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DEVELOPMENT AND VERIFICATION
OF THE LIFE-GCFR COMPUTER CODE
FOR PREDICTING
GAS-COOLED FAST-REACTOR FUEL ROD PERFORMANCE

by

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NOMENCLATURE

A	Constant in crack-healing model	$D(z)$	Diffusion coefficient of fission gas in helium
A_b	Cross-sectional area for gas transport in blanket	DMG	Cladding damage fraction
A_c	Constant describing the process of formation of short-circuiting paths	E_f	Energy per fission
A_{ct}	Cross-sectional area for gas transport in rod trap	$\dot{F}$	Fission rate
A_f	Cross-sectional area for gas transport in fueled region	F_g	Rate of fractional gas release from fuel
A_L	Constant in Eq. (13)	f_{sm}	Fractional smooth length of cladding
A_p	Calibration constant	$\dot{G}_m$	Net rate of change of fission gas in fuel due to gas migration
A_s	Constant describing the surface diffusion process	$\dot{G}_p$	Fission gas production rate
A_{sr}	Cross-sectional area for gas transport in rod spring	G_s	The amount of fission gas retained in fuel per unit volume
B	Constant in crack healing model	h	Cladding rib height
B_L	Preexponential structure factor	K	Constant in Eq. (26)
B_p	Calibration constant	L	Active fuel length
B_u	Fuel burnup	M	An integer between 0 and N_f
C	Fission-gas concentration	m_f	Linear mass of fuel
C_c	A quantity which is proportional to the coefficient of the stress in the fuel linear creep rate term	N_f	Number of axial sections to be specified in LIFE-GCFR for code analysis
C_{col}	Calibration constant to determine the columnar-equiaxed boundary	P	Fuel-cladding gas-gap pressure
C_h	Constant in Eq. (33)	P_o	Constant in Eq. (29)
C_l	Radiation-enhanced creep constant	P_g	The surface-tension-induced pressure on an average bubble
$Coefl$	Coefficient of the stress in the fuel linear creep rate term	P_{gas}	Gas pressure in an average bubble
$Coefp$	Coefficient of the stress in the total fuel nonlinear creep rate term	P_{or}	Fuel porosity
D	Diffusion coefficient of fission gas	P	Cladding rib pitch
D_{bl}	Diffusion coefficient of fission gas in lower blanket	Q_c	Constant describing the process of formation of short-circuiting paths
D_{bu}	Diffusion coefficient of fission gas in upper blanket	Q_H	Activation energy for power-law creep
D_c	Diffusion coefficient of fission gas in rod trap	Q_L	Activation energy for viscous creep
D_f	Diffusion coefficient of fission gas in fueled region	Q_p	Calibration constant
D_g	Fuel grain size	Q_s	Constant describing the surface diffusion process of fission-gas bubble
D_{go}	Initial grain size	Q_T	Activation energy for radiation-enhanced creep
D_1	Constant in Eq. (11)	q'	Fuel linear power
D_m	Limiting grain size	R	Gas constant
D_s	Diffusion coefficient of fission gas in rod spring	R_c	The outer radius of the columnar-grain zone
		R_m	Geometric progression of bubble-size ranges in GRASS-SST
		R_o	Outer radius of fuel
		R_p	Fraction of retained gas residing in bubbles

NOMENCLATURE

$R(T)$	The temperature-dependent part of the stress-free swelling for 20% CW 316 stainless steel	ΔV_{gas}	Volume change of fuel due to fission gas
r	Radial direction of fuel	$\dot{\epsilon}_A$	Steady-state athermal fission-induced creep rate
r_i	Inner radius of fuel ring	$\dot{\epsilon}_{At}$	Primary and steady-state athermal fission-induced creep rate
r_o	Outer radius of fuel ring	ϵ_{cov}	Convergence parameter for the solution of the linear differential equations in fission-gas analysis
S	Fission gas released to the fuel-cladding gap	ϵ_{cut}	Upper limit on the cut-off height of the tail of the bubble-size distribution in fission-gas analysis
S_c	Concentration of short-circuiting paths	ϵ_g	Volumetric strain for fission-gas swelling
S_o	Constant in Eq. (28)	$\dot{\epsilon}_H$	Power-law thermal creep rate
T	Temperature	$\dot{\epsilon}_L$	Viscous thermal creep rate
T_m	Fuel melting temperature	$\dot{\epsilon}_{Lt}$	Primary and steady-state viscous creep rate
t	Irradiation time	$\dot{\epsilon}_T$	Steady-state radiation-enhanced creep rate
t_{cr}	Cladding root thickness	$\dot{\epsilon}_{\text{total}}$	Total steady-state creep rate
t_{eff}	Effective cladding thickness	ρ	Fuel density
t_r	Time to rupture for cladding	ρ_o	Initial immersion density of cladding
V	Fuel volume	ρ_f	Final immersion density of cladding
V_o	Initial cladding volume	σ	Stress
V_b	Bubble migration velocity	σ_h	Fuel hydrostatic pressure
V_f	Final cladding volume	σ_n	Fuel stress normal to crack surface
V_{ib}	Volume per mole of dissolved fission gas	σ_o	As-cracked fracture strength
w	Cladding rib width	σ_F	Uncracked fracture strength
x	Axial position from top of active core	σ_t	Fracture strength after time t
z	Fuel axial coordinate	τ	Incubation neutron fluence
α	Constant in Eqs. (18) and (28)	ϕ	Fast-neutron flux
β	A temperature-dependent variable	Σ	Fractional density change related to the initial and final immersion densities
γ	Fission yield of Kr and Xe		
Δt	Time increment for a time step		
Δt_m	Maximum time increment to be used in the LIFE-GCFR analysis		
ΔV	Volume change of cladding		

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ABSTRACT

The fuel-pin modeling code LIFE-GCFR has been developed to predict the thermal, mechanical, and fission-gas behavior of a Gas-Cooled Fast Reactor (GCFR) fuel rod under normal operating conditions. It consists of three major components: thermal, mechanical, and fission-gas analysis. The thermal analysis includes calculations of coolant, cladding, and fuel temperature; fuel densification; pore migration; fuel grain growth; and plenum pressure. Fuel mechanical analysis includes thermal expansion, elasticity, creep, fission-product swelling, hot pressing, cracking, and crack healing of fuel; and thermal expansion, elasticity, creep, and irradiation-induced swelling of cladding. Fission-gas analysis simultaneously treats all major mechanisms thought to influence fission-gas behavior, which include bubble nucleation, resolution, diffusion, migration, and coalescence; temperature and temperature gradients; and fission-gas interaction with structural defects.

LIFE-GCFR predictions have been checked against experimental observations of the performance of mixed uranium-plutonium oxide fuel. The overall good agreement of predictions with test results demonstrates that LIFE-GCFR is, in its present state, a suitable tool for predicting the thermal, mechanical, and fission-gas behavior of mixed-oxide fuel rods.

As no fuel pins have been tested under the full GCFR conditions, a reference GCFR fuel-element design was analyzed with this verified LIFE-GCFR code under various anticipated operating conditions. The code predictions appear plausible. In the absence of fuel-performance data for this design case, the most that can be concluded is that LIFE-GCFR gives reasonable predictions of GCFR fuel behavior.

Finally, suggestions for further research are given. Modeling efforts in off-normal and/or design-basis transient analysis, axial blanket analysis, fission-gas analysis with fast running capability, and the analysis of highly localized fuel and cladding behavior are recommended.

I. INTRODUCTION

A. Historical Perspective

The initial conceptual design studies for the Gas-Cooled Fast Reactor (GCFR) were started by General Atomic Company (GAC) and Kernforschungszentrum Karlsruhe in 1961. A preliminary safety information document¹ was completed and submitted by GAC to the Division of Reactor Licensing (DOL) and the Advisory Committee on Reactor Safeguards of the Atomic Energy Commission in 1971 to initiate regulatory review of GCFRs. An international GCFR program has been conducted by the U.S., West Germany, Switzerland and France. In the U.S. a tentative schedule was set for the development of the GCFR program, under which the fuel development and management work would be completed by 1983, the construction permission received in 1986, and the 300-MW(e) GCFR demonstration plant built by 1991. Recently, however, the U.S. GCFR program was suspended because of budget limitations within the fast-reactor program.

The GCFR has the following advantages over the Liquid-Metal Fast-Breeder Reactor (LMFBR): (1) It has a high breeding ratio. (2) Helium doesn't become radioactive, so the GCFR does not require an intermediate coolant loop. (3) Helium has a small neutron worth and is not subject to sodium void coefficient concerns. (4) The vented fuel-rod design prevents the buildup of fission-gas pressure within the rod.

A typical nuclear steam supply system² for a GCFR, in which the whole primary system is integrated within a Prestressed Concrete Reactor Vessel, (PCRVR) is shown in Fig. 1. Fuel elements, blanket, and thermal shielding are contained in the central cavity, and main and auxiliary loops are located in cavities within the walls of the PCRVR. Steam-turbine-driven circulators circulate the helium coolant down* through the reactor core, up through the thermal shielding, and then through the steam generators back to the circulators. The core of the 300-MW(e) GCFR³ consists of 91 fuel assemblies, 27 control assemblies, and 90 radial blanket assemblies. Each fuel assembly contains 264 fuel rods which are similar to LMFBR fuel rods, but with two important differences. First, the cladding surface is ribbed over the lower 75% of the active core region to improve the surface heat transfer. Second, the pressure in the fuel rods is maintained slightly below that of the reactor coolant by collective venting to the helium purification system at the circulator inlet pressure. The primary support for the fuel rods within the duct is provided by the grid manifold. Each rod is securely fastened and sealed to the manifold by the threaded connection of the top end plug.

A typical fuel rod is shown in Fig. 2. The fuel rod consists of the following materials arranged in order from top to bottom: activated charcoal

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*Since the initiation of the present work, the GCFR design has been changed to include an upflow core. However, as discussed further in Section I.B, this change does not affect the fuel-performance models discussed here under normal operating conditions.

Fig. 1
Nuclear Steam Supply Sys-
tem for 300-MW(e) GCFR
Demonstration Plant

Fig. 2
A Typical GCFR Fuel Rod

granules, rod spring, low-molecular-weight neutron-shielding pellets, depleted- UO_2 upper-blanket pellets, mixed-oxide UO_2 - PuO_2 fuel pellets, and lower-blanket pellets. The major design parameters of the GCFR fuel element are given in Table I. The fuel is vented to the helium purification system through charcoal traps and then discharges to the intake of the circulator.

TABLE I. Major Design Parameters of 300-MW(e) GCFR Fuel Assembly

Fuel Assembly

Cross section.....	hexagonal
Length.....	3665.0 mm
Active core height.....	1130.0 mm
Number of fuel rods.....	264
Number of hanger rods.....	6
Number of instrumentation rods.....	1
Fuel rod spacer type.....	modified hexagonal grid
Number of spacer grids*.....	10
Across-flats ID*.....	183.0 mm
Across-flats OD	
(a) Above core*.....	190.6 mm
(b) Core midplane*.....	188.0 mm
Duct-wall thickness	
(a) Above core.....	3.8 mm
(b) Core midplane.....	2.5 mm
Fuel-rod pitch*.....	11.05 mm
Rod-to-rod gap*.....	3.85 mm
Rod-to-duct gap*.....	1.77 mm
Rod-to-duct gap* as % of rod-to-rod gap.....	46.1
Fuel-assembly pitch*.....	197.1 mm

Fuel Rod

Length.....	2230.0 mm
Outside diameter*.....	7.46 mm
Outside root diameter.....	7.20 mm
Inside diameter.....	6.44 mm
Cladding thickness.....	0.38 mm
Cladding material.....	20% CW 316 SS
Fuel and blanket pellet OD*.....	6.30 mm
Fuel and blanket pellet-to-cladding gap*.....	0.14 mm
Fuel length.....	1130.0 mm
Fuel material.....	mixed UO_2 - PuO_2
Fuel material planar smear density, % of theoretical.....	85.5
Axial blanket length (each), mm.....	450.0
Axial blanket material.....	depleted UO_2
Axial blanket material planar smear density, % of theoretical.....	90.0

Surface Roughening

Fraction of active core roughened, effective %	75.0**
Roughening height*.....	0.13 mm
Roughening width*.....	0.45 mm
Roughening pitch*.....	1.56 mm

*Designates values that have changed.

**Recent changes call for this value to be 100%.

The further development of the GCFR fuel design mainly involves irradiation tests and the establishment of computational tools for predicting fuel behavior under GCFR irradiation conditions. The irradiation program for the testing of GCFR-type fuel elements in the U.S. is a cooperative effort among GAC, Argonne National Laboratory (ANL), and Oak Ridge National Laboratory (ORNL). Thermal-flux irradiation of vented fuel rods GB-9 and GB-10 (Ref. 4) was conducted using the Oak Ridge Research Reactor (ORR). The GB-9 and GB-10 test rods were similar in that each was a shortened mock-up of a GCFR vented and pressure-equalized fuel rod with a mixed-oxide fuel column, a short upper-blanket region of depleted UO_2 pellets, and a charcoal trap region above the blanket region. The GB-9 rod was irradiated to a fuel burnup of 62 MWd/kg heavy metal, and GB-10 was irradiated to 112 MWd/kg heavy metal. The Experimental Breeder Reactor (EBR-II) at ANL was used for two series of fast-flux irradiations of sealed rods with ribbed cladding, designated F-1 (completed)⁵ and F-5 (in progress).⁶ The Federal Republic of Germany is conducting irradiations of two 12-rod bundles, designated HELM-2 and HELM-3,⁷ in the BR2 reactor at Mol, Belgium. The HELM test is the first to include GCFR fuel rods irradiated in a helium loop with a Pressure Equalization System (PES), charcoal trap, grid spacer, and partially ribbed cladding. The PES is an important design feature of the GCFR fuel rod in that it allows fission gases to be vented from the rod and thereby maintains an equilibrium between coolant pressure and plenum pressure. Table II summarizes the test conditions and program status of the various experiments.

TABLE II. Test Conditions and Program Status for GCFR Fuel-rod Irradiations

	GB-9	GB-10	F-1	F-5	HELM-2	HELM-3
TOP MOUNTING	NO	NO	NO	NO	YES	YES
RIBBED CLADDING	NO	YES	YES	YES	YES	YES
GRID SPACERS	NO	NO	NO	YES	YES	YES
HELIUM COOLANT	NO	NO	NO	NO	YES	YES
PES	YES	YES	NO	NO	YES	YES
CHARCOAL TRAP	YES	YES	YES	YES	YES	YES
FUEL PELLET MATERIAL	12% PuO_2 88% UO_2	12% PuO_2 88% UO_2	15% PuO_2 85% UO_2	15% PuO_2 85% UO_2	UO	12.6% PuO_2 87.4% UO_2
MAX. BURNUP, MWd/MT	54000	112000	49830	90600	7000	100000
IRRADIATION STATUS	FINISHED	FINISHED	FINISHED	IN-CORE	FINISHED	IN-CORE
PIE ^a STATUS	FINISHED	FINISHED	FINISHED	IN PROGRESS	IN PROGRESS	-

^aPostirradiation examination.

To support the GCFR fuel design and irradiation tests, a reliable computational method for predicting fuel performance under GCFR irradiation conditions is needed. The GCFR fuel designs are dependent on the fuel and material development work being performed for the LMFBR. Owing to the identical fuel and cladding material and similar operating conditions, the developing LMFBR fuel modeling technology can be used as a basis for the GCFR fuel-modeling work. Fuel-modeling codes that have been developed to predict the performance

of LMFBR fuel rods include LIFE,⁸ BEHAVE,⁹ CYGRO,¹⁰ URANUS,¹¹ COMETHE,¹² IAMBUS,¹² SIEX,¹³ and others. Of these, LIFE has been selected by the U.S. Department of Energy as the reference performance code. LIFE-3 was released in June 1976 and was documented in July 1977.¹⁴

LIFE-3 performs a one-dimensional thermal and mechanical analysis. The thermal analysis is based on the assumption of steady-state radial heat transfer in fuel and cladding: It performs a thermal-hydraulic analysis and calculates cladding temperature, fuel-cladding heat transfer coefficient, fuel temperature and densification, pore migration, grain growth, and fission gas migration and release. The mechanical analysis is based on generalized plane strain and the method of successive elastic solutions. The fuel deformation mechanisms considered are thermal expansion, elasticity, restructuring, creep, fission-product swelling, hot pressing, and cracking; cladding deformation mechanisms are thermal expansion, elasticity, creep, and irradiation-induced swelling.

Since the LIFE code was specifically developed for the analysis of sealed LMFBR fuel rods, which are cooled with liquid sodium, some modifications are necessary to apply it to the study of GCFR vented fuel rods, which use helium as a coolant. Preliminary modifications that were made to LIFE-3 for GCFR analysis (prior to the current research effort) include the addition of two code options: one allows users to specify the cladding outer surface temperature as an input to the code, and the other allows users to specify constant plenum pressure and temperature as an input to the code.¹⁴ Also, in 1976, GAC substituted the thermal properties of gaseous helium for those of liquid sodium in the LIFE-3 code, and provided empirical Nusselt-number correlations for the determination of the heat-transfer coefficient for smooth cladding.¹⁵ The Nusselt-number correlation for the ribbed portion of the rod is based on a preliminary analysis of data collected by the Swiss Federal Institute for Reactor Research. With the above modifications, the code can provide a preliminary analysis of GCFR fuel-rod performance.

GCFR fuel-modeling work was conducted at ANL in 1976 to support the planning and designing of GCFR-fuel irradiation experiments. Additional modifications were made to LIFE-3 at that time for GCFR analysis.¹⁶ These included (1) adapting the coolant-cladding heat-transfer correlation from GAC for flowing helium over 1/4 smooth and 3/4 ribbed cladding, (2) choosing an effective cladding thickness to represent the mechanical response of ribbed cladding, (3) specifying only helium in the fuel-cladding gap for gap-conductance calculations, and (4) incorporating FTR core 1 and core 4 cladding properties into the code.

The modified LIFE-3 code was then used to perform scoping analyses for GCFR pins and to predict fuel performance of the GCFR test pins irradiated in the ORR and EBR-II reactors. However, further development of the code was judged to be necessary for the following reasons: (1) Differences between LMFBR and GCFR operating conditions can cause unreasonable code predictions,

owing to the extrapolation of the empirical expressions out of the range of the LMFBR data base. (2) More experimental data are now available from fuel and cladding tests under LMFBR, LWR, and (some) GCFR irradiation conditions; better analytical models and empirical formulas can be developed based on these test data. (3) A rigorous code calibration and verification against GCFR fuel irradiation data is needed to qualify the code. These three points are addressed in detail in the present report.

B. Problem Statement and Approach

The purpose of the present work was to develop calculational methods that would combine modeling work for describing unique GCFR fuel design and irradiation conditions with the developing LMFBR fuel-modeling technology to produce an integral fuel-modeling code, LIFE-GCFR. The code was then checked against the limited data base and modified accordingly to make code predictions consistent with this data base. This modeling effort provides detailed, reliable thermal and mechanical analysis methods and predictions to GCFR fuel designers for use in analyzing fuel elements throughout their lifetime. These predictions also serve as initial conditions for accident analysis. In addition, this research supports the planning and designing of GCFR irradiation experiments.

The present work focused on the behavior of GCFR fuel rods under normal operating conditions (i.e., start-up, steady power, slow power changes, and shutdown). In this study, the fuel design was based on mixed-oxide fuel and stainless steel cladding materials. Input information included GCFR fuel design parameters (Table I), power histories, as-fabricated data and PIE results on test rods, and LWR and LMFBR modeling technology.

Four major phenomena, fission-gas release, fission-gas swelling, fission-gas diffusion through helium in the fuel-cladding gap, and fuel grain growth were examined in this work. Fuel creep, crack healing, solid fission-product swelling, and cladding swelling were also examined. This research effort involved both the establishment of new analytical models and modifications of the existing models. Rigorous procedures were followed to qualify the code as a reliable computational tool. These procedures included sensitivity studies, benchmark testing, and calibration of the code against GCFR irradiation data.*

The areas mentioned above were chosen because they strongly affect fuel temperature, fuel deformation, and fuel loading of the cladding. A code capability for reasonable fuel temperature predictions is required in order to ensure that the maximum fuel temperature under start-up, steady state, slow-power-change, and shutdown conditions is within design constraints (i.e., does not exceed the melting temperature of the fuel). Fuel deformation behavior

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*This term is used loosely to include all the data collected under the GCFR Program. The fuel rods examined contain some, but not all, of the design features of the GCFR fuel rod.

will affect fuel temperature because of the strong influence of fuel-cladding gap size on heat transfer across the gap, and on cladding mechanical performance when fuel pellets are in contact with cladding.

During the course of this research, GAC made a major change in the GCFR design. That is, helium coolant flow is to be upward instead of downward.¹⁷ The change was based mainly on the safety and licensing advantage of upflow design, which offers the potential of residual heat removal by natural circulation. In the actual code analysis of LIFE-GCFR, the fuel rod is divided axially into several sections. Calculations proceed from the fuel section near the coolant inlet toward the section near the coolant outlet. This design change does not affect the code development work or the results of GCFR fuel pin analyses discussed in this report.

II. DESCRIPTION AND EVALUATION OF PREVIOUS LIFE MODELS FOR GCFR ANALYSIS

LIFE-3 incorporates a one-dimensional, steady-state heat-transfer analysis and a finite-strain-theory structural analysis based on generalized plane strain and the method of successive elastic solutions. Figure 3 shows a flow chart of LIFE-3 at the beginning of the present work. The code input includes fuel and cladding geometrical, fabrication, and environmental parameters, material properties, and code options to be used in the analysis. Operating conditions are specified on power history cards which include reactor power, coolant outlet temperature, and fast-neutron flux. Code thermal analysis includes coolant, cladding, and fuel temperature calculations; fuel densification; pore and fission-gas bubble migration; fission-gas release; and plenum pressure calculations. In the mechanical analysis, swelling, creep, and thermoelastic strains are calculated. Fuel and cladding stresses and fuel-cladding gap conditions are also calculated. The effects of fuel cracking, crack healing, and cladding damage are then analyzed. Sections II.A to II.H, below, describe analytical models in LIFE-3 that deal with fission-gas release, fission-gas swelling, fission-gas diffusion in the fuel-cladding gas gap, fuel grain growth, fuel creep, crack healing, solid fission-product swelling, and cladding swelling. These models are believed to be inadequate because they are either inapplicable to GCFR irradiation conditions, or oversimplified in approach. In some cases, these models appear to have become obsolete as more understanding has been established. Also included in the following sections are critical evaluations of these models. In Section III, the models that were used to replace the above models are presented.

A. Fission-gas-release Model

A quasi-empirical treatment of fission-gas release is used in the LIFE-3 code. It treats (1) the diffusion or migration of fission-gas atoms (or bubbles) to various short-circuiting paths (e.g., grain boundaries, dislocations, and microcracks) that rapidly conduct the gas to free surfaces, and (2) the migration of fission-gas bubbles up the temperature gradient to the central void. The amount of fission gas retained in a unit volume of fuel is defined as G_s . The time rate of change of G_s is given by

$$\dot{G}_s = \dot{G}_p - G_s \cdot F_g + \dot{G}_m \quad (1)$$

where

$\dot{G}_p$ = fission-gas production rate,

F_g = rate of fractional gas release from fuel,

and

$\dot{G}_m$ = net rate of change of G_s due to gas migration into and out of a unit volume of fuel.

Fig. 3. Flow Chart of the LIFE-3 Fuel-modeling Code

The fission-gas production rate is given by

$$\dot{G}_p = \frac{\gamma \rho_f q'}{m_f E_f} \quad (2)$$

where

γ = fission yield of Kr and Xe

ρ_f = local fuel density

q' = fuel linear power

m_f = linear mass of fuel

E_f = energy per fission.

Fractional gas release rate is assumed proportional to the bubble migration velocity, V_b , and the concentration of short-circuiting paths, S_c . The migration of fission-gas bubbles is assumed to be due to surface diffusion.¹⁸ V_b is then given by

$$V_b = A_s \exp(-Q_s/RT) (-dT/dr)/T^2 \quad (3)$$

where

A_s, Q_s = constants describing the surface diffusion process

R = gas constant, 1.987 cal/K-mole

T = fuel temperature, K

dT/dr = radial temperature gradient of fuel.

The concentration of dislocations, grain boundaries, and microcracks is taken to depend on temperature as

$$S_c = A_c \exp(Q_c/RT) \quad (4)$$

where

A_c, Q_c = constants describing the process of formation of short-circuiting paths.

The temperature dependence in Eq. (4) is included because the annealing out of these defects is a thermally activated process. Equations (3) and (4) can be combined to give

$$F_g = A_s A_c \exp[(Q_c - Q_g)/RT](-dT/dr)/T^2. \quad (5)$$

Assuming that unreleased fission gas is all contained in bubbles moving with a velocity V_b , the time rate of change in the concentration of retained fission gas caused by fission-gas bubble migration is given by

$$\dot{G}_m = \frac{1}{r} \frac{d(V_b r G_s)}{dr}. \quad (6)$$

For modeling purposes, the fuel is divided into several concentric rings based on equal-mass criteria. For a fuel ring with inner radius r_i and outer radius r_o , $\dot{G}_m$ is given by a volume-averaged quantity, i.e.,

$$\dot{G}_m = \frac{\int_{r_i}^{r_o} d(V_b r G_s)}{\int_{r_i}^{r_o} r dr}. \quad (7)$$

As shown in Fig. 3, the fuel temperature and temperature gradient are calculated in each fuel ring before fission-gas release is calculated. Therefore, by combining Eqs. (2), (5) and (6), one can solve Eq. (1) analytically. The calculation is started from the outermost fuel ring.

B. Fission-gas-swelling Model

In the LIFE-3 code, fuel swelling due to fission gas retained in the fuel consists of two components: (1) swelling due to fission-gas bubbles based on ideal gas behavior, and (2) extra swelling attributable to the difference between ideal gas behavior and van der Waals gas behavior (i.e., incompressible gas-bubble swelling). The fission-gas-swelling model assumes that each fuel ring of a given temperature can be characterized by bubbles of a fixed size, designated as the average bubble. The basic equation for the swelling rate due to gas retained in the fuel is

$$\frac{d\epsilon_g}{dt} = C_c (P_{\text{gas}} - \sigma_h - P_g) \epsilon_g \quad (8)$$

where

ϵ_g = volumetric strain for fission-gas swelling

t = irradiation time, h

C_c = a quantity which is proportional to the coefficient of the stress in the fuel linear creep-rate term [i.e., C_{coef} in Eq. (16)]

$$P_{\text{gas}} = RTG_g/\epsilon_g \text{ (ideal gas law)}$$

$$\sigma_h = \text{fuel hydrostatic pressure}$$

$$P_g = \text{the surface-tension-induced pressure on an average bubble, equal to } A_p \exp(Q_p/RT), \text{ where } A_p \text{ and } Q_p \text{ are calibration constants.}$$

Equation (8) can be integrated over the time interval Δt to give

$$\epsilon_g(t + \Delta t) = \epsilon_g(t) \exp[-C_c(\sigma_h + P_g)\Delta t] + \frac{RT \cdot G_s}{\sigma_h + P_g} \{1 - \exp[-C_c(\sigma_h + P_g)\Delta t]\}. \quad (9)$$

In the actual coding, the fuel is divided into several equal-mass rings. One complication that affects ϵ_g is the fact that the swelling porosity is assumed to migrate inward toward the central hole. Owing to the equal-mass criterion for each fuel ring, the net amount of fission-gas porosity that moved out of a fuel ring during a given time step Δt is assumed to be replaced by mass. As described in Ref. 14, the solution of ϵ_g at $t + \Delta t$ [i.e., Eq. (9)] must be appropriately adjusted for the effects of migrating fission-gas porosity.

