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Argonne National Laboratory

CHEMLOC-II: A Computer Program Describing
the Core Heating and Cladding-Steam Reaction
for a Water-cooled Power Reactor
following a Loss of Coolant

by

James C. Hesson, John L. Anderson,
and Richard O. Ivins

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April 1968

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NOMENCLATURE

(Symbols with asterisks represent information read into the program. See end of list.)

English Letters

*A	Radial radiation view factor
*A ₂	Cross-sectional area of fuel per rod, cm ²
*A _c	Cross-sectional area of cladding per rod, cm ²
A _m	Area of pressure vessel head, cm ²
A _n	Radial radiation view factor, zone i to zone im
*A _n	Partition coefficient
A _p	Radial radiation view factor, zone I to zone Ip
A _r	Cross-sectional area of fuel rod, cm ²
A _t	Cross-sectional area of fuel rod plus associated gas channel, cm ²
*A _v	Axial radiation view factor (average effective axial distance between rod surfaces), cm
*A ₁	Steam-flow coefficient (lb/sec) ^{1/2} /hr
*A ₂	Steam-flow coefficient, sec
A ₃	Steam-flow coefficient, lb/hr
*A ₄	Steam-flow coefficient, sec ⁻¹
*C _{as}	Slumping-case parameter (1.0 or 2.0)
C _p	Specific heat, cal/(g)(°K)
*C _{pa}	Specific heat of fuel, cal/(g)(°K)
C _{pam}	Specific heat of solid fuel mixture at temperature T _{am} , cal/(g)(°K)
*C _{pb} , C _{pt}	Specific heat of bottom grid plate, top grid plate, and core wall (steel), cal/(g)(°K)
C _{pw}	Specific heat of cladding metal, cal/(g)(°K)
*C _{pcm}	Specific heat of cladding metal oxide, cal/(g)(°K)
*C _{pco}	Specific heat of cladding metal oxide, cal/(g)(°K)
C _{pg}	Specific heat of gas, X _{Cps} + (1 - X) C _{ph} , cal/(mole)(°K)
*C _{ph}	Specific heat of hydrogen, cal/(mole)(°K)
C _{pm}	Specific heat of fuel at slumping temperature, cal/(g)(°K)
C _{po}	Specific heat of extra oxidizable material (cans, etc.) which is added to cladding weight, cal/(g)(°K)
C _{pr}	Specific heat of extra material which is added to fuel weight, cal/(g)(°K)
*C _{ps}	Specific heat of steam, cal/(mole)(°K)
D	Diameter, cm
*D _{elt}	Time interval, Δt, sec
*D _f	Drip factor (correction factor for fuel dripping) (input factor)
D _{fv}	Correction factor for fuel dripping
*D _g	Diffusivity of steam in hydrogen, cm ² /sec
d	Diameter of rod, cm
d _i	Distance between rod centers, cm
E	Radiation emissivity
E _n	Emissivity, row n
E _{ij}	Emissivity, zone i, increment j
E _{ijp}	Emissivity, zone i, increment jp
E _{ijm}	Emissivity, zone i, increment jm
E _{il}	Emissivity factor, zone i to i
E _{im}	Emissivity factor, ij to imjns
E _{imj}	Emissivity, zone im, increment j
E _{ip}	Emissivity factor, ij to ipjns
E _{ipj}	Emissivity, zone ip, increment j
E _{ijp}	Emissivity factor, ij to ijp
E _{ijm}	Emissivity factor, ij to ijm
*E _{ps}	Emissivity factor, E/(2 - E)
E ₀₁	Emissivity factor, row 0 to row 1
E ₁	Emissivity, row 1
E ₂	Emissivity, row 2
*ΔE	Activation energy, cal/mole
F _{can}	Fraction of can reacted

English Letters (Contd.)

F _{clad}	Fraction of cladding reacted
F _{un}	Geometrical radiation coefficient, row 0 to row n
F _{0n}	Geometrical radiation factor, row 0 to row n
F _{d(ij)}	Relative decay heat of the fuel in a fuel-rod increment
*F _f	Fuel-fall factor
*F _{gs}	Increments of fuel slumped for steam shutoff
F _{m(ij)}	Relative area/length ratio of a fuel-rod increment
*F _{rf}	Fuel-retained factor
F _{s(ij)}	Relative length of a fuel-rod increment
F _{sv(ij)}	Index parameter indicating slumping or receipt of fallen fuel by a fuel-rod increment
***F(t)	Ratio of decay power at time t to operating power
F _{w(ij)}	Relative weight of the fuel in a fuel-rod increment
f	Flow friction factor
****f(i)	Ratio of average reactor power in zone i to average power in core
h	Heat-transfer coefficient, cal/(sec)(cm ²)(°K)
*h _{ac}	Cladding-to-fuel heat-transfer coefficient, cal/(sec)(cm ²)(°K)
h _d	Gas-to-cladding mass-transfer coefficient, for steam through hydrogen or hydrogen through steam, = D _g /δ _g cm/sec
h _g	Gas-to-cladding heat-transfer coefficient, (k _g /δ _h) cal/(sec)(cm ²)(°K)
i	Zone i
im	Zone i - 1
ip	Zone i + 1
J _h	J factor for heat transfer
J _m	J factor for mass transfer
j	Length increment j
jm	Length increment j - 1
jns	Length increment jns in zone ip which is radially opposite to increment j in zone i
jnss	Length increment jnss in zone im which is radially opposite to increments j in zone i
jp	Length increment j + 1
*K	Cladding-steam reaction rate constant, cm ² /sec
k	Thermal conductivity, cal/(sec)(cm)(°K)
k	Time increment
*k _a	Thermal conductivity of solid fuel, cal/(sec)(cm)(°K)
*k _{am}	Ratio of thermal conductivity of molten to solid fuel
*k _c	Thermal conductivity of cladding, cal/(sec)(cm)(°K)
k _e	Conductivity equivalent to radiation, cal/(sec)(cm)(°K)
k _g	Thermal conductivity of gas, X _{ks} + (1 - X) k _h , cal/(sec)(cm)(°K)
*k _h	Thermal conductivity of hydrogen, cal/(sec)(cm)(°K)
km	Time increment k - 1
*k _s	Thermal conductivity of steam, cal/(sec)(cm)(°K)
*L	Length of fuel in rod, cm
L _{ac}	Latent heat of fusion of fuel mixture, cal/g
ℓ	Distance from bottom of rod, cm
ℓ	Length for Nusselt number, cm
Δℓ	Length of an increment, cm
*M _c	Grams of cladding oxidized per mole steam, g/mole
Nu	Nusselt's number = hℓ/k
Nu _d	Nusselt's number for mass transfer = h _d ℓ/D _g
*N _i	Number of radial zones
*N _j	Number of length increments
*N _{jp}	Increments between printout
*N _{print}	Time intervals between printout
*N _{tab}	Number of decay-heat data

English Letters (Contd.)

n	Number of row
P	Reactor power
P _a	Average reactor power
P _g	Pressure of gas, atm
p	Pitch of rows of rods (distance between centers), cm
**Q _c	Heat of reaction of cladding, cal/g
*Q _d	Average reactor power per cm ³ fuel, cal/(sec)(cm ³)
q	Heat transfer from rod, per cm of rod length, cal/(sec)(cm)
q _{bc}	Heat transfer, fuel to cladding, cal/(sec)(cm)
q _{ap}	Heat conduction axially in fuel, increment j to jp, cal/(sec)(cm)
q _{aq}	Heat conduction axially in fuel, increment j to jm, cal/(sec)(cm)
q _{arp}	Heat radiation axially, increment j to jp, cal/(sec)(cm)
q _{arjp}	Heat radiation axially, increment jp to j, cal/(sec)(cm)
q _{arq}	Heat radiation axially, increment i to jm, cal/(sec)(cm)
q _{arjm}	Heat radiation axially, increment jm to j, cal/(sec)(cm)
q _{cp}	Heat conduction axially in cladding, increment j to jp, cal/(sec)(cm)
q _{cq}	Heat conduction axially in cladding, increment j to jm, cal/(sec)(cm)
q _d	Decay heat in fuel rod, cal/(sec)(cm)
q _g	Heat transfer, cladding to gas, cal/(sec)(cm)
q _{ri}	q _{arp} + q _{arjp} + q _{arq} + q _{arjm} + q _{arp} + q _{rip} + q _{rq} + q _{rim} + q _{cp} + q _{cq} , cal/(sec)(cm)
q _{rim}	Heat transfer radially, zone im to i, cal/(sec)(cm)
q _{rip}	Heat transfer radially, zone ip to i, cal/(sec)(cm)
q _{rp}	Heat transfer radially, zone i to ip, cal/(sec)(cm)
q _{rq}	Heat transfer radially, zone i to im, cal/(sec)(cm)
q _s	Heat generated by chemical reaction, cal/(sec)(cm)
q̄	Anticipated average value of q over time interval Δt or length increment Δℓ
R	Gas constant, 1.987, cal/mole °K
*R _{co}	Cladding oxide/cladding metal oxidation ratio, g/g
Re	Reynold's number, DV/μ
R _i	Radius of zone i, cm
ΔR _i	Distance from zone i to i + 1, cm
R _i	Outer radius of zone N _i , cm
R _r	Thickness of cladding oxidized, r _o - r, cm
R _{r'}	Thickness of extra oxidizable surface oxidized, cm
*R _{r0}	Initial oxidized thickness, cm
r	Radius of unreacted metal cladding, cm
r _a	Radius of fuel, cm
*r _i	Inside radius of cladding, cm
*r _o , R _o	Outside radius of rod, cm
r'	Equivalent diameter of annulus, cm
S	Surface area = S _r + V _k = S _r + S _g V _g L, cm ²
*S _f	Slump factor = A _r p _r /A _t p _t
****S(j)	Ratio of average reactor power in increments j to average power in the core
S _o	Total surface area of extra oxidizable surface, cm ²
S _r	Surface area of cladding per cm of rod length = 2πr _o , cm ² /cm
ΔS	Thickness of reactor pressure vessel head, cm
S _c	Schmidt's number, μ/pD _g
T _a	Average temperature of fuel, °K

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NOMENCLATURE (Contd.)

English Letters

T_{aL}	Pseudotemperature corresponding to all fuel mixture molten, °K
T_{am}	Melting temperature of fuel mixture, °K
T_{a0}	Initial temperature of fuel, °K
T_{ap}	Pseudotemperature of fuel, °K
T_{ap0}	Initial pseudotemperature, °K
T_{as}	Temperature of surface of fuel, °K
T_b	Average temperature of bottom grid plate, °K
T_{ba}	Ambient temperature of bottom grid plate, °K
T_{b0}	Bottom initial temperature, °K
T_c	Cladding temperature, time increment k - 1, °K
T_{cla}	Effective temperature of cladding for heat transfer to fuel, °K
T_{clg}	Effective temperature of cladding for heat transfer to gas, °K
T_{c0}	Initial cladding temperature, °K
T_{cp}	Temperature of cladding, time increment k, °K
T_{cl}	Cladding temperature at start of a time increment, °K
T_g	Average gas temperature, °K
T_{g0}	Initial steam temperature, °K
T_n	Temperature of cladding in row n, °K
T_0	Temperature of cladding in row 0, °K
T_w	Core-wall temperature, °K
T_{wa}	Ambient temperature of core wall, °K
T_{w0}	Initial wall temperature, °K
T_t	Temperature of top grid plate, °K
T_{ta}	Ambient temperature of top grid plate, °K
T_{t0}	Initial temperature of top grid plate, °K
T_l	Temperature of cladding in row l, °K
t	Time, sec
Δt	Time increment, sec
τ_m	Steam-generation coefficient, sec
τ_{max}	Maximum run time, sec
U	Heat-transfer coefficient ratio (heat transfer from increment to bottom grid plate divided by heat transfer from increment to increment)

English Letters (Contd.)

U_b	Overall heat-transfer coefficient, bottom grid plate to ambient, cal/(sec)(°K)
U_w	Overall heat-transfer coefficient, core wall to ambient, cal/(sec)(°K)
U_t	Overall heat-transfer coefficient, top grid plate to ambient, cal/(sec)(°K)
V	Velocity, cm/sec
V_a	Volume of fuel per cm of rod, cm ³ /cm
V_k	Extra area per unit length of rod = S_0/V_0L , cm ² /cm
V_{m5}	Mass-transfer factor, cm ⁻¹
V_1	Number of rods per zone = V_0/N_j
V_2	Factor for initial fuel temperature, °K
V_3	Factor for initial cladding temperature, °K
V_4	Factor for initial cladding and fuel temperatures, °K
V_5	Heat-transfer factor, cm ⁻¹
V_6	Number of rods in reactor
V_8	Heat of combustion of hydrogen, cal/mole
W	Width, cm
W	Distance between rods in row, cm
W_a	Weight of fuel and equivalent extra material per centimeter of rod, g/cm
W_b	Weight of bottom grid plate, g
W_c	Weight of cladding and equivalent extra material per centimeter of rod, g/cm
W_g	Moles of gas per sec per rod, moles/sec
W_0	Total weight of extra material added to cladding, g
W_f	Total weight of extra material added to fuel, g
W_s	Steam flow rate (total), lb/hr
W_t	Weight of top grid plate, g
W_w	Weight of core wall, g
X	Average mole fraction of steam in gas
X_1	Average mole fraction of steam in gas at condition 1
X_0	Initial mole fraction of steam in gas = 1.0
X_s	Mole fraction of steam at reacted clad oxide surface (assumed 0 for steam-limited case)
y	Distance from start of length increment, cm

Greek Letters

α	Thickness of extra oxidizable surface, cm
μ	Viscosity, poises
ρ	Density, g/cm ³
ρ_a	Fuel density, g/cm ³
ρ_c	Cladding-metal density, g/cm ³
ρ_g	Density of steam-hydrogen gas mixture, mole/cm ³
ρ_r	Average density of material (unslumped) in fuel rod, g/cm ³
ρ_t	Assumed bulk density of slumped material of fuel rod, g/cm ³
σ	Radiation constant, 1.37×10^{-12} cal/(sec)(cm ²)(°K ⁴)
σ_d	Effective gas-film thickness, mass transfer, cm
σ_h	Effective gas-film thickness, heat transfer, cm
τ	Time from start of time increment, sec

Subscripts

i	Zone (radial) i
im	Zone (radial) i - 1
ip	Zone (radial) i + 1
j	Increment (length) j
jm	Increment (length) j - 1
jp	Increment (length) j + 1
k	Time interval k
km	Time interval k - 1
jns	Increment in zone ip which is radially opposite increment j in zone i
jnss	Increment in zone im which is radially opposite increment j in zone i

* Items read into program; one symbol used
 ** Items read into program; two symbols used
 *** Items read into program; three symbols used
 **** Items read into program; table used three tables

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I. SUMMARY

The CHEMLOC-II program is a sophisticated digital-computer program for computing the extent of core heating and metal-steam reaction following a hypothetical loss-of-coolant accident, including emergency core-cooling failure, in a water-cooled reactor. The analysis of the results of such a hypothetical loss-of-coolant accident, resulting from a pipe break in the primary system's water piping, has played a major role in the design and licensing of most power reactors built to date.

The CHEMLOC-II program carries the computations from the end of blowdown (blowdown is the period from initiation of the pipe break to the time when the core is bared of coolant), through core heating, chemical reaction, failure, and collapse of the core onto the bottom supporting structure. The program does not consider the effects of an emergency cooling system. The program requires as input the distribution of the temperatures of the fuel and cladding at the end of blowdown, and the reactor power as functions of position throughout the core. The decay heating of the fuel and the steam flow rates through the core, both as functions of time, are also required input. In addition, input parameters involving core and core-support geometry, material properties, metal-water reaction rates, and the nature of core collapse or slumping are required.

For computational purposes, the core is divided into annular axial zones, each consisting of an equal number of rods, and into axial length increments. Up to 25 zones and 40 increments may be used in the program.

Temperatures of the fuel, cladding, and gas (steam-hydrogen) are computed separately by the program. The program includes the effects of heat production by decay heating in the fuel as well as by steam-metal chemical reaction. The metal available for reaction with the steam includes both the fuel cladding and extra metal in the core (exposed to steam flow), such as spacers and subassembly cans. Provisions are made for the decay heating to vary (decrease) with time and with position in the core. In computing the rate of chemical reaction, we impose limitations due to the

temperature dependence (kinetics) of the reaction as well as limitations due to the steam flow rate and diffusion of steam through hydrogen (produced by the reaction) to the reacting surfaces. Provisions are included for computing heat transfer in the core by radial conduction between the fuel and cladding, by axial conduction in the fuel and cladding, by thermal convection between the cladding and flowing gas, and by axial and radial radiation from the cladding.

The program includes heat transfer from the core to the bottom and top grid-support plates and to the wall surrounding the core. Heat is transferred, in turn, from these plates and wall to their surroundings.

Whenever the physical, thermal, and other properties and factors, such as specific heats, thermal conductivities, diffusivities, reaction rates, etc., required in the program have a temperature dependence, the values for the temperatures involved are computed in the program.

In the absence of an emergency cooling system following a loss-of-coolant accident, the temperatures in the core become so high that the cladding and fuel lose their integrity and slump or collapse. The CHEMLOC-II program includes methods of calculating the effects of core movement and material transfer on reaching slumping temperature. As the core slumps, several changes occur. One of the changes is an increase in average core density due to the movement of slumped material into the water-coolant channels.

After increments of the fuel rods in adjacent zones slump together, radial heat transfer by radiation in the slumped areas is replaced by radial heat transfer by conduction. Since the various zones will slump at different rates, the increments that are radially opposite in adjacent zones shift and a corresponding correction is made for radial heat transfer.

As various sections within the core fail, fuel and cladding may fall from slumped increments to the bottom of the core. Some of this material may fall completely out of the core, while the remainder augments the amount of fuel in the lower increments and increases the weight and decay heating as well as the cross-sectional area of the fuel in these areas. Some of the fuel from slumping increments may drip or run down to the next lower increment, thus increasing the heat-transfer rate to this increment.

When a predetermined number (an input required in the program) of length increments in a zone have slumped, the steam flow in that zone is considered to be blocked. In this way, the program takes into account the effects of core slumping on steam flow, metal-steam chemical reactions, and heat transfer by conduction, radiation, and convection.

To account for the changes that occur as the core collapses, several arbitrary factors have been incorporated into the program. Choosing appropriate values of these arbitrary factors as input to the program enables the model for the manner in which the core failure and collapse proceeds to be varied. The program was constructed in this manner because inadequate information existed at the time of development of the program to model accurately the geometry changes that might occur under the various possible conditions in a hypothetical accident. This also allows more flexibility in using the program, since various values of these factors can be used, ranging from very conservative to more realistic, depending on the purpose for which the program is to be used.

These arbitrary factors are:

1. Slump temperature. It is assumed that an increment of core slumps when it reaches this temperature.
2. Slump factor. It is assumed that the core volume of a slumped increment decreases by this factor. The apparent density of the slumped core material is the poorly known contributor to this factor.
3. Fall factor. This is the assumed fraction of a slumped increment that remains in its relative position (does not fall to the bottom of core).
4. Fuel-retained factor. Of the material falling to the bottom of the core, this fraction is assumed to remain in the core.
5. Drip factor. The normal axial heat conduction at the lower slumping interface is assumed to increase by this factor.
6. Steam-blockage factor. When this number of increments in a zone have slumped, the steam flow in that zone is assumed to cease.

Materials (other than fuel or cladding) in the core, such as subassembly cans, spacers, control rods, etc., which can accumulate heat energy, are included as additional equivalent weights of either fuel or cladding.

By means of mass and heat balances on an elemental section of a fuel rod, simultaneous iteration equations were developed for the temperatures of the fuel, cladding, and gas, as well as for the thickness of cladding oxidized and the fraction of steam in the gas throughout the core. Iteration equations for the temperatures of the bottom grid plate, top grid plate, and core wall are also included in the computer program.

The output of the program includes the following for preselected time intervals:

1. Steam flow rate for each zone and for the total core,
2. Decay heat as a fraction of reactor power,
3. Fuel, cladding, and gas temperatures throughout the core.
4. Thickness of cladding reacted and fraction of steam (or hydrogen) in the gas throughout the core,
5. Average thickness and fraction of total cladding and cans (extraneous oxidizable materials) reacted.
6. Fraction of hydrogen in the exit gas (total and for each zone).
7. Total heat of combustion of the hydrogen being released.
8. Total sensible heat of the gases being released.
9. Accumulated quantity of hydrogen released.
10. Average temperatures of the fuel, bottom grid plate, core wall, and top grid plate, including their associated parts.
11. Fraction of fuel slumped.
12. Fraction of fuel remaining in the core.

As in any mathematical simulation of a physical phenomenon, the accuracy of the computer output is limited by the accuracy of the input and the assumptions made in the program.

A major limitation on the accuracy with which the program output depicts the actual results that would occur is an adequate knowledge of the input parameters to be used. The physical, thermal, and other properties of the core materials and gas at temperatures up to the slumping of the core are known with fair accuracy. However, the core-slumping model is governed by a number of input parameters, the proper values of which are poorly known. These parameters (previously discussed) are the slumping temperature, the slump factor, the fall factor, the fuel-retained factor, the drip factor, and the steam-blockage factor. As better knowledge of the core-slumping phenomena becomes available, the parameters to be used can be selected accordingly.

Even though the program is quite sophisticated, it requires relatively short computer running times; this is because of the large values of time increments that can be used in the iterations. Time intervals as large as 5 sec or more can be used, since preintegration of certain values is used to avoid divergence in the iteration by the program.

II. INTRODUCTION

The loss-of-coolant accident resulting from a pipe break in the primary-system water pipe has been taken to be the "design basis accident" or "maximum credible accident" for most of the water-cooled nuclear power reactors built to date. During normal operation of a water-cooled reactor, circulating water (or a water and steam mixture) removes heat from the core for steam generation or other purposes. If the circulating water coolant is lost because of a pipe break (loss-of-coolant accident), the reactor would be shut down (nuclear); however, fission-product decay in the fuel would continue to furnish heat to the core. Emergency cooling systems such as in-core water-spray cooling devices are provided in the event of such an emergency; however, the in-core water-spray devices might also conceivably fail, possibly because of the same accident as that responsible for the loss of coolant in the first place.

In the event of such a loss-of-coolant accident in a water-cooled power reactor, the reactor core would undergo a rapid temperature rise due to fission-product decay heating in the fuel as well as to chemical reaction of steam with the fuel cladding (ordinarily a zirconium alloy or stainless steel). The steam would be furnished by the vaporization of water remaining in the lower-pressure vessel head. Water could also be furnished by a defective core-cooling system. The chemical reaction would take oxygen from the steam and release hydrogen. The core heating could continue through fuel melting and core collapse. The rate, extent, and character of the heating of the core, as well as the extent of the chemical reaction and quantities of hydrogen released from the steam, have been the subject of considerable interest.

In previous analyses, the problem has been approached¹⁻⁴ by considering the core to be divided into equal segments both axially and radially. The segments were grouped accordingly to the decay heating rate of the contained fuel which varies over the reactor core in proportion to the reactor power. Heating rates were then calculated on the basis of decay heating and chemical-reaction heat. For the chemical reaction, it was assumed that the steam was furnished at an equal rate to all core segments. The effects of heat transfer within the core due to radiation, conduction, and convection (transport by the gas) were neglected. The effects of changes (increase) in hydrogen concentration of the steam as it flows upward through the core were also neglected.

To improve the accuracy of computations involving the temperature increase of the core and the extent of chemical reaction of the cladding, a computer program (CHEMLOC-II) was developed to describe the core heating and chemical reactions from the end of the loss-of-coolant accident through fuel melting and core collapse. This program considers the effects of evaluating the temperatures of the gas, cladding, and fuel separately; the

effects of transfer of heat by axial conduction in the cladding and fuel, by radial conduction between cladding and fuel, by radial and axial radiation from cladding to cladding, and by convection between cladding and the flowing gas; the effects of transfer of heat from the core to the wall surrounding the core, to the top grid plate, and to the bottom grid plate; the effects of the changing hydrogen concentration in the steam; and the effects of core movement due to slumping (melting) on the steam flow and transfer of heat both axially and radially.

Others have been interested in this problem, and several computer programs for use in computing core heatup and steam-cladding reactions following loss-of-coolant accidents in water-cooled reactors have recently been developed. The following are the more important of these programs:

A. NURLOC-1.0. This program⁵ was developed by Battelle Memorial Institute at Columbus, Ohio.

B. ARC-II. This is a Phillips Petroleum Company computer code.⁶

C. TACT-V. This program⁷ was developed by the General Electric Atomic Power Equipment Department at San Jose.

D. LOCTA-R. This computer program⁸ was developed by the Westinghouse Atomic Power Division.

Waage⁹ briefly describes these various programs, as well as CHEMLOC-II, and discusses their purposes and areas of applicability to the loss-of-coolant accident. Although he makes no attempt to evaluate the validity or accuracy of the programs, he does compare salient features in tabular form; these are reproduced in Table I.

TABLE I. Comparison of Salient Features of Core-heatup Computer Programs⁹

	Computer Program					
	LOCTA-R	TACT-V	NURLOC	ARC-II	MOXY-II	CHEMLOC-II
Geometry and Heat-transfer Features of Core-heatup Computer Programs						
Originating organization	Westinghouse Atomic Power Division	General Electric Atomic Power Equipment Department	Battelle Memorial Institute	Phillips Petroleum Company	Phillips Petroleum Company	Argonne National Laboratory
Type of geometry	Radial and axial	Radial and axial	Annular ring	Quarter core	Quarter core	Radial and axial
Maximum number of nodes	60	1250	3500	350	460	2500
Part of system represented	Core fuel	Core	Vessel and core	Vessel and core	Vessel and core	Vessel and core
Conductive heat transfer	Yes	Yes	Yes	No	No	Yes
Radiative heat transfer	Yes	Yes	Yes	Yes	Yes	Yes
Reflectivity	Yes	Yes	No	Yes	Yes	Yes
View factors	Supplied as input	Supplied as input	Internally calculated	Supplied as input	Supplied as input	Supplied as input
Type of solution of conduction equation	Explicit	Explicit	Explicit	Explicit	Lumped explicit	Explicit
Zirconium-Steam Reaction and Disassembly Features of Core-heatup Computer Programs						
Zirconium-steam reaction	Parabolic	Parabolic	Parabolic	Parabolic	Parabolic	Parabolic
Steam limiting	Yes	No	Yes	Yes	Yes	Yes
Cladding melting (heat of fusion)	Yes	Yes	No	Yes	No	Yes
Fuel melting (heat of fusion)	No	No	No	Yes	No	Yes
Core migration	Cladding only	Cladding only	Yes	No	No	Yes
Emergency coolant injection	Yes	Can specify % ^a	Can specify % ^a	No	No	No
Steam-flow circulation	Supplied as input	No	Internally computed	Internally computed	Supplied as input	Supplied as input

^aFilm heat-transfer coefficient.

III. MODEL OF THE REACTOR CORE FOLLOWING THE LOSS OF COOLANT

In a reactor loss-of-coolant accident, the water coolant is lost from the core; however, steam would be generated from any water remaining in the lower vessel head and flow upward through the core. Figure 1 is a sketch of a reactor core which is considered as divided into a number of radial zones, i , of equal area, each containing an equal number of fuel rods.

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Fig. 1. Reactor Core as Zoned for CHEMLOC Calculations

In the calculation, each zone is further divided into axial increments, j , and is considered a bundle of vertical cylinders in a parallel array. The total number of zones is N_i , and the total number of length increments is N_j . Figure 2 shows a typical section of a UO_2 fuel rod with cladding. Decay heat is generated in the UO_2 fuel, and heat is gained or lost by axial conduction within the UO_2 fuel and by radial conduction from or to the cladding. The heat of chemical reaction is generated at the cladding. In addition, the cladding gains or loses heat by axial conduction within the cladding, by radial conduction from or to the UO_2 fuel, by convection from or to the steam-hydrogen gas mixture flowing past the rod, and by axial and radial radiation to adjacent rods or surfaces. As the gas flows along the cladding, steam diffuses to the surface of the cladding where it reacts chemically, producing heat and hydrogen. The hydrogen reduces the concentration of the steam as the steam flows upward. The chemical reaction reduces the thickness of the

Fig. 2

Section of a Reactor-core Fuel Rod (Zone i) Showing Heat and Mass Transfer

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cladding metal and produces an oxide film on the cladding which increases in thickness. The temperatures in the core rapidly become high enough to cause the cladding and fuel to lose their integrity and slump.

It is assumed that after the normal melting temperature of the unoxidized cladding is reached, most of the cladding and cladding oxide continues to adhere to the fuel until the slumping temperature of the fuel-cladding mixture is reached. Allowing the slumping temperature to be an input parameter permits versatility in the model, since the value can be chosen by the analyst to suit his needs and the conditions he has assumed. At this point, a fraction of the fuel-cladding mixture slumps to a lower position in the core. Some of the slumped material forms bridges between rods, some drips to lower positions, some falls to the bottom of the core, and some falls through the bottom support plate and out of the core. As more of the fuel rods fail, bridging between rods forms a support for the failed fuel-rod material. It is assumed that the upper section of the rod

is unsupported, and that it will rest upon the surface of the bridged material. As failure proceeds, the rods collapse into the slumped material, now partially molten, in a manner similar to a rod of metal being melted in a crucible.

