325
6/10/64

NAA-SR-8414

COPY

MASTER

BOOMER - A DIGITAL PROGRAM FOR EVALUATING
THE THERMAL AND KINETICS RESPONSE
OF A SNAP 2/10A REACTOR

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Price \$1.75

Available from the Office of Technical Services

Department of Commerce

Washington 25, D. C.

BOOMER - A DIGITAL PROGRAM FOR EVALUATING
THE THERMAL AND KINETICS RESPONSE
OF A SNAP 2/10A REACTOR

By
R. W. WINSON

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8
ISSUED:

MAY 31 1964

DISTRIBUTION

This report has been distributed according to the category UC-36, "Aerospace Safety" as given in "Standard Distribution Lists for Unclassified Scientific and Technical Reports" TID-4500 (26th Ed.) January 1, 1964. A total of 495 copies was printed.

CONTENTS

	Page
Abstract	4
I. Introduction	5
II. Digital Program Background	6
A. Procedure	6
B. Assumptions	7
C. Development of the Mathematical Model	9
III. Development of BOOMER Code	11
IV. Description and Use of BOOMER	17
A. Description	17
B. Use	18
C. Modification of BOOMER Results	22
V. References	24
VI. Bibliography	25
Appendices	
A. Nomenclature and Symbols	A-1
B. Derivation of the Heat Transfer Equations	B-1
C. Derivation of the Reactor Kinetics Equations	C-1
D. Hydrogen Diffusion Equations	D-1
E. Sample Data Sheets	E-1
F. Typical BOOMER Printout	F-1
G. Typical BOOMER Graphical Output	G-1

FIGURES

1. Heat Transfer Program Block Diagram	16
2. Time Between Cladding Burst and Reactor Disassembly (center rod)	23

ABSTRACT

A mathematical model of the SNAP 2/10A reactor was developed describing the reactor kinetics, heat transfer, and hydrogen diffusion within the reactor core. This theoretical model was then modified, on the basis of current test data, to realistically predict the transient response of the reactor. The model was then programmed into a digital code called BOOMER. The development of this code is described in detail in this report.

The code solves the spatially discretized partial differential equations representing the heat transfer and hydrogen diffusion within an average fuel rod, the six delay group monoenergetic kinetic equations, and all the necessary coupling equations. The output of the code presents the time solution of the SNAP 2/10A reactor transient and includes the temperature distribution axially and radially within the fuel rod, the axial temperature distribution in the coolant channel, distributed hydrogen concentration, hydrogen pressure within cladding gap, reactor power, neutron flux, and the concentrations of the delayed neutron precursors.

In the form described in this report, the primary function of BOOMER is to represent the response of the reactor to large reactivity ramp and step insertions.

I. INTRODUCTION

An extensive study was initiated in conjunction with the Aerospace Safety Program to determine the magnitude of the energy generated by a SNAP 2/10A reactor responding to large reactivity insertions. The objective of the study was to determine the mechanisms which would effectively place an upper limit on the magnitude of the energy released during uncontrolled reactor power excursions. A preliminary analytic study¹ indicated that core melting would limit the energy generation by the reactor to approximately 160 Mw-sec. A survey was conducted to ascertain whether or not another limiting mechanism existed which would terminate the reactor excursion before the 160 Mw-sec was generated. The results of this survey indicated that hydrogen loss from the core would significantly reduce the magnitude of the energy generation during reactor transients associated with large reactivity insertions.

This study was initiated to develop a detailed analytical model of the SNAP 2/10A reactor. This model was to be used in the evaluation of the transient response of the reactor to large reactivity ramp and step insertions. The transient response information was to be comprised of the time dependent values of the following items:

- a) Reactor power
- b) Integrated energy
- c) Prompt and delayed neutron precursors
- d) Spatially dependent temperature distribution within the reactor
- e) Hydrogen concentration distribution
- f) Hydrogen loss rate
- g) Pressure generation within the fuel cladding.

The reactor model was to include all the known mechanisms for terminating the reactor excursion during transients associated with large reactivity ramp and step insertions.

II. DIGITAL PROGRAM BACKGROUND

A. PROCEDURE

A detailed analytical study of the SNAP 2/10A reactor was made. As a result of this analysis, a complex mathematical model of the reactor was evolved which described in detail the heat transfer, reactor kinetics, and hydrogen release mechanisms. In essence, this model consists of the six delay group mono-energetic kinetic equations, the spatially discretized partial differential equations and algebraic equations describing the heat transfer and hydrogen diffusion within an average fuel rod, chopped cosine flux distribution, distributed prompt temperature reactivity feedback, grid plate temperature reactivity feedback, and all necessary coupling equations. This report presents in detail the mathematical formulation of this reactor model.

In order to accurately determine the limiting effect of hydrogen release on the magnitude of the energy generated during a reactor transient, it was necessary that the mechanism governing hydrogen release be accurately represented. A test program was initiated to determine the mechanism governing the release of hydrogen from the fuel under conditions of high temperature and large volumetric power generation rates. This test program was accomplished in two separate phases. The first phase of the program consisted of volumetrically heating relatively small fuel samples, from the SNAP 2/10A reactor, by passing large electrical currents through them. The temperature derivative of the specimens during these tests was approximately 8000°F/sec. The samples were mounted in an evacuated chamber which had a calibrated volume. The rate of hydrogen release was determined by monitoring the hydrogen pressure within the chamber during the fuel-heating transient. These experiments are described in detail in References 2 and 3. The second phase of the program utilized the Kinetic Experimental Water Boiler (KEWB) reactor. In this series of tests, small samples of zirconium-uranium hydride were internally heated by neutron irradiation and the hydrogen release was monitored in a manner similar to that described in the electrical resistance heating experiments.

The results of the electrical resistance heating tests showed that the test sample reached a temperature plateau at 2200°F during the period in which it was being heated. While it was at this constant temperature, hydrogen was

rapidly evolved. A thermal balance of the system indicated that the hydrogen loss was commensurate with the dissociation energy of the hydrogen released and the sample heating rate. In the KEWB heating experiments, where the sample was heated about 20 times more rapidly, this temperature plateau at 2200°F was also evident. These results indicate that, at a temperature around 2200°F, hydrogen loss is not limited by diffusion, but rather is released at rates governed by the rate of volumetric power generation and the dissociation energy for hydrogen. It should be noted, however, that the volumetric power generation in both test programs was finite. Therefore, the only conclusion that can be drawn from the test results is that a diffusion coefficient, of sufficient magnitude, exists so that the tests are power-limited and not diffusion-limited. A value for the diffusion coefficient may be calculated from the test results. This is the minimum value that the coefficient must have had in order to release hydrogen at the rates indicated. Utilizing the electrical heating data, the calculated diffusion coefficient was two orders of magnitude larger, at 2200°F, than was obtained by extrapolating the diffusion coefficient.⁴ It is possible that, at 2200°F, hydrogen loss is no longer governed by a diffusion process but rather is lost at a rate commensurate with the volumetric heat generation rate and the dissociation energy of the hydrogen. However, before any final conclusions may be drawn as to the true mechanism governing hydrogen loss at 2200°F, the results of additional experiments to be performed utilizing volumetric power generation rates an order of magnitude larger than those cited in References 2 and 3 must be evaluated.

Utilizing the data obtained from the initial experiments, a diffusion coefficient was calculated and is presented in Appendix D. This coefficient, in conjunction with the diffusion equations, describes the hydrogen loss at temperatures above 2000°F.

In order to efficiently solve the system equations describing the SNAP 2/10A reactor (Appendices B, C, and D), a digital program was written. This digital code was titled BOOMER and is the subject of this report.

B. ASSUMPTIONS

In the development of the mathematical model and subsequent digital program, several approximations and assumptions had to be made. This was necessary in order to make it economically feasible to obtain the transient response

of the reactor utilizing available computational equipment. While it is possible to make a more detailed model, the cost of obtaining the data from this model would be prohibitive. In all cases, the assumptions that were made were conservative and the transients obtained from the model are more severe than those which would be encountered in the physical reactor. Among the more pertinent assumptions, it was assumed that:

- 1) There is no axial heat transfer in the fuel. Heat is generated throughout the fuel volume in accordance with the neutron flux distribution. Due to the geometry of the fuel rod, the axial thermal impedance is greater than the radial impedance. In conjunction with this, the radial thermal gradient is far steeper than the axial gradient. Since the steepest thermal gradient is in the direction of the least impedance, most of the heat that is generated will be conducted to the coolant, and the axial heat transfer may be ignored.
- 2) There is no heat loss out of the reactor other than that removed by the coolant. For large reactivity insertions, the period of the reactor is so short that there is insufficient time for significant heat transfer from the fuel during the transient. For small reactivity insertions, the negative reactivity temperature feedback (from prompt and grid plate temperature coefficients) terminates the reactor excursion with a relatively small change in the reactor temperature. In these cases, the heat loss by radiation and conduction is insignificant compared to the heat loss to the coolant.
- 3) The temperature distribution in an average rod can be used in calculating the reactivity feedback effected by the prompt temperature coefficient. In the physical reactor, the prompt temperature coefficient is weighted more heavily in the center rods. Since the temperature of the center rods will be higher, due to the flux distribution, the physical reactor will have more feedback from the prompt temperature coefficient than is indicated by the model. This will result in the model generating a more violent excursion than would be experienced by the reactor. Thus the assumption is conservative.
- 4) Hydrogen loss is governed by a diffusion process until a fuel temperature of 3000°F is achieved. At this temperature, hydrogen loss would be governed only by the volumetric power generation and the dissociation energy of hydrogen. The results of the experimental tests, discussed in the procedure, indicate that this "power limiting" would

occur at about 2200°F. The assumption that "power limiting" occurs at 3000°F would result in a larger power excursion before hydrogen loss could terminate the transient and is therefore a conservative approximation.

- 5) As hydrogen leaves the fuel, it is immediately lost from the reactor. This loss manifests itself as a net loss in reactivity. The relationship between hydrogen loss and reactivity is taken to be $-62 \text{ } \phi / \%$ reduction in the average N_H of the core. A previous analysis shows that the negative reactivity insertion resulting from hydrogen loss from the core is not the most significant contributor to limiting the energy generated during large reactor excursions. For reactivity step insertions of less than \$1 supercritical, the reactor power excursion is terminated by the reactivity feedback associated with the prompt and grid plate temperature coefficients. For reactivity step insertions larger than \$1 supercritical, hydrogen evolution is so rapid that reactor disassembly is effected. The reactivity loss due to reactor disassembly is in the order of $10^6 / \text{sec}$, while the reactivity loss associated with hydrogen loss is $10^4 / \text{sec}$. It can be seen that the assumption that transients can be terminated by hydrogen loss is conservative.
- 6) When the power excursion is terminated by hydrogen loss, the reactor shutdown is governed by the hydrogen loss from an average rod. In the physical reactor, seven fuel elements in the center of the core would burst prior to the rupture of the average rod. Under actual excursion conditions, the reactor shutdown would be initiated earlier than is indicated by the model. Earlier shutdown would reduce the magnitude of the transient experienced by the reactor.

