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Subroutine CWASTE

Cladding thickness is progressively diminished as the result of sodium corrosion (DWCR) and wear (DWWR) of the outer surface, and chemical attack by the fuel and fission products, FCCI (DWAK) on the inner surface. Subroutine CWASTE calculates the components of wastage, repositions the cylinder boundaries and then adjusts the strain and displacement distributions to fit the new geometry. Calculation of wastage is optional and may be suppressed by entering a non-zero value of IWASTE on input record 5. Two other input constraints must be satisfied to perform the wastage calculation. First, the number of cladding cylinders, KC, must be at least 5, and second, the initial thickness of the inner wastage ring, SIS (input record 10), must be greater than zero.

A flowchart of subroutine CWASTE is shown in Figure ____.*

Wastage at the inner and outer surfaces of the cladding is treated differently. Wear and sodium corrosion of the outer surface are assumed to physically remove material. Thus, the current outer radius of the cladding, XRR (KF+KC+2) is reduced by the wear and corrosion wastage occurring during each time step. FCCI attack at the inner surface does not affect the position of the inner cladding boundary, XRR (KF+1). The outer boundary of the innermost cladding shell (the "wastage" ring) XRR (KF+2) is increased by the increment of cladding attack. Consequently, continuity of the fuel-cladding boundary is maintained. The structural effects of FCCI attack are simulated by modification of the elastic properties of the wastage ring. (See SOLVER and XLAME).

The structural shell boundaries between XRR (KF+2) and XRR (KF+KC+2) are repositioned to define new shells of equal thickness. The strain and displacement distributions from the old shells are fitted to parabolic

*Figure and table numbers will be assigned by Westinghouse - Advanced Reactor Division in the final compilation of the LIFE4 Programmers Manual.

functions in groups of 3, starting from the nearest outermost shell in each group. Revised strain and displacement distributions are obtained by interpolation of the functions using the new shell geometry. FUNCTION FCWA performs this operation.

The wastage calculation and redefinition of geometry and structural conditions is performed at the conclusion of each converged time step. The new cladding data are returned to AMAIN2 and used in the initiation of the next time step.

SUBROUTINE CWASTE

IV. FRACT

FRACT is the subroutine called by AMAIN2 at the end of each converged time step to calculate the cladding damage for each axial section. This is done by using the time fraction approach:

$$CDF = \sum \frac{\Delta t}{t_R}(T, \sigma, \phi t)$$

where Δt = time step length

and t_R = stress rupture life at the temperature, stress,
and fluence existing during the time step.

Material property correlations defining t_R are given in section . The use of the cladding damage calculation (FRACT) is optional. The calculations are enabled by setting ICHNG on input card #5 to a non-zero value.

Input to FRACT includes fluence (FLNC(J)), equivalent stress (EQSIG(K,J)), average clad cylinder temperatures (TBF6(K,J)), clad cylinder interface temperatures (TL6(K,J)) and the circumferential component of stress (SIGC(K,J)). The logic used first determines the type of cladding material. If CW316SS is used, the average circumferential stress (SUMSIG) and cladding midwall temperature (TK) are calculated. The cladding midwall temperature is given by:

$$TK = (TL6(CL1R, J) + TL6(NT2 + KC, J)) / 2.$$

where CL1R = NT2 if IWASTE $\neq$ 0,

or CL1R = NT2+1 if IWASTE = 0.

Processing continues based on the value of ITRAN. For ITRAN = 0, steady state logic determines the type of CW316, first core (NCIRC = -13) or N lot (NCIRC = -4) and calculates the appropriate clad damage fractions, DORND (1,J) and DORND (2,J) for 0σ and 1σ uncertainty, respectively. For ITRAN $\neq$ 0, the nominal NSMH damage correlation is used to calculate the transient damage fractions, DORND (3,J) and DORND (4,J) for 0σ and 1σ uncertainty, respectively.

For cladding materials other than CW316 a parallel calculational path is followed, except that the damage increment is calculated for each cladding cylinder. Rupture life is determined using the cylinder-average temperatures (TBF6) and equivalent stresses (EQSIG). The more detailed analysis provides a better basis for the performance evaluation of experimental cladding materials.

When damage fractions have been calculated for each axial section, control returns to AMAIN2. A flowchart for subroutine FRACT is given in Figure IV. .1.

FIGURE IV. .1

Flowchart for Subroutine FRACT

IV. GAPCON

GAPCON is the routine used to calculate gap conductance and fuel surface temperature. Subroutine GAPCON is called from HTTRAN for steady state analysis and from HTTR2 for transient analysis. Two gap conductance models are included in the routine; the model selector is NGAP on input card #4. If NGAP=1 the ANL gap conductance correlation is used; if NGAP=2 a mechanistic gap conductance model developed by HEDL* is chosen. This latter model is recommended for most applications. GAPCON is called once per axial section per thermal time step. Input to GAPCON includes the linear power (POW), gap inner and outer radii (RI and RO), shell interface temperatures (TL(K)), gap pressure (PGAP), plutonium concentration (CPUO), crudfil factor (CRUDF) and upper and lower boundary limits on the value of HGAP (HBNDU and HBNDL).