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Fig. 3. CHEMLOC Calculational Model, Showing Idealized Slumped Sections of Two Rods

Figure 3 shows idealized slumped sections of two rods used for the purpose of calculations. Where two adjacent rods are slumped and come in contact, heat transfer, both axial and radial, is by conduction only. When a predetermined number of rod increments in a zone have slumped, the steam flow is assumed to be blocked in that zone. A slump factor, S_f , is defined as the ratio of

the final length of an ideal slumped increment to its initial length (or the ratio of the area of an unslumped fuel rod times the average density of material in the unslumped rod to the area of the rod plus the area of the associated coolant channel times the density of the slumped fuelmix). That is,

$$S_f = A_r \rho_r / A_t \rho_t. \quad (1)$$

After the rod increments have slumped, the radial heat transfer by radiation ceases and radial heat transfer by conduction starts.

Because of the material that falls below the bridged fuel-cladding mixture, three input parameters are required in the program: (a) a drip factor, D_f , to account for the effect of heat transfer due to dripping of fuel

from a slumped increment to the unslumped increment below; (b) a fall factor, F_f , to account for the effect of fuel falling from a slumped increment to the bottom of the core; and (c) a fuel retained factor, F_{rf} , to account for the effect of fuel falling entirely out of the core.

The major effect of dripping of fuel from a slumped increment to a lower, colder increment is to increase the axial heat-transfer rate. Thus, the normal heat-transfer rate at the lower slumping interface is multiplied by the drip factor, $D_f \geq 1$.

When an increment of fuel slumps, a fraction, F_f , remains at the increment and a fraction, $1 - F_f$, falls to the bottom of the core. Of the material $(1 - F_f)$ falling to the bottom of the core, a fraction, F_{rf} , remains at the bottom, depositing around the base of the fuel rods, and a fraction, $1 - F_{rf}$, leaves the core entirely, falling through the bottom grid-support plate to the bottom of the reactor vessel. Thus, when an increment of fuel slumps, a fraction, F_f , of the fuel remains at the increment; a fraction, $(1 - F_f)(1 - F_{rf})$, falls completely out of the core; and a fraction, $(1 - F_f)(F_{rf})$, is retained in the bottom of the core.

Figure 4 shows the two limiting cases of the extent of dripping and falling of the collapsed fuel. With no dripping or falling of the collapsed

fuel, the drip factor, D_f , and the fall factor, F_f , are both equal to 1. In the most severe case, all the collapsed fuel immediately falls to the bottom of the core, where it fills the void portion of the core and $F_f = 0$. The actual case would tend to be somewhere between these limiting cases and requires an estimation of the three factors D_f , F_f , and F_{rf} .

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Fig. 4. CHEMLOC Rod Slumping Models, Showing Limiting Cases of Extent of Dripping and Falling of the Slumped Fuel

When increments of the rods in a zone, i , slump, the following changes are made in the program calculations.

1. The steam flow in the zone is assumed to be blocked when a predetermined number of increments of the rods melt and slump (this number of increments is also an input parameter).
2. The radial transfer of heat by radiation is replaced by radial transfer of heat by conduction for the slumped increments. The effects of the unequal slumping in the various zones are taken into account.

3. The axial transfer of heat by radiation is discontinued within the slumped increments.

4. The area for the axial conduction of heat is increased because of the slumping. Corrections are made for the decrease in increment length.

5. The axial conduction of heat at the lower slumping interface is increased through the use of the drip factor, D_f .

6. Material is lost from the core through the use of the fuel-retained factor, F_{rf} .

7. Material falling to the bottom of the core is accumulated there by use of the fall factor, F_f , and is deduced from, and added to, the appropriate increments.

From these factors the following parameters for a rod increment (incremental length) are calculated and stored by the program:

$F_s(i,j)$ = relative length of the increment;

$F_m(i,j)$ = relative area/length ratio of the increment;

$F_w(i,j)$ = relative weight of fuel in the increment;

$F_d(i,j)$ = relative decay heat of fuel in the increment;

and

$F_{sv}(i,j)$ = index parameter indicating slumping or receipt of fallen fuel by the increment.

Before slumping of an increment or receipt of slumped material by an increment, each of these parameters is 1.0. On slumping or receipt of slumped material, they are adjusted accordingly and used in the calculations for the increment.

In the following discussion, subscript jns refers to the increment in zone ip which is radially opposite to increment j in zone i (i.e., at the same distance from the bottom of the core) and jns refers to the increment in zone im which is radially opposite to increment j in zone i .

Before core slumping, $jns = j$ and $jns = j$. After core slumping begins, the various zones slump at different rates and the axial positions of the increments in the various zones shift relative to each other. The values of jns and jns are determined by adding the lengths $F_s(i,j)$ of the increments up to j in zone i and then computing the number of increments jns in zone ip and jns in zone im required to equal the distance to j in zone i .

The following are computed for each length increment j in each zone i for each time interval and are stored in the program for one time interval:

T_a = average temperature of the fuel, °K;
 T_{ap} = average pseudotemperature of the fuel, °K;
 T_c = temperature of the cladding, °K;
 T_g = average temperature of the gas, °K;
 R_r = thickness of cladding oxidized, cm;
 X = average mole fraction steam in the gas;
 R'_r = thickness of extra oxidizable surface oxidized, cm;
 F_{sv} = index parameter;
 F_s = relative length of increment;
 F_m = relative area/length ratio;
 F_w = relative weight of fuel;

and

F_d = relative decay heat of fuel.

Several other items are computed for immediate use but are not stored. For simplicity, the subscripts i and j will be assumed and will be shown only where necessary to avoid confusion.

In addition, several items are computed and stored for each zone i or for each increment j . Of these items, the following will appear in the subsequent discussions: for i ,

$f(i)$, W_g , q_{ap} , q_{cp} , q_{arjp} , and q_{arp} ;

and for j ,

$S(j)$.

IV. CHEMICAL-REACTION RATES

A. Zirconium-Steam Chemical Reaction

The reaction of zirconium cladding with steam follows a parabolic rate law^{4,10} when the steam is in excess at the reaction surface. For a cylindrical surface the rate is given as

$$\frac{d(r_o - r)}{dt} = \frac{K}{r_o - r} \exp\left(-\frac{\Delta E}{RT_c}\right), \text{ cm/sec}, \quad (2a)$$

where

$$K = 0.3937 \text{ cm}^2/\text{sec},$$

$$\Delta E = 45500 \text{ cal/mole},$$

and $(r_o - r)$ represents a thickness of oxidized metal which retards the reaction inversely proportional to its thickness.

At relatively high temperatures, the reaction becomes more rapid and may be limited by the diffusing of the steam to the oxide surface and the diffusing of the hydrogen from the oxide surface. In this case

$$\frac{d(r_o - r)}{dt} = \frac{\rho_g M_c}{\rho_c} h_d (X - X_s), \text{ cm/sec}, \quad (2b)$$

where

X_s = concentration of steam in gas at reacted oxide surface-- assumed very small such that $(X - X_s) = X$, mole/mole;

h_d = mass-transfer coefficient for steam through hydrogen or hydrogen through steam, cm/sec,

$$= D_g / \sigma_d;$$

σ_d = effective gas film thickness for diffusion, cm.

The mass-transfer coefficient, h_d , and the effective gas film thickness, σ_d , are discussed in Appendix A.

B. Stainless Steel-Steam Chemical Reaction

The reaction of stainless steel with steam has been studied.^{11,12} However, a theoretically based rate law has not yet been found to adequately describe the reaction over the range of temperature needed. In previous calculations^{3c} for loss-of-coolant accidents, it was assumed that the rate of

reaction was very low until the metal reached 1400°C (1673°K) (slightly above its melting point), at which point the rate of reaction is limited by the diffusing of steam to the reacting surface. In the reaction, 0.51 liter of hydrogen (0.0227 mole) is formed from the reaction of water vapor with 1 g of stainless steel (44 g of stainless steel will react with 1 mole of water vapor). Thus, the rate of reaction would be negligible up to 1400°C, and

$$\frac{d(r_o - r)}{dt} = 0 \text{ at temperature below } 1400^\circ\text{C}, \quad (2c)$$

and

$$\frac{d(r_o - r)}{dt} = \frac{\rho_g M_c}{\rho_c} h_d (X - X_s) \text{ at } T_c \text{ greater than } 1400^\circ\text{C}, \quad (2d)$$

where

$$\rho_c = 8 \text{ g/cc},$$

and

$$M_c = 44 \text{ g/mole}.$$

More recently it has been stated¹² that the reaction of stainless steel with steam follows a parabolic rate law, the same as for zirconium. Rate-law constants were determined to be

$$K = 1.41 \times 10^6 \text{ cm}^2/\text{sec},$$

and

$$\Delta E = 90800 \text{ cal/mole}.$$

In this case, Eq. (2a) could be used for the kinetic (nonsteam limited) condition at temperatures below 1400°C.

V. ENERGY GENERATION AND HEAT TRANSFER

A. Fission-product Decay Heat

The fission-product decay heat in the fuel is proportional to the power at which the reactor fuel was operated and is a function of the duration of reactor operation and of the time since the reactor shutdown. The decay heat increases with reactor power and duration of reactor operation and decreases with increased shutdown time and varies over the reactor core in the same manner as the reactor power. In general, for a cylindrical core, the variation in the axial direction is a truncated sine (or cosine) function, and the variation in the radial direction is a Bessel function of zero order.

The decay heat per centimeter of a fuel rod is

$$q_d = V_a Q_d F(t) f(i) S(j), \text{ cal/}(\text{sec})(\text{cm}). \quad (3)$$

Individual values of $S(j)$ and $f(i)$ are input for the various zones and increments, and values of $F(t)$ are input for preselected time intervals, from which values are interpolated by the program.

B. Heat Transfer in Fuel by Axial Conduction

The differential equation for the heat received by the fuel per unit length of rod by axial conduction in the fuel is

$$q = \frac{\partial}{\partial \ell} \left(k_a A_a \frac{\partial T_a}{\partial \ell} \right), \text{ cal/}(\text{sec})(\text{cm}).$$

For a rod in zone i with increment length $\Delta \ell$, the heat quantities received by the fuel in increment j from increments $j + 1$ and $j - 1$ are, respectively,

$$q_{ap} = \frac{D_{fv} F_m k_a A_a (T_{ajp} - T_{aj})}{\Delta \ell^2}, \text{ cal/}(\text{sec})(\text{cm}) \quad (4)$$

(when $j = N_j$, $q_{ap} = 0$)

$$q_{aq} = \frac{D_{fv} F_m k_{ajm} A_a (T_{ajm} - T_{aj})}{\Delta \ell^2}, \text{ cal/}(\text{sec})(\text{cm}) \quad (5)$$

$$\left(\text{when } j = 1, q_{aq} = \frac{2U F_m k_a A_a (T_b - T_{aj})}{\Delta \ell^2} \right)$$

where

D_{fv} = correction factor for fuel dripping

= 1 when the lower slumped interface is not between increments j and $j + 1$

= $2D_f k_{am}$ when the lower slumped interface is between increments j and $j + 1$.

C. Heat Transfer from Fuel to Cladding

Normally, heat is produced in the fuel and is transferred to the cladding; however, in the event of rapid cladding oxidation, the heat produced would heat the cladding above the fuel temperature and heat would be transferred from the cladding to the fuel. The rate of heat transfer from the fuel to the cladding, per centimeter of length of rod in zone i and increment j , is

$$q_{ac} = 2\pi r_a h_{ac} (T_{as} - T_c), \text{ cal/}(\text{sec})(\text{cm}). \quad (6a)$$

Ordinarily it is desirable to work with the average temperature of the fuel, T_a .

For a quasi-temperature equilibrium of the cylindrical fuel (i.e., the fuel is generating heat at a uniform volume rate and is increasing or decreasing in temperature at a uniform rate due to heat transfer through its surface at a constant rate, q_{ac}) the temperature distribution in the fuel is parabolic with respect to the radius and

$$T_a = T_{as} + \frac{q_{ac} r_a^2}{8\pi r_a^2 k_a} = T_{as} + \frac{q_{ac}}{8\pi k_a}, \text{ } ^\circ\text{K}. \quad (6b)$$

By substituting Eq. 6b into Eq. 6a, we have,

$$q_{ac} = \frac{2\pi r_a h_{ac} (T_a - T_c)}{1 + \frac{r_a h_{ac}}{4k_a}}, \text{ cal/}(\text{sec})(\text{cm}). \quad (6c)$$

D. Heat Produced by Chemical Reaction

The heat produced by the chemical reaction of the steam with the cladding is proportional to the rate of steam consumption and is generated at the cladding. The rate of heat production by chemical reaction per centimeter of fuel rod in any zone i and increment j for the reaction of steam with zirconium or stainless steel in cal/((sec)(cm)) is

q_s = minimum of

$$S\rho_c Q_c \frac{K}{r_o - r} \exp\left(-\frac{\Delta E}{RT_c}\right), \text{ kinetic limited, cal/((sec)(cm)), } (7a)$$

or

$$SQ_c M_c h_d \rho_g X, \text{ diffusion limited, cal/((sec)(cm)), } (7b)$$

or

$$= 0 \text{ when } r_o - r \geq r_o - r_f, \text{ complete reaction of the cladding. } (7c)$$

E. Heat Transfer in Cladding by Axial Conduction

The differential equation for the heat received by the cladding per centimeter of rod by axial conduction in the cladding is

$$q = \frac{\partial}{\partial \ell} \left(k_c A_c \frac{\partial T_c}{\partial \ell} \right), \text{ cal/((sec)(cm)).}$$

For the cladding on a rod in zone i with increment length $\Delta \ell$, the heat quantities received by the cladding in increment j from increments $j + 1$ and $j - 1$ are, respectively,

$$q_{cp} = \frac{D_{fv} F_m k_c A_c (T_{cjp} - T_{cj})}{\Delta \ell^2}, \text{ cal/((sec)(cm)) } (8)$$

(when $j = N_j$, $q_{cp} = 0$),

and

$$q_{cq} = \frac{D_{fv} F_m k_{cj} m A_c (T_{cjm} - T_{cj})}{\Delta \ell^2}, \text{ cal/((sec)(cm)) } (9)$$

$$\left(\text{when } j = 1, q_{cq} = \frac{2UF_m k_c A_c (T_b - T_{cj})}{\Delta \ell^2} \right).$$

F. Heat Transfer from Cladding to Gas

As the steam and hydrogen mixture flows upward along the rods, temperature differences cause heat to be transferred between the rod cladding and the gas.

The rate of heat transfer from the cladding of a rod in zone i to the gas, per centimeter of rod, is

$$q_g = S_r h_g (T_c - T_g), \text{ cal/}(\text{sec})(\text{cm}), \quad (10a)$$

where

$$S_r = 2\pi r_o = \text{surface area of the cladding per centimeter of length, cm}^2/\text{cm},$$

$$h_g = \text{heat-transfer coefficient}$$

$$= \frac{k_g}{\sigma_h}, \text{ cal/}(\text{cm}^2)(\text{sec})(^\circ\text{K}),$$

and

$$k_g = \text{heat conductivity of the gas mixture}$$

$$= Xk_s + (1 - X) k_h, \text{ cal/}(\text{sec})(\text{cm})(^\circ\text{K}).$$

The heat-transfer coefficient, h_g , and the effective gas-film thickness, σ_h , are discussed in Appendix A.

G. Radial Heat Transfer to and from Cladding by Radial Radiation (before Fuel Melting and Slumping)

The heat radiated from the cladding of a rod in zone i and increment j to zone $i + 1$, per centimeter of rod, is

$$q_{rp} = -F_s \frac{4\pi^2 r_o}{V_1} i \sigma E_{ip} A_p T_{ci(j)}^4, \text{ cal/}(\text{sec})(\text{cm}), \quad (11a)$$

and when $i = N_i$,

$$q_{rp} = -F_s \frac{4\pi^2 r_o}{V_1} 2N_i \sigma E_{ip} A_p T_{ci(j)}^4, \text{ cal/}(\text{sec})(\text{cm}). \quad (11b)$$

The heat received by the cladding of a rod in zone i and increment j by radiation from zone $i + 1$, per centimeter of rod, is

$$q_{rip} = F_s \frac{4\pi^2 r_o}{V_1} i \sigma E_{ip} A_p T_{cip(jns)}^4, \text{ cal/}(\text{sec})(\text{cm}), \quad (12a)$$

and when $i = N_i$,

$$q_{rip} = F_s \frac{4\pi^2 r_o}{V_1} 2N_i \sigma E_{ip} A_p T_w^4, \text{ cal/}(\text{sec})(\text{cm}). \quad (12b)$$

The heat radiated from the cladding of a rod in zone i and increment j to zone $i - 1$, per centimeter of rod, is

$$q_{rq} = -F_s \frac{4\pi^2 r_o}{V_1} (i-1) E_{im} A_m T_{ci(j)}^4, \text{ cal/}(\text{sec})(\text{cm}). \quad (13a)$$

The heat received by the cladding of a rod in zone i and increment j by radiation from zone $i-1$, per centimeter of rod, is

$$q_{rim} = F_s \frac{4\pi^2 r_o}{V_1} (i-1) E_{im} A_m T_{cim(jnss)}^4, \text{ cal/}(\text{sec})(\text{cm}). \quad (14a)$$

The emissivity factors, E_{ip} and E_{im} , and the view factors, A_p and A_m , are discussed together with the forms of the equations in Appendix B.

H. Heat Transfer by Radial Conduction after Fuel Melting and Slumping

When adjacent increments of fuel rods melt and slump together, heat transfer by radial radiation ceases and heat transfer by radial conduction starts in those increments.

The net heat received by radial conduction by a rod in zone i and increment j from zone $i+1$, per centimeter of rod, is the sum of

$$q_{rp} = -F_s \frac{4\pi i}{V_1} k_a k_{am} T_{ci(j)}, \text{ cal/}(\text{sec})(\text{cm}), \quad (11c)$$

and

$$q_{rip} = F_s \frac{4\pi i}{V_1} k_a k_{am} T_{cip(jns)}, \text{ cal/}(\text{sec})(\text{cm}), \quad (12c)$$

and the net heat received by radial conduction by a rod in zone i and increment j from zone $i-1$, per centimeter of rod, is the sum of

$$q_{rq} = -F_s \frac{4\pi(i-1)}{V_1} k_a k_{am} T_{ci(j)}, \text{ cal/}(\text{sec})(\text{cm}), \quad (13b)$$

and

$$q_{rim} = F_s \frac{4\pi(i-1)}{V_1} k_a k_{am} T_{cim(jnss)}, \text{ cal/}(\text{sec})(\text{cm}). \quad (14b)$$

The forms of the above equations are discussed in Appendix B.

I. Heat Transfer by Axial Radiation before Fuel Melting and Slumping

Before increments of fuel rods melt and slump, heat is transferred axially along the cladding by radiation.

The transfer of heat from an increment j of a rod in zone i to adjacent increments $j + 1$ and $j - 1$ by axial radiation, per centimeter of rod, is to increment $j + 1$:

$$q_{arp} = -\frac{A_v}{\Delta \ell} \pi r_o \sigma E_{jp} T_{cj}^4, \text{ cal/}(\text{sec})(\text{cm}), \quad (15a)$$

$$\left(\text{when } j = N_j, q_{arp} = -\frac{A_v + r_o}{\Delta \ell} \pi r_o \sigma E_{jp} T_{cj}^4 \right)$$

and to increment $j - 1$:

$$q_{arq} = -\frac{A_v}{\Delta \ell} \pi r_o \sigma E_{jm} T_{cj}^4, \text{ cal/}(\text{sec})(\text{cm}). \quad (16a)$$

The receipt of heat from increments $j + 1$ and $j - 1$ to increment j of a rod in zone i by radial radiation, per centimeter of rod, is from increment $j + 1$:

$$q_{arjp} = \frac{A_v}{\Delta \ell} \pi r_o \sigma E_{jp} T_{cjp}^4, \text{ cal/}(\text{sec})(\text{cm}), \quad (17a)$$

$$\left(\text{when } j = N_j, q_{arjp} = \frac{A_v + r_o}{\Delta \ell} \pi r_o \sigma E_{jp} T_t^4 \right)$$

and from increment $j - 1$:

$$q_{arjm} = \frac{A_v}{\Delta \ell} \pi r_o \sigma E_{jm} T_{cjm}^4, \text{ cal/}(\text{sec})(\text{cm}) \quad (18a)$$

$$\left(\text{when } j = 1, q_{arjm} = \frac{A_v}{\Delta \ell} \pi r_o \sigma E_{jm} T_b^4 \right)$$

The emissivity factors, E_{jp} and E_{jm} , and the view factor, A_v , are discussed together with the forms of the equations in Appendix B.

VI. HEAT AND MASS BALANCES

A heat and mass balance is made on one elementary length, $\Delta \ell$, of a fuel rod with cladding and associated gas flow area in zone i and increment j at time t .

A. Heat Balance on Fuel

To take account of the latent heat of the fuel as it melts, a fuel pseudotemperature is first calculated and then the actual fuel temperature is determined, using the following relationships:

$$T_{a\ell} - T_{am} = \frac{L_{ac}}{C_{pam}} \quad (19)$$

For $T_{ap} = 273$ to T_{am} , $T_a = T_{ap}$;

for $T_{ap} = T_{am}$ to $T_{a\ell}$, $T_a = T_{am}$;

and for $T_{ap} > T_{a\ell}$, $T_a = T_{ap} - (T_{a\ell} - T_{am})$. (20a)

$$\text{Fraction of fuel molten} = \frac{T_{ap} - T_{am}}{T_{a\ell} - T_{am}} \quad (21)$$

The fuel in the elementary length receives heat from the decay heating by heat transfer from the cladding and by axial heat conduction in the fuel. Its heat capacity is $C_{pa}W_a$, and its increase in pseudotemperature ΔT_{ap} in time Δt is

$$\Delta T_{ap} = \frac{F_d q_d - q_{ac} + q_{ap} + q_{aq}}{F_w W_a C_{pa}} \Delta t, ^\circ K. \quad (22)$$

B. Heat Balance on Cladding

The cladding in the elementary length receives heat by transfer from the fuel, by the chemical reaction of the steam with the cladding, by convection from the gas, by axial heat radiation and conduction in the cladding, and by radiation to and from zones $i+1$ and $i-1$. The heat capacity of the cladding is $C_{pc}W_c$, and its increase in temperature in time Δt is

$$\Delta T_c = \frac{q_{ac} + q_{ri} + q_s - q_g}{W_c C_{pc}} \Delta t, ^\circ K, \quad (23)$$

where

$$q_{ri} = q_{rp} + q_{rq} + q_{rip} + q_{rim} + q_{arp} + q_{arq} + q_{arjp} + q_{arjm} + q_{cp} + q_{cq}.$$

C. Heat Balance on Gas

The gas receives heat by convection from the cladding as it flows along the rod. The heat capacity of the gas flowing along one rod per second (unit time) is $W_g C_{pg}$, and its temperature increase in length of rod Δl is

$$\Delta T_g = \frac{q_g}{W_g C_{pg}} \Delta l, \text{ } ^\circ\text{K}, \quad (24)$$

where

C_{pg} = specific heat of the gas, cal/(mole)($^\circ\text{K}$),

$$= X C_{ps} + (1 - X) C_{ph}.$$

D. Mass Balance on Cladding

The cladding is oxidized by the chemical reaction with the steam. The rate of oxidation is equal to the rate of heat production per centimeter of rod, divided by the weight per unit thickness of the cladding and the heat of combustion per gram of the cladding.

The thickness of cladding oxidized in time Δt is therefore

$$\Delta R_r = \Delta(r_o - r) = \frac{q_s}{S \rho_c Q_c} \Delta t, \text{ cm.} \quad (25)$$

Since the reaction rate may be limited by the chemical kinetic effect, steam-diffusion effect, or lack of cladding, and since q_s must be calculated as a function of those limits, it is convenient to put the thickness of cladding oxidized in the above form.

E. Mass Balance on Gas

The concentration of steam in the gas decreases as it flows up the rod because of its consumption in the chemical reaction. On oxidation of the cladding, one mole of steam forms one mole of hydrogen; hence, the number of moles of gas flowing along the rod remains essentially constant with respect to length of rod.

The change in steam concentration ΔX in length of rod Δl can be expressed as

$$\Delta X = - \frac{q_s}{W_g Q_c M_c} \Delta l. \quad (26)$$

F. Heat Balance on Bottom Grid Plate

The bottom grid plate receives heat from the fuel rods by axial conduction and radiation and loses heat to the ambient.

The increase in temperature ΔT_b in time Δt is

$$\Delta T_b = \frac{V_1 \Delta \ell \sum_{i=1}^{N_i} (-q_{arq} - q_{arjm} - q_{cq} - q_{aq})_{j=1} - U_b(T_b - T_{ba})}{W_b C_{pb}} \Delta t. \quad (27)$$

G. Heat Balance on Wall

The wall surrounding the core receives heat from the fuel rods by radial radiation and loses heat to the ambient.

The increase in temperature ΔT_w of the wall in time Δt is

$$\Delta T_w = \frac{V_1 \Delta \ell \sum_{j=1}^{N_j} (-q_{rp} - q_{rip})_{i=N_i} - U_w(T_w - T_{wa})}{W_w C_{pb}} \Delta t. \quad (28)$$

H. Heat Balance on Top Grid Plate

The top grid plate receives heat by radiation from the top ends of the fuel rods and loses heat to the ambient. It may also receive heat from the gas mixture leaving the core. However, this latter effect is neglected.

The increase in temperature, ΔT_t , of the top grid plate in time Δt is

$$\Delta T_t = \frac{V_1 \Delta \ell \sum_{i=1}^{N_i} (-q_{arp} - q_{arjp})_{j=N_j} - U_t(T_t - T_{ta})}{W_t C_{pb}} \Delta t. \quad (29)$$

VII. ITERATION EQUATIONS FOR CORE HEATING AND CHEMICAL REACTION

A. Iteration Equations for T_{ap} , T_c , T_g , $r_o - r$, and X

The iteration equations for T_{apij} , T_{cij} , T_{gij} , $r_o - r_{ij}$, and X_{ij} , as functions of zone i and length increment j at time t and parameters involving the core are as follows:

$$T_{apij(k)} = T_{apij(km)} + \left(\frac{F_d q_d - q_{ac} + q_{ap} + q_{aq}}{F_w W_a C_{pa}} \right)_{ij(km)} \Delta t, ^\circ K, \quad (30a)$$

$$T_{cij(k)} = T_{cij(km)} + \left(\frac{q_{ac} + q_{ri} + q_s - q_g}{W_c C_{pc}} \right)_{ij(km)} \Delta t, ^\circ K, \quad (31a)$$

$$T_{gijp(km)} = T_{gij(km)} + \left(\frac{q_g}{W_g C_{pg}} \right)_{ij(km)} \Delta l, ^\circ K, \quad (32a)$$

$$r_o - r_{ij(k)} = r_o - r_{ij(km)} + \left(\frac{q_s}{S \rho_c Q_c} \right)_{ij(km)} \Delta t, \text{ cm}, \quad (33a)$$

and

$$X_{ijp(km)} = X_{ij(km)} - \left(\frac{q_s}{W_g Q_c M_c} \right)_{ij(km)} \Delta l, \text{ mole/mole}. \quad (34a)$$

B. Iteration Equations for T_b , T_w , and T_t

Iteration equations for T_b , T_w , and T_t are as follows:

$$T_{b(k)} = T_{b(km)} + \left[\frac{V_1 \Delta l \sum_{i=1}^{N_i} (-q_{arq} - q_{arjm} - q_{cq} - q_{aq})_{j=1} - U_b (T_b - T_{ba})}{W_b C_{pb}} \right]_{(km)} \Delta t, ^\circ K, \quad (35a)$$

$$T_{w(k)} = T_{w(km)} + \left[\frac{V_1 \Delta l \sum_{j=1}^{N_j} (-q_{rp} - q_{rip})_{i=N_i} - U_w (T_w - T_{wa})}{W_w C_{pw}} \right]_{(km)} \Delta t, ^\circ K, \quad (36a)$$

and

$$T_{t(k)} = T_{t(km)} + \left[\frac{V_1 \Delta \ell \sum_{i=1}^{N_i} (-q_{arp} - q_{arjp})_{j=N_j} - U_t(T_t - T_{ta})}{W_t C_{pb}} \right]_{(km)} \Delta t, ^\circ K. \quad (37a)$$

C. Initial Conditions

At time $t = 0$,

$$T_{apij(km)} = T_{ap0ij} = T_{a0ij}, ^\circ K,$$

initial fuel temperature, variable over core;

$$T_{cij(km)} = T_{c0ij}, ^\circ K,$$

initial cladding temperature, variable over core;

$$R_o - R_{ij(km)} = (r_o - r)_o, \text{ cm},$$

initial cladding oxidized, input constant;

$$T_b(km) = T_{b0}, ^\circ K,$$

initial bottom temperature, input constant;

$$T_w(km) = T_{w0}, ^\circ K,$$

initial wall temperature, input constant;

$$T_t(km) = T_{t0}, ^\circ K,$$

initial top temperature, input constant;

$$T_{ap0ij} = V_4 + V_2 f(i) S(j); \quad (30b)$$

$$T_{c0ij} = V_4 + V_3 f(i) S(j); \quad (31b)$$

V_2, V_3, V_4 , are input constants;

and $f(i)$ and $S(j)$ are input functions of i and j .

At length, $\ell = 0, j = 1, \dots$

$$T_{gij(km)} = T_{g0}, ^\circ K,$$

initial steam temperature, input constant;

$$X_{ij(km)} = X_0 = 1,$$

initial fraction steam in gas.