All the other pertinent approximations and assumptions are presented in this report at the specific points, in the development of the model, where they are utilized.

C. DEVELOPMENT OF THE MATHEMATICAL MODEL

There are several methods by which a mathematical model of a physical system may be evolved. If the physical system is basically a distributed parameter system (described by partial differential equations) it will usually be

necessary to discretize the spatially dependent variables in order to obtain a solution to the system equations. This discretization can be accomplished by direct application of finite difference techniques. Utilization of finite difference techniques can result in various models describing the same system depending upon the approximation used (i. e., forward difference, backward difference, central difference, etc.). It is also possible to obtain a model of the system without using the partial differential equations. Here, the system is spatially discretized into a finite number of nodes. Total differential equations, describing the dynamics of each node, can then be written utilizing the laws of conservation.

Each of the various techniques described will result in a mathematical model which will, if computationally stable, converge to the right transient solution if a sufficient number of nodes are taken. The question then arises as to which model or method is the best. It can be arbitrarily stated that the best nodal model is that model which yields the correct solution with a minimum number of nodes and a minimum of computation time.

Although the mathematical development presented in Appendices B, C, and D appears continuous, it should be noted that the model is actually the end result of many trials and errors. The final model is one that was found to converge to the right transient solution with a minimum of computation time. It is possible that a more efficient model exists; however, the model used in BOOMER satisfies the requirements of yielding the correct solution with acceptable computation time.

III. DEVELOPMENT OF BOOMER CODE

The system equations presented in Appendices B, C, and D lend themselves to solution by conventional computational techniques. Although the equations can be solved by the utilization of an electronic analog computer, the amount of equipment necessary for an adequate simulation would be prohibitive. Therefore, it was deemed necessary to solve the equations on a digital computer.

Although the system equations are discretized in the space domain and lend themselves nicely to digital simulation, there is the problem of integration with respect to time. Due to the complexity of the system equations and the distinct possibility of computational stability problems, it was decided to use the simplest possible integration scheme. Mathematically, this integration method can be written as follows:

$$\alpha(t) = \alpha(t - \Delta t) + \left(\frac{d}{dt} \alpha \right) \times \Delta t \quad \dots (1)$$

This scheme of integration, called rectangular integration, can always be made computationally stable if a small enough time increment, Δt , is selected. The primary advantage of integrating with this equation is the great ease with which the system equations may be programmed. In addition to this, a stable solution to the system equations may be obtained with a minimum of programming time. In essence, Equation 1 represents a digital integrator and the system equations may be programmed digitally exactly as they would be programmed on an electronic analog computer. The disadvantage of this method of integration is that it can take an excessive amount of computer time to yield a solution. However, there are many techniques which can be used, in conjunction with Equation 1, which will minimize computer time and make the technique more practical. Several of these techniques were utilized in programming BOOMER and will be described in detail.

When a physical system is stable and nonoscillatory, and is initially at rest or at steady-state, the time derivatives representing the rate of change of the system variables are identically equal to zero. When the system is perturbed by some external driving function, these time derivatives will have a finite value dependent on the magnitude of the driving function. When the disturbing function is removed, the time derivatives will decay and approach zero as the system

settles to a new rest or steady-state condition. It can be seen that the magnitude of the time derivatives is variable and has a maximum, which is dependent on the magnitude of the forcing function and the nature of the system equations, and a zero minimum. If Equation 1 is utilized as the integrator, and a value of Δt is selected so that the system is computationally stable when the time derivatives are at a maximum, the computation time necessary to reach the steady-state solution is prohibitive. However, it is relatively easy to utilize a variable Δt which is dependent on the instantaneous values of the system variable and its derivative. This will result in rapid convergence to the steady-state solution. Let $\beta(t)$ represent any arbitrary time dependent variable and $\Delta \beta(t)$ represent the incremental change in $\beta(t)$ per time iteration. Each time iteration may then be forced to result in a constant per cent change in the magnitude of the variable $\beta(t)$ as follows:

$$\frac{\Delta \beta(t)}{\beta(t)} = C$$

where C is a constant, defining percent change in $\beta(t)$ per time iteration. The magnitude of the time increment for each time iteration may then be calculated

$$\Delta \beta(t) = \frac{d\beta(t)}{dt} \Delta t = c\beta(t)$$

$$\Delta t = \frac{c\beta(t)}{\frac{d\beta(t)}{dt}} \quad \dots (2)$$

Utilizing Equation 2 to compute the magnitude of the time increment per time iteration and Equation 1 to evaluate the integral, the system can be made to converge rapidly to the steady-state solution. However, there are still several difficulties to overcome. It should be noted that regardless of how small Δt is made, within practical computation limitations, there is still an approximation involved in the integration method. Because of this approximation, there is a small error introduced into the system with each time iteration. If the value of Δt is small and does not change with each iteration, this small error causes no difficulty. However, when a variable value of Δt is utilized,

the error can cause instability. This instability can be eliminated by the utilization of a digital filter. The function of this filter is quite simple. It does not permit the magnitude of Δt to increase as rapidly as the computation indicates that it should. However, when the computation indicates that the new value of Δt be smaller than the previous value, the time increment computation is not filtered and can respond instantly. A typical digital time filter is described in the following equations which are written in FORTRAN language. Let the following values be defined:

DELT = Δt , where Δt is the instantaneous value of the time increment.

DELT 1 = Δt_1 , where Δt_1 was the time increment utilized in the previous iteration.

BT = $\beta(t)$

DBT = $\frac{d\beta(t)}{dt}$

C = a constant defining the percent change in $\beta(t)$ per time iteration.

A = 50.0, the value of the filter constant.

The following equations define the digital filter:

DELT = C * ABSF(BT/DBT)

IF (DELT-DELT 1) 20, 20, 10

10 DELT = (DELT + A * DELT 1)/(A + 1)

20 DELT 1 = DELT

BT = BT + DBT * DELT

The effectiveness of the digital filter just described can be adjusted by altering the value of A.

The integration technique just described is applicable to a system with only one variable. In a real system, there are usually many variables which must be accounted for. Each system variable, when used in Equation 2, will probably yield a different value for Δt . In order to ensure stability for the entire system, the minimum value of Δt must be used as the time iteration. Let it be assumed that all the system variables can be represented by the vector BT (I), their derivatives by the vector DBT(I), and the number of equation in the system

by NUMBER. Then the following FORTRAN statements can be used to determine the value of the time increment:

```
DØ 40 I = 1, NUMBER
```

```
40 AUTØT = MAXIF (AUTØT, ABSF (DBT (I)/BT(I))
```

```
DELT = C/AUTØT
```

By the process just described, the equations can be made to be computationally stable. However, it introduces another problem if the time constants for the individual equations are too dissimilar. In this case, the time increment necessary to ensure stability for the most rapidly changing variable may be too small to appreciably change the magnitude of the other system variables and will result in excessively large computing times. There are several relatively simple techniques which can be used to modify the time incrementation, without compromising accuracy or stability, which will result in shorter computation times. The first and most straightforward is the judicious selection of nodal points in representing space dependent variables. For example, in selecting the nodal configuration for the heat transfer model described in Appendix B, the fuel rod was divided into equal-volume nodes. The advantage of this method of space discretization is twofold. First, all of the nodes will have equal time constants, thereby eliminating computational instability so far as the heat transfer equations are concerned. Second, the nodes are concentrated in the region of maximum temperature gradient and this will result in a more accurate mathematical model requiring a minimum number of nodes. Other methods of reducing computation time are not so straightforward and require judicious examination of the physical system. With regard to BOOMER, the time constants for the reactor kinetics equations are several orders of magnitude shorter than the thermal time constants. If all of the system equations were integrated with the Δt that is initially required by the kinetics equations, the results would be disastrous. First of all, the computation time would be excessive. Secondly, the change in the thermal variables would be so small per time iteration that round-off error would be the largest contributor. The solution to the heat transfer equations, as given by the computer, would be meaningless. Examination of the physical system shows that there can be no change in any of the thermal variables until the flux level of the reactor has increased to the point of sensible heat generation. Therefore, there is no need to start solving the system heat

transfer equations until the solution of the kinetics equations yields a flux level commensurate with sensible heat generation. The equations solved should now include the heat transfer equations. However, the time increment for the kinetics is still much shorter than that required by the heat transfer equations. A realistic time increment for the heat transfer can be calculated, knowing the reactor power generation rate and the heat capacity of the core. Let the following be defined:

PWR = initial reactor power level in Btu/sec (input data).

CAP = heat capacity of the core in °F/Btu (input data).

FLUX = normalized flux level of the core (at the initial conditions of the reactor, the flux level is defined at unity) (computed).

DELTF = time increment required by the heat transfer equations (computed)

DTEMP = the allowable change in core temperature per time iteration (input data). (This is set at a temperature increment per time iteration commensurate with computational stability.)

DELTA = kinetics time increment (computed).

QG = reactor heat generation rate in Btu/sec (computed).

The time increment required by the heat transfer equations can be calculated as follows:

QG = PWR * FLUX

DELTF = DTEMP/(QG * CAP)

The time increment required to solve the heat transfer equations can now be compared to the kinetics time increment. If the kinetics time increment is smaller, the kinetics equations are iterated and the time increments are summed until the time accumulated is equal to time increment required by the heat transfer. The heat transfer equations are then incremented. The simplified block diagram shown in Figure 1 will best illustrate this process. This diagram illustrates how the program loops through the kinetics equations until the Δt is sufficiently large to require a heat transfer computation.

The discussion just presented seems to indicate that the time iteration technique is quite complex. It is true that, in order to obtain an efficient

Figure 1. Heat Transfer Block Diagram

solution (i. e., obtain a complete transient in a minimum of computation time), it is necessary to manipulate the time iteration computation method. However, it should be noted that a solution to the system equations can be obtained without excessive manipulation of the time iteration technique, and only computer time is sacrificed. If it is important to obtain answers in a minimum of time, the technique has a great advantage. Once the code is working and supplying the required data, the program may be gradually improved to reduce computation time.

IV. DESCRIPTION AND USE OF BOOMER

A. DESCRIPTION

The system equations, presented in Appendices B, C, and D, were programmed into a digital code called BOOMER. In order to facilitate programming and to have independent computation blocks which could be readily incorporated into other digital programs, BOOMER was coded as a main program and several subroutines. The primary function of the main program is to couple the various subroutines together, provide the necessary feedback equations, perform the integration process, and provide all the necessary output statements.

The following list denotes all of the subroutines used in BOOMER and describes their function:

- 1) Subroutine REAC — All of the kinetics equations including the prompt and delayed neutron equations are contained in this block.
- 2) Subroutine H2DIFU — This program contains all of the equations pertaining to hydrogen diffusion. The physical constants that are used in conjunction with the hydrogen diffusion equations are also evaluated.
- 3) Subroutine REACIN — This subroutine is used so that any arbitrary reactivity input, $\rho(t)$, may be programmed as an input to the model. Point values of reactivity and the corresponding time that the reactivity input has this value are programmed in as an input data list. The subroutine stores these values and linearly interpolates between points to give a continuous function of time.
- 4) Subroutine ARBPOW — This routine is included so that the heat transfer and hydrogen diffusion can be decoupled from the reactor kinetics. The reactor power, as an arbitrary function of time, can be programmed into the code while the reactor kinetics equations are deactivated. The instantaneous value of reactor power, $P(t)$, and the corresponding time of occurrence, T , are supplied to the code as an input list of data points. The subroutine will interpolate between adjacent time points to obtain a continuous function of time.

