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A DYNAMIC PROGRAM FOR BOILING COOLING CHANNELS

by

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Joint Nuclear Research Center
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Reactor Physics Departement
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ABSTRACT

The Fortran program FRANCESCA for IBM 360 is a dynamic code for boiling channels. The physical model is one-dimensional, and includes subcooled boiling and optionally superheating of the liquid in the bulk boiling zone.

The finite difference method of calculation is employed, with up to 100 mesh points in the active part of the channel and 10 more points in the riser. The program is intended for forced circulation and highly pressurized systems, for which the pressure drop in the channel may be considered negligible compared to the general pressure level, so that the coolant fluid properties may be assumed independent of space and time. The driving pressure may be taken as a quadratic function of the mass flow, to simulate pump characteristics, or given as a time table. The power distribution in the heating element is given as a fixed arbitrary shape, while the power level is any tabulated function of the time.

KEYWORDS

F-CODES
FORTRAN
BOILING
COOLANT LOOPS
FORCED CONVECTION
PRESSURE

Contents

Nomenclature

Latin letters

A Coolant channel cross section

C Thermal capacity in heating elements

C_p Liquid coolant specific heat

G Momentum of the fluid per unit cross section

h_c Heat transfer coefficient from heating surface to coolant--convective

h' Coefficient in boiling heat transfer mechanism = $h'Tsur^n$

I Inertia of the channel (cm)

H Enthalpy of the liquid (saturation taken as 0)

K Heat conductivity among regions in the heating element

K_f Friction coefficient

k Bankoff's slip coefficient

p Heating perimeter

q_l Liquid volume velocity (flow per unit area)

q_v Vapour volume velocity

Q Heating power addition to the coolant

R Recondansation (or vaporization)constant

R_f Two phase flow friction multiplier

T Temperature (difference from saturation temperature taken as 0)

w Total volume velocity (flow per unit cross section)

Z Height of the channel

Greek letters

α Void fraction

γ Vapour/liquid density ratio

λ Latent heat of vaporization

μ Viscosity

ρ Density of the liquid coolant

ϕ Heat flux

ϕ_c Convective heat flux

ϕ_b Boiling heat flux

χ Martinelli parameter

Ψ Vapour volume source $cm^3/cm^3 sec$

Ψ_s Vapour volume source originated at the heating surface

Ψ_b Vapour volume source in the bulk of the fluid

Δp Pressure drop

Δp_g Gravity pressure drop

Δp_f Friction pressure drop

Δp_{as} Space acceleration pressure drop

Δp_{ad} Dynamic acceleration pressure drop

Indexes

i Radial index in the heating element

j Axial index along the channel

* Variable values for the preceeding time step

FRANCESCA

A dynamic programme for boiling cooling channels

1) Purpose (*)

The code FRANCESCA, written in FORTRAN for IBM-360, performs the dynamic calculations for boiling channels according to a one dimensional model which is illustrated in ref. 1. The model includes subcooled boiling and overheating of the liquid.

The channel is represented by a heating element (geometry is chosen among cylindrical, slab, and a general geometry) where power is generated according to a given law, and transmitted to the coolant through a gap and a cladding. The coolant is represented as a one dimensional flow of pure liquid or liquid and vapour, according to the existing conditions. The relative equations are discretized and treated by the backwards difference method (up to 100 mesh points). An adiabatic riser is represented by the same method (up to 10 mesh points). Direct production of heat in the coolant is allowed for in the active part of the channel; the pressure drop along the channel and riser is calculated using empirical formulae for two phase pressure drop friction multipliers. The inlet flow of the coolant may be assumed as given or calculated at all times according to the pressure drop and a given driving force law.

The code is intended for highly pressured channels with forced circulations; therefore the saturation temperature of the coolant and all its physical constants are assumed to be independent of space and time.

2) Working equations and their finite differences form

a) Heat transmission in the power generating element.

The poisson equations is discretized in the following way at each level of the channel:

(*) Manuscript received on 27 November 1969.

$$C_i \frac{dT_{i,j}}{dt} = Pow_{ij} + K_{i-1,j}\,(T_{i-1,j} - T_{i,j}) - K_{i,j}\,(T_{i,j} - T_{i+1,j})$$

up to 10 points are admitted in the heat generating element, besides one for the inner surface of the cladding and one for the outer surface in contact with the coolant. The equation for the external surface is given by

$$1/2\ Ccl_j \frac{dT_{sur\,j}}{dt} = K_{cl\,j}\,(Ticl_j - T_{sur_j}) - P\phi_j$$

b) Heat transmission to coolant.

In the following equations the saturation temperature T_{sat} is taken as zero. The relevant equations are (see ref. 1).

(1) $\phi = \phi_c + \phi_b$

$$(2)\quad \begin{cases} \left.\begin{array}{l} \phi_c = h_c(T_{sur} - T_{liquid}) \\ \phi_b = 0 \end{array}\right\} \text{for } T_{sur}^2 < \theta(T_{sur} - T_{liquid}) \\ \left.\begin{array}{l} \phi_c = [h_c(T_c - T_{liquid}) - h' T_c^n](1 - \frac{T_{sur} - T_c}{\theta_f - \theta}) \geq 0 \\ \phi_b = h' T_{sur}^n \end{array}\right\} \text{for } T_{sur}^2 \geq \theta(T_{sur} - T_{liquid}) \\ \text{with } T_c = \frac{\theta}{2}(1 + \sqrt{1 - 4\frac{T_{liquid}}{\theta}}) \text{ and } \theta_f = 1.4^{1/n} (\frac{h_c}{h'})^{\frac{1}{n-1}} \end{cases}$$

c) Flow and energy equations into the coolant (see ref. 1).

(3) $Q = \frac{P}{A}\phi + Q\ direct$

(4) $\Psi = \Psi_s + \Psi_b$

(5) $\Psi_s = \tau \frac{P}{A} \frac{\phi_b}{\rho\gamma\lambda}$

(6) $\Psi_b = R\alpha T_{liquid}$ with $R = R_1$ for $T_{liquid} < 0$

$R = R_2$ for $T_{liquid} > 0$

$= \frac{Q}{\rho\gamma\lambda}$ for $R_2 = \infty, T_{liquid} = 0$ (no overheating of the liquid)

(7) $\frac{\partial w}{\partial Z} = (1-\gamma)\Psi$

(8) $\frac{\partial \alpha}{\partial t} = \Psi - \frac{\partial q}{\partial Z}$

(9) $q_v = \frac{\alpha}{K} w - \frac{Z_e}{K} \Psi_s$

(10) $q_l = w - q_v$

(11) $\frac{\partial}{\partial t}[(1-\alpha)H] = \frac{Q}{\rho} - \gamma\lambda\Psi - \frac{\partial}{\partial Z}(q_l H)$

(12) $H = C_p T_{liquid}$

d) Momentum equations (see Ref.1).

(13) $G = \rho q_l + \gamma \rho q_v$

(14) $I \frac{dG_{inlet}}{dt} = \Delta P_{driving} - \Delta P_{drop}$

15) $\Delta p_{drop} = \Delta p_g + \Delta p_f + \Delta p_{as} + \Delta p_{ad}$

16) $\Delta p_g = g_\rho Z$

17) $\Delta p_f = \int R_f K_f \rho \frac{1}{2} \left(\frac{G}{\rho}\right)^2 dZ$

(This integral must be thought as a general integral, as it may include local friction, as well as distributed friction)

18) $\Delta p_{ad} = \int \frac{\partial}{\partial t} (G-G_{in}) dZ$

e) Dicretization.

To pass to finite differences form, the method chosen is the backwards differences in space as well as in time.

The algebric equations given are taken as they stand, with all the variables referring to the actual time, except for the equation expressing ϕ_c in group (2) and ϕ_b in group (6) where the temperature of the liquid T^*_{liquid} and the void fraction α^* are taken from the preceding time step.

The differential equations (7, 8, 11) are written (always indicating by a star the values at the preceding time step).

$$w_j = (1-\gamma) \Delta Z \quad w_{j-1}$$

$$\alpha_j = \alpha^*_j + \Delta t \; \Psi_j - \frac{\Delta t}{\Delta Z} \frac{\Psi_j}{K} \alpha_j + \frac{\Delta t}{\Delta Z} \frac{Z_e}{K} \Psi s_j + \frac{\Delta t}{\Delta Z} q_{v\,j-1}$$

$$(1-\alpha_j)H_j = ((1-\alpha_j)H_j)^* + \frac{\Delta t}{\rho} Q_j - \Delta t \, \gamma \lambda \Psi_j - \frac{\Delta t}{\Delta Z} q_{1j} H_j + \frac{\Delta t}{\Delta Z} q_{1j-1} H_{j-1}$$

In the equation for α, the value of q_v is substituted from equation (9).