VIII. PREINTEGRATION TO PERMIT ITERATION BY REASONABLY LARGE VALUES OF Δt AND $\Delta \ell$

In solving the simultaneous iteration equations with a digital computer, we must use reasonably large values of Δt and $\Delta \ell$ to avoid excessive computer time. Intervals of the order of 5 sec for Δt and $L/25$ for $\Delta \ell$ (which is about 15 cm for a 12-ft-long rod) must be used.

For steam flow rates of about 0.3 lb per rod per hour, the heat capacity of the flowing gas is fairly low and large gas temperature changes may occur over the length $\Delta \ell$, particularly where the gas is passing an area of cladding undergoing intense chemical reaction. If the gas temperature computed for the previous length increment is used as a fixed value to compute the heat transfer for the interval $\Delta \ell$, a quantity of heat may be computed as transferred from the gas to the cladding, which is greater than the heat content of the gas, thus leading to a computed negative value of the gas temperature. The same situation might occur with respect to the fraction steam in the gas.

The heat capacity of the cladding per unit length of rod is fairly low, and the temperature of the cladding may change appreciably during the time interval Δt . If the cladding temperature computed for the previous time increment is used as a fixed value to compute the heat transferred from the cladding over the time interval Δt , a quantity of heat may be computed as transferred from the cladding which is greater than the heat content of the cladding, thus leading to a computed negative value of the cladding temperature. This is particularly possible in areas where the cladding is undergoing intense chemical reaction. The situation can also lead to computed temperature oscillations which lead to negative temperatures.

This difficulty can be alleviated by preintegration over the time interval Δt and over the length increment $\Delta \ell$ to obtain anticipated average values of heat or mass transfer to be used in the iteration.

Preintegration is desirable in the cases of q_{rp} , q_{rip} , q_{rq} , q_{rim} , q_{arp} , q_{arjp} , q_{arq} , q_{arjm} , q_{ac} , q_g , and q_s .

For heat transfer from the cladding, it is not feasible to analytically preintegrate the various expressions for heat transfer simultaneously. It is thus necessary to partition the maximum heat transfer allowable among the expressions for heat transfer and/or to consider the events as occurring sequentially and make adjustments accordingly. In this case, a composite is used. The maximum allowable heat transfer is partitioned among the first eight heat-transfer terms, and the preintegrated transfer terms are considered to occur sequentially as follows:

$$\bar{q}_{ri}, \bar{q}_{ac}, \bar{q}_g.$$

The expressions for the preintegrated rates of heat and mass transfer over the intervals Δt and $\Delta \ell$ are listed below. In these expressions, the bar over the q value indicates an average value over the length $\Delta \ell$ or time Δt .

A. Radial Radiation before Slumping

$$\bar{q}_{rp} = - \frac{F_{sij} T_{cij}}{P_n} \left[1 - \left(\frac{1}{1 + P_n D_1 E_{ip} A_p i T_{cij}^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm}) \quad (11d)$$

(when $i = N_i$, use $2N_i$ for i);

$$\bar{q}_{rip} = \frac{F_{sij} T_{cipjns}}{P_n} \left[1 - \left(\frac{1}{1 + P_n D_1 E_{ip} A_p i T_{cipjns}^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm}) \quad (12d)$$

(when $i = N_i$);

$$\bar{q}_{rip} = \frac{F_{sij} T_w}{P_n} \left[1 - \left(\frac{1}{1 + 2P_n D_1 E_{ip} A_p N_i T_w^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm});$$

$$\bar{q}_{rq} = - \frac{F_{sij} T_{cij}}{P_n} \left\{ 1 - \left(\frac{1}{1 + P_n D_1 E_{im} A_m (i-1) T_{cij}^3} \right)^{1/3} \right\}, \text{ cal/}(\text{sec})(\text{cm}); \quad (13c)$$

$$\bar{q}_{rim} = \frac{F_{sij} T_{cimjnss}}{P_n} \left\{ 1 - \left[\frac{1}{1 + P_n D_1 E_{im} A_m (i-1) T_{cimjnss}^3} \right]^{1/3} \right\}, \text{ cal/}(\text{sec})(\text{cm}); \quad (14c)$$

where

$$P_n = \frac{A_n \Delta t}{C_{pc} W_c},$$

and

$$D_1 = 3 \frac{4\pi^2 r_o \sigma}{V_1}.$$

B. Axial Radiation before Slumping

$$\bar{q}_{arp} = -\frac{T_{cij}}{P_n} \left[1 - \left(\frac{1}{1 + P_n D_n E_{jp} A_v T_{cij}^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm}) \quad (15b)$$

(when $j = N_j$, use $A_v + r_o$ for A_v);

$$\bar{q}_{arjp} = \frac{T_{cijp}}{P_n} \left[1 - \left(\frac{1}{1 + P_n D_n E_{jp} A_v T_{cijp}^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm}) \quad (17b)$$

(when $j = N_j$, use $A_v + r_o$ for A_v and T_t for T_{cijp});

$$\bar{q}_{arq} = -\frac{T_{cij}}{P_n} \left[1 - \left(\frac{1}{1 + P_n D_n E_{jm} A_v T_{cij}^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm}); \quad (16b)$$

$$\bar{q}_{arjm} = \frac{T_{cijm}}{P_n} \left[1 - \left(\frac{1}{1 + P_n D_n E_{jm} A_v T_{cijm}^3} \right)^{1/3} \right], \text{ cal/}(\text{sec})(\text{cm}) \quad (18b)$$

(when $j = 1$, $T_{cijm} = T_b$);

where

$$P_n = \frac{A_n \Delta t}{C_{pc} W_c},$$

and

$$D_n = \frac{3\pi r_o \sigma}{\Delta \ell}.$$

C. Radial Conduction after Slumping

$$\bar{q}_{rp} = \frac{-F_{sij} T_{cij} [1 - \exp(-P_n D_r i)]}{P_n}, \text{ cal/}(\text{sec})(\text{cm}); \quad (11e)$$

$$\bar{q}_{rip} = \frac{F_{sij} T_{cipjns} [1 - \exp(-P_n D_r i)]}{P_n}, \text{ cal/}(\text{sec})(\text{cm}); \quad (12e)$$

$$\bar{q}_{rq} = \frac{-F_{sij} T_{cij} \{1 - \exp[-P_n D_r (i-1)]\}}{P_n}, \text{ cal/}(\text{sec})(\text{cm}); \quad (13d)$$

$$\bar{q}_{rim} = \frac{F_{sij} T_{cimjnss} \{1 - \exp[-P_n D_r (i-1)]\}}{P_n}, \text{ cal/}(\text{sec})(\text{cm}); \quad (14d)$$

where

$$P_n = \frac{A_n \Delta t}{C_{pc} W_c},$$

and

$$D_r = \frac{4\pi k_a k_{am}}{V_1}.$$

D. Heat Transfer from Cladding to Fuel and to Gas

$$\bar{q}_{ac} = \frac{[T_a - T_{c(a)}] [1 - \exp(-C P \Delta t)]}{P \Delta t}, \text{ cal/}(\text{sec})(\text{cm}); \quad (6c)$$

$$\bar{q}_g = \frac{[T_{c(g)} - T_g] \left[1 - \exp\left(-\frac{S_r h_g \Delta \ell}{W_g C_{pg}}\right) \right] W_g C_{pg}}{\Delta \ell}, \text{ cal/}(\text{sec})(\text{cm}); \quad (10b)$$

where

$$C = \frac{2\pi r_a h_{ac}}{r_a h_{ac} + 1 + \frac{4k_a}{r_a h_{ac}}}$$

$$P = \frac{1}{C_{pc} W_c}$$

$$T_{c(a)} = T_c + P \Delta t (\bar{q}_{ri}),$$

$$T_{c(g)} = T_c + P \Delta t (\bar{q}_{ri} + \bar{q}_{ac}),$$

and

$$\begin{aligned} \bar{q}_{ri} = & \bar{q}_{rp} + \bar{q}_{rip} + \bar{q}_{rq} + \bar{q}_{rim} + \bar{q}_{arp} + \bar{q}_{acjp} + \bar{q}_{arq} + \bar{q}_{arjm} \\ & + q_{cp} + q_{cq}. \end{aligned}$$

E. Heat of Chemical Reaction

For the diffusion-limited case,

$$\bar{q}_s = \frac{Q_c M_c W_g X \left[1 - \exp\left(-\frac{Sh_d \rho_g \Delta \ell}{W_g}\right) \right]}{\Delta \ell}, \text{ cal/}(\text{sec})(\text{cm}), \quad (7d)$$

where

$$S = 2\pi r_o + V_k.$$

For small values of $\Delta \ell$ or Δt , the preintegrated expressions reduce mathematically to the original expressions.

The maximum allowable heat transfer is partitioned among four pairs of heat-transfer terms; hence, the value of A_n would normally be 4, although smaller values can be used. Smaller values tend to return the effect of the expression to its nonpreintegrated form.

IX. EXTRA OXIDIZABLE SURFACES AND CONTROL RODS

Within the core are items other than fuel and cladding, such as subassembly cans and control rods, which constitute:

1. Additional mass to be heated,
2. Extra surface for heat transfer to the gas stream, and
3. Extra surface for oxidation.

This extra material can be handled as follows: Its effective mass for heating can be distributed between the fuel and cladding, and the extra surface for oxidation and heat transfer to the gas can be added to the cladding surface.

The effective mass of control rods, etc., which are not in contact with the main steam flow before slumping, might be added to the fuel weight, and the effective mass and surface of items in contact with the main steam flow, such as subassembly cans, might be added to the cladding weight and surface. However, one might simply add all weight to the cladding.

The effective weight to be added to the fuel weight W_a , per centimeter of rod, would be

$$\frac{W_r C_{pr}}{V_6 L C_{pa}}, \text{ g/cm.}$$

The effective weight to be added to the cladding weight W_c , per centimeter of rod, would be

$$\frac{W_o C_{po}}{V_6 L C_{pc}}, \text{ g/cm.}$$

The surface to be added is

$$\frac{S_o}{V_6 L} = V_k, \text{ cm}^2/\text{cm.}$$

Normally the extra oxidizable surface is the same material as the cladding. The input items to the program involved are W_a , W_c , V_k , and α where

$$W_a = \pi r_a^2 \rho_a + \frac{W_r C_{pr}}{V_6 L C_{pa}}, \text{ g/cm;} \quad W_c = \pi (r_o^2 - r_f^2) \rho_c + \frac{W_o C_{po}}{V_6 L C_{pc}}, \text{ g/cm;}$$

$$V_k = \frac{S_o}{V_6 L}, \text{ cm}^2/\text{cm;}$$

and

α = thickness of extra oxidizable surface, cm.

X. VARIATION OF PARAMETERS WITH TEMPERATURE

The following are expressions and suggested constants for the variation of certain parameters with temperature:

A. Specific heat of fuel, UO_2

$$C_{pa} = a + bT, \text{ cal/(g)}(^{\circ}\text{K}),$$

where

$$a = 0.068 \text{ and } b = 7.50 \times 10^{-6}.$$

B. Specific heat of stainless steel

$$C_{pb} = a + bT, \text{ cal/(g)}(^{\circ}\text{K}),$$

where

$$a = 0.106 \text{ and } b = 4.00 \times 10^{-5}.$$

C. Specific heat of Zircaloy cladding metal

$$C_{pcm} = a + bT, \text{ cal/(g)}(^{\circ}\text{K}),$$

where

$$a = 0.082 \text{ and } b = 0.00.$$

D. Specific heat of Zircaloy cladding metal oxide

$$C_{pco} = a + bT, \text{ cal/(g)}(^{\circ}\text{K}),$$

where

$$a = 0.148 \text{ and } b = 0.00.$$

E. Specific heat of cladding

$$C_{pc} = C_{pcm} + (R_{co}C_{pco} - C_{pcm}) \frac{r_o - r}{r_o - r_f}.$$

F. Specific heat of hydrogen

$$C_{ph} = a + bT, \text{ cal/(mole)}(^{\circ}\text{K}),$$

where

$$a = 6.56 \text{ and } b = 7.50 \times 10^{-4}.$$

G. Specific heat of steam

$$C_{ps} = a + bT, \text{ cal/(g)(}^{\circ}\text{K)},$$

where

$$a = 7.20 \text{ and } b = 7.50 \times 10^{-3}.$$

H. Specific heat of gas

$$C_{pg} = XC_{ps} + (1 - X) C_{ph}, \text{ cal/(mole)(}^{\circ}\text{K)}.$$

I. Diffusivity of steam in hydrogen

$$D_g = \frac{a}{P_g} \left(\frac{T}{1000} \right)^b, \text{ cm}^2/\text{sec},$$

where

$$a = 7.30 \text{ and } b = 1.75.$$

J. Cladding-gas heat-transfer coefficient

$$h_g = V_s k_g, \text{ cal/(sec)(cm}^2\text{)(}^{\circ}\text{K)}.$$

K. Steam mass-transfer coefficient

$$h_d = V_{ms} D_g, \text{ cm/sec}.$$

L. Thermal conductivity of fuel, UO_2

$$k_a = a + bT + cT^2, \text{ cal/(sec)(cm)(}^{\circ}\text{K)},$$

where

$$a = 0.014, b = -1.00 \times 10^{-5}, \text{ and } c = 2.50 \times 10^{-9}.$$

M. Thermal conductivity of Zircaloy cladding

$$k_c = a + bT, \text{ cal/(sec)(cm)(}^{\circ}\text{K)},$$

where

$$a = 0.041 \text{ and } b = 0.000.$$

N. Thermal conductivity of hydrogen

$$k_h = a \left(\frac{T}{1000} \right)^b, \text{ cal/}(\text{sec})(\text{cm})(^\circ\text{K}),$$

where

$$a = 1.10 \times 10^{-3} \text{ and } b = 0.75.$$

O. Thermal conductivity of steam

$$k_s = a + b \left(\frac{T}{1000} \right), \text{ cal/}(\text{sec})(\text{cm})(^\circ\text{K}),$$

where

$$a = -0.20 \times 10^{-4} \text{ and } b = 2.00 \times 10^{-4}.$$

P. Thermal conductivity of gas

$$k_g = Xk_s + (1 - X) k_h, \text{ cal/}(\text{sec})(\text{cm})(^\circ\text{K}).$$

Q. Heat of reaction of Zircaloy with steam

$$Q_c = a + bT, \text{ cal/g},$$

where

$$a = 1610.0 \text{ and } b = 0.615.$$

R. Density of gas

$$\rho_g = P_g / 82.057T, \text{ moles/cm}^3.$$

XI. PROGRAM INPUT

Data input to the program consists of:

1. Eighty-nine individual parameters which are read in, nine on the first card, which includes integer data, and 10 per card for the remainder.
2. A tabular list of decay heat values $F(t)$ as a fraction of reactor power for various time periods in seconds. These data are used for interpolation by a subroutine. One value of t and one value of $F(t)$ are read in per card.
3. A tabular list of relative reactor power $f(i)$ in each zone i , 10 values of $f(i)$ per card.
4. A tabular list of relative reactor power $S(j)$ in each length increment j , 10 values of $S(j)$ per card.

The parameters are read in from cards as follows. The symbols are discussed on the following pages.

NTAB	CPSA	TBA	AN	HAC	CPAA	KSA	AA	WA
NPRINT	CPSB	TBZ	CAS	U	CPAB	KSB	AC	WB
NJP	KAA	TGO	DF	UB	CPBA	DGA	ALFA	WC
NJ	KAB	TTA	FLS	UT	CPBB	DGB	VK	WTP
LASTZ	KAC	TTZ	FF	UW	CPCMA	QCA	VA	WW
ELT	KCA	TWA	FRF	V5	CPCMB	QCB	RO	RHOC
DELT	KCB	TWZ	KAM	VM5	CPCOA	CAY	RZERO	A1
TMAX	KHA	V2	SF	EPS	CPCOB	DELE	RF	A2
QD	KHB	V3	TAM	A	CPHA	SIG	V6	A4
	RCZ	V4	TAL	AV	CPHB	V8	EMC	TEEMAX

Selected values $FTAB(JZ)$ of the relative decay heat $F(t)$, as a function of time $TTAB(JZ)$, t seconds after blowdown, are read in for interpolation by a subroutine. Since the time intervals are not constant, both t and $F(t)$ are read in, one t and one $F(t)$ per card. In $TTAB(JZ)$ and $FTAB(JZ)$, $JZ = 1$ to $NTAB$. The following are typical values for the relative decay heat ($NTAB = 24$) used in the sample calculation input and output given in Appendix E.

<u>TTAB(JZ)</u>	<u>FTAB(JZ)</u>	<u>TTAB(JZ)</u>	<u>FTAB(JZ)</u>
1	0.0633	500	0.0203
3	0.0584	600	0.0191
5	0.0549	800	0.0177
10	0.0496	1000	0.0166
20	0.0433	1500	0.0147

(continued)

<u>TTAB(JZ)</u>	<u>FTAB(JZ)</u>	<u>TTAB(JZ)</u>	<u>FTAB(JZ)</u>
40	0.0382	2000	0.0134
60	0.0348	3000	0.0117
100	0.0308	4000	0.0106
150	0.0276	5000	0.0098
200	0.0257	6000	0.0093
300	0.0230	8000	0.0083
400	0.0213	10000	0.0079

The relative reactor power in each zone $FI(JZ)$, $f(i)$, is read in for each zone, 10 data per card. J varies from $JZ = 1$ to $LASTZ$. The following is typical for 13 zones for a Bessel function, J_0 , radial distribution (see Appendix E). Since the JZ are consecutive, only the $FI(JZ)$ are punched on the cards.

<u>JZ = I or i</u>	<u>FI(JZ) = f(i)</u>	<u>JZ = I or i</u>	<u>FI(JZ) = f(i)</u>
1	1.43	8	0.92
2	1.35	9	0.85
3	1.27	10	0.79
4	1.20	11	0.73
5	1.13	12	0.67
6	1.06	13	0.61
7	0.99		

The relative reactor power in each length increment $SINZB(JZ)$, $S(j)$, is read in for each increment, 10 data per card. J varies from $JZ = 1$ to NJ . The following is typical for 25 increments for a truncated sine-wave axial distribution (see Appendix E). Since the JZ are consecutive, only the $SINZB(JZ)$ are punched on the cards.

<u>JZ = J or j</u>	<u>SINZB(JZ) = S(j)</u>	<u>JZ = J or j</u>	<u>SINZB(JZ) = S(j)</u>
1	0.204	14	1.486
2	0.380	15	1.454
3	0.550	16	1.402
4	0.713	17	1.329
5	0.864	18	1.237
6	1.004	19	1.129
7	1.129	20	1.004
8	1.237	21	0.864
9	1.328	22	0.713
10	1.402	23	0.550
11	1.454	24	0.380
12	1.486	25	0.204
13	1.498		

The symbols and the methods by which their values are obtained are described below.

Symbol	Description																		
A	This is the radial radiation view factor A. It is dimensionless and is estimated as discussed in Appendix B. Its value depends upon the rod pitch/diameter ratio. A correction for rod circumferential temperature variation due to fuel conductivity, k_a , can also be made. Values are approximately as follows for a square array of rods:																		
	<table><tr><th>Pitch/Diameter Ratio</th><th>A (k_a large)</th><th>A ($k_a = 0.0048$, $T = 2000^\circ\text{K}$)</th></tr><tr><td>1.0</td><td>0.66</td><td>0.23</td></tr><tr><td>1.25</td><td>0.90</td><td>0.48</td></tr><tr><td>1.50</td><td>1.18</td><td>0.55</td></tr><tr><td>1.75</td><td>1.51</td><td>0.61</td></tr><tr><td>2.00</td><td>2.10</td><td>0.68</td></tr></table>	Pitch/Diameter Ratio	A (k_a large)	A ($k_a = 0.0048$, $T = 2000^\circ\text{K}$)	1.0	0.66	0.23	1.25	0.90	0.48	1.50	1.18	0.55	1.75	1.51	0.61	2.00	2.10	0.68
Pitch/Diameter Ratio	A (k_a large)	A ($k_a = 0.0048$, $T = 2000^\circ\text{K}$)																	
1.0	0.66	0.23																	
1.25	0.90	0.48																	
1.50	1.18	0.55																	
1.75	1.51	0.61																	
2.00	2.10	0.68																	
A1 A2 A4	<p>{ These, together with TEEMAX, are the A_1, A_2, A_3, and t_m for defining the steam flow as</p> $W_s = A_1/(A_2 + t)^{1/2} \quad \text{for } t = 0 \text{ to } t_m;$ $W_s = \left[A_1/(A_2 + t_m)^{1/2} \right] \exp[-A_4(t - t_m)] \quad \text{for } t > t_m.$																		
	Since the steam-flow-rate curve may not be available for fitting to the above, a method of estimating A_1 , A_2 , A_4 , and t_m is discussed in Appendix C.																		
AA	This is the cross-sectional area of the fuel in a fuel rod in square centimeters, A_a .																		
AC	This is the initial cross-sectional area of the cladding in a fuel rod in square centimeters, A_c .																		
ALFA	This is the thickness of additional oxidizable surfaces such as subassembly cans, if any, in centimeters. For additional comment, see Chapter IX.																		
AN	This is the partition coefficient, A_n , for computing preintegrated anticipated values and is dimensionless; normally a value of 4.0 is used.																		
AV	This is the vertical radiation view factor, A_v , and is discussed in Appendix B. It has the dimension of centimeters and is the average surface distance between rods. Values are approximately as follows for a square rod array:																		

Symbol	Description	
	Pitch/Diameter Ratio	A_v
	1.0	0.30 r_o
	1.25	1.07 r_o
	1.50	1.94 r_o
	1.75	2.95 r_o
	2.00	4.20 r_o
CAS	This defines an alternate in core slumping. If 1.0 is used, fuel material falls from the core each time a length increment slumps. If 2.0 is used, fuel material ceases to fall from the core when all the void space in the core below the slumping increment is filled with fallen fuel.	
CAY	This is the rate constant for cladding reaction with steam. For zirconium cladding, use $0.3937 \text{ cm}^2/\text{sec}$. For stainless steel cladding, use $1.41 \times 10^6 \text{ cm}^2/\text{sec}$.	
CPAA CPAB	These are the constants for the specific heat of the fuel, $C_p = a + bT$, cal/(g)(°K). Suggested values for UO_2 are: CPAA = 0.068; CPAB = 7.50×10^{-6} .	
CPBA CPBB	These are the constants for the specific heat of steel for the wall, top grid, and bottom grid plates, $C_p = a + bT$, cal/(g)(°K). Suggested values are: CPBA = 0.106; CPBB = 4.00×10^{-5} .	
CPCMA CPCMB	These are the constants for the specific heat of the cladding metal, $C_p = a + bT$, cal/(g)(°K). Suggested values for Zircaloy are: CPCMA = 0.082; CPCMB = 0.00.	
CPCOA CPCOB	These are the constants for the specific heat of the cladding oxide, $C_p = a + bT$, cal/(g)(°K). Suggested values for Zircaloy are: CPCOA = 0.148; CPCOB = 0.000.	

Symbol	Description
CPHA CPHB	These are the constants for the specific heat of hydrogen, $C_p = a + bT$, cal/(mole)(°K). Suggested values are: $CPHA = 6.560$; $CPHB = 7.50 \times 10^{-4}$.
CPSA CPSB	These are the constants for the specific heat of steam, $C_p = a + bT$, cal/(mole)(°K). Suggested values are: $CPSA = 7.20$; $CPSB = 2.55 \times 10^{-3}$.
DELE	This is ΔE , the activation energy for the cladding-steam reaction. Suggested values are: for Zircaloy, DELE = 45,500.0 cal/mole; for stainless steel, DELE = 90,800.0 cal/mole.
DELT	This is Δt , the time increment, Delt. Values of up to 5.0 sec are used.
DF	This is the drip factor, D_f . Values to be used are not well known; however, values of 1.0 (no dripping) to 10.0 seem reasonable.
DGA DGB	These are the constants for the diffusivity of steam in hydrogen, $D_g = a(T/1000)^b$, cm ² /sec. Suggested values are: $DGA = 7.30$; $DGB = 1.75$.
ELT	This is the length of the fuel in the fuel rods in centimeters, L.
EMC	This is the grams of cladding oxidized per mole of steam, M_c , g/mole. Suggested values are: for Zircaloy, EMC = 45.6; for stainless steel, EMC = 44.0.
EPS	This is the emissivity factor for radiation = $E/(2 - E)$, where E is the emissivity. A suggested value is: $EPS = 0.45$ (based on $E = 0.62$).
FLS	This is the factor F_{ls} for indicating the desired number of length increments to slump in a zone before the steam flow to that zone is shut off. A value of 2.0, 3.0, or 4.0 is suggested.

Symbol	Description
FF	This is the fall factor, F_f , which is the fraction of the fuel that remains in the increment on slumping. For no falling of fuel out of the increment, FF would be 1.0. A value of FF of about 0.75 is suggested; however, the proper or best value is largely unknown at present.
FRF	This is the fallen fuel retained in the core factor, F_{rf} . The proper value is largely unknown. For no falling out of the core, its value would be 1.0. A value of 0.95 is suggested.
HAC	This is the fuel-cladding heat-transfer coefficient, h_{ac} , cal/(sec)(cm ²)(°K). A value of 0.19 is suggested.
KAA	These are the constants for the heat-transfer coefficient of the fuel, $k_a = a + bT + CT^2$, cal/(sec)(cm)(°K). Suggested values for UO ₂ are:
KAB	
KAC	
	$KAA = 0.014;$ $KAB = -1.00 \times 10^{-5};$ $KAC = 2.50 \times 10^{-9}.$
KAM	This is the ratio, k_{am} , of the thermal conductivity of molten fuel mix to that of the solid at its melting point. A value of 2.0 is suggested.
KCA	These are the constants for the heat-transfer coefficient of the cladding, $k_c = a + bT$, cal/(sec)(cm)(°K). Suggested values for Zircaloy are:
KCB	
	$KCA = 0.041;$ $KCB = 0.000.$
KHA	These are the constants for the thermal conductivity of hydrogen, $k_h = a(T/1000)^b$, cal/(sec)(cm)(°K). Suggested values are:
KHB	
	$KHA = 0.0011;$ $KHB = 0.75.$
KSA	These are the constants for the thermal conductivity of steam, $k_s = a + b(T/1000)$, cal/(sec)(cm)(°K). Suggested values are:
KSB	
	$KSA = -2.00 \times 10^{-5};$ $KSB = 2.00 \times 10^{-4}.$
LASTZ	This is the integer number of zones in the core, N_i . An integer value of about 13 is suggested.
NJ	This is the integer number of length increments in the core, N_j . An integer value of about 25 is suggested.

Symbol	Description
NJP	This is an integer factor, N_{jp} , to determine the selected length increment data (fuel, cladding, and gas temperatures; cladding thickness oxidized; and fraction of steam in the gas) to be printed out. As an example, if NJP is 3, data for the first and every third increment thereafter are printed. If NJP is 1, data for every increment are printed. $NJ - 1$ should be evenly divisible by NJP.
NPRINT	This is an integer factor, N_{print} , to determine number of time intervals ΔT (Δt) between printouts.
NTAB	This is an integer equal to the number, N_{tab} , of pairs of relative fuel decay heat versus time (in seconds) data read in. The previous sample table uses 24.
QCA	These are the constants for the heat of reaction of the cladding $Q_c = a + BT$, cal/g. Suggested values for Zircaloy are: $QCA = 1610.0;$ $QCB = -0.615.$
QCB	
QD	This is the specific reactor power, Q_d , in calories per second per cubic centimeter of fuel.
RCZ	This is the ratio, R_{co} , of the molecular weight of cladding oxide to that of the metal. For Zircaloy, it is 1.35.
RF	This is the inside radius, r_f , of the cladding, in centimeters.
RHOC	This is the density of the cladding metal, ρ_c . It is 6.5 g/cc for zirconium.
RO	This is the initial outside radius, r_o , of the rod cladding in centimeters.
RZERO	This is the initial thickness, R_{r0} , of the cladding oxidized in centimeters. A value greater than zero is necessary. A value of 10^{-4} cm is suggested.
SF	This is the slump factor, S_f . It is the ratio of the length of an ideal slumped increment to its original length. It can be computed as follows: $S_f = \frac{A_r \rho_r}{A_t \rho_t}$
SIG	This is the radiation constant, σ . It is 1.37×10^{-12} cal/(sec)(cm ²)(°K ⁴).
TAM	This is the melting or slumping temperature of the fuel, T_{am} , in °K. UO_2 melts normally at about 3073°K.

