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The SAS4A/SASSYS-1 Safety Analysis Code System

Nuclear Engineering Division

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The SAS4A/SASSYS-1 Safety Analysis Code System

Chapter 9:
DEFORM-5: Metallic Fuel Cladding Transient Behavior Model

K. J. Miles
Nuclear Engineering Division
Argonne National Laboratory

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NOMENCLATURE

Symbol	Definition	Units
A	Variable or constant in TDC-2 correlation	-
B	Variable or constant in TDC-2 correlation	-
C	Variable or constant in TDC-2 correlation	-
D	Constant in TDC-2 correlation	-
E	Constant in TDC-2 correlation	-
F	Constant in TDC-2 correlation	-
m	Stress exponent	-
P	Internal fuel element pressure	Pa
P_{ch}	Coolant channel pressure	Pa
Q/R	Creep activation temperature	K
Q_1	Constant in TDC-2 correlation	-
$\dot{r}$	Penetration rate	m/s
t_r	Time to rupture in TDC-2 correlation	hrs,s
T	Cladding temperature	K
$\dot{T}$	Temperature rate of change	K/s
TI	Irradiation temperature in TDC-2 correlation	K
$\dot{\epsilon}$	Equivalent strain rate	1/s
$\dot{\epsilon}_{oos}$	Material constant	1/s
θ	Variable in TDC-2 correlation	
σ	Equivalent stress	Pa
σ	Hoop stress in TDC-2 correlation	MPa
σ_{so}	Saturation stress	Pa

NOMENCLATURE (Cont'd)

Symbol	Definition	Units
σ_θ	Hoop stress	Pa
σ^*	Fitting coefficient in TDC-2 correlation	MPa
ϕt	Fast fluence in TDC-2 correlation	$10^{22} n/cm^2$

9.0 DEFORM-5: METALLIC FUEL CLADDING TRANSIENT BEHAVIOR MODEL

9.1 Introduction

The objective of the DEFORM-5 [9-1] model is to provide a predictive capability to quantify 1) margin to cladding failure, and 2) cladding failure timing and location in stainless steel-clad metallic fuel pins. It performs this function by using the current understanding of metallic fuel operating behavior and failure mechanisms in the form of mathematical formulations to model the relevant physical phenomena. (For a review of observed metallic fuel irradiation performance, see Ref. 9-2). In the DEFORM-5 model, calculated cladding mechanical response to transient thermal and pressure loading conditions is compared to expected failure characteristics and criteria to yield quantified measures of margin to failure, failure time, and failure location. DEFORM-5 applicability is focused on irradiated metallic fuel, in which the fuel has swollen into contact with the cladding.

9.2 Model Formulation

9.2.1 Fission Gas

Reference 9-2 reviews the current understanding of fission gas generation, release, and transport in metallic fuel. DEFORM-5 does not currently model steady-state fission gas generation and migration, but assumes that an independent assessment has been made to determine the fission gas content in the fuel element at the initial steady-state. The fission gas inventory is specified as input in the form of a axially-uniform fuel element pressure at the SAS4A/SASSYS-1 initial reference temperature. The steady-state fission gas mass is then calculated from plenum and available pore volumes using the ideal gas law. Transient fuel element and internal fuel pressures are calculated using the calculated fission gas mass and the transient temperatures in the ideal gas formulation.

9.2.2 Fuel/Cladding Eutectic Alloy Formation

Uranium- and uranium/plutonium-based metallic fuels interact chemically with iron-based cladding to form low-melting-point eutectic alloys. For typical metallic fuel element geometry and for the transient sequences analyzed with SAS4A/SASSYS-1, the impact of this phenomena is to form a molten region at the fuel/cladding interface if the fuel is contacting the cladding, if the contact temperature has been raised to a sufficient level to cause eutectic alloy formation, and if the contact temperature has been held at the elevated level long enough to form the eutectic alloy, given the formation rate at that temperature. Figure 9.2-1 shows a binary phase diagram for uranium and iron [9-3]. This diagram shows that in equilibrium, liquid material may be formed at a temperature as low as 725°C for an alloy that is 89 wt. % uranium.

