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OCA-P, A Deterministic and Probabilistic Fracture-Mechanics Code for Application to Pressure Vessels

R. D. Cheverton D. G. Ball

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

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R. D. Cheverton D. G. Ball*

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FOREWORD

The work reported here was performed at Oak Ridge National Laboratory (ORNL) under sponsorship of the U.S. Nuclear Regulatory Commission's (NRC's) Heavy-Section Steel Technology Program, which is directed by ORNL. The program is conducted as part of the ORNL Pressure Vessel Technology Program, of which C. E. Pugh is manager. The manager for the NRC is Milton Vagins.

This report is designated Heavy-Section Steel Technology Program Technical Report 70. Prior reports in this series are as follows.

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NOMENCLATURE†

a	Crack depth measured radially from inner surface, mm (in.)
a′	Radial distance from open end of crack (inner surface of cylinder) to point of application of unit load along a for 2-D flaws or radial distance to point on crack front for semielliptical flaws, mm (in.)
Δa	An increment of crack advance, or an increment of a about a, mm (in.)
a_c	Critical crack depth, mm (in.)
a/w	Fractional crack depth
a_c/w	Fractional critical crack depth
b	Inner radius of cylinder, mm (in.)
B(a)	Probability of nondetection of a flaw
c	Outer radius of cylinder, mm (in.)
c_p	Specific heat, J/kg·°C (Btu/lb·°F)
Cu, Ni, P	Concentrations of copper, nickel, and phosphorous, wt %
E	Modulus of elasticity, MPa (ksi)
f(a)	Flaw-depth density function, mm^{-1} ($in.^{-1}$)
F	Fast-neutron fluence in wall (neutron energy >1 MeV), neutrons/cm^2
F_o	Fast-neutron fluence at inner surface of cylinder, neutrons/cm^2
h	Fluid-film heat transfer coefficient, W/m^2·°C (Btu/h·ft^2·°F)
J	Strain-energy release rate, kJ/m^2 (in.·lb/$in.^2$)
k	Thermal conductivity, W/m·°C (Btu/h·ft·°F)
K_I	Mode-I stress intensity factor, MPa·$\sqrt{m}$ (ksi·$\sqrt{in.}$)
K*	Two-dimensional-flaw Mode-I stress intensity factor for a unit load (per unit surface length of flaw) applied at a′ on the crack face, ksi·$\sqrt{in.}$/lb·in.

†Either SI or English units can be used for input to OCA-P, and units for the output will be consistent with those for the input. All of the equations in the report containing constants that have units are based on the specific SI units included in the table of nomenclature and elsewhere in the report. All input units (SI and English) are those indicated in this Nomenclature.

K_j^*	Influence coefficient for semielliptical flaws
K_{Ia}	Crack arrest toughness, MPa·$\sqrt{m}$ (ksi·$\sqrt{in.}$)
K_{Ic}	Crack initiation toughness, MPa·$\sqrt{m}$ (ksi·$\sqrt{in.}$)
K_J	Stress intensity factor based on J integral ($K_J = \sqrt{JE}$), MPa·$\sqrt{m}$ (ksi·$\sqrt{in.}$)
m	Fluence attenuation coefficient, mm^{-1} ($in.^{-1}$)
N	Flaw density, flaws/m^3 (flaws/ft^3)
N_f	Number of failures
N_v	Number of vessels simulated
p	Internal pressure, MPa (ksi)
P(F|E)	Conditional probability of failure
$\hat{P}$	Conditional probability of failure based on one flaw per vessel
r	Radial distance from center of cylinder, mm (in.)
$RTNDT_o$	Reference nil-ductility temperature for unirradiated material, °C (°F)
ΔRTNDT	Change in RTNDT caused by radiation damage, °C (°F)
$\Delta RTNDT_s$	ΔRTNDT at inner surface of the cylinder, °C (°F)
$(\Delta RTNDT_s)_c$	Critical value of $\Delta RTNDT_s$, °C (°F)
t	Time in transient, s (min)
T	Temperature, °C (°F)
T_c	Bulk temperature of coolant adjacent to vessel surface, °C (°F)
T_D	Temperature above which only ductile behavior occurs, °C (°F)
T_o	Initial temperature of vessel and coolant, °C (°F)
V	Volume of weld metal, m^3 (ft^3)
w	Wall thickness, mm (in.)
α	Coefficient of thermal expansion, $°C^{-1}$ ($°F^{-1}$)
ε	Error in P(F|E)
μ	Indicates mean value
ν	Poisson's ratio
ρ	Density, kg/m^3 (lb/ft^3)
σ	Stress, MPa (ksi); standard deviation

OCA-P, A DETERMINISTIC AND PROBABILISTIC FRACTURE-MECHANICS CODE FOR APPLICATION TO PRESSURE VESSELS

R. D. Cheverton D. G. Ball*

ABSTRACT

The OCA-P code is a probabilistic fracture-mechanics code that was prepared specifically for evaluating the integrity of pressurized-water reactor vessels when subjected to overcooling-accident loading conditions. The code has two-dimensional- and some three-dimensional-flaw capability; it is based on linear-elastic fracture mechanics; and it can treat cladding as a discrete region. Both deterministic and probabilistic analyses can be performed. For the former analysis, it is possible to conduct a search for critical values of the fluence and the nil-ductility reference temperature corresponding to incipient initiation of the initial flaw. The probabilistic portion of OCA-P is based on Monte Carlo techniques, and simulated parameters include fluence, flaw depth, fracture toughness, nil-ductility reference temperature, and concentrations of copper, nickel, and phosphorous. Plotting capabilities include the construction of critical-crack-depth diagrams (deterministic analysis) and various histograms (probabilistic analysis).

1. INTRODUCTION

In the event of a severe overcooling accident (OCA) at a pressurized-water reactor (PWR) facility, preexistent flaws on the inner surface of the reactor pressure vessel, opposite the core region, where radiation embrittlement and thermal stresses can be substantial, may propagate, introducing the possibility of vessel failure.[1,2] Because of significant uncertainties in the many factors involved in evaluating flaw behavior for OCA conditions, a probabilistic approach can be useful and has been applied by several investigators.[3-5] To help in assessing the severity of the OCA situation, a probabilistic fracture-mechanics code, OCA-P, has been developed at the Oak Ridge National Laboratory (ORNL) at the request of the U.S. Nuclear Regulatory Commission (USNRC). The OCA-P code has been designed specifically for estimating the conditional probability of preexistent flaws penetrating the belt-line region of PWR pressure vessels that are subjected to temperature and pressure transient loadings. This report describes OCA-P and includes the OCA-P users' manual.

*Computer Sciences Division.

2. GENERAL DESCRIPTION OF OCA-P

The OCA-P code can be used for both deterministic and probabilistic fracture-mechanics calculations. For both cases, it accepts as input the reactor primary-system pressure and the reactor pressure-vessel downcomer coolant temperature, as functions of time in the specified transient. With this and other information available, OCA-P calculates the wall temperatures and stresses as a function of time and radial position in the wall. A fracture-mechanics analysis is then performed to obtain the stress intensity factors (K_I) as a function of crack depth and time in the transient. In a deterministic analysis, values of the static crack initiation toughness (K_{Ic}) and the crack arrest toughness (K_{Ia}) are also calculated as a part of the fracture-mechanics analysis for all crack depths and times in the transient. A comparison of K_I with K_{Ic} and K_{Ia} permits an evaluation of flaw behavior.

For a probabilistic analysis, OCA-P performs most of the above steps and, consistent with Monte Carlo methodologies, generates a large number of reactor pressure vessels, each with a different combination of the various values of the different parameters involved in the analysis of flaw behavior. For each of these vessels, a deterministic fracture-mechanics analysis is performed (calculation of K_I, K_{Ic}, K_{Ia}) to determine whether vessel "failure" takes place. The conditional probability of "failure" is simply the number of vessels that "fail" divided by the number of vessels generated.

The OCA-P code is basically a combination of OCA-II,[6] a deterministic fracture mechanics code, and a Monte Carlo-type procedure that introduces the probabilistic aspect of OCA-P. The OCA-II code is subdivided into a heat transfer code, 1-R, and a fracture-mechanics code, FM. For OCA-P, the FM portion of the code also contains the probabilistic features and is referred to as PFM. Another subcode in OCA-P provides plots of specific output data from a probabilistic analysis and is referred to as PR. Thus, as indicated by the system flowchart in Fig. 2.1, OCA-P actually consists of three basic subcodes: 1-R, PFM, and PR.

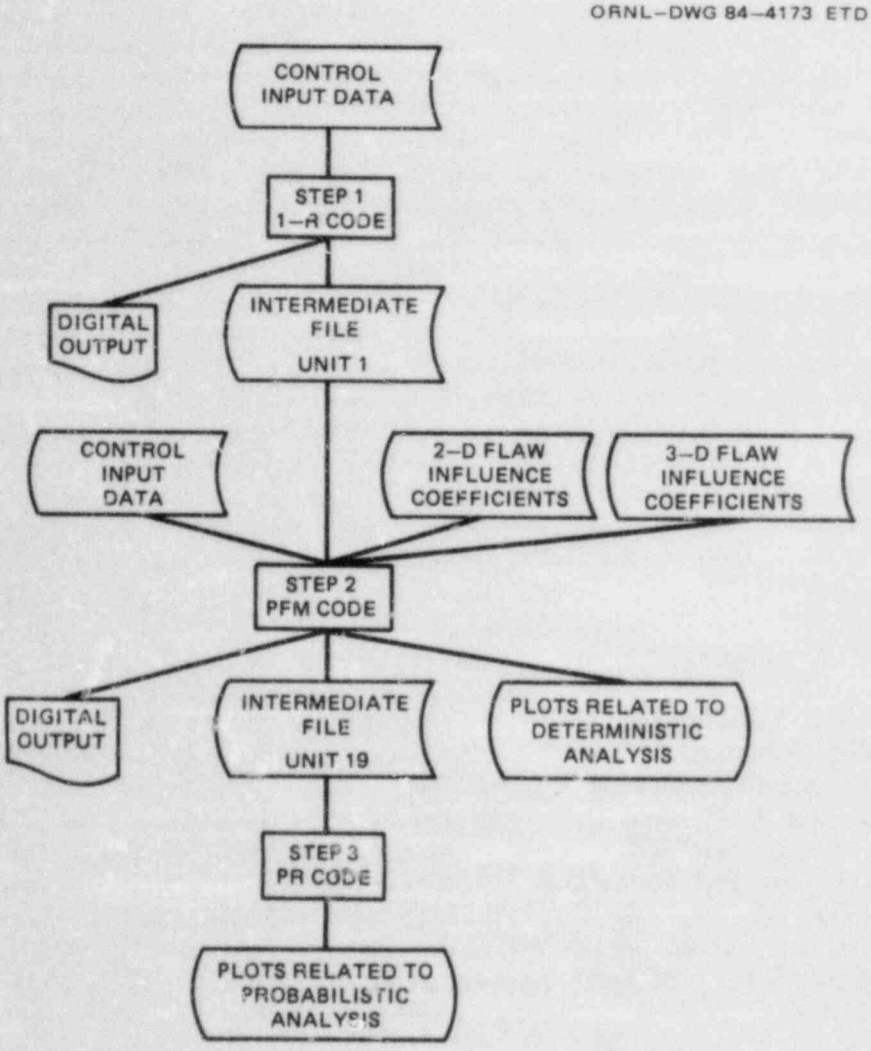

Fig. 2.1. OCA-P system flowchart.

3. THERMAL, STRESS, AND FRACTURE-MECHANICS ANALYSES

The thermal, stress, and fracture-mechanics analyses in OCA-P are performed with the equivalent of OCA-II. The various analytical steps in this portion of OCA-P and the required input are summarized in Fig. 3.1.

The specified OCA transient, which consists of the reactor primary-system pressure and the reactor vessel downcomer coolant temperature as functions of time in the transient, is input to OCA-P. The coolant temperature and a specified time-dependent fluid-film heat transfer coefficient are used in OCA-P for a one-dimensional (1-D) thermal analysis to obtain the radial temperature distribution in the vessel wall as a function of time. Radial variations in material thermal properties are permitted, and thus cladding can be treated as a discrete region. Also, as an option to calculating the wall temperatures with OCA-P, these temperatures can be obtained by other means and then inputted.

Once the wall temperatures have been determined, OCA-P performs a 1-D stress analysis for the unflawed vessel to obtain the circumferential and longitudinal pressure and thermal stresses as a function of time and radial position in the wall. If, however, the stresses are available from another source, they can be inputted rather than calculated.

The stress intensity factors are calculated with a superposition technique that makes use of influence coefficients and the above stresses, as described in Ref. 6. Influence coefficients are available in OCA-P for two-dimensional (2-D) axial and circumferential flaws on the inner and outer surfaces and for two specific three-dimensional (3-D) inner-surface flaws. The 3-D flaws are semielliptical in shape with one having a surface length-to-depth ratio of 6 (6/1 flaw) and the other having a surface length of 1.82 m (2-m flaw). Fractional depths (a/w) for the 6/1 flaw, which can be oriented axially or circumferentially, range from 0.025 to 0.2 and for the 2-m flaw, which is oriented axially, from 0.2 to 0.90. Fractional depths for the 2-D flaws range from 0.025 to 0.95. The effect of cladding on K_I can be included for the 2-D and 2-m flaws.

Influence coefficients are derived for specific sets of vessel dimensions, and coefficients for the 2-D flaws are available in OCA-P for several sets. However, the 6/1 and 2-m flaw coefficients are available for only one set of dimensions (ID = 4370 mm, OD = 4800 mm). A detailed discussion of the calculation of the influence coefficients used in OCA-P is included in Refs. 6–8.

The OCA-P code also calculates K_{Ic} and K_{Ia} as a function of time in the transient and radial position in the wall. This requires relations of the type

$$K_{Ic},\ K_{Ia} = f(T - RTNDT) ,$$

$$T = f(a/w,\ t) ,$$

$$RTNDT = RTNDT_o + \Delta RTNDT ,$$

$$\Delta RTNDT = f(Cu,\ Ni,\ P,\ F) ,$$

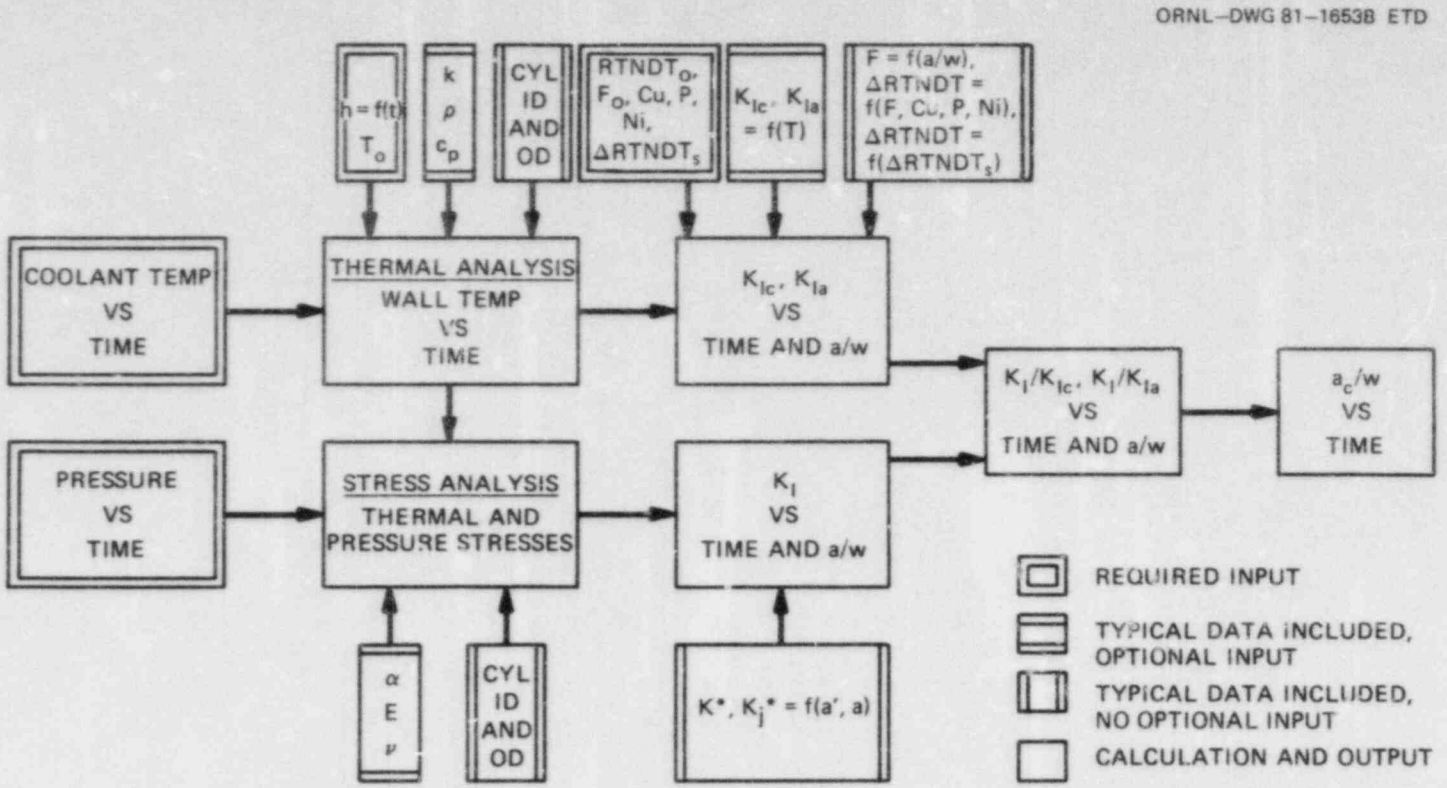

Fig. 3.1. Summary description of deterministic part of OCA-P, indicating basic input, calculations, and output.

and

$$F = f(a/w) ,$$

where

T = temperature at crack front, °C;
a = crack depth or radial position in wall from inner surface, mm;
w = wall thickness, mm;
t = time in transient, s or min;
RTNDT = nil-ductility reference temperature,[9] °C;
$RTNDT_o$ = initial (zero fluence) value of RTNDT, °C;
ΔRTNDT = increase in RTNDT due to radiation damage, °C;
Cu, Ni, P = copper, nickel, and phosphorous concentrations, wt %;
F = fast neutron fluence (neutron energy > 1 MeV), neutrons/cm^2.