The set of equations for heat transmission are then diagonalized by forward elimination and backwards substitution. When the heat transmission is convective $(T_{sur\,j}^2 < \theta(T_{sur\,j} - T_{liquid\,j})$;

the resulting equations are linear and may be solved directly; when the boiling heat transfer comes in, the variables in the heat transmission chain become uncoupled from the flow variables, because of the assumption that ϕ_c depends on the temperature of the liquid in the last time step, and the diagonalization leads to an algebric equation of order n for the surface temperature T_{surf}. This is solved by a dicotomic method, starting from 0 and a temperature corresponding to $\phi_j = \phi_{c_j}$, which certainly brackett the correct value. Once the value of the heat flux ϕ_j is obtained, the equations for the flow variables are solved without difficulty in the order given.

The integrals that appear in the momentum equations are evaluated as sum over all the mesh points.

3) The stationary calculation

For starting every problem, the equilibrium values of the variables in some steady state condition are taken. The stationary conditions are evaluated using the same set of equations with the time derivatives put to zero. In the stationary calculation the problem is siplified by the fact that the total heat flow to the coolant at each level is necessarly equal to the total power generated in the fuel element at the same axial level. The heat flux ϕ is therefore immediatly known; as long as the heat transmission is purely convective, all the relevant variables in the liquid coolant and in the fuel element are directly calculated from the known values of power, inlet velocity of coolant and enthalpy. A test on the heating surface temperature ($T^2_{surf} > \theta$ (T_{sur}-Tliquid) will show if the conditions for the boiling heat transfer are met. In the latter case, a guess at the liquid temperature T_l is taken, and ϕ_c, (equations 2) is calculated, then ϕ_b as $\phi - \phi_c$ and T_{sur} from the relation $\phi_b = b' \, T^h_{sur}$. From ϕ_b, and the other known variables, the system of the equations from (3) to (12) allows the calculation of all the variables, and equation (12) gives the new value of T_l. The process is iterated and converges very rapidly. The maximum number of iterations is fixed in the code as 20, but it will generally never be reached. If this should happen, a warning is printed in the output.

The solution of the static equations from (3) to (12) is straight-forward and is made in succession, as long as R is 0 or infinity in the equations (6). In that case Ψ is immediately calculated and the other equations are trivial. In case that R should be different from zero, i.e., when there is a finite rate of recondensation (in the subcooled boiling zone) or vaporization (in the superheated zone), it is necessary to evaluate Ψ_b, the source of vapour volume in the bulk of the coolant. This cannot be done by the iterative method, as it does not converge in the general case. (The method of solution chosen, which involves the solution of a cubic equation, is illustrated in Appendix A).

4) Programme's structure

After the read out of data, the coefficients for the heat transmission in the fuel element are evaluated according to the geometry (see options). Then the static calculation is started with a first value for the inlet velocity of coolant and, if the corresponding option is checked, iterated with new values of inlet velocity to reach the required pressure drop. The index of the first boiling node is memorized for further use with the values for all the relevant variables.

It should be noted that the static calculation assumes that the heat transfer mechanism is always boiling in the active part of the channel in the points above the first boiling node. If the heat flux in these points is not sufficient to produce nucleate boiling, the surface temperature of the heating element is set to saturation value.

Then the dynamic calculation begins.

At the beginning of each new time step, the new value of the inlet velocity is calculated from the last acceleration or interpolated in a time table according to the option chosen. The dynamic calculation proceeds from the first node starting from the inlet of coolant. A test is run at each successive node ($T^2_{surf} > \theta \; T_{liquid}$) to see if the boiling transmission occurs. In any case, however, the (subcooled) boiling boundary is not allowed to move onwards faster than one node every time step. This means that if the boiling condition is not reached at the first boiling node of the preceding step, the twophase flow equations are however applied to the successive node, as some vapour must be present proceeding from the last section.

If the inspection of the output shows that the boiling boundary is moving onwards one node at every time step, the calculation should eventually be repeated with a smaller time step for better precision. In any case the calculation is self-consistent in energy and mass balance. Physically it should be considered that in any case, when nucleation sites are already present in a given place, boiling will continue also with reduced thermal flux until the surface temperature is greater than saturation.

At the end of the calculation the total pressure drop in the channel and riser is calculated, and the momentum equation (14) is used to give the new inlet velocity for the next time step if the corresponding option is checked.

At every step the average temperature of the fuel and the total heat flow to the coolant are checked to see if a maximum have been reached, in which case a special print is made. Furthermore at every step a special TEST routine may be called to test burnout conditions or any wanted condition. In the deck the TEST routine is dummy, and a special index KTE is set to zero to prevent any further calling after the first. The user may build his own routine to include any wanted burnout correlation or special condition, utilizing the commons of the routine, which contain all the relevant variables. To use properly this option a thorough study of the FORTRAN listing is required, to avoid failures due to inconsistencies.

5) Options

a) Heating element.

Three different options are possible on the geometry of the fuel element

1) Cylindrical geometry
2) Slab geometry
3) General geometry.

If the general geometry option is checked, the thermal capacities of the different zones (up to 10) and the heat conductivities from each zone to the subsequent must be given in input and are kept constant during the transient. The power distribution among the zones must also be given in relative values (the normalization is performed by the code).

If a definite geometry is checked, three options are possible; the fuel may be subdivided in zones of constant thickness, constant area, or arbitrary thickness given in input (of course the first two options coincide in the case of slab geometry). As for the radial power distribution, a choice can be made among constant power density, constant power in successive zones, or power shape given in input (relative values). The heat capacities and thermal conductivity of fuel and cladding may be either constant or given as quadratic functions of the difference between actual temperature and a fixed reference temperature. If the variable parameters option is chosen, the evaluation of the coefficients in Poisson's equation is repeated at each time step, with the last values of the temperatures, and the diagonalization procedure must also be repeated; the execution time of the problem is consequently increased (it may double according to the nature of the problem).

The axial distribution of power is either assumed constant or given in input as relative shape (normalization is always performed by the code).

b) Static calculation.

The inlet velocity of the coolant may be given in input as a fixed value, or the exit quality may be specified and the corresponding velocity calculated by the code according to the power specification. In these cases the pressure drop is calculated by the programme and memorized as the steady state value.

Alternatively the pressure drop in the steady condition may be imposed and two options are possible: either the inlet velocity is fixed, and a local orificing at the inlet is calculated to match the required pressure drop (it may turn out to be negative if the data are not consistent), or an iterative search for inlet velocity is performed, starting from the value given in input.

The iteration procedure is done by the tangents method in the following way:

$$V_{inlet}^{(i+1)} = V_{inlet}^{(i)} - \Delta_p^{(i)} \frac{V_{inlet}^{(i)} - V_{inlet}^{(i-1)}}{\Delta_p^{(i)} - \Delta_p^{(i-1)}}$$

where the Δ_p are the difference between the imposed and the calculated pressure drop. The iteration process stops when the pressure drops agree to 1%.

Up to 10 iterations are allowed. It should be noted that the iteration procedure may not converge in case of instable thermohydrodynamic conditions. Such instability problems should be treated by fixing the inlet velocity in the static condition and observing the dynamic behaviour when a small perturbation is introduced.

c) Dynamic calculation.

The inlet velocity at each new time step may be either interpolated from a fixed time table given in input or calculated by the code according to momentum equation (14). In the latter case the driving pressure may be itself interpolated in a fixed input time table (in particular kept constant to treat parallel channel instability problems) or evaluated as a quadratic function of the difference between the last value of inlet velocity and the steady state value to simulate pump characteristics $\Delta p_{driving} = \Delta p_{driving_o} + a(V_{inlet} - V_{inlet_o}) + b\,(V_{inlet} - V_{inlet_o})^2$.

The total power in the fuel at each time step may be interpolated from a given time table or may be fixed as a sinusoidal or exponential function of time

$$Power = Power_o\,(1 + a \sin bt)$$

$$Power = Power_o\, e^{bt}$$

The inlet temperature of the coolant is also interpolated from a time table.

d) Form of the correlations.

For two phase friction factor correlation four different forms are possible:

1) $R_f = 1 + a\alpha + b\alpha^2$

2) $R_f = 1 + ax + bx^2$

3) $R_f = 1 + a\chi + b\chi^2$

4) $R_f = 1 + a\chi^{-1} + b\chi^{-2}$

The Martinelli-Nelson parameter χ is evaluated as

$\chi = \frac{1-x}{x}$ TMART where TMART is a nondimensional constant that may be given in input as such or evaluated by the code as

$$TMART = (\rho_{vapour}/\rho_{liquid})^{0.571} \times \left(\frac{\mu_{liquid}}{\mu_{vapour}}\right)^{0.143}$$

The two phase friction factor for local losses is always taken as $R_{f_{local}} = 1 + ax + bx^2$

The parameter θ appearing in equations (2) may either be given in input or calculated as:

$$\theta = \left(\frac{h_c}{nh'}\right)^{\frac{1}{n-1}} \quad \text{(see Ref. 1).}$$

All the other relevant constants are given in input. It should however be remembered that the heat transfer coefficient h_c is a function of the coolant velocity (through the Reynolds number) and is recalculated by the code every time that the inlet velocity is altered, by the formula

$$h_c = h_{c_o} \left(\frac{V_{inlet}}{V_{inlet_o}}\right)^{0.8} .$$

Therefore the value h_c given in input must correspond to the velocity V_{inlet_o} given in the same input.

