, 10^6
TMSG2   pressure decreases from PSG to 100 psia, min(sec)

TPM = two phase flow multiplier used for breaks in liquid   1.0
region

			Default Value

AB(I)   =   break area used for time greater than TB(I),   0.0
              (AB(1)>0., AB(2)...AB(16)$\geq$0.,) ft^2(m^2)   (I = 1,16)

TB(I)   =   break area AB(I) is used for time greater than TB(I), 10^6
              (TB(1) > 0.), min(sec)   (I = 1,16)

TMYBK   =   for time greater than TMYBK the break elevation is   10^6
              YBRK2, min (sec)

YBRK2   =   break elevation used after time TMYBK, ft (m)   1000.0

TMLEG(I) =   time to change YLEG, min (sec). For large YLEG   10^6
              there is no steam generator heat transfer.

              YLEG = initial value, t < TMLEG(1)
              YLEG = 1000 ft (305 m), TMLEG(1) < t < TMLEG(2)
              YLEG = initial value, TMLEG(2) < t < TMLEG(3)
              YLEG = 1000 ft (305 m), t > TMLEG(3)

WDED   =   water left in primary at end of meltdown. dded to   0.0
              containment when head fails, lb (kg).

TPUMP1, =   time to change primary pump power, min(sec)   10^6,10^6
TPUMP2

QPUMP1, =   primary coolant pump power, Btu/hr (W)
QPUMP2   0.0,0.0

              QPUMP = QPUMP1, t < TPUMP1

              QPUMP = QPUMP2, TPUMP1 < t < TPUMP2

              QPUMP = 0, t > TPUMP2

              (For QPUMP > 0, there is no steam generator condensation)

TMUP1,   =   time to change makeup/letdown flow through letdown   10^6,10^6
TMUP2

              cooler, min (sec)

WMUP1,   =   makeup/letdown flow, gpm (m^3/sec)
WMUP2   0.0,0.0

              WMUP = WMUP1, t<TMUP1

              WMUP = WMUP2, TMUP1 < t < TMUP2

              WMUP = WMUP 0, t > TMUP2

              (Program also sets WMUP = 0 for Y < H)

			Default Value
TSCT(I) I = 1,4	=	Time to change the timestep size, min (sec)	10^{10}
TSB(I) I = 1,4	=	TSB(I) is the maximum timestep in BOIL for times > TSCT(I), min (sec)	1.0
TALF1, TALF2	=	Between times TALF1 and TALF2, the void fraction in the level swell model is 1.0	$10^{10}, 10^{10}$
QZERO	=	initial core power, Btu/hr (W)	1.2966×10^7
H	=	active fuel height, ft (m)	12.0
*HO	=	unswollen initial liquid level, ft (m)	0.0
DC	=	core diameter, ft (m)	0.0
ACOR	=	flow area of core, ft^2 (m^2)	0.0
ATOT	=	total water cross section in vessel at core midplane, ft^2 (m^2)	0.0
WATBH	=	mass of water which can be stored in the bottom head, lb (kg)	0.0
D	=	fuel rod diameter, ft (m)	0.0
DF	=	pellet diameter, ft (m)	0.0
DH	=	core hydraulic diameter, ft (m)	0.0
**CLAD	=	clad thickness, ft (m)	0.0
XOO	=	initial zirconium oxide thickness, ft (m)	0.0
***RHOCU	=	ρC_p of core material, $Btu/ft^3/F$ $(J/m^2/K)$	0.0
HW	=	pool boiling coefficient, $Btu/hr/ft^2/F$ $(W/m^2/K)$ (code calculates HW if ITRAN = 1)	300.0
TGOO	=	initial water temperature in pressure vessel, F	280.00
PSET	=	safety relief valve setpoint, psig (Pa)	2450.0

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* BOIL calculates the initial primary inventory, WMTOT, from RHOL*ATOT*HO + WATBH + WDED = WMTOT. Input negative HO for actual level below the core.

** NNT*π*D*CLAD*H*ρ_{ZR} = WZRC in namelist NLHEAD, CLAD includes spacers, end pieces, etc.

*** RHOCU = $\sum_{core} MC_p/(NT* \frac{\pi}{4} D^2 H)$

			Default Value
*CSRV	=	safety relief valve coefficient	0.0
TMELT	=	core melting temperature, F (K)	4130.0
TFUS	=	melting temperature of fuel plus the temperature equivalent of the heat of fusion $(T_{melt}+\lambda/C_p)$, F (K)	5130.0
TFAIL	=	failure temperature of grid number 1, F (K)	706.0
FDROP	=	fractional holdup of melted core before slumping into bottom head starts	0.75
	=	0, for MELMOD = 3	
FCOL	=	minimum fraction core melted for total core collapse	0.75
**FDCR	=	cladding reaction is stopped when total reaction in core and in bottom head exceeds FDCR	1.0

The following five variables must be entered if FDCR < 0; the particles are spheres enclosed by two shells.

DPART	=	Diameter of the particles in the bottom head, ft (m)	0.0
DUO_2	=	Diameter of the UO_2 in the original fuel pellet, normally same as DF, ft (m) enter zero for no UO_2 in particle.	0.0
FZMCR	=	Fraction of Zr metal in the central core of particles	0.0
FZOCR	=	Fraction of ZrO_2 in the central core of particles	0.0
FZOS1	=	Fraction of ZrO_2 in the first outer shell of particles, remaining ZrO_2 (1-FZOCR-FZOS1) is in outside layer	0.0
F12	=	radiation interchange factor between top of core and heat sink above the core	0.445
WFE2	=	mass times specific heat of second radiation heat sink. Used if first iron mass melts, CM(1) is first sink. Btu/F (J/K)	0.0
TFEOO	=	initial temperature of iron heat sink above core, F (K)	280.0
WTRSG	=	initial mass of water in steam generator secondary, lb (kg)	0.0
FULSG	=	mass of water in steam generator secondary when it is full, lb (kg)	0.0
PSG	=	setpoint of steam generator secondary relief valves, psia (Pa)	1000.0
PVSL	=	initial vessel pressure, psia (Pa) (used only if ITRAN = 1)	1000.0
TCAV	=	average core temperature at end of blowdown for large LOCA. Initial fuel temperature for ITRAN = 1, F (K)	1000.0

---

* CSRV = WVENT/$\sqrt{RHOS*PSET}$, where WVENT = rated flow, lb/min (kg/sec) and

RHOS = steam density, lb/ft^3 (kg/m^3)

** If FDCR is a negative number, the fraction is calculated in the code using DPART input.

Default
Value

YLEG = distance between cold leg and bottom of core, ft (m) 16.0

ABRK = area of pipe break, ft^2 (m^2) ($\neq$ 0. only for small LOCA) 0.0

*YBRK = distance between break elevation and bottom of core 0.0
(positive for break above core bottom), ft (m)

DTPNTB = time interval between BOIL print-outs, min (sec) 60.0

DTPN, TPN = BOIL printout interval is changed to DTPN for time 5.0, 10^6
greater than TPN, or when the core uncovers if DTPN
is negative, min (sec)

VOLP = volume of primary system, ft^3 (m^3) 0.0

VOLS = initial primary steam volume, ft^3 (m^3) 0.0

TMAFW = start time for steam generator auxiliary feedwater 0.5
delivery, min (sec)

WAFW = auxiliary feedwater flow, lb/min (kg/sec) 0.0

TAFW = auxiliary feedwater temperature, F (K) 100.0

WCST = mass of water in condensate storage tank, lb (kg) 1.0×10^8

F(I) = axial power peaking factors with I = 1 at the 1.0
bottom of the core, I = 1, NDZ

PF(I) = radial region power peaking factors with I = 1 1.0
at the innermost region, I = 1, R2 - R1+1

VF(I) = fraction of core volume in each radial region, 0.1
I = 1, R2 - R1 +1

The following five data relate to the steam generator
and structures above the core and in exit gas stream,
maximum of four structures permitted, I = 1, ISTR

I = 1 must be first upper gridplate

I = 2,3,4 may be cold leg pipe, steam generator, hotleg
pipe. For ITRAN = 1, must have ISG = ISTR.

TT(I) = initial structure temperature, F (K) 0.0

**CM(I) = mass times heat capacity of structure, Btu/F (J/K) 0.0

AH(I) = heat transfer area, ft^2 (m^2) 0.0

DD(I) = flow equivalent diameter, ft (m) 0.0

AR(I) = flow area, ft^2 (m^2) 0.0

---

* For ITRAN = 1 and ABRK = 0, use HO < YBRK < HO + 1/2 VOLS/ATOT

** For the steam generator, CM should include the water in the secondary.

Default
Value

The following five data relate to the lower gridplates and bottom head. Three structures are required.