C. Evaluation of Gas-release and Swelling Models

The behavior of fission gas in oxide fuel consists of many individual physical processes,¹⁹ as shown in Table III. Briefly, fission gas (xenon and krypton) is generated via nuclear fission, primarily within the UO_2 (or U-PuO_2) grains. These gases are relatively insoluble within the fuel matrix and tend to nucleate into bubbles. The bubbles can grow by coalescence and gas-atom diffusion, and can shrink via re-resolution. The fission gas can migrate both in atomic form and in bubbles by either random or biased (in a temperature gradient) motion to the grain faces, where the bubbles tend to grow. Grain-face bubbles may also be susceptible to the effects of resolution. Subsequently, the fission gas on the grain faces can migrate to the grain edges. In addition, if the grain faces become saturated with gas, channels can form via bubble coalescence, enabling the gas to rapidly vent to the grain edges. Gas reaching a grain edge deforms the edge and contributes to the degree of interconnection between grain edges. If the grain edges and corners are interconnected to a free surface, the gas can escape to the exterior of the fuel. Alternatively, grain boundaries weakened by the accumulation of fission gases (and other fission products) may fracture extensively under stress and enable the gas to vent directly to the fuel-cladding gap. Fission gas retained in the fuel contributes to fuel swelling.

TABLE III. Individual Physical Processes That Contribute to the Behavior of Fission Gases in Nuclear Fuels

1. Production of the gases xenon and krypton by fission.
2. Nucleation of gas bubbles, either homogeneously by chance encounters of wandering gas atoms or heterogeneously on fission-fragment tracks or dislocation lines.
3. Growth of gas bubbles by atomic migration of fission-gas atoms to existing bubbles. Bubble growth can be affected by the availability of vacancies to permit the bubble to expand as gas is accumulated and by the effects of surface tension and the stress state of the surrounding fuel matrix, which determine the stable size of the bubble.
4. Re-resolution of the gas atoms within the bubble.
5. Migration of the bubbles, either as a random-walk process in the absence of directed forces acting on the bubble or as biased motion when such forces are present. The forces that act on gas bubbles in solids are generally believed to be those due to the temperature gradients, or restraining forces due to dislocations and grain boundaries. The former force always causes the bubble to move in a particular direction. The forces due to crystal defects can act either to pin the bubble if the defects are immobile or to drag the bubbles if the defects are themselves in motion. Thus, bubble motion can occur by dislocation-line sweeping or grain-boundary sweeping.
6. Coalescence of bubbles moving in either a random or a directional fashion.
7. Interaction of bubbles with the crystal defects (dislocations and grain boundaries).
8. Release of the fission gases, either to external surfaces such as the central void, cracks in the fuel, or the fuel-cladding gap or to internal surfaces such as grain boundaries. When the bubbles on grain boundaries become sufficiently large and numerous, gas-channels are formed to link up and extend to the grain-edge channels. Through interlinkage of the edge porosity, fission gas is released to one of the external surfaces.
9. Release of fission gas by direct flight of the energetic fission fragments out of an external surface. The amount released by this process is significant only at low temperatures.

The variables that govern the rates of the individual processes listed in Table III include fuel temperature, temperature gradient, fission rate, fuel burnup, fuel properties, fission-gas properties, and fuel microstructure. Given the large number of variables that are likely to affect fission-gas behavior and the variety of elementary processes that must be treated simultaneously, the comprehensive model of fission-gas release and swelling becomes very complicated. A quasi-empirical treatment of fission-gas release and swelling is used in the LIFE code. The fission-gas release model treats (1) the diffusion or migration of fission-gas bubbles to various short-circuit paths (e.g., grain boundaries, dislocations, and microcracks) that rapidly conduct the gas to free surfaces, and (2) the migration of fission-gas bubbles up the temperature gradient to the central void. The gas-release rate for a fuel ring is treated as a function of the average ring temperature and fission-gas concentration. In the LIFE-3 code, the fission-gas release model was calibrated using the results of experiments at fairly high burnups. In such experiments the gas release is typically 80-100% of the gas generated and the LIFE-3 predictions were quite comparable. However, when lower-burnup pins were checked against experimental data, LIFE-3 predictions²⁰ were found to be too high by a factor of about 1.5-2.0. This discrepancy suggested a need for a basic

modification of the gas-release model. The treatment of fission-gas release and swelling in the LIFE-3 code is based on very crude models and fails to include many important mechanisms such as bubble coalescence, bubble resolution, and fission-gas-induced swelling due to bubbles on grain boundaries, on dislocations, and along the grain edges.

The fission-gas-swelling model assumes that each fuel ring can be characterized by bubbles of a fixed size (actually, the model assumes that the pressure due to surface tension is dependent only on the average temperature for the ring). In the LIFE-3 code, the bubble pressure due to surface tension in each fuel ring is treated as a very small value. This implies that the characteristic bubble size in each fuel ring is very large. For comparison, a typical fission-gas bubble radius of 2×10^{-8} m (~ 200 Å) at a temperature of 2200 K is used. The bubble pressure due to surface tension is 0.12 MPa (17.2 psi). This value is inordinately low compared with the prediction [68.9 MPa (10^4 psi)] of the more fundamental GRASS-SST code.²¹ This treatment causes the following two problems: (1) The fission-gas swelling rate in fuel is exaggerated under conditions of low hydrostatic pressure; and (2) the fuel swelling rate decreases too rapidly with increases in hydrostatic pressure. Thus, the model is not physically realistic at low pressures and probably does not extrapolate well to high pressures (i.e., GCFR conditions).

D. Fission-gas Diffusion in Fuel-Cladding Gap

In the case of a sealed LMFBR fuel pin, the accumulation of fission gas in the fuel plenum under irradiation will increase fuel plenum pressure and deteriorate the thermal conductivity of the gas mixture. In the LIFE-3 calculation, it is assumed that gas released from the fuel is evenly mixed with plenum gas throughout the fuel-cladding open space during a given time step Δt . Axial fission-gas diffusion is not considered. However, for a GCFR fuel pin under irradiation, fission gas released from the fuel is continually vented out of the fuel pin through the PES.²² The diffusive flow of fission gas from fuel and blanket along the concentration gradient first passes through the charcoal trap within each rod. From the trap, fission gas is vented out of the fuel rod. Sensitivity analyses were performed with LIFE-GCFR to determine the effect of axial fission-gas diffusion on the fuel centerline temperature, fuel deformation, and fission-gas release. The study was made for the hottest fuel section [~ 279 mm (11 in.) long] of a GCFR peak-power pin at a linear power of 35.1 kW/m (10.7 kW/ft) to achieve a burnup of 10 at. %. The fuel was divided into six concentric rings for mechanical analysis. Case 1 assumes that after 750 days of full-power operation, the gas mixture in the fuel-cladding gap consists of 30% fission gas and 70% helium as a result of axial fission-gas diffusion through the PES. Case 2 assumes that all fission gas released from the fuel is vented out of the fueled region through the PES. That is, throughout fuel lifetime a pure helium gas exists within the fuel-cladding gap in the fueled region.

Figure 4 compares the calculated fuel centerline temperature for Case 1 with that for Case 2. Fuel temperature is a strong function of fuel-cladding gap size. The gap size generally decreases with fuel burnup, owing to fuel

swelling, until cladding swelling is initiated (at ~10000 h). The difference in fuel temperature between Case 1 and 2 increases with fuel burnup because fission-gas concentration in the fuel-cladding gap increases with burnup in Case 1. At the end of fuel life, the fuel centerline temperature for Case 1 is 240°C higher than that of Case 2. This temperature difference results in an 8% higher gas release and a 0.6% higher cladding strain for Case 1 as compared to Case 2. The above analysis shows that the amount of fission gas in the fuel-cladding gap as a result of axial gas diffusion through the PES can have a significant effect on fuel temperature, fuel deformation, and fission-gas release. Therefore, a detailed analysis of fission-gas diffusion under GCFR operating conditions is needed to determine the fission-gas concentration in the fuel-cladding gap. Furthermore, the same analysis will give some perspective on the consequences of path blockage of the PES due to the deposition of volatile products.²³

Fig. 4

LIFE-GCFR-predicted Fuel
Centerline Temperature
for the Hottest Section
of a GCFR Peak-power Rod

E. Fuel Grain-growth Model

The driving force for equiaxed grain growth is the decrease in surface free energy brought about by the decrease in the number of grains and the total grain-boundary surface area. The net result of the grain-boundary movement is shrinkage of small grains with predominantly convex surfaces and growth of large grains with concave surfaces. The grain-growth model used in the LIFE code is based on cellular grain growth with no pore retardation of grain-boundary movement. It utilizes the expression

$$D_g^2 = D_{g0}^2 + 1.553 \times 10^7 t \exp(-48026/RT) \quad (10)$$

where

D_g = grain size, μm , D_{g0} = initial grain size, μm , and t = time, h.

In UO_2 fuel, a large fraction of the porosity is located on the grain boundaries. Speight and Greenwood²⁴ performed an analysis which showed that bubbles cannot prevent movement of grain boundaries, but can retard this movement so long as they remain attached to the boundary. Small bubbles move rapidly and have a greater tendency to remain attached to the boundary, whereas larger bubbles move more slowly. For a given spacing, the larger bubbles have the greatest effect in retarding boundary movement. The above study implies that the basic assumption in Eq. (10) will cause it to overpredict grain growth. Equation (10) has been compared with experimental data from the F-1 series test; the grain size predicted by Eq. (10) was about ten times larger than that observed experimentally.²⁵ Clearly, the grain-growth mechanism described by Eq. (10) is not supported by the above experimental observations. Therefore, a new grain-growth model with a better physical basis is needed for LIFE-3.

F. Fuel Creep Model

The steady-state fuel creep treated in the LIFE code consists of²⁶

- (1) athermal fission-induced creep at low temperatures ($T < 300$ C),
- (2) radiation-enhanced creep in the temperature range from 300 to 1200 C,
- (3) viscous thermal creep at high temperature ($T > 0.5 T_m$ where T_m is the fuel melting temperature) and low stress, and (4) power-law thermal creep at high temperature and high stress. Expressions for these four creep rates are presented below.

(1) At low temperature, the steady-state athermal fission-induced creep rate $\dot{\epsilon}_A$ is a linear function of stress (σ , psi) and fission rate ($\dot{F}$, fissions/ $\text{cm}^3\text{-s}$), but is independent of temperature and grain size, and reasonably insensitive to burnup, density, and plutonium concentration. The steady-state athermal fission-induced creep rate can be described as

$$\dot{\epsilon}_A = D_1 \dot{F} \sigma \quad (11)$$

where

$$D_1 = \text{constant} = 3.72 \times 10^{-23} \text{ and } \dot{F} = \text{fission rate in fission/cm}^3\text{-s.}$$

(2) The steady-state radiation-enhanced creep rate $\dot{\epsilon}_T$ is a linear function of stress and fission rate, and is given by

$$\dot{\epsilon}_T = C_1 \sigma \dot{F} \exp(-Q_T/RT) \quad (12)$$

where

$$C_1 = \text{constant} = 1.96 \times 10^{-19}$$

$$Q_T = \text{activation energy} = 13.7 \text{ kcal/mole.}$$

(3) At high temperature and low stress, the steady-state viscous thermal creep rate $\dot{\epsilon}_L$ is proportional to stress and the inverse of grain size squared, and can be expressed as

$$\dot{\epsilon}_L = \frac{A_L}{D_g^2} \sigma \exp(-Q_L/RT) \quad (13)$$

where

$$A_L = \text{constant} = 2.23 \times 10^7$$

$$Q_L = \text{activation energy for viscous creep} = 92.5 \text{ kcal/mole.}$$

(4) At higher stress, the power-law thermal creep rate $\dot{\epsilon}_H$ depends on the 4.4 power of stress and has the form

$$\dot{\epsilon}_H = B_L \sigma^{4.4} \exp(-Q_H/RT) \quad (14)$$

where

$$B_L = \text{preexponential structure factor} = 1.0 \times 10^{-3}$$

$$Q_H = \text{activation energy for power-law creep} = 136.8 \text{ kcal/mole.}$$

In computing the total steady-state creep rate of a mixed-oxide fuel, the effect of fuel density must also be taken into account:

$$\dot{\epsilon}_{\text{total}} = [1 + 2.11(97 - \rho)]\dot{\epsilon}_L + [1 + 0.22(97 - \rho)]\dot{\epsilon}_H + \dot{\epsilon}_A + \dot{\epsilon}_T \quad (15)$$

where

$$\rho = \text{fuel density, \% TD.}$$

Combining Eqs. (11-15) gives the following expression for the total steady-state creep rate:

$$\begin{aligned} \dot{\epsilon}_{\text{total}} = & \left\{ \frac{A_L}{D_g^2} [1 + 2.11(97 - \rho)] \exp(-Q_L/RT) + D_1 \dot{F} + C_1 \dot{F} \exp(-Q_T/RT) \right\} \sigma \\ & + \{ B_L [1 + 0.22(97 - \rho)] \exp(-Q_H/RT) \} \sigma^{4.4} = C_{\text{coef1}} \sigma + C_{\text{coefp}} \sigma^{4.4} \end{aligned} \quad (16)$$

where

C_{coef1} = coefficient of the stress in the fuel linear creep rate term

C_{coefp} = coefficient of the stress in the fuel nonlinear creep rate term.

However, the primary-creep experiments of Solomon²⁷ for UO_2 helices under low-stress, high-temperature conditions and low-temperature, in-reactor conditions reveal no steady-state creep even after 2% shear strain and imply that the primary stage is significant. The importance of primary creep in oxide fuels introduces complexity into many related phenomena and analyses. Hot-pressing, fuel fracture, and fission-gas swelling are affected. As a result, fuel deformation (which determines fuel-cladding gap size in the GCFR fuel) and hence fuel thermal behavior are also affected. Therefore, primary creep should be added to the LIFE-3 fuel performance code to properly describe the fuel creep mechanism and related phenomena.

G. Crack-healing Model

The crack-healing model used in the LIFE-3 code²⁸ assumes that the process of the recovery of brittle-fracture strength is thermally activated and enhanced by fission:

$$\left(\frac{\sigma_t}{\sigma_F}\right)^2 = \left(\frac{\sigma_o}{\sigma_F}\right)^2 + \frac{A + BF}{\sigma_F^2} t \exp(-55000/RT) \quad (17)$$

where

σ_o = as-cracked strength (at $t = 0$), psi

σ_F = uncracked fracture strength, psi

σ_t = fracture strength after time t , psi

A, B = constants.

However, as more experimental data has become available, the rate of crack healing has also been shown to depend on the stress normal to the crack surface. Because the extent of cracking of the fuel pellet and subsequent recovery of the uncracked strength have a large effect on the mechanical behavior of the fuel-cladding system and on fuel temperature during both steady-power operation and power changes, improvement of the crack-healing model in LIFE-3 by addition of the stress effect is desirable in order to better describe fuel thermal and mechanical behavior.

H. Solid Fission-product Swelling and Cladding Swelling

In LIFE-3, the fuel swelling rate due to solid fission products is assumed to be 0.27% $\Delta V/V$ per at. % burnup, where V is fuel volume. Brucklacher and Dienst²⁹ performed in-reactor creep experiments with UO_2 at fuel temperatures of 350, 500, 600, 650, and 850 C. The experimental strain-rate data show the fuel swelling rate at zero stress to be $0.80 \pm 0.15\%$ $\Delta V/V$ per at. % burnup. The average solid fission-product swelling rate derived theoretically by Anselin³⁰ is 0.875% $\Delta V/V$ per at. % burnup. Other experimental swelling rates³¹ range from 0.53 to 1.15% $\Delta V/V$ per at. % burnup. The above experimental observations indicate that the fuel swelling rate in LIFE-3 due to solid fission product is too low. The low swelling rate is partly due to the exaggeration of the fission-gas swelling rate, as discussed in Section II.C.

The phenomenon of cladding swelling treated in LIFE-3 is based on correlations of observed behavior. For stress-free, irradiation-induced swelling of 20% CW 316 stainless steel, a bilinear equation was chosen to represent the data. As additional experimental data have become available on a variety of cladding samples irradiated at various temperatures and fast-neutron fluences, the correlation has been updated occasionally. The empirical correlation presently used in LIFE-3 for the fractional volume change has the following form:³²

$$\frac{\Delta V}{V_0} = (0.01)R(T) \left\{ \phi t + \frac{1}{\alpha} \ln \frac{1 + \exp[\alpha(\tau - \phi t)]}{1 + \exp(\alpha\tau)} \right\} \quad (18)$$

where

V_0 = initial cladding volume

$R(T) = \exp(0.059 + 1.031\beta - 0.723\beta^2 + 0.403\beta^3 - 0.329\beta^4)$,

$\beta = (T - 500)/100$

ϕt = neutron fluence in units of 10^{22} n/cm² ($E > 0.1$ MeV)

$\alpha = 2.0$

τ = incubation neutron fluence in units of 10^{22} n/cm²

= 4 for FTR core 1 material,

= 7 for FTR core 4 material,

= 9 for N-lot material,

T = cladding temperature in C, $350 < T < 700$.

The incremental fractional volume change during a given time step Δt is

$$\Delta(\Delta V/V_0) = (0.01)R(T)\phi\Delta t/[1 + \exp[\alpha(\tau - \phi t)]] \quad (19)$$

The fluence and temperature effects on stress-free swelling in Eq. (18) are expressed as decoupled terms. That is, at a given fluence, the stress-free swelling depends only on temperature. This temperature dependence of the stress-free swelling [i.e., $R(T)$ in Eq. (18)] gives rise to the swelling-induced stresses in the cladding. The correlation of irradiation-induced cladding swelling in Eq. (18) was taken from the June 1974 Nuclear Systems Materials Handbook (NSMH).³² Since then, more experimental data have become available, and the correlation has been updated several times. It is desirable to incorporate the latest correlation of irradiation-induced swelling for 20% CW 316 stainless steel into LIFE-3, along with the properties of other alloys considered for fast-reactor cladding application.

III. LIFE-GCFR ANALYTICAL MODELS

Section II presented an evaluation of the LIFE-3 models for fission-gas release, fission-gas swelling, fuel grain growth, fission-gas diffusion, fuel creep, crack healing, solid fission-product swelling, and cladding swelling. In this section, the corresponding LIFE-GCFR models are discussed. For describing fission-gas release and swelling under high plenum pressure, a mechanistic gas release and swelling code, GRASS-SST,²¹ is coupled to LIFE-GCFR, with feedback to both the thermal and the mechanical analyses. A model describing the axial diffusion of fission gas through helium is established, and the effect of fission-gas diffusion through the PES on fuel-cladding gap conductance is determined. A new grain-growth model is chosen by comparing several proposed models from the literature with the GCFR experimental data. Primary creep is added to the fuel constitutive equations. The crack-healing model is modified to include the effect of stress on the crack-healing process. The solid fission-product swelling rate is modified, and the correlation for the irradiation-induced swelling rate of 20% CW 316 SS is updated. Finally, several coding improvements are added.

A. Fission-gas Release and Swelling Model

Fission-gas behavior in fuel will greatly affect fuel performance in terms of temperature and deformation. As described in Section II.C, LIFE-3 uses a very crude approach to modeling fission-gas release and swelling. The models are based on some simplified mechanisms and include a number of undetermined constants which are set by trying to match code predictions with macroscopic postirradiation data on total fission-gas release and swelling. This empirical approach may result in a successful interpolation of the gas behavior within the range of the data base. However, outside the range of the data base the predictive value of the empirical model is doubtful. In addition, the approach of fitting the experimental data to the empirical correlation will not add very much to the understanding of the basic phenomena of fission-gas behavior in fuel under irradiation conditions.

Four fundamental models for fission-gas behavior have been reported to date. These are the GRASS-SST code, the BUBL³³ code, the FRAS³⁴ code, and the ORGES³⁵ code. GRASS-SST is a mechanistic computer code for predicting fission-gas behavior in nuclear fuels. GRASS-SST treats fission-gas release and fuel swelling in an internally consistent manner and simultaneously treats all major mechanisms thought to influence fission-gas behavior. The GRASS-SST steady-state and transient analysis has evolved through comparisons of code predictions with the fission-gas release and physical phenomena that occur during both reactor operation and transient direct-electrical-heating (DEH) testing of irradiated LWR fuel.³⁶

As part of the present research effort, GRASS-SST has been coupled to LIFE-GCFR's mechanical analysis (for the calculation of the fission-gas bubble swelling component of the total fuel swelling) and thermal analysis (for the calculation of the amount of fission gas released to the fuel-cladding gap and the amount of fission gas retained in the fuel). GRASS-SST was chosen over

the other fission-gas models because of its availability, its compatibility with the LIFE-GCFR calculational scheme, and its predictive capability. The steady-state GRASS-SST analysis has been verified for end-of-life fission-gas release and retention in LWR fuel. The mechanistic treatment of fission-gas phenomena has the potential for a predictive capability outside the range of conditions used for model verification.

GRASS-SST calculations include the effects of the production of gas from fissioning uranium atoms, bubble nucleation and re-resolution, bubble diffusion, bubble migration, bubble coalescence, gas-bubble/channel formation on grain faces, temperature and temperature gradients, interlinked porosity, nonequilibrium effects, and fission-gas interaction with structural defects on both the distribution of fission gas within the fuel and on the amount of fission gas released from the fuel. From these models, a realistic equation of state for xenon, bubble diffusivities based on experimental observations in the steady state, and phenomenological modeling of bubble mobilities during transient nonequilibrium conditions, GRASS-SST calculates the fission-gas-induced swelling due to retained fission-gas bubbles in the lattice, on dislocations, and on the grain boundaries. It also calculates the fission-gas release as a function of time for steady-state and transient thermal conditions. Fission gas released from the fuel reaches the fuel surface by successively diffusing from the grains to grain faces and then to the grain edges, where the gas is released through a network of interconnected tunnels of fission-gas-induced and fabricated porosity.

GRASS-SST was originally developed mainly to describe the fission-gas behavior of LWR UO_2 fuel under steady-state and transient conditions. To apply GRASS-SST to the GCFR mixed-oxide fuel, it is first assumed that there are no essential differences in fission-gas behavior between oxide and mixed-oxide fuels.^{37,38} Second, to allow for the different neutron spectra in LWRs and GCFRs, and the different fission-gas yields of uranium and plutonium, fission-gas yield is set in GRASS-SST to be 0.246 gas atom per fission for GCFR fuel,³⁹ as opposed to 0.31 for LWR fuel. Finally, since GRASS-SST does not include models describing the behavior of fission gas in the columnar-grain zone (which is not observed in most LWR fuel rods under normal operating conditions), a quasi-static treatment of fission-gas behavior in that region is established for the GCFR fuel rod. This treatment will be discussed in the latter part of this section.

Figure 5 shows a flow chart of LIFE-GCFR with GRASS-SST. After the operating conditions, such as fuel dimensions, local fuel temperatures and stresses, grain sizes, fuel densities, and linear power, are calculated in LIFE-GCFR at time t_1 , the GRASS-SST subroutine calculates the radii for the various size classes of bubbles, as well as the bubble diffusivities, mobilities, coalescence probabilities, and diffusion and migration rates. The code then solves for the bubble-size distributions and calculates the amount of fission gas released and retained, and the fuel swelling strain due to retained

Fig. 5. Flow Chart of the LIFE-GCFR Fuel-modeling Code

fission gas. The effective surface-tension-induced pressure P_g in the fuel is also calculated by GRASS-SST according to the expression

$$P_g = \frac{R_p G_s RT}{\Delta V_{gas}/V - (G_s V_{ib})} - \sigma \quad (20)$$

where

$\Delta V_{gas}/V$ = swelling strain due to fission gas

R_p = fraction of retained gas residing in bubbles

V_{ib} = volume per mole of dissolved fission gas.

The amounts of fission gas released from and retained in the fuel calculated by GRASS-SST at time t_1 are then used in LIFE-GCFR at time $t_1 + \Delta t$ for the calculation of the fuel-cladding gap conductance, fuel densities, fuel thermal conductivities, and fuel plenum pressure. The values of P_g , V_{ib} , R_p , and G_s calculated in GRASS-SST are passed to the subroutine SWELL of LIFE-GCFR to calculate fuel hydrostatic pressure and total fuel swelling.

Fig. 6. (a) Gas-release Predictions Obtained with LIFE-GCFR Using Five Different Time Steps; (b) Computer Running Time vs Time Step Used in the Code

Initial test runs of LIFE-GCFR indicated that under certain GCFR irradiation conditions, GRASS-SST encountered numerical instabilities. Investigation of this phenomena revealed that errors were introduced by a computer system (IBM 370/195) round-off process in subroutine GRASS4 where a set of linear, first-order differential equations are solved to obtain the bubble-size distribution function. Note that LIFE-GCFR performs a double-precision calculation as compared with the single-precision calculation in GRASS-SST. The subsequent utilization of GRASS-SST in a double-precision mode resulted in the elimination of these numerical instabilities.

Figure 6a shows code predictions of fractional gas release versus irradiation time for a GCFR peak-power pin with five different maximum time steps used in LIFE-GCFR. The test runs were made for the hottest fuel section [~ 279 mm (11 in.) long] of a GCFR peak-power pin at a linear power of 35.1 kW/m (10.7 kW/ft) to a burnup of 10 at. %. Basically, taking a smaller time step in LIFE-GCFR should lead

to more accurate prediction. When large time steps are taken, more iterations are needed to achieve code convergence in the LIFE-GCFR mechanical analysis and in the GRASS-SST calculation. As shown in Fig. 6a, maximum time steps of 5 and 10 h do not yield significant differences in predicted gas release with LIFE-GCFR. A time step of 10 h was chosen for subsequent runs to minimize computer running time (Fig. 6b).

In the fuel columnar zone, the sweeping of the fuel matrix by moving lenticular pores causes the release of virtually all of the volatile fission products to the central void. The location of the columnar-equiaxed boundary is calculated in LIFE-GCFR according to the criterion

$$\frac{P_{or}(R_c)}{P_{or}(R_o)} = C_{col} \quad (21)$$

where

$P_{or}(r)$ = the fuel porosity at radius r

R_o = the outer radius of the fuel where presumably no pore migration occurs

R_c = the outer radius of the columnar-grain zone

C_{col} = calibration constant.

Note that GRASS-SST does not include models for the behavior of fission gas in the columnar grains. In order to simulate fission-gas behavior in the columnar grain-growth region, when LIFE-GCFR predicts columnar grain growth, the grain size passed to GRASS-SST is set to a very small value (i.e., 3.0 μm). For that small grain size at high fuel temperatures in the columnar-grain region, almost all the fission gas migrates to grain boundaries and grain edges (through grain-face channel formation as well as diffusion) and is then released from the fuel through extensive pore interlinkage. Thus the fractional fission-gas release in the active columnar-grain zone is virtually equal to unity.