The fracture toughness relations included in OCA-P are as follows:

ASME Sect. XI lower-bound[10] curves

$$K_{IC} = 36.5 + 3.084 \exp [0.036 (T - RTNDT + 56)], \text{ MPa}\cdot\sqrt{\text{m}} \quad (1)$$

and

$$K_{Ia} = 29.5 + 1.344 \exp [0.0261 (T - RTNDT + 89)], \text{ MPa}\cdot\sqrt{\text{m}} . \quad (2)$$

ORNL mean curves

$$\bar{K}_{Ic} = 1.43 \times \text{Eq. (1)} \quad (3)$$

and

$$\bar{K}_{Ia} = 1.25 \times \text{Eq. (2)} . \quad (4)$$

Nuclear Regulatory Commission (NRC) mean curves[5]

$$[\bar{K}_{Ic} = 39.8 + 54.3 \exp [0.0187 (T - RTNDT)], (T - RTNDT) < -28°C$$

$$= 60.6 + 30.8 \exp [0.0385 (T - RTNDT)], (T - RTNDT) > -28°C] , \quad (5)$$

and

$$[\overline{K}_{Ia} = 21.9 + 48.2 \exp [0.0179 (T - RTNDT)], (T - RTNDT) \leq 28°C$$

$$= 77.0 + 7.14 \exp [0.0353 (T - RTNDT)], (T - RTNDT) > 28°C] . \quad (6)$$

The relation T = f(a/w, t) is calculated as a first step in OCA-P, as mentioned above.

The shift (ΔRTNDT) in the toughness curves is obtained as follows:

Regulatory Guide 1.99 (Rev. 1)[11]

$$\Delta RTNDT = 0.56 [40 + 1000 (Cu - 0.08) + 5000 (P - 0.008)] (F \times 10^{-19})^{0.5}, °C \quad (7a)$$

or

$$= 0.56 \times 283 (F \times 10^{-19})^{0.194}, °C , \quad (7b)$$

whichever is smaller.

Improved correlation proposed by Randall[12]

Mean:

$$\overline{\Delta RTNDT} = 0.56 [-10 + 470 Cu + 350 Cu Ni] (F \times 10^{-19})^{0.27}, °C \quad (8a)$$

or

$$= 0.56 [283 (F \times 10^{-19})^{0.194} - 48], °C , \quad (8b)$$

whichever is smaller and where Cu ≤ 0.4%.

Mean value plus two standard deviations:

$$\Delta RTNDT (2\sigma) = 0.56 [38 + 470 Cu + 350 Cu Ni] (F \times 10^{-19})^{0.27}, °C \quad (9a)$$

or

$$= 0.56 \times 283 (F \times 10^{-19})^{0.194}, °C , \quad (9b)$$

whichever is smaller.

The relation for the attenuation of the fast-neutron fluence through the wall is as follows:

$$F = F_o e^{-ma} . \tag{10}$$

An appropriate value of m that accounts to some extent for the change in neutron energy spectrum through the wall is 0.0094 mm^{-1} (Ref. 12).

For some deterministic analyses it is useful to let $\Delta RTNDT_s$, the value of $\Delta RTNDT$ at the inner surface of the vessel, be the independent variable rather than a combination of F, Cu, Ni, and P. This has been done in some parametric studies[13] by using either Eq. (8a) or (9a) in combination with Eq. (10) to obtain

$$\Delta RTNDT(a) = \Delta RTNDT_s \, e^{-0.27ma} , \tag{11}$$

which can be used in Eqs. (1)—(6) to calculate K_{Ic} and K_{Ia} without having to specify values of F, Cu, Ni, and P. However, if a specified value of $\Delta RTNDT_s$ is large enough to correspond to Eqs. (8b) and (9b), this procedure will overestimate the attenuation of $\Delta RTNDT$ and thus will overestimate the fracture toughness somewhat for $a/w > 0$.

4. PROBABILISTIC ANALYSIS

The OCA-P probabilistic model, which is similar to that developed by Gamble and Strosnider,[14] is based on Monte Carlo techniques; that is, a large number of vessels is generated, and each vessel is then subjected to a fracture-mechanics analysis to determine whether the vessel will fail. Each vessel is defined by randomly selected values of several parameters that are judged to have significant uncertainties associated with them. The calculated probability of vessel failure is simply the number of vessels that fail divided by the total number of vessels generated. It constitutes a conditional probability of failure, $P(F|E)$, because the assumption is made that the OCA (event) takes place. A logic diagram summarizing the various steps in the OCA-P probabilistic analysis is shown in Fig. 4.1.

4.1 Simulated Parameters

The specific parameters simulated in OCA-P include the fluence at the inner surface of the vessel (F_o), RTNDT, K_{Ic}, K_{Ia}, and the concentrations of copper and nickel (Cu, Ni) in the vessel material. Normal distributions are used for each of these parameters, and a typical set of standard deviations and truncation values is included in Table 4.1. The size of the flaw is also simulated and is discussed in Sect. 4.2.

Table 4.1. Parameters simulated in OCA-P

Parameter	Standard deviation[a] (σ)	Truncation
Fluence (F)	0.3 $\mu(F)$	$F = 0$
Copper	0.025%	
Nickel	0.0	
$RTNDT_o$	9°C[b]	[b]
$\Delta RTNDT$	13°C[b]	[b]
K_{Ic}	0.15 $\mu(K_{Ic})$	$\pm 3\sigma$
K_{Ia}	0.10 $\mu(K_{Ia})$	$\pm 3\sigma$

[a] Normal distribution used for each parameter.

[b] $\sigma_{(RTNDT)} = \left[\sigma^2_{(RTNDT_o)} + \sigma^2_{(\Delta RTNDT)}\right]^{1/2}$, truncated at $\pm 3\sigma$.

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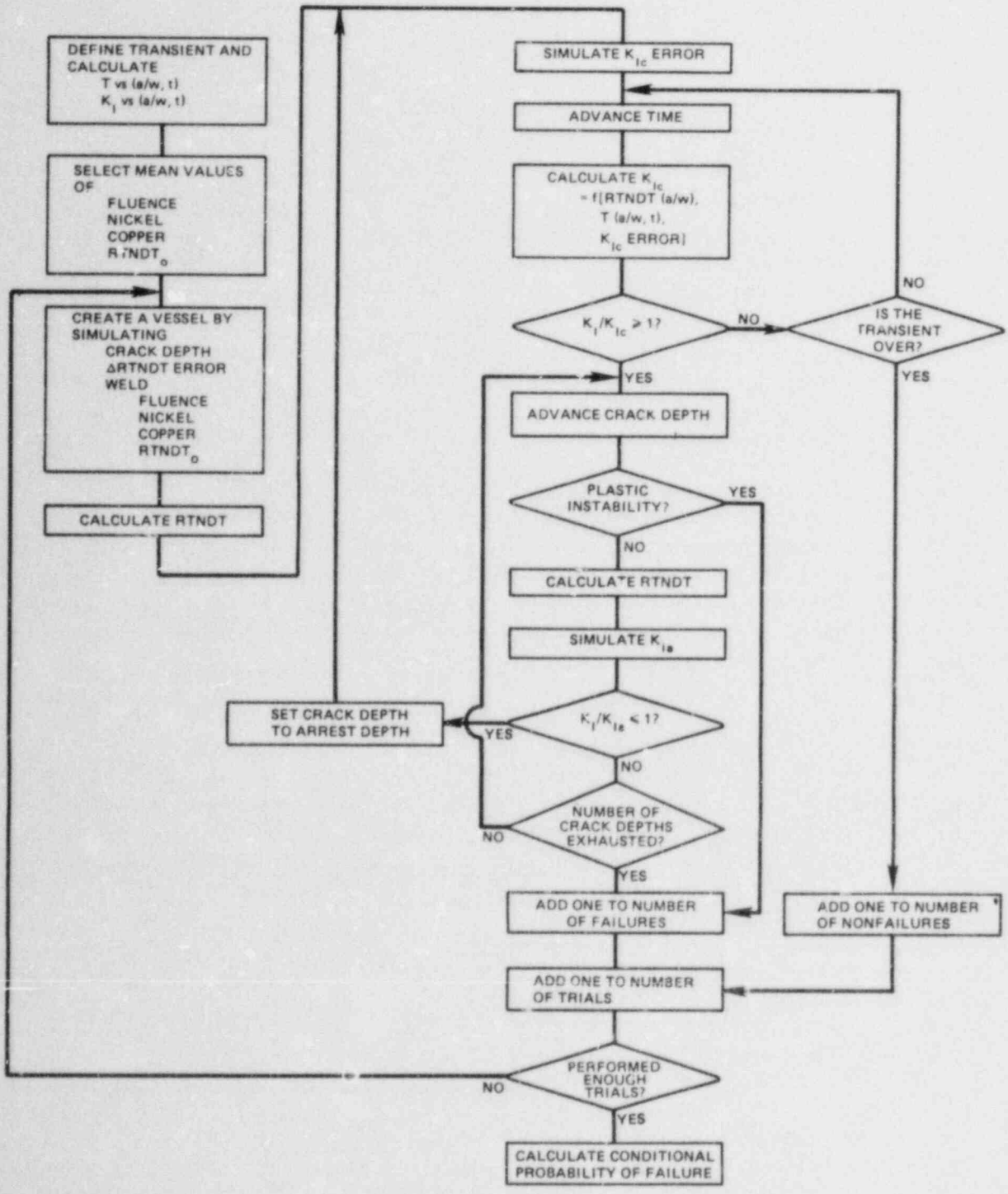

Fig. 4.1. OCA-P program logic.

4.1.1 Fluence

The fast-neutron fluence at the inner surface of the vessel, F_o, is generally an independent variable in the OCA-P analysis, in which case $P(F|E)$ is determined as a function of F_o. If more than one flaw zone is considered in a single analysis, a different value of F_o can be used for each zone; however, each value should correspond to a single value of the number of effective full power years (EFPY) of reactor operation. In effect, this makes EFPY the independent variable.

4.1.2 RTNDT = $RTNDT_o$ + ΔRTNDT

A mean value of $RTNDT_o$ must be specified for each flaw zone that is to be included in the analysis of a vessel.

Correlations for ΔRTNDT are included in Sect. 3 [Eqs. (7)–(8)] Equations (8a) and (8b) are the most appropriate because the probabilistic analysis requires mean values of the parameters simulated. Also, at the time of this writing, Eqs. (8a) and (8b) represented the most recent interpretation of the applicable experimental data.

In OCA-P a standard deviation (σ) is calculated for RTNDT = $RTNDT_o$ + ΔRTNDT; the calculation is performed in the following manner:

$$\sigma_{(RTNDT)} = [\sigma^2_{(RTNDT_o)} + \sigma^2_{(\Delta RTNDT)}]^{1/2} . \qquad (12)$$

4.1.3 $\bar{K}_{Ic}$ and $\bar{K}_{Ia}$

Equations for mean values of K_{Ic} and K_{Ia} vs (T − RTNDT) are provided in Sect. 3. The ORNL $\bar{K}_{Ic}$ and $\bar{K}_{Ia}$ curves [Eqs. (3) and (4)] were obtained by specifying that

$$\bar{K}_{Ic} = \text{Eq. (1)} + 2\sigma, \ \sigma = 0.15\ \bar{K}_{Ic} ;$$

and

$$\bar{K}_{Ia} = \text{Eq. (2)} + 2\sigma, \ \sigma = 0.10\ \bar{K}_{Ia} ;$$

where σ = one standard deviation.

Other values of σ and the multipliers in Eqs. (3) and (4) can be specified by the user as described in Sect. 8 (Card Type 6.1). The NRC $\bar{K}_{Ic}$ and $\bar{K}_{Ia}$ curves [Eqs. (5) and (6)] were obtained by fitting mean curves through the data that were used to establish the ASME Sect. XI lower-bound curves.[10]

A provision is made in OCA-P for limiting K_{Ia} to some maximum value, $(K_{Ia})_{max}$. One way to select a value of $(K_{Ia})_{max}$ is to use a

K_J value corresponding to the upper portion of an appropriate J vs Δa curve (J-resistance curve), as illustrated in Fig. 4.2. This figure shows the radial distribution of fracture toughness through the wall of the vessel at some time during a typical postulated OCA. At temperatures less than T_D, it is assumed that the flaw will behave in a frangible manner, and above T_D, only ductile tearing will take place. In accordance with this model, it is not likely that the load line will intersect the steeply rising portion of the J-Δa curve. Thus, it is sufficient to extend $(K_{Ia})_{max}$ across the T_D line as shown. It is then possible in the analysis for crack arrest to take place on the upper shelf, if the load line rises steeply enough to miss the knee of the K_{Ia} curve and then drops back down again, as it does for some of the postulated OCAs.

A particular J-Δa curve of interest corresponds to a specific low-upper-shelf weld [referred to as 61W (Ref. 15)] that was irradiated to a fluence of $\sim 1.2 \times 10^{19}$ neutrons/cm^2 at a temperature of ~290°C and was tested at ~200°C. The upper portion of the curve is essentially horizontal and equivalent to a K_J value of ~220 MPa$\cdot\sqrt{m}$. This value has been used for $(K_{Ia})_{max}$ in the OCA studies, but the user may specify a different value.

The standard deviation for the error in K_{Ic} (and K_{Ia}) is taken as a constant, γ, times the mean value of K_{Ic}; that is, $\sigma(K_{Ic}) = \gamma\mu(K_{Ic})$, where $\mu(K_{Ic})$ is a mean value of K_{Ic} calculated from Eq. (3) or (5) for the specified time and crack depth. For this crack depth and for each time step, the simulated value of K_{Ic} is obtained from

$$K_{Ic} = x\mu(K_{Ic}) , \qquad (13)$$

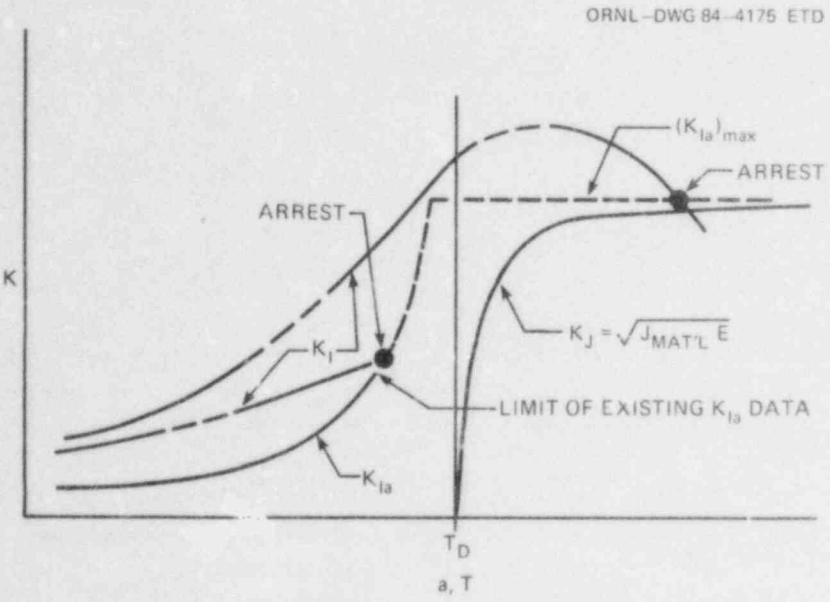

Fig. 4.2. Illustration of a method of selecting $(K_{Ia})_{max}$.

where $x \varepsilon$ normal $(1, \gamma^2)$. This is appropriate because it follows that

$$x\mu(K_{Ic}) \varepsilon \text{ normal } \{\mu(K_{Ic}), [\gamma\mu(K_{Ic})]^2\} .$$

Only one value of x is selected per crack depth.

4.2 Selection of Flaw Size and Density

At the time of this writing, the probabilistic portion of OCA-P considered only the 2-D and 2-m flaws mentioned in Sect. 3. Because the surface lengths of these flaws are fixed (∞ and ~2 m, respectively), only the depth of the flaw can be selected in the process of creating a vessel.

The flaws of primary concern to the pressurized-thermal-shock (PTS) issue are those that extend through the cladding into the base material, and there are no flaw-depth or flaw-density data pertaining to such flaws. There are data available, however, for unclad, nonnuclear vessels, and these data have been included in OCA-P as an expediency, although the uncertainty in the application of such data is large.

The flaw-depth density function included in OCA-P was taken from the Marshall report[16] and is shown graphically in Fig. 4.3. The corresponding equation is

$$f(a) = 0.16\ e^{-0.16a},\ \text{mm}^{-1} , \tag{14}$$

where

a = crack depth, mm
f(a) = (fraction of cracks with depths in the range a + a + da)/da.

Thus,

$$\int_{a=0}^{a=\infty} f(a)\ da = 1 . \tag{15}$$

Equation (14) describes the flaw-depth density prior to preservice inspection and repair. To obtain the density corresponding to the time at which the vessel goes into service, Eq. (14) must be multiplied by the probability of nondetection associated with the final preservice inspection, the assumption being made that any flaw detected is repaired or otherwise disposed of. An expression for the probability of nondetection was also taken from the Marshall report.[16] It, too, is shown in Fig. 4.3, and the corresponding equation is

$$B(a) = 0.005 + 0.995\ e^{-0.113a} , \tag{16}$$

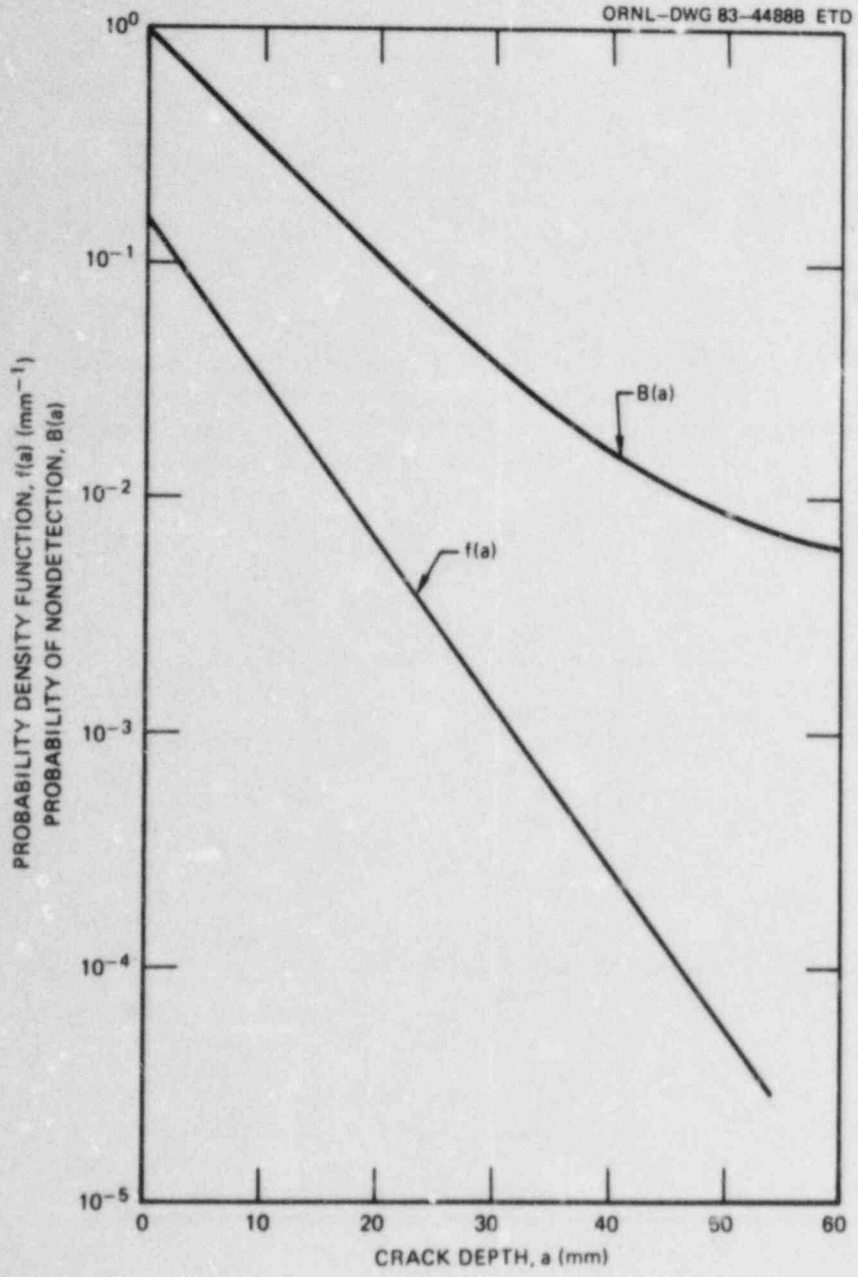

Fig. 4.3. Flaw-depth density and flaw nondetection probability functions.

where

$B(a)$ = (number of cracks in the range $a \rightarrow a + da$ when vessel goes into service)/(total number of cracks in the range $a \rightarrow a + da$ prior to repairs).