I = ISTR+1 is grid immediately below core

I = ISTR+2 is next lower gridplate

I = ISTR+3 is the bottom head

TT(I)	=	initial temperature, F (K)	0.0
CM(I)	=	mass times heat capacity of grid, Btu/F (J/K)	0.0
AH(I)	=	heat transfer area, ft^2 (m^2)	0.0
DD(I)	=	gridplate thickness, ft (m)	0.0
AR(I)	=	distance from bottom of core to gridplate (negative number), ft (m)	0.0

Namelist NLHEAD Variables

WZRC	=	mass of Zircaloy in core, lb (kg)	0.0
WFEC	=	mass of miscellaneous metal in core, lb (kg)	0.0
*WUO2	=	mass of UO_2 in core, lb (kg)	0.0
WGRID	=	mass of grid plates and structures falling into bottom head, lb (kg)	0.0
WHEAD	=	mass of hemispherical section of bottom head, lb (kg)	0.0
TMLT	=	melting temperature of debris, F (K)	4130.0
DBH	=	diameter of bottom head, ft (m)	15.0
THICK	=	vessel wall thickness, ft (m)	0.5
COND	=	thermal conductivity of debris, Btu/hr/ft/l (W/m/K)	8.0

---

* For negative WUO2, debris liquidus temperature is oxide melting point. For positive WUO2, the iron melting point is used.

Default
Value

Namelist NLHOT Variables

IHOT   = 0,1,2,3   0

IHOT controls the initial reactor cavity water temperature
TPOOL and the logic for transfer to subroutine INTER
as follows:

IHOT	No. HOTDROP timesteps	TPOOL
0	to completion	TPOOLH
1	to completion	TSAT
2	2	TPOOLH
3	2	TSAT

For IHOT = 0 or 1, HOTDROP stops boiling water when
when the debris is quenched. For IHOT = 100 or 101,
HOTDROP boiling continues until all water is vaporized.
Transfer to INTER requires minimum debris temperature
of 2500 F.

MWR   = 1, Zr-H_2O reaction rate law is taken from ORNL-TM-41   1

= 0, Zr-H_2O reaction rate law is taken from BMI-1779

DP   = debris particle diameter, inches (m)   2.0
(DP $\leq$ 2 inches)

CON   = debris thermal conductivity, Btu/hr/ft/F (W/m/K)   2.0

FLRMC   = mass times heat capacity of structural metal   1000.0
below the vessel, Btu/F (J/K)

WTR   = initial mass of water in the vessel cavity, lb (kg)   0.0
normally calculated by MARCH. Used if negative.

TPOOLH   = initial temperature of water in the vessel cavity,   100.0
used only for negative WTR, F (K)

Default
Value

Namelist NLINTR Variables

*CAYC	=	thermal conductivity of concrete, W/cm/K	0.01385
*C1 ?	=	specific heat of concrete, J/gm/K	0.996
*DENSC	=	density of concrete, gm/cm^3	2.52
TIC	=	initial temperature of concrete, K	293.0
FC1	=	weight fraction of $CaCO_3$	0.8
FC2	=	weight fraction of $Ca(OH)_2$	0.15
FC3	=	weight fraction of SiO_2	0.01
FC4	=	weight fraction of free H_2O	0.03
RBR	=	rebar, gm per gm concrete	0.112
**RO	=	radius of reactor cavity, cm	0.0
R	=	radius of curvature of bottom of melt, cm	0.0
DT	=	initial time step, sec; later time steps can range from DT to 10 sec.	0.5
TF	=	time at which computation stops, sec	36000.0
TPRIN	=	time for first printout, sec	3600.0
DPRIN	=	interval between printouts, sec	3600.0
HIM	=	interface heat transfer coefficient, metal-concrete; $W/cm^2/K$	0.01
HIO	=	same, oxide-concrete	0.01
FIOPEN	=	fraction of top surface area radiating to water above debris at internal debris temperature	0.5
NEPS	=	number of time/emissivity points $(1 \leq NEPS \leq 10)$	2

TEPS(I) = time at which emissivity changes, sec
I = 1, NEPS; TEPS(1) = initial time

TEPS(1)   = 0.0
TEPS(2)   = 3.6×10^7
TEPS(3to10) = 0.0

EPSI(I) = emissivity at times TEPS(I)
I = 1, NEPS: EPSI(1) = initial emissivity

EPSI(1)   = 0.5
EPSI(2)   = 0.5
EPSI(3to10) = 0.0

---

* CAYC, CPC, and DENSC are measured at moisture content FC4. The weight fractions must be consistent with those given for moisture content FC4. Al_2O_3 fraction is $1 - (FC1 + FC2 + FC3 + FC4)$.

** R"zero".

Default
Value

IWRC   = 0, no reactor cavity water   1

= 1, debris contacts water in reactor cavity and in containment sump (after melt front, DROO equals WALL)

IGAS   = 1, energy of concrete decomposition gases added to   1 reactor cavity water.

= 0, energy of concrete decomposition gases is not added to reactor cavity water

ZF   = depth of penetration at which computation is to   1000.0 stop, cm

WALL   = amount of radial penetration at which sump water   0.001 contacts melt, cm

TAUL   = time constant for fission product loss from   0.5 liquid debris, hrs (0.5 hrs suggested)

TAUS   = time constant for fission product loss from   5.0 solid debris, hrs (5.0 hrs suggested)

The following information is required on a single data card in a (I10, A10, 6A10) format before reading NAMELIST/CHANGE/variables.

ID   = Number of restart, zero for start of problem

ICAT   = Identification used for the catalogued restart file

TITLE   = Title printed out by Program MARCH and used on TAPE7. If the first 10 columns of TITLE are blank, the title preceeding the namelist NLMAR will be used.

Namelist/CHANGE Variables

TRST   = calculations are stopped when accident sequence time   2000.0 reaches TRST min (sec)

PRST   = calculations are stopped when containment pressure   100.0 reaches PRST psia (Pa)

*CPSTP   = Calculations will be stopped when CPU time   180.0 reaches CPSTP, sec.

IS   = Problei is stopped when NUPLACE = IS. See   10 namelist NLMAR for definition of NUPLACE.

IFPM   = same as IFPSM in namelist NLMAR   10

IFPV   = same as IFPVM in namelist NLMAR   10

MEL   = same as MELMOD in namelist NLBOIL   10

FDRP   = same as FDROP in namelist NLBOIL   -1.0

TMX   = same as TMELT in namelist NLBOIL   -1.0

TFX   = same as TFUS in namelist NLBOIL   -1.0

---

* Note the units of CPSTP are always sec.

Default
Value

IHOTX	=	same as IHOT in namelist NLHOT	10
HIMX	=	same as HIM in namelist NLINTR	-1.0
HIOX	=	same as HIO in namelist NLINTR	-1.0
IGASX	=	same as IGAS in namelist NLINTR	10
WALLX	=	same as WALL in namelist NLINTR	-1.0
*PFAIL	=	pressure at which containment fails, psia (Pa)	-1.0
**ACBRK	=	containment break area, ft^2 (m^2)	-1.0
ID	=	RSTART identifier	0

JS = 0, catalog files, stop this execution and reload program for next problem (used to stack runs)   0

  = -1, catalog files, stop this execution

  = +1, catalog files, continue problem execution

IFISH = -1, no output on microfiche   -1

  = +1, microfiche output only

  = 0, microfiche and printed copy

NCT7 = 0, TAPE7 saved on permfile   1

  = 1, TAPE7 not saved

NCRST = 0, Restart file cataloged   1

  = 1, Restart file not saved

  = 2, Restart file not saved unless the problem stops on CPSTP

LST7 = 0, no list of TAPE7 given   0

  = 1, TAPE 7 is listed on output file

IPLOT = Same as in namelist NLMAR. If no entry is made in NLMAR and on restarts, this value of IPLOT is used.   0

---

* Changes C1(L) for NT(L) = 7, in namelist NLMACE.

** Changes C3(L) for NT(L) = 7, in namelist NLMACE.

A Note on Subroutine RSTART in MARCH

The capabilities of the subroutine RSTART include:

- Stopping the execution of the problem when a prespecified limit on accident sequence time, containment pressure, or problem execution time is exceeded
- Cataloging the files created by MARCH
- Restarting the same problem with some different preselected input parameters
- Continuing the execution of the same problem, after it has been stopped, but changing some of the input parameters.

The problem can be restarted as many times as desired. The namelist CHANGE input and the single data card preceding it are repeated as many times as there are restarts.

The variables TRST, PRST, CPSTP, and IS in the namelist CHANGE stop problem execution on accident time, containment pressure, CPU time, and on certain subroutine calls, respectively.[*] The variable JS determines whether the problem is to be stopped, restarted, or continued. The variables IFISH, NCT7, NCRST, and LST7 are output options. Variables IFPM through ACBRK are the variables that can be changed on initial execution or at every restart. When they are assigned the default values shown in Table III.2 (i.e., integers to 10, real variables to -1.0) they have no effect. But when they have values different than the default values, they replace their corresponding variables in other namelists. When the problem is started for the first time, variables IFPM through ACBRK are usually assigned their default values.