A special option allows to select standard correlations for water. If it is checked the following expressions are calculated by the code for the constants that may thus be omitted in the input.

$$h_c = 0.023 \frac{K}{D_H} \text{ Reynolds}^{0.8} \text{ Prandt}^{0.4}$$

$$h' = 2.645 \; 10^{-4} \; e^{\,0.0632 \, p}$$

$$n = 4$$

$$K = 0.79 + 0.21 \; p/p_{critical}$$

$$\tau = 0.435 \text{ for } p > 9.5 \text{ Kg/cm}^2$$

$$\tau = 1/(1+3.2 \; c_p \rho_l/\lambda \rho_v) \quad \text{for } p < 9.5 \text{ Kg/cm}^2$$

In all the options mentioned care has been taken in the construction of the input in such a way that if the user omits to check any option index, the code automatically selects the option that is more convenient or more commonly used in the opinion of the author. In the same way, whenever some constant, which is not familiar to the user, is omitted, the code will choose values in agreement with the author's opinion of what is more convenient. There are of course limitations to this facility in the sense that no sensible answer may be expected if any essential datum is missing.

6) Input form

All the input data are given as two vectors, the first of the integer data, and the second of the floating data. Since entire groups of data may be zero, it is possible to read sets of significatn data; each set must be preceded by a card containing the indexes of the first and the last datum of the set adjusted to the right in columns 12 and 24. The card preceding the last set of integer data, as well as that preceding the last floating data set are indicated by -1 in columns 1 and 2. At least one set of each type must be present.

The FORMAT for integer data is 12I6, for the floating data 6E12.8.

Any number of problems may be solved in sequence in one run, and only the data changed in the preceding problem need to be given. A title card must precede each of the problems containing any alphanumeric information in columns 7 to 12 that will appear in the output. Columns 1 to 6 must be left blank, except for the last problem in each run, which will be indicated by any positive integer.

The meaning of the data is given in the key in appendix B.

7) Output

The output is self-explanatory Appendix C. Two types of prints are possible in the dynamical calculation as it is shown in the example.

The meaning of the headings in the extended print is the following

PØW = Power per cm of height

FI = heat flux

H = subcooled (or superheated) liquid enthalpy

VF = void fraction

TSUR = surface temperature

TICL = Inner cladding temperature

AVTF = average fuel temperature

TMAXF = maximum fuel temperature

TL = liquid coolant temperature

An extra print of the complete temperature map of the fuel, which is normally edited only for the steady state condition and at the end of the problem will be done every time that a maximum for the average fuel temperature is found during the transient.

In the same way an extra print of the extended type will be done whenever a maximum for the heat flow to the coolant is reached.

8) Programme performance and computer specifications

The programme has been written in FORTRAN 360 and has been assembled and tested on IBM 360/65 at the CETIS computing centre of Euratom under the IBM 360-OS in FORTRAN H livel 2 (the FORTRAN G **has** been used in the debugging phase). The total length of the programme resulted to be 69040 (10A7C) storage locations.

The computer time required is proportional to the number of mesh points times the number of time steps, and depends also on the number of radial meshes in the fuel.

A rough conservative estimation is 0.005 millihours per mesh per time step, i.e. 1 minute for an average problem of 20 meshes and 150 time steps.

The programme has passed extensive internal tests for consistency. No complete comparison with other programmes has been possible, as no one was available with the same characteristics, however a test was run against Moxon's code Splosh-2 (ref.2) forcing the subcooled zone voids to disappear by imposing a very large recondensation constant.

The agreement was very good. Some differences ($\sim$2%) appear in the void distribution, which may well be due the difference in the slip correlation (Splosh uses the Bankoff correlation modified by Jones, while in FRANCESCA the original Bankoff correlation is used) but the time behaviour of all the variables agreed completely.

References

1) G. Forti. "A Dynamic model for the cooling channels of a boiling nuclear reactor with forced circulation and high pressure level." EUR-2398/A (in print).

2) D. Moxon. "Splosh II. A dynamics programme for nuclear-thermal-hydrodynamic behaviour of water cooled reactors". EAAW-R441.

APPENDIX A

The method of solution of the stationary problem in the boiling zone when the recondensation constant R is different from 0 or ∞ .

The system of equations to be solved is:

$$\Psi_b = R\alpha T$$

$$T = H_j / C_p$$

$$\Psi = \Psi_s + \Psi_b$$

$$w_j = w_{j-1} + (1-\gamma)\ \Delta z\, \Psi$$

$$q_{v_j} = q_{v_{j-1}} + \Delta z\, \Psi$$

$$\alpha = \frac{K q_{v_j} + z\, \Psi_s}{w_j}$$

$$q_{l_j} = q_{l_{j-1}} - \gamma\, \Delta z\, \Psi$$

$$H_j = \frac{(q_l H)_{j-1} + \Psi z Q/\rho - \gamma \lambda \Delta z\, \Psi}{q_{l_j}}$$

By substitution of all the other equations into the first, and reduction to the simplest algebric form, we obtain the following cubic equation for Ψ_b:

$$\Psi_b^{\,3} + a\Psi_b^{\,2} + b\Psi_b + c = 0$$

with $a = QI - QLI - RI1 + 2\Psi_s$

$$b = - QI \cdot QLI + RI2 \cdot H_o - RI3\,\alpha_o + \Psi_s(\Psi_s + QI - QLI)$$

$$c = R_o\, H_o\, \alpha_o$$

where:

$$\alpha_o = k q_{v\,j-1} + (k\Delta Z + Z_e)\Psi_s$$

$$H_o = (q_l H)_{j-1} + Q/_\rho\,\Delta Z - \gamma\lambda\Delta Z\,\Psi_s$$

$$R_o = R/C_p\,\frac{1}{\gamma(1-\gamma)\Delta Z}$$

$$RI1 = k\,\Delta Z\gamma\lambda\,\Delta Z R_o$$

$$RI2 = k\,\Delta Z R_o$$

$$RI3 = \gamma\lambda\Delta Z R_o$$

$$QI = \frac{W_{j-1}}{\gamma\Delta Z}$$

$$QLI = \frac{q_{v\,j-1}}{(1-\gamma)\Delta Z}$$

The choice among the roots of the equation is made observing that, as $\alpha_o \geqslant 0$, the product of the roots has the sign opposite to Ho.

But Ho, as it may be seen, is proportional to the enthalpy (referred to saturation value taken as zero) of the liquid, in the case that $\Psi_b = 0$, and therefore Ψ_b cannot physically have the sign opposite to Ho. This fact rules out the possibility of complex solutions.

The equation will have one positive and two negative solutions when $H_o<0$ and viceversa for $H_o>0$. The right solution have to be chosen between the two of equal sign. An analysis of the limit cases show that the choice of the smaller in absolute value is justified.

Therefore the solution retained is in all cases the middle one. Using the trigonometrical solution this is expressed by:

$$p = \frac{1}{9} a^2 - \frac{1}{3} b^2 > 0$$

$$q = \frac{1}{6} ab - \frac{1}{27} a^3 - \frac{1}{2} c$$

$$\theta = \arccos (qp^{-3/2})$$

$$\Psi_b = \frac{1}{3} a + 2p^{1/2} \cos \left(\frac{1}{3} \theta - \frac{2}{3}\pi\right)$$

The discussion of the limit cases follows:

a) $R \to \infty$ $\quad H_o > 0$

The cubic equation reduces to a quadratic

$$- RI1\Psi_b^2 + (RI2H_o - RI3\alpha_o)\Psi_b + R_o\alpha_o H_o$$

while the third solution goes to infinity $\Psi_b \to RI1$.

Dividing by R the equation becomes

$$\Psi_b^2 - \left(\frac{H_o}{\gamma\lambda\Delta Z} - \frac{\alpha_o}{k\Delta Z}\right) - \frac{1}{k\gamma\lambda\Delta Z^2} \alpha_o H_o = 0$$

which has the solutions

$$\Psi_b = H_o/\gamma\lambda Z > 0 \qquad\qquad \Psi_b = -\frac{\alpha_o}{k\Delta Z} < 0$$

The first solution is evidently the right one, corresponding to complete evaporation of the superheated liquid.

The case $R \to \infty$ $H_0 < 0$ will not be met in practice as the recondensation constant R_1 in the subcooled zone is small. In this case the right solution should be the second, corresponding to the total recondensation of the subcooled vapour, and this will not necessarily be the smaller in absolute value. In such case the solution chosen by the code may lead to recondensation values, too low, and therefore too high void content is the subcooled zone, but this will be practically set right at the first dynamic step, because of the high value of the recondensation constant R_1.

b) $R \to 0$

The equation reduces to

$$\Psi_b^3 - \{(QLI - \Psi_s) - (QI + \Psi_s)\}\Psi_b^2 - (QI + \Psi_s)(QLI - \Psi_s)\Psi_b = 0$$

The right solution is evidently $\Psi_b = 0$ while the two others $\Psi_b = QLI - \Psi_s > 0$ and $\Psi_b = -(QI + \Psi_s) < 0$ must be ruled out. The right solution is therefore the middle one also in this case.