In SAS4A/SASSYS-1 analyses, where the fuel/cladding behavior model is concerned mainly with predicting margin to cladding failure, cladding failure time, and cladding failure location, the primary importance of eutectic alloy formation at the fuel cladding interface is an effective thinning of the cladding, and a lessening of its ability to contain the internal, hydrostatic pressure due to released fission gas. To quantify the cladding thinning in DEFORM-5, the correlation developed by Bauer [9-4] for the eutectic penetration rate as a function of absolute temperature is used. This correlation is

$$\dot{r} = 1 \times 10^{-6} \exp\left[22.847 - 27624/T\right] , \tag{9.2-1}$$

except in the range 1353 K (1080°C) to 1506 K (1233°C) where

$$\dot{r} = 1 \times 10^{-6} \left[922 + 2.9265\,(T-1388) - 0.21522\,(T-1388)^2 + 0.0011338\,(T-1388)^3\right] , \tag{9.2-2}$$

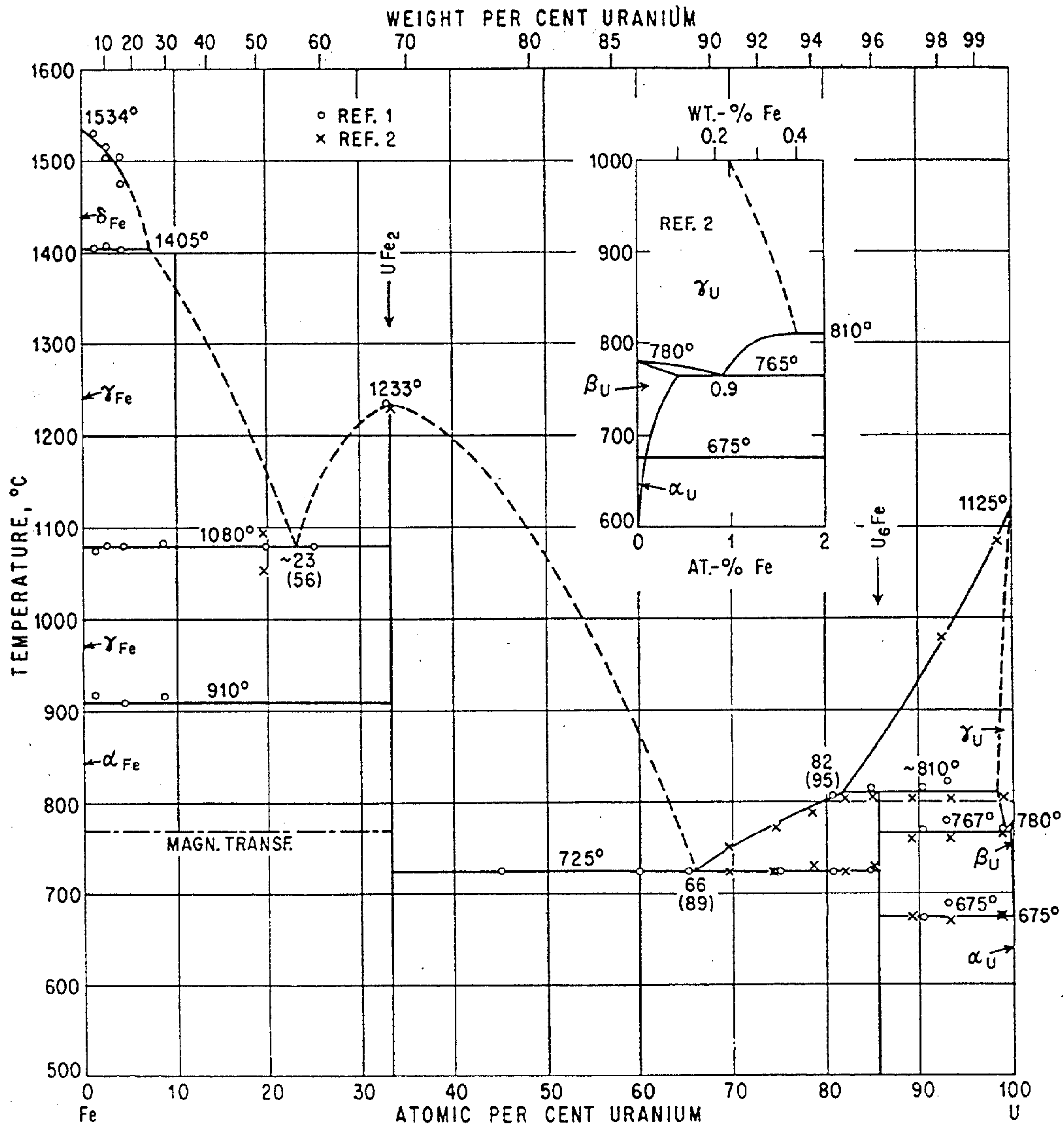

Fig. 9.2-1. Uranium-Iron Phase Diagram [9-3].

where $\dot{r}$ is the eutectic penetration rate in m/s, and T is the absolute temperature in Kelvins. This correlation is based on 1) tests in which iron capsules were dipped into molten uranium and uranium/iron alloy baths [9-5], 2) tests of EBR-II Mark-II driver fuel [9-6,9-7,9-8], and 3) tests of ternary alloy fuel (U-19Pu-10Zr) clad with stainless steel (D9) [9-4]. Waltar and Kelman [9-5] associated the rate increase in the range from 1353 K to 1506 K with the formation characteristics of the compound UFe_2. Equation 9.2-1 is used in DEFORM-5 to calculate the cladding penetration as a function of time and the effective cladding thickness at each axial location and in each SAS4A/SASSYS-1 channel.