- 5) Subroutine Radii – The radius increments necessary for dividing the fuel rod into equal volume nodes are calculated in this subroutine.
- 6) Subroutine HTCOE – This subroutine is used to evaluate the coefficients required by the heat transfer equations.
- 7) Subroutine AXPOW – The axial power distribution within the fuel rod is calculated in this subroutine. There are two options available. The power distribution in the fuel rod can be either a chopped cosine distribution, which is calculated by the subroutine, or any arbitrary distribution dependent on an input data list. The coefficients necessary for calculating the axially distributed volumetric heat generation rates are evaluated.
- 8) Subroutine TEMFCO – The spatially dependent coefficients for evaluating the prompt temperature feedback are evaluated in this subroutine.
- 9) Subroutine HTRAN – The spatially discretized heat transfer equations representing the clad fuel rods are contained in this subroutine.
- 10) Subroutine REACRP – This subroutine contains modified kinetics equations to be used when the reactivity insertion to the reactor is either a small step (less than 80¢) or slow ramp rates (less than 2¢/sec).
- 11) Subroutine AICRT – This subroutine is used to present the output data in graphical form.

In order to minimize the input data and to maximize the computing efficiency, BOOMER was programmed as a special purpose code. In its present form, BOOMER is only applicable to the SNAP 2/10A reactor. However, with very few modifications it can be made to simulate other SNAP cores.

B. USE

The basic function of BOOMER is to determine the transient response of a SNAP 2/10A reactor when it is subjected to various reactivity insertions. The transients that may be evaluated are neutron flux, delayed neutron precursors, reactor power, integrated energy, spatially distributed fuel and coolant temperatures, spatially distributed hydrogen concentration and flux, hydrogen pressure within the fuel rod, and the negative reactivity feedback terms. In addition

to the basic BOOMER computations, there are many options available. The best way to describe these options is to present the input data list and to explain in detail the function of each input. The following list of data is presented in the order required by the program:

- 1) Permanent data block consisting of 7 cards which are used for labeling the ordinate or abscissa of the graphical output.
- 2) Run Identification – This will print a title in Hollerith characters on the graphical output. This title should be centered on columns 1 through 54.
- 3) BNODER – Determines the number of radial nodes to be used in simulating the fuel rod. The number of nodes can vary between 1 and 20.
- 4) BNODEA – Assigns the number of axial nodes to be used in simulating the fuel rod and coolant channels. Up to 10 nodes may be used.
- 5) Flow – Total core coolant flow rate in lb/sec.
- 6) PWR – Initial reactor power level in watts.
- 7) TIN – Reactor inlet coolant temperature in °F.
- 8) TMAX – This provides a time limit for the transient. The program will start into the next data case if the transient time reaches TMAX seconds.
- 9) RODCO – With the code configuration presented in this report, this input must be set equal to unity.
- 10) H2CI – Initial average hydrogen concentration in atoms/cc $\times 10^{-22}$.
- 11) RHOS – Initial reactivity shutdown in dollars.
- 12) RHOFT – Reactivity ramp insertion rate in \$/sec.
- 13) RHOST – Reactivity step insertion in dollars.
- 14) GPUP – Upper grid plate coefficient in \$/°F.
- 15) GPLOW – Lower grid plate coefficient in \$/°F.
- 16) FTCA – Prompt temperature coefficient in \$/°F.
- 17) FTCB – Prompt temperature coefficient in $\$/(\text{°F})^2$.

- 18) SELPWR — This is a dual purpose input. The sign of SELPWR determines the form of the axial power distribution which will be used during the transient. A (+) sign establishes a chopped cosine distribution and a (-) sign will call for an input data list which will describe any arbitrary power distribution. The absolute value of the magnitude of SELPWR establishes the value of neutron flux at which the transient will be terminated. This computation stop is effective only if the transient has passed a flux peak and the magnitude of neutron flux is decreasing. The transient will be terminated when the flux level decays to a value determined by $(\text{PEAK FLUX})/\text{FLUX} = \|\text{SELPWR}\|$
- 19) EGYSTP — This is another computation stop and limits the amount of energy which can be integrated during the transient. The value of EGYSTP is the magnitude of the maximum integrated energy in megawatt-seconds.
- 20) CDELTA — Determines the size of the time increment. The size of CDELTA that has been used in most cases is 0.002.
- 21) POWOUT — Determines the maximum temperature increment per time iteration. The recommended value is 2.0.
- 22) Print — This determines the number of time iterations of the heat transfer equations between points plotted. There is no particular requirement on this value, but values of 25 to 100 have been successfully used.
- 23) AX — This is the unchopped length of the cosine power distribution in inches.
- 24) HOLD — If hold is set at +1.0, the reactor kinetics will be included in transient. If it is set at +2.0, the reactor kinetics will be deactivated and only the thermal and hydrogen transient, in response to a volumetric heat generation rate determined by the input HEAT, will be evaluated.
- 25) RPRINT — This determines the number of time iterations of the kinetics equations between points plotted on the graphical output. A value of 1200 has been effectively used, but can be changed to obtain a finer or a coarser output plot.

- 26) HEAT — This is a dual purpose input. The magnitude of the absolute value of HEAT determines the ratio of the points plotted on the graphical output to the number of points printed as output. With HOLD set at +2.0, the sign of HEAT will determine the volumetric heat generation rate. If the sign of HEAT is (-), the volumetric heat generation rate is an arbitrary function of time determined by an input data list. If the sign of HEAT is (+), the volumetric heat generation rate is a constant determined by the initial power generation of the reactor PWR.
- 27) REAVAR — This is set equal to +1.0 for a reactivity input which is an arbitrary function of time determined by an input data list. It is set to +10.0 for either a reactivity ramp or step insertion.
- 28) TCH — The diffusion coefficient that is utilized during the transient can be altered with this input. To obtain the BMI diffusion coefficient,⁴ set TCH to 3000.0. To obtain a diffusion coefficient commensurate with electrical resistance heating experiments,^{2,3} set TCH to 2000.0.
- 29) RHOSTP — If the reactivity input is a ramp insertion, this input will limit the total amount of reactivity which can be inserted (in dollars).
- 30) APROX — This determines what kinetics equations will be used, during the computation, when the reactivity insertion is a step. If the reactivity step is greater than APROX, subroutine REAC will be used. If it is less than or equal to APROX, subroutine REACRP will be used.
- 31) H2STP — This is a computation stop and will cause the program to start into the next data case when the instantaneous value of the average core N_H (initial value of average core N_H) is equal to H2STP.
- 32) If the sign of SELPWR was (-), calling for an arbitrary axial power distribution, the normalized power distribution must now be supplied as input data. The distribution must be supplied for each axial node starting from the coolant inlet end of the rod.
- 33) If the sign of HEAT was (-), calling for a reactor heat generation rate, in Btu/sec, which is an arbitrary function of time, the input data list must be supplied. The first data card is in fixed point and indicates the number of time points that will be stored up to 50. It should be

noted that these are time points other than zero time which is accounted for by the initial conditions. The next set of data is in floating point and the data must be supplied in the following order: power in Btu/sec, corresponding time in sec, power, time, etc.

- 34) If REAVAR was set equal to +1.0, calling for an arbitrary reactivity insertion, this data must now be supplied. The first data card is in fixed point and indicates the number of time points, other than zero, which will be stored (up to 50). The next set of data is in floating point and must be read in the order of reactivity in dollars, corresponding time, reactivity time, etc.

Sample data sheets are included in Appendix E, to clarify the programming of input data.

The output of the digital code is presented in two ways; one is printed in tabular form (printout), and the other is presented graphically. The quantity of printed output can be controlled by the manipulation of the input data RPRINT, PRINT, and HEAT. A typical printout which minimizes tabular data is presented in Appendix F.

C. MODIFICATION OF BOOMER RESULTS

It should be noted that no account of reactor disassembly is included in the BOOMER system equations. Reactor disassembly is a major contributor in terminating a reactor excursion resulting from large reactivity step or ramp insertions. The affect of reactor disassembly, on limiting the energy generated during a transient, can be easily obtained from the BOOMER graphical output and Figure 2. Knowing the size of the reactivity step initiating the transient, the time between cladding burst and reactor disassembly, τ , can be obtained from Figure 2. At the start of reactor disassembly, the reactivity loss rate is $\sim 10^6/\text{sec}$, and for all practical purposes, no more energy can be integrated. The instant of average rod cladding burst, T , can be obtained from the graphical output as illustrated in Appendix G. The maximum integrated energy is obtained from the graphical output (integrated energy curve, Appendix G) at time $T + \tau$. It should be noted that the approximation is conservative, since τ is calculated from average rod burst. The time for the reactor to start disassembly after average rod burst is less than τ seconds.

Figure 2. Time Between Cladding Burst and Reactor Disassembly (center rod)

V. REFERENCES

1. Huntsinger, M., "SNAP 10A, SNAPSHOT (Preliminary) Safety Report, " NAA-SR-6684 (February 1962)
2. Taylor, R. E., "Pulse Heating of Zirconium-Uranium Hydrides, " NAA-SR-7398 (1962)
3. Taylor, R. E., "Pulse Heating of Modified Zirconium-Uranium Hydrides, " NAA-SR-7736 (1962)
4. Dayton, R. W. and Tipton, C. R., Jr.; "Progress Relating to Civilian Application During May 1958, " BMI-1267 (1958)
5. Sommer and Dennison, "Thermal Diffusion of Hydrogen in Nonstoichiometric Zirconium - Dihydride, " NAA-SR-5066 (October 1960)

VI. BIBLIOGRAPHY

1. Brammer, W., "Thermal Gradient Self-Diffusion in Metals," Bull. Am. Phys., Sec. II (1957)
2. Crank, J., The Mathematics of Diffusion (Oxford, University Press, 1957)
3. Davis, W., "Diffusion of Gases Through Metals," KAPL-1227 (October 1954)
4. Flint, P., "The Diffusion of Hydrogen Through Metals of Construction," KAPL-659 (December 1951)
5. Markowitz, J., "Hydrogen Redistribution in Zircaloy-2 Under Thermal and Mechanical Gradients," WAPD-TM-171 (January 1957)
6. Shewmon, P., "The Redistribution of a Second Phase During Annealing in a Temperature Gradient," Trans. Mat. Soc., AIME-212 (1958)
7. Smithells, C., "The Diffusion of Gases Through Metals," Proc. of the Roy. Soc. (London), 772-197 (May 1935)