Assuming that all the cracks of interest will be located in the welds, the final probability function required is

$$P(\Delta a_i) = NV \int_{\Delta a_i} f(a)\, B(a)\, da \,, \tag{17}$$

where

$P(\Delta a_i)$ = number of cracks in a specific weld with depths in the range Δa_i as vessel goes into service,
N = number of cracks of all sizes per unit volume of weld material prior to preservice inspection,
V = volume of specific weld,
Δa_i = a specified range of crack depths about a_i such that $\sum_i \Delta a_i = w$.

Table 4.2 lists the default values of Δa_i, $\bar{a}_i$, and A and B,

where

$$A = \int_{\Delta a_1} f(a)\, B(a)\, da \Big/ \int_0^w f(a)\, B(a)\, da \,,$$

$$B = \sum_1^i \int_{\Delta a_i} f(a)\, B(a)\, da \Big/ \int_0^w f(a)\, B(a)\, da.$$

To select a flaw depth, values of B are compared with a random number between 0 and 1, and the flaw depth that corresponds to the smallest value of B that is greater than the randomly selected number is the simulated flaw depth. As an example, suppose the randomly selected number between 0 and 1 is 0.99123456. With reference to Table 4.2, the simulated crack depth would be 17.0 mm.

The relative crack depths in Table 4.2 were based on a geometric progression, and an extreme of ~57 mm was specified for the deepest crack-depth increment because deeper cracks have a very low probability of occurring as initial flaws. (For reinitiation and arrest events flaw depths up to 0.90 w are used in the analysis.) The shallowest flaw depth in Table 4.2 is equal to the shallowest flaw depth for which influence coefficients were available.

As discussed in Appendix B, the crack-depth increments included in Table 4.2 appear to be adequate for most transients. However, provisions are made in OCA-P for specifying the number of crack-depth increments,

Table 4.2. Flaw depths and related data for 2-D flaws simulated in OCA-P

Δa_i (mm)	$\bar{a}_i$ (mm)	A^a	B^b
4.3180	2.1590	0.69121788	0.69121788
4.7235	6.6797	0.22306607	0.91428395
5.1670	11.6250	0.06445519	0.97873914
5.6522	17.0345	0.01655962	0.99529877
6.1829	22.9521	0.00376842	0.99906719
6.7635	29.4253	0.00076296	0.99983014
7.3986	36.5063	0.00014054	0.99997069
8.0933	44.2523	0.00002481	0.99999550
8.8533	52.7255	0.00000450	1.00000000

$$^{a}A = \int_{\Delta a_i} f(a)\, B(a)\, da \Big/ \int_0^W f(a)\, B(a)\, da \ .$$

$$^{b}B = \sum_1^i \int_{\Delta a_i} f(a)\, B(a)\, da \Big/ \int_0^W f(a)\, B(a)\, da .$$

the size of the first increment, and the extreme value of the deepest increment (see Sect. 8). In all cases the average crack depth, which is the crack depth used in the analysis, will be located midway in the corresponding crack-depth increment, and all increments will be arranged in a geometric progression. If the smallest crack depth is less than that for which an influence coefficient is available, the influence coefficient will be obtained by interpolation between zero and the next available value.

In OCA-P, Eq. (17) is used in the following form:

$$P(\Delta a_i) = NV \int_0^W f(a)\, B(a)\, da \left[\frac{\int_{\Delta a_i} f(a)\, B(a)\, da}{\int_0^W f(a)\, B(a)\, da} \right], \qquad (18)$$

where, consistent with the data in Table 4.2,

$$\int_0^W f(a)\, B(a)\, da = 0.58732656 \ . \qquad (19)$$

The conditional probability of vessel failure, $P(F|E)$, is directly proportional to N, and thus, if OCA-P is used on a relative basis, it is not necessary to know N. This is fortunate because the uncertainty in N is orders of magnitude. The Marshall report[16] gives a range for N of 0.4 to 40 flaws of all sizes, shapes, orientations, and locations per cubic meter, and once again this information was obtained from unclad, non-nuclear vessels, whereas the flaws of concern are surface flaws that extend through the cladding into the base material of a PWR vessel.

If the results of OCA-P are used in an absolute sense, the quantity N must be estimated, and it is also necessary to estimate the fraction of vessels that have no flaws whatsoever, because these vessels are not accounted for in the flaw-depth density function [Eq. (14)]. The number of flaws in a vessel at the time the vessel goes into service is

$$NV \int_0^W f(a)\, B(a)\, da \,. \tag{20}$$

If this number is less than unity, more than one vessel must be generated to have a vessel with a flaw, and if each vessel that has a flaw has only one flaw, then

$$\frac{\text{number of vessels with flaws}}{\text{total number of vessels}} = NV \int_0^W f(a)\, B(a)\, da \,. \tag{21}$$

The OCA-P code calculates (number of failures)/(number of vessels with flaws). Therefore, if the number of flaws per vessel is less than one,

$$P(F|E) = \left(\frac{\text{number of failures}}{\text{number of vessels with flaws}}\right) \times \left(\frac{\text{number of vessels with flaws}}{\text{total number of vessels}}\right). \tag{22}$$

4.3 Consideration of Multiple Flaw Zones

In most cases encountered thus far, the weld areas in the vessel are of greatest concern with regard to propagation of a flaw. If there is more than one weld of concern in a vessel, and if it is assumed that there are fewer than one flaw per weld, then $P(F|E)$ can be obtained as follows.

Let the flaw density be uniform throughout all welds of concern. Then

$$N_{vj} = \frac{j}{\sum_j V_j} \sum_j N_{vj} \,, \tag{23}$$

and

$$P(F|E) = \frac{\sum_j N_{fj}}{\sum_j N_{vj}} N \sum_j V_j \int_0^w f(a)\, B(a)\, da \,, \tag{24}$$

where

N_{vj} = number of vessels simulated with a flaw in the jth weld,

V_j = volume of jth weld,

N_{fj} = number of vessels having a flaw in the jth weld that fail.

The actual values of N_{vj} used in the analysis often do not satisfy Eq. (23). However, they can be included in Eq. (24) as follows:

$$P(F|E) = \frac{\sum_j C_j N'_{fj}}{\sum_j C_j N'_{vj}} N \sum_j V_j \int_0^w f(a)\, B(a)\, da \,, \tag{25}$$

where

N'_{fj} = actual number of failures calculated for vessels with a flaw in jth weld,

N'_{vj} = actual number of vessels simulated that contain a flaw in the jth weld,

$$C_j = \frac{V_j}{V_1} \frac{N'_{v1}}{N'_{vj}} \,. \tag{26}$$

Equation (26) is obtained from Eq. (23) as follows:

$$\frac{N_{v1}}{N_{vj}} = \frac{V_1}{V_j} = \frac{N'_{v1}}{C_j N'_{vj}} \,. \tag{27}$$

Substituting Eq. (26) into (25) yields

$$P(F|E) = \sum_j \frac{N'_{fj}}{N'_{vj}} V_j N \int_0^w f(a)\, B(a)\, da \,. \tag{28}$$

Each term in Eq. (28) represents the probability of a flaw in the jth weld resulting in vessel failure.

4.4 Methods for Accelerating the Convergence of P(F|E)

When P(F|E) is very small, the value of N'_{vj} required to achieve reasonable accuracy (see Sect. 4.6) becomes quite large. Under some circumstances the value of N'_{vj} can be reduced by using importance sampling of one or more of the parameters simulated. Two provisions of this type are included in OCA-P as optional methods for calculating P(F|E), and both deal only with the simulation of flaw depth.

In many cases, particularly those that do not include cladding or flaws in the cladding, the first crack-depth increment does not contribute much to failure, but ~70% of the flaws normally simulated have this depth. If simulated vessels containing this flaw are counted but not calculated, the number of simulated vessels actually calculated can be reduced significantly.

The other option makes use of a stratified sampling technique[17] in which a uniform distribution of flaw depths is assumed when simulating flaw depths. The results of the subsequent analysis are then weighted by the actual flaw-depth density [Eq. (17)] to obtain

$$P(F|E) = \sum_j \sum_i \frac{N'_{fij}}{N'_{vij}} \left[\frac{\int_{\Delta a_i} f(a)B(a)da}{\int_0^w f(a)B(a)da} \right] NV_j \int_0^w f(a)B(a)da \,, \qquad (29)$$

where

N'_{fij} = number of vessels that fail with a flaw in the jth weld with depth in Δa_i,

N'_{vij} = number of vessels simulated with a flaw in the jth weld with depth in Δa_i.

The stratified-sampling procedure is useful for low-probability transients that are characterized by high pressure and a mild thermal shock.

4.5 Failure Criteria

Three failure criteria are included in OCA-P:

1. $K_I > K_{Ia}$,
2. plastic instability achieved in the remaining ligament: $\bar{\sigma}_p > \sigma_f$,
3. crack does not arrest at $a/w < 0.90$ (2-m flaw), 0.95 (2-D flaw),

where

$$\bar{\sigma}_p = p(t)\,\frac{(b + a)}{(w - a)} \text{ for axial flaws ,} \tag{30}$$

$$= p(t)\,\frac{(b + a)}{2(w - a)} \text{ for circumferential flaws ,} \tag{31}$$

$\bar{\sigma}_p$ = average pressure stress in remaining ligament,
$p(t)$ = primary-system pressure,
a = crack depth,
b = inside radius of vessel,
w = vessel wall thickness,
σ_f = flow stress for ligament.

4.6 Error Analysis

When the number of vessels simulated is quite large, as it is for the problems at hand, the central limit theorem[17] can be used to estimate the uncertainty in calculated values of the conditional probability of vessel failure as a function of the number of vessels simulated. Using this approach and specifying a 95% confidence level yields

$$P(F|E)_j = \hat{P}_j\, NV_j \int_0^w f(a)B(a)da \pm 1.96\,\sigma_j \,, \tag{32}$$

where

$P(F|E)_j$ = true value of the conditional probability of vessel failure for those vessels having flaws in the jth weld only,
σ_j = one standard deviation,

$$\hat{P}_j = \frac{N'_{fj}}{N'_{vj}} \,.$$

For the direct approach (no importance sampling)

$$\sigma_j = \left[\frac{\hat{P}_j(1 - \hat{P}_j)}{N'_{vj}}\right]^{1/2} NV_j \int_0^w f(a)B(a)da \,. \tag{33}$$

When stratified sampling is used,

$$\sigma_j = \left\{ \sum_i \left[\frac{\int_{\Delta a_i} f(a)B(a)da}{\int_0^W f(a)B(a)da} \right]^2 \left[\frac{\hat{P}_{ij}(1 - \hat{P}_{ij})}{N'_{vij}} \right] \right\}^{1/2} \times NV_j \int_0^W f(a)B(a)da \, , \quad (34)$$

where

$$\hat{P}_{ij} = \frac{N'_{fij}}{N'_{vij}} \, .$$

The value of σ corresponding to all of the vessels simulated, including those without flaws, is

$$\sigma_{P(F|E)} = \sqrt{\sum_j \sigma_j^2} \, , \quad (35)$$

and the error, ε_j, associated with the jth weld is

$$\varepsilon_j = \frac{1.96 \, \sigma_j}{\hat{P}_j \, NV_j \int_0^W f(a)B(a)da} \, . \quad (36)$$

The total error, ε, considering all welds of interest is

$$\varepsilon = \frac{1.96 \, \sigma_{P(F|E)}}{\sum_j \hat{P}_j \, NV_j \int_0^W f(a)B(a)da} \, . \quad (37)$$

Two criteria are used in OCA-P for limiting the value of N'_{vj}. One is to just achieve a user-specified value of ε_j in Eq. (36), and the other is simply a user-specified maximum value of N'_{vj}. This latter criterion is included because the former can result in an exorbitant value of N'_{vj}.

5. OCA-P INPUT CONSIDERATIONS

As indicated in Fig. 3.1, there are two categories of input for OCA-P: mandatory and optional. The mandatory input includes such parameters as T_c vs t, p vs t, T_o, h, $RTNDT_o$, F, Cu, Ni, and P, the actual input required depending on the type of analysis to be conducted. If the cladding is treated as a discrete region, the fractional cladding thickness must be specified. Optional input is optional in the sense that values are already included in the code (default values), but other values may be inputted by the user. This category includes K_{Ic} and K_{Ia} vs temperature; $(k, c_p) = f(T)$; $(\nu, \alpha, E) = f(T)$; m; mesh spacing for the thermal and stress analyses; and mean values and standard deviations for the simulated parameters.

Another optional input pertains to the thermal analysis and is the set of vessel dimensions (inner and outer diameters and cladding thickness). These dimensions must correspond to those associated with the K* file that is inputted to the PFM code. Several K* files are available for different vessel dimensions and crack orientations and are described in Sect. 3 of this report and in Ref. 6. The K* files desired by the user must be specified when requesting the OCA-P tape.

With regard to mesh spacing, mesh convergence studies indicated that ten elements in the base material with a geometric progression factor of 1.13 and two equal elements in the cladding are sufficient for the thermal analysis. For the stress analysis, two equal elements in the cladding and 13 in the base material with a geometric progression of 1.13 were found to be adequate. Thus, these two sets are used for the default values.

Input related to the probabilistic analysis is contained on cards 6.0, 6.1, and 6.2 for the PFM code (see Sect. 8.2). No input is required for the probabilistic plotting package. If only a deterministic run is desired, this can be achieved by including a slash in column 1 of Card Type 6.0 and by omitting Card Types 6.1 and 6.2.

Input for OCA-P can be in either English or SI units. The analysis is performed using English units, but if SI units are specified, appropriate conversions are made within the code to convert SI to English and then to convert English back to SI for the output. One or the other type of unit must be specified on Card Type 2.0 in 1-R and 1.0 in PFM.

6. OCA-P OUTPUT CAPABILITY

The results of OCA-P are presented in both digital and graphical form.

Digital output for deterministic analysis:

1. Wall temperature, stress, ΔRTNDT, K_I, K_{Ic}, K_{Ia}, K_I/K_{Ic}, and K_I/K_{Ia} for each crack depth at selected times (unit number = 6).
2. Crack depths corresponding to initiation and arrest events for the times at which the events take place (unit number = 17).
3. Critical values of F_o and $\Delta RTNDT_s$ corresponding to incipient initiation, when a search analysis is performed (unit number = 17).

Digital output for probabilistic analysis:

1. A summary of data pertaining to initiation and arrest events (limited to seven pages).
2. A summary of calculated probabilities and corresponding histogram data.

Plotting capabilities for deterministic analysis:

1. **Critical-crack-depth curves.**
2. **(K_I, K_{Ic}, K_{Ia}, stress, temperature) vs a/w for selected time steps.**
3. **Temperature vs (t, a/w);**
4. **K_I vs (t, a/w).**
5. **(K_I/K_{Ic}, K_I/K_{Ia}) vs (t, a/w).**

Plotting capabilities for probabilistic analysis:

1. P(F|E) vs number of trials (intervals of 10^4 trials).
2. Histogram of crack depths resulting in first initiation event.
3. Histogram of times at which failures occur.
4. Histogram of T — RTNDT corresponding to all crack initiation events.
5. Histogram of T — RTNDT corresponding to all crack arrest events.

The summary of data pertaining to initiation and arrest events for the probabilistic analysis includes the time, pressure, crack-tip temperature, flaw depth, and the simulated values of Cu, Ni, F_o, RTNDT, and K_{Ic}, all corresponding to crack initiation. Also included are crack depths corresponding to arrest and the onset of plastic instability. If a reinitiation event takes place following an arrest event, similar data are included for this event on a following line. Each line of data is identified by simulation number (vessel number), initiation number, and failure number (when appropriate).

The critical-crack-depth curves consist of plots of crack depths corresponding to various events and conditions as a function of the

times at which the events and conditions take place. The curves include the locus of points for $K_I = K_{Ic}$ (initiation curve), $K_I = K_{Ia}$ (arrest curve), $K_I = (K_I)_{max}$ [warm prestress (WPS) curve for $\dot{K} \leq 0$], $K_I =$ constant (iso K_I curve), temperature isotherms, and T — RTNDT isotherms. The WPS curve is plotted only if $\dot{K}_I < 0$ for the remainder of the transient. The iso K_I curves and the isotherms are included so that judgments can be made regarding upper-shelf behavior.

Output from OCA-P can be obtained in either English or SI units, depending upon which units are used for the input.

Samples of the digital and plotted output are included in Appendix A.

7. INSTRUCTIONS FOR EXECUTION OF OCA-P

Considerations involved in the execution of OCA-P are similar to those described in Sect. 5 of the OCA-II manual.[6] As mentioned earlier, in addition to the subcodes 1-R and FM (PFM in OCA-P) there is a subcode, PR, in OCA-P for additional plotting routines. The table of FORTRAN I/O unit numbers in OCA-P includes the units used by the OCA-P plotting package (Table 7.1.).

Three mathematical routines from the NAG* library are used by the code. They are

G05CBF(ISEED) – set random number seed,
G05CAF(X) – uniform distribution random number generator, where X is a dummy variable,
G05DDF – normal distribution random number generator (mean, standard deviation).