If NGAP=2, the HEDL gap conductance model evaluates three primary heat transfer methods across the gap and applies the appropriate factors to the final HGAP value, depending on whether the gap is open or closed. The factors calculated are for (1) radiant heat transfer (h_r), gas-conducted heat transfer (h_g), and solid-solid heat transfer (h_s) (closed gap). Conduction through the gas (h_g) uses the average temperature in the gap, so that an iterative solution is required to determine the total gap conductance. The total heat transfer coefficient, h , is given by:

$$h = h_r + h_g + h_s \quad (1)$$

Thermal and structural analyses during each time step are performed sequentially. Thus the gap conductance is based on the configuration at the end of the previous time step. A substantial change in gap conductance may lead to oscillation of the fuel-cladding interface conditions through feedback from the structural analysis. To minimize this effect the time gap conductance given by equation (1) is weighted against that of the previous time step (h_0) using the factor WHG. As a further precaution, the magnitude of the gap conductance change from the last time step is limited by the parameters HBNDU and HBNDL. However, weighting factors are not used in the transient HGAP calculations. Details of this model are given in section .

*The HEDL model is based on work done by Ross & Stoute.

If NGAP=1 the ANL gap conductance correlation is enabled. This model is a simplified calculation which ignores such factors as the solid-solid conductance and the crudfil factors. This model becomes the default calculation if the HEDL (NGAP=2) equations do not converge. When the final value of HGAP and HGL have been calculated, control returns to the calling routine, HTTRAN or HTTR2.

A flowchart for GAPCON, is given in Figure IV.Y.1.

FIGURE IV. .1
Flowchart for Subroutine GAPCON

IV.2 GOLDN

GOLDN is the subroutine called from HTRAN to calculate cladding OD temperature, the coolant-clad heat transfer coefficient and coolant temperature for encapsulated or unencapsulated fuel pins.

The steady-state axial temperature distribution in the coolant is calculated at the beginning of each time step on the basis of the axial power distribution of the fuel pin, (QSF), specified inlet and outlet coolant temperatures during the step, (TIN, TOUT), and fuel pin dimensions at the end of the previous time step, (R4B(N)). Coolant mixing and crossflow and wire-wrap effects on coolant temperatures are not included. The user has an option to bypass the coolant temperature calculations and specify the axial distribution of the cladding outside diameter (OD) temperature as input (using the CLADT input option, IR3 > 11; see Input Instructions, Table V.B.2.).

The coolant temperature $T_{Na}(n)$ at axial section n is calculated by considering the amount of heat generated in every section:

$$\int_{T_{in}}^{T_{Na}(n)} C_p dT = \frac{\sum_{i=1}^n QSF(i) - QSF(n)/2}{\sum_{i=1}^{NF} QSF(i)} \int_{T_{in}}^{T_{out}} C_p dT, \quad (1)$$

where

T_{in} = inlet coolant temperature

T_{out} = outlet coolant temperature,

$QSF(i)$ = axial power distribution factors,

NF = total number of axial fuel sections specified,

and

C_p = specific heat of the coolant.

Equation (1) is solved numerically by Newton's interpolation method with C_p approximated by a quadratic function of temperature.

The OD surface temperature $T_{Co}(n)$ of the cladding (or capsule, if the fuel element is encapsulated) at axial section n is given by:

$$T_{co}(n) = T_{Na}(n) + \frac{q(n)}{2\pi r_{co} h_c}, \quad (2)$$

where the outer radius of the cladding (or capsule) r_{co} , linear power $q(n)$, and heat-transfer coefficient h_c are evaluated at the midpoint of axial section n .

The linear power $q(n)$ in axial section n is given by:

$$q(n) = q_{avg} NF \left[\frac{QSF(n)}{\sum_{i=1}^{NF} QSF(i)} \right], \quad (3)$$

where q_{avg} is the average linear power for the fuel pin. The heat-transfer coefficient between the coolant and cladding (or capsule) is found from:

$$h_c = \frac{k_{Na}}{D_e} N_u, \quad (4)$$

where

k_{Na} = coolant thermal conductivity,

D_e = equivalent diameter, approximated by four times the coolant flow area A_{fna} associated with one fuel pin divided by the wetted perimeter of the element,

and

N_u = Nusselt number.

If the coolant flow area is input, it is used to calculate the equivalent diameter. Otherwise,

$$A_{fna} = \sqrt{3/4} P^2 - (\pi/4) [D^2 + (P - D)^2], \quad (5)$$

where D is the diameter of the fuel pin and P is the pitch (distance between fuel pin centers). The value of P is supplied as input. Equation (5) is based on the assumptions that the fuel elements are wire wrapped and the bundle is tight.

Equation (2) is solved iteratively, because h_c is a function of temperature. The parameter C_p is a quadratic function of temperature, and k_{Na} is a linear function of temperature. These properties are evaluated by using the average between T_{Na} and T_{co} .