APPENDIX A

NOMENCLATURE AND SYMBOLS

α_{gl}	= lower grid plate coefficient ($^{\circ}\text{F}/\text{\$}$)
α_{gu}	= upper grid plate coefficient ($^{\circ}\text{F}/\text{\$}$)
α_p	= prompt temperature coefficient ($^{\circ}\text{F}/\text{\$}$)
β	= total fraction of neutrons that are delayed
β_i	= fraction of total neutrons belonging to i^{th} delayed group
β_{fi}	= fraction of delayed neutrons belonging to the i^{th} group
ρ_f	= density of fuel ($\text{lb}/\text{in.}^3$)
ρ_h	= density of hydrogen gap ($\text{lb}/\text{in.}^3$)
ρ_b	= density of hydrogen barrier ($\text{lb}/\text{in.}^3$)
ρ_c	= density of cladding ($\text{lb}/\text{in.}^3$)
ρ_{co}	= density of coolant ($\text{lb}/\text{in.}^3$)
ρ	= reactivity ($\text{\$}$)
ρ_{pfb}	= prompt temperature reactivity feedback ($\text{\$}$)
ρ_{gfb}	= grid plate temperature reactivity feedback ($\text{\$}$)
ρ_o	= initial shutdown reactivity ($\text{\$}$)
τ_i	= decay constant of i^{th} delayed neutron precursor (sec^{-1})
A	= area of boundary node (cm^2)
A_x	= unchopped length of cosine distribution (in.)
C_f	= heat capacity of fuel ($\text{Btu}/\text{lb}-^{\circ}\text{F}$)
C_h	= heat capacity of hydrogen gap ($\text{Btu}/\text{lb}-^{\circ}\text{F}$)
C_b	= heat capacity of hydrogen barrier ($\text{Btu}/\text{lb}-^{\circ}\text{F}$)
C_c	= heat capacity of cladding ($\text{Btu}/\text{lb}-^{\circ}\text{F}$)
C_{co}	= heat capacity of coolant ($\text{Btu}/\text{lb}-^{\circ}\text{F}$)
C_i	= i^{th} neutron precursor population (cm^{-3})
C_{io}	= initial C_i

D = hydrogen diffusion coefficient (cm^2/sec)
 J = hydrogen flux ($\text{moles H}_2/\text{cm}^2\text{-sec}$)
 k = thermal neutron multiplication factor
 K_1 = DISRO, a factor used to convert heat to its equivalent hydrogen release counterpart ($\text{Btu/in. -cm}^2\text{-mole H}_2$)
 K_2 = conversion factor for determining worth of lost hydrogen ($100 \times \$/\% N_{\text{initial}}$)
 K_b = thermal conductivity of hydrogen barrier ($\text{Btu/sec-}^\circ\text{F}$)
 K_c = thermal conductivity of cladding ($\text{Btu/sec-}^\circ\text{F}$)
 K_f = thermal conductivity of fuel ($\text{Btu/sec-}^\circ\text{F}$)
 K_H = thermal conductivity of hydrogen gap ($\text{Btu/sec-}^\circ\text{F}$)
 L = length of fuel rod (in.)
 ℓ^* = thermal neutron diffusion lifetime (sec)
 N = hydrogen concentration (at H/ cm^3)
 $\bar{N}_{\text{initial}}$ = initial average hydrogen concentration (at H/ cm^3)
 N_N = neutron population (neutrons/ cm^3)
 N_o = initial neutron population (neutrons/ cm^3)
 P_R = reactor power at any time (units of P_i)
 P_i = initial reactor power
 P = pressure (atmospheres)
 Q_g = heat generation rate in a node (Btu/sec)
 Q_v = volumetric heat generation rate ($\text{Btu/in.}^3\text{-sec}$)
 Q_{in} = heat transferred into an elemental fuel volume (Btu/sec)
 Q_{out} = heat transferred out of an elemental fuel volume (Btu/sec)
 Q = heat flow (Btu/sec)
 Q_{of} = heat flow out of the fuel (Btu/sec)
 Q_{∞} = heat flow out of cladding (Btu/sec)
 Q_s = heat stored in an elemental volume (Btu/sec)
 Q_o = heat leaving a coolant node (Btu/sec)
 Q_a = heat added to a coolant node (Btu/sec)

Q^* = heat of transport (cal/mole)
 R_{bi} = inside radius of barrier (in.)
 R_{ci} = inside radius of cladding (in.)
 R_{co} = outside radius of cladding (in.)
 R = radius (in.) and (cm)
 R_s = Radius of fuel (in.)
 R_e = equivalent thermal resistance ($^{\circ}\text{F}\text{-sec/Btu}$)
 R_{ef} = thermal resistance of center of outer fuel node and fuel surface ($^{\circ}\text{F}\text{-sec/Btu}$)
 R_{eH} = thermal resistance of hydrogen gap ($^{\circ}\text{F}\text{-sec/Btu}$)
 R_{eb} = thermal resistance of hydrogen barrier ($^{\circ}\text{F}\text{-sec/Btu}$)
 R_{ec} = thermal resistance between inside of cladding and center of cladding ($^{\circ}\text{F}\text{-sec/Btu}$)
 R_{eo} = thermal resistance between cladding center and cladding surface ($^{\circ}\text{F}\text{-sec/Btu}$)
 $\bar{R}$ = total thermal resistance between outer fuel node and center of cladding ($^{\circ}\text{F}\text{-sec/Btu}$)
 $\mathcal{R}$ = gas constant = 1.987 (cal/mole- $^{\circ}\text{K}$)
 R_n = radius at node n
 S_o = neutron source strength (neutrons/cm³-sec)
 t = time (sec)
 T_{in} = reactor inlet temperature ($^{\circ}\text{F}$)
 T_{co} = coolant node outlet temperature ($^{\circ}\text{F}$)
 T_{ci} = coolant node inlet temperature ($^{\circ}\text{F}$)
 T_c = average coolant node temperature ($^{\circ}\text{F}$)
 T_H = average temperature of hydrogen gap gas ($^{\circ}\text{F}$)
 T_f = fuel temperature ($^{\circ}\text{F}$)
 T_s = fuel surface temperature ($^{\circ}\text{F}$)

V = volume (in.³)
 v = volume of coolant associated with average fuel rod (in.³)
 V_b = volume of barrier (in.³)
 V_c = volume of cladding (in.³)
 V_n = nodal volume (cc)
 V_{co} = total coolant volume (in.³)
 V_H = volume of hydrogen gap (in.³)
 W_H = weight of H₂ stored in gap (lb)
 $\dot{W}_T$ = total coolant flow rate (lb/sec)
 $\dot{W}$ = coolant flow rate past a single rod (lb/sec)
 Z = length of axial node (in.)

APPENDIX B

DERIVATION OF THE HEAT TRANSFER EQUATIONS

Figure B-1 illustrates a cross section of a fuel rod and shows the location of the fuel, hydrogen gap, hydrogen barrier, and cladding.

Let it be assumed that there is no heat transfer in the axial direction in a fuel rod. Therefore, all the heat generated must be transferred radially.

Figure B-1. Fuel Rod Cross Section

Figure B-2 illustrates a section of the fuel and an elemental volume. The volume of the elemental volume for a unit length is*

$$dV = 2\pi R dR \quad .$$

*Symbols are defined in Appendix A

ELEMENTAL VOLUME

Figure B-2

Let Q_v be the volumetric heat generation rate. Then the heat generated in the elemental node is

$$Q_g = Q_v dV = 2\pi R Q_v dR \quad \dots (B-1)$$

The heat transferred into the elemental volume is

$$Q_{in} = 2\pi R K_f \frac{\partial T}{\partial R} \quad \dots (B-2)$$

The heat transferred out of the elemental volume is

$$Q_{out} = -2\pi K_f (R + dR) \left[\frac{\partial T}{\partial R} + \frac{d}{dR} \left(\frac{\partial T}{\partial R} \right) dR \right]$$

or

$$Q_{out} = -2\pi K_f \left[R \frac{\partial T}{\partial R} + dR \frac{\partial T}{\partial R} + R dR \frac{\partial^2 T}{\partial R^2} \right] \quad \dots (B-3)$$

The heat stored in the elemental volume is

$$Q_s = 2\pi R dR \rho_f C_f \frac{\partial T}{\partial t} \quad \dots (B-4)$$

The heat balance equation may now be written

$$Q_s = Q_{in} + Q_g + Q_{out} \quad \dots (B-5)$$

Substituting Equations B-1, B-2, B-3, and B-4 into Equation B-5 and simplifying, the basic heat transfer equation for the fuel can be seen to be

$$\frac{\partial T}{\partial t} = \frac{Q_v}{\rho_f C_f} + \frac{K_f}{\rho_f C_f} \left[\frac{1}{R} \frac{\partial T}{\partial R} + \frac{\partial^2 T}{\partial R^2} \right] \quad \dots (B-6)$$

Utilizing the average of the forward and backward difference approximation for the first derivative and the central difference approximation for the second derivative, Equation B-6 may be written in the following form:

$$\frac{dT_n}{dt} = \frac{Q_v}{\rho_f C_f} + \frac{K_f}{\rho_f C_f} \left[\frac{T_{(n+1)} - T_{(n-1)}}{2R_n \Delta R} + \frac{T_{(n+1)} + T_{(n-1)} - 2T_n}{\Delta R^2} \right] \quad \dots (B-7)$$

Utilizing the symmetry about the center of the rod, this equation can be used to represent the instantaneous temperature in the fuel. However, the equation requires an excess number of nodes to converge. Let it be assumed that the radial temperature gradient between adjacent nodes, having known instantaneous values of temperature, can be calculated from the steady-state solution to the heat transfer equations. The steady-state equation can be obtained from Equation B-5.

$$Q_s = Q_{in} + Q_g + Q_{out} = 0 \quad \dots (B-8)$$

Utilizing Equations B-1, B-2, B-3, and B-4, and simplifying, the basic steady-state heat transfer can be seen to be

$$0 = Q_v R dR + K_f dR \frac{\partial T}{\partial R} + K_f R dR \frac{\partial^2 T}{\partial R^2}$$

or

$$\frac{d}{dR} \left(R \frac{dT}{dR} \right) + \frac{Q_v R}{K_f} = 0 \quad \dots (B-9)$$

Integrating Equation B-9 we have

$$\frac{dT}{dR} + \frac{Q_v R}{2K_f} + C_1 = 0 \quad \dots (B-10)$$

at $R = 0$

$$\frac{dT}{dR} = 0 \quad ,$$

therefore

$$C_1 = 0 \quad .$$

Integrating Equation B-10 we have

$$T = C_2 - \frac{Q_v R^2}{4K_f}$$

at $R = R_s$, $T = T_s$

therefore

$$T - T_s = \frac{Q_v}{4K_f} (R_s^2 - R^2)$$

Figure B-3

Figure B-3 illustrates three points sitting on a radius. If points A and C are known nodal temperatures, the temperature at any other point B may be calculated in the following way:

$$T_A - T_s = \frac{Q_v}{4K_f} (R_s^2 - R_A^2)$$

$$T_C - T_s = \frac{Q_v}{4K_f} (R_s^2 - R_C^2)$$

$$T_A - T_C = \frac{Q_v}{4K_f} (R_C^2 - R_A^2)$$

$$\frac{T_A - T_C}{R_C^2 - R_A^2} = \frac{Q_v}{4K_f} = \frac{T_B - T_C}{R_C^2 - R_B^2}$$

$$T_B = T_C + (T_A - T_C) \left(\frac{R_C^2 - R_B^2}{R_C^2 - R_A^2} \right) \quad \dots (B-11)$$

FUEL CROSS SECTION

Figure B-4

Figure B-4 illustrates a cross section of the fuel which is divided into n radial nodes. It can be seen that there are $2n + 1$ temperatures, where $T_{2n + 1}$ represents the fuel surface temperature and T_1 is the temperature of the center of the rod. The even numbered subscripts refer to the temperature at the center of each node and the odd numbered subscripts refer to the temperature of the boundary of two adjacent nodes. R_1 is the radius at the center of the rod, and is identically equal to zero.