All plot-related coding is written in terms of CALLs to DISSPLA† routines. Users without access to the DISSPLA software should include the following subroutine during compilation of the PFM code:

```
SUBROUTINE  PLTCTL
ENTRY  KRPLOT
ENTRY  KIPLOT
ENTRY  PI
ENTRY  ENPL04
ENTRY  FNDCON
ENTRY  PLTALL
RETURN
END
```

---

*NAG, Numerical Analysis Group, Harwell, England.

†Display Integrated Software System Plotting Language, a proprietary software package of Integrated Software Systems Corporation, San Diego, Calif. 92121.

Table 7.1. FORTRAN I/O unit number requirements of the OCA-P code

Variable name	Current definition	Description	Format	Used by the codes			Comments
				1-R	PFM	Plot package	
LIN	55	User input to the codes	Cards or card images	Yes	Yes		
LPRT	6	Results of the calculations for each time step	Printer	Yes	Yes	Yes	
LU1	1	Temperature data file	Binary[a]	Yes	Yes		Output from 1-R, input to PFM
LU2	2	Data required by the PFM code	Binary	No	Yes		2-D axial-flaw K* values
LU3	17	Summary of results: critical-crack depths for initiation and arrest	Printer	No	Yes		
LU4	3	User input of stresses across the cylinder wall	Cards or card images	No	Yes		
LU5	56	User defined K_{Ic} and K_{Ia} curves	Cards or card images	No	Yes		
LU7	7	Data required by the PFM code	Binary	No	Yes		3-D influence coefficients (K_j^*)
LU8	8	Data required by the PFM code	Binary	No	Yes		2-D circumferential-flaw K* values
LU9	19	Data to be plotted	Binary	No	Yes	Yes	Output from PFM to PR

[a]Space requirements are approximately one double word/node/time step.

8. USERS' MANUAL FOR OCA-P

In this section, "Card Types" have been designated for the purpose of organizing the input data. Each Card Type corresponds to a single READ-list, and data for a single READ-list can be included on several cards.

Refer to Nomenclature for the SI and English units required for input. SI units only are included in the Users' Manual.

8.1 Input Data for the 1-R Code

The input data for 1-R is given in this section. The READ-statements for Card Types 1.0, 2.0, 3.2, 4.0, and 5.0 through 5.6 are in subroutine INPUT. The READ-statements for Card Types 3.0 and 3.1 are in subroutine MODEL.

Card Type 1.0 — Title Card

Variable	Default	Description
HED	REACTOR-VESSEL	A title for this run. A maximum of 72 characters can be coded anywhere in columns 1 through 72.†

†This is the only card that has any particular column requirements.

Card Type 2.0 — Main Control Card

Variable	Default	Description
MODEL	0	Geometric modeling method used to generate mesh spacing between nodes. = 0: A geometric progression factor, specified on Card Type 3.0, is used for base material. A single material is used for the base material and another for the cladding. = 1: Nodes specified on Card Type 3.1 with missing nodes generated by linear interpolation. Requires specification of material properties for each element (Card Type 3.2).
NDT	None	Total number of time steps used in the analysis.
INTER	None	Number of time steps between times at which temperature output† is obtained for the stress analysis.
DT	0.15	Time increment to be used for each time step, s.
TO	None	Initial temperature for vessel wall, °C.
NUMEL	10	Number of elements; maximum 12, including cladding. The number of nodes generated is NUMNP=2*NUMEL+1; see illustration used with description of Card Type 3.2.
NGAUSS	4	Number of Gaussian points used in numerical integration.
ISISW	1	Controls input and output units. = 0: English. = 1: SI.

The temperature output times are at equal intervals. Because the temperatures are calculated at every time step regardless of those specified for output, the number of output times has no significant effect on the 1-R CPU time. When executing the PFM code, the user selects the 1-R output times to be used in the fracture-mechanics analysis.

†The temperatures of the nodes are printed on the line printer, unit number LPRT(=6), and also written in binary [unit number LU1(=1)], for use by the PFM code.

Card Type 3.0 — Geometry Card

Only required if MODEL=0 (defined on Card Type 2.0)

Variable	Default	Description
GPFACT	1.13	Geometric progression scaling factor used to generate the node spacing in base material.
X(1)	2184	Inside radius of vessel, mm.
W	216	Total wall thickness including cladding if present, mm.
FRCLTH	0	Fractional cladding thickness on inside surface of vessel (cladding thickness/wall thickness).
NUMCLA	2	Number of elements, equally spaced, in the cladding, from NUMEL (Card Type 2.0) to be used in modeling the cladding.

NUMNP nodes (where NUMNP=2*NUMEL+1) are generated between the radii of X(1) and X(1) + W for the inner and outer radii, respectively, using the above geometric progression scaling factor. The mesh spacing, D, between the first node at the inner radius and the next one is calculated as

$$D = \frac{W\ (GPFACT - 1)}{(GPFACT^{N} - 1)},$$

where N=2*NUMEL. Each succeeding space is then GPFACT times the previous one.

Card Type 3.1 — Nodal Point Definition Cards

Only required for MODEL=1 (defined on Card Type 2.0)

There are no defaults for these cards.

Variable	Description
N	Node number.
KODE(N)	Boundary condition code. = 0: External heat flow specified for this node. = 1: Temperature specified for this node.
X(N)	Radial distance of node N, mm.†
T(N)	Specified heat flux or specified temperature; W/m^2, °C.

The READ-list is (N,KODE(N),X(N),T(N),N=1,NUMNP), where NUMNP=2*NUMEL+1 and NUMEL is the number of elements specified on Card Type 2.0. The maximum number of elements in this version is 12; thus, the maximum number of nodes is 25. A record for N=1 and one for N=NUMNP must be supplied as a minimum. Nodal point definition cards must be in sequence. A missing value for N is obtained by linear interpolation between the two values supplied. For the records generated, KODE(N) and T(N) are set to zero. With KODE(N)=0 and no values specified for T(N), the node is insulated. This is overridden if any boundary conditions are specified later on Card Type 5.0.

†The inner and outer radii used here should correspond to those associated with the K* values used in PFM.

Card Type 3.2 — Element Material Type Definition Cards

Only required for MODEL=1 (defined on Card Type 2.0)

Variable	Default	Description
LM(4,M)	1	Material type for element M.

The actual material properties are defined by means of Card Type 4.0. The READ-list is (LM(4,M),M=1,NUMEL). A concise format of data entry may be used. For example, suppose NUMEL=5, and there are two types of materials. Then the data may be entered either as 1,2,2,2,2 or as 1,4*2 (or ,4*2 because default is material type 1).

The relationship between node and element numbers is explained with the aid of Fig. 8.1. There are three nodes in each element. Different material types can be specified for elements only, not nodes.

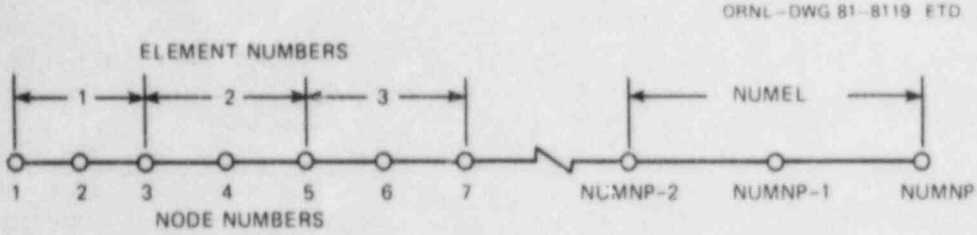

Fig. 8.1. Relationship between node and element numbers.

Card Type 4.0 — Material Property Cards

Variable	Default	Description
NUMMAT	1	Number of different material types with a maximum of 25 in this version.
XCOND(1)	41.5	Thermal conductivity, W/m•°C.
SPHT(1)	502	Specific heat, J/kg•°C.
DENS(1)	7830	Density, kg/m^3.

The READ-list is NUMMAT, (XCOND(M),SPHT(M),DENS(M),M=1,NUMMAT). Thus, the last three variables should be repeated NUMMAT times. If cladding is present (FRCLTH > 0 on Card Type 3.0), then NUMMAT is reset internally to two, the above properties will be used for the base metal, and the following properties are used for the cladding:

Variable	Default	Description
XCOND(2)	17.3	Thermal conductivity, W/m•°C.
SPHT(2)	502	Specific heat, J/kg•°C.
DENS(2)	7830	Density, kg/m^3.

Card Type 5.0 — Convective Boundary Conditions

Card Type	Variable	Default	Description
5.0	NUMCBC	1	Number of convective boundaries.
	If NUMCBC=0, skip remaining cards.		
5.1	ICBC	1	Node number with convective boundary conditions. Node 1 is the inside surface node.
5.2	NHV	None	The number of times for which the heat transfer coefficient is provided. Maximum NHV is 100.
5.3	TIMH(I)	None	Time in minutes, if NHV is positive; time in seconds, if NHV is negative.
	HV(I)	None	Heat transfer coefficient, $W/m^2 \cdot °C$.
5.4	NTBV	None	The number of times for which the bulk coolant temperatures are provided. A positive or negative value of NTBV specifies the method explained under Card Type 5.5, whereas a zero NTBV specifies the method explained under Card Type 5.6. Maximum NTBV is 100.
5.5	Only required if NTBV is positive or negative.		
	TIM(I)	None	Time in minutes if NTBV is positive; time in seconds if NTBV is negative.
	TB(I)	None	Bulk coolant temperature, °C.

The READ-list is (TIM(I),TB(I),I=1,NTBV). Thus, NTBV pairs are required. The code performs a linear interpolation for intermediate values. If only one value is given, that value will be used throughout the transient.

5.6	Only required if NTBV is zero.		
	AO, BO, CO	None	The bulk coolant temperature is calculated by means of the exponential function T_B = AO + BO * EXP (CO*t), where t is time in minutes, and AO, BO, and CO have units of °C, °C, and min^{-1}, respectively.

8.2 Input Data for the PFM Code

Input data for the PFM code is given in this section. Several subroutines are used and are identified in the first column of the tabular description of the input control cards under the heading S/R Name. These subroutines contain the READ-statement for the input variables in question.

Parametric studies [in which the fluence (FO), initial reference temperature (RTNDTO), copper concentration (CUPER), nickel concentration (PERNI), phosphorous concentration (PPER), or increase in reference temperature at the inner surface (DRTNIN) are variables] can be performed automatically with PFM. To do so, the main body of input data requirements described in this section must first be satisfied; this defines one complete execution cycle of the code. Each additional case to be included requires Card Type 4.0, which redefines one of the variables. These additional cards are included at the end of the main body of input data. The appended Card Type 4.0 need contain only the variable or variables that are to be changed (a procedure is described in Ref. 7). All remaining variables not changed by input data retain the values previously defined.

Card Type 1.0 — Main Control Card

S/R Name	Variable	Default	Description
DATA1	TYTTL(1)	Blanks	An identification for this run, using up to six alphanumeric characters enclosed in quotes. This is used solely for identifying this run and is printed on every page of output and on plots if any.
	KICTYP	3	Toughness properties used for K_{Ic} and K_{Ia}. = 3: ASME Code Section XI, Appendix A values. = 6: User defines with input data to unit LU5(=56).
	NCYCLE	999	The number of time intervals read from the temperature data. Not all of these are necessarily used in the analysis.
	ISKIP	1	The time interval number at which processing of the temperature data begins.
	ICRKTP	+4	Crack shape to be included in the analysis: An axial crack is selected if ICRKTP is positive, a circumferential one if ICRKTP is negative. = ±1 2-D only. = +2 2-D, 2-m. = +3 6/1, 2-m. = +4 6/1, 2-m, and 2-D. = ±5 6/1, 2-D.
	TREF	0	Reference temperature for vessel wall. = 0: TO from 1-R. ≠ 0: TREF (user-supplied value).
	NOPT	0	Controls printout of two different computer tabulations (referred to here as Tables 1 and 2) of the temperature, stress, and material toughness values (K_{Ic} and K_{Ia}). Table 1 contains this information at all radial points in the wall at which the temperatures are calculated. Table 2 contains the same and additional information, but only for the specific crack depths for which K* values are available. Output typical of Table 2 is illustrated in Appendix A. = 0: Only Table 2 is printed. = 1: Both tables are printed. = -1: Only Table 1 is printed.
	ISISW	1	Controls input and output units. = 0: English. = 1: SI.

Card Type 1.1 — Plot Control Card

S/R Name	Variable	Default	Description
DATA1	NPLOT	0	Controls plotting of temperature profile in cylinder wall. = 0: None is performed. = 1: Plots. Requires Cards P1 and P2.
	KRPLT	0	Controls plotting of the K-ratio K_I/K_{Ic} and K_I/K_{Ia}. = 0: None. = 1: Plots. Requires Cards P3, P4, and P5.
	KIPLOT	0	Controls plotting for K_I values. = 0: None. = 1: Plots. Requires Cards P6 and P7.
	KENPLT	0	Controls the plotting of the critical-crack-depth curve (a_c/w vs t). = 0: None. = 1: Plots. Requires Card P8.
	KALPLT	0	Controls plotting of a set of curves that includes temperature, stress, K_I, K_{ic}, K_{Ia} vs a/w; one plot is obtained for each time interval selected. = 0: None. = 1: Plots.

Card Type 2.0 — Pressure Control Card

S/R Name	Variable	Default	Description
DATA1	NPR (IBINSW=0 or 1)	0	Number of time-pressure values. A positive value indicates time in minutes on Card Type 2.1, whereas a negative value indicates time in seconds.
	NPR (IBINSW=2)	0	Number of constant pressures; Card Type 2.1.

Card Type 2.1 — Pressure Definition Card
Only required if NPR ≠ 0 on Card Type 2.0.

S/R Name	Variable	Description
DATA1	TMPR(I)	Time in minutes if NPR is positive. Time in seconds if NPR is negative. Enter 0 to hold card position if (IBINSW=2).
	PR(I)	Pressure, MPa.

The READ-list is (TMPR(I), PR(I), I=1,NPR). The pressure acting on the inside of the cylinder need not be specified for each time used in the FM analysis. The pressures at times for which pressures are not specified are obtained by linear interpolation. In the case of a parametric search type analysis involving more than one constant pressure (IBINSW=2), use PR(I) for entering the constant pressures to be analyzed and enter zero for TMPR(I).

Card Type 3.0 — Radiation Damage/Run Control Card

S/R Name	Variable	Default	Description
DATA1	IRTNSW	1	Controls method of calculation of radiation damage across the vessel wall. = 0: By *Regulatory Guide 1.99* (Rev. 1), supply FO, RTNDTO, CUPER, and PPER on Card Type 4.0. = 1: Eqs. (9a) and (9b); supply FO, RTNDTO, CUPER, and PERNI on Card Type 4.0. = 2: Eq. (9a); supply RTNDTO, DRTNDT on Card Type 4.0.
	ATTCON	0.0094	Fluence attenuation constant, mm^{-1} .
	ISTRSW	0	Controls input of stresses on unit 3. = 0: Stresses calculated internally. = 1: Stresses input on unit 3 to match time intervals selected.

Card Type 3.1 — Incipient Initiation Search Control

S/R Name	Variable	Default	Description
DATA1	IBINSW	0	Controls the search for incipient initiation (II) without warm-prestress curve (WPS). = 0: No search. = 1: Search performed for $(F_o)_c$ or $(\Delta RTNDT_s)_c$ for the transient inputted. = 2: Search performed for $(F_o)_c$ or $(\Delta RTNDT_s)_c$ for a series of constant pressures on Card Type 2.1.
	ISEASW	0	Type of flaw used in II search without WPS. = 0: 2-D flaw. = 1: 6/1 flaw.
	AWMIN	0.0249	Minimum a/w considered for initiation in a search (IBINSW=1 or 2).
	AWMAX	0.15	Maximum a/w considered for initiation in a search (IBINSW=1 or 2).
	TUPLIM	278 or 5×10^{19}	Upper limit of $\Delta RTNDT_s$ or F_o to be used in the search; °C, neutrons/cm^2.

Card Type 4.0 — Radiation Damage/Fracture Toughness

S/R Name	Variable	Default	Description
DATA1	FO	None	Inside-surface fluence (F_o), neutrons/cm^2; neutron energy > 1 MeV.
	RTNDTO	None	Initial reference temperature ($RTNDT_o$), °C.
	CUPER	None	Copper content (CUPER ≤0.35), wt %.
	PPER	None	Phosphorous content, wt %.
	PERNI	None	Nickel content, wt %.
	DRTNIN	None	$\Delta RTNDT_s$, °C.

For parametric studies involving FO, RTNDTO, CUPER, and PERNI, an additional Card Type 4.0 is required for each subsequent case and is added at the end of the complete set of input data described on the following pages. These six variables (FO, RTNDTO, CUPER, PPER, PERNI, and DRTNIN) are read in on the additional Card Types 4.0 for the parametric studies; however, only the values changed from the previous card need to be included as explained in Sect. 5.1 OCA-I manual. Similarly, when using $\Delta RTNDT_s$ as the independent variable for calculating radiation damage (IRTNSW=2), Card Type 4.0 may be added for parametric studies involving DRTNIN.

Card Type 4.1 — FE Control Card

S/R Name	Variable	Default	Description
INPUT	MODEL	0	Geometric modeling method used to generate mesh spacing between nodes. = 0: A geometric progression factor specified on Card Type 4.2 is used. = 1: To model cladding; Card Type 4.3 must be provided.
	NUMEL	15	Number of elements; the maximum is 17. The number of nodes generated is NUMNP = 2*NUMEL+1. See illustration used with description of Card Type 3.2 for the 1-R code.
	NGAUSS	2	Number of Gauss points used in numerical integration. NGAUSS is set equal to 2 for circumferential cracks.

Card Type 4.2 — Geometry Card

Only required if MODEL=0 (defined on Card Type 4.1)

Variable	Default	Description
GPFACT	1.13	Geometric progression scaling factor used to generate the node spacing.

Using the above geometric progression scaling factor, NUMNP nodes (where NUMNP=2*NUMEL+1) are generated between the inner and outer radii used in the 1-R analysis. The mesh spacing D between the first node at the inner radius and the next one is calculated as

$$D = \frac{W\ (GPFACT - 1)}{(GPFACT^{N} - 1)},$$

where N=2*NUMEL. Each succeeding space is then GPFACT times the previous one.

Card Type 4.3 — Cladding Definition Card

Only required if MODEL=1 (defined on Card Type 4.1)

S/R Name	Variable	Default	Description
MODELO	NECLAD	2	Number of elements in the cladding.
MODELO	X(N)	None	Fractional cladding thickness (cladding thickness/wall thickness). From the cladding-base interface to the outer radius, a geometric modeling method is used to generate the remainder of the mesh. The default GPFACT is used in this generation of (NUMEL-NECLAD) elements.

Card Type 4.4 — Material Properties

S/R Name	Variable	Default	Description
INPUT	NUMMAT	1	Number of different materials to be described.
	NUMTME	1	Number of temperatures at which E is defined.
	TEMP1(I)		Temperature, °C.
	E(I,1)	†	Young's modulus of elasticity, MPa.
	.		
	.		
	.		
	E(I,NUMMAT)	†	Young's modulus at TEMP1(I) for material NUMMAT.