When using the CLADT option to input cladding OD temperatures (TCLOF(N)), the current temperatures, TCLO(N), are calculated using:

$$TCLO(N) = T_{in} + (TCLOF(N) - T_{in}) POW(N)/POWT(N) \quad (6)$$

where POW(N) is the current local linear power, and POWT(N) is the local linear power which was input to correspond to TCLOF(N). The linear dependence of temperature rise on power is an approximation but has been found to be satisfactory provided that POWT(N) is not substantially different (within $\pm 20\%$) from the operating power, POW(N).

A flowchart for GOLDN is given in Figure IV. .1.

Figure IV. .1
Flowchart for Subroutine GOLDN

IV. . PLENP

Subroutine PLENP is called from HTTRAN to calculate plenum pressure (PLPR). The calculation is done for each thermal time step in both steady state and transient analyses. Input to the routine are radii (RL6(K,J)) and temperatures (TL6(K,J)) for the inner and outer fuel surfaces and the cladding inner surface, the total number of moles of gas in the pin (TOGAS) and the number of moles of gas trapped in a closed central void (XNOMOL, may be ≥ 0).

The plenum pressure calculation is based on the ideal gas law:

$$P = nRT/V$$

where

V = total volume = plenum vol. + gap vol. + void vol.

n = number of moles of gas, TOGAS

T = volume average temperature of gas in plenum, gap and void

R = universal gas constant, QQ(175).

A flow chart for PLENP is given in Figure IV. .1.

Figure IV. .1
Flowchart for Subroutine PLENP

VI. CLADDING TIME-TO-RUPTURE AND DAMAGE FRACTION

The steady-state time to rupture, t_R , (in hours) is given by:

$$\log_{10} t_R = A + B/T + C (\log_{10} \sigma)/T$$

where

T = average clad temperature in °K

σ = average cladding hoop stress in MPa

A, B, and C = constants given in Table A below;
the smallest calculated time-to-rupture value is used.

TABLE A

MATERIAL		CONSTANTS		
		A	B	C
CW 316		-16.638	34054	-7113
(FFTF)	or	-12.637	22213	-3591
CW 316		-18.460	37209	-7579
(N-1ot)	or	-15.506	26351	-4000

The damage fraction increment calculated for the current time step is given by:

$$\Delta CDF = \Delta T / t_R$$

where

DEL T = time step length (hrs)

t_R = time-to-rupture

The final clad damage fraction is found by summing the Δ CDF's for each time-step. A stress rupture plot is given in Figure VI. 1. for CW316(N-10t) cladding with an average temperature of 650°C.

The transient time-to-rupture value is given by:

$$\log t_R = A + B \log_{10} \log_{10} \frac{\sigma^*}{\sigma} + \frac{Q_1}{R_2 e T} + C \tanh \phi t + \text{FAE}$$

where

FAE	=	(FRACTM)	(DEGIRR)	(TEFF)
fuel		fracture	irradiation	thermal
adequacy		mode	degradation	effects
effect				

where

$$\text{FRACTM} = \frac{1}{2} [(\tanh (\frac{D + E\sigma + F T'}{G})) + 1]$$

$$\text{DEGIRR} = H (\tanh \frac{\phi t}{I}) (\tanh \frac{\Delta T}{J}) (1 - \tanh (\frac{T_i}{K})^M) \\ (N - P (\tanh (\frac{\dot{T}}{R_1} + S)))$$

$$\text{TEFF} = 1 - \tanh \sum \frac{L \Delta t}{\exp(Q_2/R_2 T)}$$

where

Δt = time increment, sec.

t_R = time-to-rupture, hrs.

Q_1 = 82141

R_2 = 1.987

e = 2.303

σ = average hoop stress, MPa

σ^* = 689.5

ϕt = n/cm^2 , $E > 0.1$ MeV, $\times 10^{22}$

FIGURE VI. .1
LIFE4 STRESS RUPTURE FOR N-LOT CW316
(STEADY STATE)

CLADDING TEMP = 650°C

T' = transient cladding midwall temperature, °F
 T = transient clad midwall temperature, °K
 T_i = cladding irradiation temperature, time-averaged over steady state, °F
 ΔT = $T' - T_i$
 $\dot{T}$ = ramp rate, °F/sec
 Q_2 = 62000
 A = -16
 B = 6.4
 C = -0.95
 D = 125
 E = 0.145
 F = -0.0492
 G = 25.
 H = -4.0
 I = 2.5
 J = 75
 K = 1050
 L = 2×10^{12}
 M = 25
 N = 0.9
 P = 0.1
 R_1 = 20.
 S = -4.

The transient damage fraction increment for the current time step is given by:

$$\Delta CDF = DELT / t_R$$

The final damage fraction is the sum of the CDF's for each time step.

Documentation for the above correlation is given in TC-160-20 (Jan-Mar 1979 quaterly), W. F. Brizes, "Fuel Cladding Transient Damage Correlations for Reference and Advanced Alloys."