It can be seen that the radius at the surface, R_s , is identified as $R_{n + 1}$. Utilizing Equations B-7 and B-11, we may now write the finite difference equations describing the temperature distribution in a fuel rod in the radial direction.

$$T_1 = T_4 + (T_2 - T_4) \left[\frac{\left(\frac{R_2 + R_3}{2} \right)^2}{\left(\frac{R_2 + R_3}{2} \right)^2 - \left(\frac{R_2}{2} \right)^2} \right] \quad \dots (B-12)$$

$$\frac{dT_2}{dt} = \frac{Q_v}{\rho_f C_f} + \frac{2K_f}{\rho_f C_f} \left[\frac{1}{R_2} \left(\frac{T_3 - T_1}{R_2} \right) + 2 \left(\frac{T_3 + T_1 - 2T_2}{R_2^2} \right) \right] \quad \dots (B-13)$$

The equations for any node J may be written

$$T_{2J-1} = T_{2J} + (T_{(2J-2)} - T_{2J}) \left[\frac{\left(\frac{R_J + R_{(J+1)}}{2} \right)^2 - R_J^2}{\left(\frac{R_J + R_{(J+1)}}{2} \right)^2 - \left(\frac{R_{(J-1)} + R_J}{2} \right)^2} \right] \quad \dots (B-14)$$

$$\frac{dT_{2J}}{dt} = \frac{Q_v}{\rho_f C_f} + \frac{2K_f}{\rho_f C_f} \left\{ \frac{T_{(2J+1)} - T_{(2J-1)}}{R_{(J+1)}^2 - R_J^2} + 2 \left[\frac{T_{(2J+1)} + T_{(2J-1)} - 2T_{2J}}{(R_{(J+1)} - R_J)^2} \right] \right\} \quad \dots (B-15)$$

Figure B-5

Figure B-5 illustrates an enlarged section of the fuel rod. If it is assumed that the fuel is divided into n nodes, then the following temperatures are defined.

$T_{(2n+1)}$ = Fuel surface

$T_{(2n+2)}$ = Center of hydrogen gap

$T_{(2n+3)}$ = Inside of hydrogen barrier

$T_{(2n+4)}$ = Center of hydrogen barrier

$T_{(2n+5)}$ = Inside of cladding

$T_{(2n+6)}$ = Center of cladding

$T_{(2n+7)}$ = Cladding surface

Let the following variables be defined:

Q_{of} = Heat flow out of the fuel in Btu/sec

Q_{oc} = Heat flow out of the cladding in Btu/sec

Since the individual thermal capacities of the hydrogen, hydrogen barrier, and cladding are small, we may lump them together and obtain the following equation for the temperature of the cladding.

$$\frac{dT_{(2n+6)}}{dt} = \frac{1}{\rho_H V_H C_H + \rho_b V_b C_b + \rho_c V_c C_c} (Q_{of} - Q_{oc}) \quad \dots (B-16)$$

Since all the heat storage has been assumed to be centered in the cladding and the fuel, the temperature distribution between the fuel and the cladding is based only on conduction. If the fuel rod is L inches long and it is divided into m axial nodes, then the length of each axial node is

$$Z = L/m \quad \dots (B-17)$$

For heat conduction through a plane wall the following equation is true:

$$Q = \frac{KA\Delta T}{\Delta \ell} \quad ,$$

or

$$QR = \Delta T \quad ,$$

where R is defined as the thermal resistance. For heat transfer through a cylindrical wall,

$$Q = \frac{2\pi KZ(T_A - T_B)}{\log_e(R_B/R_A)} \quad ,$$

and the equivalent resistance is defined as

$$R_e = \frac{\log_e (R_B/R_A)}{2 \pi K Z} . \quad \dots (B-18)$$

The last point in the fuel where the volumetric heat generation manifested itself was located at $2n$. The temperature differential between this point and the fuel surface can be attributed to conduction. The thermal resistance between $2n$ and $(2n + 1)$ can be obtained utilizing Equation B-18, and is defined by the following equation:

$$R_{ef} = \frac{\log_e \left(\frac{2R_{(n+1)}}{R_n + R_{(n+1)}} \right)}{2 \pi K_f Z} , \quad \dots (B-19)$$

where

$R_{(n+1)}$ = Fuel surface radius

Let the following radii be defined:

R_{bi} = Inside radius of the barrier

R_{ci} = Inside radius of the cladding

R_{co} = Outside radius of the cladding

The thermal resistance of the hydrogen gap is

$$R_{eH} = \frac{\log_e \left(\frac{R_{bi}}{R_{(n+1)}} \right)}{2 \pi K_H Z} \quad \dots (B-20)$$

The thermal resistance of the barrier is

$$R_{eb} = \frac{\log_e \left(\frac{R_{ci}}{R_{bi}} \right)}{2 \pi K_b Z} \quad \dots (B-21)$$

The thermal resistance of the cladding between the outside of the barrier and the center of the cladding is

$$R_{ec} = \frac{\log_e \left(\frac{R_{ci} + R_{co}}{2 R_{ci}} \right)}{2 \pi K_c Z} \quad \dots (B-22)$$

The total thermal resistance between the outermost fuel node, point $2n$, and the center of the cladding, point $2n + 6$ is

$$\bar{R} = R_{ef} + R_{eH} + R_{eb} + R_{ec} \quad \dots (B-23)$$

The heat flow out of the fuel can now be seen to be

$$Q_{of} = [T_{2n} - T_{(2n+6)}] / \bar{R} \quad \dots (B-24)$$

The fuel surface temperature

$$T_{2n+1} = T_{2n} - [T_{2n} - T_{(2n+6)}] \frac{R_{ef}}{\bar{R}} \quad \dots (B-25)$$

The hydrogen center temperature

$$T_{2n+2} = T_{2n} - [T_{2n} - T_{(2n+6)}] \frac{(R_{ef} + R_{eH}/2)}{\bar{R}} \quad \dots (B-26)$$

The barrier inside temperature

$$T_{2n+3} = T_{2n} - [T_{2n} - T_{(2n+6)}] \frac{(R_{ef} + R_{eH})}{\bar{R}} \quad \dots (B-27)$$

The barrier center temperature

$$T_{2n+4} = T_{2n} - [T_{2n} - T_{(2n+6)}] \frac{(R_{ef} + R_{eH} + R_{eb}/2)}{\bar{R}} \quad \dots (B-28)$$

The cladding inside temperature

$$T_{2n+5} = T_{2n} - [T_{2n} - T_{(2n+6)}] \frac{(R_{ef} + R_{eH} + R_{eb})}{\bar{R}} \quad \dots (B-29)$$

It should be noted that the temperatures at the center of the hydrogen gap and hydrogen barrier were approximated as lying halfway between their boundary temperatures. This approximation has no effect on the coupling between the cladding and the fuel and will not affect the overall transient response of the model. Because of the relatively small thickness of the barrier and the gap, the approximation is excellent. More accurate values for these temperatures could have been obtained by calculating the thermal resistance from the edge to the center of the barrier and gap, but this was not considered necessary.

The thermal resistance from the center of the cladding, point $2n + 6$, to the cladding surface, point $2n + 7$, can be seen to be

$$R_{eo} = \frac{\log_e \left(\frac{2R_{co}}{R_{co} + R_{ci}} \right)}{2\pi K_c Z} \quad \dots (B-30)$$

The heat transferred out of the cladding is

$$Q_{oc} = \frac{T_{(2n+6)} - T_{(2n+7)}}{R_{eo}} \quad \dots (B-31)$$

It will be assumed that the cladding is completely surrounded by coolant and that the temperature of the cladding surface, T_{2n+7} , is equal to the average coolant temperature in that axial node. At this point it will be convenient to change the nomenclature for the subscripts. The temperatures will now be referred to as $T(I, J)$ where

J = Axial position of the node. J can vary from 1 to m , the number of axial nodes.

I = Radial position of the node. I can vary from 1 to $2n + 7$ where n is the number of radial nodes.

Let the following values be defined:

The average coolant node temperature

$$T_c(J) = T(2n + 7, J) \quad \dots (B-32)$$

The inlet temperature of a coolant node is $T_{ci}(J)$ and the outlet temperature is $T_{co}(J)$. It is assumed that the coolant inlet temperature for the first node is identically equal to the reactor coolant inlet temperature T_{in} ;

$$T_{ci}(1) = T_{in} \quad \dots (B-33)$$

It will be assumed that there is a linear axial temperature gradient across a coolant node. Therefore,

$$T_{co}(J) = 2T_c(J) - T_{ci}(J) \quad ; \quad \dots (B-34)$$

$$T_{ci}(J+1) = T_{co}(J) \quad \dots (B-35)$$

It will be assumed that there is incompressible coolant flow. The heat leaving the cladding is obtained by rewriting Equation B-31 utilizing the new nomenclature.

$$Q_{oc}(J) = \frac{T_{(2n+6, J)} - T_{(2n+7, J)}}{R_{eo}} \quad \dots (B-36)$$

The heat added to a coolant node is

$$Q_a(J) = Q_{oc}(J) + \dot{W}_{co} T_{ci}(J) \quad \dots (B-37)$$

The heat leaving a coolant node is

$$Q_o(J) = \dot{W}_{co} T_{co}(J) \quad \dots (B-38)$$

Utilizing Equations B-31 and B-32 and writing a heat balance equation for a coolant node, the following equation is obtained:

$$\frac{dT_c(J)}{dt} = \frac{1}{\rho_{co} V(J) C_{co}} [Q_a(J) - Q_o(J)] \quad , \quad \dots (B-39)$$

where $V(J)$ is the volume of the coolant node.

If we define the fuel rod as an average rod, the total coolant flow rate as $\dot{W}_T$, the power of the reactor as P_R , and utilize the fact that there are 37 fuel rods, the power generated by the rod is

$$Q_g = \frac{P_R}{37} \quad , \quad \dots (B-40)$$

and the coolant flow rate past the rod is

$$\dot{W} = \frac{\dot{W}_T}{37} \quad \dots (B-41)$$

The total volume of coolant in the core is V_{co} ; therefore, the volume of coolant associated with the average rod is

$$V = \frac{V_{co}}{37} \quad \dots (B-42)$$

If there are m equal axial nodes, the volume of a coolant node is

$$V(J) = \frac{V}{m} \quad \dots (B-43)$$

There is an axial power distribution, as illustrated in Figure B-6, along the fuel rod. This distribution is given by the following equation:

$$\phi = \cos \left[\frac{\pi L}{Ax} \left(\frac{Z}{L} - 0.5 \right) \right] , \quad 0 \leq \frac{Z}{L} \leq 1$$

where

L = length of fuel rod

Ax = Unchopped length of the cosine.