APPENDIX B

FRANCESCA INPUT KEY

Fixed Data

1 IMAX' Number of mesh points in the axial direction ≤ 100

2 NF Number of zones in fuel ≤ 10

3 IP1 Extensive outputs is printed every IP1 restricted prints

4 ISTD
- 0 Normal input
- 1 standard input for water

5 ITIPO
- 0 Cylindrical fuel element
- 1 slab fuel element
- -1 general fuel element

6 IVAR
- 0 Fuel element properties are constant
- 1 properties are function of temperature

7 JPØW
- 0 Power density is constant in the fuel element
- 1 power in radial zones given in input
- -1 power is the same on all radial zones

8 ISHAP
- 0 Power constant along the channel in the axial direction
- 1 power shape given in input

9 IØR
- 0 No operation
- 1 search for orificing at the channel inlet of the coolant

10 IVIN
- 0 Inlet velocity of the coolant is calculated by the code during the transient
- 1 inlet velocity is given as tabulated function of time

11 IEX
- 0 Driving pressure is function of inlet velocity of coolant $\Delta p = \Delta p_o + a\,(v - v_o) + b\,(v - v_o)^2$
- 1 driving pressure is given as function of time

12 IPOW
- 0 Total power in fuel is given as tabulated function of time
- 1 power = $P_o\,(1 + a \sin bt)$
- -1 power = $P_o\, e^{bt}$

13	IFRIC	0	Two phase friction multiplier is given as quadratic function of quality x $= 1 + ax + bx^2$
		-1	multiplier is given as function of void fraction
		1	multiplier is given as function of χ = TMART $\frac{1-x}{x}$
		2	multiplier is given as function of χ^{-1}
14	IRIS		Number of mesh points in the riser (put zero if no riser is present) <10
15 16 17	KKR(I)		Index of meshes in riser where local flow resistance exists
18			Leave blank
19	IDF	0	radial zones in the fuel have constant area
		1	uniform radial mesh width
		-1	radii of fuel zones given in input
20	ITET	0	Teta evaluated by standard method
		1	Teta given in input
21-30	KKC(I)		Index of meshes in boiling channel where local flow resistance exists (grids)
31	KKC(I)		Leave blank
32	IDVM		Dummy

FRANCESCA INPUT KEY

Floating Data

n°	Name	Description	Units	Notes
1	ZTØT	Height of active channel	cm	
2	PØWER	Total power in fuel at equilibrium	watt	
3	FRDF	Ratio of power density directly added to the liquid coolant to power density produced in the fuel	-	
4	DT	Time step for dynamic calculation	sec	
5	TEND	Final time for transient calculation	sec	
6	PS	Printing time interval (restricted output)	sec	Extended print is produced every 1P1 such intervals (see fixed input)
7	A	Channel flow area	cm^2	
8	DIAF	Fuel pellet diameter (or thickness for slab geometry)	cm	Not employed for general geometry (ITIPO = -1)
9	GAPTH	Thickness of the gap	cm	May be taken as zero
10	CLTH	Thickness of the cladding	cm	Should not be taken as zero
11	ROF	Fuel density	g/cm^3	

12	CPF	Fuel specific heat	joule/gr°C	
13	AKF	Fuel thermal conductivity	watt/cm°C	
14	RGAP	Thermal resistance of the gap	cm^2°C/watt	
15	RØCL	Density of the cladding	g/cm^3	
16	CPCL	Specific heat of the cladding	joule/gr°C	
17	AKCL	Thermal conductivity of the cladding	watt/gr°C	
18	SWID	Fuel element width	cm	For slab geometry only
19	HINLET	Inlet temperature of coolant for steady state	°C or °K	
20	VINLET	Inlet velocity of coolant for steady state or a first guess at it	cm/sec	
21	FFK	Friction coefficient in the active channel	cm^{-1}	
22	FFRK	Friction coefficient in the riser	cm^{-1}	Omitted if no riser is present
23	XOUT	Vapour quality at outlet		If a value is given, the code will evaluate the inlet velocity accordingly
24	DPEQ	Total pressure drop in the channel for steady state	bar	If a value is given, the code will evaluate the inlet orificing (IOR=1) or make a search for inlet velocity (ten trials is a maximum) The search may fail in special conditions (instability)

25	TSAT	Saturation temperature of the coolant	°C or °K	
26	RO	Liquid coolant density	gr/cm3	
27	ROVAP	Vapour density	gr/cm3	
28	CP	Specific heat of coolant	joule/gr°C	
29	HLAT	Latent heat of vaporization	joule/gr	
30	HC	Convective heat transfer coefficient	watt/cm^2°C	Omit if ISTD = 1
31	HB	Boiling heat transfer constant $\phi = HB \cdot T^n$	watt/cm^2°C^n	Omit if ISTD = 1
32	AN	Exponent in boiling heat transfer correlation $\phi = HB \cdot \Delta T^n$	-	Omit if ISTD = 1
33	TAU	τ = Bowring ratio of heat transmitted through bubbles to total heat transmitted in boiling mechanism	-	Omit if ISTD = 1
34	AK	Bankoff's slip constant	-	Omit if ISTD = 1
35	ZE	Relaxation parameter for void profile in diabatic flow	cm	May be left zero lacking better information (the order of magnitude is the hydraulic diameter)
36	R1	Recondensation time constant for subcooled boiling	(sec°C)$^{-1}$	Put zero lacking better information

37	R2	Vaporization time constant for superheated liquid (put zero if equilibrium is wanted in the bulk boiling region)	$(sec°C)^{-1}$	Put zero lacking better information
38	AFRIC	Coefficients for two phase flow friction factor multiplier (FFM = 1+AFRIC x +BFRIC x^2)	-	
39	BFRIC			
40	ALOC	Coefficients for local losses two phase multiplier (FFM = 1+ALOC x +BLOC x^2)	-	
41	BLOC			
42	TMART	Coefficient in Lokhart-Martinelli parameter definition: $\chi = \frac{1-x}{x} \cdot TMART$	-	Only if IFRIC = 1,2
43	CØEF1	Coefficient for momentum flow of liquid at outlet	-	Omit lacking better information. They will be taken as 1
44	CØEF2	Same for vapour	-	
45	CØEF3	Same for liquid at inlet	-	
46	ZIN	Inlet pipe height	cm	
47	CFFI	Inlet friction coefficient	-	
48	ZR	Riser height	cm	
49	ARIS	Riser flow area	cm^2	
50	GRAV	Gravity direction cosinus (+1 for upwards flow)	-	
51	APØW	Coefficients for power variation in transient (see IPØW)	-	
52	BPØW			
53	APEX	Coefficient for external driving pressure	sec/cm	
54	BPEX	DPEX = p_o (1 + APEX Δ_v + BPEX Δ_v^2)	$(sec/cm)^2$	

55	TKF	T_o	in formula $K=K_o+a(T-T_o)+b(T-T_o)^2$ for fuel variable heat conductivity		Omit if IVAR = 0 if IVAR=1 and no variation is wanted put T_o=0
56	AKF1	a			
57	AKF2	b			
58	TCPF	T_o	in same formula for fuel variable specific heat		idem
59	CPF1	a			
60	CPF2	b			
61	TKCL		same for variable clad conductivity		idem
62	AKCL1				
63	AKCL2				
64	TCCL		same for variable clad specific heat		idem
65	CPCL1				
66	CPCL2				
67 to 69	CFRF(I)		Values for local pressure drop coefficients in riser	-	
70 to 79	CKFF(I)		Same for active channel	-	
80 to 89	RFØ(I)		Radii of successive regions in fuel pellet	cm	Only if IDF = -1

90 to 99	PFAC(I)	Corresponding power factors (normalization is performed by the code)	-	Give only if JPØW = 1
100	TINPUT	value given in input	°C	Only if ITET = 1
101	PRESS	Average pressure	bar	Only if ISTD = 1
102	VISC	Viscosity of liquid coolant	poise	Only if ISTD = 1
103	WCØN	Cpnductivity of coolant	watt/cm°C	Only if ISTD = 1
104	VISCV	Viscosity of vapour	poise	Only if IFRIC = 12 and TMART = 0
105	DIAH	Hydraulic diameter	cm	
106		Not employed		
107	ELSUR	Area of the heating surface per cm of height	cm	Only for general geometry
108	CLCAP	Thermal capacity of the cladding per unit height	joule/cm°C	Only for general geometry
109	ACONCL	Thermal conductivity of the cladding	watt/cm°C	Only for general geometry
110 to 119	FMASS(I)	Mass/cm in every zone in the fuel element (from inside to outside)	gr/cm	Only for general geometry
120 to 129	CAP(I)	Thermal capacities in the fuel element zones of unit height	joule/cm°C	Only for general geometry
130 to 139	CONF(I)	Thermal conductivities from one zone to the successive in the outer direction (p.unit height)	watt/cm°C	Only for general geometry

T A B U L A T I O N S

Only when the corresponding option is checked

140 to 149	TIMEV(I)	Times for inlet velocities tabulation	sec	First time in each table is always zero
150 to 159	VVAL(I)	Corresponding values for inlet velocities	cm/sec	If the first value is zero, the steady state value is kept. After the last value of time the velocity is kept constant to the last value in the table
160 to 169	TIMEH(I)	Times for inlet temperatures tabulation	sec	
170 to 179	HVAL(I)	Corresponding values	°C or °K	
180 to 189	TIMEPR(I)	Times for external driving pressure tabulation	sec	
190 to 199	PRE(I)	Corresponding values for driving pressure	bar	
200 to 299	PØW(I)	Axial power distribution	-	Relative values. Normalization is performed by the code.
300 to 349	TIMEP(I)	Times for total power tabulation	sec	
350 to 399	PVAL(I)	Corresponding values of power	watt	
400	DUM	Total inertia of the channel (cm). If zero, the total inertia will be taken as sum of the lengths of the channel, plus riser, plus inlet pipe.		