Grain size is one of the most important parameters that affect fission-gas release and swelling of reactor fuels. Sensitivity analyses were performed to determine the effect of fuel grain size on fission-gas behavior. The study was made for the hottest section of GCFR fuel pin. The fuel was divided into six concentric equal-mass rings for mechanical and fission-gas analysis. After 500 h of irradiation, predicted fractional fission-gas release from fuel with initial grain sizes of 5, 10, 25, 50, and 100 μm was 38%,

Fig. 7. LIFE-GCFR-calculated Fractional Fission-gas Release from Fuel with Grain Sizes of 5, 10, 25, 50, and 100 μm

the columnar grain zone occupied the inner half-volume of the fuel, the majority of the fission-gas swelling came from retained gas in the outer half-volume of the fuel where the fuel temperature was fairly low (1533-1089 K). Figure 8 indicates that during the first 5,000 h of irradiation, smaller-grain fuel shows more overall gas swelling. However, after that time, the situation is reversed and the swelling becomes markedly greater for larger-grain fuel. This can be explained with reference to Figs. 9 and 10, which show LIFE-GCFR-calculated lattice, grain-boundary, and grain-edge swelling versus irradiation time for fuel with 5- and 100- μm grains, respectively. For large-grain fuel at fairly low temperature, gas bubbles in the fuel grains remain trapped within the grains and therefore, the major contribution to total fuel swelling is from lattice swelling (Fig. 10). This lattice swelling is much greater than for small-grain fuel (Fig. 9). Figure 11 compares LIFE-GCFR predictions of steady-state gas release with measured results for pins G-1, G-2, G-3, and G-6 of the F-1 series test,⁵ and pins GD60 and GH77 of the F-5 series test.⁴⁰

37%, 35%, 34%, and 33%, respectively (Fig. 7).^{*} At that time, the innermost two rings comprised an active columnar-grain zone and virtually all fission gas generated in that region was released to the fuel central void. Therefore, a fractional gas release of 33% (i.e., 2 rings/6 rings) was due to formation of the columnar zone and the rest of the gas release was from the fuel equiaxed and undisturbed zones. At the end of irradiation ($\sim 18,000$ h), while the inner half-volume of fuel became an active columnar-grain zone, predicted fractional gas release was 88%, 81%, 66%, 59%, and 54%, respectively, for fuel with initial grain sizes of 5, 10, 25, 50, and 100 μm (Fig. 7). That is, about 38% of the total gas generated in fuel with 5- μm grains was released from the equiaxed and undisturbed zone, as compared with only 4% of the total gas generated in fuel with 100- μm grains.

Figure 8 shows LIFE-GCFR-calculated results for fuel swelling due to fission gas vs irradiation time in fuel with 5-, 10-, 25-, 50-, and 100- μm grains. Since

^{*}Figures 7-10 are based on sensitivity studies for the peak-power fuel rod in the GCFR Demonstration Plant design. Peak linear power is 36 kW/m and peak burnup at 18,000 h is 9.1 at. %.

With the exception of the values for pins G-1 and G-2 (discussed below in Section IV), the LIFE-GCFR predictions of gas release are in reasonable agreement with experimental data. Thus, the GRASS-SST subroutine provides a predictive capability for GCFR as well as LMFBR fuels.

Fig. 8

LIFE-GCFR-calculated Fission-gas Swelling in Fuel with 5-, 10-, 25-, 50-, and 100- μ m Grains

Fig. 9

LIFE-GCFR-calculated Lattice, Grain-boundary, and Grain-edge Swelling for fuel with 5- μ m Grains

Fig. 10. LIFE-GCFR-calculated Lattice, Grain-boundary, and Grain-edge Swelling for Fuel with 100- μ m Grains

Fig. 11. LIFE-GCFR-predicted Steady-state Gas Release vs Experimental Data. Numbers in parentheses are the peak linear power in kW/m and the peak burnup in at. %, respectively

B. Fuel Grain-growth Model

In the LIFE calculation, fission-gas release is dependent only on fuel temperature and temperature gradient, as described by Eq. (5). However, when a fundamental fission-gas release and swelling model is utilized in LIFE-GCFR, it is found (Fig. 7) that grain size is one of the most important parameters that affect fission-gas release (or, conversely, retention) during steady-state irradiation. Fuel grain growth will also affect the fuel thermal-creep rate [i.e., Eq. (13)]. Therefore, a realistic grain-growth model is needed in LIFE-GCFR for analysis of fission-gas behavior and fuel mechanical response during steady-power irradiation.

Five correlations describing the grain-growth kinetics in the equiaxed and undisturbed fuel region have been investigated:

(1) The grain-growth model currently used in the LIFE code, based on cellular grain growth with no pore retardation, utilizes the expression

$$D_g^2 = D_{go}^2 + 1.553 \times 10^7 t \exp(-48026/RT). \quad (22)$$

(2) An expression for grain growth in UO_2 has been developed, based on unpublished data of Roberts and Wrona:⁴¹

$$D_g^2 = D_{go}^2 + 3.0 \times 10^7 t^{0.61} \exp(-49400/RT). \quad (23)$$

The experiments were performed at temperatures between 1600 and 2000 C over a short period (up to 32 hours).

(3) A cubic grain-growth equation⁴² has been obtained by assuming a vapor transport mechanism with pore pressure in equilibrium with UO_2 surface tension:

$$D_g^3 = D_{go}^3 + 8.57 \times 10^{14} t \exp(-124000/RT). \quad (24)$$

(4) A fourth-order grain-growth equation for vapor transport with constant pore pressure has been developed:⁴³

$$D_g^4 = D_{go}^4 + 6.18 \times 10^{13} t \exp(-92490/RT). \quad (25)$$

According to Olsen,⁴³ the above correlation is the best representation of the existing grain-growth data.

(5) Another grain-growth model,⁴⁴ which assumes that grain growth continues only until some limiting grain size has been reached, utilizes the following expression for the rate of change of the grain size with respect to time:

$$\frac{dD_g}{dt} = K \left(\frac{1}{D_g} - \frac{1 + 0.002 Bu}{D_m} \right) \quad (26)$$

where

$$K = 5.24 \times 10^7 \exp(-63812/RT), \mu m^2/h$$

D_m = the limiting grain size

$$= 2.23 \times 10^3 \exp(-7620/T), \mu m$$

Bu = fuel burnup, Mwd/TU.

The five grain-growth laws expressed in Eqs. (22) to (26) have been compared with experimental data from the F-1 series test.⁵ The fueled region in these pins is 343 mm (13.5 in.) long, with a pellet OD of 6.591 mm (0.2595 in.) and a 1.47-mm (0.058-in.)-dia. central hole. Table IV shows the as-fabricated characteristics of pins G-1, G-2, G-3, G-6 and G-7.

TABLE IV. As-fabricated Characteristics of F-1 Fuel Pins

	Fuel Pin				
	G-1	G-2	G-3	G-6	G-7
Weight of oxide fuel, g	109.50	111.08	111.07	107.72	107.90
O/M ratio	1.992	1.971	1.980	1.972	1.984
Fuel length, m (in.)	0.346 (13.63)	0.347 (13.65)	0.343 (13.50)	0.342 (13.46)	0.343 (13.50)
Smear density, % TD	82.64	84.12	83.00	82.65	82.54
Fuel-cladding diametral gap, mm (mils)	0.097-0.124 (3.8-4.9)	0.076-0.097 (3.0-3.8)	0.089 (3.5)	0.102-0.117 (4.0-4.6)	0.094-0.114 (3.7-4.5)

During irradiation in EBR-II, power ratings and fuel temperatures were fairly constant (after fuel restructuring). The variations from the time-averaged fuel temperatures of G-1, G-2, G-3, G-6 and G-7 were about ± 20 C. The peak burnups of G-1, G-2, G-3 and G-6 were 5.6, 5.2, 2.7, and 4.7 at. %, respectively. Table V shows grain sizes measured during PIE and calculated from Eqs. (22-26) at the columnar-equiaxed boundary for the G-1, G-2, G-3, G-6, and G-7 pins. As shown in Table V, the grain-growth model currently used in the LIFE code [i.e., Eq. (22)] will overpredict the grain size by an order of magnitude. Equation (23) will predict a grain size about two to three times larger than that observed experimentally. Equation (24) will, in general, underpredict grain size by 40%. Grain size predicted by the Ainscough model [Eq. (26)] will be two to three times smaller than the experimental data. A comparison of Eq. (25) with the experimental data is shown in Fig. 12. The diagonal line indicates the position of perfect agreement between Eq. (25) and the data. As is evident from Fig. 12, Eq. (25) predicts the data reasonably well for the G-1, G-2, G-3, G-6, and G-7 pins, with burnups between 2.1 and 5.6 at. %. This result suggests that grain growth kinetics are dominated by the vapor transport mechanism with a constant pore pressure.

The grain-growth model of Eq. (25), with the fourth-order relationship between grain size and time, represents the data reasonably well for both out-of-reactor and in-reactor (i.e., F-1 series test) experimental data and, therefore, is recommended for use in LIFE-GCFR. However, Eqs. (23), (24) and (26) are also incorporated into LIFE-GCFR as optional grain-growth models for further comparison as more postirradiation data became available.

TABLE V. Comparison of Grain Sizes (in μm) Measured and Predicted by Five Different Grain-growth-Laws for G-1, G-2, G-3, G-6, and G-7 Pins

Test Pin	Axial Section	Measured	Eq. 22	Eq. 23	Eq. 24	Eq. 25	Eq. 26
G-1	3	50	587	152	41	61	28
	2	60	422	109	24	45	19
	1	50	625	162	45	65	29
G-2	3	50	613	150	39	61	26
	2	50	450	110	24	46	18
	1	60	473	114	25	48	19
G-3	3	60	426	116	29	50	23
	2	60	300	1	17	36	15
	1	65	485	132	36	57	25
G-6	3	50	625	156	41	63	30
	2	60	440	108	23	45	21
	1	40	597	148	38	60	28
G-7	3	40	522	127	30	53	24
	2	40	364	88	17	37	16
	1	50	502	122	28	51	22

Fig. 12

Comparison of Eq. (25) with
Experimental Fuel Grain-growth
Data from F-1 Series Test

C. Fission-gas Diffusion Model

The effect of axial fission-gas diffusion in the fuel-cladding gap, under high-pressure helium, on fuel-cladding gap conductance and fuel centerline temperature was discussed in Section II.D. The GCFR fuel rod PES essentially equalizes the internal and external pressures on the fuel-rod cladding, eliminates large fission-gas plenums and internal fuel-rod pressure buildup, and provides a means of detecting and locating fuel elements with leaks in the cladding. Gases and vapors effusing from the fuel and upper blanket first pass through the charcoal traps within each rod. From the trap, the gases are vented out of the fuel rod. Figure 13 shows the calculated fuel centerline and outer-surface and cladding inner-surface temperature distribution along the axial direction for the reference (see Table I) GCFR peak-power pin at 1010 h. The origin for the axial position X is the top of the fueled region. The total active fuel length, L , is 1.13 m. As shown in Fig. 13, some natural convection may occur in the central hole of the fuel owing to the large axial temperature gradient, but in the fuel-cladding gap, the diffusive flow of the fission gas along the concentration gradient is the dominant mode of transport.

Fig. 13

Fuel Centerline and Outer-surface and Cladding Inner-surface Temperature vs Axial Fuel Position for a GCFR Peak-power Rod at 1010 h

The diffusion equation for fission gas along its concentration gradient can be expressed as

$$\frac{\partial C(z,t)}{\partial t} = \dot{S}(z,t) + \frac{\partial}{\partial z} \left[D(z) \frac{\partial}{\partial z} C(z,t) \right] \quad (27)$$

where

$C(z,t)$ = fission gas concentration, moles/in.³

$\dot{S}(z,t)$ = rate of fission-gas release to the fuel-cladding gap, moles/in.³-h

$D(z)$ = diffusion coefficient of fission gas, in.²/h

z = distance above the bottom of the active fuel.

The amount of fission gas released to the fuel-cladding gap per unit volume of fuel-cladding open space is calculated by LIFE-GCFR and can be approximated by

$$S(z,t) = S_0 t^\alpha \exp(-\beta t) \sin\left(\frac{\pi z}{L}\right) \quad (28)$$

where

$$S_0 = \text{constant}$$

$$L = \text{active fuel length.}$$

The interdiffusion coefficient of fission gas (Xe and Kr) in high-pressure helium is given by⁴⁵

$$D = 320.85 \left(\frac{T}{T_0}\right)^{1.66} (P_0/P), \text{ in.}^2/\text{h} \quad (29)$$

where

$$T_0 = 273 \text{ K}$$

$$P_0 = 0.101 \text{ MPa}$$

$$P = \text{fuel-cladding gas-gap pressure, MPa.}$$

Under the GCFR plenum pressure of 8.7 MPa (1280 psi), Eq. (29) can be expressed as

$$D = 3.6848 (T/T_0)^{1.66}, \text{ in.}^2/\text{h.} \quad (30)$$

Equation (27) is solved numerically by using DISPL,⁴⁶ a software package for kinetics-diffusion problems in one and two spatial dimensions. Owing to the different cross-sectional areas for fission-gas transport through fuel, blanket, shielding material, spring, and charcoal trap, a two-dimensional approach (i.e., t and z directions) is set in DISPL to solve Eq. (27). The GCFR fuel rod has been investigated at two power levels to determine the fission-gas concentration distribution in the fuel-cladding open space at various irradiation times. These are 60% and 100% linear power of a GCFR peak-power rod. Table VI shows constants S_0 , α , and β in Eq. (28), the diffusion coefficient of fission gas under high-pressure helium, and the cross-sectional area for gas transport in different fuel components (i.e., fuel, blanket, shielding material, spring, and charcoal trap). Data listed in Table VI are input to DISPL to solve for the fission-gas concentration as a function of fuel axial position

and irradiation time. Figures 14 and 15 show fission-gas concentration versus fuel axial position on a semi-log scale at various times from 0.02 to 18000 h for the 60%- and 100%-power cases, respectively. Note that fission gas is vented out of the fuel rod through the upper blanket and rod charcoal trap. Interpretations of these figures are given below.

Fig. 14

DISPL-predicted Fission-gas Concentration vs Fuel Axial Position for a GCFR Fuel Rod with an Average Linear Power of 60% or 17.9 kW/m (5.5 kW/ft)

Fig. 15

DISPL-predicted Fission-gas Concentration vs Fuel Axial Position for a GCFR Fuel Rod with an Average Linear Power of 100% or 29.8 kW/m (9.09 kW/ft)

TABLE VI. Values of Parameters Used in Calculating DISPL-predicted Results

Parameter ^a	Linear Power Level	
	60%	100%
S_0 , moles/in. ³	4.85×10^{-11}	8.56×10^{-7}
α	2.345	1.310
β , h ⁻¹	7.22×10^{-5}	8.51×10^{-6}
A_f , in. ²	2.15×10^{-3}	1.52×10^{-3}
A_b , in. ²	2.16×10^{-3}	2.16×10^{-3}
A_{sp} , in. ²	3.26×10^{-2}	3.26×10^{-2}
A_{ct} , in. ²	5.05×10^{-2}	5.05×10^{-2}
D_f , in. ² /h		
$0.00 < X/L < 0.025$	24.24	54.33
$0.25 < X/L < 0.50$	26.32	66.74
$0.50 < X/L < 0.75$	28.80	69.50
$0.75 < X/L < 1.00$	28.60	60.59
D_{bu} , in. ² /h	13.65	13.65
D_{bl} , in. ² /h	18.74	18.74
D_s , in. ² /h	13.65	13.65
D_c , in. ² /h	13.65	13.65

^aParameters defined as follows:

- A_b = cross-sectional area for gas transport in blanket
- A_{ct} = cross-sectional area for gas transport in rod trap
- A_f = cross-sectional area for gas transport in fueled region
- A_{sp} = cross-sectional area for gas transport in rod spring
- D_{bl} = diffusion coefficient in lower blanket
- D_{bu} = diffusion coefficient in upper blanket
- D_c = diffusion coefficient in rod trap
- D_f = diffusion coefficient in fueled region
- D_s = diffusion coefficient in rod spring.

In each figure, at the beginning of fuel lifetime (e.g., $t = 0.02$ h), fission-gas concentration follows the shape of the fission-gas release term [i.e., the sine curve in Eq. (28)] as expected, since there is little gas transported by diffusion at that time. As irradiation proceeds, fission gas diffuses along the fuel axial direction either upward to the fuel upper plenum where it is vented out of the fuel rod, or downward to the fuel-cladding gap at the lower blanket region (i.e., the closed end of the fuel rod) where it accumulates. After ~500 and ~100 h of irradiation for the 60%- and 100%-power rods, respectively, the axial gradient in fission-gas concentration at the closed end of the fuel rod is approximately zero, as shown in Figs. 14 and 15.

At the end of fuel life, with a plenum pressure of 8.7 MPa, the total gas (i.e., helium + fission gas) in the fuel-cladding gap contains 5% and 2% fission gas for the 100 and 60% power rod, respectively. LIFE-GCFR test runs were conducted to compare the fuel performance under a fuel-cladding gas gap with pure helium and with 5% fission gas. Figure 16 shows fuel centerline temperature versus irradiation time at the hottest section of the GCFR peak-power rod (i.e., the 100%-power case) under the above two gas-gap conditions. The maximum fuel centerline temperature difference is about 40 C, which is well within

the uncertainties of code predictions. Therefore, the difference in fuel performance obtained by modeling the gas in the fuel-cladding gap as pure helium, rather than 5% fission gas, is minimal.

Fig. 16

LIFE-GCFR-predicted Fuel Centerline Temperature for the Hottest Section of a GCFR Peak Power Rod with Two Different Gas Compositions in the Fuel-Cladding Gap

The assumption of pure helium in the gap is further justified by the following considerations: The fission-gas concentration at the end of fuel life shown in Figs. 14 and 15 is calculated based on a constant-power irradiation. In the GCFR demonstration plant, if the core power level were raised, the internal gas temperature of the fuel rod would increase more than that of the primary coolant, causing expansion of the helium/fission-product gas mixture out of the rod; the opposite would occur if the power level were reduced. This process is called "breathing." As the power level increases, from 5% to full design power, the average gas temperature within the peak-power rod rises from 677 C (1250 F) to 1397 C (2546 F), thus causing 76% of the initial gas mixture within the rod to be "exhaled." Repeated breathing cycles due to the varying power demand could pump virtually all of the fission gas out of the fuel rod into the PES during normal reactor operation. Furthermore, during reactor refueling, the primary loop pressure will be reduced to atmospheric pressure, whereupon most of the gas mixture within the fuel rod will be expelled from the fuel through convective transport. Therefore, combined diffusive and convective gas transport will vent virtually all the fission gas out of the fuel pin.

Based on the above analysis and argument, a very simple model may be utilized in LIFE-GCFR. It assumes that all the fission gas released from the fuel matrix is vented out of the fuel rod through the PES under normal GCFR operating conditions. The properties of pure helium gas are used in the calculation

of thermal conductivity and gap conductance between fuel and cladding unless a plug develops. Plugs may occur at various points along the fuel rod, or in the PES itself as a result of the accumulation of cesium uranate (mainly Cs_2UO_4) along the fission-gas transport path. Postirradiation data^{5,47} from pins irradiated in EBR-II show that flow blockage (if it occurred at all) would occur at the fuel-blanket interface. However, this result pertains mainly to the EBR-II pins, which are short and experience only a mild axial flux gradient. If plugging occurs, this model will select the code option for calculation of fuel-cladding gap conductance and fuel plenum pressure based on the LMFBF sealed rod analysis. Effects of plugged passages on the performance of the 300-MW(e) GCFR fuel pins will be discussed in Section V.

D. Fuel Creep Model

The primary creep experiments discussed in Section II.F indicate that the primary stage of fuel creep under low-stress, high-temperature conditions and low-temperature, in-reactor conditions is significant and should be appropriately modeled in a fuel performance code. The same experiments (i.e., Ref. 27) yielded expressions that match the primary and steady-state creep-rate data reasonably well:

$$\dot{\epsilon}_{Lt} = (0.75 A_p t^{-0.25} + 1) \dot{\epsilon}_L \quad (31)$$

and

$$\dot{\epsilon}_{At} = (0.65 B_p t^{-0.35} + 1) \dot{\epsilon}_A \quad (32)$$

where

$\dot{\epsilon}_{Lt}$ = primary and steady-state viscous creep rate, h^{-1}

$\dot{\epsilon}_{At}$ = primary and steady-state athermal fission-induced creep rate, h^{-1}

A_p, B_p = constants.

The above primary creep mechanism has been added to LIFE-GCFR, using a strain-hardening approach similar to the treatment of cladding primary creep in subroutine CREEC (where the creep equation for stress and a dummy time variable are solved by a simple Newton's iteration scheme). Figure 17 compares the fuel outside radius with different sets of A_p, B_p values in Eqs. (31) and (32) for the highest-power section of a GCFR peak-power pin. The difference in fuel outer radius between the sets $A_p = 0, B_p = 0$ and $A_p = 1.0, B_p = 10.0$ is insignificant (<0.15 mil). However, with $A_p = 10.0$ and $B_p = 100$, the fuel outer radius decreases significantly early in life. That is because for $A_p = 10$ and $B_p = 100$, the fuel is very soft and at this early stage in fuel life, the overall fuel deformation is dominated by hot pressing of as-fabricated fuel porosity. The values of A_p and B_p will be treated as calibration constants during the code's fine-tuning stage.

Fig. 17

LIFE-GCFR-predicted Fuel Outer Radius for the Hottest Section of a GCFR Peak-power Rod

E. Fuel Crack-healing Model

The isothermal crack healing model in the LIFE code (as described in Section II.G) ignores the influence of hydrostatic pressure on the crack-healing rate. The work done by Ainscough and Rigby⁴⁸ shows that the healing rate varies directly with hydrostatic pressure (owing to hot pressing). The healing rate can be expressed as

$$\frac{\sigma_t}{\sigma_F} = \frac{\sigma_o}{\sigma_F} \left[1 + \frac{A + BF}{T} t \exp(-55000/RT) (1 - C_h \sigma_n) \right]^{1/3} \quad (33)$$

where

C_h = a constant

σ_n = fuel stress normal to crack surface ($\sigma_n < 0$ is the compressive stress).

The rest of the symbols in Eq. (33) have the same meanings as in Eq. (17). Figure 18 shows a comparison of the time required for complete crack healing as predicted by the isothermal crack-healing model [i.e., Eq. (17)] and the stress-dependent crack-healing model [i.e., Eq. (33)]. The comparison is made for GCFR fuel under a hydrostatic pressure of 6.9 MPa (1000 psi) with initial cracks of $\sigma_o/\sigma_F = 0.2$. As shown in Fig. 18, the complete crack-healing time predicted by Eq. (33) is about an order of magnitude shorter than that predicted by Eq. (17).

Fig. 18

Fuel Crack-healing Time as a Function of Fuel Temperature for a Cracked Fuel with $\sigma_0/\sigma_F = 0.2$

The treatment of stress-dependent crack healing in LIFE-GCFR is the same as that in a LIFE-4 update.⁴⁹ Figure 19 shows the crack populations predicted by Eqs. (17) and (33) versus irradiation time for the hottest section of a 300-MW(e) GCFR peak-power pin. Complete crack healing is predicted by Eq. (33) after 270 h of irradiation at a linear power of 34.45 kW/m (10.5 kW/ft). According to the isothermal crack-healing model, however, the fuel cracks do not heal completely throughout the fuel lifetime of 18000 h. The cracks left unhealed are those in the fuel outer region, where the fuel temperature is low.

Fig. 19

LIFE-GCFR-predicted Number of Fuel Cracks vs Fuel Irradiation Time for the Hottest Section of a GCFR Peak-power Pin

F. Updating the Solid Fission-product Swelling Rate and the Empirical Correlation for Stress-free Cladding Swelling

In Section II.H, the solid fission-product swelling rate used in the LIFE code was shown to be low relative to experimental data and theoretical calculations. A survey of swelling data indicates a solid fission-product swelling rate of 0.73% $\Delta V/V$ per at. % burnup for the LWR oxide fuel.³¹ Based on irradiation tests performed under a wide range of conditions, Anselin³⁰ found the solid fission-product swelling rates for mixed-oxide fuel to be nearly the same

as for UO_2 . A review of solid fission-product swelling data by General Electric⁵⁰ indicated that a swelling rate of 0.80% $\Delta V/V$ per at. % burnup should be used for mixed-oxide fuel. A swelling rate of 0.8% $\Delta V/V$ per at. % burnup was incorporated into LIFE-GCFR as a nominal value. However, owing to the scatter in the data and the dependence of solid fission-product swelling on irradiation conditions, fuel pin design, and the properties of the fuel material, the solid fission-product swelling rate is treated in LIFE-GCFR as a calibration constant and can be varied within the range of $\pm 10\%$ from its nominal value during the code fine-tuning stage.

The phenomenon of cladding swelling treated in the LIFE code is based on correlations from NSMH. As the amount of experimental data increases on a variety of cladding samples irradiated under various temperatures and fast-neutron fluences, the correlation is updated occasionally in NSMH. The MK-6 stress-free swelling correlation⁵¹ was developed for 20% CW 316 stainless steel with the fractional volume change, $\Delta V/V_0$, given by

$$\frac{\Delta V}{V_0} = \frac{V_f - V_0}{V_0} = \frac{\Sigma}{1 - \Sigma} \quad (34)$$

where V_0 and V_f are the initial and final volumes of the swelling specimens; the fractional density change Σ is related to the initial and final immersion densities, ρ_0 and ρ_f , of the swelling specimens by

$$\Sigma = - \frac{\rho_f - \rho_0}{\rho_0} = (0.01)R \left\{ \phi t + \frac{1}{\alpha} \ln \frac{1 + \exp[\alpha(\tau - \phi t)]}{1 + \exp(\alpha\tau)} \right\} \quad (35)$$

where

$$R(T) = \exp(0.0419 + 1.498\beta + 0.122\beta^2 - 0.332\beta^3 - 0.441\beta^4)$$

$$\beta = (T - 500)/100$$

$$\phi t = \text{neutron fluence in units of } 10^{22} \text{ n/cm}^2 \text{ (E > 0.1 MeV)}$$

$$\alpha = 0.75$$

$$\tau = \text{incubation neutron fluence in units of } 10^{22} \text{ n/cm}^2$$

$$= 4.742 - 0.2326\beta + 2.717\beta^2 \text{ for FTR core 1 material,}$$

$$= 9.3 \text{ for N-101 material}$$

$$T = \text{cladding temperature in } ^\circ\text{C, } 350 < T < 700.$$

The incremental mechanical analysis procedure in LIFE-GCFR requires the use of the time derivative of Eq. (34), i.e.,

$$\frac{d(\Delta V/V_o)}{dt} = \frac{d\Sigma}{dt} \frac{1}{(1 - \Sigma)^2} \quad (36)$$

where, from Eq. (35),

$$\frac{d\Sigma}{dt} = (0.01)R \frac{1}{1 + \exp[\alpha(\tau - \phi t)]}. \quad (37)$$

The incremental volumetric swelling strain $\delta(\Delta V/V_o)$ during Δt is given by

$$\delta\left(\frac{\Delta V}{V_o}\right) = (0.01)R \frac{1}{1 + \exp[\alpha(\tau - \phi t)]} \left(1 + \frac{\Delta V}{V_o} \Big|_t\right)^2 \Delta t \quad (38)$$

where

$$\frac{\Delta V}{V_o} \Big|_t = \text{volumetric swelling strain accumulated up to the time } t.$$

Equation (38) has been incorporated into LIFE-GCFR. The modifications are mainly in subroutine HKNS.