To accomplish its objectives, the subroutine RSTART utilizes some internal run control statments that are specific to the system at BCL. They may not be available at other installations. If such is the case, the user could replace RSTART with a subroutine with the same name whose function is to CALL EXIT and stop the execution of the problem. In this case, variables IFPM through IPLOT in namelist CHANGE would be assigned their default values, and files, if desired, would need to be saved by explicit catalog statements external to the program. Also, it would be necessary to include in the code, one small subroutine called SECOND, which returns current CPU time as its only formal parameter every time it is called. If this is not possible, subroutine SECOND should be made to return zero as its formal parameter, and CPSTP in namelist CHANGE should be defaulted to a large value and it should not be used to control problem execution.

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[*] Note that the user can also stop the problem with input variables DTS, NDTM, and TF and ZF in namelists NLMACE, NLBOIL, and NLINTR, respectively. 200 HOTDROP calls will also stop problem.

V. DESCRIPTION OF MARCH OUTPUT

The first part of the output is a list of all the input para-
meters including those that have defaulted. The input parameters are
grouped according to subroutine names in which they are used or accord-
ing to functional systems such as emergency core cooling (ECC) systems,
ECC recirculation heat exchanger, spray recirculation heat exchanger,
etc.

Next, the units used in that particular output are listed. The units
are either British or SI. The units employed in the output are independent
of those used in the input. Therefore, it is possible to input data to the
code in one set of units and obtain output in the other.

After listing the units used in the output, one can print the defini-
tion of the output variables from MACE, or BOIL, or HEAD, or HOTDROP, or
INTER, or from all subroutines by setting the IPDEF to the appropriate option
in namelist NLMAR in input. Along with the definitions, the units used for
each output variable are also given. There are two units listed. The first
one is used if the output is in British units and the second one is used if
the output is in SI units.

Next, the initial conditions in the containment building compart-
ments are given.

If the accident is a large Loss Of Coolant Accident (LOCA), what
follows is the subroutine INITIAL output giving the mass flow rate and
enthalpy of the initial blowdown fluid into containment bulding. Next,
the containment building response is calculated and printed as output from
subroutine MACE. The initial blowdown input to containment and the con-
tainment response calculations are done over small time steps. Therefore,
the outputs from subroutines INITIAL and MACE are repeated after every time
step until the completion of the initial blowdown stage of the accident.

If the accident is not a large LOCA or if the initial blowdown stage
has been completed in case of a large LOCA, the ouput from the primary system
analysis code, BOIL, is given next. Any leakage from the primary system into
the containment building is calculated in BOIL, and provides the input for the
containment response analysis calculations performed in subroutine MACE. The

frequency with which the BOIL and MACE outputs are printed during this stage of the accident is input controlled, however. The output from BOIL is printed every DTPNTB minutes and the output from MACE is printed every DTPNT minutes where DTPNTB and DTPNT are input variables in namelists NLBOIL and NLMACE, respectively. When the core starts to melt and slump to the bottom head, the core slump parameters from BOIL are printed at every time step, and those nodes that have melted and slumped to the bottom head are assigned node temperatures of 225.4°K (0°F) and the steam temperature in those nodes are arbitratily set to 273.15°K (32.0°F) in the regular BOIL output unless WDED > ∿100 lb.

If the concentrations of hydrogen, oxygen, and steam are in the flamability region, hydrogen may be burned. The timing of the hydrogen burn is controlled by the IBURN parameter in namelist NLMAR in input.

After the BOIL calculations have been completed, the debris starts to melt the pressure vessel bottom head and the control is transferred to subroutine HEAD. During the process of vessel head melt-through, the subroutine HEAD and MACE outputs are given alternately after every time step.

After the bottom head has failed, the debris is assumed to fall to the containment floor and to react with any water in the reactor cavity. During this time, the subroutine HOTDROP is active along with the subroutine MACE and the outputs from these subroutines are given for each time step in the calculations.

During HEAD and HOTDROP operation, the output from the MACE subroutine is shortened unless the time happens to fall within the interval specified by the DTPNT input parameter in namelist NLMACE and IPDTL has been set to either 1 or 7 in namelist NLMAR in input.

After the reactor cavity water has been evaporated, the subroutine INTER calculations start. If the IHOT parameter in the namelist NLHOT has been set to 2 or 3, the INTFR calculations start after the 2nd call to HOTDROP.

As it is for BOIL and MACE, the frequency with which the INTER output is printed is also controlled by an input parameter, namely DPRIN in namelist

NLINTR. The units in the INTER output have been left the same as they were in the original INTER program as written by Sandia Laboratories. The units are based on cm as the unit of length, gram as the unit of mass, and second as the unit of time. The power unit is watt and temperatures are given in degree Kelvin.

The last table printed in the output is a summary table. It gives a short description of the case under consideration. For example, it tells what kind of reactor is being considered, the type of accident, and whether safety systems are assumed operable or not. It lists the important events during the accident, such as when the safety systems turned on and off (if they are assumed operable), when the core starts to uncover and melt, when it slumps to the bottom head, when the calculations are transferred from BOIL to HEAD, from HEAD to HOTDROP, etc. It also gives the primary system and the containment pressures, debris mass and temperature, fraction clad reacted, sump mass and temperature if they are defined at the time when the particular event takes place.

Sample MACE, BOIL, HEAD, HOTDROP, and INTER outputs are given in Appendix B in Tables B.1 - B.5, respectively. These outputs are from a large LOCA case in a BWR assuming no ECC system is operative and the containment sprays do not come on line until 100 minutes after the accident has started.

VI. MARCH CODE CHARACTERISTICS

The MARCH code is at present operational on the Control Data Corporation's (CDC) CYBER 73 and CYBER 74 computer systems at Battelle's Columbus Laboratories. The code is written in FORTRAN EXTENDED. Using the FTN version 4.6 compiler it takes about 80 seconds to compile on the CYBER 74 machine and about 120 seconds on CYBER 73. The core memory space required to run the code on these computers is about 214 K (octal) words. The execution times for the code depend on the problem being investigated. However, as an example, for a large LOCA in a BWR with no ECC operation, it takes about 100 seconds execution time on CYBER 74 (240 seconds on CYBER 73) to carry the accident sequence through subroutines INITIAL, BOIL, HEAD, HOTDROP, and into INTER with about 150 cm (or 10 hrs) of concrete melt at an accident time of 680 min. The source deck for the code consists of about 10,000 card images.

VII. MARPLT: A PROGRAM TO PLOT THE RESULTS FROM THE MARCH CODE

The MARPLT program is used to plot on a Calcomp plotter the data that are generated by the MARCH code. Those results from the BOIL and MACE subroutines in the MARCH code that can be plotted are stored on files. Later, those files are attached to the run in which MARPLT is to be executed. The file that contains the data from BOIL is attached to the run with a logical unit #9, and that from MACE is assigned to the unit #11. The data specifying the number and type of plots desired and the title information on the plots are input to the program on cards. Table VII.1 shows the structure of the card input data deck. As can be seen from Table VII.1, plots can be made with multiple curves (up to 5 curves per plot frame). Axis titles and minimum and maximum values on each axis can be specified or the program can use default titles or calculate the minimum and maximum values from the data. The data set numbers that are required on card 3(a) in Table VII.1 and the parameters that are plotted in correspondence with those numbers are given in Tables VII.2 and VII.3 for MACE and BOIL data, respectively.

The MARPLT program utilizes the DISSPLA graphics package distributed by the Integrated Software Systems Corporation[18] and uses the extended core storage facility on CDC computer systems.

Examples of plots obtained using the MARPLT program are given in Appendix C. These plots are for a large LOCA in a BWR. Figure C.1 shows the maximum core temperature and the average core temperature as a function of time after the accident. Figure C.2 shows the fraction of core melted (using the meltdown model A in MARCH) as a function of time. These two plots are from BOIL output data. The figures C.3 and C.4 give the containment pressure and temperature as a function of time, and they are calculated in subroutine MACE in MARCH.

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(18) Integrated Software Systems Corporation, 4186 Sorrento Valley Blvd., San Diego, California 92121.

TABLE VII.1   INPUT FOR MARPLT

Card No.	Format	Variable	Description
1	2I5	NSTART	= first timestep plotted (negative suppresses data output list.)
		NSTOP	= last timestep plotted.
2	16I5	ITAPE	=0, Read MACE data from unit #11, variables 101-413 = -1, Read MACE data from unit #11, variables 1-29 = 1, Read BOIL data from unit #9
		NGRAF	Number of frames
		NPLT(I)	Number of curves on each frame, NPLT ≤ 5.
		I=1,NGRAF	
3	16I5	LTYPE(I) I=1,NGRAF	Type of Axis,$\begin{array}{cc} \underline{X} & \underline{Y} \end{array}$ = 0, LIN-LIN = 1, LOG-LIN = 2, LIN-LOG = 3, LOG-LOG
4(a)	16I5	ISET (J)	Data set number(s) for each frame.
		J=1,NPLT	(See Tables VI.2 and VI.3 for corresponding data set numbers.)
*4(b)	5A10	NLEGY	Title for Y-Axis. Read only if first value of ISET (J) is negative or if more than one curve. Otherwise, default titles are used.
*4(c)	2A10	LEG (J) J=1,NPLT	Legend for each curve. If there is only one curve on the frame, skip this card.