9.2.3 Cladding Strain

In DEFORM-5, a calculation of the cladding strain is performed to provide input to the cladding failure assessment. The basic approach adopted for calculating cladding strain is that developed by DiMelfi and Kramer [9-9,9-10] in their studies on plastic flow in steel cladding, and implemented in the FPIN2 computer code (see Section 11.3.6). The hoop stress in the cladding, σ_θ, is determined for a thin shell under internal pressure loading:

$$\sigma_\theta = \left[P - P_{ch}\right] \frac{a}{h} \tag{9.2-3}$$

where P is the internal pressure, P_{ch} is the coolant channel pressure, a is the inner cladding radius, and h is the cladding thickness. Assuming the hydrostatic loading of a thin, cylindrical shell, the hoop stress is converted to an equivalent stress:

$$\sigma = \frac{\sqrt{3}}{2} \sigma_\theta \tag{9.2-4}$$

and this stress is then used in the flow equation developed by DiMelfi and Kramer:

$$\dot{\epsilon} = \dot{\epsilon}_{oos} \left[\frac{\sigma}{\sigma_{so}} \right]^m \exp(-Q/RT) \; , \tag{9.2-5}$$

where $\dot{\epsilon}$ is the equivalent strain rate, $\dot{\epsilon}_{oos}$ is a material constant, σ is the equivalent stress, σ_{so} is the saturation stress, m is the stress exponent, Q/R is the creep activation temperature, and T is the absolute steel temperature.

This formulation was chosen because it allows the use of the same model for all cladding types of interest. Through the use of appropriate cladding parameters, SS316, D9, and HT-9 can all be modeled within the DEFORM-5 context. (In the absence of data, the following parameters for SS 316 are used for D9).