G. Proposed Methods for Miscellaneous Code Improvement

In this section, modifications to LIFE-GCFR are presented which improve the code versatility, increase user convenience, and eliminate several bugs in the code.

G.1. Extending Axial Sections for Fuel Analysis

The GCFR cladding design in the active core from cool to hot region (axially) contains cladding that is 25% smooth and 75% ribbed. At the transition region from the smooth to the ribbed surface, the temperature drops very sharply, and this might cause large thermal stress in the cladding.⁵² It is desirable to have more detailed thermal and mechanical information along the axial sections. Therefore, LIFE-GCFR has been modified to include the capability of analyzing up to ten axial sections (as compared with the original six axial sections). Figure 20 shows the predicted cladding midwall temperature versus fuel axial position of a GCFR peak-power rod at the beginning of fuel life. In Fig. 20 the data points marked with squares are predicted by running LIFE-GCFR with nine axial sections (i.e., two smooth cladding sections, six ribbed cladding sections, and one plenum section), and those marked with circles are predicted by running LIFE-GCFR with five axial sections (i.e., one smooth section, three ribbed sections, and a plenum section). As shown in Fig. 20, it is very difficult, if not impossible, to draw the temperature distribution curve by connecting only the four latter points. The advantage of extending the number of axial sections for fuel analysis in this case is

obvious. In Fig. 20 a temperature drop of about 43 C at the smooth-ribbed transition region is caused by the (~2-fold) enhancement of coolant-cladding heat transfer on the ribbed cladding surface. The actual temperature drop and transition length are dependent on cladding rib design at the transition region and the effective fluid-dynamic length for increasing turbulence and axial heat transfer, and can't be determined by LIFE-GCFR owing to its simplified one-dimensional (radial) heat transfer analysis in fuel and cladding.

Fig. 20

LIFE-GCFR-predicted Cladding Mid-wall Temperature for a GCFR Peak-power Rod at Beginning of Life

G.2. Providing Different Ratios of Smooth-to-ribbed Cladding Length for Code Analysis

The current fuel design contains 25% smooth cladding and 75% ribbed cladding in the active fuel region. However, a possible design change⁵³ is under consideration, which calls for a completely ribbed cladding in the active core region. Some GCFR test pins may have different ratios of smooth-to-ribbed length. To include the above possible cladding designs in the code, LIFE-GCFR is designed in such a way that the portion of the cladding at the cool end of the active core region is smooth, with fractional length f_{sm} ; and the rest, with fractional length $(1 - f_{sm})$, is ribbed. The fractional length f_{sm} is given by

$$f_{sm} = \frac{M}{N_f} \quad (39)$$

where

N_f = number of axial sections to be specified in LIFE-GCFR for code analysis

M = an integer between 0 and N_f .

For a given N_f , M equal to 0 means a completely ribbed cladding in the active core region, and M equal to N_f means a totally smooth cladding. To analyze the current GCFR fuel with $f_{sm} = 0.25$, N_f can be set equal to either 4 (with $M = 1$) or 8 (with $M = 2$). M is an input parameter to the LIFE-GCFR code.

G.3. Code Option for LMFBR Fuel Analysis

LIFE-GCFR is capable of performing fuel-pin analysis for LMFBR fuel through proper selection of input parameters to the code. This has been done by setting a flag to distinguish the GCFR irradiation conditions and coolant properties from those of the LMFBR.

G.4. Dump Option at a Specific Time

In the LIFE code, calculated fuel information is stored in a dump file only when the specified computer time (on the job-control-language card) runs out. LIFE-GCFR is constructed to store all calculated data in a dump file at a given time. This option is useful for code restart calculations and for analysis of fuel performance under abnormal situations. For example, a GCFR peak-power pin is irradiated in the reactor core for a given period (say, 5 at. % burnup) followed by a hypothetical overpower transient. Prior to the transient, all the calculated data from LIFE-GCFR, which includes the results of thermal, mechanical, and detailed fission-gas analysis, are stored in the dump file. These data can be read into a transient code for further fuel transient analysis. Note that LIFE-GCFR in the current state of development is not capable of performing fuel transient analysis.

G.5. Correcting a Bug Associated with Input of Relative Radial Power Distribution Across the Fuel Rod

In the LIFE calculation, a maximum number of 15 annular shells can be used for thermal analysis of fuel. However, when relative radial power distribution across the fuel rod for these 15 annular shells is input to the code, only the first 10 numbers can be read into the code. A minor modification of the FORTRAN "READ" statement in subroutine AREAD was made to eliminate the above inconsistency.

IV. LIFE-GCFR CODE STRUCTURE AND VERIFICATION

Figure 5 shows a simplified flow chart of the LIFE-GCFR analysis after all the proposed models discussed in Section III were incorporated into it. Input data are read and initial conditions are set in the main program with the aid of subroutines AREAD and BEGIN. The first power-history card, which contains parameters such as reactor power, coolant outlet temperature, and fast-neutron flux, is read. MAIN then calls HTTRAN for the analysis of coolant, cladding, and fuel temperature; fuel densification; pore migration; and plenum pressure. Next SOLVER is called by MAIN to perform the iterative mechanical analysis based on the geometry at the beginning of the time step and the temperatures calculated for the end of the time step. After mechanical convergence is achieved (determined by COMPO), MAIN calls the subroutine GRASS to calculate detailed fission-gas behavior. Fuel cracking and healing, cladding damage, and cladding wastage (for LMFBR pin analysis only) are then calculated. Properties and geometry are updated at the end of the time step, and the analysis proceeds to the next time step. LIFE-GCFR includes the MAIN program, 37 subroutines, and a block data. Block data initializes the variables and provides material and physical properties for fission-gas analysis in GRASS subroutines. The subroutines in LIFE-GCFR are briefly described in alphabetical order in Table VII.

Code debugging and streamlining of LIFE-GCFR was conducted to eliminate defects in the algorithms. LIFE-GCFR was subjected to the same rigorous set of benchmark tests^{21,54} as the LIFE-3 and GRASS-SST codes. Briefly, code mechanical analyses of an internally pressurized and an externally pressurized closed tube were checked against analytical and finite-element calculations. Code calculation of fission-gas behavior was checked against a classic literature problem, based on a solid theoretical foundation for which a rigorous numerical solution exists.²¹ The sensitivity studies were also performed to determine the optimum values of time-step selection and convergence criteria. Table VIII shows the optimum values to be used in LIFE-GCFR calculations.

The code predictions for fuel central void and columnar grain zone radii, fuel density, burnup, fission-gas release, fuel grain growth, and total cladding strains have been checked against postirradiation data from GCFR test pins GB-9, GB-10, G-1, G-2, G-3, G-6, G-7, GD60 and GH77. The GB-9 and GB-10 pins were irradiated in the ORR thermal reactor with PES operating, and pins G-1, G-2, G-3, G-6, and G-7 of the F-1 series test and GD60 and GH77 of the F-5 series test were irradiated in EBR-II with sealed plenums. In these experiments, fuel smear densities ranged from 82.5 to 90.2% TD, peak linear powers ranged from 40.68 kW/m (12.4 kW/ft) to 48.89 kW/m (14.9 kW/ft), peak burnups ranged from 2.64 to 11 at. %, cladding inner-surface temperatures ranged from 626 to 738 C, and peak fast fluences ranged from 4.3×10^{19} to 5.3×10^{22} n/cm².

TABLE VII. Summary of LIFE-GCFR Subroutines

Subroutine	Called By	To Call	Main Function
AREAD	MAIN	BEGIN CONSTS RITE2	To read input data.
BEGIN	AREAD	-----	To initialize variables at the beginning of calculation.
BSFCN	CREEC	-----	To perform a primary creep analysis for 20%CW Type 316 stainless steel.
BSFC5	CREEC	-----	To perform a primary creep analysis for annealed Type 316 stainless steel.
CALLGR	MAIN	GRASS	To transfer data between MAIN and GRASS.
CGROW	PORMIG	-----	To calculate fuel grain size and determine the boundary of columnar and equiaxed grain zone.
CLTMP	HTTRAN	-----	To calculate cladding temperature.
COMPO	SOLVER	-----	To determine whether the mechanical analysis has converged. If not, to calculate new guessed total strains.
CONSTS	AREAD	-----	To provide constants of materials properties and correlations in code calculation.
CRACK	MAIN	-----	To calculate fuel cracking and crack healing.
CREEC	SOLVER	-----	To calculate equivalent stress and equivalent creep-strain increments for cladding.
CREEF	SOLVER	-----	To calculate equivalent stress and equivalent creep-strain increments for fuel.
CWASTE	MAIN	-----	To calculate the effect of sodium corrosion on cladding outer-boundary and the effect of cesium attack on cladding inner-boundary.
DUMPR	MAIN	-----	To store information on tape for restart calculation.
FRACT	MAIN	-----	To calculate cladding damage.
GAPCON	HTTRAN	-----	To calculate the fuel outer-surface temperature.
GASOUT	HTTRAN	-----	To calculate fission-gas release from and remaining in fuel based on semi-empirical model.
GRASS	CALLGR	GRASS2 GRASS4	To calculate detailed fission-gas release and swelling based on a mechanistic treatment of fission-gas behavior in fuel.
GRASS1	GRASS3	-----	To perform redundant calculation for GRASS3.
GRASS2	GRASS	-----	To calculate bubble diffusivities, mobilities, coalescence probabilities, diffusion and migration rate, and gas-atom resolution rates.

TABLE VII (Contd.)

Subroutine	Called By	To Call	Main Function
GRASS3	GRASS4	GRASS1	To calculate the loss rate of bubble in each size class (exclude the loss rate due to coalescence with the same size class) and the rate bubble added to the size class.
GRASS4	GRASS	GRASS3	To calculate bubble-size distribution in fuel.
GRASS5	GRASS2	-----	To calculate the equilibrium bubble radius for each bubble size class based on Harrison's extrapolated equation of state for Xe.
GRASS6	AREAD	-----	To read fission-gas-related data from restart file.
GRASS7	DUMPR	-----	To write fission-gas-related data on dump tape.
GOLDN	HTTRAN	-----	To calculate coolant temperature and cladding outer-surface temperature.
HKNS	SOLVER	-----	To calculate the increment of irradiation-induced cladding swelling.
HTTRAN	MAIN	CLTMP GAPCON GASOUT GOLDN PLENP PORMIG	To perform fuel thermal analysis.
PLENP	HTTRAN	-----	To calculate fuel plenum pressure for a sealed fuel pin.
PORMIG	HTTRAN	CGROW	To calculate fuel temperature and fuel restructuring.
RITE1	RITE3	-----	To print fuel stresses, strains and displacements.
RITE2	AREAD	-----	To summarize input information.
RITE3	MAIN	RITE1	To print the results of thermal calculations.
SOLVER	MAIN	COMPO CREEC CREEF HKNS SWELL VZJRW XLAME	To perform the fuel mechanical analysis.
SWELL	SOLVER	-----	To calculate the hydrostatic pressure, the elastic strain and the incremental inelastic strain.
VZJRW	SOLVER	-----	To calculate the ring boundary pressure and displacements.
XLAME	SOLVER	-----	To calculate the shear modulus and Poisson's ratio for uncracked fuel and cladding.

TABLE VIII. Values of Various Parameters Used in LIFE-GCFR Calculations

Parameter	Value	Description
Δt_m	10 h	Maximum time increment to be used in the LIFE-GCFR analysis.
A_p	1.0	Primary creep constant in Eq. 31.
B_p	10.0	Primary creep constant in Eq. 32.
S_s	0.8% $\Delta V/V$ per at.% burnup	Solid fission-product swelling rate.
IDLE	0	Selector for grain-growth model, i.e., Eq. 25.
R_m	10.0	Constant which defines the geometric progression of bubble size ranges.
C_{rt}	0.01	Relative error permitted in the integration of bubble size distribution function in GRASS-SST.
F_g	0.246 atom per fission	Number of noble gas atoms produced per fission event.
b	1.0×10^{-18}	Resolution constant in fission-gas analysis.
ϵ_{cov}	1.0×10^{14}	Convergence parameter for the solution of the linear differential equations in fission-gas analysis.
ϵ_{cut}	1.0×10^{13}	Upper limit on the cut off height of the tail of the bubble size distribution in fission-gas analysis.

Fig. 21. LIFE-GCFR-predicted vs Measured Radii of the Fuel Central Void and Columnar-grain Zone for the GCFR Test Pins

Figure 21 shows LIFE-GCFR-predicted versus measured radius of the fuel central void (at lower left) and columnar-grain zone (at upper right) for test pins GB-9,⁵⁵ GB-10, G-1, G-2, G-3, G-6, and G-7. The diagonal line indicates perfect agreement between predictions and experimental data. Note that all the test pins shown in Fig. 21 have annular fuel pellets except for GB-10, which has solid fuel pellets. The current GCFR fuel rod utilizes a solid pellet design (Table I). As is evident from Fig. 21, LIFE-GCFR predicts the fuel central void and columnar-grain zone radii reasonably well.

As discussed in Section II.B, the grain-growth model used in LIFE-GCFR [i.e., Eq. (25)], with the fourth-order

relationship between grain size and time, gives calculated grain sizes in reasonable agreement with the experimental data for GCFR test pins G-1, G-2,

Fig. 22. LIFE-GCFR-calculated Fuel Density vs Measured Density for F-1 Test Rods

G-3, G-6, and G-7 (Fig. 12). The grain diameters are measured and predicted at the boundary between fuel equiaxed and columnar-grain zones. Figure 22 shows LIFE-GCFR-calculated fuel density versus measured density for pins G-1, G-3, and G-6. The calculated fuel density in LIFE-GCFR includes the effect of fuel pore migration, swelling, and cracking. The measured density of elements G-1, G-3, and G-6 was determined using a Quantimet image analyzer.⁵ The agreement between calculated and measured fuel density is fairly good.

As discussed in Section III.A, LIFE-GCFR predictions of fission-gas release agree reasonably well with the experimental measurements for test pins G-3, G-6, GD60 and GH77 (Fig. 11). Fractional gas release in these test pins ranges from 50 to 70% TH.

However, LIFE-GCFR underpredicts fission-gas release for the high-release pins G-1 and G-2. Note that the LIFE-GCFR calculation does not include the analysis of axial blankets. The length of the axial blankets (including upper and lower blanket) is 45% of the active fuel length in G-1 and G-2 pins. For these high-rated rods (i.e., linear power > 46 kW/m) with fairly high fuel burnup (>5 at. %), fission gas released from axial blankets may become significant and cannot be ignored.¹² If 10% of the total gas release is assumed to be from the axial blankets, then LIFE-GCFR-predicted and measured data are in reasonable agreement for the G-1 and G-2 pins. The discrepancy in gas release data between the code calculations and measurements for the G-1 and G-2 pins may also be due, in part, to the uncertainties in the gas content measurements.

Figure 23 shows LIFE-GCFR-predicted fuel burnup versus measured burnup for test pins GB-9, GB-10, G-1, G-2, G-3, and G-6. The predicted values agree reasonably well with the experimental measurements.

Figure 24 compares LIFE-GCFR predictions of cladding strain with measured values for pins G-1, G-2, G-3, G-6, G-7, GB-9, and GB-10. Nominal error bars of $\pm 0.1\%$ strain are indicated by the dashed lines. Cladding deformations are mainly controlled by void swelling and irradiation-induced creep of the cladding material; the responsible processes are inner gas pressure, fuel-cladding contact pressure, thermal stresses, and stresses arising from nonuniform swelling across the cladding wall. Test pins GB-9 and GB-10 were irradiated in the ORR thermal reactor where fast-neutron flux is low and no irradiation-induced cladding swelling is observed. Test pins G-1, G-2, G-3, G-6, and G-7

were irradiated in EBR-II, with peak fast-neutron fluences ranging from 2.3 to 5.3×10^{22} n/cm²--less than the incubation fluence of the cladding material in the F-1 test (i.e., no significant cladding swelling strain developed). Therefore, the cladding strains shown in Fig. 24 are cladding creep strains. From Fig. 24, it is evident that the LIFE-GCFR-calculated cladding strains are in reasonable agreement with the experimental data.

Fig. 23. LIFE-GCFR-predicted vs Measured Fuel Burnup

Fig. 24. LIFE-GCFR-predicted vs Measured Cladding Total Strain

The above comparison of code predictions with postirradiation examination results on the GCFR test pins concentrates on fuel restructuring, fuel density, fuel burnup, fission-gas release, and total cladding strain. The overall good agreement of predictions with the GCFR test results demonstrates that LIFE-GCFR is, in its present state, a suitable tool for predicting the thermal, mechanical, and fission-gas behavior of the GCFR fuel rods under steady-power irradiations.

The input instructions and output descriptions for LIFE-GCFR are given in Appendixes A and B, respectively.

V. GCFR FUEL PERFORMANCE PREDICTED BY LIFE-GCFR

The results of LIFE-GCFR analyses of the reference GCFR fuel element are given in this section. The design parameters and operating conditions were supplied by GAC and are shown in Tables I and IX, respectively. Steady-state performance studies were conducted for fuel elements at 60, 100 and 115% of

TABLE IX. Operating Conditions for the Peak-power Rod in the 300-MW(e) GCFR Demonstration Plant Design

Parameter	Value
Peak Power, kW/m (kW/ft)	36.1 (11.0)
Peak Fast Flux, n/cm ² ·s	1.95 x 10 ¹⁵
Inlet Coolant Temperature, °C (°F)	353 (667)
Outlet Coolant Temperature, °C (°F)	538 (1000)
System Pressure, MPa (psi)	8.8 (1280)
Peak Burnup, MWd/MT	100000
Irradiation Time, FPD	750

For all the power-history cases studied with LIFE-GCFR in this investigation, five axial sections were used in the analyses: plenum region, smooth-cladding fuel region, and three ribbed-cladding fuel regions. An effective cladding thickness, t_{eff} , has been chosen to represent the mechanical response of ribbed cladding in a one-dimensional stress analysis. This effective cladding thickness is defined by

$$t_{eff} = t_{cr} + \frac{hw}{p} \quad (40)$$

where t_{cr} , h , w and p are the cladding root thickness, rib height, rib width, and rib pitch, respectively.

Figure 25 compares fuel centerline temperatures at $X/L = 0.375$ for fuel elements at 60, 100, and 115% power under steady-state irradiation. Axial position, X , is measured from the top of the fueled region. The total active fuel length, L , is 1.13 m. As shown in Fig. 25, for highly rated fuel rods (100- and 115%-power cases), the process of fuel restructuring is completed in a matter of a few hundred hours. During that period, some of the initial porosity in the fuel is removed by pore migration, and a central void is formed. Temperature drops of 178 and 250 C due to fuel restructuring are predicted by LIFE-GCFR during the first few hundred hours of irradiation for the 100- and 115%-power cases, respectively.

full-power and neutron-flux values. To simulate daily operating conditions, fuel performance for the 100% power history was studied by imposing a reactor shutdown and start-up every 250 full-power hours. For the steady-state case at 100% power, fuel behavior was studied under the hypothetical conditions where passages of the PES were plugged at the upper fuel-blanket interface after fuel burnups of 3 and 6 at. %.

Fig. 25. Steady-state GCFR Fuel Centerline Temperatures at $X/L = 0.375$ for the 60-, 100-, and 115%-power Runs

For the 60%-power history, however, owing to the low fuel temperature and gradual temperature gradient, the process of fuel restructuring is very slow and no significant central-void formation occurs. According to the LIFE-GCFR prediction, there is no appreciable temperature drop for the 60%-power case early in life due to pore migration, as shown in Fig. 25. As irradiation proceeds, the fuel centerline temperature decreases with burnup because of fuel swelling, which tends to decrease the fuel-cladding gap size until cladding swelling is initiated. The inflection points on the curves of fuel centerline temperature versus fuel irradiation time can be identified by dividing the incubation fluence for cladding stress-free swelling (i.e., 7.0×10^{22} n/cm², $E > 0.1$ MeV for FTR core 4 material) by the corresponding local neutron-flux values. The corresponding times for the initiation of cladding swelling at $X/L = 0.375$ for the 115-, 100-, and 60%-power cases are 9000, 10350, and 17000 h, respectively.

Fig. 26. Steady-state GCFR Fuel-element Gap Sizes at $X/L = 0.375$ for the 60-, 100-, and 115%-power Runs

Figure 26 shows gap size versus irradiation time for the 60-, 100-, and 115%-power cases at $X/L = 0.375$. The gap size generally decreases with burnup owing to fuel swelling until cladding swelling is initiated as described above. The initial increase in gap size during the first 500 hours for the steady-state cases at 100 and 115% power as shown in Fig. 26 is due to hot pressing of as-fabricated fuel porosity and the porosity associated with fuel cracks. Under steady-power irradiation, LIFE-GCFR predicts no gap closure for any of the power cases throughout the fuel lifetime of 18000 h. Therefore, if the PES works as designed, there is no net primary pressure loading on the ribbed GCFR cladding.

Figures 27 and 28 show the cladding hoop and axial stresses as a function of irradiation time at $X/L = 0.375$ for the 100- and 60%-power cases, respectively. During reactor start-up, the cladding stresses are essentially thermoelastic and both hoop and axial stresses are tensile near the cladding outer surface and compressive near the cladding inner surface. The reduction in magnitude of both hoop and axial stresses during the first 7000 and 12000 h for the 100- and 60%-power cases, respectively, can be attributed to creep relaxation. No swelling effect is expected during this period because the neutron fluence is still below the incubation fluence for the onset of cladding stress-free swelling. The swelling effect on the stresses shows up at 9000 and 16000 h for the 100- and 60%-power history, respectively. These stresses finally level off at 1200 h and stay fairly constant for another

6000 h, until the end of life (Fig. 27). Under the operating conditions for the 60- and 100%-power cases, the calculated cladding temperatures are below the peak swelling temperature (580 C); this indicates that the cladding swelling gradient follows the cladding temperature gradient, with more swelling near the cladding inner surface than near the outer surface.⁵² Therefore, after swelling becomes significant, hoop and axial stresses (Figs. 27 and 28) are tensile at the cladding outer surface and compressive at the cladding inner surface.

Fig. 27. Cladding Hoop- and Axial-stress Distributions vs Irradiation Time for the 100%-power History

Fig. 28. Cladding Hoop- and Axial-stress Distributions vs Irradiation Time for the 60%-power History

Fig. 29. GCFR Fuel-element Gap Sizes at $X/L = 0.375$ for Steady-state and Power-cycling Histories (100% Power)

Figure 29 compares fuel-element gap size for the steady-state case at 100% power to a power-cycling case with a reactor shutdown and start-up every 250 full-power hours. In Fig. 29 the gap size is smaller in the power-cycling case than in the steady-state case. This can be attributed to power-cycling-induced fuel cracking and relocation. Physically, fuel cracking and relocation can occur during each start-up/shutdown cycle as a result of cycle-induced thermal stress. In LIFE-GCFR, fuel cracking and relocation phenomena are modeled by a reduced-modulus approach.¹⁴ When fuel cracks occur, excess elastic

strain is redistributed as inelastic volumetric and deviatoric (i.e., shear) strain, which remain after shutdown. The accumulations of inelastic volumetric and deviatoric strain during repeated power cycling result in a larger radial displacement at the fuel surface than that for uncracked fuel (Fig. 29).

The steady-state and the power-cycling case have been compared with respect to displacements at the fuel outer surface as well as at the cladding inner surface. No noticeable difference has been observed regarding the displacements at the cladding inner surface, which suggests that fuel cracking and relocation alone account for the reduction of gap size in the power-cycling case.

In the power-cycling case, the gap first closes at ~3 at. % burnup, but then reopens at ~6.5 at. % burnup. During the gap closure period, fuel-cladding interfacial pressure builds up slowly with time to a maximum value of 11.0 MPa (1.6 ksi) at ~4.4 at. % burnup and then decreases gradually until the gap reopens. No substantial pressure buildup occurs during that period because the power-cycling-induced fuel cracking and relocation makes the fuel easier to deform in response to the interfacial pressure than uncracked fuel, owing to the reduced fuel modulus.

Fig. 30. LIFE-GCFR-calculated Fractional Fission-gas Release as a Function of Irradiation Time for the 60-, 100-, and 115%-power Runs

The convective gas transport caused by repeated breathing cycles vents most of the fission gas out of the fuel pin through the PES in the power-cycling case. During the gap closure period, passage of the gas mixture to the PES is still possible owing to extensive fuel cracking and relocation, which creates open spaces between fuel and cladding, and the existence of the fuel central void which is formed early in life. Therefore, any effective plugging of the passage through the fueled region is unlikely during the gap closure period in the power-cycling case.

Figure 30 compares fractional fission-gas release for the steady-state cases at 60, 100, and 115% power. According to LIFE-GCFR calculations, fractional gas release at the end of life (~18000 h) is 74, 63 and 34% TH for the 115-, 100-, and 60%-power cases, respectively. Since fractional fission-gas release is strongly dependent on fuel temperature, it is expected that the 115%-power case has the highest gas release and the 60%-power case

has the lowest gas release. For the 100- and 115%-power cases, the rapid increase in fission-gas release at the beginning of fuel life is due to fuel restructuring. A columnar-grain zone is formed in these highly rated fuel rods during the first few hundred hours of full-power irradiation, and virtually all fission gas generated in that region is released to this fuel central void. For the 60%-power case, however, columnar-grain zone is expected to form and hence, rapid gas release is not anticipated (see Fig. 30). Table X shows fission-gas retention within the fuel lattice, on the grain boundaries, and on the grain edges for the 60-, 100-, and 115%-power cases at the end of life. The results shown in Fig. 30 and Table X indicate that the higher-power rod retains less fission gas within the fuel lattice, on the grain boundaries, and on the grain edges.

TABLE X. Fission-gas Retention within the Fuel Lattice, on the Grain Boundaries, and on the Grain Edges for the 60-, 100-, and 115%-power Cases

Power History of Fuel Rod	Fission-gas Retention (% TH)		
	In Fuel Lattice	On Grain Boundaries	On Grain Edges
60% Power	59.1	0.92	3.60
100% Power	34.0	0.64	0.79
115% Power	24.1	0.48	0.35

Fig. 31

LIFE-GCFR-calculated Fraction of Retained Fission Gas vs Fractional Radius for the 60%-power Case at $X/L = 0.125$

Figure 31 shows the end-of-life radial distribution of retained fission gas in the fuel lattice, on the grain boundaries, and on the grain edges for the 60%-power case at $X/L = 0.125$. In Fig. 31, r/r_0 is the fractional radius, where r_0 is the radius of the fuel pellet. For the low-temperature region (i.e., the outermost region of the fuel in Fig. 31), the mobility of fission gas is too low to permit appreciable gas-bubble movement. Therefore, most of the generated gas is predicted to remain within the fuel grains. In contrast, an appreciable amount of fission gas has been released from the inner region of the fuel (i.e., $r/r_0 < 0.5$ in Fig. 31) through the following steps: Fission gas generated in the fuel grains first reaches the fuel-grain faces by successive diffusion of fission-gas bubbles, containing one or more gas atoms, in random and biased (i.e., up the temperature gradient) modes. In addition to the diffusion of

fission-gas bubbles from the grain boundaries to the grain edges, the formation and linkup of channels on the grain faces has enabled the fission gas retained on these grain faces to vent to the grain edges. Through interlinkage of the edge porosity, fission gas on the grain edges is released from the fuel.