Repeat the group of cards 4(a), 4(b), 4(c) for each frame (NGRAF times)

5	I5	MINMAX	Flag for reading minimum and maximum values for axes. If MINMAX ≤ 0, program will find them.

If MINMAX ≤ 0, skip card 6. If MINMAX > 0, repeat card 6 for each frame (NGRAF times).

TABLE VII.1   INPUT FOR MARPLT (CONTINUED)

Card No.	Format	Variable	Description
6	4E10.0,	XMIN	Minimum for X-axis
	2I5	XMAX	Maximum for X-axis
		YMIN	Minimum for Y-axis
		YMAX	Maximum for Y-axis
		IFINDX	
		IFINDY	= 0, find min and max
			= 1, find min only
			= 2, find max only
			= 3, use specified values
*7	5A10	NLEG	Title for each frame.

Repeat card 7 NGRAF times.

* The last character in the titles and legends must be a $ sign.

TABLE VII.2 DATA SET NUMBERS FOR MACE PLOTS (TAPE11)

Parameter Number	Parameter Plotted	Units	
$100*I+1$[a]	total compartment pressure	PSIA	PA
$100*I+2$	steam partial pressure	PSIA	PA
$100*I+3$	hydrogen partial pressure	PSIA	PA
$100*I+4$	adiabatic hydrogen burn pressure	PSIA	PA
$100*I+5$	compartment temperature	F	K
$100*I+6$	mass of steam	LB	KG
$100*I+7$	mass of hydrogen	LB	KG
$100*I+8$	fraction fission product decay heat	--	--
$100*I+9$	mole fraction steam	--	--
$100*I+10$	mole fraction hydrogen	--	--
$100*I+11$	mole fraction oxygen	--	--
$100*I+12$	non-condensibles partial pressure	PSIA	PA
$100*I+13$	mole fraction others	--	--

None of the following parameters can be plotted on the same frame with any of the 52 parameters above.

1	vertical concrete penetration	CM	
2	radial concrete penetration	CM	
3	mass of water in ECC storage tank	LB	KG
4	ECC water temperature	F	K
5	total ECC pump and accumulator flow	LB/M	KG/S
6	ECC injection rate to vessel	L3/M	KG/S
7	containment spray temperature	F	K
8	spray flow rate	LB/M	KG/S
9	mass of ice in icebed	LB	KG
10	total energy leaked from containment	BTU	J
11	total sensible energy release	BTU	J
12	total mass of steam leaked	LB	KG

TAPE VII.2 DATA SET NUMBERS FOR MACE PLOTS (TAPE11)(Continued)

Parameter Number	Parameter Plotted	Units	
13	total volume of gases leaked	FT^3	M^3
14	containment volumetric leak rate	FT^3/M	M^3/S
15	fraction of decay heat leaked	--	--
16	fraction of decay heat in sump	--	--
17	mass of water in sump	LB	KG
18	temperature of water in sump	F	K
19	mass of water in reactor cavity	LB	KG
20	temperature of water in reactor cavity	F	K
21	water and steam input to containment	LB/M	KG/S
22	hydrogen input to containment	LB/M	KG/S
23	containment wall temperature, NOD(1)	F	K
24	containment wall temperature, NOD(2)	F	K
25	containment wall temperature, NOD(3)	F	K
26	containment wall temperature, NOD(4)	F	K
27	containment wall temperature, NOD(5)	F	K
28	total volume of gases vented J to K	FT^3	M^3
29	volumetric vent rate J to K	FT^3/M	M^3/S

(a) I = compartment number, I = 1, 4.

TABLE VII.3 DATA SET NUMBERS FOR PLOT DATA FROM BOIL (TAPE9)

Number	Parameter to be Plotted
1	maximum core temperature
2	average core temperature
3	temperature of water in pressure vessel
4	primary system saturation temperature
5	primary system pressure
6	water - steam mixture level
7	ECC flow rate into pressure vessel
8	water leakage through primary system break area
9	steam leakage through primary system break area
10	steam leakage rate from primary system
11	hydrogen leakage rate from primary system
12	steam mass in primary system
13	hydrogen mass in primary system
14	temperature of gases in upper plenum
15	decay p/
16	energy generated from $Zr - H_2O$ reactions
17	fraction clad reacted
18	total integrated energy from $Zr - H_2O$ reactions
19	core exit gas temperature
20	rate of energy loss to steam generator
21	mass of water in steam generator secondary
22	fraction core melted
23	total water and steam leak rate
24	mass of water in primary
25	temperature of gas leaked to containment

VIII.   SUMMARY

The MARCH code analyzes events occurring in a LWR primary system and containment during accidents which include as initiating events large pipe breaks, small pipe breaks, and transients and which, when compounded by the failure of engineered safety features, result in uncovery of the core and fuel melting. The code predicts the key thermal and flow conditions in a core meltdown accident including:

(1) blowdown of the primary system coolant to the containment,

(2) heatup and boiloff of water in the reactor vessel,

(3) heatup, clad oxidation, and slumping of the fuel,

(4) release of volatile fission products from molten fuel,

(5) primary system pressure,

(6) heatup and failure of the bottom head of the pressure vessel,

(7) interaction of the core debris with water in the reactor cavity,

(8) core-concrete interaction,

(9) containment composition, temperature, pressure, and inter-compartment flows.

The code performs the calculations from the time of the commencement of the accident through the stages of blowdown, core heatup, boiloff, core meltdown, pressure vessel bottom head melting and failure, debris-water interaction in the reactor cavity, and the interaction of the molten debris with the concrete containment base pad. The mass and energy additions into the containment building during these stages are continuously evaluated and the pressure-temperature response of the containment with or without the engineered safety features is calculated. The containment can be divided

into eight or less inter-connected compartment volumes and the engineered safety features which can be modeled include ECCS, containment sprays, containment building coolers, containment fans, PWR ice condensers, BWR pressure suppression pools, and ECC and containment spray recirculation heat exchangers. The analyses also account for combustion of hydrogen and heat losses to structures and walls in the containment, controlled venting of the containment atmosphere to a pressure suppression chamber, or to the outside atmosphere.

The MARCH code is written in FORTRAN EXTENDED. The code takes input and outputs data in either SI or British system of units. All input data are provided through the use of NAMELIST's. Many of the variables have default values. The amount of printed output is user controlled. A smaller program, MARPLT, plots the data from the MARCH code on a Calcomp plotter.

APPENDIX A

Table A.1 Sample Card Input for MARCH

BCL Control Cards

```
WOOTN,AC=G6616-0851,ST74,T600,WOOTON
REQUEST(TAPE6,*Q)
REQUEST,TAPE5,*PF,
REQUEST,TAPE4,*PF,
COPYBR,INPUT,TAPE5,
COPYBR,INPUT,TAPE4,
REWIND,TAPE5,
REWIND,TAPE4,
ATTACH,OLD,MAR,ID=WOOTN,
COPYBF,OLD,LGO,
RETURN,OLD,
REWIND,LGO,
MAP(OFF)
LGO,TAPE5,PL=50000,
```

File 5

```
BWR SAMPLE PROBLEM
 $NLMAR
 IECC=0,NPAIR=2,IPDTL=7,
 VOLC=1.67E6,DTINIT=.025,TAP=2.628E6,
 DTINIT=.25,
 $END
 $NLINTL
 T(1)=0.,0.5, W(1)=2*1.2087E6, EW(1)=2*633.35,
 $END
 STEEL     CONCRETE
 DRYWELL1  DRYWELL2  CONCSHELL MISCSTEEL MISCONC

 $NLSLAB
 NMAT=2, NSLAB=5,
 DEN(1)=487.,157., HC(1)=.113,.238, TC(1)=25.,.8,
 IVL(1)=1,4*2, IVR(1)=1,4*2,
 NNO1(1)=2*9,2*3,10, NNO2(1)=2*0,9,2*0,
 MAT1(1)=2*2,2*1,2,MAT2(1)=3*2,1,2,
 SAREA(1)=19500.,19500.,73236.,199257.,11718.,
 HIF(1)=2*0.,100.,2*0., DTOX(1)=3*0.,1.,0.,
 X(1)=0.,.01,.03,.07,.15,.31,.63,1.27,2.335,
 X(10)=0.,.01,.03,.07,.15,.31,.63,1.27,2.335,
 X(19)=0.,.01,.021,.03,.05,.09,.17,.33,.65,1.29,2.57,3.5,
 X(31)=0.,.007,.015,
 X(34)=0.,.01,.03,.07,.15,.31,.63,1.27,2.1,2.96,
 TEMP(1)=9*135.,34*80.,
 $END
 $NLECC
 RWSTM=2.49E6,ECCRC=.43,CSPRC=2.,DTSUB=-100.,WTCAV=-100.,
 $END
 $NLECX
 $END
 $NLCSX
 SQR=1.847E8,SWPR=61090.,SWSR=65833.,STP1R=185.,STS1R=90.,
 $END
 $NLCOOL
 $END
```