Symbol	Description
TAL	<p>This is a pseudotemperature, T_{al}, equivalent to all fuel molten for a given increment, °K. It is equal to</p> $T_{am} + \frac{L_{ac}}{C_{pm}}, \text{ } ^\circ\text{K},$ <p>where</p> <p>T_{am} = slumping temperature of the fuel (see above), °K,</p> <p>L_{ac} = latent heat of fusion (or slumping) of the fuel mix, cal/g,</p> <p>C_{pm} = specific heat of the fuel at T_{am}, cal/(g)(°K), = (CPAA) + (CPAB)(TAM).</p>
TBA	Ambient temperature of bottom grid plate, °K, T_{ba} .
TBZ	Initial temperature of bottom grid plate, °K, T_{b0} .
TTA	Ambient temperature of top grid plate, °K, T_{ta} .
TTZ	Initial temperature of top grid plate, °K, T_{t0} .
TWA	Ambient temperature of core wall, °K, T_{wa} .
TWZ	Initial temperature of core wall, °K, T_{w0} . For a boiling-water reactor normally operating at 1000 psig steam pressure, these six temperatures would be about 558°K (285°C or 545°F). For a pressurized-water reactor in a system generating steam at 1000 psig, these six temperatures would be slightly higher.
TGO	This is the initial steam temperature, T_{g0} , entering the core, °K. If we assume a pressure of about 21 psig, this temperature would be about 400°K.
TEEMAX	This is a time parameter used for the steam flow. (See discussion on A1, A2, and A3.)
TMAX	This is the input for the length of the computer run, t_{max} , in seconds.
U	<p>This is a dimensionless factor for the length of the overall heat transfer between the bottom ends of the fuel rods and the bottom grid plate, in terms of the overall heat conductivity of an incremental length of rod. If the end of the rod has a good thermal path to the grid plate, $U = 1$; if the path is equivalent to an additional length of rod $\Delta l/2$, $U = .1/2$; if the path is equivalent to an additional length of rod $2\Delta l/2$, $U = 1/3$; etc. A value of 1.0 to 0.5 is suggested.</p>

Symbol	Description
UB	These are the overall heat-transfer coefficients in cal/(sec)(°K) from the bottom grid plate, U_b ; top grid plate U_t ; and core wall to their ambient, U_w , respectively. The values depend upon the reactor configuration, etc. The actual values used are relatively unimportant if they are not excessively large. A value for each of about $5 \times 10^{-4} S \text{ cal}/(\text{sec})(^\circ\text{K})$, where S is the surface area in square centimeters exposed to the ambient, is suggested.
UT	
UW	
V2	These are the parameters, V_2 , V_3 , and V_4 , for the initial fuel and cladding temperatures.
V3	
V4	

$$T_a = V_4 + V_2 \frac{P}{P_a}, ^\circ\text{K};$$

for the cladding;

$$T_c = V_4 + V_3 \frac{P}{P_a}, ^\circ\text{K};$$

where P/P_a is the ratio of the local to average reactor power ($P/P_a = f(i)S(J)$), and V_4 is the ambient temperature (about 558°K). The values of V_2 and V_3 can be obtained from calculation of the heat retained in the core after blowdown. V_2 and V_3 can also be obtained by computing these values for the operating temperature of the core and then multiplying the values by the estimated fraction of heat retained in the core after blowdown.

V5	This is a factor V_5 for heat transfer from the gas to the cladding and is discussed in Appendix A. It is a function of rod diameter and pitch, cm^{-1} .
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Approximate values of $V_5 r_0$ for laminar flow are as follows:

$p/2r_0$	Square Array	Triangular Array	$p/2r_0$	Square Array	Triangular Array
1.0	16.45	41.52	1.6	2.95	3.42
1.1	8.93	13.66	1.7	2.64	3.02
1.2	6.22	8.30	1.8	2.39	2.71
1.3	4.81	6.03	1.9	2.19	2.46
1.4	3.95	4.72	2.0	2.03	2.26
1.5	3.37	3.97			

For V_5 , use the values in this table divided by r_0 .

Symbol	Description
V6	This is the total number of fuel rods in the reactor, V_6 .
V8	This is the heat of combustion of hydrogen, V_8 , cal/mole, = 57,980.
VA	This is the volume of fuel per centimeter of rod, $\text{cm}^3/\text{cm} = \pi r_a^2$.
VK	This is the area of extra oxidizable surface, V_k , per centimeter of fuel rod length, cm^2/cm .
VM5	This is a factor V_{m5} for mass transfer of steam from the gas stream to the cladding, cm^{-1} , and is discussed in Appendix A. For laminar flow, it is equal to V5.
WA	This is W_a , the weight of fuel per centimeter of rod length (g/cm).
WB	This is W_b , the weight in grams of the bottom grid plate.
WC	This is W_c , the weight of the cladding plus effective weight of control rods and extra oxidizable surfaces (cans) per centimeter of rod length (g/cm).
WTP	This is W_t , the weight in grams of the top grid plate.
WW	This is W_w , the weight in grams of the core side wall.

XII. READOUT OF PROGRAM

The following is read out by the program:

A. Readout of Input Data

At the start of the program, the 89 individual input data, as well as the values for the radial power-distribution ratio by zone, $f(i)$, and the values for the axial power-distribution ratio by increment, $S(j)$, are read out for record and checking.

B. Readout of Computed Data

During the program run at preselected time intervals (every NPRINT time interval, DELT), the following computed values are read out:

1. Time, t , sec.
2. Total steam flow rate W_s , lb/hr.
3. Decay heat as fraction, $F(t)$, of reactor power.
4. Average thickness of "can" reacted, R_r , cm.
5. Fraction of "can" material reacted.
6. Average thickness of cladding reacted, R_r , cm.
7. Fraction of cladding material reacted.
8. Mole fraction of hydrogen in the gas leaving the core.
9. Heat of combustion of hydrogen leaving core, cal/sec.
10. Sensible heat (above T_{g0}) of gas leaving core, cal/sec.
11. Accumulated total hydrogen released from core, g moles.
12. Bottom-grid-plate temperature, T_b , °K.
13. Top-grid-plate temperature, T_t , °K.
14. Core-wall-plate temperature, T_w , °K.
15. Average fuel temperature, T_a , °K.
16. Fraction of original fuel remaining in core.
17. Fraction of fuel increments slumped.
18. For all zones and for preselected length increments (every NJP length increment),
 - a. Distance from bottom of core, l , cm.
 - b. Fuel temperature, T_a , °K.
 - c. Cladding temperature, T_c , °K.
 - d. Gas temperature, T_g , °K.
 - e. Thickness of cladding (or can) oxidized, $r_o - r$, cm.
 - f. Fraction steam in the gas, X .

XIII. TYPICAL RESULTS OF CHEMLOC-II COMPUTER RUNS

CHEMLOC-II computer runs have been made for several assumed reactor-core designs. The 3300-MW(t) boiling-water reactor (BWR) core, discussed here to illustrate the operation of the program, is typical. Three different slumping temperatures were assumed: 2023, 2473, and 3073°K. A computer run was made for each of these temperatures to assess the effects of varying the slumping temperature.

The assumed dimensional parameters for the core are shown in Table II; and the assumed values for variable parameters are shown in Table III. For physical, thermal, and other properties of the materials, the values recommended in Chapter XI (Program Input) were used. The program readout of the input data for the run at a slumping temperature of 2473°K is shown in Appendix F.

The program runs were made using a time increment of 5 sec, 13 radial zones, and 25 axial length increments. A machine time of 10 min gave real times of 1500-2150 sec, depending upon printout intervals, as follows:

Time Increment, sec, DELT	No. of Time Increments per Printout, NPRINT	No. of Axial Length Increments per Printout, NJP	Real Time, sec
5	5	1	1500
5	10	1	1800
5	10	3	2150

TABLE II. Assumed Dimensional Parameters for a
3300-MW(t) Boiling-water Reactor Core

ID of reactor vessel, in.	251
Reactor pressure, psig	1,000
Power, MW(t)	3,300
<u>Fuel Rods (UO₂)</u>	
No. of fuel rods	37,436
No. of fuel assemblies	764
Length of fuel, in.	144
Thickness of Zircaloy cans, in.	0.085
OD of Zircaloy cladding, in.	0.562
Cladding thickness, in.	0.032
Fuel-pellet diameter, in.	0.488
Pitch (square array), in.	0.738
<u>Control Rods</u>	
No. of assemblies	185
Rods per assembly	1
Control-rod material	Boron in stainless steel
Thickness, in.	0.312
Width, in.	9.75 cruciform

Output of the computer runs was used to plot the fuel temperatures, percent cladding and can reacted, and average grid plate and wall temperatures shown in Figs. 5, 6, and 7, respectively.

TABLE III. Assumed Values of Variable Parameters for a
3300-MW(t) Boiling-water Reactor Core

Specific reactor operating power, cal/cm ³	47.6
Steam evaporation temperature, °C	127
Ambient temperature, °C	285
Slumping temperature ^a of fuel-cladding mixture, °C	2800, 2200, 1750
Fraction of core heat retained at end of blowdown, %	~75
Average fuel temperature at end of blowdown, °C	646
Weights: Bottom grid plate, g	18.04×10^6
Top grid plate, g	8.33×10^6
Core wall, g	24.33×10^6
Radiation emissivity of cladding	0.60
Ratio of heat conductivity of molten and solid fuel mix	2.00
Fraction of core material falling to bottom of core on slumping	0.40
Fraction of core material falling from core on slumping	0.02
Slump factor	0.50
Fraction slumping in a zone required to stop steam flow	0.16
Drip factor	10.0
Steam flow rate (variable), lb/hr, at indicated time after blowdown	
0 sec	57,600
25 sec	40,729
50 sec	33,255
100 sec	25,729
500 sec	12,569
1000 sec	8,670
2000 sec	4,305
Core decay heating (variable), % of reactor operating power, at indicated time after blowdown	
0 sec	0.0480
25 sec	0.0430
50 sec	0.0405
100 sec	0.0363
500 sec	0.0261
1000 sec	0.0220
2000 sec	0.0187
4000 sec	0.0158

^aThree different cases.

Slumping Temperature, 2800°C

Slumping Temperature, 2200°C

Slumping Temperature, 1750°C

Fig. 5

Calculational Results of Axial Variation of
Zone 1 Fuel Temperatures for a 3300-MW(t)
Boiling-water Reactor. (308-1195)

Slumping Temperature, 2800°C

Slumping Temperature, 2200°C

Slumping Temperature, 1750°C

Fig. 6

Calculational Results of Percent Cladding and Can Reacted for a 3300-MW(t) Boiling-water Reactor. (308-1197)

Slumping Temperature, 2800°C

Slumping Temperature, 2200°C

Slumping Temperature, 1750°C

Fig. 7

Calculational Results of Average Fuel, Grid Plate, and Wall Temperatures for a 3300-MW(t) Boiling-water Reactor. (308-1198)

As stated above, these computer runs were made to determine the effects of changes in the assumed slumping temperature on the program output. Based on the input parameters used, the estimated time when the grid plate would fail for the three cases of assumed slumping temperature would be:

Slumping Temperature, °C	Time for Initial Grid-plate Failure, sec
1750	1850
2200	1950
2800	2250

The computations, based on the assumed slumping model and input parameters used, indicate that the main effects of changing the assumed slumping temperatures are as follows:

- 1) At lower slumping temperatures, the percent cladding and can reacted (hydrogen released) may be significantly less. The differences in the quantity of hydrogen produced may be on the order of 100%.
- 2) At lower slumping temperatures, the temperature of the bottom grid plate increases more rapidly and reaches a failure temperature earlier. However, the differences in time to reach failure temperatures are only on the order of 20%.

The most important effect of slumping temperature appears to be in the quantity of hydrogen released.

XIV. FORTRAN PROGRAM

A. Identification

Title: CHEMLOC-II B226, Calculation of Reactor-core Heating and Metal-Water Reactions following a Loss of Coolant Accident

Source Language: FORTRAN 3600

B. Purpose

This program evaluates the following functions of distance l_j (from the bottom of a fuel rod) and reactor-core zone i at time t_k since the start of gas flow through the core.

1. The fuel-rod temperature, T_{aij} , where

$$T_{apij} = T_{ap0ij} + \int_0^t \frac{q_{dij}F_{dij} - q_{acij} + q_{apij} + q_{aqij}}{W_a F_{wij} C_{paij}} dt \quad (30c)$$

and

$$T_{aij} = \begin{cases} T_{apij}, & \text{if } T_{apij} < T_{am}, \\ T_{am}, & \text{if } T_{am} \leq T_{apij} < T_{al}, \\ T_{apij} - (T_{al} - T_{am}), & \text{if } T_{apij} \geq T_{al}. \end{cases} \quad (20b)$$

2. The fuel-rod cladding temperature,

$$T_{cij} = T_{coij} + \int_0^t \frac{q_{acij} + q_{rij} + q_{sij} - q_{gij}}{W_c C_{pcij}} dt. \quad (31c)$$

3. The average gas temperature,

$$T_{gij} = T_{g0} + \int_0^1 \frac{q_{gij}}{W_{gi} C_{pgij}} dl. \quad (32b)$$

4. The thickness of cladding reacted,

$$(r_o - r_i)_j = (r_o - r)_0 + \int_0^t \frac{q_{sij}}{S \rho_c Q_{cij}} dt. \quad (33b)$$

5. The mole fraction of steam in the gas flow,

$$X_{ij} = 1.0 - \int_0^1 \frac{q_{sij}}{W_{gi} Q_{cij} M_c} d\ell. \quad (34b)$$

6. The bottom-plate temperature,

$$T_b = T_{b0} + \int_0^t \frac{V_1 \Delta \ell \left[\sum_{i=1}^{LASTZ} (-q_{arq} - q_{arjm} - q_{cq} - q_{aq})_{j=1} \right] - U_b(T_b - T_{ba})}{W_b C_{pb}} dt, \quad (35b)$$

where LASTZ = number of reactor-core zones.

7. The side-wall temperature,

$$T_w = T_{w0} + \int_0^t \frac{V_1 \Delta \ell \left[\sum_{j=1}^{NJ} (-q_{rp} - q_{rip})_{i=LASTZ} \right] - U_w(T_w - T_{wa})}{W_w C_{pw}} dt, \quad (36b)$$

where NJ = number of rod-length increments.

8. The top-plate temperature,

$$T_t = T_{t0} + \int_0^t \frac{V_1 \Delta \ell \left[\sum_{i=1}^{LASTZ} (-q_{arp} - q_{arjp})_{j=NJ} \right] - U_t(T_t - T_{ta})}{W_t C_{pt}} dt. \quad (37b)$$

9. The average thickness of can reacted,

$$\Delta r_{can} = \frac{1}{(NJ)(LASTZ)} \sum_{j=1}^{NJ} \sum_{i=1}^{LASTZ} (r_o - r_i)_j.$$

10. The fraction of can reacted,

$$F_{can} = \frac{\Delta r_{can}}{\alpha}.$$

11. The average thickness of cladding reacted,

$$\Delta r_{\text{clad}} = \frac{1}{(NJ)(\text{LASTZ})} \sum_{j=1}^{NJ} \sum_{i=1}^{\text{LASTZ}} (r_o - r_i)_j,$$

where the maximum value of $(r_o - r_i)_j$ is limited to $r_o - r_f$.

12. The fraction of cladding reacted,

$$F_{\text{clad}} = \frac{\Delta r_{\text{clad}}}{r_o - r_f}$$

13. The fraction of hydrogen in the gas leaving the reactor core,

$$F_H = \frac{\sum_{i=1}^{\text{LASTZ}} \left[(1 - X_{ij})_{j=NJ} W_{gi} \right]}{\sum_{i=1}^{\text{LASTZ}} W_{gi}}$$

14. The energy of combustion of hydrogen leaving the reactor core,

$$E_C = \frac{453.6 V_8 W_S F_H}{3600(18.02)}$$

15. The total energy above TGZ in the gas leaving the reactor core,

$$T_E = \frac{V_6}{\text{LASTZ}} \sum_{i=1}^{\text{LASTZ}} \left\{ [CPHA + (CPSA - CPHA) X_{ij}] (T_{gij} - T_{g0}) W_{gi} \right. \\ \left. + \left[\frac{CPHB}{2} + \frac{(CPSB - CPHB)}{2} X_{ij} \right] (T_{gij}^2 - T_{g0}^2) W_{gi} \right\}_{j=NJ}$$

16. The accumulated hydrogen released,

$$A_H = \frac{V_6 \Delta t}{\text{LASTZ}} \sum_{i=1}^{\text{LASTZ}} \left[(1 - X_{ij})_{j=NJ} W_{gi} \right]$$

17. The average fuel temperature,

$$AFT = \frac{\sum_{i=1}^{\text{LASTZ}} \sum_{j=1}^{NJ} (T_{apij} F_{wij})}{\sum_{i=1}^{\text{LASTZ}} \sum_{j=1}^{NJ} F_{wij}}$$

18. The fraction of fuel remaining,

$$AFW = \frac{1}{(NJ)(LASTZ)} \sum_{i=1}^{LASTZ} \sum_{j=1}^{NJ} F_{wij}$$

19. The fraction of fuel slumped,

$$FFS = \frac{SSUM}{(NJ)(LASTZ)},$$

where SSUM is the number of length increments that have shortened due to slumping.

C. Computer and Program Requirements

1. Machine configuration: Minimum CDC-3600.
2. Programming system configuration: SCOPE monitor plus standard FORTRAN library subroutines.
3. Other routines required: A subroutine DISCOT to perform interpolation. (See "Single or Double Interpolation Subroutine for Continuous or Discontinuous Functions," Ei-AQF ALLi, by J. H. Sum, Allison Division, General Motors Corp., Indianapolis, Indiana.)

D. Input Information Required

The following card types are required as input information to this program and are listed in the order in which they must appear in the data deck:

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Contents</u>
1	1-4	I4	NTAB = the number of cards of type 11 to follow (NTAB must be ≤ 50).
	5-8	I4	NPRINT = the output interval for t_k ; i.e., output is printed for every NPRINT th value of t .
	9-12	I4	NJP = the output interval for ℓ_j ; i.e., output is printed for every NJP th value of ℓ .
	13-16	I4	NJ = the number of length increments of size $\Delta\ell$ to be taken along a fuel rod of length L ; i.e., $\Delta\ell = L/NJ$. (NJ must be ≤ 40 .)

Card Type	Columns	Format	Contents
2	17-20	I4	LASTZ = number of zones in the reactor core. (LASTZ must be ≤ 25 .)
	21-28	E8.0	ELT = L = total length of a fuel rod (cm).
	29-36	E8.0	DELT = Δt = calculation time increment (sec).
	37-44	E8.0	TMAX = $t_{\max}$ = final value of t at which calculations are to be made (sec).
	45-52	E8.0	QD = Q_d = specific reactor power (cal/sec-cm ³).
	1-8	E8.0	CPAA } constants for the specific heat of fuel;
	9-16	E8.0	CPAB } i.e., $C_{pa} = CPAA + (CPAB)(T_a)$.
			constants for the specific heat of the
	17-24	E8.0	CPBA } wall, the top grid plate, and the bottom
	25-32	E8.0	CPBB } grid plate; i.e., $C_{pw} = CPBA +$ $(CPBB)(T_w)$; $C_{pt} = CPBA + (CPBB)(T_t)$; $C_{pb} = CPBA + (CPBB)(T_b)$.
	33-40	E8.0	CPCMA } constants for the specific heat of the
	41-48	E8.0	CPCMB } cladding metal; i.e., $C_{pcm} = CPCMA +$ $(CPCMB)(T_c)$.
	49-56	E8.0	CPCOA } constants for the specific heat of the
	57-64	E8.0	CPCOB } cladding oxide; i.e., $C_{pco} = CPCOA +$ $(CPCOB)(T_c)$.
	65-72	E8.0	CPHA } constants for the specific heat of hydro-
	73-80	E8.0	CPHB } gen; i.e., $C_{ph} = CPHA + (CPHB)(T_g)$.
3	1-8	E8.0	CPSA } constants for the specific heat of steam;
	9-16	E8.0	CPSB } i.e., $C_{ps} = CPSA + (CPSB)(T_g)$.
	17-24	E8.0	KAA } constants for the heat-transfer coeffi-
	25-32	E8.0	KAB } cient of fuel; i.e., $k_a = KAA +$
	33-40	E8.0	KAC } $(KAB)(T_a) + (KAC)(T_a^2)$.
	41-48	E8.0	KCA } constants for the heat-transfer coeffi-
	49-56	E8.0	KCB } cient of the cladding; i.e., $k_c = KCA +$ $(KCB)(T_c)$.
	57-64	E8.0	KHA } constants for the thermal conductivity of
	65-72	E8.0	KHB } hydrogen; i.e., $k_h = KHA(T_g/1000)^{KHB}$.
	73-80	E8.0	RCZ = R_{co} = ratio of the molecular weight of cladding oxide to the molecular weight of the metal.
4	1-8	E8.0	KSA } constants for the thermal conductivity of
	9-16	E8.0	KSB } steam; i.e., $k_s = KSA + (KSB)(T_g/1000)$.

Card Type	Columns	Format	Contents
	17-24	E8.0	DGA } constants for the diffusivity of steam in DGB } hydrogen; i.e., $D_g = DGA(T_g/1000)DGB$.
	25-32	E8.0	
	33-40	E8.0	QCA } constants for the heat of reaction of the QCB } cladding; i.e., $Q_c = QCA + (QCB)(T_c)$.
	41-48	E8.0	
	49-56	E8.0	CAY = K = rate constant for cladding reaction with steam (cm^2/sec).
	57-64	E8.0	DELE = ΔE = activation energy for cladding-steam reaction (cal/mole).
	65-72	E8.0	SIG = σ = radiation constant ($\text{cal/sec-cm}^2\text{-}^\circ\text{K}^4$).
	73-80	E8.0	V8 = V_8 = heat of combustion of hydrogen (cal/mole).
5	1-8	E8.0	TBA = T_{ba} = ambient temperature of bottom grid plate ($^\circ\text{K}$).
	9-16	E8.0	TBZ = T_{b0} = initial temperature of bottom grid plate ($^\circ\text{K}$).
	17-24	E8.0	TGO = T_{g0} = initial temperature of steam entering core ($^\circ\text{K}$).
	25-32	E8.0	TTA = T_{ta} = ambient temperature of top grid plate ($^\circ\text{K}$).
	33-40	E8.0	TTZ = T_{t0} = initial temperature of top grid plate ($^\circ\text{K}$).
	41-48	E8.0	TWA = T_{wa} = ambient temperature of core wall ($^\circ\text{K}$).
	49-56	E8.0	TWZ = T_{w0} = initial temperature of core wall ($^\circ\text{K}$).
	57-64	E8.0	V2 = V_2 } constants used to determine: 1. Initial V3 = V_3 } fuel temperature = $f(V_2, V_4)$. 2. Initial V4 = V_4 } cladding temperature = $f(V_3, V_4)$.
6	65-72	E8.0	
	73-80	E8.0	
	1-8	E8.0	AA = A_a = cross-sectional area of fuel in a fuel rod (cm^2).
	9-16	E8.0	AC = A_c = cross-sectional area of cladding in a fuel rod (cm^2).
	17-24	E8.0	ALFA = α = additional oxidizable surface area (cm^2).
	25-32	E8.0	VK = area of additional oxidizable surface per centimeter of fuel-rod length (cm^2/cm).

<u>Card Type</u>	<u>Columns</u>	<u>Format</u>	<u>Contents</u>
	33-40	E8.0	$VA = V_a$ = volume of fuel per centimeter of rod (cm^3/cm).
	41-48	E8.0	$RO = r_o$ = initial outside radius of rod cladding (cm).
	49-56	E8.0	$RZERO = (r_o - r)_o = R_{r0}$ = initial thickness of cladding oxidized (cm).
	57-64	E8.0	$RF = r_f$ = inside radius of cladding (cm).
	65-72	E8.0	$V6 = V_6$ = total number of fuel rods in reactor.
	73-80	E8.0	$EMC = M_c$ = grams of cladding oxidized per mole of steam.
7	1-8	E8.0	$AN = A_n$ = partition coefficient for computing preintegrated values.
	9-16	E8.0	$CAS = C_{as}$ = 1.0, implies fuel material falls from core each time a length increment slumps. 2.0, implies fuel material ceases to fall from core when all void space below the slumping increments is filled.
	17-24	E8.0	$DF = D_f$ = the drip factor.
	25-32	E8.0	FLS = factor indicating number of length increments that must slump in a zone to shut off steam flow to the zone.
	33-40	E8.0	$FF = F_f$ = fall factor = fraction of fuel that remains in a slumped length increment.
	41-48	E8.0	$FRF = F_{rf}$ = fuel-retained factor = fraction of fallen fuel that remains in lower increments of the core.
	49-56	E8.0	$KAM = K_{am}$ = ratio of thermal conductivity of molten fuel mix to that of solid fuel at its melting point.
	57-64	E8.0	$SF = S_f$ = slump factor = length of an ideally slumped increment divided by its un-slumped length.
	65-72	E8.0	$TAM = T_{am}$ = melting or slumping temperature of the fuel ($^{\circ}\text{K}$).
	73-80	E8.0	$TAL = T_{al}$ = a pseudotemperature equivalent to a condition of all fuel molten for a given increment ($^{\circ}\text{K}$).

Card Type	Columns	Format	Contents
8	1-8	E8.0	WA = W_a = weight of fuel per centimeter of rod length (g/cm).
	9-16	E8.0	WB = W_b = weight of bottom grid plate (g).
	17-24	E8.0	WC = W_c = weight of cladding plus effective weight of control rods and extra surfaces (cans) per centimeter of rod length (g/cm).
	25-32	E8.0	WTP = W_t = weight of top grid plate (g).
	33-40	E8.0	WW = W_w = weight of core side wall (g).
	41-48	E8.0	RHOC = ρ_c = density of cladding metal (g/cc).
	49-56	E8.0	$\left. \begin{array}{l} A1 = A_1 \\ A2 = A_2 \\ A4 = A_4 \\ TEEMAX = t_m \end{array} \right\} \begin{array}{l} \text{constants used to define steam} \\ \text{flow } W_s \text{ (lb/hr) at time } t \text{ (sec).} \\ W_s = A_1/(A_2+t)^{1/2}, \text{ for } 0 \leq t \leq t_m. \\ W_s = [A_1/(A_2+t_m)^{1/2}] e^{-A_4(t-t_m)}, \\ \text{for } t > t_m. \end{array}$
	57-64	E8.0	
	65-72	E8.0	
	73-80	E8.0	
9	1-8	E8.0	HAC = h_{ac} = fuel-cladding heat-transfer coefficient (cal/sec-cm ² -°K).
	9-16	E8.0	U = dimensionless factor for overall heat transfer between bottom ends of fuel rods and bottom grid plate.
	17-24	E8.0	$\left. \begin{array}{l} UB = U_b \\ UT = U_t \\ UW = U_w \end{array} \right\} \begin{array}{l} \text{overall heat-transfer coefficients} \\ \text{from bottom grid plate, top grid plate,} \\ \text{and core wall to their respective} \\ \text{ambients (cal/sec-°K).} \end{array}$
	25-32	E8.0	
	33-40	E8.0	
	41-48	E8.0	V5 = a factor for heat transfer from the gas to the cladding (cm ⁻¹).
	49-56	E8.0	VM5 = a factor for mass transfer of steam from the gas stream to the cladding (cm ⁻¹).
	57-64	E8.0	EPS = E_{ps} = $E/(2-E)$ = emissivity factor for radiation.
	65-72	E8.0	A = radial radiation view factor.
	73-80	E8.0	AV = A_v = vertical radiation view factor (cm).
10	1-80	10E8.0	FI _i = f_i , $i = 1, \text{ LASTZ}$, the ratio of average power in zone i to average power in the core (10 values per card).

Card Type	Columns	Format	Contents
11	1-8	E8.0	TTAB = time (sec).
	9-16	E8.0	FTAB = ratio of decay power to operating power at time TTAB.
			} NTAB cards of type 11.
12	1-80	10E8.0	SINZB _j , j = 1, NJ, the relative reactor power in each length increment (10 values per card).

Data for additional cases should start with card type 1.

E. Program Execution Time

The test case for this program simulates a reactor configuration with 13 zones (i.e., LASTZ = 13) and 25 fuel-rod length increments per rod (i.e., NJ = 25) and uses a time increment of $\Delta t = 2$ sec over the range $0 \leq t \leq 150$ sec. The execution time for the test case was 1 min 57 sec, including the time required to load the program into memory.

F. Possible Program Output

The printed results of this program consist of:

1. A list of the input data.
2. Labeled columns of zone i , T_{aij} , T_{cij} , T_{gij} , $(r_o - r_i)_j$, and X_{ij} for $\ell_j = \Delta \ell / 2$ and every NJPth value of $\ell \leq L$ at $t_k = 0$ and every NPRINTth value of $t \leq TMAX$.
3. A list of values for t , W_s , $F(t)$, Δr_{can} , F_{can} , Δr_{clad} , F_{clad} , F_H , EC , TE , A_H , T_b , T_t , T_w , AFT , AFW , and FFS at $t_k = 0$ and every NPRINTth value of $t \leq TMAX$.

G. Program Materials Available

1. Writeup of program B226.
2. Source listings for the main code (B226) and subroutine DISCOT (see Appendix E).
3. Source decks for the main code (B226) and subroutine DISCOT.
4. Binary decks for the main code (B226) and subroutine DISCOT.
5. Sample input for the test case and sample output from the test case (see Appendix E).

APPENDIX A

Heat - and Mass-transfer Coefficients and Effective Gas-film Thicknesses

The flow of steam through a core in a loss-of-coolant accident would be of laminar nature because of the relatively low flow rates of steam through the core possible in a loss-of-coolant accident (1/3 to 3 lb of steam per rod per hour).

For laminar flow, the effective gas-film thicknesses for heat transfer, σ_h , and for mass transfer, σ_d , neglecting an entrance effect, are equal and are functions of the geometry only.