Fig. 32
LIFE-GCFR-calculated Fraction of Retained Fission Gas vs Fractional Radius for the 115%-power Case at $X/L = 0.625$

Figure 32 shows the radial distribution of retained fission gas in the fuel lattice and on the grain boundaries for the 115%-power case at $X/L = 0.625$. Fission gas retained on the grain edges is too insignificant to be shown in Fig. 32. For the 115%-power case, the inner 70% of the cross-sectional area comprises fuel central void and columnar-grain zone, from which virtually all the fission gas has been released. Near the outer surface of the fuel ($0.84 < r/r_0 < 1$), about 10% of the generated fission gas is retained in the fuel.

As discussed in Section III.C, the accumulation of cesium uranate along the fission-gas transport path may block passage to the PES. Consideration is given here to the effects on fuel performance of a hypothetical tightly plugged passage occurring at the upper fuel-blanket interface (sample calculation) after 3 and 6 at. % burnup. Figure 33 compares the

fuel-cladding gas-gap pressure at 100% steady-power irradiation under the following gap conditions: (1) normal operation without plugging (solid line), (2) a tightly plugged passage at 3 at. % burnup (dashed line), and (3) a tightly plugged passage at 6 at. % burnup (dotted line). Figure 34 shows fuel centerline temperatures at $X/L = 0.625$ under the above three gap conditions. At the onset of passage plugging, the fuel-cladding open space, which includes central void, fuel-cladding gap, and lower blanket-cladding gap, is about the same for the two burnups. The reason for this is that the decrease in fuel-cladding gap volume from 3 to 6 at. % burnup due to fuel swelling is compensated by the cladding swelling that is initiated at 4.94 at. % burnup. Based on the analysis given in Section III.C, LIFE-GCFR calculations assume that

Fig. 33. Fuel-cladding Gas-gap Pressure vs Steady-power Irradiation Time for Three Different Gap Conditions

before passage plugging occurs at the upper fuel-blanket interface, a pure helium gas fills the fuel-cladding open space. Hence, the amount of helium gas trapped inside the fuel element below the plugging point at 3 at. % burnup ($\sim 2.18 \times 10^{-3}$ moles) is about the same as at 6 at. % burnup ($\sim 2.05 \times 10^{-3}$ moles). From Fig. 30, the fission-gas release rate for the 100%-power case at ~ 6000 h (i.e., 3 at. % burnup) is approximately the same as that at ~ 12000 h (i.e., 6 at. % burnup). Therefore, as shown in Fig. 33, the initial increase rate in the fuel-cladding gas-gap pressure is about the same for both the 3 and 6 at. % cases. The amount of temperature increase after the plugging is also about the same, as shown in Fig. 34. This is evidently because the increment of fission-gas concentration inside the plugged fuel volume is the same for both cases. The effect of the increase of fission-gas concentration in the fuel-cladding gap is a decrease in the thermal conductivity of the gas mixture and a decrease in gas-gap conductance, which results in a higher fuel temperature.

Fig. 34

Fuel Centerline Temperature vs Irradiation Time at $X/L = 0.625$ for Three Different Gap Conditions

From Figs. 33 and 34, performance of GCFR fuel with a fission-gas passage plugged at 3 at. % burnup is worse than that at 6 at. % burnup. In the former case, fuel-cladding gap pressure can reach 28.9 MPa (4.2 ksi). During the pressure buildup stage, the high pressure inside the envelope might be relieved by blowing the plug so as to reopen the gas passage and return to normal operation. Otherwise, LIFE-GCFR calculates a maximum cladding strain of 11.5% $\Delta D/D_0$, which will result in a 16.4% decrease in coolant flow area associated with a single fuel element. Fuel centerline temperature at $X/L = 0.625$ is predicted to be 2427°C (4400°F), which is 440°C (792°F) higher than the temperature for normal operation without the fission-gas-path blockage. For fuel with a plugged fission-gas passage at 6 at. %, gas-gap pressure, maximum cladding strain, and fuel centerline temperature are calculated by LIFE-GCFR to be 23.2 MPa (3.4 ksi), 7.59% $\Delta D/D$, and 2214°C (4018°F), respectively.

Table XI summarizes predicted fuel data at 7.92 at. % burnup for fuel with no fission-gas-passage plugging, and with plugged passages at 3 and 6 at. % burnup. According to LIFE-GCFR predictions, no fuel melting occurs as a result of gas passage plugging at 3 and 6 at. % burnup. However, the cladding damage fraction based on stress-rupture properties increases considerably for the two plugged cases.

TABLE XI. LIFE-GCFR-predicted Data at 7.92 at. % Burnup for Fuel with Three Different Gap Conditions

Fuel	Fuel-cladding Gas-gap Pressure, MPa(ksi)	Axial Fuel Position	Fuel Centerline Temperature, C(F)	Cladding Equivalent Shear Stress, MPa(ksi)		Cladding Creep Strain, %	Cladding Total Strain, %	Type 1 Cladding Damage Fraction, %
				I. D.	O. D.			
No Passage Blockage	8.8 (1.28)	0.125	1368(2495)	20.94 (3.05)	21.87 (3.18)	0.044	1.114	2.86×10^{-9}
		0.375	1733(3151)	26.76 (3.90)	29.81 (4.34)	0.267	2.530	5.68×10^{-8}
		0.625	1931(3508)	12.99 (1.89)	16.18 (2.36)	0.291	4.146	3.65×10^{-6}
		0.875	1522(2771)	1.83 (0.27)	0.17 (0.02)	0.016	1.685	2.47×10^{-6}
Passage Plugged at 3 at.% Burnup	28.2 (4.11)	0.125	1493(2719)	94.07 (13.69)	138.86 (20.21)	0.457	1.590	5.70×10^{-7}
		0.375	2042(3708)	110.04 (16.02)	183.35 (26.69)	2.302	4.600	1.57×10^{-4}
		0.625	2296(4164)	132.94 (19.35)	177.42 (25.82)	4.760	8.450	1.43×10^{-2}
		0.875	1802(3276)	150.15 (21.85)	140.09 (20.39)	2.045	3.791	7.76×10^{-1}
Passage Plugged at 6 at.% Burnup	21.0 (3.05)	0.125	1422(2592)	53.03 (7.72)	93.26 (13.57)	0.182	1.295	5.46×10^{-9}
		0.375	1863(3385)	58.20 (8.47)	122.53 (17.83)	0.816	3.127	4.49×10^{-7}
		0.625	2117(3842)	76.71 (11.16)	106.66 (15.52)	1.521	5.333	5.99×10^{-5}
		0.875	1627(2960)	98.99 (14.41)	79.12 (11.52)	0.706	2.423	1.00×10^{-2}

The cladding failure analysis in LIFE-GCFR is based on a time-fraction criterion.⁵⁷ Briefly, it assumes that the cladding damage fraction DMG during time step i is given by

$$(\Delta \text{DMG})_i = (\Delta t / t_r)_i \quad (41)$$

where Δt is the time interval and t_r is the time to rupture for the i th stress, temperature and fast-fluence state. Damage accumulated for each time step is calculated according to

$$\text{DMG} = \sum_{i=1}^n (\Delta t / t_r)_i. \quad (42)$$

Failure of the whole cladding is assumed to occur at a time when $\text{DMG} = 1$ in any cladding ring. As shown in Table XI, fuel with the fission-gas passage plugged at 3 at. % burnup will exhibit a significantly greater cladding damage fraction than unplugged fuel at the same axial position of $X/L = 0.875$. However, the resulting damage is only 2.5%, which is not high enough to cause cladding rupture.

The results of the above GCFR fuel-rod analyses may be summarized as follows:

- (1) For GCFR fuel rods at 115, 100 and 60% power, LIFE-GCFR predicts no fuel-cladding mechanical interaction throughout fuel lifetime. There is no net primary pressure loading on the ribbed cladding.
- (2) Power-cycling-induced fuel cracking and relocation tends to close the fuel-cladding gap. However, no substantial pressure buildup (<11.0 MPa) is calculated during the gap-closure period.
- (3) Fission-gas release has a strong dependence on fuel temperature. Higher-power pins have higher fractional fission-gas release. The rapid increase in fractional fission-gas release observed early in fuel life for high-power pins can be attributed to the formation of an active columnar-grain zone during fuel restructuring.
- (4) The tight blockage of the fission-gas transport path through the PES has an adverse effect on fuel performance. The earlier the plugging occurs, the worse the fuel will perform toward the end of fuel life. Plugging of the fission-gas passage at 3 at. % burnup causes the following changes relative to unplugged fuel at the end of life: fuel centerline temperature increases by 440 C, fuel-cladding gap pressure increases by 20.1 MPa, cladding creep strain increases by 6.3% $\Delta D/D_0$, and cladding damage fraction increases from virtually zero to 2.5%. However, even with these increases, no evidence of fuel melting or cladding failure was calculated.

VI. CONCLUSIONS AND RECOMMENDATIONS

LIFE-GCFR is a fuel performance code that provides a mechanistic treatment of fission-gas behavior in a GCFR fuel element under steady-power irradiation. The calculations performed by LIFE-GCFR include three major components: thermal analysis, mechanical analysis, and fission-gas analysis. The thermal calculations are based on the assumption of steady-state radial heat flux in the fuel and cladding. Coolant, cladding, and fuel temperature, fuel densification, pore migration, fuel grain growth, and plenum pressure are calculated in the thermal analysis. The effect of fission-gas porosity on fuel temperature is included in the analysis. The grain-growth model utilizes the fourth-order relationship between grain size and time. It represents the data reasonably well for both out-of-reactor data and in-reactor experimental data from GCFR irradiation tests. Pure helium-gas properties are used in the heat-transfer calculation of the temperature drop across the fuel-cladding gas gap for the situation where the PES is working properly. As discussed in Section III.C, owing to diffusive transport of fission gas along the axial direction inside the fuel rod, virtually all of the fission gas released from the fuel matrix is vented out of the fuel rod through the PES.

The mechanical analysis is based on the generalized plane-strain assumption and the method of successive elastic solutions. Fuel deformation mechanisms included in the calculation are thermal expansion, elasticity, restructuring, creep, fission-product swelling, hot pressing, fuel cracking, and crack healing. Cladding deformation mechanisms are thermal expansion, elasticity, creep, and irradiation-induced swelling. Fuel primary creep is included in the fuel constitutive equations. The crack-healing model includes the effect of stress on the crack-healing process. Fuel swelling consists of fission-gas swelling, which is calculated in the fission-gas analysis, and solid fission-product swelling, which has a constant swelling rate of 0.8% $\Delta V/V$ per at. % burnup in the code. The MK-6 stress-free swelling correlation for 20% CW Type 316 stainless steel cladding from the NSMH is implemented in LIFE-GCFR to describe the phenomenon of cladding swelling.

The fission-gas analysis is performed with a modified version of the mechanistic computer code GRASS-SST, which treats fission-gas release and fuel swelling in an internally consistent manner and simultaneously treats all major mechanisms thought to influence fission-gas behavior (both the distribution of fission gas within the fuel and the amount of fission gas released from the fuel). These major mechanisms include the production of gas from fissioning uranium atoms, bubble nucleation and re-resolution, bubble diffusion, bubble migration, bubble coalescence, gas bubble/channel formation on grain faces, temperature and temperature gradients, interlinked porosity, and fission-gas interaction with structural defects. GRASS-SST was developed mainly to describe the fission-gas behavior of LWR fuel; changes have been made to apply GRASS-SST to GCFR mixed-oxide fuel. The most significant change involved adding a quasi-static treatment of fission-gas behavior in the columnar-grain zone. Also, the fission-gas yield applicable to mixed-oxide fuel is now used.

The thermal, mechanical, and fission-gas analyses are interactively coupled in LIFE-GCFR. All calculated data that vary with operating conditions are updated for every time step. Within the time step, however, the thermal, mechanical, and fission-gas analyses are decoupled; this is done by keeping the time steps sufficiently short (<10 h).

LIFE-GCFR predictions have been checked against experimental observations from the GCFR test program. The results indicate that predictions of central void radius, columnar-grain zone radius, cladding strain, fuel density, end-of-life fission-gas release, grain size, and fuel burnup are in reasonable agreement with experimental data. The overall good agreement of predictions with GCFR test results demonstrates that the fuel pin modeling code LIFE-GCFR is, in its present state, a suitable tool for predicting the thermal, mechanical, and fission-gas behavior of GCFR fuel rods.

With this verified LIFE-GCFR code, the reference GCFR fuel element was analyzed for cases of 60, 100, and 115% of full-power irradiation, a power-cycling history with a reactor shutdown and start-up every 250 full-power hours, and hypothetical conditions where passage of the PES was plugged at the upper fuel-blanket interface after fuel burnups of 3 and 6 at. %. Results are as follows: (1) For the GCFR fuel rod at 115, 100 and 60% power, LIFE-GCFR predicts no fuel-cladding mechanical interaction throughout the fuel lifetime. There is no net primary loading on the ribbed cladding. (2) The calculated cladding temperatures are below the peak swelling temperature (580 C) in the stress-free swelling correlation for 20% CW Type 316 stainless steel cladding under the operating conditions for 60, 100 and 115% of full power. After cladding swelling becomes significant, hoop and axial stresses are tensile at the cladding outer surface and compressive at the cladding inner surface. (3) Power-cycling-induced fuel cracking and relocation tends to close the fuel-cladding gap. However, no substantial interfacial pressure buildup is calculated during the gap-closure period. (4) Fission-gas release has a strong dependence on fuel temperature. A higher-power rod exhibits higher fractional fission-gas release. The rapid increase in fractional fission-gas release early in life for the highly rated power pin can be attributed to the formation of a columnar-grain zone during fuel restructuring. (5) A tight blockage of the fission-gas transport path (from the fuel to the PES) has a considerable effect on fuel performance. The earlier the plugging occurs, the more serious are the effects on fuel performance. However, no fuel melting or cladding failure is predicted for the plugged cases that have been investigated.

In the work reported here, LIFE-GCFR has been generated, verified, and demonstrated to be a reliable code for the prediction of fast-reactor fuel performance under experimental operating conditions. In addition, reasonable (in a qualitative sense) results were obtained for GCFR fuel under design conditions that have not yet been duplicated experimentally. Code versatility has been improved by extending the maximum number of axial sections from 6 to 10 for detailed fuel analysis, providing different ratios of smooth-to-ribbed

cladding length for code analysis, including optional LMFBR fuel element analysis, and adding a dump-restart capability at a specific time. However, additional improvements can be made to enhance the code performance of LIFE-GCFR and extend its applicability. Suggestions for further research follow.

A. Off-normal and/or Design-basis Transient Analysis

For GCFR safety analysis and for licensing purposes, it is desirable to include fuel transient analysis in LIFE-GCFR. Modeling technology for fuel transient analysis is available from both the LWR⁵⁸ and the LMFBR⁵⁹ communities. In fact, the GRASS-SST subroutine, which performs the fission-gas analysis in LIFE-GCFR, has the capability of performing the transient fission-gas analysis. Additional work is needed to enable LIFE-GCFR to calculate transient temperatures and system pressure responses. A finite-difference algorithm⁹ may be used for calculating transient temperatures.

B. Modeling of the Axial Blanket

In the current LIFE-GCFR, the presence of the axial blanket (i.e., upper and lower blanket with depleted UO_2) is completely ignored in the code calculation. Actually, owing to the constant conversion of fertile material (i.e., ^{238}U) to fissile material (i.e., mainly ^{239}Pu) in the blanket region, the blanket can be regarded as a portion of fuel with very low power after a certain period of irradiation which depends on the actual core designs. The total length of upper and lower blanket in the reference GCFR fuel element is 900 mm, which is about 80% of the fueled length. The amount of fission gas released from the axial blanket may be significant. For example, in modeling the fuel performance of the French RAPSODIE 1 experiment, the COMETHE code uses a correction factor of 1.16 in fission-gas yield (0.25) to simulate the gas release in axial blankets.¹² More gas release will increase the loading of the PES. Fission gas retained in axial blankets will contribute to blanket swelling and result in a smaller cross-sectional area for axial diffusion of fission gas out of the fuel element, thus affecting fuel performance. Therefore, including the modeling of the axial blanket in LIFE-GCFR is recommended.

C. Fission-gas Analysis Model

LIFE-GCFR utilizes subroutine GRASS-SST to perform detailed fission-gas analyses of GCFR fuel. As a result of its mechanistic treatment of fission-gas release and swelling, and its extensive inclusion of all major mechanisms thought to influence fission-gas behavior, about 90% of the total computer running time is spent in the fission-gas analysis. It is very expensive to analyze fuel performance with LIFE-GCFR. A faster-running version of GRASS-SST, FASTGRASS,⁶⁰ and a correlation-based version of GRASS-SST, PARAGRASS,⁶¹ are being developed at ANL. After these two versions become available, it is recommended that they be included as optional fission-gas analysis models in LIFE-GCFR so that users can choose between detailed analysis and fast running time.

D. Modeling of Highly Localized Fuel and Cladding Behavior

Fuel cracking (which can cause concentrated loading on the cladding in the vicinity of the fuel cracks), the behavior of the ribbed cladding, and the formation of cladding ridges, which occurs preferentially at the fuel-pellet ends, are examples of highly localized phenomena that cannot be modeled adequately by the current LIFE-GCFR. However, these phenomena are of great importance to cladding failure analysis. Therefore, it is desirable to analyze these problems, either within LIFE-GCFR through major modifications in code structure (probably involving 2-D finite-element techniques) or outside LIFE-GCFR by means of auxiliary computational tools.

APPENDIX A

Input Instructions for LIFE-GCFR*

Table A.I illustrates the input needed to describe the geometrical, fabrication, and environmental parameters, select the material properties, and specify code options to be used in the analysis of the fuel element. Each input record described in Table A.I is identified by the variable ITYPE, which is also the "CARD NO." in the table. Included with the input instructions is a set of recommended values which may be either a single number or a range of numbers. Use of these values will call the recommended calibrated models contained in the LIFE-GCFR code. Tables A.II and A.III illustrate how special parameters may be input into LIFE-GCFR. Table A.IV shows the input needed for the power history of the fuel element. In addition to providing for the specification of power changes and steady-state operation, this input may be used to control the frequency and the level of the fission-gas analysis output. Table A.V shows the optional input for cladding outer surface temperature. It should be noted that the parameter values used in the CLADT option remain in effect until new values are specified. Changes in the coolant flow rate and/or axial flux/power distributions during the power history will necessitate new CLADT parameter values.

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*Modification of M. C. Billone et al., "LIFE-III Fuel Element Performance Code," ERDA-77-56, July 1977.

TABLE A.1. Input Variables for LIFE-GCFR

CARD NO.	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION	RECOMMENDED VALUE
1	[Case title and description, FORMAT (I2, 1X, 19A4, 11)]			
	01-02 04-79 80	ITYPE TITLE IRSTAR	Record number. Any alphanumeric characters needed to describe case. If positive, the case is a restart and ISTAR is the file sequence number of the restart data on file 15. Restart cases do not require input records no. 2-22 and no. 99. Next records will be the rod power history (see Table A. IV).	01
2	[Problem size parameters, FORMAT (I2, 3X, 11(1X, I4))]			
	01-02 07-10	ITYPE NN	Record number. Total number of axial sections. Includes a top plenum axial which is considered the highest numbered section. $2 \leq NN \leq 10$.	02 $2 \leq NN \leq 10$
	12-15	NT	Number of shells used for thermal analysis of fuel, $1 \leq NT \leq 15$.	08
	17-20	KF	Number of cylinders used for mechanical and fission-gas analysis of fuel. The calibrated fuel thermal analysis model in LIFE-GCFR requires that NT be an integer multiple of KF.	08
	22-25	KC	The number of shells (and structural cylinders) for the thermal and mechanical analysis of the cladding. Interpolation routines in the cladding wastage model require that $KC \geq 5$.	04
	27-30	ITERNO	Largest number of iterations before time step is reduced.	30
3	[Output and program control parameters, FORMAT (I2, 3X, 11(1X, I4))]			
	01-02 09-10	ITYPE NGCFR	Record number. For semi-empirical gas-release and swelling models: 10+number of smooth-cladding sections for GCFR pin. 0 for LMFBR pin. For GRASS-SST analysis: 60+number of smooth-cladding sections for GCFR pin. 50 for LMFBR pin.	03
	12-15	IB	Produces detailed output at every IB+1 increment of average burnup (at.%).	
	17-20	IL	Produces detailed output at every elapsed (IL+1)th of allotted computing time. (Guarantees some output even for unsuccessful runs.)	0
	22-25	ITRWR	If positive, prints information on number of iterations used.	0
	27-30	IPW	Maximum allowable power change in W/ft in any time step.	250
4	[Material properties selectors, FORMAT (I2, 3X, 11(1X, I4))]			
	01-02 09-10 14-15	ITYPE NOK NOH	Record number. Selector for fuel thermal conductivity model. Selector for cladding swelling models: -1 : ST304 -2 : CW316 (NSMH Rev.5) -3 : ST316 -4 : CW316 (NSMH Rev.0) -8 : CW316 (NSMH Rev.7)	04 03 -8

TABLE A.I (Contd.)

CARD NO.	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION	RECOMMENDED VALUE
4	19-20	NCRC	Selector for cladding creep models: -5 : ST316-w/primary and secondary creep -6 : CW316-secondary creep only -7 : ST304-secondary creep only -8 : CW316-w/primary and secondary creep	-8
	24-25	NCRF	Selector for fuel creep model	1
	29-30	NSWL	Selector for fuel swelling model	6
	34-35	NGAP	Selector for gap conductance model	2
5	[Selectors (input either 0 or 1) for models, FORMAT (I2, 3X, 11(1X, I4))]			
	01-02	ITYPE	Record number	05
	09-10	IPLUT	Currently inactive	0
	14-15	IPORM	Selector for pore migration model	1
	19-20	NOCRK	Disallows fuel cracking when NOCRK positive	0
	24-25	IREST	Currently inactive	1
	29-30	ICHNG	Determines cladding damage by lifetime fraction calculation if ICHNG $\neq$ 0	1
	34-35	NGPP	Currently inactive	
	39-40	KPWR	Positive value of KPWR suppresses power reduction with burnup, making PDPU=0 instead of PDPU=QQ(183)	0
	44-45	IWASTE	Positive value of IWASTE bypasses the cladding waste age calculation	1
6	[Indicators for special, additional input records (see Tables A. II and A. III), FORMAT (I2, 3X, 11(1X, I4))]			
	01-02	ITYPE	Record number	06
	07-10	KFLX	Indicator for specifying radially dependent power-generation factors. KFLX=0 specifies radially constant power generation	0
	12-15	IDLE	Selector for fuel grain growth models: 0 : The fourth-order grain-growth law (i.e., Eq. 25 in main text) 1 : NSMH grain-growth law (i.e., Eq. 23 in main text) 2 : Previous LIFE grain-growth law (i.e., Eq. 22 in main text) 3 : The cubic grain-growth law (i.e., Eq. 24 in main text) 4 : Constant grain size 5 : Ainscough model (i.e., Eq. 26 in main text) NEWQQ > 0 indicates that some QQ(I) data will be input (see Table A. II)	0
	17-20	NEWQQ		0
7	[Relative mass in NT fuel shells, FORMAT (I2, 3X, 15(2X, I3))]			
	01-02	ITYPE	Record number	07
	09-80	LP(I)	The PORMIG model uses equal masses in all fuel shell, irrespective of this specification	1 for all NT
8	[Determines the grouping of fuel thermal shells into radial structural cylinders, FORMAT (I2, 3X, 15(4X, L1))]			
	01-02	ITYPE	Record number	08
	09-80	LGC(I)	LGC(I) is a logical variable, T if true, F if blank or false. If LGC(I) is T, there is a one-to-one correspondence between the fuel cylinders and shells and no other LGC values need be input. If LGC(I) is F, the remaining NT values of LGC determine if the outer shell boundary is a cylinder boundary and	

TABLE A.I (Contd.)

CARD NO.	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION	RECOMMENDED VALUE
8			LGC(I)=T. A shell boundary that is not a cylinder boundary has LGC(I)=F. The specification given on this card is ignored by the present version of the code. (I=1, NT+1)	
9	[Fuel rod geometry, FORMAT (I2, 10X, 5E12.5)]			09
	01-02	ITYPE	Record number	
	13-24	FL	Length of the fuel (in.)	
	25-36	CL	Effective total cladding length (in.). CL should be chosen to provide the correct plenum volume.	
10	[Fabrication parameters and capsule geometry, FORMAT (I2, 10X, 5E12.5)]			10 ≥0.00001
	01-02	ITYPE	Record number	
	13-24	SIS	Inside cladding scratch depth (in.)	
	25-36	SOS	Outside cladding scratch (in.)	
	37-48	RCPI	Cladding capsule inside radius (in.)	
	49-60	RCPO	Cladding capsule outside radius (in.). RCPO smaller or equal to RCPI specifies an unencapsulated fuel element. When using the recommended CLADT option (see Table A. V) capsule data are not utilized.	
11	[Fuel dimensions, FORMAT (I2, 10X, 5E12.5)]			11
	01-02	ITYPE	Record number	
	13-72	RVB(I)	Initial center void radius (in.). I=1,5 (or NF where NF=NN-1=number of fueled sections). For NF ≥ 6 read values on extra card with FORMAT (12X, 5E12.5).	
12	[Fuel dimensions, FORMAT (I2, 10X, 5E12.5)]			12
	01-02	ITYPE	Record number	
	13-72	RUB(I)	Fuel pellet outside radius (in.) [I=1,5(or NF)] See card no. 11	
13	[Cladding dimensions, FORMAT (I2, 10X, 5E12.5)]			13
	01-02	ITYPE	Record number	
	13-72	RCA(I)	Cladding inside radius (in.). [I=1,5(or NN)]. For NN ≥ 6, read value(s) on an extra card with FORMAT (12X, 5E12.5)	
14	[Cladding dimensions, FORMAT (I2, 10X, 5E12.5)]			14
	01-02	ITYPE	Record number	
	13-72	R4B(I)	Cladding outside radius (in.). [I=1,5(or NN)] See card no. 13	
15	[Coolant conditions, FORMAT (I2, 10X, 5E12.5)]			15 0.0 and TOUT on 1st power history card (see Table A. IV)
	01-02	ITYPE	Record number	
	13-24	AFNA	Coolant flow area associated with a single fuel element (ft ²).	
	25-36	PITCH	Distance between two fuel-element centers (in.). Used to calculate AFNA if AFNA is zero	
	37-48	COOL	Coolant-inlet temperature (F)	
	49-60	TCON	Total coolant temperature rise per unit average linear power [F/(kW/ft)]. TCON determines the coolant outlet temperature, TOUT, until TOUT is specified on a power-history record. A specified TOUT determines TCON to be consistent with TOUT.	

TABLE A.I (Contd.)