The READ-list is:
(NUMMAT,NUMTME,(TEMP1(I),(E(I,J),J=1,NUMMAT),I=1,NUMTME))

---

†The defaults for E(1,1) and E(1,2) are 193.0E3 and 186.0E3, respectively.

Note: Material 1 corresponds to the base material, while material 2 corresponds to the cladding, if modeled.

Card Type 4.5 — Material Properties (Continued)

S/R Name	Variable	Default	Description
INPUT	NUMTMA	1	Number of temperatures at which ALFA is defined.
	TEMP2(I)		Temperature, °C.
	ALFA(I,1)	†	Coefficient of linear expansion, $°C^{-1}$.
	ALFA(I, NUMMAT)	†	Coefficient of linear expansion at TEMP2(I) for material NUMMAT.

The READ-list is:
(NUMTMA,(TEMP2(I),(ALFA(I,J),J=1,NUMMAT),I=1,NUMTMA))

---

†The defaults for ALFA(1,1) and ALFA(1,2) are 14.5E—6 and 17.9E—6, respectively.

Note: Material 1 corresponds to the base material; material 2 corresponds to the cladding, if modeled.

Card Type 4.6 — Material Properties (Continued)

S/R Name	Variable	Default	Description
INPUT	NUMTMP	1	Number of temperatures at which ν is defined.
	TEMP3(I)		Temperature, °C.
	PNU(I,1)	†	Poisson's ratio.
	PNU(I, NUMMAT)	†	Poisson's ratio at TEMP3(I) for material NUMMAT.

The READ-list is:
(NUMTMP,(TEMP3(I),(PNU(I,J),J=1,NUMMAT),I=1,NUMTMP))

†The defaults for PNU(1,1) and PNU(1,2) are 0.3.

Note: Material 1 corresponds to the base material; material 2 corresponds to the cladding, if modeled.

Card Type 5.0 — Selection of Time Intervals Card

S/R Name	Variable	Default	Description
DATA1	IRUN(I)	0	The interval number, from the temperature data, to be processed. Maximum number is 61 time intervals. The default 0 processes all intervals from ISKIP through NCYCLE (on Card Type 1.0).

The temperature output intervals from the 1-R code are at equal time increments. In the case of the 1-R code, all the time intervals over the specified analysis time are calculated regardless of those specified for output, and no appreciable increase in CPU time is incurred if the number of output intervals is large. However, not all the temperature intervals need be processed by the PFM code. The variable IRUN allows the user to select only those intervals (maximum 61) at which temperature output is available for processing by the PFM code.

Card Type P (Plotting Cards)

Only those required by the various parameters on Card Type 1.1 should be used. All axes lengths are in mm (in.)

Card Type	S/R Name	Variable	Default	Description
P1	P1	GLX(1)	None	Length of a/w axis.
		XMAX(1)	None	Maximum value of a/w (1.0).
		XTCK(1)	None	Number of major tick marks on a/w axis.
		GLX(2)	None	Length of time axis.
		XMAX(2)	None	Maximum value of time, min.
		XTCK(2)	None	Number of major tick marks on time axis.
P2	P1	GLY	None	Length of temperature axis.
		YMIN	None	Minimum temperature, °C.
		YMAX	None	Maximum temperature, °C.
		YTCK	None	Number of major tick marks on temperature axis.
P3	KRPLOT	GLX(1)	None	Length of a/w axis.
		XMAX(1)	None	Maximum value of a/w (1.0).
		XTCK(1)	None	Number of major tick marks on a/w axis.
		GLX(2)	None	Length of time axis.
		XMAX(2)	None	Maximum value of time, min.
		XTCK(2)	None	Number of major tick marks on time axis.
P4	KRPLOT	GLY	None	Length of K-ratio† axis.
		YMAX	None	Maximum K-ratio.
		YTCK	None	Number of major tick marks on K-ratio axis.
P5	KRPLOT	KONPLT	None	Controls the selection of the sets of time and a/w plots of the K-ratios to be made. = 1: K_I/K_{Ic} only. = 2: Both K_I/K_{Ic} and K_I/K_{Ia}.
P6	KIPLOT	GLX(1)	None	Length of a/w axis.
		XMAX(1)	None	Maximum value of a/w (1.0).
		XTCK(1)	None	Number of major tick marks on a/w axis.
		GLX(2)	None	Length of time axis.
		XMAX(2)	None	Maximum value of time, min.
		XTCK(2)	None	Number of major tick marks on time axis.

†K_I/K_{Ic} and K_I/K_{Ia}.

Card Type P (Plotting Cards) (continued)

Card Type	S/R Name	Variable	Default	Description
P7	KIPLOT	GLY	None	Length of K_I axis.
		YMAX	None	Maximum K_I, MPa$\cdot\sqrt{m}$.
		YTCK	None	Number of major tick marks on K_I axis.
P8	ENPLOT	GLX	None	Length of time axis.
		XMAX	None	Maximum value of time, min.
		XTCK	None	Number of major tick marks on time axis.
		IROTSW	0	Plot rotation switch. = 0: No rotation. = 1: Rotate plot 90°.
		NKIS	2	Number of K_I contour lines; NKIS ≤ 6.
		VALKI	110,220	K_I contour line values, MPa$\cdot\sqrt{m}$.
		NTDS	0	Number of isotherms |NTDS| ≤ 6. +: (T − RTNDT) isotherms. −: temperature isotherms.
		VALTD	None	Isotherm values, °C.

Card Type 6.0 — Probabilistic Control Parameters

S/R Name	Variable	Default	Description
RDPTSS	NSIM	0	Maximum number of trials to be generated for each weld if IACCEL=0 or 1, for each flaw depth if IACCEL=2.
	IACCEL	0	Controls use of importance sampling. = 0: no importance sampling = 1: first-increment flaw does not initiate but is counted in number of trials, thus accelerating convergence. = 2: uniform sampling of crack depth (NSIM trials used for each crack depth).
	VOLWLD	1	Volume of weld 1 on Card Type 6.2, m^3.
	WELDN	1	Number of flaws/m^3.
	CONVPC	10	Maximum percent error in $P(F\|E)$ for each weld at a 95% confidence level.
	FLWSTR	551.7	Flow stress for plastic instability determination, MPa.
	USKIA	220	$(K_{Ia})_{max}$, MPa$\cdot\sqrt{m}$.
	NPCRK	9	Number of increments to be used for initial crack depth (maximum of 15).
	AWINT	4.3	Size of first crack-depth increment, mm.
	CDLIM	57.2	Extreme dimension of deepest crack-depth increment, mm. A geometric progression of NPCRK increments is generated between 0 and CDLIM to model initial crack depths. K_I values are sampled at midpoint of each increment.

Card Type 6.1 — Probabilistic Distribution Parameters

S/R Name	Variable	Default	Description
RDPTSS	SDFDRT	13	ΔRTNDT standard deviation, °C.
	SDFKIC	0.15	K_{Ic} standard deviation (fraction of mean). If positive, use ORNL mean curve, Eq. (3); if negative, use NRC mean curve, Eq. (5).
	SDFKIA	0.1	K_{Ia} standard deviation (fraction of mean). If positive, use ORNL mean curve, Eq. (4); if negative, use NRC mean curve, Eq. (6).
	SDLDRT	3.0	ΔRTNDT-distribution truncation point (number of standard deviations).
	SDLKIC	3.0	K_{Ic}-distribution truncation point (number of standard deviations).
	SDLKIA	3.0	K_{Ia}-distribution truncation point (number of standard deviations).
	CONKIC	1.43	K_{Ic}-equation multiplier.
	CONKIA	1.25	K_{Ia}-equation multiplier.

Card Type 6.2 — Weld Characteristics

S/R Name	Variable	Default	Description
RDPTSS	NWELDS	1	Number of welds to be simulated.
	PFO(I)	†	Mean inside-surface fluence, neutrons/cm^2.
	PCU(I)	†	Mean copper content, %.
	PNI(I)	†	Mean nickel content, %.
	RTNDTO(I)	None	Mean initial reference temperature, °C.
	SIGFO(I)	0.3	Fluence standard deviation, fraction of mean.
	SIGCU(I)	0.025	Copper standard deviation, %.
	SIGNI(I)	0.0	Nickel standard deviation, %.
	SIGRTO(I)	9	Initial reference temperature standard deviation, °C.
	VOLFAC(I)	1.0	Fraction to adjust $P(F\|E)_1$ for weld I based on the volume of the weld relative to weld 1. VOLFAC(1) = 1.0.

The READ-list is: NWELDS, [PFO(I), PCU(I), PNI(I), PRTNO(I), SIGFO(I), SIGCU(I), SIGNI(I), SIGRTO(I), VOLFAC(I), I = 1, NWELDS].

---

†If NWELDS = 1, these parameters are obtained from Card Type 4.0, if not provided here.

Card Type M — User-Specified K_{Ic} and K_{Ia} Curves

Only required if KICTYP=6 on Card Type 1.0

The values are read by subroutine RPKICV from unit LU5(=56).

Variable	Description
HEDKIC	A descriptive title associated with the following toughness values as a means of identification. A maximum of 72 characters can be placed anywhere in columns 1 through 72 (see footnote with Card Type 1.0, Sect. 8.1).
NKIC	Number of temperature—K_{Ic} pairs, with a maximum of 20 pairs.
VKIC(I,1)	Temperatures at which K_{Ic} values are supplied, °C.
VKIC(I,2)	A list of the corresponding K_{Ic} values, MPa$\cdot\sqrt{m}$.
NKIA	Number of temperature—K_{Ia} pairs, with a maximum of 20 pairs.
VKIA(I,1)	A list of the temperatures at which K_{Ia} values are supplied.
VKIA(I,2)	A list of the corresponding K_{Ia} values.

The READ-list for the tabular values of K_{Ic} is NKIC,((VKIC(I,J), I=I,NKIC), J=1,2), with a similar one for K_{Ia}. Temperature values are read first; then all of the corresponding toughness values are read.

A piecewise cubic polynomial (spline) is fitted through the supplied values, and the polynomial is evaluated for the K_{Ic} and K_{Ia} values at the specified temperature. Thus, only a few pairs of values need be specified to define a smooth curve.

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Appendix A

SAMPLES OF OCA-P DIGITAL AND GRAPHICAL OUTPUT

The graphical and digital sample output for the postulated transient described in Fig. A.1 is included in Figs. A.2—A.7 and in the reproduced copies of the OCA-P standard digital output.

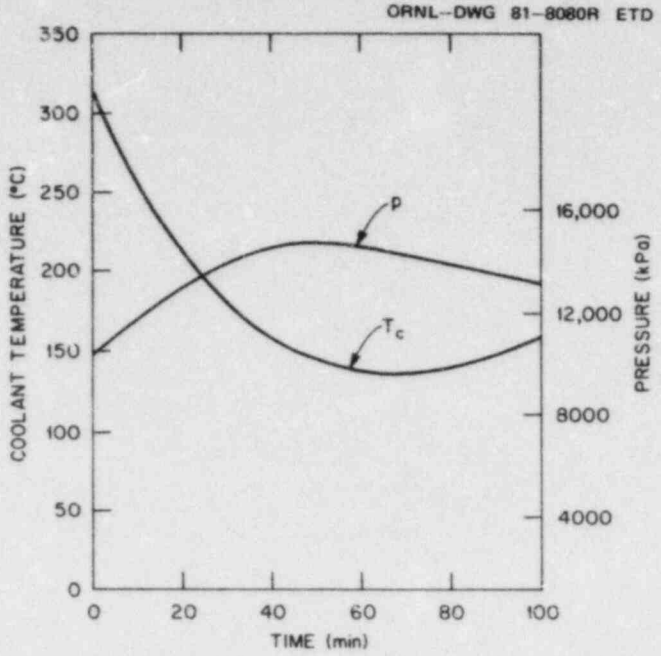

Fig. A.1. Typical postulated overcooling accident for PWRs.

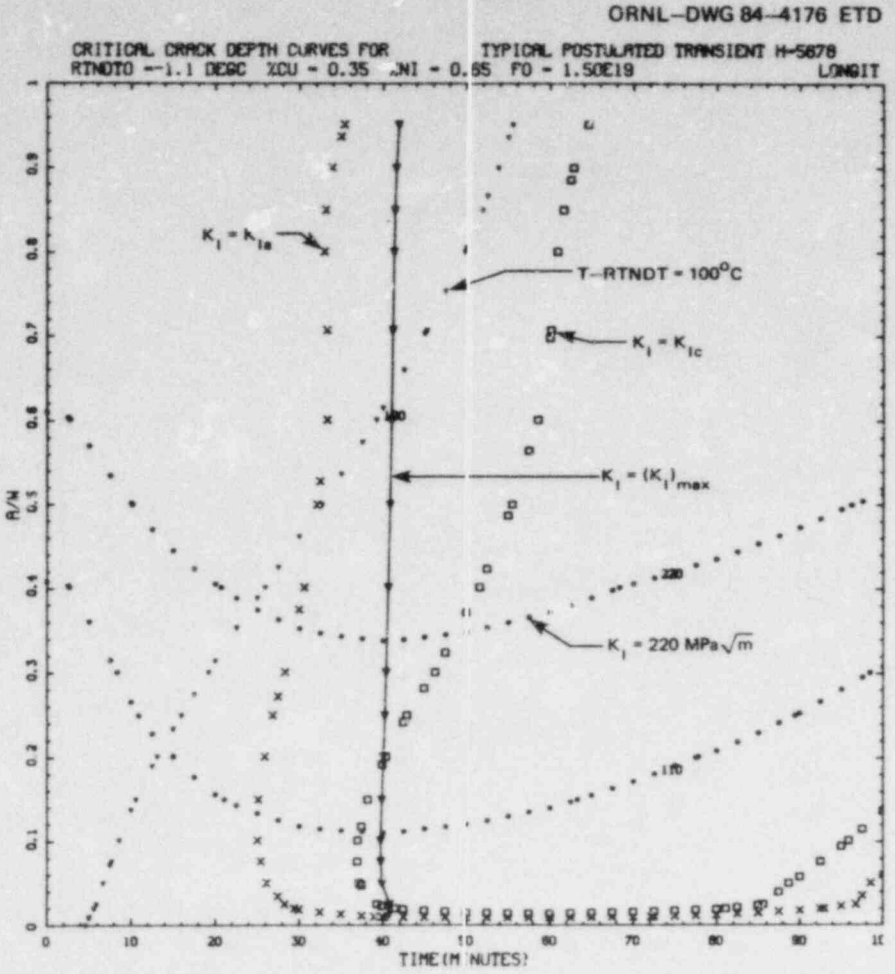

Fig. A.2. Critical-crack-depth curves based on 2-D, inner-surface, axial flaws with cladding included as a discrete region.

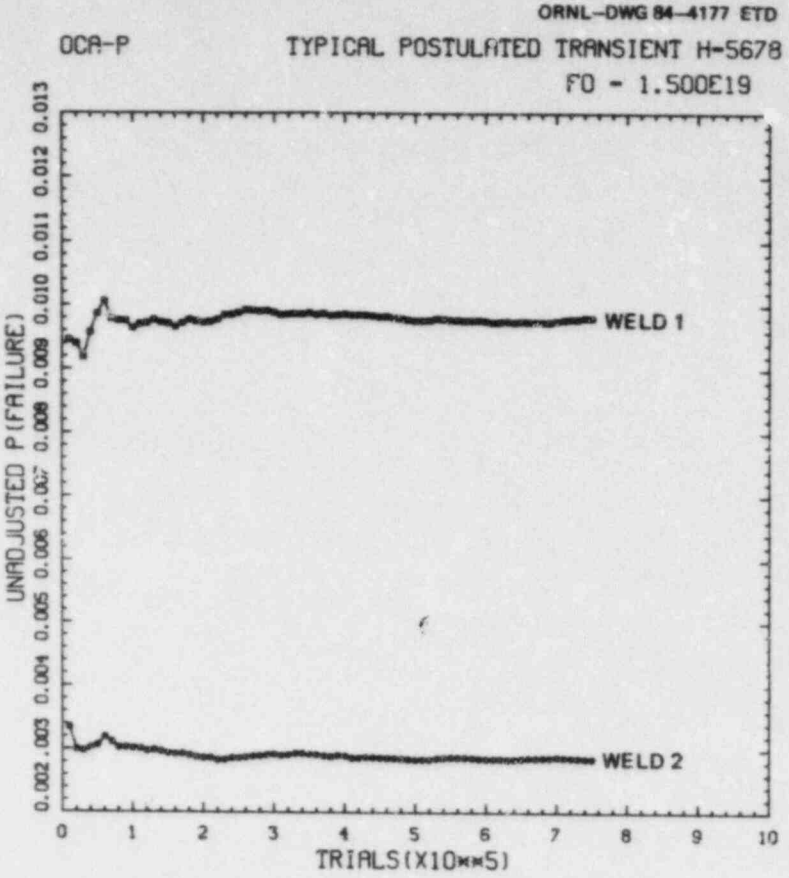

Fig. A.3. P(F|E) vs number of trials.

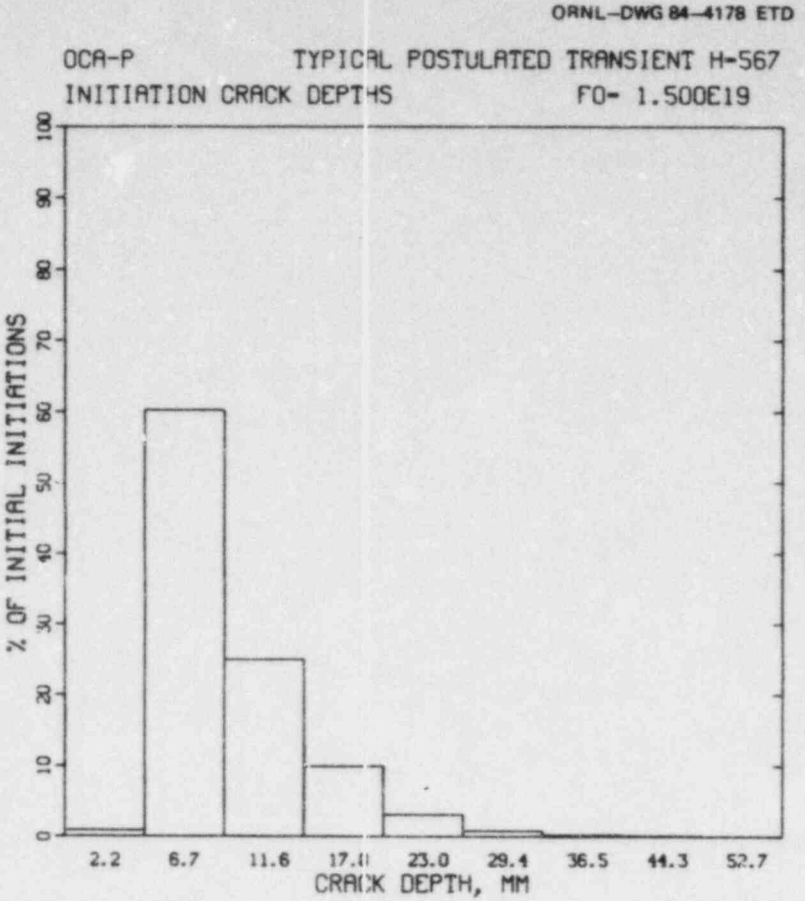

Fig. A.4. Percent of total initial initiations vs crack-depth increment.