POOR ORIGINAL

Table A.1 Sample Card Input for MARCH (Cont.)

```
     $NLMACE
    NCAV=1,VCAV=2727.,
    NCAV=1,VCAV=50000.,
    NCUS=2,ICECUB=-1,FALL=.8,
    WPOOL=9.67E6,TPOOL=100.,VDRY=50000.,VTORUS=1.572E6,WVMAX=324200.,
    NSMP=-2,NSMP2=2.
    VC(1)=270130.,1.4c6,AREA(1)=4000.,12000.,HU4(1)=.5,.9,
    TEMPO(1)=135.,90.,
    N=2,
    NS(1)=2,NU(1)=2,NT(1)=-7,C1(1)=45.0,C2(1)=.583,C3(1)=7.0,C4(1)=0.,
    NS(2)=1,NC(2)=2,NT(2)=1,C1(2)=10.,C2(2)=7450.,C3(2)=100.,C4(2)=400.,
    KT(1,2)=1,KI(2,1)=1,
     $END
    $NLBOIL
    NNT=49600,NR=49600,ISTR=2,ISG=0,IHR=1,
    QZERO=1.3162E10,H=12.5,HO=-6.7,DC=15.96,ACOR=84.3,ATOT=251.,
    WATBH=200000.,D=.04025,DF=.03417,DH=.0437,CLAD=.005543,XOO=3.28E-6,
    RHOCU=68.79,PSET=1180.,CSFV=5342.,WFE2=2400.,TFEQO=540.,
    YBRK=8.33,DTPNTB=5.,VOLP=24590.,VOLS=9638.,
    TT(1)=5*540.,
    CM(1)=2393.,16320.,4413.,10330.,21110.,
    AH(1)=1295.,6636.,250.,8300.,687.,
    DD(1)=.43,.5,.17,.021,.52.,
    AP(1)=250.,66.5,0.,-8.3,-16.6,
    ATOT=168.5,HO=-9.95,AR(4)=-12.,-19.9,
    F(1)=.47,.49,.53,.64,.77,.95,1.12,1.27,1.35,1.44,1.47,1.5,
    1.5,1.47,1.44,1.35,1.27,1.12,.95,.77,.64,.53,.49,.47,
    PF(1)=1.5,1.3,1.2,1.1,1.,.95,.9,.8,.7,.55,
    VF(1)=10*.1,
    FDC9=.528,
    $END
    $NLHEAD
    WZRC=174658.,WFEC=30447.,WUO2=366400.,WGRID=175928.,WHEAD=93501.,
    OBH=20.947,THICK=.522,
    $END
    $NLHOT
    FLRMC=12000.,OP=.12,
    CP=2.,
    $END
    $NLINTR
    RO=322.6,R=6000.,WALL=1000.,
    TF=3.,
    TF=36010.,
    $END
```

File 4

```
         OBWRAE     BWR LARGE LOCA, NO ECC
    $CHANGE
    PRST=1000.,
    IHOTX=2,
    IHOTX=0,
    CPSTP=200.,
    TRST=1000.,
    IPLOT=3,
    JS=-1,IFISH=0,NCT7=0,NCRST=1,LST7=1,
    $
```

Table B.1   Sample Output From Subroutine MACE in MARCH

```
                              MACE OUTPUT AT TIME =    40.500 MINUTES

              NUPLACE =   2
              ITERATION COUNTERS.  NTSP =       195   NITF =        0    NITU =       0    MARCH =      42
              LATEST MACE TIMESTEP =     1.000  MIN.
              LATEST MARCH TIMESTEP =    1.000  MIN.                      NFAIL =      0

                    CONTAINMENT PARAMETERS

      VOLUME
        NO.       PTOT        PAIR        TEMP       SAT TEMP       HOS         ASWR         FP        PSTEAM
         1      2.0292E+01  5.3366E+00  6.5959E+02  1.8928E+02  6.5514E+03  1.1987E-01  7.9851E-02  1.4955E+01
         2      2.0292E+01  1.8405E+01  1.2392E+02  1.2544E+02  7.8366E+03  1.4743E+01  2.0593E-02  1.8874E+00

VOLUME
  NO.      WNTR        WOXY        WHYDR       WCO2        WCO         PNTR        POXY        PHYDR       PCO2        PCO
   1     4.4793E+02  1.3611E+02  2.0097E+02  2.9720E-01  1.0000E-20  7.1045E-01  1.8885E-01  4.4370E+00  2.9857E-04  1.5233E-23
   2     8.8375E+04  2.6855E+04  2.4572E+02  5.8636E+01  2.2112E-19  1.4104E+01  3.7492E+00  5.4589E-01  5.9273E-03  3.5289E-23
 TOTAL   8.8823E+04  2.6991E+04  4.4669E+02  5.8934E+01  2.3112E-19

VOLUME
  NO.       QRS        DTSUR        MSCW        EGRVTY      MGRVTY      ETOSUMP     MTOSUMP
   1     1.9396E+05  4.2132E+02  0.          0.          0.          0.          0.
   2     2.6884E+05  1.3504E-01  0.          0.          0.          4.9706E+06  6.1942E+04
 TOTAL   4.6279E+05              0.          0.          0.          4.9706E+06  6.1942E+04

            MASS AND ENERGY ADDITION RATES INTO THE SOURCE VOLUME (COMPARTMENT NO. 1)

                       MASS RATE      ENERGY RATE(BTU/MIN OR W)
            STEAM      4.1525E-01     5.7159E+02
            HYDROGEN   1.3751E+01     3.1565E+04

            ACCUMULATED ENERGY BALANCE PARAMETERS

   TOTQDK =1.6054E+08   TOTQH2 =0.          TOTQIN =3.9847E+08   TOTQRS = 3.272E+07   TOTULK =0.

   TOTAL WATER+STEAM MASS IN CONTAINMENT=1.0308E+07
                    CONTAINMENT SPRAY PARAMETERS

   WSPRA =6.1671E+04    TSPRA =1.0643E+02
   WSPRAR=6.1671E+04    TSPRA =1.0643E+02    QCSHX =6.8656E+07
   WSPRAI=0.            TSPRAI=0.
   MRC   =2.6726E+05    TRC  =1.9044E+02    WVRC =1.7889E+02

            BWR SUMP PARAMETERS

                TEMP        MASS        ENERGY
   DRY WELL  0.          0.          0.
   WET WELL  1.2487E+02  9.9647E+06  9.2543E+08          FPSUMP = 7.4136E-02

   WSMP =0.            WSFP =0.           WBOIL =0.           WVAP =0.           QDLBWR =2.8276E+04  QPOOL =3.4855E+05
   MSCWW =2.7819E+02

            INTER-COMPARTMENT TRANSFERS

                     FRACTION OF   ENERGY       VOLUME
    SOURCE  RECEIVER SOURCE VOL.   TRANSFERED   TRANSFERED
    VOLUME  VOLUME   TRANSFERED    PER MINUTE   PER MINUTE

      1        2     3.9639E-02    3.7683E+05   1.8698E+04
```