Relationships between the heat- and mass-transfer coefficients (h_g and h_d), film thicknesses, and Nusselt's number are

$$h_g = k_g / \sigma_h = k_g \text{Nu} / \ell, \text{ cal}/(\text{sec})(\text{cm}^2)(^\circ\text{K});$$

$$h_d = D_g / \sigma_d = D_g \text{Nu}_d / \ell, \text{ cm}/\text{sec}.$$

Heat- and mass-transfer coefficients for laminar flow have been calculated for pipes, parallel plates, annuli, and rods on triangular lattices.^{13,14}

Assuming uniform heat fluxes in laminar flow through a pipe, duct, or annulus, the Nusselt number,

$$\text{Nu} = \frac{h \ell}{k_g},$$

and the equivalent dimensionless number for mass transfer,

$$\text{Nu}_d = \frac{h_d \ell}{D_g},$$

become constant as the velocity, temperature, and concentration gradients become fully developed. Thus, the heat- and mass-transfer coefficients become functions of the fluid conductivity or diffusivity and the geometry of the pipe, annulus, or duct.

An approximate solution for the value of the Nusselt number for heat or mass transfer applicable to longitudinal laminar flow (fully developed) through an array of cylinders can be obtained from the simple model of an annulus surrounding a cylinder. The inner radius of the annulus is r_0 (the radius of the cylinder); the outer radius r' of the annulus is determined so that the flow area associated with each rod is equal to the actual area. With a square array of rods,

$$r' = p/\pi^{1/2} = 0.564 p;$$

with a triangular array of rods,

$$r' = (3^{1/2} \cdot 2/\pi)^{1/2} p/2 = 0.525 p.$$

Based on this annulus model, the Nusselt number for heat transfer and for mass transfer can be evaluated. The mathematical techniques have been discussed in several texts,^{13,15-17} and only the result is reported here. The analysis performed assumed that the heat flux or mass flux per unit length was constant. This assumption is necessary to evaluate the temperature or concentration profiles. The heat- and mass-transfer coefficients were based on the rod surface temperature and surface concentration and the "cup mixing" temperature or bulk temperature and bulk concentration in the gas stream. The result was

$$Nu = Nu_d = 2.18,$$

where

$$Nu = h(r' - r_o)/k_g$$

and

$$Nu_d = h_d(r' - r_o) D_g.$$

Note that the Nusselt number is based on the thickness, $r' - r_o$, of the gas annulus.

This result can be checked numerically with the work of Sparrow et al.¹⁴ Assuming triangular spacing of 0.375-in.-diam rods on 0.60-in. centers, the heat-transfer coefficient from the above calculation is

$$h = 6.73 k_g, \text{ cal}/(\text{cm}^2)(\text{sec})(^\circ\text{K}).$$

Sparrow et al. present a plot of a Nusselt number defined as

$$Nu = \frac{h_d}{k_g}.$$

Thus, the Nusselt number becomes a function of the ratio of center spacing to rod diameter. The heat-transfer coefficient for such a geometry is

$$h = 6.7 k_g, \text{ cal}/(\text{cm}^2)(\text{sec})(^\circ\text{K}).$$

The annulus results developed above agree quite well with Sparrow's results for center spacing to rod-diameter ratios of 1.2-1.8. This range of spacings includes most current power reactors.

The above results apply where fully developed heat-transfer or mass-transfer conditions exist. At the entrance, and where spacers disturb the velocity, temperature, and concentration profiles, the Nusselt number and hence the coefficients of heat and mass transfer would be much larger. However, for laminar flow in pipes, annuli, or ducts, where the distances between walls are relatively small and where relatively large thermal conductivities and diffusivities exist in the gas stream, the equilibrium values are quickly reached. This effect has been discussed in detail in various texts.^{13,15}

Eckert and Drake¹⁵ have presented graphs suitable for estimating the entrance effects. Based on these calculations, the temperature and flow profiles, and hence steady-state values of h and h_d , are developed in a length of about $3/4$ cm (or the entrance effect extends for about $3/4$ cm) for the rod-diameter ratios assumed above.

Thus, with distances of 1 ft or more between spacers, the entrance effects should be negligible in calculations of the overall heat and mass transfer.

The relationships between the heat- and mass-transfer coefficients and Nusselt numbers are

$$Nu = \frac{h}{k_g} (r' - r_o), \text{ dimensionless};$$

$$h = \frac{Nu k_g}{r' - r_o}, \text{ cal}/(\text{sec})(\text{cm}^2)(^\circ\text{K});$$

$$Nu_d = \frac{h_d}{D_g} (r' - r_o), \text{ dimensionless};$$

and

$$h_d = \frac{Nu_d D_g}{r' - r_o}, \text{ cm/sec.}$$

Table IV shows values of Nu and Nu_d based on $(r' - r_o)$ computed for various ratios of r'/r_o for fully developed laminar flow in semiannuli.

TABLE IV. Values of Nu and Nu_d for
Fully Developed Laminar Flow
in Semiannuli

r'/r_o	Nu, Nu _d	r'/r_o	Nu, Nu _d
1.0	2.056	1.8	2.372
1.1	2.096	1.9	2.413
1.2	2.134	2.0	2.452
1.3	2.173	2.2	2.532
1.4	2.212	2.4	2.612
1.5	2.252	2.6	2.691
1.6	2.292	2.8	2.769
1.67	2.320	3.0	2.846
1.7	2.332		

For turbulent flow, the effective gas-film thickness for heat transfer, σ_h , is a function of Reynold's number, $Re (= DV\rho/\mu)$, and Nusselt's number, $Nu (= C_p\mu/k)$; and the effective gas-film thickness for mass transfer, σ_m , is a function of Reynold's numbers and Schmidt's number, $Sc (= \mu/\rho D_g)$. As an example, from the Chilton-Colburn modification of Reynold's analogy¹⁸ for a pipe,

$$\frac{h_g}{C_p V \rho} \left(\frac{C_p \mu}{k} \right)^{2/3} = J_h = \frac{h_d}{V} \left(\frac{\mu}{\rho D} \right)^{2/3} = J_m = \frac{f}{2} = 0.023 \left(\frac{DV\rho}{\mu} \right)^{-0.2},$$

and

$$h_g = \frac{k_g}{\sigma_h} = \frac{k_g}{D} 0.023 \left(\frac{C_p \mu}{k} \right)^{1/3} \left(\frac{DV\rho}{\mu} \right)^{0.8},$$

$$\sigma_h = \frac{D}{0.023 \left(\frac{C_p \mu}{k} \right)^{1/3} \left(\frac{DV\rho}{\mu} \right)^{0.8}},$$

$$h_d = \frac{D_g}{\sigma_d} = \frac{D_g}{D} 0.023 \left(\frac{\mu}{\rho D_g} \right)^{1/3} \left(\frac{DV\rho}{\mu} \right)^{0.8},$$

and

$$\sigma_d = \frac{D}{0.023 \left(\frac{\mu}{\rho D_g} \right)^{1/3} \left(\frac{DV\rho}{\mu} \right)^{0.8}}.$$

APPENDIX B

Radiant Heat Transfer in Core1. Emissivity Factors

In the consideration of emissivity factors, gray-body radiation and diffuse (nonspecular) reflection are assumed.

The calculation of emissivity factors is very complicated, and they are usually interconnected with geometrical factors.

As a simplifying assumption, the emissivity factor for radiation between two large surfaces which are nearly equal is approximately

$$\frac{1}{\frac{1}{E_1} + \frac{1}{E_2} - 1},$$

where E_1 and E_2 are the emissivities of the individual surfaces.

The approximate emissivity factors are as follows for the core calculations from a rod in zone i increment j to zone $i + 1$ and to zone $i - 1$:

$$E_{ip} = \frac{1}{\frac{1}{E_{ij}} + \frac{1}{E_{ipj}} - 1},$$

and

$$E_{im} = \frac{1}{\frac{1}{E_{ij}} + \frac{1}{E_{imj}} - 1}.$$

From a rod in zone i increment j to increment $j + 1$ and to increment $j - 1$,

$$E_{jp} = \frac{1}{\frac{1}{E_{ij}} + \frac{1}{E_{ijp}} - 1},$$

and

$$E_{jm} = \frac{1}{\frac{1}{E_{ij}} + \frac{1}{E_{ijm}} - 1}.$$

This method of computing emissivity factors is only approximate. However, more accurate but much more involved methods are available.¹⁹

The values of emissivity as a function of temperature and cladding oxide thickness are not sufficiently well known to warrant individual computation in the program.

An average emissivity factor, E_{ps} , based on the desired emissivity E , is input to the program, where

$$E_{ps} = \frac{1}{\frac{2}{E} - 1} = \frac{E}{2 - E}.$$

The program uses this value for the emissivity factor in all cases.

2. Axial Heat Transfer by Radiation

Here the axial heat transfer by radiation from the cladding of a rod, in zone i , length increment j to the adjacent increments $j + 1$ and $j - 1$ is considered.

The axial heat transfer from increment j in the direction of increment $j + 1$ per unit length of rod, where the simplified emissivity factor is used, is

$$q = - \int_0^{\infty} \pi r_o \sigma E_{jp} (T_{cij}^4 - T_{ci}^4) A_v^2 (A_v^2 + l^2)^{-3/2} dl, \text{ cal/}(\text{sec})(\text{cm}).$$

If we assume that A_v is small compared to the total length of the rods, and if we assume that

$$T_{cij}^4 - T_{ci}^4$$

is proportional to distance, or that

$$T_{cij}^4 - T_{ci}^4 = \frac{(T_{cij}^4 - T_{cijp}^4) l}{\Delta l},$$

the above integral can be evaluated.

The results are

$$q = \frac{A_v \pi r_o \sigma E_{jp} (T_{cij}^4 - T_{cijp}^4)}{\Delta l},$$

from which

$$q_{arp} = \frac{-A_v \pi r_o \sigma E_{jp} T_{cij}^4}{\Delta \ell}, \text{ cal/}(\text{sec})(\text{cm}) \quad (15a)$$

$$q_{arjp} = \frac{A_v \pi r_o \sigma E_{jp} T_{cijp}^4}{\Delta \ell}, \text{ cal/}(\text{sec})(\text{cm}) \quad (17a)$$

and in a similar manner,

$$q_{arq} = \frac{-A_v \pi r_o \sigma E_{jm} T_{cij}^4}{\Delta \ell}, \text{ cal/}(\text{sec})(\text{cm}), \quad (16a)$$

and

$$q_{arjm} = \frac{A_v \pi r_o \sigma E_{jm} T_{cijm}^4}{\Delta \ell}, \text{ cal/}(\text{sec})(\text{cm}). \quad (18a)$$

3. Radial Heat Transfer by Radial Radiation

Here we consider the radial heat transfer by radiation from the cladding of the average rod in zone i to the rods in zones $i + 1$ and $i - 1$.

Since, in general, a rod in zone i may not see a rod in zone $i + 1$ or in zone $i - 1$, but may see only other rods in zone i , and since computations are based on the average group temperatures of the rods in a zone, a method of computations based on the zone temperatures must be used. This can be done by treating radiation as a thermal conductivity.

In a core, the rods are usually spaced on a rectangular lattice (or perhaps a triangular lattice). The radial transfer of heat will be through the lattice at different angles in the various angular positions in the core. Rows of rods in some geometry normal to the direction of radiation will exist. For rectangular lattices, angles of direction of radiation of 90° and 45° to the lattice rows are the extreme cases since 0° is the same as 90° , etc. Results based on these extreme angles are nearly the same, and the average values of the two results can be used for all angles.

We consider rows of rods normal to the radial direction of heat radiation. The distance between the centers of rods in a given row is W , and the distance between centers of rows of rods is d . The rows are numbered $n = 0, 1, 2, 3$, etc., in the direction of radiation. The temperatures of all rods in a given row are equal. We first assume that the surface around a given rod is at a uniform temperature (fuel conductivity, k_a , is large compared to radiation).

The radiation from a rod in a row in the direction of the other rows, multiplied by the number of the row receiving the radiation, is

$$q = -\pi r_o \sigma \sum_{n=1}^{\infty} n(T_0^4 - T_n^4) \bar{F}_{on},$$

where $\bar{F}_{on}$ is a radiation factor that is difficult to evaluate; it incorporates the emissivities E_0 and E_n and the geometrical factor F_{on} . Perry¹⁹ discusses its approximation. We can obtain an approximate value by separating $\bar{F}_{on}$ into an emissivity factor E_{on} and the geometrical factor F_{on} .

If we assume that $E_n = E_1$, we have

$$\bar{F}_{on} = E_{01} F_{on}.$$

If we assume that

$$T_0^4 - T_n^4$$

is proportional to distance, or

$$T_0^4 - T_n^4 = n(T_0^4 - T_1^4),$$

we have

$$q = -\pi r_o \sigma E_{01} (T_0^4 - T_1^4) \sum_{n=1}^{\infty} F_{on} n^2.$$

This is the radiation that passes through the volume of width W , unity length, and depth d around a rod. The temperature difference across the depth d is $T_0 - T_1$.

If we consider radiation as conduction of heat with an equivalent conductivity of k_e ,

$$q = -k_e \frac{W}{d} (T_0 - T_1),$$

and

$$k_e = \pi r_o \sigma E_{01} \frac{(T_0^4 - T_1^4) d}{(T_0 - T_1) W} \sum_{n=1}^{\infty} F_{on} n^2,$$

or

$$k_e = \pi r_o \sigma E_{01} 4 T^3 A,$$

where

$$A = \frac{d}{W} \sum_{n=1}^{\infty} F_{on} n^2,$$

and

$$4T^3 = T_0^3 + T_0T_1^2 + T_1T_0^2 + T_1^3.$$

The heat transfer between zones i and $i + 1$ per unit length is

$$q_i = \frac{-2\pi R_i k_e (T_{ci} - T_{cip})}{\Delta R_i}, \text{ cal/}(\text{sec})(\text{cm}),$$

and per rod it is

$$q = \frac{-2\pi^2 r_o \sigma E_{ip} 4T^3 A (T_{ci} - T_{cip}) R_i}{\Delta R_i V_1}, \text{ cal/}(\text{sec})(\text{cm}),$$

or

$$q = \frac{-2\pi^2 r_o \sigma E_{ip} A_p (T_{ci}^4 - T_{cip}^4) R_i}{\Delta R_i V_1}, \text{ cal/}(\text{sec})(\text{cm}).$$

To evaluate $R_i/\Delta R_i$, we have, for zones of equal volume,

$$R_i = \frac{R_t(i)^{1/2}}{N_i^{1/2}},$$

$$\begin{aligned} \Delta R_i &= \frac{R_t(2i+1)^{1/2}}{(2N_i)^{1/2}} - \frac{R_t(2i-1)^{1/2}}{(2N_i)^{1/2}} \\ &= \frac{R_t \left[(i+0.5)^{1/2} - (i-0.5)^{1/2} \right]}{(N_i)^{1/2}}, \end{aligned}$$

$$\frac{R_i}{\Delta R_i} = \left(i^2 + \frac{1}{2} \right)^{1/2} + \left(i^2 - \frac{1}{2} \right)^{1/2}$$

and

$$\frac{R_i}{\Delta R_i} = 2i,$$

with an error of less than 3.5% for $i = 1$, less than 0.2% for $i = 2$, etc.

Substituting this value for $R_i/\Delta R_i$ in the previous equation results in

$$q = \frac{-4\pi^2 r_o i \sigma E_{ip} A_p (T_{ci}^4 - T_{cip}^4)}{V_1}$$

Incorporation of the parameter for relative increment length, F_s , and separation of the terms results in

$$q_{rp} = - \frac{F_s 4\pi^2 r_o i \sigma E_{ip} A_p T_{ci}^4(j)}{V_1} \quad (11a)$$

and similar expressions.

The geometrical view factor, A , is subscripted as A_p and A_m for use in radiation between zones i and $i + 1$, and i and $i - 1$, respectively, since a correction for variation in circumferential temperature of the fuel rods due to finite fuel thermal conductivity can be made, which may be different in the two cases.

The corrected values are

$$A = \frac{d}{W} \left[\sum_{n=1} F_{on} n^2 - \frac{\left(\sum_1 F_{on} n \right)^2}{\sum_1 F_{on} + \frac{1.2k_a}{4\pi r_o \sigma E_{il} T_c^3}} \right]$$

For

$$A = A_p,$$

use

$$E_{il} = E_{ip}$$

and

$$T_c^3 = \frac{T_{ci}^3 + T_{cip}^3}{2}$$

For

$$A = A_m,$$

use

$$E_{il} = E_{im}$$

and

$$T_c^3 = \frac{T_{ci}^3 + T_{cim}^3}{2}$$

For the current program, accuracies in the known values of emissivity do not warrant individual calculations of A_p and A_m as functions of temperature in the program.

An input value of A , based on the desired average temperature at which correction is desired (say 2000°K), is used. The program uses this value of A for A_p and A_m .

Values for A are approximately as follows for a square array of rods:

Pitch/ Diameter Ratio	A (k_a large)	A ($k_a = 0.0048$, $T = 2000^\circ\text{K}$)
1.00	0.66	0.23
1.25	0.90	0.48
1.50	1.18	0.55
1.75	1.51	0.61
2.00	2.10	0.68

APPENDIX C

Steam-generation Rate

In a loss-of-coolant accident caused by the failure of a primary water pipe, more or less water would remain in the lower pressure vessel head after operating-pressure blowdown. Heat input from the surroundings, of which the pressure vessel head constitutes the major item, evaporates the water at a rate determined by the rate of heat input. As the vessel head cools, the rate of steam generation decreases.

The following equation gives the rate of steam generation based on a decreasing heat supply.

$$\text{For } 0 \leq t \leq t_m, W_s = \left[A_1 / (t + A_2)^{1/2} \right] \text{ lb/hr;}$$

$$\text{for } t > t_m, W_s = \left[A_1 / (t_m + A_2)^{1/2} \right] \exp[A_4(t - t_m)], \text{ lb/hr,}$$

where A_1 , A_2 , A_4 , and t_m are input constants, and t is the time in seconds from the end of blowdown.

By varying these constants, one can match almost any steam-generation rate curve that has a theoretical basis.

When the heat is supplied by the vessel head only, the constants can be computed as follows:

$$A_1 = \frac{(3600)(\Delta T_o)(A_h)}{(453.59)(528.7)} \left(\frac{C_p \rho k}{\pi} \right)^{1/2},$$

$$A_2 = \text{blowdown time, sec,}$$

$$A_4 = -\frac{\pi^2}{4} \frac{k}{C_p \rho} \frac{1}{(\Delta S)^2},$$

and

$$t_m = 0.22 \frac{C_p \rho}{k} (\Delta S)^2 - A_2, \text{ sec.}$$

Figure 8 shows a graphic solution of the above equation for a steel pressure vessel head.

Fig. 8
Generalized Steam-generation Rate Used
as an Input Parameter for CHEMLOC

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APPENDIX D

Preintegrated Rates of Heat and Mass Transfer1. Radial and Axial Radiation before Slumping

To preintegrate the rate of heat radiation for variable temperature over the time interval Δt , we assume that the cladding radiates heat independently of the receipt of radiant heat. In other words, the cladding would radiate heat for the time interval Δt and then receive radiant heat for an equivalent length of time.

Since the cladding in a zone i and length increment j radiates heat to zones $i + 1$ and $i - 1$ (length increment j) and to length increments $j + 1$ and $j - 1$ (zone i), it is assumed that the heat content of only $1/A_n = 1/4$ of the cladding is available for radiation to each of these locations.

The general equation for heat radiation to each of these locations from an increment of cladding is

$$q = -DT_c^4, \text{ cal/sec cm of rod,}$$

where

$$\begin{aligned} D &= \frac{4\pi^2 r_o \sigma A E_{ps} i}{V_1}, \text{ radiation to } i + 1, \\ &= \frac{4\pi^2 r_o \sigma A E_{ps} (i - 1)}{V_1}, \text{ radiation to } i - 1, \\ &= \frac{\pi r_o \sigma A_v E_{ps}}{\ell}, \text{ radiation to } j + 1 \text{ or } j - 1. \end{aligned}$$

From a heat balance on the cladding,

$$\frac{dT_c}{P} = q dt = -DT_c^4 dt,$$

where

$$P = \frac{A_n}{C_{pc} W_c}.$$

Then

$$\int_{T_{c1}}^{T_c} T_c^{-4} dT_c = \int_0^T -DP dt$$

and

$$T_c^{-3} - T_{c1}^{-3} = 3DP\tau,$$

or

$$T_c = (T_{c1}^{-3} + 3DP\tau)^{-1/3}.$$

The average value of q over the time interval Δt , per initial unit length of rod, is

$$\begin{aligned}\bar{q} &= F_s \frac{1}{\Delta t} \int_0^{\Delta t} q \, d\tau = \frac{1}{\Delta t} \int_0^{\Delta t} -D(T_{c1}^{-3} + 3DP\tau)^{-4/3} d\tau \\ &= -\frac{F_s}{P\Delta t} \left[-(T_{c1}^{-3} + 3DP\tau)^{-1/3} \right]_0^{\Delta t} \\ &= -\frac{F_s}{P\Delta t} \left[T_{c1} - (T_{c1}^{-3} + 3DP\Delta t)^{-1/3} \right],\end{aligned}$$

or

$$\bar{q} = -F_s \frac{T_{c1}}{P\Delta t} \left[1 - \left(\frac{1}{1 + 3DP\Delta t T_{c1}^3} \right)^{1/3} \right].$$

By substituting the values for T_{c1} , D , and P , we obtain the values for $\bar{q}_{rp}$, $\bar{q}_{rq}$, $\bar{q}_{arp}$, and $\bar{q}_{arq}$. Values for $\bar{q}_{rip}$, $\bar{q}_{rim}$, $\bar{q}_{arjp}$, and $\bar{q}_{arjm}$ are obtained in a similar manner.

2. Radial Conduction after Slumping

The general equation for radial heat conduction which replaces radiation after slumping is

$$q = -DT_c, \text{ cal/}(\text{sec})(\text{cm}) \text{ of slumped rod,}$$

where

$$\begin{aligned}D &= \frac{4\pi i k_a}{V_1}, \text{ for conduction to } i+1 \\ &= \frac{4\pi(i-1)k_a}{V_1}, \text{ for conduction to } i-1.\end{aligned}$$

Again, for a heat balance on the cladding,

$$\frac{dT_c}{P} = q dt = -DT_c dt,$$

$$\int_{T_{c1}}^{T_c} \frac{dT_c}{T_c} = \int_0^\tau -DP dt,$$

$$T_c = T_{c1} \exp(-DP\tau),$$

and

$$\bar{q} = F_s \frac{1}{\Delta t} \int_0^{\Delta t} q dt = -F_s \frac{T_{c1}}{P\Delta t} [1 - \exp(-PD\Delta t)].$$

By substituting the values for T_{c1} , D , and p , we obtain values for $\bar{q}_{rp}$ and $\bar{q}_{rq}$. Values for $\bar{q}_{rip}$ and $\bar{q}_{rim}$ are obtained in a similar manner.

3. Heat Transfer between Fuel and Cladding

The equation for heat transfer between the fuel and the cladding, per unit length of rod, is

$$q_{ac} = D(T_a - T_c),$$

where

$$D = \frac{2\pi r_a h_{ac}}{1 + r_a h_{ac} / 4k_a}$$

The cladding has a total heat capacity less than the fuel and its temperature will change, due to heat transfer between the fuel and cladding, more than that of the fuel. The preintegration will be based on a temperature change of the cladding (but not of the fuel) during the time interval Δt .

Again, a heat balance on the cladding yields

$$\frac{dT_c}{P} = q_{ac} dt = D(T_a - T_c) dt,$$

$$\int_{T_{c(a)}}^{T_c} \frac{dT_c}{T_a - T_c} = \int_0^\tau DP dt,$$

$$T_a - T_c = [T_{c(a)} - T_c] \exp(-DP\tau),$$

$$\bar{q}_{ac} = \frac{1}{\Delta t} \int_0^{\Delta t} q_{ac} dt,$$

and

$$\bar{q}_{ac} = \frac{T_{c(a)} - T_c}{P\Delta t} [1 - \exp(-DP\Delta t)].$$

4. Heat Transfer between Cladding and Gas

The equation for heat transfer between the cladding and gas per unit length of rod is

$$q_g = D [T_{c(g)} - T_g],$$

where

$$D = S_r h_g.$$

The total heat capacity of the gas passing the cladding is relatively less than the total heat capacity of the cladding. The preintegration will be based on a temperature change of the gas over the length increment $\Delta \ell$.

A heat balance on the gas yields

$$C_{pg} W_g dT_g = q_g d\ell = S_r h_g [T_{c(g)} - T_g] d\ell,$$

$$\int_{T_{g1}}^{T_g} \frac{dT_g}{T_{c(g)} - T_g} = \int_0^y \frac{1}{C_{pg} W_g} S_r h_g d\ell,$$

$$T_{c(g)} - T_g = [T_{c(g)} - T_{g1}] \exp\left(-\frac{S_r h_g}{C_{pg} W_g} y\right),$$

and

$$\begin{aligned} \bar{q}_g &= \frac{1}{\Delta \ell} \int_0^{\Delta \ell} q_g dy \\ &= \frac{1}{\Delta \ell} \int_0^{\Delta \ell} S_r h_g [T_{c(g)} - T_{g1}] \exp\left(-\frac{S_r h_g}{C_{pg} W_g} y\right) dy \\ &= \frac{C_{pg} W_g}{\Delta \ell} [T_{c(g)} - T_{g1}] \left[1 - \exp\left(-\frac{S_r h_g}{C_{pg} W_g} \Delta \ell\right)\right]. \end{aligned}$$

5. Chemical-reaction Heat, Diffusion Limited

The equation for the chemical reaction heat for the diffusion-limited case per unit length of rod is

$$q_s = Q_c M_c Sh_d \rho_g X.$$

For the preintegration, the variation of X over the length interval Δl is considered.