Figure B-6

The power generated in any axial fuel node I can be calculated in the following way. We have

$$\frac{Z}{L}(1) = 0 \quad ,$$

and

$$\frac{Z}{L}(J+1) = \frac{J}{m} \quad ,$$

where m is the number of equal volume axial nodes.

Therefore, the fraction of total fuel rod heat generated in each axial node is

$$\text{DIS}(J) = \frac{\int_{\frac{Z}{L}(J)}^{\frac{Z}{L}(J+1)} \cos \left[\frac{\pi L}{Ax} \left(\frac{Z}{L} - 0.5 \right) \right] d \frac{Z}{L}}{\int_0^1 \cos \left[\frac{\pi L}{Ax} \left(\frac{Z}{L} - 0.5 \right) \right] d \frac{Z}{L}}$$

or

$$\text{DIS}(J) = \frac{\sin \left\{ \frac{\pi L}{Ax} \left[\frac{Z}{L}(J+1) - 0.5 \right] \right\} - \sin \left\{ \frac{\pi L}{Ax} \left[\frac{Z}{L}(J) - 0.5 \right] \right\}}{2 \sin \left(\frac{0.5 \pi L}{Ax} \right)} \quad \dots (B-44)$$

The volumetric heat generation rate in each axial fuel node is then

$$Q_G(J) = \frac{Q_g \times [\text{DIS}(J)]}{\pi R_s^2 \left(\frac{L}{m} \right)} \quad \dots (B-45)$$

APPENDIX C

DERIVATION OF THE REACTOR KINETICS EQUATIONS

The basic reactor kinetics equations are:

$$\frac{dN_N}{dt} = \frac{(\delta k - \beta)}{\ell^*} N_N + \sum_{i=1}^6 \lambda_i C_i + S_o \quad \dots (C-1)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\ell^*} N_N - \lambda_i C_i \quad , \quad \dots (C-2)$$

where S_o is the neutron source level.

At steady-state source power $N_N = N_o$, $\delta k = \delta k_o$, and

$$\frac{dN_N}{dt} = 0$$

$$\frac{dC_i}{dt} = 0 \quad .$$

Therefore, from Equation C-2 we have

$$\frac{\beta_i}{\ell^*} N_o = \lambda_i C_{io}, \quad \dots (C-3)$$

or

$$\sum_{i=1}^6 \frac{\beta_i}{\ell^*} N_o = \sum_{i=1}^6 \lambda_i C_{io} = \frac{\beta}{\ell^*} N_o \quad ;$$

from Equations C-1 and C-3, it can be seen that

$$S_o = -\frac{\delta k_o}{\ell^*} N_o \quad ;$$

from Equation C-2 it can be seen that

$$N_o = \frac{\lambda_i \ell^* C_{io}}{\beta_i}$$

and from Equation C-2

$$C_{io} = \frac{\beta_i}{\ell^* \lambda_i} N_o$$

Normalizing Equation C-1, we have

$$\frac{d(N_N/N_o)}{dt} = \frac{(\delta k - \beta) N_N}{\ell^* N_o} + \sum_{i=1}^6 \frac{\lambda_i C_i}{N_o} + \frac{S_o}{N_o},$$

or

$$\frac{d(N_N/N_o)}{dt} = \frac{(\delta k - \beta) N_N}{\ell^* N_o} + \sum_{i=1}^6 \frac{\beta_i C_i}{\ell^* C_{io}} - \frac{\delta k_o}{\ell^*};$$

let

$$\beta_{fi} = \frac{\beta_i}{\beta},$$

then

$$\frac{d(N_N/N_o)}{dt} = \frac{\beta}{\ell^*} \left[(\rho - 1) \frac{N_N}{N_o} + \sum_{i=1}^6 \beta_{fi} \frac{C_i}{C_{io}} - \rho_o \right], \quad \dots (C-4)$$

where ρ_o is the initial shutdown, in dollars.

Normalizing Equation C-2 in a similar manner, we have

$$\frac{d(C_i/C_{io})}{dt} = \lambda_i \left(\frac{N_N}{N_o} - \frac{C_i}{C_{io}} \right). \quad \dots (C-5)$$

If it is assumed that P_i is the initial or shutdown power generation in the reactor, then the instantaneous value of reactor power is

$$P_R = P_i \frac{N_N}{N_O} \quad \dots (C-6)$$

The prompt temperature feedback is weighted by the mean square of the flux distribution. The axial prompt temperature feedback weighting function is defined as follows:

$$FWT(J) = \frac{[DIS(J)]^2}{\sum_{J=1}^m [DIS(J)]^2} \quad \dots (C-7)$$

The average temperature for an axial fuel node J is

$$T_a(J) = \frac{\sum_{I=1}^{2n+1} T(I,J)}{2n+1} \quad \dots (C-8)$$

The prompt temperature reactivity feedback is then

$$\rho_{pfb} = -\alpha_p \sum_{J=1}^m [FWT(J)] [T_a(J)] \quad \dots (C-9)$$

The reactivity feedback from the grid plates is

$$\rho_{gfb} = -(\alpha_{gl})(T_{in}) - (\alpha_{gu}) [T_{co}(m)] \quad \dots (C-10)$$

APPENDIX D

HYDROGEN DIFFUSION EQUATIONS

The equation describing the hydrogen flux within a cylindrical fuel rod is

$$J = -D \frac{\partial N}{\partial R} - \frac{DNQ^*}{RT^2} \frac{\partial T}{\partial R} \quad (\text{From Reference 5}) \quad \dots (D-1)$$

where

J = Hydrogen flux (moles H_2 /cm²-sec)

D = Hydrogen diffusion coefficient (cm²/sec)

N = Hydrogen concentration (at. H/cm³)

Q^* = Heat of transport (1270 cal/mole)

T = Temperature (°K)

R = Gas constant [1.987 (cal/mole-K°)]

R = Radius (cm)

Using the same nomenclature as used in the heat transfer equations, and utilizing backward finite difference approximations, Equation D-1 may be reduced to the following general form.

$$J(I+1, J) = -D(I, J) \frac{[N(I, J) - N(I-1, J)]}{[R(I+1, J) - R(I, J)]} - \frac{D(I, J)N(I, J)Q^*}{RT^2(2I, J)} \frac{[T(2I+1, J) - T(2I-1, J)]}{[R(I+1, J) - R(I, J)]} \dots (D-2)$$

where $J(I, J) = 0$.

The notation used in Equation D-2 applies when the cylindrical rod is divided into J axial nodes and each axial node is divided into I annular ring nodes. The volume of one of these nodal rings is

$$V(I, J) = \pi L(J) [R^2(I+1) - R^2(I)] \quad \dots (D-3)$$

The rate of change of the hydrogen concentration in one of these nodes is

$$V(I, J) \frac{dN(I, J)}{dt} = 2\pi L(J) [R(I, J) J(I, J) - R(I+1, J) J(I+1, J)] \quad \dots (D-4)$$

This is the forward difference approximation to the general partial differential equation:

$$\frac{\partial(NV)}{\partial t} = \frac{\partial(JA)}{\partial R} dR \quad \dots (D-5)$$

Equation D-4 is applicable when hydrogen is considered to diffuse only in the radial direction.

To ensure computational stability, equal time constants for each node are maintained by dividing the fuel rod into equal volume nodes. The volume of each node is given by

$$V(I,J) = \frac{\pi R_s^2 L}{nm} \quad , \quad \dots (D-6)$$

where R_s and L are the total radius and length of the fuel rod, respectively, and n and m are the number of radial and axial nodes, respectively.

In general, the radii for the equal volume nodes can be represented by

$$R(I + 1) = \left[\frac{R_T^2}{n} + R^2(I) \right]^{1/2} \quad \dots (D-7)$$

In addition,

$$R(1) = 0 \quad , \quad \dots (D-8)$$

and

$$R(n + 1) = R_s = \text{Radius of the fuel surface.} \quad \dots (D-9)$$

In solving the foregoing equations, it is assumed that

$$J(I, 1) = 0 \quad , \quad \dots (D-10)$$

since no flux can emanate from a zero volume node. The hydrogen diffusion coefficient of a node, $D(I,J)$, is dependent on the node temperature. The following two expressions were used in determining $D(I,J)$ for use in the above equations:

$$D(I,J) = 0.4 e^{-10,450/T(I,J)} \quad \dots (D-11)$$

The above expression is reported in Reference 4 .

$$D(I,J) = 0.4 e^{-10,450/T(I,J)} + 0.2 e^{-\left[\frac{10,450}{T_{CH}} + \frac{T_{CH}}{25.6} + \frac{T(I,J)}{25.6}\right]} \quad \dots (D-12)$$

The expression represented by Equation D-12 was developed to match experimental tests (References 2 and 3). It should be noted that the node temperature, $T(I,J)$, is acquired from solving the heat transfer equations in the cylindrical rod. T_{CH} is a parameter developed for modifying the diffusion coefficient to determine the effect of the diffusion on the reactor transient. For normal operation, the value of T_{CH} is 2000°F and the units required by Equation D-12 are $^{\circ}\text{R}$.

The hydrogen concentration in a node at time t can be determined from

$$N(I,J)_t = N(I,J)_t - \Delta t + \frac{dN(I,J)}{dt} \Delta t \quad , \quad \dots (D-13)$$

which is seen to be an approximation of

$$N(I,J)_t = N(I,J)_{\text{initial}} + \int \frac{dN(I,J)}{dt} dt \quad \dots (D-14)$$

The weight of hydrogen gas stored in the hydrogen gap at any time t can be represented by

$$W_H(t) = W_{H_{\text{initial}}} + C_1 \int \sum_{J=1}^m J(n,J) dt \quad \dots (D-15)$$

Since the time constant for the hydrogen gas pressure is several orders of magnitude less than the time constant associated with hydrogen diffusion within

the fuel, the pressure variation can be assumed to be instantaneous. Utilizing the perfect gas equation, the pressure of the hydrogen gas in the gap is

$$P(t) = \frac{R T_H}{V_H} W_H(t) \quad \dots (D-16)$$

T_H is the average temperature of the gas in the hydrogen gap and may be represented by

$$T_H = \frac{\sum_{J=1}^m T(2n+2, J)}{m} \quad \dots (D-17)$$

The boundary value of the hydrogen concentration is determined at any time from the instantaneous value of pressure and temperature of the gas gap

$$N(n+1, J) = \frac{1}{2.775} \left[\log_{10} P + 8.64 + \frac{8370}{T(2n+1, J)} \right] \quad \dots (D-18)$$

Equation D-18 is the equation of state at the fuel boundary.