Table B.2 Sample Output From Subroutine BOIL in MARCH

```
                    BOIL OUTPUT AT TIME=     21.500 MIN.
                    TIME INTERVAL IS=    1.000 MIN.

TIME = 2.150E+01   Y   =-1.054E+01   YDOT =-1.187E-02   WMASS=-1.055E+05   ALF  = 0.        H2ORP= 0.
QZORP= 0.          QCLAD=-6.455E+07   TFCR = 2.703E-02   QMM  = 4.958E+07   TFALL= 5.400E+02 TFE  = 1.029E+03
RACT = 3.319E+06   TFPL = 9.481E-01   TGEX = 2.353E+03   FCM  = 1.327E-01   QDK  = 2.178E+08 QCONV= 6.762E+06
HSTM = 1.499E+00   HSTM = 2.576E+03   WH2  = 1.355E+01   H2EN = 1.07E+04    TGRO1= 5.400E+02 TGRO2= 2.266E+02
QSTP = 6.721E+05   QFP  = 1.898E+06   WTRSG= 0.          TSAT = 2.267E+02   TPOOL= 2.267E+02 PRES = 1.961E+01
WFLS4= 0.          QSLAG= 5.300E+06   FOX  = 5.600E-01   FMET = 3.680E-01   TCORE= 2.915E+03 THEAD= 4.455E+02
STEXC= 2.065E-12   H2EXC= 1.312E+01   WSBRK= 0.          WLRK = 0.          QSG  = 0.        WECC = 0.
WHTOT= 9.446E+04   STM  = 2.548E+00   HYD  = 2.317E+01   PSV  = 2.367E-01   PHV  =-1.937E+01 TOTMW= 1.626E+07
VOLW = 1.589E+03   VOLS = 2.300E+04   TPM  = 1.000E+00   YLIQ =-1.054E+00   TOTQN= 0.

  Z        FNM(I)      XO(I)       TG(I)       TRO(1)     TRO(3)     TRO(5)     TRO(7)     TRO(9)
1.042E+00  0.         1.056E-04   1.797E+03   2.165E+03  1.740E+03  1.514E+03  1.409E+03  1.207E+03
2.093E+00  5.084E-01  9.382E-04   4.119E+03   4.130E+03  2.441E+03  1.953E+03  1.777E+03  1.473E+03
3.125E+00  1.000E+00  7.302E-04   4.120E+03   4.170E+03  4.130E+03  4.130E+03  3.151E+03  2.036E+03
4.157E+00  1.000E+00  3.033E-04   4.122E+03   4.130E+03  4.130E+03  4.130E+03  4.130E+03  3.706E+03
5.208E+00  1.000E+00  1.391E-04   4.122E+03   4.130E+03  4.130E+03  4.130E+03  3.921E+03  3.615E+03
6.252E+00  1.000E+00  5.371E-05   4.127E+03   4.130E+03  4.130E+03  4.044E+03  3.774E+03  3.214E+03
7.292E+00  1.000E+00  5.027E-05   4.127E+03   4.130E+03  4.130E+03  3.889E+03  3.623E+03  2.995E+03
8.333E+00  7.829E-01  1.265E-05   4.124E+03   4.130E+03  4.130E+03  3.627E+03  3.347E+03  2.746E+03
9.376E+00  1.965E-01  5.674E-06   4.043E+03   3.658E+03  3.184E+03  2.939E+03  2.397E+03
1.042E+01  0.         3.380E-06   3.811E+03   3.402E+03  2.899E+03  2.527E+03  2.334E+03  1.909E+03
1.146E+01  0.         7.245E-06   3.548E+03   2.712E+03  2.324E+03  2.041E+03  1.892E+03  1.557E+03
1.250E+01  0.         3.282E-06               2.426E+03  2.091E+03  1.848E+03  1.717E+03  1.425E+03

 GAST      STRT       MIXEN      STHEN      H2ENI
2.804E+03  1.029E+03  9.331E+03  2.576E+03  1.007E+04
1.636E+03  1.253E+03  5.253E+03  1.867E+03  5.625E+03
5.988E+02  5.883E+02  1.884E+03  1.328E+03  1.945E+03

CRF(1)= 1.9AE-01   CRF(2)= 1.93E-01   CRF(3)= 1.78E-01   CRF(4)= 3.31E-02   CRF(5)= 2.20E-02   CRF(6)= 6.61E-03   CRF(7)= 6.61E-04
QF(1)= 5.50E-02    QF(2)= 1.02E-01    QF(3)= 8.93E-02    QF(4)= 5.74E-02    QF(5)= 7.15E-02    QF(6)= 1.56E-01    QF(7)= 4.68E-01
```

Table B.3 Sample Output From Subroutine HEAD in MARCH

```
                  SUBROUTINE HEAD OUTPUT AT TIME =    71.500  MIN
                           TIME INTERVAL IS =     2.000 MIN
```

```
    XM    =  .245      TD    = 5.386E+03   TEO  = 6.455E+03   TW   = 2.8 0E+03   TB    =  673.
    QQK1  = 1.179E+08   QKO   = 1.157E+08   QRAO = 0.          QSTORH= 8.475E+07  QMELTH= 3.235E+07
    FCM   = 1.00        FOM   = 1.00        FOX  =  .577       FMET = .192        TFPL  = .769
    SIG   = 2.614E+03   STRESS=  322.       OPRES = 0.         ENIT = 7.00
    CASE  = 4.00        DELH  =  .319       DELO =  .996E-01   RM   =  11.1       ROOT  = 0.          XDOT  = .167E-01
    T1    =  .174E+04   DCV   =  .167       DCVTED= .317       TH   =  .522       FIM   = .226        FOM   = .774
    SIG1  =  .261E+04   SIG2  =  .500E+05   STRS1 =  172.
```

```
CRF(1)= 9.00E-01  CRF(2)= 9.00E-01   CRF(3)= 8.10E-01   CRF(4)= 1.50E-01   CRF(5)= 1.00E-01  CRF(6)= 3.00E-02  CRF(7)= 3.00E-03
 QF(1)= 5.18E-02   QF(2)= 1.22E-01    QF(3)= 6.50E-02    QF(4)= 4.65E-02    QF(5)= 6.61E-02   QF(6)= 1.32E-01   QF(7)= 5.17E-01
```