A mass balance on the gas stream yields

$$W_g dX = -Sh_d \rho_g X dl,$$

$$\int_{X_1}^X \frac{dX}{X} = - \int_0^y \frac{Sh_d \rho_g}{W_g} dy,$$

$$X = X_1 \exp \left(- \frac{Sh_d \rho_g}{W_g} y \right),$$

$$\bar{q}_s = \frac{1}{\Delta l} \int_0^{\Delta l} q_s dy,$$

$$\bar{q}_s = \frac{1}{\Delta l} \int_0^{\Delta l} Q_c M_c Sh_d \rho_g X_1 \exp \left(- \frac{Sh_d \rho_g}{W_g} y \right) dy,$$

and

$$\bar{q}_s = \frac{Q_c M_c W_g X_1}{\Delta l} \left[1 - \exp \left(- \frac{Sh_d \rho_g \Delta l}{W_g} \right) \right].$$

APPENDIX E

FORTRAN Program B226 and Sample Input and Output for a Test Case

1. FORTRAN Program B226

```

C      PROGRAM B226
C
C      MOD 4
C
      DIMENSION TAP(25,40),TA(25,40),TCP(25,40),TC(25,40)
      DIMENSION RRP(25,40),RR(25,40),TG(25,40),X(25,40),FSV(25,40)
      DIMENSION FM(25,40),FS(25,40),FW(25,40),FD(25,40),FI(25)
      DIMENSION SINZB(40),FTAB(50),TTAB(50),ABF(25),EL(40),NL(25)
      DIMENSION WG(25),CK15(25),CK16(25),CK17(25),CK18(25)
      DIMENSION NIF(25),ITM(25),QAP(25),QCP(25),QARJP(25),QARP(25)
      TYPE REAL KAA,KAB,KCA,KCB,KA,KC,KHA,KHB,KSA,KS,KAC,KAM
400  FORMAT(1H1/* DATA//5X*NTAB*8X*NPRINT*9X*NJP*10X*NJ*10X*LASTZ*9X
      1  *ELT*9X*DELT*9X*TMAX*10X*QD*/4X,I4,4(9X,I4),5X,4E13.5//
      2  5X*CPAA*9X*CPAB*9X*CPBA*9X*CPBB*9X*CPCMA*8X*CPCMB*8X*CPCOA*
      3  38X*CPCOB*8X*CPHA*9X*CPHB*/10E13.5//
      4  5X*CPSA*9X*CPSB*10X*KAA*10X*KAB*10X*KAC*10X*KCA*10X*KCB*10X*KHA*
      5  10X*KHB*10X*RCZ*/10E13.5//
      6  6X*KSA*10X*KS*10X*DGA*10X*DGB*10X*QCA*10X*QCB*10X*CAY*
      7  9X*DELE*10X*SIG*10X*V8*/10E13.5//
      8  6X*TBA*10X*TBZ*10X*TGD*10X*TTA*10X*TTZ*10X*TWA*10X*TWZ*10X*V2*
      9  11X*V3*11X*V4*/10E13.5//
      A  6X*AA*11X*AC*10X*ALFA*10X*VK*11X*VA*11X*RO*10X*RZERO*
      B  9X*RF*11X*V6*11X*EMC*/10E13.5//
      C  6X*AN*11X*CAS*10X*DF*11X*FLS*10X*FF*11X*FRF*10X*KAM*
      D  10X*SF*11X*TAM*10X*TAL*/10E13.5//
      E  6X*WA*11X*WB*11X*WC*11X*WTP*10X*WW*10X*RHOC*10X*AI*
      F  11X*A2*11X*A4*9X*TEEMAX*/10E13.5//
      G  6X*HAC*10X*U*12X*UB*11X*UT*11X*UW*11X*V5*11X*VM5*10X*EPS*
      H  10X*A*12X*AV*/10E13.5)
401  FORMAT(2E8.0)
402  FORMAT(2X,I2,3X,5E14.5)
403  FORMAT( /* T = *F5.0 /* L = *F9.4 /* WS= *F10.2/ * F(T) = *F10.4/
      1      * ZONE*9X*TA*12X*TC*12X*TG*10X*RO-RI*11X*X*)
404  FORMAT(5I4,4E8.0)
405  FORMAT( 10E8.0)
407  FORMAT(/* T = *F5.0/* AVE. THICKNESS CAN REACTED = *E12.5
      1/* FRACTION CAN REACTED = *E12.5/* AVE. THICKNESS CLAD REACTED = *
      2 E12.5/* FRACTION CLAD REACTED = *E12.5/
      3* FRACTION H2 IN GAS LEAVING = *E12.5/* ENERGY H2 LEAVING = *E12.5
      4 /* ENERGY ABOVE TGO = *E12.5/* ACCUMULATED H2 RELEASED = *E12.5/
      5 * BOTTOM PLATE TEMPERATURE = *E12.5/
      6* TOP TEMPERATURE = * E12.5/* WALL TEMPERATURE = *E12.5/
      7* AVERAGE FUEL TEMPERATURE = *E12.5/
      8 * FRACTION FUEL REMAINING = *E12.5/
      9 * FRACTION FUEL SLUMPED = *E12.5)
408  FORMAT(/* ALL WG(I) ARE ZERO. NO MORE FLOW.*/)
409  FORMAT(1X,2I4/(1X,10E11.3))
410  FORMAT( /* FI */(10F9.4))
411  FORMAT( /* 5X*TTAB*6X*FTAB*)
412  FORMAT( /* SINZB*/(10F9.4))
413  FORMAT(4X,F5.0,5XF6.4)
414  FORMAT(1H1)
      PI=3.14159265359
      R=1.987
      XO=1.0
703  READ 404,NTAB,NPRINT,NJP,NJ,LASTZ,ELT,DELT,TMAX,QD
      IF(EOF,60) 100,705
705  READ 405,CPAA,CPAB,CPBA,CPBB,CPCMA,CPCMB,CPCOA,CPCOB,CPHA,CPHB,
      2 CPSA,CPSB,KAA,KAB,KAC,KCA,KCB,KHA,KHB,RCZ,