FRANCESCA CODE FOR BOILING CHANNELS

TEST PROBLEM FOR FRANCESCA CODE

INPUT DATA

FIXED

1	10	2	8	3	2	4	0	5	0	6	0	7	0	8	0
9	0	10	1	11	0	12	0	13	0	14	3	15	0	16	0
17	0	18	0	19	0	20	0	21	0	22	0	23	0	24	0

FLOATING

1	0.400000E 03	2	0.500000E 05	3	0.0	4	0.100000E-01	5	0.100000E 01	6	0.500000E-01
7	0.130000E 01	8	0.150000E 01	9	0.0	10	0.600000E-01	11	0.100000E 02	12	0.330000E 00
13	0.250000E-01	14	0.500000E 00	15	0.300000E 01	16	0.100000E 01	17	0.125000E 00	18	0.0
19	0.318000E 03	20	0.450000E 03	21	0.100000E-01	22	0.100000E-01	23	0.0	24	0.0
25	0.330000E 03	26	0.750000E 00	27	0.350000E-01	28	0.500000E 01	29	0.150000E 04	30	0.350000E 01
31	0.200000E-01	32	0.400000E 01	33	0.300000E 00	34	0.800000E 00	35	0.100000E 01	36	0.0
37	0.0	38	0.450000E 02	39	-0.280000E 02	40	0.200000E 02	41	0.0	42	0.0
43	0.0	44	0.0	45	0.0	46	0.100000E 03	47	0.200000E 01	48	0.150000E 03
49	0.150000E 01	50	0.100000E 01								
301	0.100000E 01										
351	0.600000E 05										

FUEL DATA

```
  FUEL RADIUS          DENSITY          MASS/CM      CLAD RADIUS      EXT.RADIUS
  0.75000E 00      0.10000E 02      0.17671E 02      0.75000E 00      0.81000E 00


   8 REGIONS IN FUEL
RADII
   0.26516     0.37500     0.45928     0.53033     0.59293     0.64952     0.70156     0.75000
RELATIVE POWER
   0.12500     0.12500     0.12500     0.12500     0.12500     0.12500     0.12500     0.12500


   TEMPERATURE INDEPENDENT CONSTANTS

            CPF              KF              CPCL             KCL
 0.330000E 00    0.250000E-01    0.100000E 01    0.125000E 00
```

STATIC CALCULATION

```
CHANNEL DATA
 HEIGHT       400.0 CM    SECTION      1.300 CM2    COOLANT DENSITY    0.75000 G/CM3    GRAVITY=    980.000 CM/SEC**2
 INLET PIPE HEIGHT      100.0
 RISER HEIGHT       150.0
 TOTAL CHANNEL POWER IN FUEL     0.50000E 05WATT
 TOTAL CHANNEL POWER IN COOLANT 0.0          WATT

                   OPTIONS

 FIXED INLET VELOCITY


 INLET VELOCITY /VINLET/=    450.00000CM/SEC
 EXIT QUALITY /XOUT/=    0.03597
 AVERAGE VOID FRACTION /AVF/=    0.12096
 POWER FLUX TO COOLANT /THF/= 0.50000E 05WATT
 POWER OUTPUT 0.50000E 05

 PRESSURE DROP      1.39845 BAR
  INLET         0.37725     CHANNEL       0.78493              RISER                0.23627
  FRICTION      0.97037     GRAVITY       0.40641              SPACE ACCEL.         0.02166

 HEAT TRANSFER CONSTANTS
   HC 0.35000E 01           HB  0.20000E-01                    AN      4.000                      TAU      0.300
   TETA       3.52          TETAF       6.08                    K      0.800                      ZE       1.00
```

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.12500E 03	0.24561E 02	-0.48604E 02	0.0	0.32730E 03	0.33954E 03	0.55688E 03	0.75111E 03	0.32028E 03
2	0.12500E 03	0.24561E 02	-0.37208E 02	0.0	0.32958E 03	0.34182E 03	0.55916E 03	0.75339E 03	0.32256E 03
3	0.12500E 03	0.24561E 02	-0.25812E 02	0.0	0.33185E 03	0.34410E 03	0.56144E 03	0.75567E 03	0.32484E 03
4	0.12500E 03	0.24561E 02	-0.14416E 02	0.0	0.33413E 03	0.34638E 03	0.56372E 03	0.75795E 03	0.32712E 03
5	0.12500E 03	0.24561E 02	-0.54821E 01	0.27978E-01	0.33545E 03	0.34769E 03	0.56504E 03	0.75926E 03	0.32890E 03
6	0.12500E 03	0.24561E 02	0.0	0.86987E-01	0.33587E 03	0.34812E 03	0.56546E 03	0.75969E 03	0.33000E 03
7	0.12500E 03	0.24561E 02	0.0	0.17896E 00	0.33587E 03	0.34812E 03	0.56546E 03	0.75969E 03	0.33000E 03
8	0.12500E 03	0.24561E 02	0.0	0.25089E 00	0.33587E 03	0.34812E 03	0.56546E 03	0.75969E 03	0.33000E 03
9	0.12500E 03	0.24561E 02	0.0	0.30869E 00	0.33587E 03	0.34812E 03	0.56546E 03	0.75969E 03	0.33000E 03
10	0.12500E 03	0.24561E 02	0.0	0.35614E 00	0.33587E 03	0.34812E 03	0.56546E 03	0.75969E 03	0.33000E 03

RISER	
0.0	0.35614E 00
0.0	0.35614E 00
0.0	0.35614E 00

FUEL TEMPERATURE MAP

1	751.11	680.77	629.28	578.82	528.68	478.70	428.79	378.92
2	753.39	683.05	631.56	581.10	530.96	480.97	431.06	381.20
3	755.67	685.33	633.84	583.38	533.24	483.25	433.34	383.48
4	757.95	687.61	636.12	585.66	535.52	485.53	435.62	385.76
5	759.26	688.92	637.43	586.97	536.84	486.85	436.94	387.07
6	759.69	689.35	637.86	587.40	537.26	487.27	437.36	387.50
7	759.69	689.35	637.86	587.40	537.26	487.27	437.36	387.50
8	759.69	689.35	637.86	587.40	537.26	487.27	437.36	387.50
9	759.69	689.35	637.86	587.40	537.26	487.27	437.36	387.50
10	759.69	689.35	637.86	587.40	537.26	487.27	437.36	387.50

DYNAMIC CALCULATION

OPTIONS

VINLET GIVEN IN INPUT

POWER TABULATED

TIME	0.0	1.00
POWER	0.	60000.