Table B.4 Sample Output From Subroutine HOTDROP in MARCH

```
                  SUBROUTINE HOTDROP OUTPUT AT TIME =    77.540  MIN
                           OVER THE TIME INTERVAL OF     .100  MIN
```

```
    CLADMW= 9.856E+08   DWS   = 3.519E+03   FCMAX =  1.00      FOM  = 1.00        FZR  = .562        HQ    = 391.
    STM   = 2.187E+05   QQK   = 1.494E+08   QWTR  = 1.354E+10  T    = 4.150E+03   TE   = 5.219E+03   TGAS  = 313.
    TFPL  =  .769       TPOOL =  251.       TYME  =  .440      WTR  = 1.507E+05   XINCH= 4.615E-02   QMW   = 1.407E+09
    FMET  =  .184       FOX   =  .585       H     =  91.0      HEFF = 51.7        QMW  = .141E+10     TEMIN = 277.
    WS    =  .222E+06
```

```
CRF(1)= 9.00E-01  CRF(2)= 9.00E-01   CRF(3)= 8.10E-01   CRF(4)= 1.50E-01   CRF(5)= 1.00E-01  CRF(6)= 3.00E-02  CRF(7)= 3.00E-03
 QF(1)= 5.13E-02   QF(2)= 1.25E-01    QF(3)= 6.22E-02    QF(4)= 4.52E-02    QF(5)= 6.53E-02   QF(6)= 1.29E-01   QF(7)= 5.22E-01
```

```
          SUBROUTINE INTER OUTPUT AT TIME=    198.781 MIN
                   THE TIME INTERVAL IS=       .167 MIN
                   CONCRETE MELT TIME=      7202.4 SEC (       2.0 HRS )

T=  7202. SEC.      R= 6000.00 CM      Z=  11.98 CM
                                   METAL          OXIDE
          TEMP. (K)                2434.           2591.
          MASS (GM)                .2118E+09       .2599E+09
          VOL. (CC)                .3281E+08       .3709E+08
          DEPTH (CM)               84.25           100.40
          SP. GR.                  6.46            7.01
          M. P. (K)                1618.           2553.
          COND.(W/CM2/K/CM)        .5568           .0345
          C. '. (J/GM/K)           .689            .686
          DELTA (CM)               0.000           .582

   DELTAC=  .980 CM      EFF. SURF. EMISS.=  .500
   SURF. TEMP.= 773.0
   RO= 352.12    DROO= 29.52

   MASSES
   UO2        ZRO2        FEO         CAO        SIO2        AL2O3       CR2O3      NIO
   .1562E+09  .6434E+08   .6049E+07   .2146E+08  .3825E+05   .3825E+06   .1089E+07  0.
   FE         ZR          CR          NI
   .1454E+09  .3159E+08   .2211E+08   .1270E+08

   HEAT BALANCES (W)
                           METAL          OXIDE
          INTERNAL         .3945E+07      .1998E+08
          ENTERING         .3010E+07      .6907E+07
          LEAVING          -.5019E+07     -.2815E+07
          REACTIONS        .2521E+07      0.
          DISSOC.          0.             -.4610E+07
          CONCRETE         -.6499E+07     -.8322E+07
          INTERCHANGE      .3976E+07      -.3976E+07
          RADIATED         -.1092E+01     0.
          SENSIBLE HT.     .1934E+07      .7168E+07
   HEAT TO BOILING WATER=  0.
   WATER IN CONT. SUMP= .4667E+10      IN REACTOR CAVITY=0.              WATER TEMP.= 387.1

CONCRETE DECOMPOSITION
   VOLUME=  .2539E+04 CC/S. MASS=   .6256E+04 GM/S. HEAT FROM MELT=   .1482E+08 W. DECOMP.=   .1034E+08 W

GASES ADDED TO ATMOSPHERE--
   RATES (GM/S) - CO2=  .1479E+04   CO=  .4600E+03   H2O=  .2792E+03   H2=  .1517E+02
   TOTALS (GM) =  CO2=  .9755E+07   CO=  .2358E+07   H2O=  .3298E+07   H2=  .7941E+05
   RATE OF HEAT ADDED TO ATMOSPHERE (W) =  .3520E+07   TOTAL (J) =  .2411E+11

GAS BLOWING RATES (GM/S)
                           METAL          OXIDE
          CO2              0.             .7233E+03
          H2O              0.             .1365E+03
          CO               .4600E+03      0.
          H2               .1517E+02      0.


   TAUM       TAUOX       TFPL        FOX        FMET        QFP         FZR
   .5000      .5000       .7218       .6028      .1190       1.076E+03   6.012E-01

CRF(1)= 9.84E-01  CRF(2)= 9.86E-01  CRF(3)= 9.69E-01  CRF(4)= 8.56E-01  CRF(5)= 1.08E-01  CRF(6)= 7.35E-02  CRF(7)= 1.08E-02
QF(1)= 4.34E-02   QF(2)= 1.62E-01   QF(3)= 3.35E-02   QF(4)= 2.93E-02   QF(5)= 5.37E-02   QF(6)= 9.03E-02   QF(7)= 5.86E-01
```
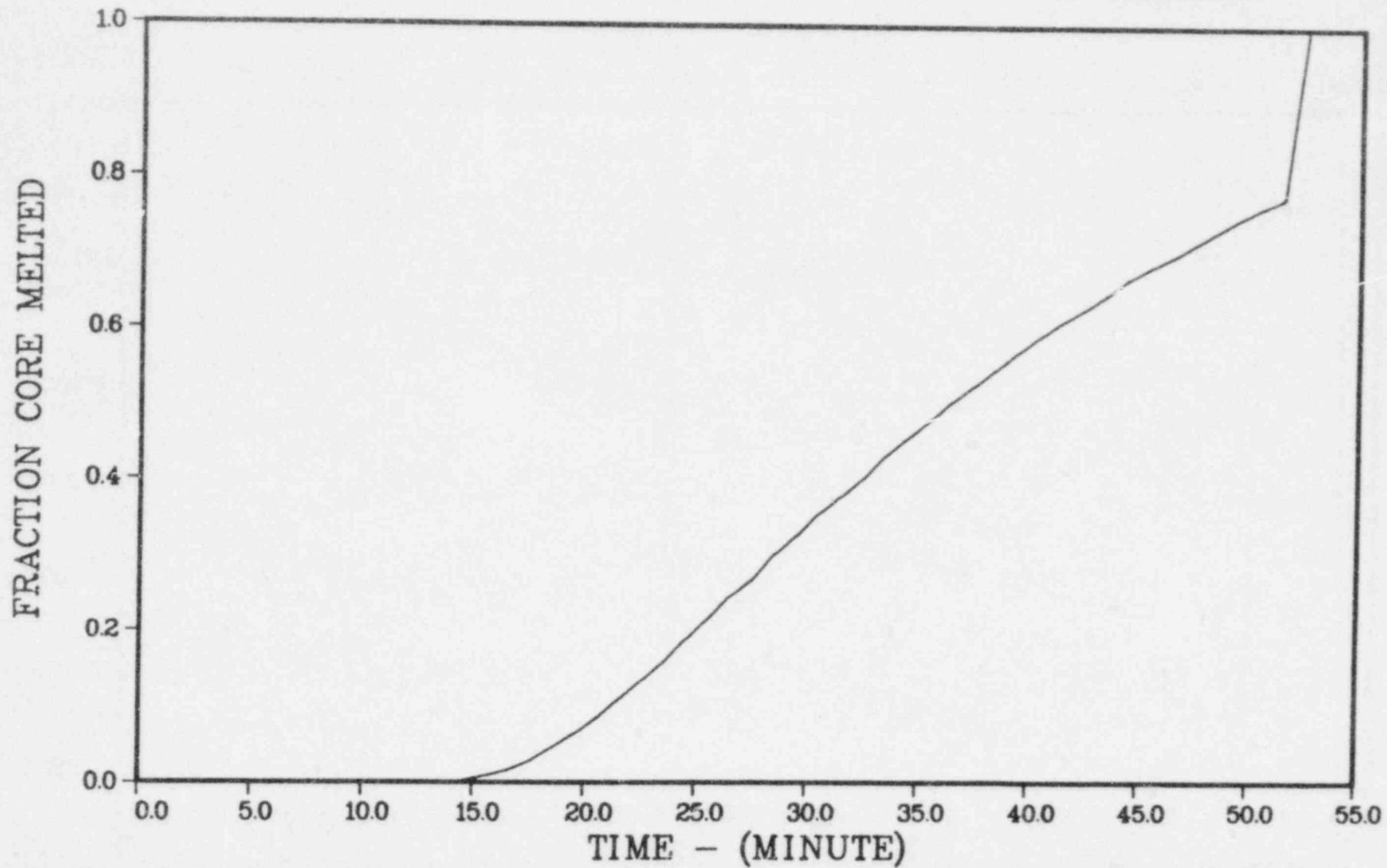
BWR LARGE LOCA SAMPLE PROBLEM
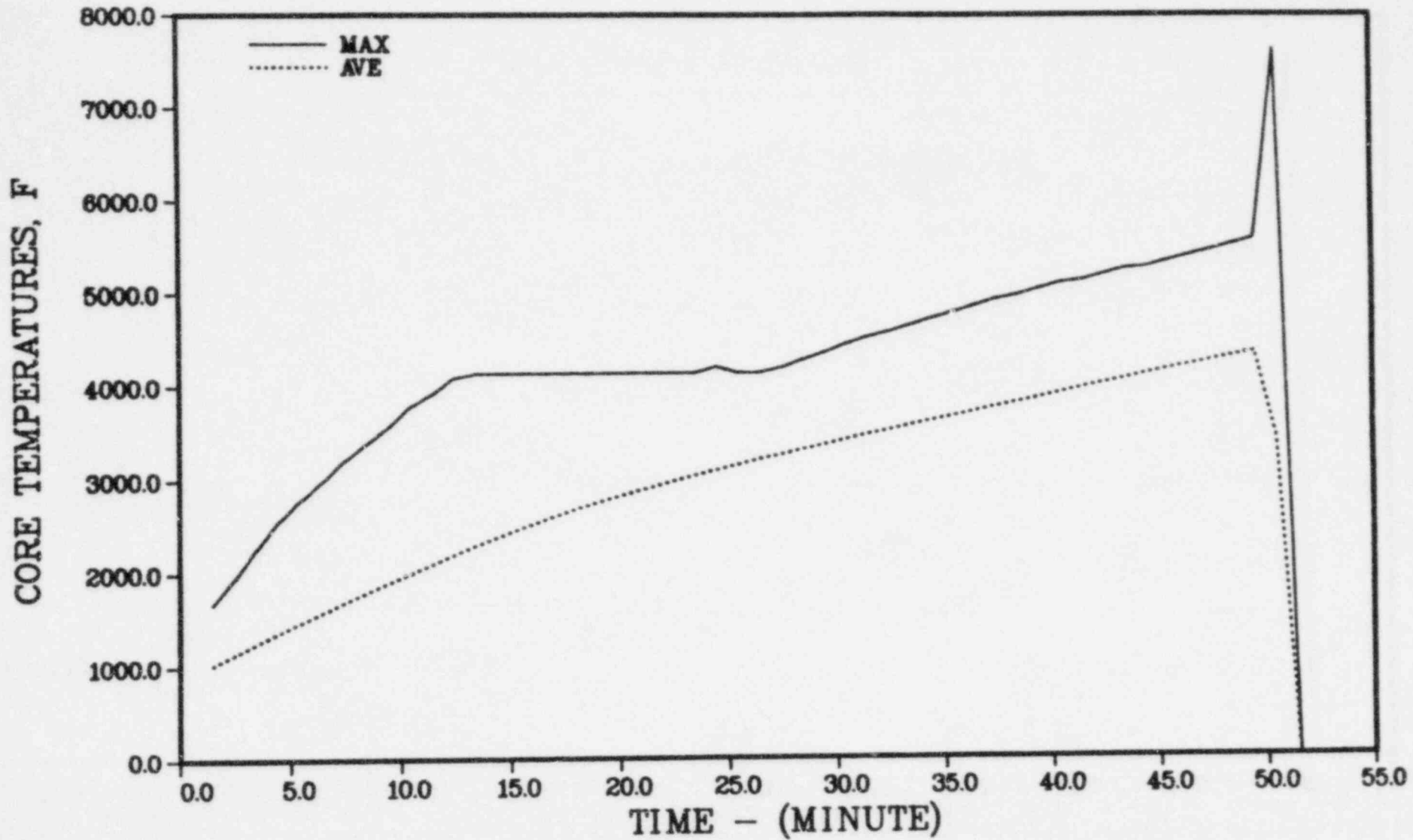
Figure C.1 Sample Plot of Subroutine BOIL Output Data in MARCH