CARD NO.	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION	RECOMMENDED VALUE
16	[Initial plenum-gas conditions, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	16
	13-24	CASI	Initial moles of helium in plenum volume.	
	25-36	XENON	Initial moles of xenon tag gas in plenum volume.	
	37-48	PLENT	Plenum temperature throughout power history (F). If PLENT is not input (blank or zero), the plenum temperature is equal to the coolant outlet temperature during the power history.	
49-60	PLPRX	Constant plenum pressure for a vented pin (psi). If PLPRX is zero, plenum pressure is determined by gas in plenum.		
17	[External conditions, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	17
	13-24	PTOP	Axial force on top of cladding (lb).	
	25-36	PO	Average external pressure on cladding (psi).	
	37-48	VEL	Velocity of the coolant (ft/s). Used only in cladding-wastage calculation.	
18	[Fuel density, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	18
	13-72	RH3(I)	As-fabricated fuel density (g/cm ³). [I=1,5(or NF)]. See card no. 11.	
19	[Plutonium content, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	19
	13-24	CPUO	Initial plutonium concentration of the fuel (weight fraction); i.e., (1 - x) in (U _x Pu _{1-x})O ₂ . CPUO must not be zero.	
20	[Axial-flux profile, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	20
	13-72	QSFO(I)	Non-normalized axial fast-flux shape factors for all axial sections. These factors are superseded if the CLADT option is invoked during the power history (see Table A. V). [I=1,5(or NN)]. See card no. 13.	
21	[Axial power profile, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	21
	13-72	QSF1(I)	Non-normalized axial-power profile for all axial fuel sections. This profile is used until the CLADT option is invoked during the power history (see Table A. V). [I=1,5(or NF)]. See card no. 11.	
22	[Optimal values used in LIFE-GCFR, FORMAT (I2, 10X, 5E12.5)]			
	01-02	ITYPE	Record number	22
	13-24	DSMX1	Convergence criteria for error permitted in stress (psi) and strain (×10 ⁻⁷ in./in.). Default value=4.	
	25-36	FCTR	Incremental time-step multiplier. After a successful step the code attempts a larger increment of time. Default value=1.5	10.
	37-48	DELT	Maximum allowed time-step size until a new DELMAX on a power history record is read. (in hours)	
23	[Input modifications to material constants (optional, see Table A. II)]			

TABLE A.I (Contd.)

CARD NO.	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION	RECOMMENDED VALUE
24	[Input relative radial power distribution across fuel element (optional, see Table A. III)]			
99	[Last fuel element description input record]			
	01-02	ILAST	This variable is checked for its value which must be equal to 99 or the program stops indicating user has made an input error by not supplying the correct number of input records or an incomplete record.	99

TABLE A.II. Input Modifications to Materials Constants

Any constant QQ contained in subroutine CONSTS may be replaced as follows:

1. Set NEWQQ equal to 1 on card #6.
2. Read card #23.
 READ (5, 270) ITYPE, NUMQQ
 270 FORMAT (I2, 3X, LL(1X, I4))

 ITYPE = 23 (columns 01-02)
 NUMQQ = number of constants to be input (columns 07-10)
3. Read NUMQQ cards containing one new constant each.
 READ (5, 320) INDXQQ, QQ(INDXQQ)
 320 FORMAT (3X, I3, 6X, E12.5)

INDXQQ is the index of the QQ constant that is to be replaced.
 QQ(INDXQQ) is the new value of the constant to be used.

If the user desires, the cards containing the new constants may be punched according to the following example.

To make QQ(86) equal to 4.0:

Column:	01	02	03	04	05	06	07	08	09	10	11	12
Punch:	Q	Q	(		8	6	)		=			

Column:	13	14	15	16	17	18	19	20	21	22	23	24
Punch:										4	.	0

The code will use and output:
 QQ(86) = 4.0

TABLE A.III. Input Relative Radial Power Distribution
across Fuel Element

A radial power distribution across a rod may be input as follows:

1. Set KFLX = 1 on CARD NO. 6.
2. Read CARD NO. 24.

READ (5,290) ITYPE, (FH(NTA), NTA = 1,5)

290 FORMAT (I2, 10X, 5E12.5)

For $5 < \text{NTA} \leq 10$ read value(s) on an extra card.

(NTA = 6, NT)

For $\text{NTA} > 10$ read values on two extra cards.

(NTA = 6, 10)

(NTA = 11, NT)

FORMAT (12X, 5E12.5)

NOTE: FH(NTA) is the relative power value at the NT radial-temperature node.

TABLE A.IV. Fuel-element Power History

CARD #	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION
N/A	1-12	TIM	Length of the time interval (h). The interval will either be the time for a power change from the previously specified power or the interval for continuing the steady-state power.
	13-24	REPOW	Reactor Power (MW) (see definition of CP below). It is suggested that REPOW = average linear power (kW/ft) of the fuel element and CP = 1.0.
	25-36	TOUT	The sodium outlet temperature (°F). If TOUT is specified, TCON is recalculated (see record #15). If TOUT is blank or zero on this record, it is determined from TCON and the fuel-element average power for this time step.
	37-48	CP	Constant used to multiply REPOW to obtain the average linear power for the fuel element, POWAV (kW/ft). POWAV = CP*REPOW. If CP is blank or zero on this record, the previous nonzero CP remains in effect.
	49-60	CF	Constant used to obtain the average fast flux $[(n/cm^2 \cdot s)/(kW/ft), E > 0.1 \text{ MeV}]$ for the fuel element. If CF is blank on this record, the previous nonzero CF remains in effect.

TABLE A.IV (Contd.)

CARD #	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION
	61-72	DELMAX	Maximum time increment to be used in the analysis (h). LIFE-III will ordinarily attempt DELMAX time increments to complete the TIM time step. If DELMAX is blank on this record, DELTM of card #22 is used.
	73-74	IR3	This parameter serves as an output request indicator and an option selector for CLADT (Table VII). Negative IR3 indicates the last card of the power history of a fuel element. IR3 = -1, indicates the end of the problem and another problem is following. IR3 = -2 indicates the last card of the last fuel element. IR3 > 11 invokes the CLADT option and thereafter IR3 = IR3 - 12. IR3 < NN prints detailed output for axial section IR3. IR3 > NN prints detailed output for all axial sections.
	80	IGS	Level of GRASS printout (1-4). IGS=8, dumps all information on tape 15 and stops at the end of time interval TIM.

TABLE A.V. Option for Cladding Temperature Input

CARD #	COLUMNS	VARIABLE NAME	VARIABLE DESCRIPTION
N/A	Cladding OD temperatures FORMAT (8X, 9F8.2)		
	09-72	TCLOF(N)	Cladding OD temperature (*F) for all sections N, (N = 1, NF) at AVPOW (see below). Any TCLOF(N) = 0 results in default calculation of cladding temperature. NF = total number of fuel sections
N/A	Relative flux shape FORMAT (8X, 9F8.2)		
	09-72	QSFO(N)	Fast-flux shape for all fuel sections N (N = 1, NF). Previously used value QSFO(NN) is preserved for the plenum section.
N/A	Average power for input cladding temperatures and new power shape FORMAT (10F8.2)		
	01-08	AVPOW	Average fuel-element power at which TCLOF is evaluated
	09-72	QSF1(N)	Power shape for all sections N, (N = 1, NF)

APPENDIX B

Output Descriptions for LIFE-GCFR*

The LIFE-GCFR output is generated on the normal output file which is printed at the conclusion of the problem. Data are accumulated on this file during processing, so abnormal termination of a LIFE-GCFR case will still produce at least partial results. Three categories of output are produced by LIFE-GCFR: an input edit, a short report of results that is sometimes referred to as intermediate output, and a complete tabulation of results from fission-gas, thermal, and mechanical analysis. A description of the output categories produced by LIFE-GCFR follows.

B.1. Input Edit

A listing of the input deck is the first part of the code output. This listing is generated by coding statements that simply read and write the alphanumeric characters on the input file until an end-of-file is detected. Following the input list, the input parameters are printed with brief descriptive labels. Additionally, the assigned values (either by coding statement or input) of the QQ array of material properties constants are printed. Tables B.I and B.II are samples of the input-edit section of the output.

**TABLE B.I. Listing of the LIFE-GCFR
Input Deck for a Sample Case**

1	01	STEADY STATE	PERFORMANCE	STUDY FOR 300 MW(E)	GCPR	SOLID FUEL									
2	02	5	8	8	4	30									
3	03	61	9	0	0	250									
4	04	3	-8	-8	1	6	2								
5	05	0	1	0	1	1	0	1	1						
6	06	0	0	1											
7	07	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	08	T													
9	09			44.50		100.0									
10	10			0.00005		0.0				0.0		0.0			
11	11			0.001		0.001			0.001		0.001				
12	12			0.124		0.124			0.124		0.124				
13	13			0.12677		0.12677			0.12677		0.12677		0.12677		
14	14			0.14685		0.14321			0.14321		0.14321		0.14321		
15	15					0.435			667.0		32.0				
16	16			2.5		0.0			667.0		1280.0				
17	17			0.0		1280.0			100.0						
18	18			9.828		9.828			9.828		9.828				
19	19			0.177											
20	20			0.825		1.175			1.175		0.825			0.1	
21	21			0.825		1.175			1.175		0.825				
22	22			4.0		1.5			10.						
23	23	2													
24	QQ(147) =			8.0D10											
25	QQ(172) =			0.0											
26	99														
27	1.0			0.001		669.		1.15	1.758E+14				11		
28	9.0			9.09		1000.							11	102	
29	500.			9.09		1000.							11	4	
30	500.			9.09		1000.							11	4	
31	500.			9.09		1000.							11	4	
32	500.			9.09		1000.							11	4	
33	2000.			9.09		1000.							11	4	
34	2000.			9.09		1000.							11	4	
35	2000.			9.09		1000.							11	4	
36	2000.			9.09		1000.							11	4	
37	2000.			9.09		1000.							11	4	

*Modification of M. C. Billone et al., "LIFE-III Fuel Element Performance Code," ERDA-77-56, July 1977, and J. Rest, "GRASS-SST: A Comprehensive, Mechanistic Model for the Prediction of Fission-gas Behavior in Nuclear Fuels during Steady-state and Transient Conditions: Users Manual and Model Development Update," to be published as an ANL Report.

**TABLE B.II. Input Description and Listing of the Assigned
Values of Calculational Parameters**

```

STEADY STATE PERFORMANCE STUDY FOR 300 MW(E) GCFR SOLID FUEL
*PROBLEM TITLE*  STEADY STATE PERFORMANCE STUDY FOR 300 MW(E) GCFR SOLID FUEL

*PROBLEM SIZE*                *PRINT AND OTHER CONTROLS*        *SPECIAL INPUT INDICATORS*

  MN= 5  AXIAL SECTIONS          NGCFR=61  LMFR/GCFR&GRASS OPT.      KFLX=0  POS., RADIAL FLUX INPUT
  NT= 8  FUEL TEMP. RINGS         IS= 9  BURNUP DEP. PRINTOUT      IDLE=0  GRAIN GROWTH LAW-EQUIAXED ZONE
  NS= 8  FUEL STRL. RINGS         IL= 0  TIME DEP. PRINTOUT      NEHQ=1  POS., SOME QQ VALUES INPUT
  KC= 4  CLAD RINGS              ITRHR= 0  TIMESTEP DEP. PRINTOUT
  ITERNO=30  ITER. ALLOW FOR CONV.  IPW= 250  MAX DELTA POW. FOR DELT

*MATERIAL PROPERTY CORRELATIONS*

  NOK= 3  FUEL THERMAL COND.      PORMIG
  NOH=-8  CLADDING SHELING        HKNS
  NCRC=-8  CLADDING CREEP         CREEC
  NCF= 1  FUEL CREEP              CREEF
  NSHL= 6  FUEL SHELING           SHELL
  NGAP= 2  GAP CONDUCTANCE        GAPCON

*OPTIONS*

  IPLUT= 1  ZERO B. PASS FLTMP /PLUTO MODEL
  IPORM= 1  ZERO E. PASS PORMIG MODEL
  NCORR= 1  POS. BYPASS CRACK MODEL
  IPREST= 1  POS. BYPASS RESTRUCT. DELT LIMIT
  ICHNG= 1  ZERO BYPASS CLAD DMG. CALC. CHNG
  NGPP= 0  NOT USED PRESENTLY
  KPMR= 1  ZERO POWER REDUCED BY BURNUP
  IHASTE= 1  POS. BYPASS CLAD WASTE CWASTE

*ROD GEOMETRY* (COLD)

  FUEL LENGTH,FL= 44.500(IN)      CLAD LENGTH,CL=100.000(IN)
  CLAD CAPSULE DIMENSION, (IN)  I.R.,RCPI=.0      O.R.,RCPO=.0

  FUEL I.R. AND O.R.(IN) FOR NN-1 AXL. SECT.
  RVB(N)= 0.00100 0.00100 0.00100 0.00100
  RUB(N)= 0.12400 0.12400 0.12400 0.12400
  CLAD I.R. AND O.R.(IN) FOR NN AXL. SECT.      I.R. SCRATCH,SIS=.00005  O.R. SCRATCH,SOS=.0      (R4B=R4B-SOS)
  RCA(N)= 0.12677 0.12677 0.12677 0.12677 0.12677
  R4B(N)= 0.14685 0.14321 0.14321 0.14321 0.14321

*SODIUM COND. OR SPECIFIED CLAD TEMP.*
  SODIUM FLOW AREA (FT**2),AFNA=.0.0      DIST. BETWEEN ROD CENTERS (IN),PITCH=0.43500  (DEFAULT FOR AFNA=0.)
  COOLANT INLET TEMP.(F),COOL= 667.00      COOLANT TEMP. CHANGE PER KW/FT,TCON= 32.000
  CLAD O.R. TEMP.(F) (IF.NE.0),TCLOF(N)= 0. 0. 0. 0. 0.

*FILL GAS CONDITIONS*
  INITIAL PLENUM GAS (MOLES) GASI= 0.2500 01      TAG GAS (MOLES) XENON= 0.0
  PLENUM TEMP.(F) PLENT= 667.0(DEFAULT=TOUT)      PLENUM PRES.(PSI) PLPRX=1280.00(DEFAULT=F(GASI))

*FUEL PROPERTIES*
  FAB. DENSITY RH3(N)= 9.828 9.828 9.828 9.828
  PLUTONIUM FRACTION OF FUEL,CPUO= 0.1770
  RELATIVE MASSES FOR NT RINGS,LP(I)= 1 1 1 1 1 1 1 1

*EXTERNAL CONDITIONS*
  ROD AXIAL LOAD (LBS),PTOP= 0.0      EXTERNAL PRES. (PSIA),PO=1280.0      SODIUM VELOCITY (FT/SEC),VEL=100.00

```

TABLE B.II (Contd.)

AXIAL FLUX (QSF0) AND POWER (QSF1) PROFILES (NON-NORMALIZED)

QSF0(N)= 0.825 1.175 1.175 0.825 0.300

QSF1(N)= 0.825 1.175 1.175 0.825 0.0

TIME STEP AND CONVERGENCE CONTROLS

DSHX1= 4.0 FCTR= 1.5 DELTH= 10.0

THERMAL CALIBRATION PARAMETERS

FUEL THERMAL CONDUCTIVITY			AHE	QSPOR	ASPOR	QVPCOR	AVPCOR	CHIPOR	DHRFOR	GSIZE0	EMULT	VMULT
-0.607D-01	0.304D-01	0.751D-12	0.150	81000.0	0.400D 09	98000.0	0.155D 09	0.370D 03	24361.6	10.0	2.0000	0.7100

MECHANICAL CALIBRATION PARAMETERS

GASCUT		APG1	QPG1	ACKSW	QCKSW
-0.700D 01	18000.0	0.800D 00	13500.0	0.100D 05	30000.0

QQ(I), I=1,200 VALUES

1	0.108D 01	-0.607D-01	0.304D-01	0.751D-12	0.680D-05	0.580D-08	0.800D 01	0.450D-02	0.910D-05	0.221D-08
11	0.300D 10	0.200D 06	0.675D 05	0.472D 05	0.810D 01	0.435D-02	0.543D 02	-0.188D-01	0.209D-05	0.346D 00
21	-0.792D-04	0.341D-07	0.110D 08	0.200D 01	0.276D 04	0.200D 08	0.200D 01	0.500D 00	0.276D 04	0.118D 03
31	-0.315D 04	0.260D 00	0.440D-04	0.242D 02	-0.812D 01	0.128D 02	-0.365D 01	0.174D-01	0.600D 01	0.200D 03
41	0.900D 00	0.400D 01	0.131D 03	0.838D 02	0.892D 00	0.108D 00	0.156D 00	0.805D 00	0.830D 00	0.201D 01
51	0.633D-01	0.883D-01	0.747D 00	0.226D-01	0.347D-01	0.178D-03	0.330D-03	0.856D 00	-0.265D 00	-0.146D 02
61	0.582D 01	0.825D 00	-0.104D 00	-0.140D 02	0.338D 01	0.567D-11	0.196D 01	-0.870D-09	0.166D 01	0.500D 00
71	0.628D 10	0.700D 05	-0.867D 02	0.160D 04	0.689D 05	0.200D-03	0.300D-02	0.180D 00	0.616D 00	0.132D-03
81	0.104D 11	-0.700D 01	0.180D 05	0.800D 00	0.135D 05	0.100D 05	0.300D 05	0.0	0.0	0.0
91	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101	-0.614D-09	0.137D-05	-0.124D-02	0.531D 00	-0.885D 02	0.689D-02	-0.112D 01	0.621D-08	-0.119D-04	0.817D-02
111	-0.239D 01	0.256D 03	-0.187D-03	0.195D 00	-0.499D 02	0.689D-02	-0.112D 01	0.287D-04	-0.298D-01	0.799D 01
121	0.382D-06	-0.730D-03	0.424D 00	-0.772D 02	0.817D-04	-0.660D-01	0.138D 02	-0.179D-01	0.114D 02	0.0
131	0.0	0.225D-04	0.107D 02	0.991D 01	0.989D 01	0.798D 01	0.100D 02	0.810D 05	0.400D 09	0.980D 05
141	0.155D 09	0.370D 08	0.249D 05	0.109D 02	0.200D 01	0.713D 00	0.800D 11	0.0	0.0	0.100D 01
151	0.100D 02	0.383D 05	0.100D-02	0.280D-19	0.372D-22	0.819D 05	0.137D 06	0.137D 05	0.0	0.0
161	0.100D 01	0.100D 01	0.100D 01	0.100D 01	0.100D 01	0.100D 01	0.100D 01	0.100D 01	0.100D 01	0.100D 01
171	0.125D 01	0.0	0.0	0.0	0.0	0.0	0.900D 00	0.0	0.0	0.100D 02
181	0.197D 03	0.268D 03	0.127D-01	0.950D 16	0.0	0.0	0.0	0.0	0.0	0.0
191	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

B.2. Short Output

After each converged time step a few results are printed. These results are important in evaluating how rapidly the power history is being processed. Fuel cracking and healing occurrences during the fuel-element lifetime are part of this output. A sample of the short output and a description of the variables is given in Table B.III.

B.2.1. Power History Cards

Each time a power history card is read from the input, the "POWER HISTORY CARD" label is written, followed by the values for TIM, REPOW, TOUT, CP, CF, DELMAX, IR3, and IGS. These user-input variables are defined in Table A.IV.

B.2.2. Summary Results

The columns in the summary results are, in order, values for the following variables: TIT, DELT, BUB, POWAV, PLPR, and, for each fuel section, PRT(J), HOLM(J), TLG(J,1), and CIND(J), where

TIT = total time (h) elapsed in the fuel-rod history,

DELT = time increment (h) for converged results,

BUB = average burnup (at. %),

POWAV = average linear power of the rod (kW/ft),

PLPR = plenum pressure (psia),

PRT(J) = interface pressure between the fuel and cladding (psia),

HOLM(J) = size of the fuel central hole (mils),

TLG(J,1) = fuel temperature (°F) at central-hole radius,

and

$$CIND(J) = 100 * \left[\frac{\text{diametrical change in cladding OD}}{\text{cold cladding OD}} - \sum_{K=2}^{KC} \frac{(\text{cladding swelling} + \text{thermal expansion})}{(KC-1)} \right],$$

TABLE B.III. Short Output of LIFE-GCFR after Each Converged Time Step

```

*****POWER HISTORY CARD
0.900000 01 0.909000 01 0.100000 04 0.0      0.0      0.0      11      1
1.22 0.2150 00 0.00 0.25 1280.0 / 1280.0 1.00 717.-0.002/ 1280.0 1.00 737.-0.002/ 1280.0 1.00 740.-0.002
1280.0 1.00 722.-0.002/
1.43 0.2150 00 0.00 0.50 1280.0 / 1280.0 1.00 768.-0.002/ 1280.0 1.00 808.-0.002/ 1280.0 1.00 813.-0.002
1280.0 1.00 777.-0.002/
1.65 0.2150 00 0.00 0.75 1280.0 / 1280.0 1.00 820.-0.001/ 1280.0 1.00 881.-0.001/ 1280.0 1.00 889.-0.001
1280.0 1.00 832.-0.001/
1.86 0.2150 00 0.00 1.00 1280.0 / 1280.0 1.00 873.-0.001/ 1280.0 1.00 956.-0.001/ 1280.0 1.00 966.-0.001
1280.0 1.00 889.-0.001/
FUEL CRACKS J= 2 K= 8 L= 1 LM(J,K)= 1
FUEL CRACKS J= 3 K= 8 L= 1 LM(J,K)= 1
2.08 0.2150 00 0.00 1.25 1280.0 / 1280.0 1.00 927.-0.001/ 1280.0 1.00 1033.-0.001/ 1280.0 1.00 1046.-0.001
1280.0 1.00 947.-0.001/
FUEL CRACKS J= 2 K= 7 L= 1 LM(J,K)= 1
FUEL CRACKS J= 3 K= 7 L= 1 LM(J,K)= 1
2.29 0.2150 00 0.00 1.50 1280.0 / 1280.0 1.00 981.-0.001/ 1280.0 1.10 1111.-0.000/ 1280.0 1.10 1127.-0.000
1280.0 1.00 1005.-0.001/
FUEL CRACKS J= 1 K= 8 L= 1 LM(J,K)= 1
FUEL CRACKS J= 2 K= 6 L= 1 LM(J,K)= 1
FUEL CRACKS J= 3 K= 6 L= 1 LM(J,K)= 1
FUEL CRACKS J= 4 K= 8 L= 1 LM(J,K)= 1
2.51 0.2150 00 0.00 1.74 1280.0 / 1280.0 1.00 1037.-0.000/ 1280.0 1.22 1191.-0.000/ 1280.0 1.22 1210.-0.000
1280.0 1.00 1065.-0.001/
FUEL CRACKS J= 1 K= 7 L= 1 LM(J,K)= 1
FUEL CRACKS J= 2 K= 5 L= 1 LM(J,K)= 1
FUEL CRACKS J= 2 K= 8 L= 2 LM(J,K)= 2
FUEL CRACKS J= 3 K= 5 L= 1 LM(J,K)= 1
FUEL CRACKS J= 3 K= 8 L= 2 LM(J,K)= 2
FUEL CRACKS J= 4 K= 7 L= 1 LM(J,K)= 1
2.72 0.2150 00 0.00 1.99 1280.0 / 1280.0 1.04 1093.-0.000/ 1280.0 1.22 1273. 0.000/ 1280.0 1.23 1294. 0.000
1280.0 1.05 1125.-0.000/
FUEL CRACKS J= 1 K= 6 L= 1 LM(J,K)= 1
FUEL CRACKS J= 2 K= 4 L= 1 LM(J,K)= 1
CRACKS HEAL J= 2 K= 5 L= 1 LM(J,K)= 0
FUEL CRACKS J= 2 K= 7 L= 2 LM(J,K)= 2
FUEL CRACKS J= 3 K= 4 L= 1 LM(J,K)= 1
CRACKS HEAL J= 3 K= 5 L= 1 LM(J,K)= 0
FUEL CRACKS J= 3 K= 7 L= 2 LM(J,K)= 2
FUEL CRACKS J= 4 K= 6 L= 1 LM(J,K)= 1
2.94 0.2150 00 0.00 2.24 1280.0 / 1280.0 1.08 1150. 0.000/ 1280.0 1.22 1356. 0.000/ 1280.0 1.23 1380. 0.001
1280.0 1.09 1186.-0.000/
2** 0 0 0 0 0 1 1 1** 0 0 0 1 0 1 2 2** 0 0 0 1 0 1 2 2** 0 0 0 0 0 1 1 1
0
FUEL CRACKS J= 1 K= 5 L= 1 LM(J,K)= 1
CRACKS HEAL J= 2 K= 4 L= 1 LM(J,K)= 0
CRACKS HEAL J= 3 K= 4 L= 1 LM(J,K)= 0
FUEL CRACKS J= 4 K= 5 L= 1 LM(J,K)= 1
3.15 0.2150 00 0.00 2.49 1280.0 / 1280.0 1.08 1207. 0.000/ 1280.0 1.22 1440. 0.001/ 1280.0 1.23 1467. 0.001
1280.0 1.09 1248. 0.000/
CRACKS HEAL J= 1 K= 5 L= 1 LM(J,K)= 0
FUEL CRACKS J= 1 K= 8 L= 2 LM(J,K)= 2

```

where

K = cladding shells (not including K = 1, the wastage shell).

Each fuel section is separated by a "/".

B.2.3. Cracking Activity

Either "FUEL CRACKS" or "CRACK HEAL" for indices J, K, L, and total cracks, LM(J,K) for indices J, K where

J = axial section,

K = structural fuel cylinder,

and

L = direction (1 = circumferential, 2 = axial, and 3 = radial) perpendicular to the plane of the crack.

B.2.4. Fuel-crack History

The total number of fuel cracks in each structural cylinder is printed after every tenth converged time step. The crack inventory is preceded by IT which is the sequence number of the rod power history being processed. An "*0" separates the crack inventories for consecutive axial sections.

B.3. Complete Output Report

A complete LIFE-GCFR output report consists of results from fission-gas, thermal, and mechanical analysis. During processing, the main program will signal subroutine GRASS, and call subroutine RITE3 at user-specified intervals of the rod power history to produce a complete set of results at the end of a time step. Below are samples and explanations of the output report. This output report is separated in sections for clarity. Tables B.IV to B.XIV are provided to give a sample of the output followed by an explanation of the results included in the sample listing.

TABLE B.IV. Listing of Data Input to Subroutine GRASS

```

TIT= 510.0000   DELT= 9.0620   NF= 4   NT= 8   FLCM= 113.0300   PLPR= 1280.0000
RHOG(J,K)=      9.2465   9.4096   9.4113   9.4268   9.4542   9.4900   9.5236   9.5711
10.0650  10.1185  10.1079  9.8240  9.4468  9.4246  9.4708  9.5727
10.0788  10.1306  10.1497  9.9377  9.5113  9.4143  9.4531  9.5653
9.1332   9.4752   9.4282   9.4043   9.4227   9.4585   9.4937   9.5273
TK(J,K)= 1965.0708 1827.8495 1692.3772 1558.7859 1429.9133 1307.7958 1193.5728 1087.7299
2274.4382 2165.6087 2025.6329 1868.0123 1690.0627 1504.2142 1327.9750 1167.2695
2306.0615 2202.3111 2067.0592 1916.4255 1744.9915 1559.5881 1379.7123 1214.4047
2056.6883 1924.0972 1791.7372 1657.1733 1524.6529 1397.5814 1277.7182 1165.8620

```

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
TIT	Total time elapsed at this point in the fuel-rod history	hour
DELT	Time increment in rod lifetime for which these results were obtained	hour
NF	Number of fuel axial sections	
NT	Number of cylinders into which the fuel is divided for fission-gas analysis	
FLCM	Fuel length	cm
PLPR	Fuel plenum pressure	psi
RHOG	Actual fuel density, including the effects of thermal expansion, swelling, elastic strain, and porosity migration	g/cm ³
TK	Average fuel temperature	K

TABLE B.IV (Contd.)