```



```

3 KSA, KSB, DGA, DGB, QCA, QCB, CAY, DELE, SIG, V8,
4 TBA, TBZ, TGO, TTA, TTZ, TWA, TWZ, V2, V3, V4,
5 AA, AC, ALFA, VK, VA, RO, RZERO, RF, V6, EMC,
6 AN, CAS, DF, FLS, FF, FRF, KAM, SF, TAM, TAL,
7 WA, WB, WC, WTP, WW, RHOC, A1, A2, A4, TEEMAX,
8 HAC, U, UB, UT, UW, V5, VM5, EPS, A, AV
  READ 405, (FI(JZ), JZ=1, LASTZ)
  READ 401, (TTAB(JZ), FTAB(JZ), JZ=1, NTAB)
  READ 405, (SINZB(JZ), JZ=1, NJ)
  PRINT 400, NTAB, NPRINT, NJP, NJ, LASTZ, ELT, DELT, TMAX, QD,
1  CPAA, CPAB, CPBA, CPBB, CPCMA, CPCMB, CPCOA, CPCOB, CPHA, CPHB,
2  CPSA, CPSB, KAA, KAB, KAC, KCA, KCB, KHA, KHB, RCZ,
3  KSA, KSB, DGA, DGB, QCA, QCB, CAY, DELE, SIG, V8,
4  TBA, TBZ, TGO, TTA, TTZ, TWA, TWZ, V2, V3, V4,
5  AA, AC, ALFA, VK, VA, RO, RZERO, RF, V6, EMC,
6  AN, CAS, DF, FLS, FF, FRF, KAM, SF, TAM, TAL,
7  WA, WB, WC, WTP, WW, RHOC, A1, A2, A4, TEEMAX,
8  HAC, U, UB, UT, UW, V5, VM5, EPS, A, AV
  PRINT 410, (FI(JZ), JZ=1, LASTZ)
  PRINT 411
  DO 706 JZ=1, NTAB
706 PRINT 413, TTAB(JZ), FTAB(JZ)
  PRINT 412, (SINZB(JZ), JZ=1, NJ)
  PRINT 414
  AB=VA*QD
  A3=A1/SQRTF(A2+TEEMAX)
  BSUM=0.0
  C1=PI*RO*SIG
  C7=2.0*PI
  SR=C7*RO+VK
  DELL=ELT/NJ
  C3=-SR*DELL
  C8=-C7*RF*HAC
  V1=V6/LASTZ
  CSHA=CPSA-CPHA
  CSHB=CPSB-CPHB
  DELI=1.0/DELL
  DELSQI=1.0/(DELL**2)
  DFA=2.0*DF*KAM
  CON4=453.6/(3600.*V1*18.02)
  CON15=12.0*PI*C1/V1
  CON16=3.0*AV*C1*DELI
  CON17=4.0*PI/V1
  CON18=3.0*(AV+RO)*C1*DELI
  CON19=AA*DELSQI
  CON20=AC*DELSQI
  FATKM=FTAB(1)
  FR=FRF*(1.0-FF)
  FFR=1.0-FF-FR
  FWM=1.0/SF
  H=-DELE/R
  IPASS=0
  MPRINT =NPRINT
  NK=0
  QRSUM=0.0
  RFH=RF*HAC/4.0
  RHOCI=DELT/RHOC
  RMR=RO-RF
  IF(VK .EQ. 0.0)      ALFA=RMR
  RNJL=1.0/(NJ*LASTZ)
  SJC=-VM5*DGA/(82.057*(1000.)*DGB)
  SF1=SF*FF
  DSF=1.0/(SF1*SF)
  SSUM=0.0
  SUMH2=0.0
  TAM2=TAM**2
  TB=TBZ

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```

TEE=0.0
TKSB=KSB*.001
TGO2=TGO**2
TSUM=0.0
TT=TTZ
TW=TWZ
ZP=LASTZ
DO 2 JJ=1,NJ
EL(JJ)=(JJ-0.5)*DELL
2 CONTINUE
DO 3 II=1, LASTZ
ABF(II)=AB*FI(II)
COUNT=II
CK15(II)=CON15*COUNT
CK16(II)=CON15*(COUNT-1.0)
CK17(II)=-CON17*COUNT
CK18(II)=-CON17*(COUNT-1.0)
ITM(II)=1
NIF(II)=0
NL(II)=0
TG(II,1)=TGO
X(II,1)=XO
WG(II)=1.0
DO 3 J4=1,NJ
FD(II,J4)=1.0
FM(II,J4)=1.0
FS(II,J4)=1.0
FSV(II,J4)=1.0
FW(II,J4)=1.0
3 CONTINUE
CK15(LASTZ)=CON15*2.0*LASTZ
4 IF(TEE .GT. TEEMAX) 7,6
6 WS=A1/SQRTF(A2+TEE)
GO TO 8
7 WS=A3*EXP(A4*(TEE-TEEMAX))
8 WGI=WS*CON4/ZP
DO 10 JJ=1, LASTZ
IF(WG(JJ) .NE. 0.0) WG(JJ)=WGI
10 CONTINUE
12 DO 50 J=1,NJ
JM=J-1
JP=J+1
DO 50 I=1, LASTZ
IM=I-1
IP=I+1
IF(IPASS)15,13
C
C TA, TC, RR AT T=0.0 , ALL J
C
13 TA(I,J)=V4+FI(I)*V2*SINZB(J)
TAP(I,J)=TA(I,J)
TC(I,J)=V4+FI(I)*V3*SINZB(J)
TCG=TC(I,J)
RR(I,J)=RZERO
GO TO 34
15 AM=A
AP=A
CPA=CPAA+CPAB*TA(I,J)
CPCM=CPCMA+CPCMB*TC(I,J)
CPCO=CPCOA+CPCOB*TC(I,J)
CPC=CPCM+(RCZ*CPCO-CPCM)*(RR(I,J)/RMR)
EIM=EPS
EIP=EPS
EJM=EPS
EJP=EPS
P=1.0/(CPC*WC)
DTP=DELT*P

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```

DTPA=AN*GTP
DTPI=1.0/DTP
DTPIA=1.0/DTPA
KC=KCA+KCB*TC(I,J)
PIM=EIM*AM*DTPA
PIP=EIP*AP*DTPA
PJM=EJM*DTPA
PJP=EJP*DTPA
IF(TA(I,J) .GT. TAM) 20,22
20 KA=KAM*(KAA+KAB*TAM+KAC*TAM2)
GO TO 24
22 KA=KAA+KAB*TA(I,J)+KAC*TA(I,J)**2
24 DKKA=KA*DTPA
ECPT=1.0-EXP(-C8*DTP/(1.0+RFH/KA))
IF(FSV(I,J) .EQ. 1.0) 6000,6114
6000 IF(TAP(I,J) .GE. TAL) 6001,6114
6001 IF(NIF(I) .EQ. JM) GO TO 6109
FS(I,J)=SF1 $ FM(I,J)=DSF $ FSV(I,J)=0.0
FD(I,J)=FF $ FW(I,J)=FF $ ITM(I)=0.0 $ SSUM=SSUM+1.0
KNN=NIF(I)+1
IF(KNN .LE. 0) KNN=1
FRR=FR
DO 6106 K=KNN,JM
IF(FSV(I,K) .NE. 1.0) GO TO 6106
FW(I,K)=FW(I,K)+FRR
IF(FW(I,K) .GE. FWM) 6104,6108
6104 FRX=FW(I,K)-FWM
FD(I,K)=FD(I,K)+(FRR-FRX)*SINZB(J)/SINZB(K)
PLACE=1.0
TAPS=TAP(I,K)
TAP(I,K)=TAP(I,K)+(TAL-TAP(I,K))*(FRR-FRX)*SF
IF(TAP(I,K) .LT. 0.0) GO TO 6105
FW(I,K)=FWM
FRR=FRX
FM(I,K)=FWM
FSV(I,K)=0.0
GO TO 6106
6105 PRINT 409,I,J,TAPS,TAL,FRR,FRX,SF,FW(I,K),PLACE
CALL EXIT
6106 CONTINUE
FW(I,J)=FW(I,J)+FRR
FD(I,J)=FD(I,J)+FRR
FS(I,J)=FW(I,J)*SF
FM(I,J)=FWM/FS(I,J)
NIF(I)=J
GO TO 6114
6108 FD(I,K)=FD(I,K)+FRR*SINZB(J)/SINZB(K)
PLACE=2.0
TAPS=TAP(I,K)
TAP(I,K)=TAP(I,K)+(TAL-TAP(I,K))*FRR/FW(I,K)
IF(TAP(I,K) .LT. 0.0) GO TO 6105
NIF(I)=K-1
GO TO 6114
6109 FSV(I,J)=0.0 $ SSUM=SSUM+1.0
IF(CAS .EQ. 2.0) GO TO 6112
FW(I,J)=FW(I,J)-FFR
FD(I,J)=FD(I,J)-FFR
6112 FS(I,J)=FW(I,J)*SF
FM(I,J)=FWM/FS(I,J)
NIF(I)=J
6114 AL=0.0
IF(ITM(I) .EQ. 1) 6122,6124
6122 AL=J
GO TO 6128
6124 AL=0.0
DO 6126 N1=1,J
6126 AL=AL+FS(I,N1)

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6128 IF(I-LASTZ)6130,6142
6130 IF(ITM(I) .EQ. 1 .AND. ITM(IP) .EQ. 1) 6132,6134
6132 JNS=J
      GO TO 6140
6134 ALP=0.0
      DO 6136 N2=1,NJ
      ALP=ALP+FS(IP,N2)
      IF(ALP .GE. AL) 6138,6136
6136 CONTINUE
      JNS=NJ+1
      GO TO 6140
6138 JNS=N2
6140 IF(I-1)6142,6152
6142 IF(ITM(I) .EQ. 1 .AND. ITM(IM) .EQ. 1) 6144,6146
6144 JNSS=J
      GO TO 6152
6146 ALM=0.0
      DO 6148 N3=1,NJ
      ALM=ALM+FS(IM,N3)
      IF(ALM .GE. AL) 6150,6148
6148 CONTINUE
      JNSS=NJ+1
      GO TO 6152
6150 JNSS=N3
6152 TCI=TC(I,J)
      TCI3=TCI**3
6200 IF(I .EQ. 1 .OR. JNSS .GT. NJ) 6202,6204
6202 QRQ=0.0
      QRIM=0.0
      GO TO 6214
6204 IF(JNSS .EQ. J) 6206,6208
6206 QRQ=-QRIP
      QRIM=-QRP
      GO TO 6214
6208 TCIM=TC(IM,JNSS)
      IF(FSV(I,J) .EQ. 1.0 .OR. FSV(IM,JNSS) .EQ. 1.0) 6210,6212
6210 QRQ=-TCI*(1.0-CUBERTF(1.0/(1.0+CK16(I)*PIM*TCI3)))
      QRIM=TCIM*(1.0-CUBERTF(1.0/(1.0+CK16(I)*PIM*TCIM**3)))
      GO TO 6214
6212 QUAN=1.0-EXP(CK18(I)*DKKA)
      QRQ=-TCI*QUAN
      QRIM=TCIM*QUAN
6214 IF(I .EQ. LASTZ) 6216,6218
6216 QRP=-TCI*(1.0-CUBERTF(1.0/(1.0+CK15(LASTZ)*PIP*TCI3)))
      QRIP=TW*(1.0-CUBERTF(1.0/(1.0+CK15(LASTZ)*PIP*TW**3)))
      QRSUM=QRSUM-FS(I,J)*(QRP+QRIP)*DTPIA
      GO TO 6250
6218 IF(JNS .GT. NJ) 6220,6222
6220 QRP=0.0
      QRIP=0.0
      GO TO 6250
6222 TCIP=TC(IP,JNS)
      IF(FSV(I,J) .EQ. 1.0 .OR. FSV(IP,JNS) .EQ. 1.0) 6224,6230
6224 QRIP=TCIP*(1.0-CUBERTF(1.0/(1.0+CK15(I)*PIP*TCIP**3)))
      QRP=-TCI*(1.0-CUBERTF(1.0/(1.0+CK15(I)*PIP*TCI3)))
      GO TO 6250
6230 QUAN=1.0-EXP(CK17(I)*DKKA)
      QRIP=TCIP*QUAN
      QRP=-TCI*QUAN
6250 IF(J .EQ. 1) 6254,6252
6252 QAQ=-QAP(I)
      QCQ=-QCP(I)
      QARQ=-QARJP(I)
      QARJM=-QARP(I)
      GO TO 6270
6254 QAQ=2.0*U*FM(I,J)*CON19*KA*(TB-TA(I,J))
      QCQ=2.0*U*FM(I,J)*CON20*KC*(TB-TCI)

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      IF (FSV(I,J) .EQ. 1.0) 6258,6256
6256 QARQ=0.0
      QARJM=0.0
      GO TO 6260
6258 QARQ=-TCI*(1.0-CUBERTF(1.0/(1.0+CON16*PJM*TCI3)))
      QARJM=TB*(1.0-CUBERTF(1.0/(1.0+CON16*PJM*TB**3)))
6260 BSUM=BSUM-DTPIA*(QARQ+QARJM)-QAQ-QCQ
6270 IF(J .EQ. NJ) 6282,6272
6272 DFV=1.0
      IF(FSV(I,JP) .NE. 1.0 .AND. FSV(I,J) .EQ. 1.0) DFV=DFA
      QAP(I)=DFV*FM(I,J)*CON19*KA*(TA(I,JP)-TA(I,J))
      QCP(I)=DFV*FM(I,J)*CON20*KC*(TC(I,JP)-TCI)
      IF(FSV(I,J) .EQ. 1.0 .OR. FSV(I,JP) .EQ. 1.0) 6276,6274
6274 QARP(I)=0.0
      QARJP(I)=0.0
      GO TO 6290
6276 QARJP(I)=TC(I,JP)*(1.0-CUBERTF(1.0/(1.0+CON16*PJP*TC(I,JP)**3)))
      IF(FSV(I,J) .EQ. 1.0 .OR. FSV(I,JP) .EQ. 1.0) 6278,6280
6278 QARP(I)=(EJP/EJM)*QARQ
      GOTO 6290
6280 QARP(I)=-TCI*(1.0-CUBERTF(1.0/(1.0+CON16*PJP*TCI3)))
      GOTO 6290
6282 QCP(I)=0.0
      QAP(I)=0.0
      QARJP(I)=TT*(1.0-CUBERTF(1.0/(1.0+CON18*PJP*TT**3)))
      QARP(I)=-TCI*(1.0-CUBERTF(1.0/(1.0+CON18*PJP*TCI3)))
6284 TSUM=TSUM-DTPIA*(QARP(I)+QARJP(I))
6290 QRI=FS(I,J)*DTPIA*(QRP+QRIP+QRO+QRIM)+DTPIA*(QARP(I)+QARJP(I)+
1 QARQ+QARJM)+QCP(I)+QCQ
6060 TCA=TCI+DTP*QRI
      TATC=(TA(I,J)-TCA)*ECPT
      TCG=TCA+TATC
      QACE=TATC*DTP
C
C      TG CALC      JP GE 2
C
      IF(WG(I))34,32
32 TG(I,JP)=TC(I,J)
      X(I,JP)=0.0
      QS=0.0
      QGI=0.0
      GO TO 45
34 HH      =V5*(X(I,J)*(KSA+TKSB*TG(I,J))+(1.0-
1 X(I,J))*KHA*(TG(I,J)*.001)*KHB)
      CPG=X(I,J)*(CSHA+CSHB*TG(I,J))+CPHA+CPHB*TG(I,J)
      IF(CPG .GT. 10.0) CPG=10.0
      CPGW=CPG*WG(I)
      QGI      =DELI*(TCG-TG(I,J))*CPGW*(1.0-EXP(C3*HH/CPGW))
      TG(I,JP)=TG(I,J)+DELL*QGI/CPGW
      IF(TG(I,JP).LT. 0.0) 135,35
135 PRINT 409,I,J,TG(I,J),DELL,QGI,CPGW
      CALL EXIT
C
C      X CALC.      JP GE 2, ALL TIMES
C
35 QSX=0.0
      RIJMK=RO-RR(I,J)
      QC=QCA+QCB*TC(I,J)
      IF(RR(I,J)-ALFA) 36,44,44
36 SS=VK
      IF(VK .EQ. 0.0) 38,40
38 SS=C7*RIJMK
      GO TO 42
40 IF(RR(I,J) .LT. RMR) SS=SS+C7*RIJMK
42 BETAJM      =SS*SJC*DELL*TG(I,J)**(DGB-1.0)/WG(I)
      QSX      =SS*RHOC*QC*CAY*EXP(H/TC(I,J))/RR(I,J)
      QSX2=DELI*QC*EMC*WG(I)*X(I,J)*(1.0-EXP(BETAJM))

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      IF(QSX .GT. QX2) QX = QX2
44  QS = QSX
      X(I,JP) = X(I,J) - DELL*QS / (WG(I)*QC*EMC)
      IF(X(I,JP) .LT. 0.0) X(I,JP) = 0.0
      IF(J .EQ. NJ) SUMH2 = SUMH2 + (1.0 - X(I,JP))*WG(I)
C
C      TA,TC,RR CALCS. FOR NEXT T
C
45  IF(IPASS .EQ. 0) GO TO 50
      PLACE = 4.0
      TAPS = TAP(I,J)
      TAP(I,J) = TAP(I,J) + DELT*(ABF(I)*FATKM*FD(I,J)*SINZB(J) -
1  QACE+QAP(I)+QAQ)/(CPA*WA*FW(I,J))
      IF(TAP(I,J) .LT. 0.0) GO TO 150
      PLACE = 5.0
      TCP(I,J) = TC(I,J) + DTP *(QACE+QRI+QS-QGI)
      IF(TCP(I,J) .LT. 0.0) GO TO 150
      PLACE = 6.0
      RRP(I,J) = RR(I,J) + RHOCI*QS/(SS*QC)
      IF(RRP(I,J) .LT. 0.0) 150,50
150  PRINT 409,I,J,PLACE,FD(I,J),QACE,QAP(I),QAQ,FW(I,J),QRI,QS,
      1 QGI,P,DELT,ABF(I),FATKM,SINZB(J),CPA,WA,RHOCI,SS,QC,
      2 TC(I,J),RR(I,J),TAPS
      3 ,FS(I,J),DTPIA,QRP,QRI,QRQ,QRIM,
      4 QARP(I),QARJP(I),QARQ,QARJM,QCP(I),QCQ
      CALL EXIT
50  CONTINUE
      IF(MPRINT .EQ. NPRINT) 55,82
55  MPRINT = 0
      DELCAN = 0.0
      DELCLAD = 0.0
      FH = 0.0
      JQTEST = NJP - 1
      TE = 0.0
      TFT = 0.0
      TFW = 0.0
      WGEYE = 0.0
      DO 72 JQ = 1, NJ
      JQ1 = JQ + 1
      JQTEST = JQTEST + 1
      IF(JQ .EQ. NJ) 56,58
56  DO 57 IZ = 1, LASTZ
      WGEYE = WGEYE + WG(IZ)
      FH = FH + (1.0 - X(IZ,JQ1))*WG(IZ)
      TE = TE + ((CPHA + CSHA *X(IZ,JQ1))*(TG(IZ,JQ1) - TGO) +
1  ((CPHB + CSHB *X(IZ,JQ1))*0.5)*(TG(IZ,JQ1)**2 - TGO2))*WG(IZ)
57  CONTINUE
58  IF(JQTEST .EQ. NJP) 60,62
60  JQTEST = 0
      PRINT 403,TEE,EL(JQ),WS,FATKM
62  DO 70 JA = 1, LASTZ
      IF(JQTEST .EQ. 0) PRINT 402,JA,TA(JA,JQ),TC(JA,JQ),
      1 TG(JA,JQ1),RR(JA,JQ),X(JA,JQ1)
      TFT = TFT + TAP(JA,JQ)*FW(JA,JQ)
      TFW = TFW + FW(JA,JQ)
      DELCAN = DELCAN + RR(JA,JQ)
      IF(RR(JA,JQ) .GT. RMR) 64,66
64  DELCLAD = DELCLAD + RMR
      GO TO 70
66  DELCLAD = DELCLAD + RR(JA,JQ)
70  CONTINUE
72  CONTINUE
      AFT = TFT / TFW
      AFW = TFW * RNJL
      FFS = SSUM * RNJL
      TE = TE * V1
      IF(FH .NE. 0.0) FH = FH / WGEYE

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ACCH2=SUMH2*DELT*V1
EC=V8*WGI*V1*ZP*FH
IF( VK ) 76,74
74 DELCAN=0.0
FCAN=0.0
GO TO 78
76 DELCAN=DELCAN*RNJL
FCAN=DELCAN/ALFA
78 DELCLAD=DELCLAD*RNJL
FCLAD=DELCLAD/RMR
PRINT 407 , TEE, DELCAN, FCAN, DELCLAD, FCLAD, FH, EC, TE, ACCH2, TB, TT, TW,
1 AFT, AFW, FFS
IF(ZP .LE. 0.0) PRINT 408
82 CPB=CPBA+CPBB*TB
CPBW=CPBA+CPBB*TW
CPBT=CPBA+CPBB*TT
TB=TB+DELT*(V1*DELL*(DSUM )-UB*(TB-TBA))/(CPB*WB)
TW=TW+DELT*(V1*DELL *QRSUM-UW*(TW-TWA))/(CPBW*WW)
TT=TT+DELT*(V1*DELL *TSUM-UT*(TT-TTA))/(CPBT*WTP)
BSUM=0.0
QRSUM=0.0
TSUM=0.0
NK=NK+1
TEE=NK*DELT
MPRINT=MPRINT+1
IF(TEE-TMAX)83,83,703
83 TKM=TEE-DELT
CALL DISCOT(TKM,TKM,TTAB,FTAB,FTAB,-020,NTAB,0,ANS)
FATKM=ANS
IF(IPASS)85,84
84 IPASS=1
GO TO 4
85 DO 98 JJ=1, LASTZ
IF(NL(JJ) .GE. FLS) 86,87
86 IF(WG(JJ) .NE. 0.0) ZP=ZP-1.0
WG(JJ)=0.0
87 NL(JJ)=0
DO 96 JQ=1,NJ
IF(TAP(JJ,JQ) .LT. TAM) 89,90
89 TA(JJ,JQ)=TAP(JJ,JQ)
GO TO 94
90 IF(TAP(JJ,JQ) .LT. TAL) 91,92
91 TA(JJ,JQ)=TAM
GO TO 94
92 TA(JJ,JQ)=TAP(JJ,JQ)-TAL+TAM
NL(JJ)=NL(JJ)+1
94 TC(JJ,JQ)=TCP(JJ,JQ)
RR(JJ,JQ)=RRP(JJ,JQ)
96 CONTINUE
98 CONTINUE
IF(ZP .LE. 0.0)99,4
99 WGI=0. $ WS=0.0 $ GO TO 12
100 CALL EXIT
END
SUBROUTINE DISCOT (XA,ZA,TABX,TABY,TABZ,NC,NY,NZ,ANS)
DIMENSION TABX(500),TABY(500),TABZ(500),NPX(8),NPY(8),YY(8)
CALL UNS (NC,IA,IDX,IDZ,IMS)
IF (NZ-1) 5,5,10
5 CALL DISSER (XA,TABX,1,NY,IDX,NN)
NNN=IDX+1
CALL LAGRAN (XA,TABX(NN),TABY(NN),NNN,ANS)
GOTO 70
10 ZARG=ZA
IP1X=IDX+1
IP1Z=IDZ+1
IF (IA) 15,25,15
15 IF (ZARG-TABZ(NZ)) 25,25,2C

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DISCOT01
DISCOT02
DISCOT03
DISCOT04
DISCOT05
DISCOT06
DISCOT07
DISCOT08
DISCOT09
DISCOT10
DISCOT11
DISCOT12
DISCOT13

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20	ZARG=TABZ(NZ)	DISCOT14
25	CALL DISSER (ZARG,TABZ,1,NZ,IDZ,NPZ)	DISCOT15
	NX=NY/NZ	DISCOT16
	NPZL=NPZ+IDZ	DISCOT17
	I=1	DISCOT18
	IF (IMS) 30,30,40	DISCOT19
30	CALL DISSER (XA,TABX,1,NX,IDX,NPX)	DISCOT20
	DO 35 JJ=NPZ,NPZL	DISCOT21
	NPY(I)=(JJ-1)*NX+NPX(1)	DISCOT22
	NPX(I)=NPX(1)	DISCOT23
35	I=I+1	DISCOT24
	GOTO 50	DISCOT25
40	DO 45 JJ=NPZ,NPZL	DISCOT26
	IS=(JJ-1)*NX+1	DISCOT27
	CALL DISSER (XA,TABX,IS,NX,ICX,NPX(I))	DISCOT28
	NPY(I)=NPX(I)	DISCOT29
45	I=I+1	DISCOT30
50	DO 55 I=1,IP17	DISCOT31
	NLOC=NPX(I)	DISCOT32
	NLOCY=NPY(I)	DISCOT33
55	CALL LAGRAN (XA,TABX(NLOC),TABY(NLOCY),IP1X,YY(I))	DISCOT34
	CALL LAGRAN (ZARG,TABZ(NPZ),YY,IP1Z,ANS)	DISCOT35
70	RETURN	DISCOT36
	END	DISCOT37
	SUBROUTINE UNS (IC,IA,IDX,IDZ,IMS)	DISCOT38
	IF (IC) 5,5,10	DISCOT39
5	IMS=1	DISCOT40
	NC=-IC	DISCOT41
	GOTO 15	DISCOT42
10	IMS=0	DISCOT43
	NC=IC	DISCOT44
15	IF (NC-100) 20,25,25	DISCOT45
20	IA=0	DISCOT46
	GOTO 30	DISCOT47
25	IA=1	DISCOT48
	NC=NC-100	DISCOT49
30	IDX=NC/10	DISCOT50
	IDZ=NC-IDX*10	DISCOT51
	RETURN	DISCOT52
	END	DISCOT53
	SUBROUTINE LAGRAN (XA,X,Y,N,ANS)	DISCOT54
	DIMENSION X(200),Y(200)	DISCOT55
	SUM=0.0	DISCOT56
	DO 3 I=1,N	DISCOT57
	PROD=Y(I)	DISCOT58
	DO 2 J=1,N	DISCOT59
	A=X(I)-X(J)	DISCOT60
	IF (A) 1,2,1	DISCOT61
1	B=(XA-X(J))/A	DISCOT62
	PROD=PROD*B	DISCOT63
2	CONTINUE	DISCOT64
3	SUM=SUM+PROD	DISCOT65
	ANS=SUM	DISCOT66
	RETURN	DISCOT67
	END	DISCOT68
	SUBROUTINE DISSER (XA,TAB,I,NX,ID,NPX)	DISCOT69
	DIMENSION TAB(2000)	DISCOT70
	NPT=ID+1	DISCOT71
	NPB=NPT/2	DISCOT72
	NPU=NPT-NPB	DISCOT73
	IF (NX-NPT) 10,5,10	DISCOT74
5	NPX=I	DISCOT75
	RETURN	DISCOT76
10	NLOW=I+NPB	DISCOT77
	NUPP=I+NX-(NPU+1)	DISCOT78
	DO 15 II=NLOW,NUPP	DISCOT79
	NLOC=II	DISCOT80

	IF (TAB(II)-XA) 15,20,20	DISCOT81
15	CONTINUE	DISCOT82
	NPX=NUPP-NPB+1	DISCOT83
	RETURN	DISCOT84
20	NL=NLOC-NPB	DISCOT85
	NU=NL+ID	DISCOT86
	DO 25 JJ=NL,NU	DISCOT87
	NDIS=JJ	DISCOT88
	IF (TAB(JJ)-TAB(JJ+1)) 25,30,25	DISCOT89
25	CONTINUE	DISCOT90
	NPX=NL	DISCOT91
	RETURN	DISCOT92
30	IF (TAB(NDIS)-XA) 40,35,35	DISCOT93
35	NPX=NDIS-ID	DISCOT94
	RETURN	DISCOT95
40	NPX=NDIS+1	DISCOT96
	RETURN	DISCOT97
	END	DISCOT98

2. Test-case Input

24	25	3	25	13	365.76	2.0	150.	67.421		
0.068	7.5E-6	0.106	4.0E-5	0.082	0.0	0.148	0.0	6.56	.00075	
7.20	.00255	0.014	-1.0E-5	2.5E-9	0.041	0.0	11.0E-4	0.75	1.35	
-.2E-4	2.0E-4	7.30	1.75	1610.	-.0615	.3937	45500.	1.37E-12	57980.	
558.	558.	400.	558.	558.	558.	558.	735.	29.0	558.	
0.6787	0.36	.1549	.4135	.67876	.53594	.0001	.474218	39372.	45.6	
4.0	2.0	10.0	4.0	0.6	0.95	2.0	0.50	3073.	3700.	
6.99806	4.0E+6	1.86	5.0E+6	10.0E+6	6.5	124000.	9.0	-2.53E-4	2140.	
0.190	1.0	165.0	165.0	165.0	8.3	8.3	0.45	0.5	1.0	
1.43	1.35	1.27	1.20	1.13	1.06	0.99	0.92	0.85	0.79	
0.73	0.67	0.61								
1	.0633									
3	.0584									
5	.0549									
10	.0496									
20	.0443									
40	.0382									
60	.0348									
100	.0308									
150	.0276									
200	.0257									
300	.0230									
400	.0213									
500	.0202									
600	.0191									
800	.0177									
1000	.0166									
1500	.0147									
2000	.0134									
3000	.0117									
4000	.0106									
5000	.0098									
6000	.0093									
8000	.0083									
10000	.0077									
0.204	0.380	0.550	0.713	0.864	1.004	1.129	1.237	1.328	1.402	
1.454	1.486	1.498	1.486	1.454	1.402	1.329	1.237	1.129	1.004	
0.864	0.713	0.550	0.380	0.204						

3. Test-case Output

DATA

NTAB 24	NPRINT 25	NJP 3	NJ 25	LASTZ 13	ELT 3.65760+002	DELT 2.00000+000	TMAX 1.50000+002	OD 6.74210+001	
CPAA 6.80000-002	CPAR 7.50000+006	CPBA 1.06000-001	CPRB 4.00000-005	CPCMA 8.20000-002	CPCMB 0.00000+000	GPCOA 1.48000-001	CPCOB 0.00000+000	CPHA 6.56000+000	CPHR 7.50000-004
CPSA 7.20000+000	CPSR 2.55000-003	KAA 1.40000-002	KAB -1.00000-005	KAC 2.50000-009	KCA 4.10000-002	KCB 0.00000+000	KHA 1.10000-003	KHB 7.50000-001	KCZ 1.35000+000
KSA -2.00000-005	KSR 2.00000-004	DGA 7.30000+000	DGB 1.75000+000	DCA 1.61000+003	DCB -6.15000-002	DAY 3.93700-001	DELE 4.55000+004	SIG 1.37000-012	V8 5.79000+004
TBA 5.58000+002	TRZ 5.58000+002	TGO 4.00000+002	TTA 5.58000+002	TTZ 5.58000+002	TWA 5.58000+002	TWZ 5.58000+002	V2 7.35000+002	V3 2.90000+001	V4 5.58000+002
AA 6.78700-001	AC 3.60000-001	ALFA 1.54900-001	VK 4.13500-001	VA 6.78760-001	RO 5.35940-001	RZERO 1.00000-004	RF 4.74218-001	V6 3.93720+004	EMC 4.55000+001
AN 4.00000+000	CAS 2.00000+000	BF 1.00000+001	FLS 4.00000+000	FF 6.00000-001	FRF 9.50000-001	KAM 2.00000+000	SF 5.00000-001	TAM 3.07300+003	TAI 3.70000+003
WA 6.99806+000	WP 4.00000+006	WC 1.86000+000	WTP 5.00000+006	WW 1.00000+007	RHOC 6.50000+000	A1 1.24000+005	A2 9.00000+000	A4 -2.53000-004	TEEMAX 2.14000+003
HAC 1.90000-001	U 1.00000+000	UB 1.65000+002	UT 1.65000+002	UW 1.65000+002	V5 8.30000+000	VMS 8.30000+000	EPS 4.50000-001	A 5.00000-001	AV 1.00000+000

F1

1.4300	1.3500	1.2700	1.2000	1.1300	1.0600	0.9900	0.9200	0.8500	0.7900
0.7300	0.6700	0.6100							

TTAR	FTAR
1	0.0633
3	0.0584
5	0.0549
10	0.0496
20	0.0443
40	0.0382
60	0.0348
100	0.0308
150	0.0276
200	0.0257
300	0.0230
400	0.0213
500	0.0202
600	0.0191
800	0.0177
1000	0.0166
1500	0.0147
2000	0.0134
3000	0.0117
4000	0.0106
5000	0.0098
6000	0.0093
8000	0.0083
10000	0.0077

SINZB

0.2040	0.3800	0.5500	0.7130	0.8640	1.0040	1.1290	1.2370	1.3280	1.4020
1.4540	1.4840	1.4980	1.4860	1.4540	1.4020	1.3290	1.2370	1.1290	1.0040
0.8640	0.7130	0.5500	0.3800	0.2040					

T = 0
 L = 7.3152
 WS = 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO=RI	X
1	7.72414+002	5.66460+002	4.61013+002	1.00000-004	1.00000+000
2	7.60419+002	5.65987+002	4.60839+002	1.00000-004	1.00000+000
3	7.48424+002	5.65513+002	4.60666+002	1.00000-004	1.00000+000
4	7.37928+002	5.65099+002	4.60514+002	1.00000-004	1.00000+000
5	7.27432+002	5.64685+002	4.60362+002	1.00000-004	1.00000+000
6	7.16936+002	5.64271+002	4.60210+002	1.00000-004	1.00000+000
7	7.06441+002	5.63857+002	4.60058+002	1.00000-004	1.00000+000
8	6.95945+002	5.63443+002	4.59907+002	1.00000-004	1.00000+000
9	6.85449+002	5.63029+002	4.59755+002	1.00000-004	1.00000+000
10	6.74553+002	5.62674+002	4.59625+002	1.00000-004	1.00000+000
11	6.67456+002	5.62319+002	4.59495+002	1.00000-004	1.00000+000
12	6.58460+002	5.61964+002	4.59365+002	1.00000-004	1.00000+000
13	6.49463+002	5.61609+002	4.59234+002	1.00000-004	1.00000+000

T = 0
 L = 51.2064
 WS = 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO=RI	X
1	1.30740+003	5.87568+002	5.63021+002	1.00000-004	1.00000+000
2	1.26547+003	5.85914+002	5.61755+002	1.00000-004	1.00000+000
3	1.22355+003	5.84260+002	5.60490+002	1.00000-004	1.00000+000
4	1.18687+003	5.82812+002	5.59384+002	1.00000-004	1.00000+000
5	1.15018+003	5.81365+002	5.58279+002	1.00000-004	1.00000+000
6	1.11350+003	5.79918+002	5.57174+002	1.00000-004	1.00000+000
7	1.07681+003	5.78470+002	5.56071+002	1.00000-004	1.00000+000
8	1.04013+003	5.77023+002	5.54969+002	1.00000-004	1.00000+000
9	1.00345+003	5.75575+002	5.53868+002	1.00000-004	1.00000+000
10	9.72003+002	5.74335+002	5.52925+002	1.00000-004	1.00000+000
11	9.40560+002	5.73094+002	5.51982+002	1.00000-004	1.00000+000
12	9.09117+002	5.71854+002	5.51040+002	1.00000-004	1.00000+000
13	8.77674+002	5.70613+002	5.50099+002	1.00000-004	1.00000+000

T = 0
 L = 95.0976
 WS = 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO=RI	X
1	1.74464+003	6.04820+002	5.96894+002	1.00000-004	1.00000+000
2	1.67825+003	6.02200+002	5.94557+002	1.00000-004	1.00000+000
3	1.61187+003	5.99581+002	5.92223+002	1.00000-004	1.00000+000
4	1.55378+003	5.97289+002	5.90183+002	1.00000-004	1.00000+000
5	1.49569+003	5.94997+002	5.88145+002	1.00000-004	1.00000+000
6	1.43760+003	5.92705+002	5.86108+002	1.00000-004	1.00000+000
7	1.37952+003	5.90414+002	5.84074+002	1.00000-004	1.00000+000
8	1.32143+003	5.88122+002	5.82042+002	1.00000-004	1.00000+000
9	1.26334+003	5.85830+002	5.80012+002	1.00000-004	1.00000+000
10	1.21355+003	5.83865+002	5.78273+002	1.00000-004	1.00000+000
11	1.16376+003	5.81901+002	5.76536+002	1.00000-004	1.00000+000
12	1.11398+003	5.79936+002	5.74801+002	1.00000-004	1.00000+000
13	1.06419+003	5.77972+002	5.73067+002	1.00000-004	1.00000+000

T = 0
 L = 138.9888
 WS = 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO=RI	X
1	2.03157+003	6.16141+002	6.12338+002	1.00000-004	1.00000+000
2	1.94913+003	6.12888+002	6.09256+002	1.00000-004	1.00000+000
3	1.86670+003	6.09636+002	6.06176+002	1.00000-004	1.00000+000
4	1.79456+003	6.06790+002	6.03484+002	1.00000-004	1.00000+000
5	1.72243+003	6.03944+002	6.00793+002	1.00000-004	1.00000+000
6	1.65030+003	6.01097+002	5.98105+002	1.00000-004	1.00000+000
7	1.57817+003	5.98251+002	5.95418+002	1.00000-004	1.00000+000
8	1.50603+003	5.95405+002	5.92734+002	1.00000-004	1.00000+000
9	1.43390+003	5.92559+002	5.90051+002	1.00000-004	1.00000+000
10	1.37207+003	5.90120+002	5.87754+002	1.00000-004	1.00000+000
11	1.31024+003	5.87680+002	5.85458+002	1.00000-004	1.00000+000
12	1.24841+003	5.85241+002	5.83164+002	1.00000-004	1.00000+000
13	1.18659+003	5.82801+002	5.80872+002	1.00000-004	1.00000+000

T = 0
 L = 182.8800
 WS = 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO=RI	X
1	2.13247+003	6.20122+002	6.18923+002	1.00000-004	1.00000+000
2	2.04439+003	6.16647+002	6.15499+002	1.00000-004	1.00000+000
3	1.95631+003	6.13171+002	6.12077+002	1.00000-004	1.00000+000
4	1.87924+003	6.10130+002	6.09084+002	1.00000-004	1.00000+000
5	1.80216+003	6.07089+002	6.06091+002	1.00000-004	1.00000+000
6	1.72509+003	6.04049+002	6.03100+002	1.00000-004	1.00000+000
7	1.64802+003	6.01008+002	6.00110+002	1.00000-004	1.00000+000
8	1.57095+003	5.97967+002	5.97121+002	1.00000-004	1.00000+000
9	1.49388+003	5.94926+002	5.94133+002	1.00000-004	1.00000+000
10	1.42781+003	5.92319+002	5.91573+002	1.00000-004	1.00000+000
11	1.36175+003	5.89713+002	5.89014+002	1.00000-004	1.00000+000
12	1.29569+003	5.87106+002	5.86456+002	1.00000-004	1.00000+000
13	1.22963+003	5.84500+002	5.83898+002	1.00000-004	1.00000+000

T = 0
 L = 226.7712
 WS = 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO=RI	X
1	2.03157+003	6.16141+002	6.17397+002	1.00000-004	1.00000+000
2	1.94913+003	6.12888+002	6.14077+002	1.00000-004	1.00000+000
3	1.86670+003	6.09636+002	6.10758+002	1.00000-004	1.00000+000
4	1.79456+003	6.06790+002	6.07853+002	1.00000-004	1.00000+000
5	1.72243+003	6.03944+002	6.04947+002	1.00000-004	1.00000+000
6	1.65030+003	6.01097+002	6.02042+002	1.00000-004	1.00000+000
7	1.57817+003	5.98251+002	5.99135+002	1.00000-004	1.00000+000
8	1.50603+003	5.95405+002	5.96229+002	1.00000-004	1.00000+000
9	1.43390+003	5.92559+002	5.93322+002	1.00000-004	1.00000+000
10	1.37207+003	5.90120+002	5.90830+002	1.00000-004	1.00000+000
11	1.31024+003	5.87680+002	5.88337+002	1.00000-004	1.00000+000
12	1.24841+003	5.85241+002	5.85845+002	1.00000-004	1.00000+000
13	1.18659+003	5.82801+002	5.83352+002	1.00000-004	1.00000+000

T = 0

L = 270.6624
 WS= 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO-RI	X
1	1.74464+003	6.04820+002	6.08329+002	1.00000-004	1.00000+000
2	1.67825+003	6.02200+002	6.05533+002	1.00000-004	1.00000+000
3	1.61187+003	5.99581+002	6.02734+002	1.00000-004	1.00000+000
4	1.55378+003	5.97289+002	6.00284+002	1.00000-004	1.00000+000
5	1.49569+003	5.94997+002	5.97832+002	1.00000-004	1.00000+000
6	1.43760+003	5.92705+002	5.95378+002	1.00000-004	1.00000+000
7	1.37952+003	5.90414+002	5.92923+002	1.00000-004	1.00000+000
8	1.32143+003	5.88122+002	5.90466+002	1.00000-004	1.00000+000
9	1.26334+003	5.85830+002	5.88007+002	1.00000-004	1.00000+000
10	1.21355+003	5.83865+002	5.85898+002	1.00000-004	1.00000+000
11	1.16376+003	5.81901+002	5.83787+002	1.00000-004	1.00000+000
12	1.11398+003	5.79936+002	5.81676+002	1.00000-004	1.00000+000
13	1.06419+003	5.77972+002	5.79562+002	1.00000-004	1.00000+000

T = 0
 L = 314.5536
 WS= 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO-RI	X
1	1.30740+003	5.87568+002	5.93013+002	1.00000-004	1.00000+000
2	1.26547+003	5.85914+002	5.91081+002	1.00000-004	1.00000+000
3	1.22355+003	5.84260+002	5.89146+002	1.00000-004	1.00000+000
4	1.18687+003	5.82812+002	5.87450+002	1.00000-004	1.00000+000
5	1.15018+003	5.81365+002	5.85752+002	1.00000-004	1.00000+000
6	1.11350+003	5.79918+002	5.84052+002	1.00000-004	1.00000+000
7	1.07681+003	5.78470+002	5.82350+002	1.00000-004	1.00000+000
8	1.04013+003	5.77023+002	5.80645+002	1.00000-004	1.00000+000
9	1.00345+003	5.75575+002	5.78938+002	1.00000-004	1.00000+000
10	9.72003+002	5.74335+002	5.77472+002	1.00000-004	1.00000+000
11	9.40560+002	5.73094+002	5.76005+002	1.00000-004	1.00000+000
12	9.09117+002	5.71854+002	5.74536+002	1.00000-004	1.00000+000
13	8.77674+002	5.70613+002	5.73065+002	1.00000-004	1.00000+000

T = 0
 L = 358.4448
 WS= 41333.33
 F(T) = 0.0633

ZONE	TA	TC	TG	RO-RI	X
1	7.72414+002	5.66460+002	5.73359+002	1.00000-004	1.00000+000
2	7.60419+002	5.65987+002	5.72522+002	1.00000-004	1.00000+000
3	7.48424+002	5.65513+002	5.71683+002	1.00000-004	1.00000+000
4	7.37928+002	5.65099+002	5.70946+002	1.00000-004	1.00000+000
5	7.27432+002	5.64685+002	5.70208+002	1.00000-004	1.00000+000
6	7.16936+002	5.64271+002	5.69468+002	1.00000-004	1.00000+000
7	7.06441+002	5.63857+002	5.68726+002	1.00000-004	1.00000+000
8	6.95945+002	5.63443+002	5.67981+002	1.00000-004	1.00000+000
9	6.85449+002	5.63029+002	5.67235+002	1.00000-004	1.00000+000
10	6.76453+002	5.62674+002	5.66594+002	1.00000-004	1.00000+000
11	6.67456+002	5.62319+002	5.65951+002	1.00000-004	1.00000+000
12	6.58460+002	5.61964+002	5.65306+002	1.00000-004	1.00000+000
13	6.49463+002	5.61609+002	5.64660+002	1.00000-004	1.00000+000

T = 0
 AVE. THICKNESS CAN REACTED = 1.00000-004
 FRACTION CAN REACTED = 6.45578-004

AVE. THICKNESS CLAD REACTED = 1.00000-004
 FRACTION CLAD REACTED = 1.62017-003
 FRACTION H2 IN GAS LEAVING = 1.86712-009
 ENERGY H2 LEAVING = 3.12872-002
 ENERGY ABOVE TGO = 4.11563+005
 ACCUMULATED H2 RELEASED = 1.07924-006
 BOTTOM PLATE TEMPERATURE = 5.58000+002
 TOP TEMPERATURE = 5.58000+002
 WALL TEMPERATURE = 5.58000+002
 AVERAGE FUEL TEMPERATURE = 1.29303+003
 FRACTION FUEL REMAINING = 1.00000+000
 FRACTION FUEL SLUMPED = 0.00000+000

T = 50
 L = 7.3152
 WS = 16143.42
 F(T) = 0.0367

ZONE	TA	TC	TG	RO-RI	X
1	7.39564+002	7.33385+002	6.33449+002	1.00004-004	1.00000+000
2	7.28578+002	7.22652+002	6.25908+002	1.00003-004	1.00000+000
3	7.17604+002	7.11930+002	6.18375+002	1.00002-004	1.00000+000
4	7.08011+002	7.02555+002	6.11788+002	1.00001-004	1.00000+000
5	6.98426+002	6.93188+002	6.05207+002	1.00001-004	1.00000+000
6	6.88849+002	6.83828+002	5.98631+002	1.00000-004	1.00000+000
7	6.79279+002	6.74474+002	5.92060+002	1.00000-004	1.00000+000
8	6.69717+002	6.65127+002	5.85493+002	1.00000-004	1.00000+000
9	6.60165+002	6.55789+002	5.78933+002	1.00000-004	1.00000+000
10	6.51979+002	6.47785+002	5.73310+002	1.00000-004	1.00000+000
11	6.43800+002	6.39788+002	5.67693+002	1.00000-004	1.00000+000
12	6.35625+002	6.31795+002	5.62078+002	1.00000-004	1.00000+000
13	6.27262+002	6.23619+002	5.56329+002	1.00000-004	1.00000+000

T = 50
 L = 51.2064
 WS = 16143.42
 F(T) = 0.0367

ZONE	TA	TC	TG	RO-RI	X
1	1.29095+003	1.28561+003	1.28184+003	5.43533-004	9.58023-001
2	1.24299+003	1.23646+003	1.23325+003	3.94234-004	9.71780-001