For type 316 stainless steel, Kramer and coworkers [9-11] derived the following parameters:

m	=	5.35
Q/R	=	38,533 K
$\dot{\epsilon}_{oos}$	=	1.062×10^{14} s^{-1}
σ_{so}	=	(2000 - 9.12T) (92,000-40.2T) Pa

For type HT-9 stainless steel, Kramer and coworkers [9-12] derived the following parameters:

m	=	2.263
Q/R	=	36,739 K
$\dot{\epsilon}_{oos}$	=	5.1966×10^{10} s^{-1}
σ_{so}	=	$3.956 \times 10^{-3} \times 2.12 \times 10^{11} (1.144 - 4.856 \times 10^{-4}T)$ Pa

9.2.4 Cladding Failure

The determination of cladding breach, or margin to cladding breach, is based on the eutectic thinning of the cladding and the reduced ability to contain the internal pressure. Besides the eutectic thinning, the cladding wall thickness is reduced as plastic flow takes place. Different accident scenarios and pin conditions lead to different modes of breach, whether through cladding penetration or plastic strain or a combination.

In the DEFORM-5 calculation, the time-dependent cladding damage fraction is calculated based on the time remaining to breach, following Kramer and DiMelfi's assessment [9-13] of the TDC-2 transient damage correlation for cold-worked 316 (and also for D9) stainless steel fuel pin cladding [9-14]:

$$\ln t_r = A + B \ln \ln \left[\frac{\sigma^*}{\sigma}\right] + \frac{Q_1}{T} + \mathrm{TRAMP} + C \tanh \phi t \tag{9.2-6}$$

where

t_r = time to rupture, hours

A = -43.06

B = 7.312

C = -1.73

Q_1 = 41339

D = 1000

E = 200

F = 0.438

$$\sigma^* = 775 - \left[387.5 - 387.5 \tanh\left[\frac{D-TI}{E}\right]\right] \tanh\left[\frac{\phi t}{2.0}\right] + 125 \left[\tanh\left[\frac{\sigma}{550}\right]^{10}\right] \left[1-\tanh\left[\frac{TI}{583} - F\right]^{25}\right] \left[\tanh\left[\frac{\phi t}{2.5}\right]\right]$$

TRAMP	=	$-0.28 + 1.18 \tanh\{-0.5\,[(\ln \dot{T}) - 1]\}$
σ	=	hoop stress, MPa (use thin wall formula with midwall tube diameter)
ϕt	=	fluence n/cm^2, $E > 0.1$ MeV, X10^{22}
T	=	transient temperature, K
TI	=	steady-state irradiation temperature, K
$\dot{T}$	=	transient temerature ramp rate, K/sec

In DEFORM-5, the fast fluence is calculated from the input local linear power, the channel flux-to-power ratio, and number of full-power days of steady-state irradiation.

For HT-9, the time remaining to breach is assumed to be given by [9-15]:

$$t_r = \theta \exp[Q/RT] , \qquad (9.2\text{-}7)$$

where

t_r	=	time to rupture, seconds
$\ln \theta$	=	$A + B \ln \ln \left[\dfrac{\sigma^*}{\sigma}\right]$
A	=	$-34.8 + \tanh\left[\dfrac{\sigma-200}{50}\right] + C$
B	=	$\dfrac{12}{1.5 + 0.5 \tanh\left[\dfrac{\sigma-200}{50}\right]}$
C	=	$-\left\{0.5\left[1 + \tanh\left[\dfrac{\sigma-200}{50}\right]\right]\right\}\left\{0.75\left[1 + \tanh\left[\dfrac{\dot{T}-58}{17}\right]\right]\right\}$
σ^*	=	730 MPa
σ	=	hoop stress, MPa
T	=	transient temperature, K