TIME STEP FOR CALCULATION 0.01000

TIME 0.050 SEC
POWER 0.50501E 05 THF 0.49994E 05 AVF 0.12096 XOUT 0.03597

VINLET 450.000 PDROP 1.398

AVERAGE FUEL TEMPERATURE 563.357
MAX.FUEL TEMP. 759.690 IN NODE 10
MAX.CLAD TEMP. 348.115 IN NODE 10
MAX.HEAT FLUX 24.559 IN NODE 4

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.100 SEC
POWER 0.51001E 05 THF 0.49996E 05 AVF 0.12096 XOUT 0.03597

VINLET 450.000 PDROP 1.398

AVERAGE FUEL TEMPERATURE 563.372
MAX.FUEL TEMP. 759.705 IN NODE 10
MAX.CLAD TEMP. 348.116 IN NODE 10
MAX.HEAT FLUX 24.560 IN NODE 4

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.12750E 03	0.24559E 02	-0.48605E 02	0.0	0.32730E 03	0.33954E 03	0.55690E 03	0.75113E 03	0.32028E 03
2	0.12750E 03	0.24559E 02	-0.37209E 02	0.0	0.32957E 03	0.34182E 03	0.55918E 03	0.75341E 03	0.32256E 03
3	0.12750E 03	0.24558E 02	-0.25813E 02	0.0	0.33185E 03	0.34410E 03	0.56146E 03	0.75569E 03	0.32484E 03
4	0.12750E 03	0.24560E 02	-0.14417E 02	0.0	0.33413E 03	0.34638E 03	0.56374E 03	0.75797E 03	0.32712E 03
5	0.12750E 03	0.24559E 02	-0.54828E 01	0.27971E-01	0.33545E 03	0.34769E 03	0.56505E 03	0.75928E 03	0.32890E 03
6	0.12750E 03	0.24559E 02	0.0	0.86972E-01	0.33587E 03	0.34812E 03	0.56548E 03	0.75971E 03	0.33000E 03
7	0.12750E 03	0.24559E 02	0.0	0.17895E 00	0.33587E 03	0.34812E 03	0.56548E 03	0.75971E 03	0.33000E 03
8	0.12750E 03	0.24559E 02	0.0	0.25088E 00	0.33587E 03	0.34812E 03	0.56548E 03	0.75971E 03	0.33000E 03
9	0.12750E 03	0.24559E 02	0.0	0.30868E 00	0.33587E 03	0.34812E 03	0.56548E 03	0.75971E 03	0.33000E 03
10	0.12750E 03	0.24559E 02	0.0	0.35614E 00	0.33587E 03	0.34812E 03	0.56548E 03	0.75971E 03	0.33000E 03

RISER	
0.0	0.35560E 00
0.0	0.35581E 00
0.0	0.35598E 00

TIME 0.150 SEC
POWER 0.51501E 05 THF 0.50008E 05 AVF 0.12096 XOUT 0.03597

VINLET 450.000 PDROP 1.399

AVERAGE FUEL TEMPERATURE 563.397
MAX.FUEL TEMP. 759.731 IN NODE 10
MAX.CLAD TEMP. 348.121 IN NODE 10
MAX.HEAT FLUX 24.566 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.200 SEC
POWER 0.52001E 05 THF 0.50024E 05 AVF 0.12097 XOUT 0.03598

VINLET 450.000 PDROP 1.399

AVERAGE FUEL TEMPERATURE 563.433
MAX.FUEL TEMP. 759.768 IN NODE 10
MAX.CLAD TEMP. 348.127 IN NODE 10
MAX.HEAT FLUX 24.575 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.13000E 03	0.24570E 02	-0.48603E 02	0.0	0.32730E 03	0.33955E 03	0.55696E 03	0.75119E 03	0.32028E 03
2	0.13000E 03	0.24571E 02	-0.37207E 02	0.0	0.32958E 03	0.34183E 03	0.55924E 03	0.75347E 03	0.32256E 03
3	0.13000E 03	0.24570E 02	-0.25811E 02	0.0	0.33186E 03	0.34411E 03	0.56152E 03	0.75575E 03	0.32484E 03
4	0.13000E 03	0.24570E 02	-0.14415E 02	0.0	0.33414E 03	0.34639E 03	0.56380E 03	0.75803E 03	0.32712E 03
5	0.13000E 03	0.24574E 02	-0.54811E 01	0.27985E-01	0.33545E 03	0.34770E 03	0.56511E 03	0.75934E 03	0.32890E 03
6	0.13000E 03	0.24575E 02	0.0	0.87010E-01	0.33587E 03	0.34813E 03	0.56554E 03	0.75977E 03	0.33000E 03
7	0.13000E 03	0.24575E 02	0.0	0.17898E 00	0.33587E 03	0.34813E 03	0.56554E 03	0.75977E 03	0.33000E 03
8	0.13000E 03	0.24575E 02	0.0	0.25091E 00	0.33587E 03	0.34813E 03	0.56554E 03	0.75977E 03	0.33000E 03
9	0.13000E 03	0.24575E 02	0.0	0.30870E 00	0.33587E 03	0.34813E 03	0.56554E 03	0.75977E 03	0.33000E 03
10	0.13000E 03	0.24575E 02	0.0	0.35616E 00	0.33587E 03	0.34813E 03	0.56554E 03	0.75977E 03	0.33000E 03
			RISER						
			0.0	0.35549E 00					
			0.0	0.35558E 00					
			0.0	0.35571E 00					

TIME 0.250 SEC
POWER 0.52501E 05 THF 0.50048E 05 AVF 0.12100 XOUT 0.03598

VINLET 450.000 PDROP 1.399

AVERAGE FUEL TEMPERATURE 563.478
MAX.FUEL TEMP. 759.816 IN NODE 10
MAX.CLAD TEMP. 348.134 IN NODE 10
MAX.HEAT FLUX 24.587 IN NODE 10

FIRST BOILING NODE 5

EXIT LIQUID SUPERHEAT 0.0

TIME 0.300 SEC
POWER 0.53001E 05 THF 0.50079E 05 AVF 0.12104 XOUT 0.03599

VINLET 450.000 PDROP 1.400

AVERAGE FUEL TEMPERATURE 563.533
MAX.FUEL TEMP. 759.874 IN NODE 10
MAX.CLAD TEMP. 348.144 IN NODE 10
MAX.HEAT FLUX 24.606 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.13250E 03	0.24592E 02	-0.48597E 02	0.0	0.32731E 03	0.33957E 03	0.55706E 03	0.75130E 03	0.32028E 03
2	0.13250E 03	0.24592E 02	-0.37198E 02	0.0	0.32959E 03	0.34185E 03	0.55934E 03	0.75358E 03	0.32256E 03
3	0.13250E 03	0.24592E 02	-0.25800E 02	0.0	0.33187E 03	0.34413E 03	0.56162E 03	0.75586E 03	0.32484E 03
4	0.13250E 03	0.24592E 02	-0.14404E 02	0.0	0.33415E 03	0.34641E 03	0.56390E 03	0.75813E 03	0.32712E 03
5	0.13250E 03	0.24602E 02	-0.54724E 01	0.28035E-01	0.33545E 03	0.34772E 03	0.56521E 03	0.75945E 03	0.32891E 03
6	0.13250E 03	0.24606E 02	0.0	0.87164E-01	0.33588E 03	0.34814E 03	0.56564E 03	0.75987E 03	0.33000E 03
7	0.13250E 03	0.24606E 02	0.0	0.17911E 00	0.33588E 03	0.34814E 03	0.56564E 03	0.75987E 03	0.33000E 03
8	0.13250E 03	0.24606E 02	0.0	0.25102E 00	0.33588E 03	0.34814E 03	0.56564E 03	0.75987E 03	0.33000E 03
9	0.13250E 03	0.24606E 02	0.0	0.30880E 00	0.33588E 03	0.34814E 03	0.56564E 03	0.75987E 03	0.33000E 03
10	0.13250E 03	0.24606E 02	0.0	0.35623E 00	0.33588E 03	0.34814E 03	0.56564E 03	0.75987E 03	0.33000E 03
			RISER						
			0.0	0.35551E 00					
			0.0	0.35552E 00					
			0.0	0.35557E 00					

TIME 0.350 SEC
POWER 0.53501E 05 THF 0.50112E 05 AVF 0.12109 XOUT 0.03600

VINLET 450.000 PDROP 1.401

AVERAGE FUEL TEMPERATURE 563.598
MAX.FUEL TEMP. 759.943 IN NODE 10
MAX.CLAD TEMP. 348.155 IN NODE 10
MAX.HEAT FLUX 24.623 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.400 SEC
POWER 0.54001E 05 THF 0.50154E 05 AVF 0.12116 XOUT 0.03602

VINLET 450.000 PDROP 1.401

AVERAGE FUEL TEMPERATURE 563.673
MAX.FUEL TEMP. 760.023 IN NODE 10
MAX.CLAD TEMP. 348.167 IN NODE 10
MAX.HEAT FLUX 24.646 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.13500E 03	0.24626E 02	-0.48586E 02	0.0	0.32732E 03	0.33960E 03	0.55720E 03	0.75145E 03	0.32028E 03
2	0.13500E 03	0.24624E 02	-0.37180E 02	0.0	0.32960E 03	0.34188E 03	0.55948E 03	0.75373E 03	0.32256E 03
3	0.13500E 03	0.24623E 02	-0.25779E 02	0.0	0.33188E 03	0.34416E 03	0.56176E 03	0.75600E 03	0.32484E 03
4	0.13500E 03	0.24622E 02	-0.14381E 02	0.0	0.33416E 03	0.34644E 03	0.56404E 03	0.75828E 03	0.32712E 03
5	0.13500E 03	0.24638E 02	-0.54531E 01	0.28125E-01	0.33546E 03	0.34774E 03	0.56535E 03	0.75960E 03	0.32891E 03
6	0.13500E 03	0.24646E 02	0.0	0.87476E-01	0.33588E 03	0.34817E 03	0.56578E 03	0.76002E 03	0.33000E 03
7	0.13500E 03	0.24646E 02	0.0	0.17939E 00	0.33588E 03	0.34817E 03	0.56578E 03	0.76002E 03	0.33000E 03
8	0.13500E 03	0.24646E 02	0.0	0.25126E 00	0.33588E 03	0.34817E 03	0.56578E 03	0.76002E 03	0.33000E 03
9	0.13500E 03	0.24646E 02	0.0	0.30900E 00	0.33588E 03	0.34817E 03	0.56578E 03	0.76002E 03	0.33000E 03
10	0.13500E 03	0.24646E 02	0.0	0.35641E 00	0.33588E 03	0.34817E 03	0.56578E 03	0.76002E 03	0.33000E 03
			RISER						
			0.0	0.35563E 00					
			0.0	0.35557E 00					
			0.0	0.35555E 00					