3	1.19754+003	1.19039+003	1.18746+003	2.87598-004	9.81391-001
4	1.15920+003	1.15183+003	1.14899+003	2.20910-004	9.87458-001
5	1.12192+003	1.11452+003	1.11165+003	1.73805-004	9.91911-001
6	1.08546+003	1.07819+003	1.07521+003	1.42227-004	9.95101-001
7	1.04963+003	1.04264+003	1.03944+003	1.22505-004	9.97260-001
8	1.01424+003	1.00764+003	1.00416+003	1.11166-004	9.98596-001
9	9.79170+002	9.73027+002	9.69232+002	1.05172-004	9.99339-001
10	9.49211+002	9.43501+002	9.39430+002	1.02534-004	9.99675-001
11	9.19345+002	9.14083+002	9.09754+002	1.01182-004	9.99849-001
12	8.89518+002	8.84709+002	8.80157+002	1.00523-004	9.99933-001
13	8.58408+002	8.54085+002	8.49312+002	1.00214-004	9.99973-001

T = 50
 L = 95.0976
 WS = 16143.42
 F(T) = 0.0367

ZONE	TA	TC	TG	RO-RI	X
1	2.12488+003	2.11039+003	2.11847+003	1.01044-002	5.42101-020
2	2.12136+003	2.10409+003	2.11104+003	1.14556-002	1.73472-018
3	1.99689+003	2.08933+003	2.02879+003	9.58534-003	1.13505-009

4	1.78395+003	1.91662+003	1.83006+003	5.93377-003	3.94357-009
5	1.60242+003	1.64525+003	1.61722+003	2.90761-003	5.36764-001
6	1.48829+003	1.50330+003	1.49267+003	1.71500-003	7.66778-001
7	1.40079+003	1.40519+003	1.40098+003	1.07259-003	8.65272-001
8	1.32547+003	1.32473+003	1.32358+003	6.81048-004	9.19945-001
9	1.25713+003	1.25373+003	1.25403+003	4.33698-004	9.53177-001
10	1.20204+003	1.19743+003	1.19826+003	2.95789-004	9.71638-001
11	1.14938+003	1.14419+003	1.14525+003	2.06014-004	9.83909-001
12	1.09845+003	1.09307+003	1.09417+003	1.51389-004	9.91762-001
13	1.04572+003	1.04048+003	1.04129+003	1.21037-004	9.96530-001

T = 50
 L = 138.9888
 WS = 16143.42
 F(T) = 0.0367

ZONE	TA	TC	TG	RO-RI	X
1	2.00282+003	1.98726+003	1.99759+003	1.00000-004	0.00000+000
2	1.92671+003	1.91292+003	1.92216+003	1.00042-004	6.84228-049
3	1.85676+003	1.84489+003	1.85290+003	2.41392-004	0.00000+000
4	1.83919+003	1.83101+003	1.83739+003	7.69924-004	1.46937-039
5	1.88453+003	1.87534+003	1.88147+003	3.61114-003	3.15544-030
6	1.90407+003	1.89344+003	1.90024+003	5.98166-003	2.03288-020
7	1.83488+003	1.85470+003	1.84115+003	6.02722-003	2.18279-011
8	1.64215+003	1.70389+003	1.66222+003	3.49989-003	1.65626-001
9	1.49532+003	1.51407+003	1.50096+003	1.78248-003	6.35399-001
10	1.40133+003	1.40782+003	1.40298+003	1.07524-003	7.94262-001
11	1.32083+003	1.32151+003	1.32064+003	6.59851-004	8.81487-001
12	1.24789+003	1.24560+003	1.24666+003	4.06011-004	9.33601-001
13	1.17483+003	1.17091+003	1.17267+003	2.46938-004	9.67443-001

T = 50
 L = 182.8800
 WS = 16143.42
 F(T) = 0.0367

ZONE	TA	TC	TG	RO-RI	X
1	2.10912+003	2.09400+003	2.10394+003	1.00000-004	0.00000+000
2	2.02248+003	2.00810+003	2.01755+003	1.00000-004	3.37350-080
3	1.93588+003	1.92232+003	1.93128+003	1.00000-004	0.00000+000
4	1.85996+003	1.84717+003	1.85567+003	1.00000-004	1.15913-068
5	1.78447+003	1.77261+003	1.78059+003	1.00000-004	2.98705-059
6	1.72102+003	1.71054+003	1.71766+003	3.02143-004	1.92439-049
7	1.70306+003	1.69496+003	1.70072+003	1.19130-003	2.98465-040
8	1.69563+003	1.68672+003	1.69257+003	2.83097-003	3.31322-029
9	1.62397+003	1.63835+003	1.62840+003	3.01558-003	3.54703-011
10	1.49690+003	1.51829+003	1.50317+003	1.79489-003	3.52196-001
11	1.39607+003	1.40372+003	1.39814+003	1.04058-003	6.52636-001
12	1.31013+003	1.31152+003	1.31045+003	6.14362-004	8.08921-001
13	1.22654+003	1.22453+003	1.22567+003	3.53984-004	9.04505-001

T = 50
 L = 226.7712
 WS = 16143.42
 F(T) = 0.0367

ZONE	TA	TC	TG	RO-RI	X
1	2.01874+003	2.00611+003	2.01443+003	1.00000-004	0.00000+000
2	1.93700+003	1.92502+003	1.93294+003	1.00000-004	0.00000+000
3	1.85532+003	1.84404+003	1.85157+003	1.00000-004	0.00000+000
4	1.78374+003	1.77310+003	1.78025+003	1.00000-004	2.19454-098
5	1.71220+003	1.70223+003	1.70902+003	1.00000-004	8.79710-088

6	1.64073+003	1.63145+003	1.63786+003	1.00000-004	5.61351-077
7	1.57422+003	1.56576+003	1.57171+003	1.70037-004	2.41098-067
8	1.53952+003	1.53210+003	1.53727+003	8.53651-004	3.95087-056
9	1.48294+003	1.47610+003	1.48096+003	1.14123-003	2.52731-037
10	1.42024+003	1.43211+003	1.42347+003	1.19111-003	3.06500-010
11	1.33606+003	1.34030+003	1.33715+003	7.22300-004	4.40537-001
12	1.26044+003	1.26071+003	1.26050+003	4.39884-004	6.92780-001
13	1.18512+003	1.18309+003	1.18445+003	2.63772-004	8.45912-001

T = 50

L = 270.6624

WS= 16143.42

F(T) = 0.0367

ZONE	TA	TC	TG	RO=RI	X
1	1.74403+003	1.73551+003	1.74136+003	1.00000-004	0.00000+000
2	1.67749+003	1.66946+003	1.67503+003	1.00000-004	0.00000+000
3	1.61102+003	1.60350+003	1.60878+003	1.00000-004	0.00000+000
4	1.55282+003	1.54574+003	1.55076+003	1.00000-004	3.60086-126
5	1.49467+003	1.48804+003	1.49280+003	1.00000-004	8.50211-115
6	1.43654+003	1.43035+003	1.43486+003	1.00000-004	4.04622-103
7	1.37844+003	1.37270+003	1.37694+003	1.00000-004	1.16555-092
8	1.32142+003	1.31616+003	1.32010+003	1.14662-004	7.93959-081
9	1.27388+003	1.26922+003	1.27275+003	2.85281-004	2.17866-061
10	1.22612+003	1.22184+003	1.22512+003	3.14559-004	1.30753-033
11	1.17174+003	1.17044+003	1.17145+003	2.36841-004	3.59537-001
12	1.11833+003	1.11623+003	1.11788+003	1.67751-004	6.47091-001
13	1.06307+003	1.06055+003	1.06250+003	1.28170-004	8.23686-001

T = 50

L = 314.5536

WS= 16143.42

F(T) = 0.0367

ZONE	TA	TC	TG	RO=RI	X
1	1.31842+003	1.31502+003	1.31765+003	1.00000-004	0.00000+000
2	1.27568+003	1.27246+003	1.27497+003	1.00000-004	0.00000+000
3	1.23299+003	1.22995+003	1.23233+003	1.00000-004	0.00000+000
4	1.19563+003	1.19276+003	1.19502+003	1.00000-004	1.47854-150
5	1.15831+003	1.15560+003	1.15775+003	1.00000-004	1.58237-138
6	1.12101+003	1.11846+003	1.12049+003	1.00000-004	3.46092-126
7	1.08372+003	1.08134+003	1.08325+003	1.00000-004	4.65950-115
8	1.04657+003	1.04436+003	1.04615+003	1.00284-004	1.48071-102
9	1.01026+003	1.00823+003	1.00988+003	1.03061-004	1.64336-082
10	9.79097+002	9.77218+002	9.78757+002	1.03959-004	3.67686-054
11	9.47580+002	9.46071+002	9.47315+002	1.02275-004	3.50818-001
12	9.15709+002	9.14401+002	9.15494+002	1.01000-004	6.42883-001
13	8.82163+002	8.81018+002	8.82137+002	1.00401-004	8.22011-001

T = 50

L = 358.4448

WS= 16143.42

F(T) = 0.0367

ZONE	TA	TC	TG	RO=RI	X
1	7.93565+002	7.94911+002	7.93801+002	1.00000-004	0.00000+000
2	7.80305+002	7.81562+002	7.80521+002	1.00000-004	0.00000+000
3	7.67058+002	7.68229+002	7.67255+002	1.00000-004	0.00000+000
4	7.55474+002	7.56570+002	7.55655+002	1.00000-004	8.07200-170
5	7.43900+002	7.44922+002	7.44065+002	1.00000-004	2.15781-157
6	7.32334+002	7.33284+002	7.32485+002	1.00000-004	1.18572-144
7	7.20776+002	7.21655+002	7.20913+002	1.00000-004	4.03855-133

8	7.09309+002	7.10118+002	7.09432+002	1.00000-004	3.25422-120
9	6.98434+002	6.99175+002	6.98545+002	1.00000-004	9.01697-100
10	6.89270+002	6.89954+002	6.89370+002	1.00000-004	4.43252-071
11	6.79898+002	6.80692+002	6.80012+002	1.00000-004	3.50786-001
12	6.70126+002	6.70955+002	6.70282+002	1.00000-004	6.42868-001
13	6.59840+002	6.60642+002	6.60592+002	1.00000-004	8.22005-001

T = 50

AVE. THICKNESS CAN REACTED = 8.05245-004

FRACTION CAN REACTED = 5.19849-003

AVE. THICKNESS CLAD REACTED = 8.05245-004

FRACTION CLAD REACTED = 1.30463-002

FRACTION H2 IN GAS LEAVING = 8.60334-001

ENERGY H2 LEAVING = 5.63063+006

ENERGY ABOVE TGO = 2.61605+005

ACCUMULATED H2 RELEASED = 5.64498+003

BOTTOM PLATE TEMPERATURE = 5.59566+002

TOP TEMPERATURE = 5.58676+002

WALL TEMPERATURE = 5.59961+002

AVERAGE FUEL TEMPERATURE = 1.32062+003

FRACTION FUEL REMAINING = 1.00000+000

FRACTION FUEL SLUMPED = 0.00000+000

T = 100

L = 7.3152

WS= 11877.05

F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	7.46886+002	7.41562+002	6.75462+002	1.00011-004	9.99999-001
2	7.34836+002	7.29740+002	6.65904+002	1.00007-004	1.00000+000
3	7.22813+002	7.17943+002	6.56367+002	1.00004-004	1.00000+000
4	7.12308+002	7.07635+002	6.48034+002	1.00003-004	1.00000+000
5	7.01821+002	6.97343+002	6.39714+002	1.00002-004	1.00000+000
6	6.91350+002	6.87066+002	6.31407+002	1.00001-004	1.00000+000
7	6.80894+002	6.76803+002	6.23111+002	1.00001-004	1.00000+000
8	6.70452+002	6.66553+002	6.14826+002	1.00000-004	1.00000+000
9	6.60027+002	6.56319+002	6.06553+002	1.00000-004	1.00000+000
10	6.51094+002	6.47549+002	5.99465+002	1.00000-004	1.00000+000
11	6.42174+002	6.38792+002	5.92387+002	1.00000-004	1.00000+000
12	6.33262+002	6.30041+002	5.85314+002	1.00000-004	1.00000+000
13	6.23988+002	6.20936+002	5.77951+002	1.00000-004	1.00000+000

T = 100

L = 51.2064

WS= 11877.05

F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	1.46765+003	1.47777+003	1.47207+003	1.69409-003	8.23069-001
2	1.37681+003	1.37780+003	1.37705+003	1.08099-003	9.07429-001
3	1.30548+003	1.30273+003	1.30310+003	7.24841-004	9.46290-001
4	1.25342+003	1.24927+003	1.25017+003	5.18395-004	9.64693-001
5	1.20588+003	1.20102+003	1.20221+003	3.72714-004	9.76736-001
6	1.16105+003	1.15587+003	1.15716+003	2.70093-004	9.84986-001
7	1.11804+003	1.11277+003	1.11404+003	1.99687-004	9.90717-001
8	1.07637+003	1.07118+003	1.07231+003	1.53892-004	9.94650-001
9	1.03572+003	1.03075+003	1.03165+003	1.26520-004	9.97209-001
10	1.00135+003	9.96644+002	9.97289+002	1.13336-004	9.98548-001
11	9.67344+002	9.62963+002	9.63312+002	1.06255-004	9.99307-001
12	9.33514+002	9.29489+002	9.29523+002	1.02743-004	9.99695-001

13 8.96755+002 8.93144+002 8.92788+002 1.01062-004 9.99886-001

T = 100
L = 95.0976
WS = 11877.05
F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	2.27974+003	2.26935+003	2.27480+003	1.01044-002	0.00000+000
2	2.25583+003	2.24599+003	2.25161+003	1.14556-002	0.00000+000
3	2.20481+003	2.19637+003	2.20295+003	1.14197-002	0.00000+000
4	2.14330+003	2.13264+003	2.13924+003	1.15931-002	0.00000+000
5	2.09706+003	2.09580+003	2.09350+003	1.17688-002	0.00000+000
6	1.93898+003	2.01483+003	1.96492+003	9.20434-003	0.00000+000
7	1.67615+003	1.74153+003	1.69891+003	4.45756-003	2.01023-001
8	1.50512+003	1.52159+003	1.51108+003	2.18552-003	7.14839-001
9	1.39328+003	1.39747+003	1.39442+003	1.23847-003	8.57648-001
10	1.31559+003	1.31550+003	1.31523+003	7.80236-004	9.16648-001
11	1.24669+003	1.24447+003	1.24557+003	4.94132-004	9.51344-001
12	1.18296+003	1.17968+003	1.18141+003	3.13942-004	9.72800-001
13	1.11507+003	1.11129+003	1.11311+003	1.96933-004	9.87418-001

T = 100
L = 138.9888
WS = 11877.05
F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	2.20265+003	2.19007+003	2.19852+003	1.00000-004	0.00000+000
2	2.12178+003	2.11062+003	2.11816+003	1.00042-004	0.00000+000
3	2.04739+003	2.03794+003	2.04439+003	2.41392-004	0.00000+000
4	2.03832+003	2.03053+003	2.03642+003	7.69924-004	0.00000+000
5	2.05556+003	2.04719+003	2.05260+003	3.61114-003	0.00000+000
6	2.04913+003	2.03998+003	2.04518+003	5.98166-003	0.00000+000
7	1.98472+003	1.97626+003	1.98140+003	6.05296-003	0.00000+000
8	1.91290+003	1.90528+003	1.91019+003	6.25656-003	0.00000+000
9	1.83974+003	1.83106+003	1.83634+003	6.45043-003	0.00000+000
10	1.67346+003	1.73892+003	1.69481+003	4.49867-003	0.00000+000
11	1.50075+003	1.51822+003	1.50618+003	2.15799-003	5.91395-001
12	1.38466+003	1.38969+003	1.38603+003	1.17730-003	7.96819-001
13	1.27648+003	1.27591+003	1.27587+003	6.16072-004	9.06891-001

T = 100
L = 182.8800
WS = 11877.05
F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	2.32325+003	2.31098+003	2.31913+003	1.00000-004	0.00000+000
2	2.22652+003	2.21470+003	2.22246+003	1.00000-004	0.00000+000
3	2.12977+003	2.11850+003	2.12588+003	1.00000-004	0.00000+000
4	2.04468+003	2.03398+003	2.04098+003	1.00000-004	0.00000+000
5	1.96096+003	1.95105+003	1.95760+003	1.00000-004	0.00000+000
6	1.89104+003	1.88236+003	1.88817+003	3.02143-004	0.00000+000
7	1.87045+003	1.86306+003	1.86814+003	1.19130-003	0.00000+000
8	1.84117+003	1.83348+003	1.83836+003	2.83097-003	0.00000+000
9	1.76665+003	1.75962+003	1.76420+003	3.03423-003	0.00000+000
10	1.69904+003	1.69257+003	1.69682+003	3.18187-003	0.00000+000
11	1.62992+003	1.62380+003	1.62796+003	3.29977-003	0.00000+000
12	1.48891+003	1.50639+003	1.49399+003	2.03293-003	3.33275-001
13	1.34918+003	1.35264+003	1.34960+003	9.74629-004	7.27902-001

T = 100
 L = 226.7712
 WS = 11877.05
 F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	2.22819+003	2.21782+003	2.22465+003	1.00000-004	0.00000+000
2	2.13630+003	2.12636+003	2.13288+003	1.00000-004	0.00000+000
3	2.04441+003	2.03496+003	2.04115+003	1.00000-004	0.00000+000
4	1.96352+003	1.95453+003	1.96043+003	1.00000-004	0.00000+000
5	1.88264+003	1.87416+003	1.87977+003	1.00000-004	0.00000+000
6	1.80182+003	1.79390+003	1.79920+003	1.00000-004	0.00000+000
7	1.72682+003	1.71957+003	1.72452+003	1.70037-004	0.00000+000
8	1.68232+003	1.67589+003	1.68022+003	8.53651-004	0.00000+000
9	1.61593+003	1.61002+003	1.61408+003	1.14123-003	0.00000+000
10	1.55061+003	1.54520+003	1.54897+003	1.22915-003	0.00000+000
11	1.48412+003	1.47919+003	1.48268+003	1.30050-003	0.00000+000
12	1.41438+003	1.41870+003	1.41552+003	1.35279-003	0.00000+000
13	1.29778+003	1.29974+003	1.29785+003	7.00821-004	5.57080-001

T = 100
 L = 270.6624
 WS = 11877.05
 F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	1.92583+003	1.91866+003	1.92350+003	1.00000-004	0.00000+000
2	1.84993+003	1.84313+003	1.84774+003	1.00000-004	0.00000+000
3	1.77408+003	1.76768+003	1.77206+003	1.00000-004	0.00000+000
4	1.70748+003	1.70143+003	1.70560+003	1.00000-004	0.00000+000
5	1.64091+003	1.63524+003	1.63919+003	1.00000-004	0.00000+000
6	1.57430+003	1.56900+003	1.57274+003	1.00000-004	0.00000+000
7	1.50768+003	1.50277+003	1.50629+003	1.00000-004	0.00000+000
8	1.44241+003	1.43792+003	1.44119+003	1.14662-004	0.00000+000
9	1.38679+003	1.38278+003	1.38574+003	2.85281-004	0.00000+000
10	1.33158+003	1.32791+003	1.33065+003	3.14559-004	0.00000+000
11	1.27565+003	1.27230+003	1.27484+003	3.34569-004	0.00000+000
12	1.21943+003	1.21639+003	1.21872+003	3.54971-004	0.00000+000
13	1.14713+003	1.14610+003	1.14668+003	2.41328-004	4.87977-001

T = 100
 L = 314.5536
 WS = 11877.05
 F(T) = 0.0310

ZONE	TA	TC	TG	RO-RI	X
1	1.44753+003	1.44468+003	1.44689+003	1.00000-004	0.00000+000
2	1.39766+003	1.39496+003	1.39706+003	1.00000-004	0.00000+000
3	1.34787+003	1.34531+003	1.34730+003	1.00000-004	0.00000+000
4	1.30427+003	1.30185+003	1.30374+003	1.00000-004	0.00000+000
5	1.26071+003	1.25843+003	1.26022+003	1.00000-004	0.00000+000
6	1.21718+003	1.21503+003	1.21673+003	1.00000-004	0.00000+000
7	1.17366+003	1.17165+003	1.17325+003	1.00000-004	0.00000+000
8	1.13028+003	1.12842+003	1.12991+003	1.00284-004	0.00000+000
9	1.08786+003	1.08616+003	1.08753+003	1.03061-004	0.00000+000
10	1.05131+003	1.04973+003	1.05101+003	1.03959-004	0.00000+000
11	1.01477+003	1.01331+003	1.01450+003	1.04735-004	0.00000+000
12	9.78176+002	9.76838+002	9.77936+002	1.05591-004	0.00000+000
13	9.37391+002	9.36374+002	9.37137+002	1.02794-004	4.79845-001

T = 100

L = 358.4448
 WS = 11877.05
 F(T) = 0.0310

ZONE	TA	TC	TG	RO=RI	X
1	8.46308+002	8.47485+002	8.46542+002	1.00000-004	0.00000+000
2	8.30009+002	8.31106+002	8.30220+002	1.00000-004	0.00000+000
3	8.13743+002	8.14762+002	8.13933+002	1.00000-004	0.00000+000
4	7.99526+002	8.00478+002	7.99699+002	1.00000-004	0.00000+000
5	7.85331+002	7.86218+002	7.85488+002	1.00000-004	0.00000+000
6	7.71154+002	7.71977+002	7.71296+002	1.00000-004	0.00000+000
7	7.56995+002	7.57755+002	7.57123+002	1.00000-004	0.00000+000
8	7.42936+002	7.43635+002	7.43050+002	1.00000-004	0.00000+000
9	7.29477+002	7.30116+002	7.29579+002	1.00000-004	0.00000+000
10	7.18095+002	7.18684+002	7.18187+002	1.00000-004	0.00000+000
11	7.06724+002	7.07265+002	7.06807+002	1.00000-004	0.00000+000
12	6.95350+002	6.95842+002	6.95423+002	1.00001-004	0.00000+000
13	6.83028+002	6.83622+002	6.83102+002	1.00000-004	4.79807-001

T = 100
 AVE. THICKNESS CAN REACTED = 1.37780-003
 FRACTION CAN REACTED = 8.89479-003
 AVE. THICKNESS CLAD REACTED = 1.37780-003
 FRACTION CLAD REACTED = 2.23227-002
 FRACTION H2 IN GAS LEAVING = 9.63092-001
 ENERGY H2 LEAVING = 4.63735+006
 ENERGY ABOVE TGO = 2.10631+005
 ACCUMULATED H2 RELEASED = 1.00200+004
 BOTTOM PLATE TEMPERATURE = 5.61243+002
 TOP TEMPERATURE = 5.59697+002
 WALL TEMPERATURE = 5.63059+002
 AVERAGE FUEL TEMPERATURE = 1.45291+003
 FRACTION FUEL REMAINING = 1.00000+000
 FRACTION FUEL SLUMPED = 0.00000+000

T = 150
 L = 7.3152
 WS = 9833.84
 F(T) = 0.0277

ZONE	TA	TC	TG	RO=RI	X
1	7.53553+002	7.48738+002	7.01093+002	1.00019-004	9.99999-001
2	7.40569+002	7.35968+002	6.90045+002	1.00012-004	9.99999-001
3	7.27635+002	7.23246+002	6.79039+002	1.00007-004	1.00000+000
4	7.16347+002	7.12142+002	6.69433+002	1.00005-004	1.00000+000
5	7.05090+002	7.01068+002	6.59854+002	1.00003-004	1.00000+000
6	6.93860+002	6.90019+002	6.50298+002	1.00002-004	1.00000+000
7	6.82655+002	6.78994+002	6.40762+002	1.00001-004	1.00000+000
8	6.71474+002	6.67992+002	6.31246+002	1.00001-004	1.00000+000
9	6.60320+002	6.57016+002	6.21754+002	1.00000-004	1.00000+000
10	6.50766+002	6.47613+002	6.13622+002	1.00000-004	1.00000+000
11	6.41232+002	6.38230+002	6.05507+002	1.00000-004	1.00000+000
12	6.31710+002	6.28858+002	5.97402+002	1.00000-004	1.00000+000
13	6.21682+002	6.18989+002	5.88863+002	1.00000-004	1.00000+000

T = 150
 L = 51.2064
 WS = 9833.84
 F(T) = 0.0277

ZONE	TA	TC	TG	RO=RI	X
1	1.87791+003	1.96913+003	1.91126+003	8.21139-003	0.00000+000

2	1.62404+003	1.66854+003	1.64151+003	3.61582-003	4.40684-001
3	1.46931+003	1.48046+003	1.47535+003	1.83578-003	8.00176-001
4	1.37057+003	1.37226+003	1.37248+003	1.13752-003	9.01921-001
5	1.29512+003	1.29314+003	1.29452+003	7.54496-004	9.45734-001
6	1.23567+003	1.23231+003	1.23411+003	5.14606-004	9.66830-001
7	1.18293+003	1.17897+003	1.18099+003	3.54397-004	9.79466-001
8	1.13377+003	1.12958+003	1.13167+003	2.47286-004	9.87620-001
9	1.08692+003	1.08272+003	1.08475+003	1.78399-004	9.92977-001
10	1.04785+003	1.04377+003	1.04565+003	1.41799-004	9.96028-001
11	1.00969+003	1.00581+003	1.00749+003	1.20382-004	9.97968-001
12	9.72039+002	9.68425+002	9.69848+002	1.09074-004	9.99070-001
13	9.29670+002	9.26416+002	9.27445+002	1.03375-004	9.99663-001

T = 150
L = 95.0976
WS = 9833.84
F(T) = 0.0277

ZONE	TA	TC	TG	RO-RI	X
1	2.40213+003	2.39341+003	2.39818+003	1.01044-002	0.00000+000
2	2.37078+003	2.36187+003	2.36646+003	1.14556-002	0.00000+000
3	2.32983+003	2.32114+003	2.32602+003	1.14197-002	0.00000+000
4	2.27108+003	2.26323+003	2.26829+003	1.15931-002	0.00000+000
5	2.20118+003	2.19494+003	2.20042+003	1.17688-002	0.00000+000
6	2.12683+003	2.11882+003	2.12415+003	1.19461-002	0.00000+000
7	2.07593+003	2.08106+003	2.07454+003	1.21304-002	0.00000+000
8	1.88396+003	1.95325+003	1.90759+003	8.59289-003	0.00000+000
9	1.59299+003	1.62617+003	1.60502+003	3.45281-003	4.84347-001
10	1.44684+003	1.45569+003	1.44999+003	1.82210-003	7.86092-001
11	1.34731+003	1.34918+003	1.34786+003	1.06182-003	8.87931-001
12	1.26506+003	1.26402+003	1.26466+003	6.30705-004	9.38921-001
13	1.17786+003	1.17526+003	1.17673+003	3.47742-004	9.72094-001

T = 150
L = 138.9888
WS = 9833.84
F(T) = 0.0277

ZONE	TA	TC	TG	RO-RI	X
1	2.37539+003	2.36467+003	2.37208+003	1.00000-004	0.00000+000
2	2.29077+003	2.28120+003	2.28779+003	1.00042-004	0.00000+000
3	2.21336+003	2.20521+003	2.21085+003	2.41392-004	0.00000+000
4	2.20447+003	2.19707+003	2.20252+003	7.69924-004	0.00000+000
5	2.19934+003	2.19161+003	2.19660+003	3.61114-003	0.00000+000
6	2.17243+003	2.16433+003	2.16896+003	5.98166-003	0.00000+000
7	2.10492+003	2.09737+003	2.10192+003	6.05296-003	0.00000+000
8	2.02670+003	2.01970+003	2.02396+003	6.25656-003	0.00000+000
9	1.94813+003	1.94165+003	1.94564+003	6.45043-003	0.00000+000
10	1.87694+003	1.87129+003	1.87532+003	6.62363-003	0.00000+000
11	1.79971+003	1.81964+003	1.80561+003	6.65943-003	0.00000+000
12	1.56745+003	1.59546+003	1.57653+003	3.18247-003	3.77947-001
13	1.38092+003	1.38525+003	1.38164+003	1.32648-003	7.93926-001

T = 150
L = 182.8800
WS = 9833.84
F(T) = 0.0277

ZONE	TA	TC	TG	RO-RI	X
1	2.50503+003	2.49455+003	2.50166+003	1.00000-004	0.00000+000
2	2.40008+003	2.38990+003	2.39669+003	1.00000-004	0.00000+000
3	2.29515+003	2.28536+003	2.29181+003	1.00000-004	0.00000+000

4	2.20276+003	2.19339+003	2.19953+003	1.00000-004	0.00000+000
5	2.11293+003	2.10425+003	2.10998+003	1.00000-004	0.00000+000
6	2.03835+003	2.03073+003	2.03582+003	3.02143-004	0.00000+000
7	2.01164+003	2.00476+003	2.00937+003	1.19130-003	0.00000+000
8	1.96575+003	1.95881+003	1.96314+003	2.83097-003	0.00000+000
9	1.88375+003	1.87738+003	1.88145+003	3.03423-003	0.00000+000
10	1.80848+003	1.80259+003	1.80637+003	3.18187-003	0.00000+000
11	1.73233+003	1.72696+003	1.73045+003	3.29977-003	0.00000+000
12	1.65485+003	1.64999+003	1.65313+003	3.42005-003	0.00000+000
13	1.49092+003	1.50625+003	1.49460+003	2.34111-003	3.11120-001

T = 150
L = 226.7712
WS = 9833.84
F(T) = 0.0277

ZONE	TA	TC	TG	RO-RI	X
1	2.40651+003	2.39760+003	2.40355+003	1.00000-004	0.00000+000
2	2.30627+003	2.29765+003	2.30333+003	1.00000-004	0.00000+000
3	2.20599+003	2.19772+003	2.20313+003	1.00000-004	0.00000+000
4	2.11732+003	2.10939+003	2.11455+003	1.00000-004	0.00000+000
5	2.02867+003	2.02113+003	2.02604+003	1.00000-004	0.00000+000
6	1.94016+003	1.93308+003	1.93773+003	1.00000-004	0.00000+000
7	1.85822+003	1.85172+003	1.85608+003	1.70037-004	0.00000+000
8	1.80491+003	1.79908+003	1.80291+003	8.53651-004	0.00000+000
9	1.73042+003	1.72507+003	1.72866+003	1.14123-003	0.00000+000
10	1.65777+003	1.65285+003	1.65619+003	1.22915-003	0.00000+000
11	1.58387+003	1.57939+003	1.58248+003	1.30050-003	0.00000+000
12	1.50847+003	1.50443+003	1.50725+003	1.35803-003	0.00000+000
13	1.41560+003	1.41335+003	1.41433+003	1.52656-003	0.00000+000

T = 150
L = 270.6624
WS = 9833.84
F(T) = 0.0277

ZONE	TA	TC	TG	RO-RI	X
1	2.08237+003	2.07608+003	2.08032+003	1.00000-004	0.00000+000
2	1.99853+003	1.99253+003	1.99657+003	1.00000-004	0.00000+000
3	1.91475+003	1.90907+003	1.91291+003	1.00000-004	0.00000+000
4	1.84095+003	1.83556+003	1.83922+003	1.00000-004	0.00000+000
5	1.76720+003	1.76213+003	1.76560+003	1.00000-004	0.00000+000
6	1.69334+003	1.68859+003	1.69188+003	1.00000-004	0.00000+000
7	1.61947+003	1.61506+003	1.61815+003	1.00000-004	0.00000+000
8	1.54728+003	1.54327+003	1.54614+003	1.14662-004	0.00000+000
9	1.48455+003	1.48094+003	1.48355+003	2.85281-004	0.00000+000
10	1.42292+003	1.41961+003	1.42204+003	3.14559-004	0.00000+000
11	1.36052+003	1.35751+003	1.35975+003	3.34569-004	0.00000+000
12	1.29757+003	1.29483+003	1.29689+003	3.54971-004	0.00000+000
13	1.22178+003	1.21928+003	1.22089+003	4.07864-004	0.00000+000

T = 150
L = 314.5536
WS = 9833.84
F(T) = 0.0277

ZONE	TA	TC	TG	RO-RI	X
1	1.56056+003	1.55811+003	1.56005+003	1.00000-004	0.00000+000
2	1.50438+003	1.50204+003	1.50388+003	1.00000-004	0.00000+000
3	1.44832+003	1.44611+003	1.44785+003	1.00000-004	0.00000+000
4	1.39919+003	1.39709+003	1.39874+003	1.00000-004	0.00000+000
5	1.35015+003	1.34817+003	1.34973+003	1.00000-004	0.00000+000

6	1.30114+003	1.29927+003	1.30075+003	1.00000-004	0.00000+000
7	1.25215+003	1.25040+003	1.25179+003	1.00000-004	0.00000+000
8	1.20332+003	1.20170+003	1.20299+003	1.00284-004	0.00000+000
9	1.15559+003	1.15411+003	1.15530+003	1.03061-004	0.00000+000
10	1.11431+003	1.11293+003	1.11405+003	1.03959-004	0.00000+000
11	1.07308+003	1.07180+003	1.07284+003	1.04735-004	0.00000+000
12	1.03174+003	1.03057+003	1.03152+003	1.05591-004	0.00000+000
13	9.84066+002	9.83005+002	9.83775+002	1.07872-004	0.00000+000

T = 150
 L = 358.4448
 WS = 9833.84
 F(T) = 0.0277

ZONE	TA	TC	TG	RO=RI	X
1	8.93127+002	8.94290+002	8.93383+002	1.00000-004	0.00000+000
2	8.74074+002	8.75155+002	8.74303+002	1.00000-004	0.00000+000
3	8.55083+002	8.56085+002	8.55287+002	1.00000-004	0.00000+000
4	8.38497+002	8.39432+002	8.38681+002	1.00000-004	0.00000+000
5	8.21952+002	8.22821+002	8.22117+002	1.00000-004	0.00000+000
6	8.05441+002	8.06246+002	8.05589+002	1.00000-004	0.00000+000
7	7.88962+002	7.89705+002	7.89094+002	1.00000-004	0.00000+000
8	7.72596+002	7.73279+002	7.72714+002	1.00000-004	0.00000+000
9	7.56844+002	7.57468+002	7.56949+002	1.00000-004	0.00000+000
10	7.43493+002	7.44068+002	7.43587+002	1.00000-004	0.00000+000
11	7.30167+002	7.30693+002	7.30251+002	1.00000-004	0.00000+000
12	7.16841+002	7.17319+002	7.16915+002	1.00001-004	0.00000+000
13	7.02396+002	7.02824+002	7.02447+002	1.00001-004	0.00000+000

T = 150
 AVE. THICKNESS CAN REACTED = 1.86146-003
 FRACTION CAN REACTED = 1.20172-002
 AVE. THICKNESS CLAD REACTED = 1.86146-003
 FRACTION CLAD REACTED = 3.01588-002
 FRACTION H2 IN GAS LEAVING = 1.00000+000
 ENERGY H2 LEAVING = 3.98673+006
 ENERGY ABOVE TGO = 1.89159+005
 ACCUMULATED H2 RELEASED = 1.37137+004
 BOTTOM PLATE TEMPERATURE = 5.62907+002
 TOP TEMPERATURE = 5.61009+002
 WALL TEMPERATURE = 5.67381+002
 AVERAGE FUEL TEMPERATURE = 1.56580+003
 FRACTION FUEL REMAINING = 1.00000+000
 FRACTION FUEL SLUMPED = 0.00000+000

APPENDIX F--Program Readout of Input Data for an Assumed 3300-MW(t) BWR Core

DATA

NTAB 24	NPRINT 5	NJP 1	NJ 25	LASTZ 13	ELT 3.65740+002	DELT 5.00000+000	TMAX 5.00000+003	OD 4.76200+001
CPAA	CPAB	CPBA	CPBB	CPMA	CPMB	CPMA	CPMB	CPMB
6.80000+002	7.50000+006	1.00000+001	4.00000+005	7.49000+002	1.22700+005	1.45000+001	3.00000+000	6.57000+000
CPSA	CPSB	KAA	KAB	KAC	KCA	KCB	KHA	KHB
7.96000+000	2.56000+003	1.30000+002	-7.05000+006	1.40000+000	-6.70000+003	5.70000+005	1.10000+003	7.50000+001
KSA	KSB	DGA	DGB	GCA	GCB	CAY	DELE	SIG
-2.00000+005	2.00000+004	7.30000+000	1.75000+000	1.01000+003	-6.15000+002	3.93700+001	4.55000+004	1.37000+012
TBA	TBZ	TGO	TTA	ITZ	TWA	TWZ	V2	V3
5.58000+002	5.58000+002	4.00000+002	5.58000+002	5.58000+002	5.58000+002	5.58000+002	3.61000+002	3.14000+002
AA	AC	ALFA	VK	VA	RD	RZERO	RF	V6
1.20669+000	7.37200+001	2.15900+001	1.09230+000	1.20669+000	7.13740+001	1.00000+004	6.32460+001	3.74360+004
AN	CAS	DF	FLS	FF	FRF	KAM	SF	TAM
4.00000+000	2.00000+000	1.00000+001	4.00000+000	6.00000+001	9.50000+001	2.00000+000	5.00000+001	2.47300+003
WA	WB	WC	WTP	WW	RHNC	A1	A2	A4
1.23082+001	1.80410+007	4.43510+000	8.33100+006	2.43300+007	6.40000+000	2.88000+005	2.50000+001	7.00000+004
HAC	U	UB	UT	UW	VS	VM5	EPS	A
1.90000+001	1.00000+000	1.65000+002	1.65000+002	1.65000+002	8.30000+000	8.30000+000	4.30000+001	5.00000+001

F1

1.3600	1.3000	1.2500	1.2000	1.1500	1.0900	1.0200	0.9500	0.8700	0.8400
0.8300	0.6000	0.5400							

TTAB

TTAB	FTAB
1	0.0480
3	0.0470
5	0.0460
10	0.0450
20	0.0430
40	0.0410
60	0.0390
100	0.0360
150	0.0340
200	0.0320
300	0.0290
400	0.0275
500	0.0260
600	0.0250
800	0.0235
1000	0.0220
1500	0.0200
2000	0.0187
3000	0.0170
4000	0.0160
5000	0.0150
6000	0.0145
8000	0.0133
10000	0.0125

SINZB

0.2300	0.3750	0.5350	0.6650	0.8300	0.9700	1.0900	1.2000	1.3200	1.3900
1.4700	1.5200	1.5500	1.5200	1.4600	1.3700	1.2800	1.1800	1.0700	0.9600
0.8450	0.7250	0.6000	0.4750	0.3500					

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U.S. ATOMIC ENERGY COMMISSION
MAJOR CONTRACTOR'S RECOMMENDATION FOR
DISPOSITION OF SCIENTIFIC AND TECHNICAL DOCUMENT

(See Instructions on Reverse Side)

1. AEC REPORT NO.
ANL-73612. SUBJECT CATEGORY NO.
UC-803. TITLE CHEMLOC-II: A Computer Program Describing the Core
Heating and Cladding-Steam Reaction for a Water-cooled
Power Reactor following a Loss of Coolant

4. TYPE OF DOCUMENT (Check one):

- ☒ a. Scientific and technical report.
- ☐ b. Conference paper not to be published in a journal:
Title of conference _____
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