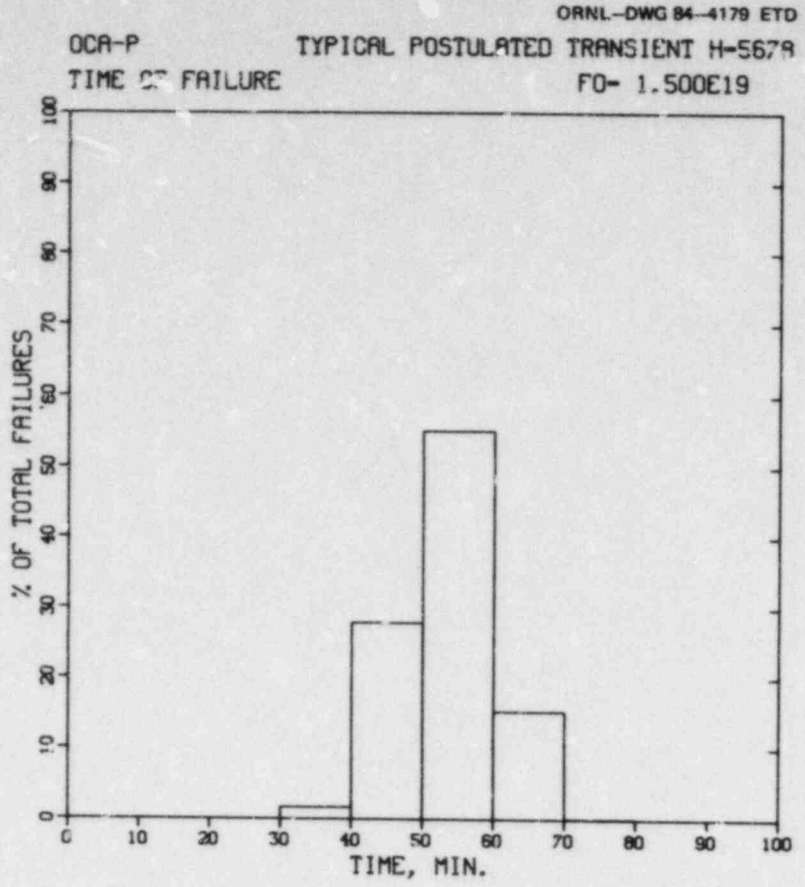

Fig. A.5. Percent of total failures vs time.

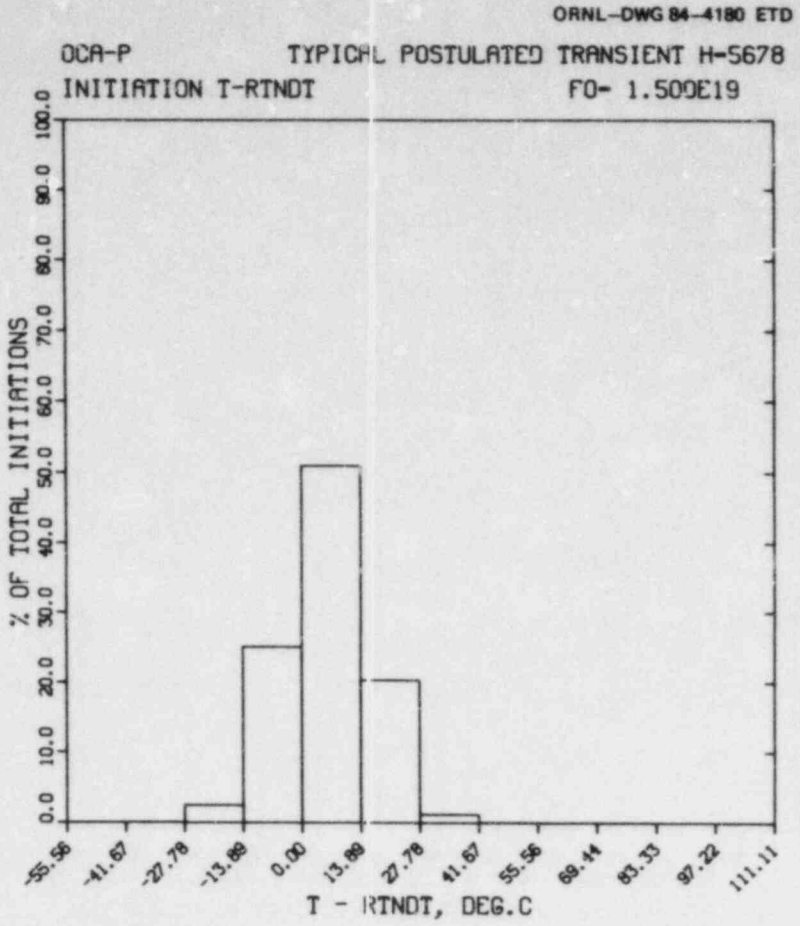

Fig. A.6. Percent of total initiations vs (T — RTNDT) at initiation.

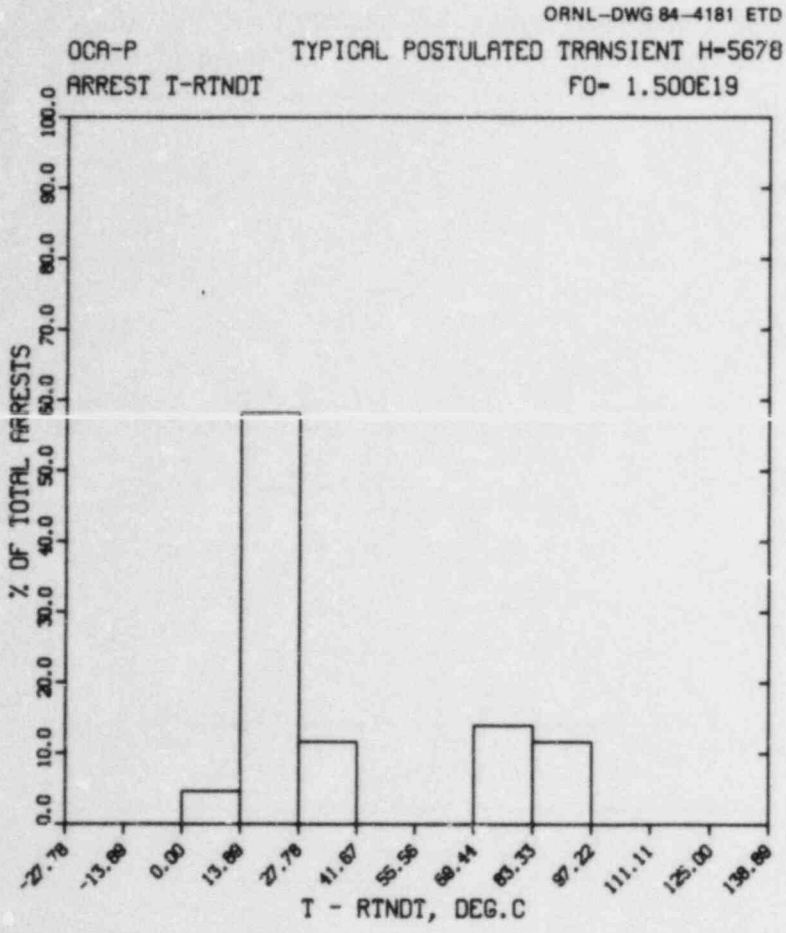

Fig. A.7. Percent of total arrests vs (T − RTNDT) at arrest.

1-R Output for a Typical Postulated Transient

PRINT INPUT CARD IMAGES W/CARD COLUMNS INDICATED EVERY 10TH CARD--

```
CARD
NO./COL. 1.......10........20........30........40........50........60........70........80
  1      TYPICAL POSTULATED TRANSIENT CLAD H=5678
  2      , 40000, 200, .15, 298.9, , , 1/MODEL,NDT,INTER,DT,TINIT
  3      , , , 0.025,2/ GPEACT,X(1),W,FRCLTH
  4      / MATERIAL PROP.
  5      / NUMCBC
  6      / ICBC
  7      1
  8      0 5678.3/  H
  9      11
 10        0 310.0
NO./COL. 1.......10........20........30........40........50........60........70........80
 11        10 254.4
 12        20 211.1
 13        30 180.0
 14        40 158.9
 15        50 146.7
 16        60 138.9
 17        70 137.8
 18        80 140.0
 19        90 148.3
 20       100 160.0
```

```
ONE DIMENSIONAL AXISYMMETRIC HEAT CONDUCTION ANALYSIS OF


TYPICAL POSTULATED TRANSIENT CLAD H=5678

GEOMETRIC MODELING METHOD (MODEL)
 = 0 USER SPECIFIED NO. OF ELEMENTS + G.P FACTOR.
 = 1 USER SPEC. NO. OF ELEM.& NODAL POINTS( WITH
     A LIMITED AMOUNT OF AUTO GENERATION)=          0

NUMBER OF INCREMENTS---------------- NDT =      40000

OUTPUT INTERVAL------------------ INTER =        200

TIME INTERVAL----------------------- DT =      0.150 SECONDS

INITIAL TEMPERATURE(AT TIME ZERO)     TO =      298.9 DEG.C

NUMBER OF ELEMENTS----------------- NUMEL =         10

INTEGRATION ORDER(# GAUSS POINTS) NGAUSS =          4

UNIT SWITCH    0=ENGLISH, 1=SI-----ISISW =          1

 *** NUMBER OF NODAL POINTS =    21

GEOM.PROG.FACTOR        =    1.13

INSIDE RADIUS  (MM)     = 2184.40

TOTAL WALL THICKNESS  (MM)   =  215.90

FRACTIONAL CLADDING THICKNESS=  0.0250

NUMBER OF ELEM. FROM NUMEL TO
BE USED IN MODELING THE CLADDING =        2

 *** CLADDING THICKNESS   (MM)   =  5.3975
```

NODAL POINT COORDINATES

NODAL POINT NO.	BOUND. COND. TYPE	R-COORD. (MM)	SPECIFIED TEMP(B.C.TYPE=1) OR HEAT FLOW(B.C.TYPE=0) DEG.C OR W/SQM
1	0	2184.399	0.000
2	0	2185.749	0.000
3	0	2187.098	0.000
4	0	2188.448	0.000
5	0	2189.797	0.000
6	0	2194.307	0.000
7	0	2199.404	0.000
8	0	2205.163	0.000
9	0	2211.671	0.000
10	0	2219.025	0.000
11	0	2227.335	0.000
12	0	2236.725	0.000
13	0	2247.336	0.000
14	0	2259.326	0.000
15	0	2272.875	0.000
16	0	2288.186	0.000
17	0	2305.486	0.000
18	0	2325.036	0.000
19	0	2347.128	0.000
20	0	2372.091	0.000
21	0	2400.299	0.000

ELEMENT CONNECTIVITY

ELEM. NO.	NODE NUMBERS I	J	K	MATERIAL NO.

NUMBER OF MATERIALS ------ 2

MATERIAL PROPERTIES

MAT. NO.	CONDUCTIVITY W/M.DEG K.	SPECIFIC HEAT J/KG.DEG K	DENSITY KG/CU.M
1	41.530	502.476094	7836.539
2	17.304	502.476094	7836.539

NUMBER OF CONVECTIVE BOUNDARY CONDITIONS - 1

SPECIFIED CONVECTIVE BOUNDARY CONDITION(S) NODE POINTS
1

SEQ NO	TIME SECONDS	HEAT TRANSFER COEFFICIENT W/SQM.DEGC
1	0.0	5678.3

TIME DEPENDENT COOLANT TEMPERATURES

SEQ.NO.	TIME (MINUTES)	TEMPERATURE
1	0.0	310.0
2	10.0	254.4
3	20.0	211.1
4	30.0	180.0
5	40.0	158.9
6	50.0	146.7
7	60.0	138.9
8	70.0	137.8
9	80.0	140.0
10	90.0	148.3
11	100.0	160.0

```
OUTPUT INTERVAL NUMBER =  1 TIME =  0.0 MIN.(    0.000 S., 0.000D+00HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =      0    COOLANT TEMPERATURE = 310.0
  1  298.9   2  298.9   3  298.9   4  298.9   5  298.9   6  298.9   7  298.9   8  298.9   9  298.9  10  298.9
 11  298.9  12  298.9  13  298.9  14  298.9  15  298.9  16  298.9  17  298.9  18  298.9  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  2 TIME =  0.5 MIN.(   30.000 S., 8.333D-03HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =    200    COOLANT TEMPERATURE = 307.2
  1  305.9   2  305.3   3  304.7   4  304.1   5  303.5   6  302.7   7  301.8   8  301.0   9  300.3  10  299.7
 11  299.3  12  299.1  13  298.9  14  298.9  15  298.9  16  298.9  17  298.9  18  298.9  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  3 TIME =  1.0 MIN.(   60.000 S., 1.667D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =    400    COOLANT TEMPERATURE = 304.4
  1  304.0   2  303.9   3  303.6   4  303.4   5  303.2   6  302.8   7  302.3   8  301.8   9  301.2  10  300.6
 11  300.1  12  299.6  13  299.3  14  299.1  15  299.0  16  298.9  17  298.9  18  298.9  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  4 TIME =  1.5 MIN.(   90.000 S., 2.500D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =    600    COOLANT TEMPERATURE = 301.7
  1  301.9   2  301.9   3  302.0   4  302.0   5  302.0   6  302.0   7  301.8   8  301.6   9  301.3  10  300.9
 11  300.5  12  300.0  13  299.6  14  299.3  15  299.1  16  299.0  17  298.9  18  298.9  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  5 TIME =  2.0 MIN.(  120.000 S., 3.333D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =    800    COOLANT TEMPERATURE = 298.9
  1  299.6   2  299.8   3  300.1   4  300.3   5  300.5   6  300.7   7  300.9   8  300.9   9  300.9  10  300.7
 11  300.5  12  300.2  13  299.9  14  299.5  15  299.3  16  299.1  17  299.0  18  298.9  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  6 TIME =  2.5 MIN.(  150.000 S., 4.167D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =   1000    COOLANT TEMPERATURE = 296.1
  1  297.2   2  297.6   3  298.1   4  298.5   5  298.8   6  299.3   7  299.7   8  300.0   9  300.2  10  300.2
 11  300.2  12  300.1  13  299.9  14  299.7  15  299.4  16  299.2  17  299.0  18  299.0  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  7 TIME =  3.0 MIN.(  180.000 S., 5.000D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =   1200    COOLANT TEMPERATURE = 293.3
  1  294.7   2  295.3   3  295.9   4  296.5   5  297.0   6  297.6   7  298.2   8  298.8   9  299.2  10  299.5
 11  299.7  12  299.8  13  299.8  14  299.6  15  299.5  16  299.3  17  299.1  18  299.0  19  298.9  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  8 TIME =  3.5 MIN.(  210.000 S., 5.833D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =   1400    COOLANT TEMPERATURE = 290.5
  1  292.3   2  293.0   3  293.7   4  294.4   5  295.1   6  295.9   7  296.7   8  297.4   9  298.1  10  298.6
 11  299.1  12  299.4  13  299.5  14  299.5  15  299.4  16  299.3  17  299.2  18  299.0  19  299.0  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER =  9 TIME =  4.0 MIN.(  240.000 S., 6.667D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =   1600    COOLANT TEMPERATURE = 287.8
  1  289.8   2  290.6   3  291.5   4  292.3   5  293.1   6  294.1   7  295.0   8  296.0   9  296.8  10  297.6
 11  298.3  12  298.8  13  299.1  14  299.3  15  299.3  16  299.3  17  299.2  18  299.1  19  299.0  20  298.9
 21  298.9

OUTPUT INTERVAL NUMBER = 10 TIME =  4.5 MIN.(  270.000 S., 7.500D-02HOURS)
NO. OF COMPUTATIONAL TIME STEPS(TOTAL) =   1800    COOLANT TEMPERATURE = 285.0
  1  287.2   2  288.2   3  289.2   4  290.1   5  291.0   6  292.2   7  293.3   8  294.4   9  295.5  10  296.5
 11  297.3  12  298.0  13  298.6  14  298.9  15  299.1  16  299.2  17  299.2  18  299.1  19  299.0  20  299.0
 21  298.9
```

PFM Output for a Typical Postulated Transient

```
DATE  12/05/83  22.02.11

PRINT INPUT CARD IMAGES W/CARD COLUMNS INDICATED EVERY 10TH CARD--

CARD
NO./COL. 1.......10........20........30........40........50........60........70........80
  1      ' '
  2      3,201, , 1, , , 1/ KICTYP,NCYCLE,ISKIP,ICRKTP
  3      , , , 1/PLOT CONTROL CARD
  4      11/ MDR
  5        0 10.34
  6       10 11.79
  7       20 12.96
  8       30 13.93
  9       40 14.55
 10       50 14.69
NO./COL. 1.......10........20........30........40........50........60........70........80
 11       60 14.48
 12       70 14.13
 13       80 13.79
 14       90 13.44
 15      100 13.10
 16      1/IRTNSW
 17      0/IBINSW
 18      1.50E19, -1.1, 0.35, , 0.65/ FO, RTNDTO, %CU, %P %NI
 19      1/ MODEL NUMEL
 20      2, 0.025/ NECLAD, FRACT CLAD THICKNESS
NO./COL. 1.......10........20........30........40........50........60........70........80
 21      2/ NUMMAT,E
 22      / ALFA
 23      / PNU
 24      1,6,11,16,21,26,31,36,41,46,51,56,61,66,71,76,81,86,91,96,101
 25      106,111,116,121,126,131,136,141,146,151,156,161,166,171,176,181,
 26      186,191,196,201/ SEL RUNS
 27      250,100, 10, , , , , 1, 10/ CCD PLOT PARAMETERS
 28      750000, , , , 5/NSIM, IACCEL, VOLWLD, WELDN, CONVPC
 29      /   PROB. DISTRIBUTION PARAMETERS
 30      2, 1.5E19, 0.35, 0.65, -1., , , , , ,
NO./COL. 1.......10........20........30........40........50........60........70........80
 31        1.2E19, 0.33, 0.60, +2., , , , , 0.5/ WELD CHARACTERISTICS
```