VARIABLE NAME	VARIABLE DESCRIPTION												UNIT
RS	Fuel zone radius												cm
TS	Fuel zone boundary temperature												C
PRS	Fuel zone hydrostatic pressure												psi
POROS	Fuel porosity fraction												
GRSIZ	Fuel grain size												cm
FD11A	Fissions per unit fuel volume/fissions per unit fuel length												cm ⁻²
CX3KJX	Deformed fuel volume/reference fuel volume												

TABLE B.V. GRASS-SST Printed Output for NPRINT = 4

***** GRASS OUTPUT *****

TIME= 0.183600000 97

----- AXIAL SECTION= 1 RADIAL SECTION= 8

(NPRINT = 4)

RS(J,K)= 0.299342D 00 RS(J,K+1)= 0.319689D 00 TS(J,K)= 0.865513D 03 TS(J,K+1)=0.763946D 03 POROS = 0.129904D 00
 H(INPUT)= 0.326231D 05 PRF(K) = 0.498760D 00 PRFOLD = 0.499291D 00 GESWF(J,K)=0.27058D-05 RHOOLD = 0.100005D 01

<u>VARIABLE</u> <u>NAME</u>	<u>VARIABLE</u> <u>DESCRIPTION</u>	<u>UNIT</u>
TIME	Total accumulated time	s
RS(J,K), RS(J,K + 1)	Fuel zone radii (J = axial section, K = radial section)	cm
TS(J,K), TS(J,K + 1)	Fuel zone boundary temperatures	°C
POROS	Fuel porosity fraction	-
H(INPUT)	Input time step	s
PRF(K)	Pore interlinkage probability fraction	-
PRFOLD	PRF(K) during the previous time step	-
GESWF(J,K)	Grain-edge gas bubble volume at beginning of time step	cm ³
RHOOLD	Ratio of current fuel density to fuel density during previous time step	-

TK= 0.1087730D 04 TGRAD= -0.4992D 04 DTDI= -0.8211D-05 TFPV= 0.2815D 14 GASII= 0.6924D 13 GDIAH= 0.1000D-02

SAVG	RAD	BDSURF	BOEVCD	BDAIOM	BVSURF	BVEVCD	BVAIOM	PEKGBY	RRGBIP
0.10000D 01	0.23930D-07	0.22438D-15	0.22442D-27	0.56294D-15	0.66874D-13	0.95259D-25	0.16777D-12	0.15849D-09	0.17872D-07
0.10000D 02	0.52490D-07	0.96928D-17	0.22442D-28	0.54466D-22	0.30487D-13	0.10953D-24	0.17132D-18	0.13764D-09	0.16593D-06
0.10000D 03	0.11739D-06	0.38746D-18	0.22442D-29	0.13467D-22	0.13632D-13	0.11246D-24	0.47382D-18	0.68519D-10	0.47058D-07
0.10000D 04	0.27243D-06	0.13357D-19	0.22442D-30	0.31225D-23	0.58740D-14	0.14056D-24	0.13732D-17	0.27749D-10	0.12596D-07
0.10000D 05	0.66309D-06	0.38060D-21	0.22442D-31	0.66657D-24	0.24134D-14	0.20268D-24	0.42267D-17	0.15312D-10	0.31305D-08
0.10000D 06	0.17040D-05	0.87271D-23	0.22442D-32	0.12949D-24	0.93913D-15	0.34395D-24	0.13934D-16	0.67772D-11	0.71496D-09
0.10000D 07	0.46097D-05	0.16295D-24	0.22442D-33	0.23009D-25	0.34715D-15	0.63095D-24	0.49019D-16	0.29591D-11	0.15083D-09
0.10000D 08	0.12183D-04	0.33394D-26	0.22442D-34	0.42570D-26	0.13135D-15	0.12572D-23	0.16744D-15	0.13943D-11	0.35103D-10

TABLE B.V (Contd.)

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
TK	Average fuel temperature	K
TGRAD	Temperature gradient across zone (J,K)	°C/cm
TFPV	Fission rate per unit volume	fissions/s/cm ³
GASIN	Fission-gas generation rate	atoms/s/cm ³
GDIAM	Grain diameter	cm
SAVG(N)	Average number of gas atoms/bubble for bubbles in size class N	-
RAD(N)	Average radius of bubbles in the Nth size class	cm
BDSURF]	Diffusion coefficient for bubble movement based on surface	cm ² /s
BDEVCD]	diffusion and evaporation-condensation mechanisms, respectively	
BDATOM	Semi-empirical/phenomenological diffusion coefficient	cm ² /s
BVSURF]	Bubble velocities based on surface diffusion and evaporation-	cm/s
BVEVCD]	condensation mechanisms, respectively	
BVATOM	Bubble velocity based on BDATOM	cm/s
PBKGBY(N)	Rate at which bubbles in the Nth size class are migrating from the grains to the grain boundaries. For N = 1, PBKGBY represents only the biased component of this migration rate [for random migration component (N = 1), see FLXGB1 and FLXGB2 below]	s ⁻¹

TABLE B.V (Contd.)

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
RRGBIP(N)	Rate at which bubbles in the Nth size class are migrating from the grain faces to the grain edges	s ⁻¹
(NPRINT = 4)		
NMAXB NMAXD NCDI NMAXG NCGBI IMAX2 FLXGB1 FLXGB2 TIMEFC FEDEN FBSAT		
8 7 6 8 8 32 0.4136D-09 0.9319D-07 0.1685D 07 0.2079D 03 0.1185D 04		
TAU= 0.326231D 05 H(ACTUAL)= 0.326231D 05 H(SUGG)= 0.598090D 05 HH= 0.660000D 05 KK= 1 IMAX1=22 DISTRIBUTIONS FOLLOW		
NMAXB	Largest index for bubble-size range	-
NMAXD	Smallest bubble-size class which will not be pinned to dislocations	-
NCDI	Largest bubble-size class pinned to dislocations	-
NMAXG	Smallest bubble-size class which will not be pinned to grain boundaries	-
NCGBI	Largest bubble-size class pinned to grain boundaries	-
IMAX2	The total number of differential equations to be solved for the region (J,K)	
FLXGB1	Rate of gas-atom migration to grain boundaries due to random diffusion with an initial concentration, C0, specified at time t = TIMEFC	s ⁻¹
FLXGB2	Total rate of gas-atom diffusion to grain boundaries due to random diffusion (includes FLXGB1)	s ⁻¹

TABLE B.V (Contd.)

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
TIMEFC	Time since last change in fission rate ($\geq 1\%$)	s
FBCN	Projected grain-face areal coverage per unit volume by bubbles	cm ⁻¹
FBSAT	Grain-face areal coverage per unit volume by bubbles required for channel formation	cm ⁻¹
TAU	Time for which integration has been completed ($\leq H(\text{INPUT})$)	s
H(ACTUAL)	Time increment completed during current call to GRASS4	s
H(SUG)	Suggested value of time increment for next call to GRASS4	s
HH	Upper limit on the value of an integration step	s
KK	Convergence flag (KK = +1 if convergence achieved, KK = -1 if convergence not achieved)	
IMAX1	Number of coupled equations for the bubble-size distribution functions to be solved for the region (J,K)	
BULK REGION 8 0.9597D 19 0.6029D 15 0.8120D 16 0.1066D 16 0.1784D 06 0.2599D-14 0.3962D-54 0.0 DSLC REGION 8 0.1807D 12 0.1281D 13 0.2230D 14 0.3001D 13 0.6120D 03 0.2893D-16 GBDY REGION 8 0.3500D 17 0.2910D 13 0.2940D 14 0.1653D 15 0.6774D 14 0.1634D 13 0.1951D 10 0.6786D-05		(NPRINT = 3.4)
BULK	Bubble densities for all size classes of unpinned bubbles in the fuel matrix	no. of bubbles/cm ³
DSLC	Bubble densities for all size classes pinned to dislocations	no. of bubbles/cm ³
GBDY	Bubble densities for all size classes pinned to grain faces	no. of bubbles/cm ³

TABLE B.V (Contd.)

(NPRINT = 2,3,4)

J	K	PG	RP	BV	BVC	BVIC	GS	GESW	HPRS
1	8	0.548833D 05	0.231424D 00	0.833443D-03	0.112672D-03	0.720771D-03	0.226997D-04	0.983360D-07	0.128000D 04

SUMATH= 0.125572D 20 FTGRJK= 0.202736D-02 GOUTJK= 0.460853D-07 GGTJK= 0.2273167D-04 BULKFR= 0.914722D 00 EGRE= 0.9202016D-07
 VOL= 0.1088960D 01 BVSB= 0.6969465D-03 BVSG= 0.133584D-03 BVSE= 0.2911556D-05 GDDYFR= 0.832902D-01 GASO= 0.5639794D 10
 GKIN= 0.3557692D 16 GKOUT= 0.177443D 16 TKOLD= 0.1087998D 04 RATIO= 0.968175D 00 EDGEFR= 0.198751D-02 EPRF= 0.0

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
J	Index for axial section	-
K	Index for radial section numbered from innermost section	-
PG	Effective surface-tension-induced pressure	psi
RP	Fraction of retained gas residing in bubbles	-
BV	Fractional fission-gas-bubble volume strain	-
BVC	Volume of gas in bubbles per unit volume of fuel	-
BVIC	Fractional gas-bubble strain due to incompressible part of bubble volume	-
GS	Gas retained	moles
GESW	$\frac{3}{4\pi}$ * volume of gas transferred to grain edges from the grain faces in time DT	cm ³
HPRS	Hydrostatic pressure	psi
SUMATH	Retained gas in the radial sections	atoms/cm ³
FTGRJK	Fractional fission-gas release from region (J,K)	-
GOUTJK	Amount of gas released from region (J,K) in time TIT	moles
GGTJK	Total gas generated in region (J,K) at time TIT	moles

TABLE B.V (Contd.)

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
BULKFR	Fraction of total retained fission gas still within grains	-
EGRE	Rate at which fission gas vents from grain faces to the grain edges owing to grain-face channel formation	s ⁻¹
VOL	Volume of fuel region (J,K)	cm ³
BVSB	Fractional gas-bubble strain due to bubbles in fuel lattice	-
BVSG	Fractional gas-bubble strain due to bubbles on grain faces	-
BVSE	Fractional gas-bubble strain due to bubbles on grain edges	-
GBDYFR	Fraction of total retained fission gas trapped on grain faces	-
GASO	Amount of gas released into central hole during time step owing to migration up the thermal gradient	moles
GKIN	Number of gas atoms transported to grain edges during time step H(Actual)	atoms
GKOUT	Number of gas atoms released from grain edges to exterior of fuel during time step H(Actual)	atoms
TKOLD	Value of TK at previous time step	K
RATIO	Fractional radius of region (J,K)	-
EDGEFR	Fraction of total retained fission gas trapped along grain edges	-

TABLE B.V (Contd.)

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
EPRF	Number of gas atoms that are released from the grain edges to the exterior of the fuel owing to an increase in the fractional grain-edge porosity interconnection probability between the current and the previous time step	atoms
(NPRINT = 3.4)		
GR(J)= 0.6402407D-06 RGTJ(J)= 0.15709D-03 BVSJ= 0.2303935D-02 BVSBJ= 0.1513212D-02 BVSGJ= 0.4105780D-03 BVSEJ= 0.3801448D-03		
(NPRINT = 2,3.4)		
GRT= 0.2500299D 01 GRFT= 0.2989863D-03 GGT= 0.8807473D-03 RGT= 0.5308998D-03 RGGL= 0.5907574D 00 RGGF= 0.5205468D-01 BVST= 0.1536076D-02 FGRDT= 0.6875271D-02 FTGR= 0.3394682D 00 TFGR= 0.0 RGGE= 0.1674127D-01 ERR= 0.9778033D-03		
***** END OF GRASS OUTPUT FOR THIS TIME STEP *****		
GR(J)	Total gas released from an axial section during one external time step, DEL	moles
RGTJ(J)	Amount of retained fission gas in axial section J	moles
BVSJ	Fractional gas-bubble strain in axial section J	-
BVSBJ	Fractional gas-bubble strain in axial section J due to bubbles retained within fuel grains	-
BVSGJ	Fractional gas-bubble strain in axial section J due to bubbles trapped on grain faces	-
BVSEJ	Fractional gas-bubble strain in axial section J due to bubbles trapped on grain edges	-

TABLE B.V (Contd.)

<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
GRT	Total free gas within the element	moles
GRFT	Total gas released from fuel at time TIT	moles
GGT	Total gas generated	moles
RGT	Total retained gas	moles
RGGL	Fraction of generated gas retained in grain lattice	-
RGGF	Fraction of generated gas trapped on grain faces	-
BVST	Fractional gas-bubble strain in fuel rod	-
FGRDT	Fractional gas release in time DELT	-
FTGR	Fractional fission gas release from fuel	-
TFGR	Amount of gas released during transient divided by the amount retained in fuel at initiation of transient	-
RGGE	Fraction of generated gas trapped in grain-edge porosity	-
ERR	Total fractional numerical error for calculation	-

TABLE B.VI. Summary of GRASS-SST Output to be Transferred to LIFE-GCFR

PG(J,K)=	0.6272D 04	0.1617D 05	0.3482D 05	0.2349D 05	0.2272D 05	0.3097D 05	0.3946D 05	0.5488D 05
0.7609D 04	0.1848D 05	0.2381D 05	0.2842D 05	0.3794D 05	0.2003D 05	0.2917D 05	0.4258D 05	
0.8329D 04	0.1685D 05	0.2138D 05	0.3980D 05	0.2466D 05	0.2369D 05	0.2423D 05	0.4249D 05	
0.2421D 04	0.8847D 04	0.1880D 05	0.3762D 05	0.2117D 05	0.2444D 05	0.3299D 05	0.4315D 05	
BVI(J,K)=	2.2766	2.2430	2.2132	2.1866	2.1632	2.1429	2.1252	2.1100
2.3681	2.3330	2.2926	2.2525	2.2123	2.1765	2.1461	2.1214	
2.3790	2.3445	2.3041	2.2643	2.2245	2.1868	2.1547	2.1280	
2.3012	2.2662	2.2348	2.2060	2.1803	2.1577	2.1331	2.1212	
RP(J,K)=	0.9633	0.8773	0.5682	0.5024	0.5365	0.5386	0.5344	0.2314
0.8215	0.6278	0.4162	0.7122	0.5816	0.6550	0.6722	0.6686	
0.8390	0.6514	0.4633	0.4873	0.7493	0.6360	0.6720	0.6695	
0.9703	0.9466	0.8309	0.4644	0.5133	0.5386	0.5379	0.5334	

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<u>VARIABLE NAME</u>	<u>VARIABLE DESCRIPTION</u>	<u>UNIT</u>
PG	Effective surface-tension-induced pressure	psi
BVI	Fuel volumetric strain due to fission-gas retention in fuel	--
RP	Fraction of retained gas residing in bubbles	--

TABLE B.VII. Time-step Information

TIME= 510.00(HRS) STEP NO.= 3 DELT= 9.062(HRS) TLEFT=3079.49			
TOT. TIME STEPS= 100 TOT. CONVERG. STEPS= 100			
TOTAL ITERATIONS (SOLVER) (ITRT(J))= 489 620 639 527 143			
<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
TIT	Time	h	Total time elapsed at this point in the fuel-rod history
IT	Step No.	-	Sequence number of the input-history card that is being processed
DELT	DELT	h	Time increment in rod lifetime for which these results were obtained
TVZJ	TLEFT	s	Computer processing time remaining to complete this problem
IHT	Time Steps	-	Total number of time steps used in the analysis up to this point in the element lifetime
KRAPH	Converg. Steps	-	Number of converged time steps
NTRT(J)	(ITRT(J))	-	Accumulated number of iterations in each axial section needed to converge stress-strain results in subroutine SOLVER

TABLE B.VIII. Descriptions of Fuel-element Environment

**FUEL ROD ENVIRONMENT

FUEL ROD AVG. POW.=10.331(KW/FT) (POW(L),L=1,NN)= 8.53 12.14 12.14 8.52 0.0
 (1+EPZ)* POW(L)= 8.62 12.28 12.29 8.62
 POWT(N),N=1,NF 0.0 0.0 0.0 0.0

FAST FLUENCE (.GT. .1MEV) (FLNC(L),L=1,NN)= 0.27542D 22 0.39226D 22 0.39226D 22 0.27542D 22 0.10015D 22
 FAST FLUX (FLUX(L),L=1,NN)= 0.15163D 16 0.21596D 16 0.21596D 16 0.15163D 16 0.55140D 15

NA TEMPS.(F), TIN= 667.0 TOUT=1000.0 NA TEMPS. AT MID SECT. (TNA(L),L=1,NN) 701.4 784.7 882.5 965.7 1000.0

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
POWAV	AVG. POW.	kW/ft	Average power of the fuel element
POW(L)	POW(L)	kW/ft	Power of each section with axial-strain adjustments
POWZ(L)	(1+EPZ)*(POW(L))	kW/ft	Power of each section neglecting total axial strain.
POWT(L)	POWT(L)	kW/ft	Power at each section that corresponds to axial-power-profile input by CLADT option (Table A.V)
FLNC(L)	FLNC(L)	n/cm ²	Fast fluence in each section
FLUX(L)	FLUX(L)	n/cm ² .s	Fast flux in each section
VEL	VEL	ft/s	Coolant velocity (defined and used only for transient calculations)
TIN	TIN	F	Coolant inlet temperature
TOUT	TOUT	F	Coolant output temperature
TNA(L)	TNA(L)	F	Temperature of the coolant at the middle of each section. TNA(L) = TOUT if CLADT option has been used

TABLE B.IX. Capsule Information

FUEL ELEMENT IS UNENCAPSULATED - or capsule data shown below:

CAPSULE O.D. (RCPO = 0.18750) TEMPS AT THE MIDDLE OF EACH SECTION FOLLOW
 700.32 701.00 701.69 702.00
 CAPSULE I.D. (RCPI = 0.16750) TEMPS AT THE MIDDLE OF EACH SECTION FOLLOW
 700.32 701.01 701.69 702.00
 CAPSULE AVERAGE TEMPERATURES, F, FOLLOW
 CAPSULE LINEAR IRRADIATION SWELLINGS FOLLOW
 0.000000 0.000000 0.000000 0.000000
 700.32 701.01 701.69 702.00
 CAPSULE LINEAR THERMAL EXPANSIONS, IN/IN, FOLLOW
 0.006291 0.006298 0.006306 0.006309

<u>VARIABLE</u>	<u>LABEL</u>	<u>UNITS</u>	<u>DESCRIPTION</u>
RCPO	RCPO	in.	Cladding capsule outside radius
TCPO(L)	O.D. TEMPS	F	Capsule outside temperatures for each section
RCPI	RCPI	in.	Capsule inside radius
TCPI(L)	I.D. TEMPS	F	Capsule inside temperatures for each section
TCP(L)	AVERAGE TEMPERATURES	F	Capsule average temperatures for each section
ATCP(L)	THERMAL EXPANSIONS	in./in.	Average linear thermal expansion for each section
SWCP(L)	SWELLINGS	in./in.	Linear irradiation swelling for each section

TABLE B.X. Cladding Thermal Information

**CLADDING THERMAL DATA (4 CLAD RINGS) CLAD. O.R. INDEX = N3+ 5 CLAD. LENGTH=100.964(IN)
RING BOUNDARIES RL6 / TEMP.(F) AT BOUNDARIES TL6 / AVG. RING THERM. EXPAN. ATBF6

AXIAL SECTION = 1

(RL6(J,M),M=N3+1,N3+ 5)= 0.12790 0.13325 0.13840 0.14336 0.14815
(TL6(J,M),M=N3+1,N3+ 5)= 967.37 951.93 937.58 924.19 911.62
(ATBF6(J,M),M=KF1,KFC)= 0.00915 0.00896 0.00880 0.00866
ACCUMULATED CLAD WASTAGE (IN) O.R. CORROSION=-0.75170-43 O.R. WEAR=-0.83840-45 I.R. ATTACK=-0.15460 39

AXIAL SECTION = 2

(RL6(J,M),M=N3+1,N3+ 5)= 0.12794 0.13229 0.13649 0.14057 0.14453
(TL6(J,M),M=N3+1,N3+ 5)= 1004.50 986.35 970.20 954.45 939.49
(ATBF6(J,M),M=KF1,KFC)= 0.00953 0.00934 0.00916 0.00898
ACCUMULATED CLAD WASTAGE (IN) O.R. CORROSION= 0.92060-71 O.R. WEAR=-0.22280-46 I.R. ATTACK=-0.16050-56

AXIAL SECTION = 3

(RL6(J,M),M=N3+1,N3+ 5)= 0.12807 0.13243 0.13664 0.14072 0.14469
(TL6(J,M),M=N3+1,N3+ 5)= 1098.05 1080.98 1064.89 1049.67 1035.23
(ATBF6(J,M),M=KF1,KFC)= 0.01060 0.01041 0.01023 0.01006
ACCUMULATED CLAD WASTAGE (IN) O.R. CORROSION= 0.37250-79 O.R. WEAR=-0.35140-55 I.R. ATTACK= 0.84560-71

AXIAL SECTION = 4

(RL6(J,M),M=N3+1,N3+ 5)= 0.12812 0.13247 0.13668 0.14077 0.14473
(TL6(J,M),M=N3+1,N3+ 5)= 1115.82 1103.92 1092.73 1082.17 1072.15
(ATBF6(J,M),M=KF1,KFC)= 0.01084 0.01070 0.01053 0.01046
ACCUMULATED CLAD WASTAGE (IN) O.R. CORROSION= 0.23470 58 O.R. WEAR=-0.35140-55 I.R. ATTACK=-0.10380 21

AXIAL SECTION = 5

(RL6(J,M),M=N3+1,N3+ 5)= 0.12799 0.13233 0.13654 0.14062 0.14458
(TL6(J,M),M=N3+1,N3+ 5)= 1000.00 1000.00 1000.00 1000.00 1000.00
(ATBF6(J,M),M=KF1,KFC)= 0.00958 0.00956 0.00953 0.00955
ACCUMULATED CLAD WASTAGE (IN) O.R. CORROSION= 0.23170-68 O.R. WEAR= 0.53100 58 I.R. ATTACK= 0.81210-78

Variable	Label	Units	Description
KC	CLAD RINGS	-	Number of cladding shells for thermal and mechanical analysis
CCL	CLAD LENGTH	in.	Current total cladding length
RL6	RL6(J, M)	in.	Shell boundary radii (equal thickness except for first cladding shell, the wastage shell)
TL6	TL6(J, M)	F	Temperatures at shell boundaries
ATBF6	ATBF6(J, M)	in./in.	Average cladding-shell thermal expansion
TWCR	CORROSION	in.	Corrosion depth at outer boundary of the cladding
TWWR	WEAR	in.	Wear depth at outer boundary of the cladding
TWAK	ATTACK	in.	Attack depth at inner boundary of the cladding

TABLE B.XI. Fuel Thermal Information

**FUEL THERMAL DATA (3 FUEL REGIONS, 8 STRUCT. RINGS, 8 THERMAL. RINGS) FUEL LENGTH= 45.031(IN)

AXIAL SECTION = 1

CONDUCTANCE (BTU/HR/F/FT**2) F-C,HG= 988.56 C-NA,HC= 1786.60 F-C GAP= 2.034(MILS)

FUEL DOES NOT MELT

FUEL CRACKS LM(J,K),K=1,KF 0 0 0 0 0 0 0 9

RHH(J,K), K=1,KF

9.7732 9.8879 9.8454 9.8304 9.8310 9.8285 9.8289 9.8280

RHO(M),M=1,KF

9.2463 9.4096 9.4114 9.4267 9.4540 9.4897 9.5233 9.5714

TBM(M), M=1,KF

3077.73 2830.73 2586.88 2346.41 2114.44 1894.63 1689.03 1498.51

ATBM(M),M=1,KF

0.01967 0.01745 0.01536 0.01340 0.01161 0.01000 0.00858 0.00733

CX3(M), M=1,KF

1.05698 1.05083 1.04611 1.04283 1.03987 1.03570 1.03209 1.02681

XI(M), M=1,3

0.00113250 0.68214423 2.34665709

RLR(M), M=1,4

0.00254107 0.00354107 0.06035897 0.12586200

TLR(M), M=1,4

3202.686 3201.934 2754.172 1407.103

RL(M),M=1,N3

0.00254 0.04502 0.06335 0.07745 0.08934 0.09979 0.10921 0.11785 0.12586

TL(M),M=1,N3

3202.69 2952.77 2708.69 2465.07 2227.76 2001.13 1788.14 1589.92 1497.10

PRSL(J,M), M=1,NT

0.136380 04 0.134610 04 0.133120 04 0.136980 04 0.143210 04 0.150120 04 0.159070 04 0.328360 03

PG(J,M), M=1,NT

0.627220 04 0.161680 05 0.348220 05 0.234860 05 0.227190 05 0.309740 05 0.394620 05 0.548830 05

PGAS(J,M), M=1,NT

0.102820 05 0.228330 05 0.713570 05 0.636240 05 0.629700 05 0.860900 05 0.114300 06 0.360340 06

FUEL POROSITY POR(M),M=1,NT

0.10221 0.09422 0.10099 0.10505 0.10752 0.10874 0.10961 0.11027

FISSION GAS POROSITY=

0.0034550.0017340.0005550.0005860.0005650.0003810.0002620.000076

SHELLING DUE TO FISSION PORE MIGRATION

0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

GRAIN SIZE (MICRONS),M=1,NT+1

44.5 29.4 18.6 12.2 10.2 10.0 10.0 10.0 10.0

TABLE B.XI (Contd.)

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
KF	STRUCT. RINGS	-	Number of cylinders the fuel is divided into for mechanical analysis
NT	THERMAL RINGS	-	Number of fuel shells used in the thermal analysis
FL	FUEL LENGTH	in.	Current total
HG	F-C, HG	Btu/h/ft ² / F	Fuel-cladding gap conductance
HC	C-NA, HC	Btu/h/ft ² / F	Cladding-coolant film heat coefficient
GAP	F-C GAP	mils	Fuel-cladding gap size used in gap-conductance calculation
	FUEL DOES NOT MELT	-	If fuel temperatures do not exceed 4950°F, this label is output
	-or-		
RMELT	RMELT	in.	Radii where specific melt temperatures occur
TMELT	TMELT	F	Temperatures (4950, 5000, 5050°F) at the melt radii
LM	FUEL CRACKS	-	Crack inventory for axial section K refers to fuel structural cylinders
RHHH	RHH (J,K)	g/cm ³	Room-temperature fuel theoretical density, corrected for remaining fabricated porosity and crack volume
RHO	RHO(M)	g/cm ³	Actual fuel density, including the effects of thermal expansion, swelling, elastic strain, and porosity migration
TB	TBM	F	Average temperature in each structural cylinder
ATB	ATBM	in./in.	Average linear thermal expansion in each structural cylinder

TABLE B.XI (Contd.)