TIME 0.450 SEC
POWER 0.54501E 05 THF 0.50197E 05 AVF 0.12126 XOUT 0.03604

VINLET 450.000 PDROP 1.402

AVERAGE FUEL TEMPERATURE 563.758
MAX.FUEL TEMP. 760.114 IN NODE 10
MAX.CLAD TEMP. 348.181 IN NODE 10
MAX.HEAT FLUX 24.669 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.500 SEC
POWER 0.55001E 05 THF 0.50246E 05 AVF 0.12137 XOUT 0.03607

VINLET 450.000 PDROP 1.403

AVERAGE FUEL TEMPERATURE 563.851
MAX.FUEL TEMP. 760.215 IN NODE 10
MAX.CLAD TEMP. 348.197 IN NODE 10
MAX.HEAT FLUX 24.696 IN NODE 10

FIRST BOILING NODE 5

EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.13750E 03	0.24668E 02	-0.48570E 02	0.0	0.32733E 03	0.33964E 03	0.55738E 03	0.75164E 03	0.32029E 03
2	0.13750E 03	0.24663E 02	-0.37153E 02	0.0	0.32962E 03	0.34192E 03	0.55966E 03	0.75392E 03	0.32257E 03
3	0.13750E 03	0.24662E 02	-0.25745E 02	0.0	0.33190E 03	0.34420E 03	0.56194E 03	0.75620E 03	0.32485E 03
4	0.13750E 03	0.24661E 02	-0.14343E 02	0.0	0.33418E 03	0.34648E 03	0.56422E 03	0.75848E 03	0.32713E 03
5	0.13750E 03	0.24684E 02	-0.54204E 01	0.28258E-01	0.33547E 03	0.34778E 03	0.56553E 03	0.75979E 03	0.32892E 03
6	0.13750E 03	0.24696E 02	0.0	0.87975E-01	0.33588E 03	0.34820E 03	0.56596E 03	0.76021E 03	0.33000E 03
7	0.13750E 03	0.24696E 02	0.0	0.17982E 00	0.33588E 03	0.34820E 03	0.56596E 03	0.76021E 03	0.33000E 03
8	0.13750E 03	0.24696E 02	0.0	0.25164E 00	0.33588E 03	0.34820E 03	0.56596E 03	0.76021E 03	0.33000E 03
9	0.13750E 03	0.24696E 02	0.0	0.30933E 00	0.33588E 03	0.34820E 03	0.56596E 03	0.76021E 03	0.33000E 03
10	0.13750E 03	0.24696E 02	0.0	0.35669E 00	0.33588E 03	0.34820E 03	0.56596E 03	0.76021E 03	0.33000E 03
			RISER						
			0.0	0.35585E 00					
			0.0	0.35573E 00					
			0.0	0.35565E 00					

TIME 0.550 SEC
POWER 0.55501E 05 THF 0.50300E 05 AVF 0.12151 XOUT 0.03610

VINLET 450.000 PDROP 1.404

AVERAGE FUEL TEMPERATURE 563.954
MAX.FUEL TEMP. 760.327 IN NODE 10
MAX.CLAD TEMP. 348.213 IN NODE 10
MAX.HEAT FLUX 24.725 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.600 SEC
POWER 0.56001E 05 THF 0.50356E 05 AVF 0.12166 XOUT 0.03614

VINLET 450.000 PDROP 1.404

AVERAGE FUEL TEMPERATURE 564.067
MAX.FUEL TEMP. 760.449 IN NODE 10
MAX.CLAD TEMP. 343.231 IN NODE 10
MAX.HEAT FLUX 24.754 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.14000E 03	0.24719E 02	-0.48550E 02	0.0	0.32735E 03	0.33968E 03	0.55760E 03	0.75187E 03	0.32029E 03
2	0.14000E 03	0.24713E 02	-0.37118E 02	0.0	0.32964E 03	0.34197E 03	0.55988E 03	0.75415E 03	0.32258E 03
3	0.14000E 03	0.24709E 02	-0.25699E 02	0.0	0.33192E 03	0.34425E 03	0.56216E 03	0.75643E 03	0.32486E 03

4	0.14000E 03	0.24706E 02	-0.14289E 02	0.0	0.33420E 03	0.34653E 03	0.56444E 03	0.75871E 03	0.32714E 03
5	0.14000E 03	0.24739E 02	-0.53732E 01	0.28436E-01	0.33548E 03	0.34782E 03	0.56575E 03	0.76002E 03	0.32893E 03
6	0.14000E 03	0.24754E 02	0.0	0.88675E-01	0.33589E 03	0.34823E 03	0.56617E 03	0.76045E 03	0.33000E 03
7	0.14000E 03	0.24754E 02	0.0	0.18044E 00	0.33589E 03	0.34823E 03	0.56617E 03	0.76045E 03	0.33000E 03
8	0.14000E 03	0.24754E 02	0.0	0.25217E 00	0.33589E 03	0.34823E 03	0.56617E 03	0.76045E 03	0.33000E 03
9	0.14000E 03	0.24754E 02	0.0	0.30980E 00	0.33589E 03	0.34823E 03	0.56617E 03	0.76045E 03	0.33000E 03
10	0.14000E 03	0.24754E 02	0.0	0.35711E 00	0.33589E 03	0.34823E 03	0.56617E 03	0.76045E 03	0.33000E 03

RISER	
0.0	0.35619E 00
0.0	0.35600E 00
0.0	0.35585E 00

TIME 0.650 SEC
POWER 0.56501E 05 THF 0.50417E 05 AVF 0.12184 XOUT 0.03619

VINLET 450.000 PDROP 1.405

AVERAGE FUEL TEMPERATURE 564.189
MAX.FUEL TEMP. 760.583 IN NODE 10
MAX.CLAD TEMP. 348.250 IN NODE 10
MAX.HEAT FLUX 24.786 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.700 SEC
POWER 0.57001E 05 THF 0.50484E 05 AVF 0.12204 XOUT 0.03624

VINLET 450.000 PDROP 1.407

AVERAGE FUEL TEMPERATURE 564.320
MAX.FUEL TEMP. 760.727 IN NODE 10
MAX.CLAD TEMP. 348.270 IN NODE 10
MAX.HEAT FLUX 24.823 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.14250E 03	0.24778E 02	-0.48526E 02	0.0	0.32737E 03	0.33974E 03	0.55785E 03	0.75215E 03	0.32029E 03
2	0.14250E 03	0.24770E 02	-0.37075E 02	0.0	0.32966E 03	0.34202E 03	0.56013E 03	0.75443E 03	0.32258E 03
3	0.14250E 03	0.24763E 02	-0.25641E 02	0.0	0.33195E 03	0.34430E 03	0.56241E 03	0.75671E 03	0.32487E 03
4	0.14250E 03	0.24760E 02	-0.14220E 02	0.0	0.33423E 03	0.34659E 03	0.56469E 03	0.75899E 03	0.32716E 03
5	0.14250E 03	0.24803E 02	-0.53109E 01	0.28660E-01	0.33549E 03	0.34786E 03	0.56600E 03	0.76030E 03	0.32894E 03
6	0.14250E 03	0.24823E 02	0.0	0.89580E-01	0.33589E 03	0.34827E 03	0.56643E 03	0.76073E 03	0.33000E 03
7	0.14250E 03	0.24823E 02	0.0	0.18123E 00	0.33589E 03	0.34827E 03	0.56643E 03	0.76073E 03	0.33000E 03
8	0.14250E 03	0.24823E 02	0.0	0.25288E 00	0.33589E 03	0.34827E 03	0.56643E 03	0.76073E 03	0.33000E 03
9	0.14250E 03	0.24823E 02	0.0	0.31042E 00	0.33589E 03	0.34827E 03	0.56643E 03	0.76073E 03	0.33000E 03
10	0.14250E 03	0.24823E 02	0.0	0.35766E 00	0.33589E 03	0.34827E 03	0.56643E 03	0.76073E 03	0.33000E 03

RISER	
0.0	0.35666E 00
0.0	0.35639E 00
0.0	0.35617E 00

TIME 0.750 SEC
POWER 0.57501E 05 THF 0.50551E 05 AVF 0.12226 XOUT 0.03630

VINLET 450.000 PDROP 1.408

AVERAGE FUEL TEMPERATURE 564.461
MAX.FUEL TEMP. 760.882 IN NODE 10
MAX.CLAD TEMP. 348.290 IN NODE 10
MAX.HEAT FLUX 24.858 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.800 SEC
POWER 0.58001E 05 THF 0.50623E 05 AVF 0.12251 XOUT 0.03636