$\dot{T}$	=	heating rate, K/s
Q	=	70170 cal/mole
R	=	1.986 cal/mole-K

9.3 Solution Techniques and Code Implementation

9.3.1 Initialization

The DEFORM-5 calculation is specified by setting ISSFUE = 0, ISSFU2 = 1, and IMETAL > 0 in the SAS4A/SASSYS-1 input deck. (See Table 9.3-1 for a listing of DEFORM-5-related input data). On the first transient time step, DEFORM-5 sets constants used in the strain rate and transient damage correlations and the eutectic penetration rate correlation, initializes integral program variables, and calculates the local cladding fluence as a function of the input-specified local linear power rating and input data FLTPOW (Block 62, location 61) and FPDAYS (Block 62, location 1). If input variable BURNFU (Block 65, location 54) has been specified, then its numerical value is taken to be the cladding fluence in units of 10^{22} neutrons/cm^2; this is an approximation often used for EBR-II-irradiated fuel elements. If a steady-state irradiation temperature for use in cladding damage calculations is specified in input variable TIRRFU (Block 65, location 200), it is stored on the first time step for future use. All of the first-time-step initialization is performed on entry to subroutine D5INIT.

If input variable IPINFG (Block 51, location 486) has the value 0, then on the first time step, the initial fuel element fill and fission gas masses for the DEFORM-5 fission gas model are calculated in subroutine FAILUR. Using the fission gas plenum geometry (See PLENL and RBRPL, Block 61, locations 53 and 102), the fuel geometry (See AXHI and ROUTFP, Block 61, locations 8 and 128), the fuel porosity (See PRSTY, Block 13, location 1073), an assumed fill pressure of 10^5 Pa, an input initial pressure (See P0GAS, Block 63, location 27) at the reference temperature (See TR, Block 13, location 419), the ideal gas constant (See RGASSI, Block 13, location 1086) and the molecular weights of the fission and fill gases (See FGMM and HEMM, Block 13, locations 600 and 1225), the masses of fill gas and fission gas are computed from the ideal gas law.

Table 9.3-1. DEFORM-5 Input Data

Equation Symbol	Equation Number	SAS4A/SASSYS-1 Input			Suggested Value
		Name	Block	Location	
-	-	IPO	1	12	>0
-	-	IPOBOI	1	13	>0
-	-	TR	13	419	27.
-	-	FGMM	13	600	131.
-	-	TFSOL	13	786	-
-	-	PRSTY	13	1073	-
-	-	RGASSI	13	1086	8.31434
-	-	HEMM	13	1225	4.
-	-	FIRLIM	13	1266	-
-	-	SECLIM	13	1267	-
-	-	THRLIM	13	1268	-
-	-	DTFAL1	13	1269	-
-	-	DTFAL2	13	1270	-
-	-	DTFAL3	13	1271	-
-	-	FGFI	13	1275	-
-	-	IFUELV	51	15	0
-	-	ISSFUE	51	32	0
-	-	MFAIL	51	86	-
-	-	ISSFU2	51	122	1
-	-	IMETAL	51	189	>0
-	-	IFUELC	51	193	0 or 1
-	-	ICTYPE	51	225	0
-	-	IGASRL	51	278	-
-	-	IRAPEN	51	280	0 or 1
-	-	IGSPRS	51	282	0 or 1

Table 9.3-1. DEFORM-5 Input Data (Cont'd)

Equation Symbol	Equation Number	SAS4A/SASSYS-1 Input			Suggested Value
		Name	Block	Location	
-	-	IFPIN2	51	285	0
-	-	IPINFG	51	486	0
-	-	IPORFG	51	488	-
-	-	AXHI	61	8	-
-	-	PLENL	61	53	-
-	-	RBRPL	61	102	-
-	-	ROUTFP	61	128	-
-	-	FPDAYS	62	1	-
-	-	FLTPOW	62	61	-
-	-	P0GAS	63	27	>0
-	-	FRUPT	64	81	-
-	-	FMELTM	65	2	-
-	-	BURNFU	65	54	-
-	-	TIRRFU	65	200	-

On time steps following the first, entry D5INI2 is executed to save cladding temperatures, fission gas pressures, coolant pressures, and to calculate the time derivative of the cladding temperature at the beginning of the transient DEFORM-5 calculation.