It should be noted that Equation D-2 is applicable only for temperatures less than 1925°K, the melting point of the fuel. For higher node temperatures, hydrogen loss is no longer governed by a diffusion process. At temperatures of 1925°K and above, Equation D-2 is modified to the following form:

$$J(I+1, J) = \frac{Q_v V(I, J)}{K_1 R(I+1)} + J(I, J) \frac{R(I)}{R(I+1)} \quad , \quad \dots (D-19)$$

where Q_v is the volumetric heat generation rate and K_1 is a constant used to convert energy to its equivalent hydrogen release counterpart.

Equation D-18 was obtained from the state equation,

$$\log_{10} P = AN - B - \frac{C}{T_f} \text{ (Reference 5)} \quad \dots (D-20)$$

The reactivity worth of the hydrogen lost from the fuel at any time is

$$\rho = K_2 \left[\bar{N}_{\text{initial}} - \sum_{I=1}^m \sum_{J=1}^n \frac{N(I,J)}{mn} \right] , \quad \dots (D-21)$$

where $\bar{N}_{\text{initial}}$ is the initial average hydrogen concentration.

To account for the nodal hydrogen dissociation heat loss, Equation B-7 must be modified to the following:

$$\begin{aligned} \frac{dT_n}{dt} = & \frac{Q_v}{\rho_f C_f} + \frac{K_f}{\rho_f C_f} \left[\frac{T_{(n+1)} - T_{(n-1)}}{2R_n \Delta R} + \frac{T_{(n+1)} + T_{(n-1)} - 2T_n}{\Delta R^2} \right] \\ & - \frac{K_3}{\rho_f C_f V_n} \left[A_n J_n - A_{(n-1)} J_{(n-1)} \right] . \end{aligned} \quad \dots (D-22)$$

A and J represent the area and hydrogen flux at a node boundary, respectively. K_3 is a constant which converts gm-atoms of hydrogen dissociated to its equivalent thermal energy counterpart. V_n represents the nodal volume. When A_n is in (in.²) and J_n is in (gm-atoms/cm²), K_3 is

$$\frac{39.6 \text{ kcal}}{\text{mole H}_2 \text{ dissociated}} \times \frac{3.968 \text{ Btu}}{\text{kcal}} \times (2.54)^2 \frac{\text{cm}^2}{\text{in.}^2}$$

which reduces to

$$\frac{1012.5 \text{ Btu}}{\text{gm-atom H}_2} \frac{\text{cm}^2}{\text{in.}^2} .$$

The dissociation energy (39.6 kcal/mole) was determined from results of electrical resistivity heating experiments.

It should be noted that hydrogen dissociation has been assumed to occur volumetrically. Actually, it will occur at the fuel surface until the "power limiting" provision is actuated. In view of the small magnitude of energy

associated with hydrogen dissociation, before "power limiting," as compared to the volumetric energy generation, this variation has little effect on the transients.

For small reactivity insertions, an approximation to the kinetics equations is used. The equations are

$$\frac{d(C_i/C_{io})}{dt} = \lambda_i \left(\frac{\Phi}{\Phi_o} - \frac{C_i}{C_{io}} \right) ; \quad \dots (D-23)$$

$$\frac{\Phi}{\Phi_o} = \frac{\rho_o - \sum_{i=1}^6 \beta_i \left(\frac{C_i}{C_{io}} \right)}{\rho - 1.0} . \quad \dots (D-24)$$

APPENDIX E
SAMPLE DATA SHEETS

FORTTRAN CODE SHEET

DECK NO _____ PROGRAMMER _____ DATE _____ PAGE _____ of _____ JOB NO. _____

[illegible]

NAA-SR-8414
E-2

FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. _____ PROGRAMMER _____ DATE _____ PAGE _____ of _____ JOB NO. _____

	NUMBER	D	IDENTIFICATION	DESCRIPTION	DO NOT KEY PUNCH
1	3	- 0.1		BNØDER	
13	3	- 0.1		BNØDEA	
25	0	- 0.0		FLØW	
37	1	- 0.5		PWR	
49	7	- 0.2	73 80	TIN	
61	6	- 0.3	9	TMAX	
1	1	- 0.1		RØDCØ	
13	6 5	- 0.1		HZCI	
25	1	- 0.1		RHØS	
37	0	- 0.0		RHØFT	
49	2	- 0.1	73 80	RHØST	
61	9	- 0.3	1 0	GPUP	
1	9	- 0.3		GPLØW	
13	1	- 0.3		FTCA	
25	0	- 0.0		FTCB	
37	1	- 0.4		SELPWR	
49	1	- 0.3	73 80	EGYSTP	
61	2	- 0.2	1 1	CDELT	
1	2	- 0.1		PØWØUT	
13	1	- 0.3		PRINT	
25	1 3 1	- 0.2		AX	
37	1	- 0.1		HØLD	
49	5	- 0.4	73 80	RPRINT	
61	1	- 0.2	1 2	HEAT	

FORTRAN FLOATING 8 DIGIT DECIMAL DATA

DECK NO. _____ PROGRAMMER _____ DATE _____ PAGE _____ of _____ JOB NO. _____

	NUMBER	D	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	1	- 0 2		REAVAR
13	3	- 0 4		TCH
25	1 1	- 0 2		RHØSTP
37	7	- 0 0		APPRØX
49	8	- 0 0	73 60	H2STP
61		-	1 3	
1		-		
13		-		
25		-		
37		-		
49		-	73 60	
61		-		
1		-		
13		-		
25		-		
37		-		
49		-	73 60	
61		-		
1		-		
13		-		
25		-		
37		-		
49		-	73 60	
61		-		

114-C-16

NAA-SR-8414
E-4

APPENDIX F
TYPICAL BOOMER PRINTOUT

0.30000000E 01 0.30000000E 01 0. 0.99999999E-06 0.70000000E 02
 0.59999999E 03 0.09999999E 01 0.65000000E 01-0.09999999E 01 0.
 0.20000000E 01-0.90000000E-03-0.90000000E-03-0.99999999E-04 0.
 0.09999999E 04 0.15000000E 03 0.20000000E-02 0.20000000E 01 0.09999999E 03
 0.13100000E 02 0.09999999E 01 0.50000000E 04 0.09999999E 02 0.09999999E 02
 0.30000000E 04 0.11000000E 02 0.70000000E 00 0.80000000E 00

INITIAL CONDITIONS

COOLANT FLOWRATE= 0. LBS/SEC
 COOLANT INLET TEMPERATURE= 0.70000E 02 LBS/SEC
 TOTAL REACTOR POWER= 1.00000E-06 WATTS
 REACTIVITY SHUTDOWN=-1.00 DOLLARS

INPUT DATA

REACTIVITY STEP INPUT= 2.00 DOLLARS
 REACTIVITY INPAMP= 0. DOLLARS/SECOND
 UPPER GRID PLATE TEMPERATURE COEFFICIENT=-0.90000E-03DOLLARS/DEGREE F
 LOWER GRID PLATE COEFFICIENT=-0.90000E-03DOLLARS/DEGREE F
 FUEL TEMPERATURE COEFFICIENTS FTCA=-1.00000E-04DOLLARS/DEGREE F FTCH= 0. DOLLARS/DEG F**2
 INITIAL VH CONCENTRATION AT EACH NODE= 6.50ATOMS*10**(-22)/CC
 NUMBER OF RADIAL NODES= 3. NUMBER OF AXIAL NODES= 3.
 HOT ROD TEMPERATURE COEFFICIENT= 1.00
 MAXIMUM ALLOWED EXCURSION TIME= 0.60000E 03SECONDS
 INTEGRATED ENERGY STOP=150.00MEGAWATTS

COMPUTING CONSTANTS

SELPR=00. CDELT=0.0020 POWOUT=2.00 PRINT= 100. AX= 13.10

REACTOR KINETICS

TIME= 0. INTEGRATED CORE ENERGY= 0. MEGAWATT*SECONDS

REACTIVITY FEEDBACK

RHBT=-1.00000E 00 RHOTB=-0.13300E-00 RHOSD=-0.86700E 00 RHOR= 0.

FLUX= 0.10000E 01 LFLUX= 0.

GROUP	C	DC
1	0.10000E 01	0.
2	0.10000E 01	0.
3	0.10000E 01	0.
4	0.10000E 01	0.
5	0.10000E 01	0.
6	0.10000E 01	0.

AXIAL NODE	POWER DISTRIBUTION	TEMPERATURE FEEDBACK COEFFICIENTS
1	0.26363E-00	0.19173E-00
2	0.47275E-00	0.61655E 00
3	0.26363E-00	0.19173E-00

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
1	0.14333E-11	0.	0.	1	0.70000E 02
				2	0.70000E 02
				3	0.70000E 02
				4	0.70000E 02
				5	0.70000E 02
				6	0.70000E 02
				7	0.70000E 02
				8	0.70000E 02
				9	0.70000E 02
				10	0.70000E 02
				11	0.70000E 02
				12	0.70000E 02

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
2	0.25711E-11	0.	0.	1	0.70000E 02
				2	0.70000E 02
				3	0.70000E 02
				4	0.70000E 02
				5	0.70000E 02
				6	0.70000E 02
				7	0.70000E 02
				8	0.70000E 02
				9	0.70000E 02
				10	0.70000E 02
				11	0.70000E 02
				12	0.70000E 02

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
3	0.14338E-11	0.	0.	1	0.70000E 02
				2	0.70000E 02
				3	0.70000E 02
				4	0.70000E 02
				5	0.70000E 02
				6	0.70000E 02
				7	0.70000E 02
				8	0.70000E 02
				9	0.70000E 02
				10	0.70000E 02
				11	0.70000E 02
				12	0.70000E 02

COOLANT OUTLET TEMPERATURE = 0.70000E 02DEGREES F

AXIAL NODE	COOLANT TEMPERATURE	COOLANT DERIVATIVES
1	0.70000E 02	0.
2	0.70000E 02	0.
3	0.70000E 02	0.

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
1	1	0.	-0.	0.65000E 01
	2	0.	-0.	0.65000E 01
	3	0.	0.35633E-19	0.65000E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
2	1	0.	-0.	0.65000E 01
	2	0.	-0.	0.65000E 01
	3	0.	0.35633E-19	0.65000E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
3	1	0.	-0.	0.65000E 01
	2	0.	-0.	0.65000E 01
	3	0.	0.35633E-19	0.65000E 01

NAA-SR-8414
F-4

PEAK POWER HAS BEEN REACHED

REACTOR KINETICS

TIME= 0.12934L 01 INTEGRATED CORE ENERGY= 0.23306E 01MEGAWATT*SECONDS

REACTIVITY FEEDBACK

RHOT= 0.96101E 00 RHOFB=-0.17199E-00 RHOSD=-0.86700E 00 RHOR= 0.

FLUX= 0.22162E 14 DFLUX=-0.27339E 12

GROUP	C	DC
1	0.28843E 11	0.27445E 12
2	0.70856E 11	0.67378E 12
3	0.25736E 12	0.24402E 13
4	0.68728E 12	0.64728E 13
5	0.24495E 13	0.22398E 14
6	0.57709E 13	0.49431E 14

REACTOR KINETICS

TIME= 0.14049L 01 INTEGRATED CORE ENERGY= 0.45820E 01MEGAWATT*SECONDS

REACTIVITY FEEDBACK

RHOT= 0.90688E 00 RHOFB=-0.22612E-00 RHOSD=-0.86700E 00 RHOR= 0.