BWR LARGE LOCA SAMPLE PROBLEM

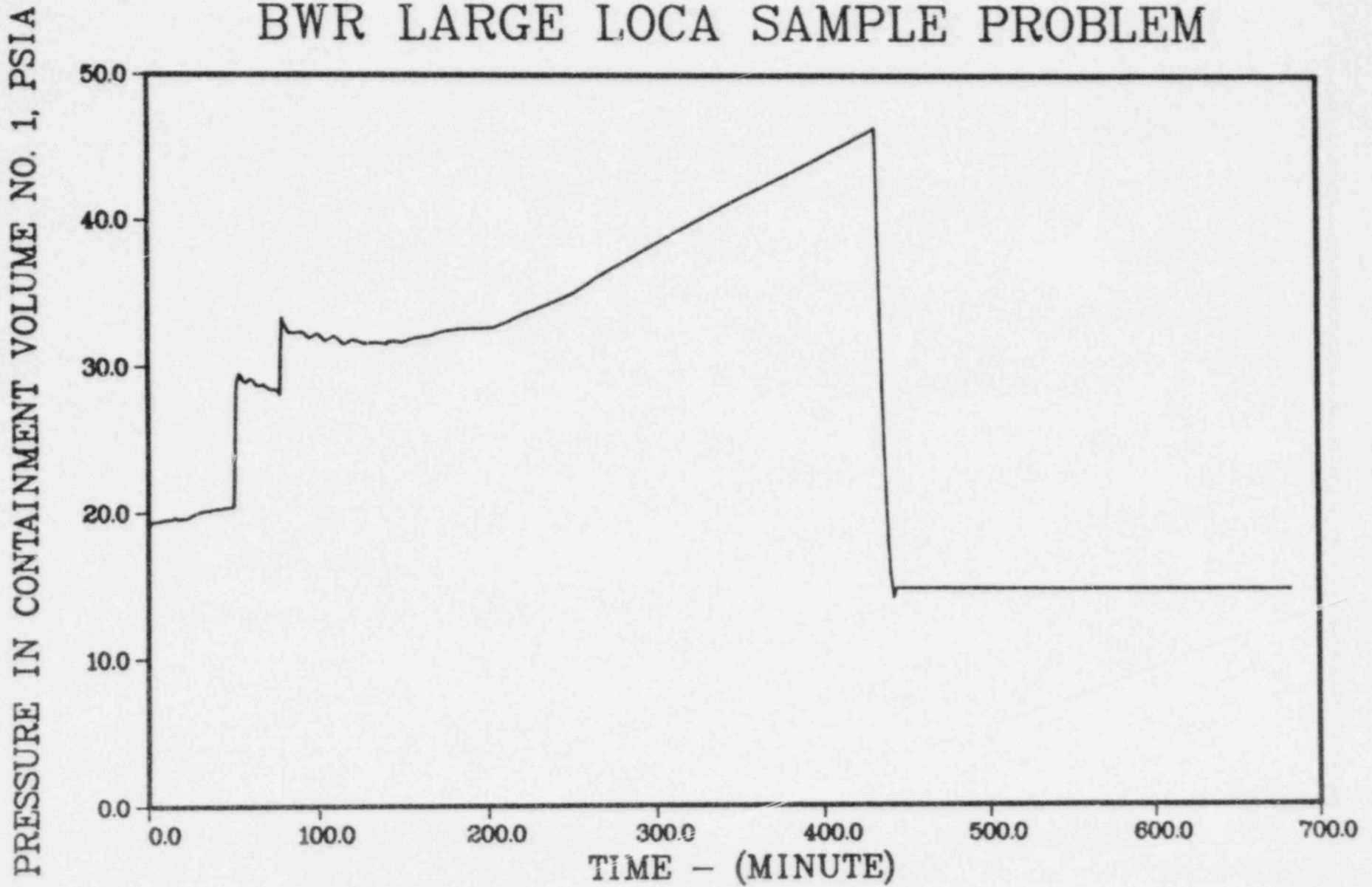Figure C.2   Sample Plot of Subroutine BOIL Output Data in MARCH

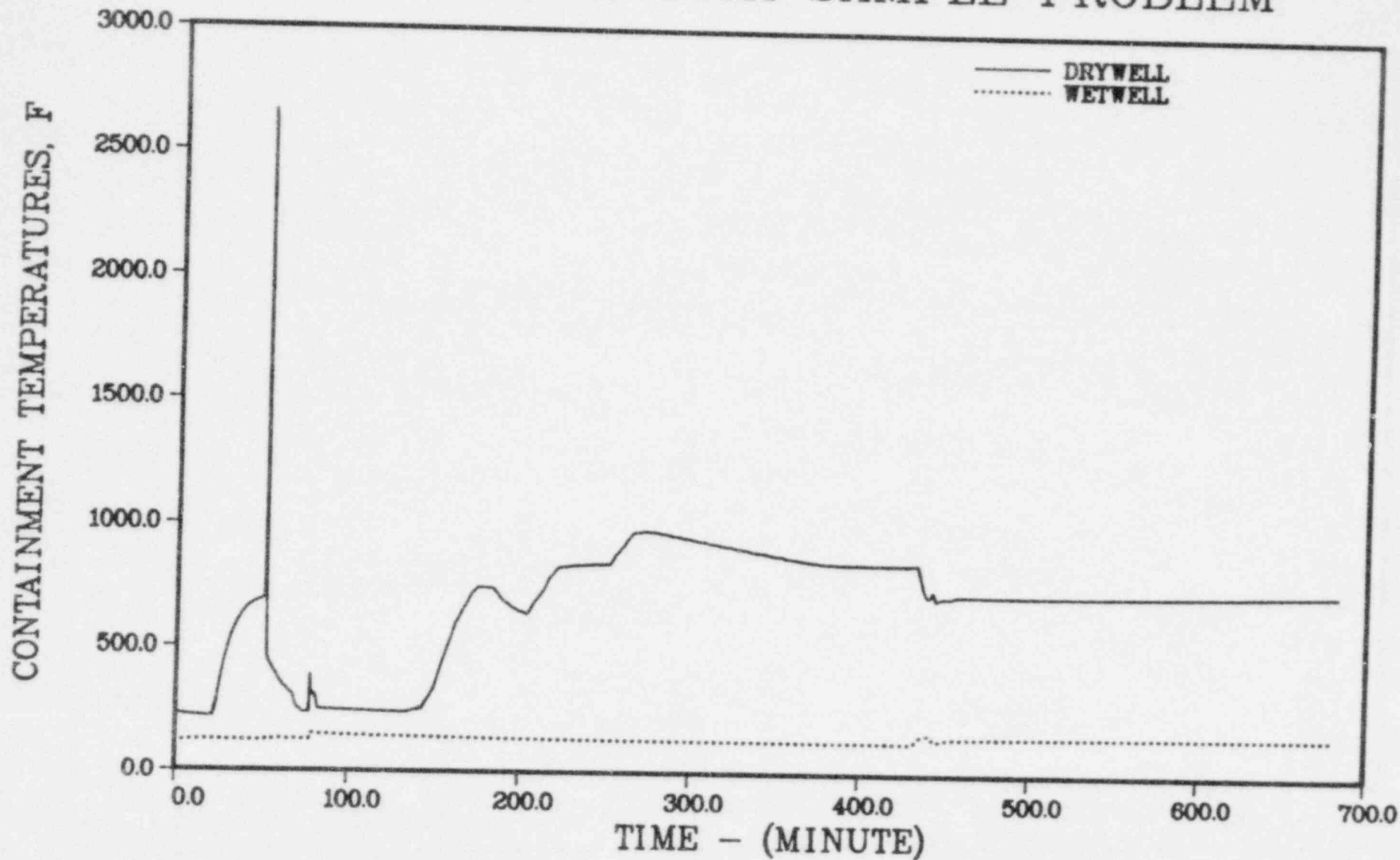Figure C.3 Sample Plot of Subroutine MACE Output Data in MARCH

Figure C.4 Sample Plot of Subroutine MACE Output Data in MARCH

APPENDIX D

GLOSSARY OF ACRONYMS

AFW   Auxiliary feed water

BWR   Boiling water reactor

CORRAL Containment of radionuclides released in a LOCA

CSHX   Containment spray heat exchanger

CSR   Containment spray recirculation

ECC   Emergency core cooling

ECR   Emergency coolant recirculation

HH   High head

LH   Low head

LOCA   Loss of coolant accident

LWR   Light water reactor

MARCH   Meltdown accident response characteristics

PWR   Pressurized water reactor

RSS   Reactor safety study

RWST   Refueling water storage tank

SIS   Safety injection system

UHI   Upper head injection

4. TITLE AND SUBTITLE (Add Volume No., if appropriate)	2. (Leave blank)
MARCH (Meltdown Accident Response Characteristics) Code Description and User's Manual	
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16. ABSTRACT (200 words or less)

   The MARCH code, written at Batt   's Columbus Laboratories for the U.S. Nuclear Regulatory Commission, describes th .esponse of LWR systems to accidents which can result in core meltdown. The calculations are performed from the start of the accident through the stages of blowdown, core heat up, boiloff, core meltdown, pressure vessel bottom head failure, debris-water interaction in the reactor cavity and the interaction of the molten debris with the concrete base pad. The mass and energy additions into the containment during these stages are continuously evaluated and the pressure-temperature response of the containment is calculated. The containment can be divided into eight or less inter-connected compartments. The engineered safety features which can be modeled included ECCS, containment sprays, building coolers, fans, PWR ice condensers, BWR pressure suppression pools, and ECC and containment spray recirculation heat exchangers. The analyses account for metal-water reactors, combustion of hydrogen, and heat losses to structures in the containment.

   The MARCH code is written in FORTRAN EXTENDED. All input data are provided through the use of NAMELIST's. The code takes input and outputs data in either SI or British system of units. Many of the variables have default values. The amount of printed output is user controlled. A smaller program, MARPLT, is used to process and plot the data from the MARCH code on a Calcomp plotter. In this report, the models which are used in

17. KEY WORDS AND DOCUMENT ANALYSIS	17a. DESCRIPTORS
-meltdown -core-concrete interactions	the MARCH code, input requirements, and output options are described.
-core meltdown	
-accident analysis -hydrogen burning	
-containment response -loss-of-coolant -transients	
-hypothetical accidents accidents	

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