9.3.2 Fuel/Cladding Eutectic Alloy Formation

Equation 9.2-1 is used to calculate the cladding penetration rate on the inner cladding surface, independent of the input-specified values of IMETAL and ICTYPE (Block 51, locations 189 and 225), in subroutine EUTPEN. The rapid penetration rate in the range from 1353 K to 1506 K is specified with a positive value of input variable IRAPEN (Block 51, location 280); otherwise the rate is given by the exponential form in Eq. 9.2-1. In order for the rapid penetration rate to be effective, the local fuel surface temperature must be above the input fuel solidus temperature, TFSOL(IFUELV) (See Block 13, location 786, and Block 51, location 15).

To accommodate large temperature changes on a heat transfer time step in fast transients, the temperature change across the time step is assumed to be linear and Eq. 9.2-1 is numerically integrated over the time step to avoid loss of accuracy. On each heat transfer time step, a new value of the cladding inner radius and the cladding thickness are calculated for use in subsequent cladding damage and strain rate calculations.

9.3.3 Fission Gas

On each time step, the fill and fission gas masses computed on the first time step, Section 9.3.1, are used with the transient temperatures to set the time-dependent internal-cladding and internal-fuel pressures. If input variable IGSPRS (Block 51, location 282) is set to 0, the pressure in the fuel porosity and the fission gas plenum is equilibrated in the transient to simulate rapid fission gas transport through the fuel, an option for long, slow accident sequences. Otherwise (IGSPRS > 0), steady-state gas in the fuel porosity remains in place and is heated with the fuel temperatures. In the transient, the volume of the fuel porosity is adjusted according to the input value of IPORFG (Block 51, 488), to estimate the impact of fuel density changes on porosity volume as the fuel changes temperature. These calculations are performed in subroutine FAILUR.

9.3.4 Cladding Strain

In the transient, subroutine STRANC computes the incremental cladding strains for each time step from the formulation in Section 9.2.3. If input variable ICTYPE (Block 51, location 225) has the value 1 or 2, then the parameters for 316 stainless steel are used. If ICTYPE has the value 3, then the parameters for HT-9 are used. The cladding inner radii and thicknesses at all axial locations are adjusted to reflect the transient cladding strains.

9.3.5 Cladding Failure

In the transient, subroutine FALMAR computes the cladding rupture time and the corresponding life fraction at all axial locations using the formulation in Section 9.2.4. The computed life fractions will be printed, but will not trigger cladding failure, and subsequent post-failure model execution, unless the input value of MFAIL (Block 51, location 86) has been set to 8 on input. In order to initiate LEVITATE or PLUTO2 with this failure criterion, it is also necessary to specify FIRLIM, SECLIM, THRLIM, DTFAL1, DTFAL2, DTFLA3 (Block 13, locations 1266-1271) and FMELTM (Block 65, location 2).

In addition, the local coolant margin to boiling, expressed as the ratio of the absolute coolant temperature to the absolute saturation temperature, is also computed in FALMAR for subsequent printing.

Subroutine DFORM5 computes cladding failures to initiate plenum fission gas release in the coolant boiling model (See Chapter 12). For IGASRL > 0 (See Block 51, location 278), input variable FRUPT(1) (See Block 64, location 81) contains the cladding life fraction for failure of all the pins in the channel. This failure computation is independent of MFAIL.

9.3.6 Printed Output

DEFORM-5 printed output is produced from subroutine OUTPT5 on a main time step frequency set by input variables IPO and IPOBOI (Block 1, locations 12 and 13). When called, subroutine OUTPT5 prints the following quantities for all axial location: inner and outer cladding radii, cladding thickness, internal pin pressure, coolant channel pressure, cladding hoop stress and strain, incremental cladding strain and strain rate on the last step, cladding life fraction, coolant boiling fraction, time to rupture, time for cladding penetration, and the amount of penetration of the cladding.

REFERENCES

NOTICE

Several references in this document refer to unpublished information. For a list of available open-literature citations, please contact the authors.