FLUX= 0.17521E 14 DFLUX=-0.45358E 14

GROUP	C	DC
1	0.56721E 11	0.21681E 12
2	0.13921E 12	0.53077E 12
3	0.50355E 12	0.18981E 13
4	0.13319E 13	0.48862E 13
5	0.45559E 13	0.14759E 14
6	0.98514E 13	0.23210E 14

TIME= 0.14049E 01 SECONDS HYDROGEN PARTIAL PRESSURE= 0.14067E-01 ATMOSPHERES

TOTAL GAP PRESSURE= 0.14850E 01 ATMOSPHERES PERCENT H2 REMAINING=100.000

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
1	0.25121E 02	0.38340E 03	0.99050E-08	1	0.40509E 03
				2	0.40404E 03
				3	0.40091E 03
				4	0.39900E 03
				5	0.38346E 03
				6	0.36987E 03
				7	0.32142E 03
				8	0.27463E 03
				9	0.22784E 03
				10	0.19800E 03
				11	0.16817E 03
				12	0.16231E 03

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
2	0.45048E 02	0.59229E 03	0.35075E-04	1	0.62673E 03
				2	0.62518E 03
				3	0.62053E 03
				4	0.61770E 03
				5	0.59311E 03
				6	0.57160E 03
				7	0.49119E 03
				8	0.41351E 03
				9	0.33583E 03
				10	0.28630E 03
				11	0.23678E 03
				12	0.22705E 03

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
3	0.25121E 02	0.38340E 03	0.99050E-08	1	0.40509E 03
				2	0.40404E 03
				3	0.40091E 03
				4	0.39900E 03
				5	0.38346E 03

NAA-SR-8414
F-6

6	0.36987E 03
7	0.32142E 03
8	0.27463E 03
9	0.22784E 03
10	0.19800E 03
11	0.16817E 03
12	0.16231E 03

COOLANT OUTLET TEMPERATURE = 0.12455L 03DEGREES F

AXIAL NODE	COOLANT TEMPERATURE	COOLANT DERIVATIVES
1	0.16231E 03	0.68258E 03
2	0.22701E 03	0.11331E 04
3	0.16231E 03	0.68258E 03

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
1	1	0.11350E 04	0.55189E-13	0.65000E 01
	2	0.10912E 04	0.46240E-12	0.65000E 01
	3	0.94033E 03	-0.26369E-11	0.65000E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
2	1	0.17830E 04	0.43793E-11	0.65000E 01
	2	0.17221E 04	0.39448E-10	0.65000E 01
	3	0.14966E 04	-0.80836E-10	0.65000E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
3	1	0.11350E 04	0.55189E-13	0.65000E 01
	2	0.10912E 04	0.46240E-12	0.65000E 01
	3	0.94033E 03	-0.26369E-11	0.65000E 01

CLADDING HAS BURST AT TIME= 0.85840E 01 SECONDS

REACTOR KINETICS

TIME= 0.99450E 01 INTEGRATED CORE ENERGY= 0.28009E 02MEGA*ATT*SECONDS

REACTIVITY FEEDBACK

RH0T=-0.42229E-00 RH0FB=-0.15553E 0; RH0SD=-0.86700E 00 RH0R= 0.

FLUX= 0.91039E 12 DFLUX= 0.14307E 13

GROUP	C	DC
1	0.32101E 12	0.72886E 10
2	0.70446E 12	0.62323E 10
3	0.15848E 13	-0.75314E 11
4	0.16579E 13	-0.22587E 12
5	0.10629E 13	-0.17526E 12
6	0.96223E 12	-0.16161E 12

NAA-SR-8414
F-8

TIME= 0.99450E 01 SECONDS HYDROGEN PARTIAL PRESSURE= 0.10000E-19 ATMOSPHERES

TOTAL GAP PRESSURE= 0.10000E-19 ATMOSPHERES PERCENT H2 REMAINING= 99.911

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
1	0.13053E 01	0.14497E 04	0.36772E 02	1	0.14621E 04
				2	0.14598E 04
				3	0.14530E 04
				4	0.14488E 04
				5	0.14448E 04
				6	0.14412E 04
				7	0.14384E 04
				8	0.14356E 04
				9	0.14329E 04
				10	0.14311E 04
				11	0.14294E 04
				12	0.14290E 04

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
2	0.23408E 01	0.21632E 04	0.51696E 04	1	0.21886E 04
				2	0.21841E 04
				3	0.21705E 04
				4	0.21622E 04
				5	0.21525E 04
				6	0.21440E 04
				7	0.21404E 04
				8	0.21369E 04
				9	0.21334E 04
				10	0.21311E 04
				11	0.21289E 04
				12	0.21285E 04

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
3	0.13053E 01	0.14497E 04	0.36772E 02	1	0.14621E 04
				2	0.14598E 04
				3	0.14530E 04
				4	0.14488E 04
				5	0.14448E 04

6	0.14412E 04
7	0.14384E 04
8	0.14356E 04
9	0.14329E 04
10	0.14311E 04
11	0.14294E 04
12	0.14290E 04

COOLANT OUTLET TEMPERATURE= 0.13879E 04 DEGREES F

AXIAL NODE	COOLANT TEMPERATURE	COOLANT DERIVATIVES
1	0.14290E 04	0.40111E 02
2	0.21285E 04	0.50952E 02
3	0.14290E 04	0.40111E 02

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
1	1	0.32362E 02	0.38596E-08	0.65000E 01
	2	0.34164E 02	0.92173E-08	0.65000E 01
	3	0.35308E 02	0.46387E-05	0.64976E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
2	1	0.44934E 02	0.59313E-07	0.64999E 01
	2	0.45154E 02	0.46046E-06	0.64997E 01
	3	0.44768E 02	0.73345E-04	0.64531E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
3	1	0.32362E 02	0.38596E-08	0.65000E 01
	2	0.34164E 02	0.92172E-08	0.65000E 01
	3	0.35308E 02	0.46387E-05	0.64976E 01

REACTOR KINETICS

TIME= 0.13032E 02 INTEGRATED CORE ENERGY= 0.30219E 02 MEGA*ATT*SECONDS

REACTIVITY FEEDBACK

RHGT=-0.70143E 00 RHGFB=-0.18344E 01 RHGSD=-0.86700E 00 RHGR= 0.

FLUX= 0.55779E 12 DFLUX= 0.68097E 12

GROUP	C	DC
1	0.33580E 12	0.27445E 10
2	0.70525E 12	-0.45176E 10
3	0.13290E 13	-0.85996E 11
4	0.10713E 13	-0.15503E 12
5	0.64562E 12	-0.10063E 12
6	0.58688E 12	-0.89911E 11

REACTOR KINETICS

TIME= 0.40924E 02 INTEGRATED CORE ENERGY= 0.34605E 02MEGAWATT*SECONDS

REACTIVITY FEEDBACK

RHGT=-0.29240E 01 RHGFB=-0.40570E 01 RHGSD=-0.86700E 00 RHGR= 0.

FLUX= 0.36473E 11 DFLUX= 0.17037E 12

GROUP	C	DC
1	0.28026E 12	-0.30237E 10
2	0.37587E 12	-0.10354E 11
3	0.13640E 12	-0.11139E 11
4	0.47737E 11	-0.34154E 10
5	0.38720E 11	-0.26293E 10
6	0.37345E 11	-0.28322E 10

REACTOR KINETICS

TIME= 0.49785E 02 INTEGRATED CORE ENERGY= 0.34853E 02MEGAWATT*SECONDS

REACTIVITY FEEDBACK

RHGT=-0.35221E 01 RHGFB=-0.46551E 01 RHGSD=-0.86700E 00 RHGR= 0.

FLUX= 0.22151E 11 DFLUX=-0.89308E 11

GROUP	C	DC
1	0.25402E 12	-0.28746E 10
2	0.29347E 12	-0.82741E 10
3	0.68055E 11	-0.51091E 10
4	0.27414E 11	-0.15730E 10
5	0.23415E 11	-0.13859E 10
6	0.22772E 11	-0.17410E 10

TIME= 0.49785E 02 SECONDS HYDROGEN PARTIAL PRESSURE= 0.10000E-19 ATMOSPHERES

TOTAL GAP PRESSURE= 0.10000E-19 ATMOSPHERES PERCENT H2 REMAINING= 95.658

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
1	0.32205E-01	0.16746E 04	0.22650E 03	1	0.16776E 04
				2	0.16773E 04
				3	0.16755E 04
				4	0.16743E 04
				5	0.16732E 04
				6	0.16727E 04
				7	0.16720E 04
				8	0.16720E 04
				9	0.16720E 04
				10	0.16720E 04
				11	0.16720E 04
				12	0.16720E 04

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
2	0.57752E-01	0.23527E 04	0.11850E 05	1	0.23738E 04
				2	0.23671E 04
				3	0.23575E 04
				4	0.23476E 04
				5	0.23433E 04
				6	0.23352E 04
				7	0.23374E 04
				8	0.23374E 04
				9	0.23374E 04
				10	0.23374E 04
				11	0.23374E 04
				12	0.23352E 04

AXIAL NODE	POWER GENERATION	AVERAGE RADIAL TEMP.	CENTER FUEL PRESSURE-ATMOS	RADIAL NODE	FUEL TEMP DEGREES F
3	0.32205E-01	0.16746E 04	0.22650E 03	1	0.16776E 04
				2	0.16773E 04
				3	0.16755E 04
				4	0.16743E 04
				5	0.16732E 04

NAA-SR-8414
F-12

6 0.16727E 04
 7 0.16720E 04
 8 0.16720E 04
 9 0.16720E 04
 10 0.16720E 04
 11 0.16720E 04
 12 0.16720E 04

COOLANT OUTLET TEMPERATURE= 0.19433E 04 DEGREES F

AXIAL NODE	COOLANT TEMPERATURE	COOLANT DERIVATIVES
1	0.16720E 04	-0.
2	0.23352E 04	0.
3	0.16720E 04	-0.

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
1	1	0.18904E-00	0.30050E-08	0.65000E 01
	2	-0.28670E-00	0.29366E-06	0.64980E 01
	3	0.71523E 00	0.13685E-04	0.62785E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
2	1	-0.27708E 01	0.83942E-06	0.64959E 01
	2	-0.25622E 01	0.19479E-04	0.63311E 01
	3	-0.23491E 01	0.96610E-04	0.45801E 01

AXIAL NODE	RADIAL NODE	FUEL TEMP DERIVATIVE	HYDROGEN FLUX	NH
3	1	0.18904E-00	0.30050E-08	0.65000E 01
	2	-0.28690E-00	0.29366E-06	0.64980E 01
	3	0.71523E 00	0.13685E-04	0.62785E 01

END OF FILE A2 ,JOB COMPLETED.

NAA-SR-8414
 F-13

APPENDIX G
TYPICAL BOOMER GRAPHICAL OUTPUT

NAA-SR-8414

G-2

NAA-SR-8414
G-3

NAA-SR-8414
G-4

NAA-SR-8414
G-5

NAA-SR-8414
G-6