TYPICAL POSTULATED TRANSIENT H=5678 OCA-P

FRACTURE TOUGHNESS CODE (IF KICTYP = 6 , VALUES
ARE READ IN & DESCRIBED LATER IN THIS RUN) KICTYP = 3

MAX. # OF TIME INTERVALS TO BE READ NCYCLE = 201

TIME INTERVAL # TO START PROCESSING DATA ISKIP = 1

CRACK SHAPE TO BE USED ICRKTP = 1
=1 2-D; =2 2-D,2-M; =3 6-1,2-M;
=4 6/1,2-D,&2-M; =5 6/1,2-D

REF TEMPERATURE FOR STRESS CALCULATIONS TREF = 0.
= 0 USE TEMP IN FIRST TIME INTERVAL

WRITE TABLE-1 FOR TEMPS,KIC,ETC.THRU CYL. WALL
= -1 THEN STOP; = 0 NO PRINTING;
= +1 CONTINUE PROCESSING KI VALUES NOPT = 0

UNITS SWITCH =0 ENGLISH; =1 SI ISISW = 1

TEMPERATURE PLOTTING
= 0 NO PLOTS, = 1 PLOT NPLOT = 0
KI RATIO PLOTTING
= 0 NO PLOTS, = 1 PLOT KRPLOT = 0
KI PLOTTING
= 0 NO PLOTS, = 1 PLOT KIPLT = 0
ENVELOPE PLOTTING
= 0 NO PLOTS, = 1 PLOT KENPLT = 1
STRESS/TEMP/KI/KIC/KIA PLOTTING
= 0 NO PLOTS, = 1 PLOT KALPLT = 0

TIME DEPENDENT PRESSURES NPR = 11

SEQ.NO.	TIME (MINUTES)	PRESSURE (MPA)
1	0.0	10.340
2	10.0	11.790
3	20.0	12.960
4	30.0	13.930
5	40.0	14.550
6	50.0	14.690
7	60.0	14.480
8	70.0	14.130
9	80.0	13.790
10	90.0	13.440
11	100.0	13.100

RADIATION DAMAGE/RUN CONTROL

RADIATION DAMAGE CALC SWITCH	IRTNSW	=	1
ATTENUATION CONSTANT	ATTCON	=	0.0094
STRESS INPUT SWITCH 0=CALC BY FE METHOD, 1=INPUT ON UNIT3 0=DEEPEST POINT, 1=MAX ON CRACK FRONT	ISTRSW	=	0

INCIPIENT INITIATION SEARCH CONTROL

INCIPIENT INITIATION SEARCH SWITCH 0=NO SEARCH, 1=SEARCH, 2=PARAMETRIC SEARCH	IBINSW	=	0
FLAW SHAPE CONTROL SWITCH 0=LONG(2-D), 1=(6 TO 1) ELLIPITICAL	ISEASW	=	0
MIN A/W USED ON THRESHOLD SEARCH	AWMIN	=	0.0249
MAX A/W USED ON THRESHOLD SEARCH	AWMAX	=	0.1510
UPPER LIMIT ON THRESHOLD SEARCH	TUPLIM	=	0.50D+03

TOUGHNESS PROPERTIES(-1 MEANS NOT INPUT)

FLUENCE, INSIDE SURFACE	FO	=	1.500D+19
REFERENCE TEMP., INITIAL	RTNDTO	=	-1.100
PER CENT CU	CUPER	=	0.350
PER CENT P	PPER	=	-1.000
PER CENT NI	PERNI	=	0.650
DELTA RTNDT(INNER SURFACE)	DRTNIN	=	-1.0

FINITE ELEMENT PARAMETERS (STRESS CALCULATIONS)

GEOMETRIC MODELING METHOD
= 0 USER SPECIFIED NO. OF ELEMENTS + G.P FACTOR.
= 1 USER SPEC. NO. OF ELEM.& A/W OF CLADDING-BASE METAL INTERFACE MODEL = 1

NUMBER OF ELEMENTS---------- NUMEL = 15

INTEGRATION ORDER(# GAUSS POINTS) NGAUSS = 2

NUMBER OF NODAL POINTS---------- NUMNP = 31

A/W OF CLADDING-BASE METAL INTERFACE 0.0250

FE MESH NODAL POINT COORDINATES

NODAL POINT NO.	R-COORD. (MM)	NODAL POINT NO.	R-COORD. (MM)
1	2184.399	16	2215.762
2	2185.749	17	2220.328
3	2187.098	18	2225.487
4	2188.448	19	2231.317
5	2189.797	20	2237.905
6	2190.987	21	2245.350
7	2192.332	22	2253.762
8	2193.852	23	2263.268
9	2195.570	24	2274.009
10	2197.510	25	2286.147
11	2199.703	26	2299.863
12	2202.181	27	2315.362
13	2204.982	28	2332.875
14	2208.146	29	2352.666
15	2211.722	30	2375.029
		31	2400.299

ELEMENT CONNECTIVITY

ELEM. NO.	NODE NUMBERS I	J	K	MATERIAL NO.
1	1	2	3	2
2	3	4	5	2
3	5	6	7	1
4	7	8	9	1
5	9	10	11	1
6	11	12	13	1
7	13	14	15	1
8	15	16	17	1
9	17	18	19	1
10	19	20	21	1
11	21	22	23	1
12	23	24	25	1
13	25	26	27	1
14	27	28	29	1
15	29	30	31	1

MATERIAL PROPERTIES FOR STRESS CALCULATIONS

NUMBER OF MATERIALS ------ 2

TEMP(DEGC.)	MODULUS OF ELASTICITY(MPA) - E		
	(MAT 1)	(MAT 2)	(MAT 3)
0.0	1.931D+05	1.862D+05	0.000D+00

TEMP(DEGC.)	COEFF OF EXPANSION(PER DEGC.) - ALFA		
	(MAT 1)	(MAT 2)	(MAT 3)
0.0	1.446D-05	1.787D-05	0.000D+00

TEMP(DEGC.)	POISSONS RATIO - PNU		
	(MAT 1)	(MAT 2)	(MAT 3)
0.0	0.300	0.300	0.300

SELECTED TIME INTERVAL NUMBERS FOR KI CALCULATIONS

1	6	11	16	21	26	31	36	41	46
51	56	61	66	71	76	81	86	91	96
101	106	111	116	121	126	131	136	141	146
151	156	161	166	171	176	181	186	191	196
201	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0									

CYLINDER DIMENSIONS (MM)

INNER RADIUS, RI = 2184.399

OUTER RADIUS, RO = 2400.299

WALL THICKNESS, W = 215.900

TEMPERATURE GRID GEOMETRY OVER CYLINDER WALL

GRID NO.	RADIUS
1	2184.3995
2	2185.7488
3	2187.0982
4	2188.4476
5	2189.7970
6	2194.3072
7	2199.4039
8	2205.1630
9	2211.6709
10	2219.0248
11	2227.3347
12	2236.7248
13	2247.3357
14	2259.3260
15	2272.8751
16	2288.1855
17	2305.4863
18	2325.0362
19	2347.1276
20	2372.0909
21	2400.2994

CALCULATED 2-D CRACK DEPTH VALUES =

0.0	2.2	4.3	5.4	10.9	16.5	21.9	32.4	43.5	54.0
65.0	86.7	107.9	129.8	152.7	173.0	183.5	194.3	205.5	

REF TEMPERATURE FOR STRESS CALCULATIONS TREF = 298.9 DEGC.

TYPICAL POSTULATED TRANSIENT H=5678 LONGIT. CRACK

KICTYP = 3, RTNDT0 = -1.1 DEGC, %CU = 0.350, %NI = 0.650, F0 =1.50E19,

SEQ NO.	RADIUS MM.	DEPTH MM.	A/W	TEMPER. DEGC.	DLRTNDT DEGC.	CIRCUMF. STRESS MPA	KI	KIC	KI/KIC	KIA	KI/KIA	ELLIPTIC ANGLE
TEMPERATURE INTERVAL NUMBER = 1, TIME = 0.000 MIN., PRESSURE = 10.340 MPA												
1	2184.4	0.00	0.000	298.9	170.	106.05	0.00	2483.98	0.000	434.26	0.000	
2	2186.6	2.15	0.010	298.9	169.	105.94	9.45	2543.75	0.004	441.40	0.021	
3	2188.7	4.29	0.020	298.9	169.	105.82	13.51	2604.31	0.005	448.59	0.030	
4	2189.8	5.41	0.025	298.9	168.	109.84	15.23	2636.36	0.006	452.38	0.034	
5	2195.3	10.86	0.050	298.9	167.	109.54	22.28	2797.89	0.008	471.26	0.047	
6	2200.9	16.50	0.076	298.9	165.	109.24	27.39	2973.71	0.009	491.47	0.056	
7	2206.3	21.91	0.101	298.9	163.	108.95	32.31	3151.05	0.010	511.52	0.063	
8	2216.8	32.38	0.150	298.9	160.	108.39	41.60	3519.80	0.012	552.24	0.075	
9	2227.9	43.50	0.201	298.9	157.	107.81	51.92	4028.07	0.013	606.48	0.086	
10	2238.4	53.97	0.250	298.9	152.	107.27	63.60	4667.58	0.014	672.09	0.095	
11	2249.4	65.02	0.301	298.9	148.	106.70	75.33	5430.33	0.014	747.16	0.101	
12	2271.1	86.68	0.401	298.9	140.	105.63	106.69	7220.62	0.015	912.84	0.117	
13	2292.3	107.95	0.500	298.9	133.	104.60	151.63	9415.21	0.016	1101.09	0.138	
14	2314.2	129.79	0.601	298.9	126.	103.57	212.17	12188.89	0.017	1322.42	0.160	
15	2337.1	152.72	0.707	298.9	118.	102.52	306.74	15746.95	0.019	1586.87	0.193	
16	2357.4	172.97	0.801	298.9	112.	101.62	416.57	19510.52	0.021	1849.12	0.225	
17	2367.9	183.51	0.850	298.9	109.	101.16	473.58	21719.33	0.022	1996.46	0.237	
18	2378.7	194.31	0.900	298.9	107.	100.70	520.28	24169.86	0.022	2155.16	0.241	
19	2389.9	205.47	0.952	298.9	104.	100.22	561.78	26913.33	0.021	2327.66	0.241	
TEMPERATURE INTERVAL NUMBER = 6, TIME = 2.500 MIN., PRESSURE = 10.702 MPA												
1	2184.4	0.00	0.000	297.2	170.	119.48	0.00	2336.43	0.000	416.43	0.000	
2	2186.6	2.15	0.010	297.9	169.	115.97	10.47	2454.27	0.004	430.70	0.024	
3	2188.7	4.29	0.020	298.5	169.	112.82	14.72	2570.21	0.006	444.55	0.033	
4	2189.8	5.41	0.025	298.8	168.	115.42	16.45	2629.85	0.006	451.61	0.036	
5	2195.3	10.86	0.050	299.3	167.	113.24	23.53	2840.88	0.008	476.23	0.049	
6	2200.9	16.50	0.076	299.8	165.	111.24	28.59	3065.22	0.009	501.86	0.057	
7	2206.3	21.91	0.101	300.0	163.	109.97	33.43	3276.29	0.010	525.49	0.064	
8	2216.8	32.38	0.150	300.2	160.	108.47	42.58	3690.70	0.012	570.71	0.075	
9	2227.9	43.50	0.201	300.2	157.	107.93	52.88	4222.27	0.013	626.69	0.084	
10	2238.4	53.97	0.250	300.1	152.	107.97	64.68	4867.41	0.013	692.06	0.093	
11	2249.4	65.02	0.301	299.9	148.	108.26	76.64	5619.48	0.014	765.31	0.100	
12	2271.1	86.68	0.401	299.4	140.	108.83	108.84	7361.17	0.015	925.33	0.118	
13	2292.3	107.95	0.500	299.2	133.	108.90	155.14	9501.40	0.016	1108.22	0.140	
14	2314.2	129.79	0.601	299.0	126.	108.44	217.53	12232.38	0.018	1325.77	0.164	
15	2337.1	152.72	0.707	298.9	118.	107.61	315.00	15764.71	0.020	1588.15	0.198	
16	2357.4	172.97	0.801	298.9	112.	106.75	428.29	19517.44	0.022	1849.59	0.232	
17	2367.9	183.51	0.850	298.9	109.	106.29	487.27	21723.42	0.022	1996.73	0.244	
18	2378.7	194.31	0.900	298.9	107.	105.81	535.80	24172.38	0.022	2155.32	0.249	
19	2389.9	205.47	0.952	298.9	104.	105.32	579.41	26915.16	0.022	2327.77	0.249	

TYPICAL POSTULATED TRANSIENT H=5679 LONGIT. CRACK

KICTYP = 3, RTNDTO = -1.1 DEGC, %CU = 0.350, %NI = 0.650, FO =1.50E19,

SEQ NO.	RADIUS MM.	DEPTH MM.	A/W	TEMPER. DEGC.	DLRTNDT DEGC.	CIRCUMF. STRESS MPA	KI	KIC	KI/KIC	KIA	KI/KIA	ELLIPTIC ANGLE
TEMPERATURE INTERVAL NUMBER = 11, TIME = 5.000 MIN., PRESSURE = 11.065 MPA												
1	2184.4	0.00	0.000	284.7	170.	175.46	0.00	1505.14	0.000	309.03	0.000	
2	2186.6	2.15	0.010	286.4	169.	167.05	15.20	1637.90	0.009	327.13	0.046	
3	2188.7	4.29	0.020	288.1	169.	159.09	21.12	1776.39	0.012	345.57	0.061	
4	2189.8	5.41	0.025	288.9	168.	151.36	23.37	1850.40	0.013	355.26	0.066	
5	2195.3	10.86	0.050	290.4	167.	145.33	31.65	2068.95	0.015	383.26	0.083	
6	2200.9	16.50	0.076	291.9	165.	138.97	37.55	2317.98	0.016	414.17	0.091	
7	2206.3	21.91	0.101	293.0	163.	134.03	43.11	2557.90	0.017	443.09	0.097	
8	2216.8	32.38	0.150	294.9	160.	125.91	53.27	3052.78	0.017	500.45	0.106	
9	2227.9	43.50	0.201	296.4	157.	119.43	64.37	3679.31	0.017	569.48	0.113	
10	2238.4	53.97	0.250	297.3	152.	114.91	77.01	4415.92	0.017	646.59	0.119	
11	2249.4	65.02	0.301	298.1	148.	111.42	89.54	5272.04	0.017	731.84	0.122	
12	2271.1	86.68	0.401	298.8	140.	107.28	123.70	7203.69	0.017	911.33	0.136	
13	2292.3	107.95	0.500	299.1	133.	105.24	173.23	9477.88	0.018	1106.27	0.157	
14	2314.2	129.79	0.601	299.1	126.	104.10	240.04	12281.64	0.020	1329.56	0.181	
15	2337.1	152.72	0.707	299.1	118.	103.26	344.37	15835.67	0.022	1593.24	0.216	
16	2357.4	172.97	0.801	299.0	112.	102.57	468.59	19582.51	0.024	1853.99	0.251	
17	2367.9	183.51	0.850	299.0	109.	102.19	525.90	21782.84	0.024	2000.63	0.263	
18	2378.7	194.31	0.900	299.0	107.	101.78	574.58	24227.71	0.024	2158.85	0.266	
19	2389.9	205.47	0.952	299.0	104.	101.34	614.53	26969.16	0.023	2331.12	0.264	
TEMPERATURE INTERVAL NUMBER = 16, TIME = 7.500 MIN., PRESSURE = 11.427 MPA												
1	2184.4	0.00	0.000	271.9	170.	228.87	0.00	960.93	0.000	229.35	0.000	
2	2186.6	2.15	0.010	274.3	169.	216.91	19.78	1071.54	0.018	246.41	0.080	
3	2188.7	4.29	0.020	276.7	169.	205.43	27.40	1190.94	0.023	264.28	0.104	
4	2189.8	5.41	0.025	277.9	168.	187.07	30.21	1256.30	0.024	273.84	0.110	
5	2195.3	10.86	0.050	280.1	167.	178.19	39.76	1439.52	0.028	299.93	0.133	
6	2200.9	16.50	0.076	282.4	165.	168.53	46.67	1657.73	0.028	329.80	0.142	
7	2206.3	21.91	0.101	284.2	163.	160.73	53.14	1873.87	0.028	358.31	0.148	
8	2216.8	32.38	0.150	287.4	160.	147.26	64.74	2341.06	0.028	416.99	0.155	
9	2227.9	43.50	0.201	290.2	157.	135.59	77.15	2950.69	0.026	488.84	0.158	
10	2238.4	53.97	0.250	292.2	152.	126.67	91.13	3679.55	0.025	569.51	0.160	
11	2249.4	65.02	0.301	294.0	148.	119.10	104.68	4553.41	0.023	660.57	0.158	
12	2271.1	86.68	0.401	296.3	140.	108.59	141.66	6583.47	0.022	855.35	0.166	
13	2292.3	107.95	0.500	297.7	133.	102.24	195.25	9004.06	0.022	1066.84	0.183	
14	2314.2	129.79	0.601	298.4	126.	98.31	267.24	11969.03	0.022	1305.42	0.205	
15	2337.1	152.72	0.707	298.8	118.	95.84	379.43	15670.14	0.024	1581.35	0.240	
16	2357.4	172.97	0.801	298.9	112.	94.43	507.40	19515.93	0.026	1849.49	0.274	
17	2367.9	183.51	0.850	298.9	109.	93.86	571.10	21754.36	0.026	1998.76	0.286	
18	2378.7	194.31	0.900	299.0	107.	93.35	619.45	24227.16	0.026	2158.82	0.287	
19	2389.9	205.47	0.952	299.0	104.	92.86	654.24	26987.13	0.024	2332.23	0.281	

OCA-P PROBABILISTIC CONTROL PARAMETERS

NUMBER OF SIMULATIONS	NSIM =	750000
ACCELERATION(0=NONE, 1=NO FIRST INCR, 2=IMPORTANCE)	IACCEL =	0
VOLUME OF MATERIAL IN WELD 1	VOLWLD =	1.00
FLAWS/(M**3)	WELDN =	1.00
SPECIFIED MAX % ERROR IN P(F/E)	CONVPC =	5.00
FLOW STRESS(MPA)	FLWSTR =	551.6
KIA MAX (MPA*M**0.5)	USKIA =	219.8
INITIAL CRACK DEPTH PARAMETERS		
NUMBER OF INCREMENTS	NPCRK =	9
SIZE OF FIRST INCRMT (MM)	AWINT =	4.32
LIMIT OF INCREMENTS (MM)	CDLIM =	57.15
STD DEV FOR DELTA RTNDT	SDFDRT =	13.33
STD DEV FACTOR FOR KIC MEAN	SDFKIC =	0.15
STD DEV FACTOR FOR KIA MEAN	SDFKIA =	0.10
TRUNCATION STD DEV FOR D. RTNDT	SDLDRT =	3.00
TRUNCATION STD DEV FOR KIC	SDLKIC =	3.00
TRUNCATION STD DEV FOR KIA	SDLKIA =	3.00
KIC EQUATION MULTIPLIER	CONKIC =	1.43
KIA EQUATION MULTIPLIER	CONKIA =	1.25
KIC SWITCH(0=OCA-II, 1=NUREG778)	IKICSW =	0
KIA SWITCH(0=OCA-II, 1=NUREG778)	IKIASW =	0
NUMBER OF WELDS	NWELDS =	2