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
CX3K	CX3	-	Deformed fuel volume/reference fuel volume
X	XM	g/cm	Mass of the fuel per unit length for the columnar, equiaxed, and undisturbed fuel regions
RL6	RLR	in.	Radial boundaries of the columnar, equiaxed, and un-restructured region boundaries
TL6	TLR	F	Temperatures at the columnar, equiaxed, and un-restructured region boundaries
F7	F(M)	-	Relative power density in the NT shells (output only when KFLX = 1 on input)
RL	RL	in.	Radial boundaries that define NT shells
TL	TL	F	Temperatures at the NT radial boundaries
PRSL	PRSL	psi	Fuel zone hydrostatic pressure
PG1	PG	psi	Effective surface-tension-induced pressure
PGAS	PGAS	psi	Fission-gas bubble pressure
POR(M)	POR(M)	-	Fuel porosity in each NT fuel shell
GSIZE	GRAIN SIZE	μ m	Grain size of the fuel at the NT boundaries of the fuel shells

TABLE B.XII. Fission Gas Information

**FISSION GAS DATA

AXIAL SECTION = 1

F.G. REMAIN. IN FUEL (MOLES) GS(J,K)= 0.1641D-04 0.1944D-04 0.2111D-04 0.2157D-04 0.2244D-04 0.2264D-04
0.2265D-04 0.2270D-04

AXIAL SECTION = 2

F.G. REMAIN. IN FUEL (MOLES) GS(J,K)= 0.1010D-06 0.8770D-07 0.1828D-06 0.4094D-05 0.3015D-04 0.3084D-04
0.3199D-04 0.3223D-04

AXIAL SECTION = 3

F.G. REMAIN. IN FUEL (MOLES) GS(J,K)= 0.8615D-07 0.6956D-07 0.1247D-06 0.8777D-06 0.2974D-04 0.3016D-04
0.3187D-04 0.3225D-04

AXIAL SECTION = 4

F.G. REMAIN. IN FUEL (MOLES) GS(J,K)= 0.8566D-05 0.1785D-04 0.1996D-04 0.2125D-04 0.2173D-04 0.2249D-04
0.2261D-04 0.2263D-04

CUMULATIVE F.G. RELEASE (MOLES) TOGAS-GASI-XE = 0.2990D-03= 33.980 PCT. OF TOT.F.G. GENERATED= 0.8799D-03 0.8807D-03

PLENUM PRESSURE= 1280.000(Psia) GAS COMPOSITION= 0.012 PERCENT FISSION GAS

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
GS(J, K)	GS(J, K)	mol	Amount of fission gas retained in each structural cylinder of the fuel
X	TOGAS-GASI-XE	mol	Fission gas released from fuel
YP	PERCENT		Percentage of generated fission gas that is released from fuel
PLPR	PLENUM PRESSURE	psia	Plenum pressure
XPG	GAS COMPOSITION		Percentage of fission gas in total gas

TABLE B.XIII. Stress-Strain Results

SECTION=1 TIME= 510.0 DELT= 9.062 *** STRESS,STRAIN RESULTS FROM MECHANICAL ANALYSIS ***

POWER= 8.532(KW/FT) BURNUP= 0.237(A/O) MAX CLAD DMG(0)= 0.0 (PCT) GAP STATUS= 0 (0=OPEN,POS=STICK,NEG=SLIP)

FUEL-CLAD GAP= 2.034(MILS) XPR(KF1)-PLPR= 0.0 (PSI) CLAD O.D. CHANGE= 0.88858(PERCENT)

K = 1 2 3 4 5 6 7 8 ** ** *

** RING BOUNDARY INTERFACE PRESSURES,XPR

1280.0	1359.8	1353.2	1346.9	1350.7	1361.6	1376.5	1395.3	1280.0	1537.9	1592.9	1494.4

1280.0

STRESSES RADIAL SIGR / CIRC. SIGC / AXIAL SIGZ

-1358.6	-1355.8	-1349.6	-1349.0	-1355.6	-1369.5	-1386.4	-1335.1	-1412.5	-1556.1	-1542.5	-1384.9
-1361.5	-1337.2	-1318.9	-1375.0	-1455.3	-1534.0	-1632.7	415.7	-7696.2	-3016.6	1253.1	5132.5
-1368.2	-1346.9	-1327.1	-1387.4	-1486.3	-1601.5	-1754.4	-65.7	-7850.5	-3330.0	961.2	4997.3

HYDROSTATIC PRESSURE, CPRS(K)

1362.8	1346.6	1331.9	1370.5	1432.7	1501.7	1591.2	328.4	5653.0	2637.6	-223.9	-2915.0

EQUIVALENT SHEAR STRESS

8.5	16.1	27.6	34.0	117.4	206.6	324.7	1566.6	6362.2	1629.9	2661.7	6450.8

TOTAL STRAINS RADIAL EPR / CIRC. EPC / AXIAL EPZ

2.269D-02	1.744D-02	1.419D-02	1.212D-02	1.021D-02	7.097D-03	4.516D-03	3.350D-04	9.347D-03	8.992D-03	8.678D-03	8.395D-03
2.201D-02	2.142D-02	2.017D-02	1.909D-02	1.816D-02	1.726D-02	1.634D-02	1.539D-02	8.874D-03	8.825D-03	8.833D-03	8.872D-03
1.080D-02	1.080D-02	1.080D-02	1.080D-02	1.080D-02	1.080D-02	1.080D-02	1.080D-02	8.862D-03	8.862D-03	8.862D-03	8.862D-03

INCREMENT. CREEP STRAINS RADIAL DPR / CIRC. DPC / AXIAL DPZ

6.253D-06	7.691D-06	9.186D-06	6.085D-06	1.206D-05	1.289D-05	1.357D-05	5.653D-05	1.304D-06	3.097D-07	5.040D-07	1.219D-06
1.757D-06	7.948D-06	6.698D-06	1.341D-06	3.593D-06	3.164D-06	2.761D-06	4.178D-05	6.282D-07	1.096D-07	2.936D-07	6.286D-07
-8.011D-06	-2.571D-07	2.489D-06	4.744D-06	8.466D-06	9.722D-06	1.081D-05	1.475D-05	6.756D-07	2.002D-07	2.103D-07	5.902D-07

TOTAL CREEP STRAINS RADIAL TPR / CIRC. TPC / AXIAL TPZ

4.189D-03	8.865D-04	8.633D-03	2.850D-03	6.050D-03	6.050D-03	7.791D-05	1.837D-05	3.035D-05	7.344D-05	3.510D-03	4.867D-03
3.510D-03	4.867D-03	5.117D-03	5.086D-03	5.104D-03	5.541D-03	5.795D-03	5.139D-03	3.754D-05	6.497D-06	1.765D-05	3.785D-05
-7.699D-03	5.753D-03	4.254D-03	3.203D-03	2.254D-03	9.129D-04	2.552D-04	1.458D-03	4.037D-05	1.188D-05	1.270D-05	3.559D-05

THERM. COMP. OF TOT. CREEP STRAINS RADIAL THTPR / CIRC. THTPC / AXIAL THTPZ

2.384D-04	6.760D-04	1.378D-04	9.952D-05	6.145D-06	3.010D-05	4.790D-06	3.074D-07	5.487D-06	3.276D-07	3.590D-07	7.350D-07
1.920D-03	2.009D-03	1.341D-03	6.431D-04	1.959D-04	4.362D-05	4.390D-06	1.998D-07	2.644D-06	1.159D-07	2.088D-07	3.783D-07
-4.304D-03	-2.685D-03	-1.479D-03	7.426D-04	-2.021D-04	-1.352D-05	3.998D-07	1.076D-07	-2.843D-06	-2.118D-07	1.502D-07	3.562D-07

INCREMENTAL LINEAR SWELLING, DSR(J,K)

1.553D-05	6.488D-06	2.477D-06	8.944D-06	1.206D-05	1.275D-05	1.334D-05	1.592D-05	3.092D-11	2.730D-11	2.431D-11	2.184D-11

TOTAL LINEAR SWELLING, TSR(J,K)

-1.140D-03	-8.636D-04	-2.744D-04	6.334D-04	1.476D-03	1.746D-03	2.008D-03	2.135D-03	1.325D-09	1.170D-09	1.042D-09	9.365D-10

SWS6(J,K)/3 / EHP6(J,K)/3 / TSR=(SWS6+EHP6)/3 / EGS6(J,K)/3 / EGS6K(J,K)/3

6.317D-04	6.356D-04	6.342D-04	6.337D-04	6.338D-04	6.335D-04	6.337D-04	6.336D-04	6.337D-04	6.336D-04	6.337D-04	6.336D-04
-3.107D-03	-2.293D-03	-1.324D-03	4.280D-04	4.151D-04	7.465D-04	1.050D-03	1.240D-03	1.355D-03	7.941D-04	4.159D-04	4.278D-04
1.355D-03	7.941D-04	4.159D-04	4.278D-04	4.274D-04	3.660D-04	3.246D-04	2.613D-04	1.152D-03	5.778D-04	1.852D-04	1.952D-04
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

THERMAL CREEP STRAIN, EPSOL/ ACCUM. CREEP STRAIN, TEQEP

8.622D-03	7.584D-03	6.696D-03	6.808D-03	6.565D-03	6.998D-03	6.745D-03	5.514D-03	5.489D-06	3.323D-07	3.606D-07	7.351D-07
8.622D-03	7.584D-03	6.696D-03	6.808D-03	6.565D-03	6.998D-03	6.745D-03	5.514D-03	7.793D-05	1.864D-05	3.048D-05	7.345D-05

STRESS-AFFECTED CLAD SWEL. TSAS / CLAD CREEP DUE TO SWEL, TSAIC

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.168D-10	1.382D-10	2.030D-10	4.410D-10								

RADIAL DISPLACEMENTS OF BOUNDARIES, UDISP(J,K)

-5.498D-06	9.911D-04	1.307D-03	1.506D-03	1.649D-03	1.755D-03	1.821D-03	1.860D-03	1.863D-03	1.126D-03	1.176D-03	1.222D-03
1.265D-03	1.305D-03										

STRUCTURAL RING BOUNDARIES, XRR(J,K)+UDISP(J,K)

0.0025606	0.0450279	0.0633515	0.0774527	0.0893376	0.0997826	0.102103	0.1178519	0.1258625	0.1278964	0.1332526	0.1384000
0.1433612	0.1481549										

TABLE B.XIII (Contd.)

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
J	SECTION	-	Axial section number
TIT	TIME	h	Total time elapsed in the fuel-rod history
DELT	DELT	h	Time increment used to produce converged results
POWL	POWER	kW/ft	Power for this section
BU1	BURNUP	at. %	Burnup for this section
DMG1	MAX CLAD DMG	%	Maximum cladding-damage fraction
L	DMG( )	-	Cladding shell (starting from inner surface of cladding where maximum cladding damage occurred)
IRW	GAP STATUS	-	Indicator for fuel-cladding gap
GAPMIL	GAP	mil	Fuel-cladding gap size
FLPUSU	XPR(KF1)-PLPR	psi	Difference between fuel-cladding interface and plenum pressures
DDODA	CLAD O.D. CHANGE	%	Percent change of cladding diameter based on original cold dimension
XPR	INTERFACE PRESSURES	psi	Interface pressures at the fuel and cladding structural-cylinder boundaries
SIGR SIGC SIGZ	STRESSES	psi	Average stresses in each fuel and cladding structure cylinder
CPRS	HYDROSTATIC PRESSURE	psi	$-\frac{1}{3}(\sigma_r + \sigma_\theta + \sigma_z)$

TABLE B.XIII (Contd.)

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
EQS	EQUIVALENT SHEAR STRESS	psi	$\left(\frac{1}{2}\right)^{1/2} [(\sigma_r - \sigma_\theta)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_\theta - \sigma_z)^2]^{1/2}$
EPR EPC EPZ	TOTAL STRAINS	in./in.	Total strain = $\epsilon_{\text{elastic}} + \alpha T + \epsilon_{\text{creep}} + \epsilon_{\text{swelling}}$
DPR DPC DPZ	INCREMENT CREEP STRAINS	in./in.	Incremental creep strains during the time DELT
TPR TPC TPZ	TOTAL CREEP STRAINS	in./in.	Total creep strains
THTPR THTPC THTPZ	THERMAL COMP. TOTAL CREEP STRAINS	in./in.	Thermal creep strains
DSR	INCREMENTAL LINEAR SWELLING	in./in.	Incremental linear swelling during the time DELT
TSR	TOTAL LINEAL SWELLING	in./in.	Total linear swelling
SWZ	SWS6	in./in.	Solid fission-product contribution to swelling
HPR	EHP6	in./in.	Hot-pressing contribution to swelling
FGS	TSR-(SWS6+EHP6)/3	in./in.	Total fission-gas swelling
EGSK	EGSK	in./in.	Swelling due to fission-gas bubbles based on ideal gas law
EGSMK	EGSMK	in./in.	Swelling due to fission-gas porosity migration

TABLE B.XIII (Contd.)

<u>Variable</u>	<u>Label</u>	<u>Units</u>	<u>Description</u>
EPSOL	THERMAL CREEP STRAIN	in./in.	Fuel and cladding thermal-equivalent creep strain
TEQEP	ACCUM CREEP STRAIN	in./in.	Total fuel and cladding equivalent creep strain
TSAS	STRESS-AFFECTED CLAD SWELL	in./in.	Stress-affected cladding swelling
TSAIC	CLAD CREEP DUE TO SWELL	in./in.	Equivalent cladding strain due to swelling effects on irradiation creep
UDISP	RADIAL DISPLACEMENTS OF BOUNDARIES	in.	Boundary displacements of the fuel and cladding cylinders
RL	RING BOUNDARIES	in.	Boundaries of the structural cylinders at the conclusion of the mechanical analysis

TABLE B.XIV. Cladding-damage Information

AX.SECT.	TYPE	CLAD-LIFE FRACT. K=KF1,KFC			
1	1	0.5340-10	0.1510-12	0.1960-14	0.3740-12
1	2	0.1430-03	0.8560-05	0.5450-05	0.1920-04
2	1	0.9990-09	0.2730-11	0.3580-13	0.6390-11
2	2	0.8770-03	0.5450-04	0.2600-04	0.1110-03
3	1	0.6850-07	0.1110-03	0.2330-11	0.9230-09
3	2	0.2120-01	0.3610-02	0.1040-02	0.4200-02
4	1	0.4200-07	0.1310-03	0.4730-12	0.5430-09
4	2	0.1910-01	0.3890-02	0.1720-02	0.5170-02

<u>Variable</u>	<u>Label</u>	<u>Unit</u>	<u>Description</u>
J	AX.SECT.	-	Axial section number
ITYPE	TYPE	--	1 : Cladding-damage calculation based on a time-fraction criterion 2 : Cladding-damage calculation based on thermal-creep-strain limit
DMG	CLAD-LIFE FRACT.	-	Cladding damage fraction
K	K	-	Cladding mechanical ring number

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REFERENCES

1. *Gas-Cooled Fast Breeder Reactor Preliminary Safety Information Document*, General Atomic Company Report GA-10298, Vol. 1 (Feb 1971).
2. G. Meleese-d'Hospital and R. H. Simon, *Status of Gas-Cooled Fast Breeder Reactor Programs*, Nucl. Eng. Des. 40, 5 (1977).
3. A. R. Veca, H. J. Snyder, P. Rau, and M. Peehs, *Fuel Elements Design for the 300-MW(e) Gas Cooled Fast-Breeder Reactor*, Nucl. Eng. Des. 40, 81 (1977).
4. A. W. Longest and J. A. Conlin, *Results from Irradiation of Vented GCFR Fuel Rods in the GB-9 and GB-10 Capsule Experiments*, Oak Ridge National Laboratory Report ORNL-5258 (Sept 1978).
5. R. V. Strain and C. E. Johnson, *Postirradiation Examinations of Fuel Pins from the GCFR F-1 Series of Mixed-oxide Fuel Pins at 5.5% Burnup*, Argonne National Laboratory Report ANL-76-129 (May 1978).
6. S. Greenberg and T. S. Hsieh, *ANL Fast-flux (EBR-II) Series F-5, Reactor Development Program Progress Report*, Argonne National Laboratory Report ANL-RDP-90, p. 5.1 (Dec 1979).
7. W. Jung and W. Krug, *Gas-Cooled Fast Breeder Reactor Fuel Bundle Irradiations in the BR2 Helium Loop*, Nucl. Eng. Des. 40, 157 (1977).
8. V. Z. Jankus and R. W. Weeks, *LIFE-I, a FORTRAN-IV Computer Code for the Prediction of Fast Reactor Fuel-Element Behavior*, Argonne National Laboratory Report ANL-7736 (Nov 1970).
9. R. R. Sherry and D. B. Atcheson, *Users Manual for the BEHAVE-SST*, General Electric Co. Report GEFR-00001 (Feb 1977).
10. J. B. Newman, J. F. Giovengo, and L. P. Comden, *The CYGRO-4 Fuel Rod Analysis Computer Program*, Nucl. Eng. Des. 46, 1 (1978).
11. K. Lassmann, *URANUS-A Computer Programme for the Thermal and Mechanical Analysis of the Fuel Rods in a Nuclear Reactor*, Nucl. Eng. Des. 45, 325 (1978).
12. P. Verbeek, H. Tobbe, N. Hoppe, and B. Steinmetz, *Liquid-Metal Fast Breeder Reactor Fuel Rod Performance and Modeling at High Burnup*, Nucl. Technol. 39, 167 (1978).
13. D. S. Dutt and R. B. Baker, *SIEX--a Correlated Code for the Prediction of Liquid Metal Fast Breeder Reactor (LMFBR) Fuel Thermal Performance*, Hanford Engineering Development Laboratory Report HEDL-TME 74-55 (June 1975).
14. M. C. Billone et al., *LIFE-III Fuel Element Performance Code*, ERDA Report ERDA-77-56 (July 1977).
15. *Gas-Cooled Fast Breeder Reactor Quarterly Progress Report for the Period February 1, 1976 through April 30, 1976*, General Atomic Company Report GA-A13868 (May 1976).

16. Reference 10 and M. C. Billone, Argonne National Laboratory, unpublished information (1977).
17. *GCFR Upflow/Downflow Study Summary Report*, General Atomic Company Report GA-A15455 (Aug 1979).
18. F. A. Nichols, *Behavior of Gaseous Fission Products in Oxide Fuel Elements*, Westinghouse Advanced Reactor Division Report WARD-TM-570 (Oct 1966).
19. D. R. Olander, *Fundamental Aspects of Nuclear Reactor Fuel Elements*, Hanford Engineering Development Laboratory Report TID-26711-pl, pp. 199-202 (1976).
20. R. E. Stoller, *Modeling Fission Gas Release and Retention in Fuel and Blanket Pins*, Proc. Core Components Working Group Information Meeting, Richland, Washington, May 13-15, 1980, HEDL Report TC-1711, Vol. 2, p. 306 (1980).
21. J. Rest, *GRASS-SST: A Comprehensive, Mechanistic Model for the Prediction of Fission-gas Behavior in UO₂-Base Fuels During Steady-State and Transient Conditions*, Argonne National Laboratory Report ANL-78-53 (June 1978).
22. R. J. Campana, *Pressure Equalization System for Gas-Cooled Fast Breeder Reactor Fuel Elements*, Nucl. Technol. 12, 185 (1971).
23. B. D. Epstein, *A Review of the Literature Pertinent to Fission-Product Migration and Interaction in Fuel Rods*, General Atomic Company Report GA-A13423 (June 1975).
24. M. V. Speight and G. W. Greenwood, *Grain Boundary Mobility and Its Effects in Materials Containing Inert Gas*, Phil. Mag. 9, 683 (1964).
25. T. C. Hsieh, J. Rest, and M. C. Billone, *Fuel Performance Code Development*, Reactor Development Program Progress Report, Argonne National Laboratory Report ANL-RDP-97, p. 5.1 (July 1980).
26. J. T. A. Roberts et al., *Development of a Mechanical Model of In-Reactor Fuel Behavior: Status Report*, Argonne National Laboratory Report ANL-8028 (July 1973).
27. A. A. Solomon, *Relationship Between Primary and Steady-State Creep of UO₂ at Elevated Temperature and Under Neutron Irradiation*, Deformation of Ceramic Materials, R. C. Brandt and R. E. Tressler, Eds., Plenum Publ. Corp., New York, p. 313 (1975).
28. J. T. A. Roberts and B. J. Wrona, *Crack Healing in UO₂*, J. Am. Ceram. Soc. 56(6), 297 (1973).
29. D. Brucklacher and W. Dienst, *Creep Behavior of Ceramic Nuclear Fuels under Neutron Irradiation*, J. Nucl. Mater. 42, 285 (1972).
30. F. Anselin, *The Role of Fission Products in the Swelling of Irradiated UO₂ and (U,Pu)O₂ Fuel*, General Electric Co. Report GEAP-5583 (Jan 1969).

31. *MATPRO-VERSION 10: A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior*, Nuclear Regulatory Commission Report TREE-NUREG-1180 (Feb 1978).
32. *Nuclear Systems Materials Handbook*, Hanford Engineering Development Laboratory Report TID-26666, Vol. 1 (1978).
33. H. R. Warner and F. A. Nichols, *A Statistical Fuel Swelling and Fission Gas Release Model*, Nucl. Appl. Technol. 9, 148 (1970).
34. E. E. Gruber, *Calculation of Transient Fission-Gas Release from Oxide Fuels*, Argonne National Laboratory Report ANL-8143 (Nov 1974).
35. M. H. Wood and J. R. Matthews, *A Simple Operational Gas Release and Swelling Model*, J. Nucl. Mater. 91, 35 (1980).
36. S. M. Gehl, M. G. Seitz, L. R. Kelman, and J. Rest, *Relationship Between Fission-Gas Release and Microstructural Change During Transient Heating of Pressurized Water Reactor Fuel*, Proc. ANS Topical Mtg. on Thermal Reactor Safety, 1977, CONF-770708, Vol. 3, pp. 3-261 to 3-282.
37. R. O. Meyer, C. E. Beyer, and J. C. Voglewede, *Fission Gas Release from Fuel at High Burnup*, Nuclear Regulatory Commission Report NUREG-0418 (Mar 1978).
38. W. R. Smalley, *Evaluation of Saxton Core III Fuel Materials Performance*, Westinghouse Report WCAP-3385-57 (July 1974).
39. T. R. England and R. E. Schenter, *ENDF/B-4 Fission-Product Files: Summary of Major Nuclide Data*, Los Alamos Scientific Laboratory Report LA-6116-MS (Oct 1975).
40. S. Greenberg and T-C. S. Hsieh, *ANL Fast-flux (EBR-II) Series F-5*, Reactor Development Program Progress Report, Argonne National Laboratory Report ANL-RDP-95, p. 5.1 (May 1980).
41. Reference 32, Property Code 4203.
42. F. A. Nichols, *Theory of Grain Growth in Porous Compacts*, J. Appl. Phys. 37, 4599 (1966).
43. C. S. Olsen, *UO₂ Pore Migration and Grain Growth Kinetics*, Trans. 5th Intl. Conf. on Structural Mechanics in Reactor Technology Berlin, W. Germany, Aug 13-17, 1979, T. A. Jaeger and B. A. Boley, Eds., North-Holland Publ. Co., Amsterdam, Vol. C, paper C 1/9.
44. J. B. Ainscough, B. W. Oldfield, and J. O. Ware, *Isothermal Grain Growth Kinetics in Sintered UO₂ Pellets*, J. Nucl. Mater. 49, 117 (1973-1974).
45. R. J. Campana et al., *Interdiffusion of Krypton and Xenon in High Pressure Helium*, Presented at Intl. Symp. on Thermodynamics of Nuclear Materials, Jülich, W. Germany, Jan 29-Feb 2, 1979.
46. G. K. Leaf et al., *DISPL: A Software Package for One and Two Spatially Dimensioned Kinetics-Diffusion Problems*, Argonne National Laboratory Report ANL-77-12 (Nov 1978).

47. M. G. Adamson, *Transport and Reactions of Cesium Fission Products in Oxide Fuel Rods*, Am. Ceram. Soc. Bull. 55, 819 (1976).
48. J. B. Ainscough and F. Rigby, *Measurements of Crack Sintering Rates in UO₂ Pellets*, J. Nucl. Mater. 47, 246 (1973).
49. W. S. Lovejoy and S. K. Evans, *A Crack Healing Correlation Predicting Recovery of Fracture Strength in LMFBR Fuel*, Trans. Am. Nucl. Soc. 23, 174 (1976).
50. *Reference Fuel Studies Annual Report, February 1976-January 1977*, General Electric Co. Report GEFR-00076 (Feb 1977).
51. J. F. Bates and M. K. Korenko, *Updated Design Equation for Swelling of 20% CW AISI 316 SS*, Hanford Engineering Development Laboratory Report HEDL-TME 78-3 (Jan 1978).
52. Y. Y. Liu, T. C. Hsieh, and M. C. Billone, *Calculating of Stresses in GCFR Cladding under Normal Operating Conditions*, Argonne National Laboratory Report ANL-79-58 (Nov 1979).
53. R. J. Campana, General Atomic Company, personal communication.
54. M. C. Billone and V. Z. Jankus, *Benchmark Testing of the Structural Analysis in the LIFE-II Fast-Reactor Fuel Element Code*, Argonne National Laboratory Report ANL-8091 (Jan 1974).
55. R. V. Strain, C. W. Renfro, and L. A. Neimark, *Postirradiation Examinations of the GB-9 Element*, Argonne National Laboratory Report ANL-8067 (Oct 1976).
56. S. Greenberg, *Examination of General Atomic Fast-flux (EBR-II) Series F-1*, Reactor Development Program Progress Report, Argonne National Laboratory Report ANL-RDP-84, p. 6.1 (June 1979).
57. M. C. Billone, *UNCLE-T, A Computer Code for the Analysis of Steady-State and Transient Performance of (U,Pu)C and (U,Pu)N Fuels*, Argonne National Laboratory Report ANL-AFP-79 (Oct 1979).
58. L. J. Siefken et al., *FRAP-T5--A Computer Code for the Transient Analysis of Oxide Fuel Rods*, EG&G Report CDAP-TR-79-043 (Nov 1979).
59. T. S. Roth, B. E. Sundquist, and A. Biancheria, *Status of the LIFE-4 Codes*, Ref. 20, Vol. 1, p. 286.
60. J. Rest and S. Gehl, *The Mechanistic Prediction of Fission-Gas Behavior During In-Cell Transient Heating Tests on LWR Fuel Using the GRASS-SST and FASTGRASS Computer Codes*, Ref. 43, paper C 1/6.
61. K. R. Greene and J. Rest, *Modeling of Fuel/Fission-product Behavior, Light-Water-Reactor Safety Research Program: Quarterly Progress Report, April-June 1980*, Argonne National Laboratory Report NUREG/CR-1801, ANL-80-107, pp. 1-26 (Oct 1980).

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