VINLET 450.000 PDROP 1.409

AVERAGE FUEL TEMPERATURE 564.610
MAX.FUEL TEMP. 761.047 IN NODE 10
MAX.CLAD TEMP. 348.312 IN NODE 10
MAX.HEAT FLUX 24.895 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.14500E 03	0.24844E 02	-0.48498E 02	0.0	0.32740E 03	0.33979E 03	0.55814E 03	0.75247E 03	0.32030E 03
2	0.14500E 03	0.24834E 02	-0.37024E 02	0.0	0.32969E 03	0.34208E 03	0.56042E 03	0.75475E 03	0.32260E 03
3	0.14500E 03	0.24824E 02	-0.25571E 02	0.0	0.33198E 03	0.34437E 03	0.56270E 03	0.75703E 03	0.32489E 03
4	0.14500E 03	0.24819E 02	-0.14136E 02	0.0	0.33426E 03	0.34665E 03	0.56498E 03	0.75931E 03	0.32717E 03
5	0.14500E 03	0.24873E 02	-0.52339E 01	0.28926E-01	0.33551E 03	0.34791E 03	0.56629E 03	0.76062E 03	0.32895E 03
6	0.14500E 03	0.24895E 02	0.0	0.90685E-01	0.33590E 03	0.34831E 03	0.56671E 03	0.76105E 03	0.33000E 03
7	0.14500E 03	0.24895E 02	0.0	0.18221E 00	0.33590E 03	0.34831E 03	0.56671E 03	0.76105E 03	0.33000E 03
8	0.14500E 03	0.24895E 02	0.0	0.25374E 00	0.33590E 03	0.34831E 03	0.56671E 03	0.76105E 03	0.33000E 03
9	0.14500E 03	0.24895E 02	0.0	0.31118E 00	0.33590E 03	0.34831E 03	0.56671E 03	0.76105E 03	0.33000E 03
10	0.14500E 03	0.24895E 02	0.0	0.35834E 00	0.33590E 03	0.34831E 03	0.56671E 03	0.76105E 03	0.33000E 03

RISER	
0.0	0.35726E 00
0.0	0.35692E 00
0.0	0.35662E 00

TIME 0.850 SEC
POWER 0.58501E 05 THF 0.50699E 05 AVF 0.12277 XOUT 0.03643

VINLET 450.000 PDROP 1.410

AVERAGE FUEL TEMPERATURE 564.769
MAX.FUEL TEMP. 761.223 IN NODE 10
MAX.CLAD TEMP. 348.335 IN NODE 10
MAX.HEAT FLUX 24.935 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

TIME 0.900 SEC
POWER 0.59001E 05 THF 0.50777E 05 AVF 0.12306 XOUT 0.03650

VINLET 450.000 PDROP 1.411

AVERAGE FUEL TEMPERATURE 564.937
MAX.FUEL TEMP. 761.411 IN NODE 10
MAX.CLAD TEMP. 348.360 IN NODE 10
MAX.HEAT FLUX 24.976 IN NODE 10

FIRST BOILING NODE 5
EXIT LIQUID SUPERHEAT 0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.14750E 03	0.24916E 02	-0.48468E 02	0.0	0.32743E 03	0.33986E 03	0.55847E 03	0.75283E 03	0.32031E 03
2	0.14750E 03	0.24904E 02	-0.36966E 02	0.0	0.32972E 03	0.34215E 03	0.56075E 03	0.75511E 03	0.32261E 03
3	0.14750E 03	0.24893E 02	-0.25491E 02	0.0	0.33201E 03	0.34444E 03	0.56303E 03	0.75739E 03	0.32490E 03
4	0.14750E 03	0.24886E 02	-0.14038E 02	0.0	0.33430E 03	0.34673E 03	0.56531E 03	0.75967E 03	0.32719E 03
5	0.14750E 03	0.24948E 02	-0.51425E 01	0.29235E-01	0.33552E 03	0.34797E 03	0.56662E 03	0.76098E 03	0.32897E 03
6	0.14750E 03	0.24976E 02	0.0	0.91989E-01	0.33591E 03	0.34836E 03	0.56704E 03	0.76141E 03	0.33000E 03
7	0.14750E 03	0.24976E 02	0.0	0.18336E 00	0.33591E 03	0.34836E 03	0.56704E 03	0.76141E 03	0.33000E 03
8	0.14750E 03	0.24976E 02	0.0	0.25476E 00	0.33591E 03	0.34836E 03	0.56704E 03	0.76141E 03	0.33000E 03
9	0.14750E 03	0.24976E 02	0.0	0.31209E 00	0.33591E 03	0.34836E 03	0.56704E 03	0.76141E 03	0.33000E 03
10	0.14750E 03	0.24976E 02	0.0	0.35915E 00	0.33591E 03	0.34836E 03	0.56704E 03	0.76141E 03	0.33000E 03

	RISER	
	0.0	0.35800E 00
	0.0	0.35758E 00
	0.0	0.35720E 00

TIME 0.950 SEC
POWER 0.59501E 05 THF 0.50860E 05 AVF 0.12337 XOUT 0.03658

VINLET 450.000 PDROP 1.413

AVERAGE FUEL TEMPERATURE 565.113
MAX.FUEL TEMP. 761.608 IN NODE 10

MAX.CLAD TEMP.   348.384   IN NODE   10
MAX.HEAT FLUX   25.020   IN NODE   10

FIRST BOILING NODE   5
EXIT LIQUID SUPERHEAT   0.0

TIME   1.000 SEC
POWER 0.60000E 05   THF 0.50945E 05   AVF   0.12369   XOUT   0.03667

VINLET   450.000   PDROP   1.414

AVERAGE FUEL TEMPERATURE   565.298
MAX.FUEL TEMP.   761.816   IN NODE   10
MAX.CLAD TEMP.   348.410   IN NODE   10
MAX.HEAT FLUX   25.064   IN NODE   10

FIRST BOILING NODE   5
EXIT LIQUID SUPERHEAT   0.0

I	POW	FI	H	VF	TSUR	TICL	AVTF	TMAXF	TL
1	0.15000E 03	0.24995E 02	-0.48434E 02	0.0	0.32745E 03	0.33993E 03	0.55883E 03	0.75324E 03	0.32031E 03
2	0.15000E 03	0.24980E 02	-0.36902E 02	0.0	0.32976E 03	0.34223E 03	0.56111E 03	0.75552E 03	0.32262E 03
3	0.15000E 03	0.24968E 02	-0.25401E 02	0.0	0.33205E 03	0.34452E 03	0.56339E 03	0.75780E 03	0.32492E 03
4	0.15000E 03	0.24958E 02	-0.13925E 02	0.0	0.33435E 03	0.34681E 03	0.56567E 03	0.76008E 03	0.32721E 03
5	0.15000E 03	0.25031E 02	-0.50373E 01	0.29582E-01	0.33554E 03	0.34803E 03	0.56698E 03	0.76139E 03	0.32899E 03
6	0.15000E 03	0.25064E 02	0.0	0.93482E-01	0.33591E 03	0.34841E 03	0.56740E 03	0.76182E 03	0.33000E 03
7	0.15000E 03	0.25064E 02	0.0	0.18469E 00	0.33591E 03	0.34841E 03	0.56740E 03	0.76182E 03	0.33000E 03
8	0.15000E 03	0.25064E 02	0.0	0.25594E 00	0.33591E 03	0.34841E 03	0.56740E 03	0.76182E 03	0.33000E 03
9	0.15000E 03	0.25064E 02	0.0	0.31315E 00	0.33591E 03	0.34841E 03	0.56740E 03	0.76182E 03	0.33000E 03
10	0.15000E 03	0.25064E 02	0.0	0.36010E 00	0.33591E 03	0.34841E 03	0.56740E 03	0.76182E 03	0.33000E 03

RISER

H	VF
0.0	0.35887E 00
0.0	0.35837E 00
0.0	0.35792E 00

FUEL TEMPERATURE MAP

1	753.24	682.90	631.41	580.93	530.77	480.70	430.55	380.16
2	755.52	685.18	633.68	583.21	533.05	482.98	432.84	382.45
3	757.80	687.46	635.96	585.49	535.33	485.26	435.12	384.73
4	760.08	689.73	638.24	587.77	537.61	487.53	437.40	387.02
5	761.39	691.05	639.55	589.08	538.92	488.84	438.70	388.28
6	761.82	691.47	639.98	589.51	539.35	489.27	439.11	388.69
7	761.82	691.47	639.98	589.51	539.35	489.27	439.11	388.69
8	761.82	691.47	639.98	589.51	539.35	489.27	439.11	388.69
9	761.82	691.47	639.98	589.51	539.35	489.27	439.11	388.69
10	761.82	691.47	639.98	589.51	539.35	489.27	439.11	388.69

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Alfred Nobel

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