	MEAN VALUE				STANDARD DEVIATION				VOL
WELD	FLUENCE	%CU	%NI	RTNDTO	F FACTR	%CU	%NI	RTNDTO	FAC
1	1.50D+19	0.35	0.65	-1.0	0.30	0.025	0.000	9.4	1.000
2	1.20D+19	0.33	0.60	2.0	0.30	0.025	0.000	9.4	0.500

CRACK DEPTHS AND DENSITIES

2.16D+00	6.68D+00	1.16D+01	1.70D+01	2.30D+01	2.94D+01	3.65D+01	4.43D+01	5.27D+01
6.91D-01	2.23D-01	6.45D-02	1.66D-02	3.77D-03	7.63D-04	1.41D-04	2.48D-05	4.51D-06

OCA-P CRACK INITIATION SUMMARY TYPICAL POSTULATED TRANSIENT H=5678

SIM NO	INI NO	FAIL NO	TIME MIN	PRESS (MPA)	INI DEPTH	TEMP DEG.	PI/ARR DEPTH	SIM %CU	SIM %NI	SIM FLUENCE	SIM RTNDT	DRTNDT	KI	SIM KIC	ERR KIC	WELD NO
9	1	1	52.5	14.6	11.6	161.0	154.3	0.380	0.650	2.133D+19	171.45	151.61	78.50	76.29	0.81	1
23	2	2	45.0	14.6	6.7	168.4	154.3	0.363	0.650	1.887D+19	174.88	149.00	72.29	71.66	0.71	1
33	3	3	62.5	14.4	17.0	154.4	160.7	0.365	0.650	1.360D+19	154.09	135.10	82.64	82.11	0.72	1
131	4	4	47.5	14.7	6.7	164.9	154.3	0.386	0.650	2.553D+19	189.44	159.61	71.86	71.07	0.91	1
152	5	5	57.5	14.5	6.7	153.6	154.3	0.326	0.650	1.420D+19	157.15	130.62	68.66	68.41	0.64	1
218	6	6	40.0	14.5	6.7	176.2	154.3	0.368	0.650	1.871D+19	188.53	148.71	73.12	71.17	0.78	1
237	7	7	50.0	14.7	6.7	161.4	154.3	0.350	0.650	1.786D+19	167.40	147.15	71.48	70.02	0.69	1
365	8	8	50.0	14.7	11.6	163.9	154.3	0.356	0.650	2.122D+19	167.96	151.43	79.92	77.06	0.73	1
406	9	9	57.5	14.5	11.6	155.7	154.3	0.399	0.650	2.216D+19	166.14	152.98	75.70	75.18	0.79	1
446	10	10	50.0	14.7	17.0	167.5	154.3	0.382	0.650	1.666D+19	177.76	141.59	91.43	87.87	0.93	1
[illegible]	11	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
743	12	12	57.5	14.5	17.0	158.9	154.3	0.363	0.650	1.880D+19	166.77	145.58	86.47	86.13	0.87	1
845	13	13	55.0	14.6	6.7	156.0	154.3	0.38[illegible]	0.650	2.219D+19	188.35	154.62	69.56	69.01	0.97	1
854	14	14	60.0	14.5	6.7	151.2	160.7	0.369	0.650	1.854D+19	167.13	148.39	67.82	67.19	0.77	1
899	15	15	60.0	14.5	6.7	151.2	160.7	0.372	0.650	2.357D+19	185.75	156.75	67.82	67.53	0.97	1
971	16	16	55.0	14.6	11.6	158.3	154.3	0.348	0.650	1.856D+19	172.83	146.85	77.06	76.55	0.86	1
1016	17	17	42.5	14.6	11.6	174.8	154.3	0.391	0.650	2.199D+19	185.88	152.66	82.45	77.75	0.83	1
1051	18	18	57.5	14.5	11.6	155.7	154.3	0.371	0.650	1.236D+19	173.45	133.70	75.70	74.94	0.88	1
1061	19	19	50.0	14.7	17.0	167.5	154.3	0.331	0.650	1.875D+19	170.93	139.42	91.43	90.19	0.84	1
1073	20	20	47.5	14.7	11.6	167.4	154.3	0.359	0.650	1.283D+19	161.51	134.87	80.71	79.79	0.62	1
1118	21	21	52.5	14.6	6.7	158.6	154.3	0.400	0.650	1.287D+19	173.11	136.44	70.52	69.76	0.79	1
1232	22	22	45.0	14.6	6.7	168.4	154.3	0.374	0.650	1.529D+19	176.24	141.98	72.29	71.59	0.72	1
1257	23	23	52.5	14.6	6.7	158.6	154.3	0.365	0.650	1.452D+19	179.44	140.30	70.52	69.00	0.85	1
1440	24	24	50.0	14.7	6.7	161.4	154.3	0.361	0.650	2.498D+19	195.70	158.82	71.48	70.03	1.00	1
1579	25	25	52.5	14.6	6.7	158.6	154.3	0.339	0.650	1.628D+19	171.59	141.12	70.52	70.03	0.77	1
1612	26	26	52.5	14.6	6.7	158.6	154.3	0.362	0.650	2.279D+19	173.61	155.56	70.52	68.67	0.78	1
1621	27	27	45.0	14.6	6.7	168.4	154.3	0.349	0.650	1.894D+19	175.42	149.13	72.29	71.54	0.71	1
1716	28	28	47.5	14.7	6.7	164.9	154.3	0.374	0.650	1.439D+19	180.35	140.01	71.86	71.81	0.82	1
1739	29	29	52.5	14.6	23.0	167.8	154.3	0.364	0.650	1.719D+19	167.53	140.79	101.94	101.75	0.89	1
1785	30	30	50.0	14.7	6.7	161.4	154.3	0.368	0.650	2.598D+19	180.17	160.24	71.48	68.78	0.82	1
1808	31	31	50.0	14.7	6.7	161.4	154.3	0.316	0.650	2.582D+19	178.69	148.35	71.48	69.15	0.81	1
1834	32	32	42.5	14.6	11.6	174.8	154.3	0.381	0.650	2.484D+19	185.90	156.95	82.45	81.80	0.87	1
1837	33	33	52.5	14.6	6.7	158.6	154.3	0.358	0.650	1.592D+19	162.01	143.31	70.52	68.71	0.64	1
1887	34	34	57.5	14.5	11.6	155.7	154.3	0.373	0.650	1.471D+19	181.13	139.20	75.70	74.84	0.97	1
2112	35	35	47.5	14.7	17.0	171.2	154.3	0.379	0.650	1.349D+19	164.65	134.83	92.39	87.05	0.67	1
2115	36	36	57.5	14.5	6.7	153.6	154.3	0.364	0.650	1.823D+19	163.25	147.83	68.66	67.73	0.71	1
2193	37	37	40.0	14.5	6.7	176.2	154.3	0.359	0.650	1.802D+19	178.82	147.44	73.12	71.42	0.66	1
2253	38	38	52.5	14.6	6.7	158.6	154.3	0.306	0.650	2.529D+19	160.43	142.51	70.52	68.06	0.62	1
2360	39	39	40.0	14.5	6.7	176.2	154.3	0.398	0.650	1.843D+19	194.22	148.20	73.12	67.76	0.80	1
2731	40	40	60.0	14.5	6.7	151.2	160.7	0.372	0.650	1.639D+19	161.65	144.26	67.82	66.06	0.70	1
2780	41	41	60.0	14.5	6.7	151.2	160.7	0.369	0.650	2.433D+19	185.95	157.88	67.82	67.56	0.97	1
2799	42	42	52.5	14.6	6.7	158.6	154.3	0.350	0.650	2.318D+19	174.73	156.16	70.52	68.66	0.79	1
2893	43	43	47.5	14.7	6.7	164.9	154.3	0.332	0.650	2.351D+19	172.76	152.27	71.86	71.19	0.72	1
3018	44	44	50.0	14.7	17.0	167.5	154.3	0.357	0.650	2.223D+19	186.20	151.27	91.43	89.21	1.07	1
3023	45	45	60.0	14.5	6.7	151.2	160.7	0.372	0.650	1.821D+19	175.06	147.80	67.82	67.22	0.86	1
3196	46	46	55.0	14.6	6.7	156.0	154.3	0.361	0.650	1.450D+19	166.30	140.26	69.56	69.19	0.75	1
3201	47	47	60.0	14.5	6.7	151.2	160.7	0.327	0.650	2.304D+19	186.33	149.15	67.82	67.22	0.97	1
3276	48	48	60.0	14.5	6.7	151.2	160.7	0.372	0.650	1.945D+19	174.33	150.06	67.82	67.50	0.85	1
3288	49	49	50.0	14.7	11.6	163.9	154.3	0.352	0.650	2.040D+19	166.17	150.07	79.92	79.22	0.73	1
3423	50	50	60.0	14.5	6.7	151.2	160.7	0.311	0.650	1.564D+19	154.77	127.62	67.82	66.58	0.63	1
3461	51	51	40.0	14.5	11.6	179.0	154.3	0.400	0.650	2.064D+19	178.47	150.47	83.17	76.73	0.67	1
3490	52	52	42.5	14.6	6.7	172.1	154.3	0.364	0.650	2.133D+19	183.04	153.22	72.76	71.65	0.76	1

TYPICAL POSTULATED TRANSIENT H=5678 1. FLAWS/M**3 FO = 1.500D+19

WELD	UNADJUSTED P(F/E)	95%CI	%ERR	P(INITIA)	N*V	ADJUSTED P(F/E)	%ERR	NTRIALS
1	9.81D-03	1.70D-04	1.74	9.84D-03	1.000	9.81D-03		750000
2	2.86D-03	9.25D-05	3.24	2.88D-03	0.500	1.43D-03		750000
					VESSEL	1.12D-02	1.57	

DEPTHS FOR INITIAL INITIATION (MM)

	2.16	6.68	11.62	17.03	22.95	29.42	36.51	44.25	52.72
NUMBER	139	9786	4051	1610	499	121	30	7	0
PERCENT	0.9	60.2	24.9	9.9	3.1	0.7	0.2	0.0	0.0

TIMES OF FAILURE(MINUTES)

	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	0.0	0.0
NUMBER	0	0	0	273	4508	8916	2464	11	0	0	0	0	
PERCENT	0.0	0.0	0.0	1.7	27.9	55.1	15.2	0.1	0.0	0.0	0.0	0.0	

INITIATION T-RTNDT(DEG.C)

	-55.6	-41.7	-27.8	-13.9	0.0	13.9	27.8	41.7	55.6	69.4	83.3	97.2	111.1
NUMBER	0	7	395	4074	8285	3302	189	6	0	0	0	0	
PERCENT	0.0	0.0	2.4	25.1	51.0	20.3	1.2	0.0	0.0	0.0	0.0	0.0	

ARREST T-RTNDT(DEG.C)

	-27.8	-13.9	0.0	13.9	27.8	41.7	55.6	69.4	83.3	97.2	111.1	125.0	138.9
NUMBER	0	0	4	50	10	0	0	12	10	0	0	0	
PERCENT	0.0	0.0	4.7	58.1	11.6	0.0	0.0	14.0	11.6	0.0	0.0	0.0	

Appendix B

SENSITIVITY OF CALCULATED VALUE OF P(F|E) TO THE NUMBER AND RELATIVE VALUES OF THE SIMULATED CRACK-DEPTHS

As indicated in Sect. 4.2, the flaw-depth density function in Eq. (17) must be integrated over several discrete flaw-depth increments for the purpose of simulating flaw depth in a probabilistic analysis. As would be expected, the accuracy with which P(F|E) is calculated is dependent on the number and relative size of the increments. In general, the greater the number of increments the greater the accuracy, and the smaller the number the shorter the computer time.

An appropriate selection of flaw depths was made on the basis of sensitivity studies in which the number of flaw-depth increments was varied, and for a given number of increments the size of the first increment was varied. In both cases a judgment was made on the basis of comparing values of the conditional probability of crack initiation, P(I|E).

For the first part of this study, the numbers of increments considered were 7, 9, 11, and 13. For each of these trials, the first increment extended from 0–4.3 mm, and the extreme dimension of the deepest increment was 57.2 mm. [Deeper flaws were not included because as indicated by Eq. (17) the probability of deeper flaws existing as initial flaws is very small.] With the exception of the first, the size of each increment was established on the basis of a geometric progression.

The relative values of P(I|E) for the cases involving different numbers of increments were believed to be dependent to some extent on the severity of the transient. Thus, comparative studies were conducted for several transients. For most cases these transients were characterized by an exponential decay of the coolant temperature and a constant pressure of 15 MPa. The initial temperature of the coolant and vessel was 288°C; the exponential decay constant was 0.15 min^{-1}, which tends to be on the high side for most of the postulated transients. The fluid-film heat-transfer coefficient was ~6000 $W/m^2 \cdot °C$, which is also on the high side. The asymptotic coolant temperature was changed to vary the severity of the transient; values considered ranged from 66° to 149°C. A summary of conditions for the analysis is presented in Table B.1.

Results of the first part of the sensitivity study are presented in Table B.2, which shows the effect on P(I|E) of changing the number of crack-depth increments for four different transients. The indicated uncertainty of the numbers is associated with the number of vessels simulated rather than the number of crack-depth increments. With this in mind it is observed that the variation in P(I|E) because of the different number of increments is within the accuracy of the calculated values of P(I|E). Thus, to reduce computer costs there is a tendency to select the smallest number of increments.

The reason for concern over the size of the first crack-depth increment, which extends from zero crack depth upward, is that the relatively shallow flaws are more abundant, and the first increment contains a range of subcritical crack depths. If the average crack depth for

Table B.1. Summary of conditions used in flaw-depth convergence study

Parameters	
Vessel dimensions, mm	
Inside diameter	4368
Wall thickness	216
Cladding thickness	5.4
Heat transfer coefficient, $W/m^2 \cdot °C$	5678
Bulk coolant temperature, °C	$T_f + (288 - T_f) \exp(-0.15\ t)$ (t = time, min)
Fluence, neutrons/cm^2	1×10^{19}
Copper concentration, %	0.30
Nickel concentration, %	0.60
$RTNDT_o$, °C	−6.7
Pressure, MPa	
Exponential transients	15.2
LBLOCA	0
Flaw type	Long axial (2-D)

Table B.2. Influence of number of simulated crack depths on P(I|E)

Number of increments	T_f, °C							
	66		93		121		149	
	P(I|E) (10^{-1})	IFI[a] (%)	P(I|E) (10^{-2})	IFI (%)	P(I|E) (10^{-3})	IFI (%)	P(I|E) (10^{-5})	IFI (%)
7	2.7 ± 0.1	45	7.3 ± 0.3	19	6.1 ± 0.4	5	9 ± 2	0
9	2.6 ± 0.1	46	7.1 ± 0.3	21	6.0 ± 0.4	5	9 ± 2	0
11	2.7 ± 0.1	46	6.9 ± 0.3	20	5.9 ± 0.4	5	8 ± 2	0
13	2.7 ± 0.1	47	6.9 ± 0.3	21	5.9 ± 0.4	5	8 ± 2	0

[a]Percent of total initiation events in first crack-depth increment.

that increment is critical, all flaws in that increment are considered critical, and thus P(F|E) tends to be overestimated. Decreasing the size of the first increment will reduce the overestimation unless it is made too small, in which case the problem is transferred to the second increment.

To investigate the effect of the size of the first increment, calculations were made for the most severe of the above transients (T_f = 66°C) and also for a large-break loss-of-coolant accident (LBLOCA), which was characterized by zero pressure and a step change in coolant temperature from 288° to 21°C; nine crack-depth increments and a range of sizes for the first increment were used.

As indicated in Tables B.3 and B.4, it was necessary to reduce the size of the first increment from 4.3 to 2.5 mm for the exponential transient and from 4.3 to 1.8 mm for the LBLOCA to effectively eliminate crack initiation with the first crack-depth increment. The corresponding reductions in P(I|E) are 20% and 44%, respectively. As expected, the change is greater for the more severe transient.

It is of interest to note that for the LBLOCA (Table B.4), a further decrease in the size of the first increment resulted in an increase

Table B.3. Effect of size of first increment on P(I|E) based on exponential transient with T_f = 66°C

Size of first increment (mm)	P(I|E) (10^{-2})	IFI[a] (%)
4.3	2.6 ± 0.1	46
3.9	2.4 ± 0.1	35
3.6	2.2 ± 0.1	21
3.2	2.2 ± 0.1	10
2.5	2.2 ± 0.1	1

[a]Percent of total initiation events in first crack-depth increment.

Table B.4. Effect of size of first increment on P(I|E) based on LBLOCA transient

Size of first increment (mm)	P(I|E) (10^{-1})	IFI[a] (%)
4.3	5.83 ± 0.02	70
3.8	5.79 ± 0.02	65
3.3	5.65 ± 0.04	59
2.8	5.25 ± 0.06	47
2.3	4.2 ± 0.1	27
2.0	3.9 ± 0.1	15
1.8	3.8 ± 0.1	4
1.5	4.0 ± 0.1	0.5
1.3	4.1 ± 0.1	0.1

[a]Percent of total initiation events in first crack-depth increment.

in $P(I|E)$. This too had been anticipated because making the increment smaller would eventually result in a range of subcritical cracks in the adjacent increment.

On the basis of these studies it was concluded that a Δa of 4.3 mm for the first increment and a total of nine increments would be adequate for most transients. However, the user of OCA-P has the option of using a smaller first increment and up to a total of 15 increments.

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OCA-P is a probabilistic fracture-mechanics code that was prepared specifically for the purpose of evaluating the integrity of PWR pressure vessels when subjected to overcooling-accident loading conditions. The code has two-dimensional and some three-dimensional-flaw capability; it is based on linear elastic fracture mechanics; and it can treat cladding as a discrete region. Both deterministic and probabilistic analyses can be performed, and for the former analysis it is possible to conduct a search for critical values of the fluence and the nil ductility reference temperature corresponding to incipient initiation of the initial flaw. The probabilistic portion of OCA-P is based on Monte Carlo techniques, and simulated parameters include fluence, flaw depth, fracture toughness, nil ductility reference temperature, and concentrations of copper, nickel and phosphorous. Plotting capabilities include the construction of critical-crack-depth diagrams (determinstic analysis) and various histograms (probabilistic analysis).

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