Cumulative Damage Fraction as a SFR Fuel Design Criterion

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1. Introduction

The Prototype Generation IV Sodium-Cooled Fast Reactor (PGSFR) employs U-Zr metal fuel [1] which has been qualified through sufficient irradiation tests. Fuel cladding can be failed due to its mechanical deformation, for which cladding strain and cumulative damage fraction (CDF) are limited within an allowable range. Metal fuel melting is also chosen as a fuel design criterion, although molten fuel does not cause a fuel failure as in the case of oxide fuel system where the melting point of oxide fuel is much higher than that of cladding. Meanwhile cladding wastage is not regarded to result directly in a fuel failure, but plays one of phenomena which deteriorate fuel integrity.

Unlike an LWR fuel, high temperature SFR fuel needs to take into account thermal creep rupture which shall be limited with CDF. This paper briefly describes the validity of CDF as a safety criterion for SFR fuel design.

2. Failure Mechanisms of SFR Metal Fuel

SFR fuel damage or failure mechanisms are significantly simpler and more manifest than the cases of LWR. SFR design does not allow coolant boiling. Metal cladding corrosion in the sodium coolant is not of concern due to their compatibility. SFR fuel cladding is tolerant to brittle failure or ballooning. Instead a breach in SFR fuel cladding is of the ductile pinhole type.

However SFR is operated at an elevated temperature for which its component designs address creep which deforms materials with time through a thermally activated mechanism. In the nuclear industry the design rules of the structures against creep including CDF methodology have been codified in ASME Sec. III Div. 5.

In addition to thermal creep, SFR cladding experiences irradiation creep which is prevalent under high neutron flux even at a lower temperature where thermal creep can be ignored [2]. The creep deformation of SFR fuel cladding is largest in the region near the fuel plenum where cladding temperature is highest, which is attributable mainly to thermal creep. Swelling is ruled out as a damage mechanism since the PGSFR fuel system uses ferritic-matensitic steels; FC92 for fuel cladding and HT9 for fuel assembly.

Cladding wastage resulting not only from fuel-cladding chemical interaction but also from eutectic melting between U from fuel and Fe from cladding enhances the mechanical deformation of cladding by accelerating thinning of cladding thickness. It is incorporated in the stress calculation.

3. Fuel Design Criteria for Safety Evaluation

3.1. Cladding Strain

As strain is measureable, it is straightforward to introduce cladding strain as a fuel design criterion. It has been employed in LWR fuel design as well [3].

3.2. Cladding CDF

Thermal creep damage is accumulated with time in the material subjected to stress under an elevated temperature. The usage of lifetime is calculated using Eq. (1) with an assumption of linear life-fraction summation of creep damage.

$$CDF = \int_0^t \frac{dt}{t_r(\sigma, T)} \quad (1)$$

where t_r is rupture life calculated using time-to-rupture curves which are measured under constant stress σ and temperature T.

Time-fraction approach is more convenient than strain fraction approach since time is easily measurable. However time is not material property, and creep damage is not linearly proportional to time all over the creep deformation regime.

Due to the shortcomings of CDF approach resulting from uncertainties of material data, operating condition, and time-fraction rule itself, it is usually to draw conservative design curves by accounting for these uncertainties and/or adding sufficient margin in the CDF limit.

3.3. Cladding Temperature and Time

In a creep-dominant regime, only cladding temperature is not sufficient as a fuel design criterion since dwell time is required for calculating creep damage. Temperature and time limits can be derived using Eq. (1) under a given cladding stress, i.e., at a specified fuel design and burnup.

4. CDF as a Fuel Design Criterion

4.1. CDF as a Fuel Design Criterion

CDF has been adopted as a fuel acceptance criterion in the previous SFR where oxide or metal fuel was used. Table I presents a comparison of CDF limit for normal operating condition for SFR designs.

Table I: Comparison of CDF limit for NO

Case	CDF limit	Conditions
CRBR	CDF(all events)+ margin < 1	Max. design temperature & Max. uncertainty in material properties
PRISM	CDF < 0.001	Equivalent to failure of 0.01 percent of the PRISM fuel pins
	CDF < 0.2 (S-PRISM)	Peak CDF values are in the range of 10^{-4} to 10^{-3}
Japan	CDF < 0.1 or 0.5	Peak CDF at irradiation test was 0.015 at MFA-1 test
India (PFBR)	CDF < 0.25	Based on U.S. RDT (Reactor Development and Technology) standard, however, CDF limit is increased from 0.1 to 0.25
Russia	CDF < 0.2~0.3	Should be defined by irradiation experience
France	CDF < 0.1	RAMSES-II & RCC-MRx (0.1 for the irradiated & 1 for the unirradiated)
U.S.	CDF < 0.1	RDT Standard

In CRBR design, a procedure of CDF application to fuel-pin failure analysis was developed. In GE's metal-fueled SFRs, CDF methodology was adopted in PRISM design, and later in S-PRISM design [4]. In Japan, cladding temperature was limited in Monju design [5], and currently cladding breach criteria are temperature as well as CDF [6]. In India's PFBR design, cladding temperature was proposed as a guideline based on CDF limit. If temperature is specified, duration needs to be defined at the same time [7]. Russia has the same approach as India [6].

The fuel acceptance criteria have been derived to satisfy the functional and operational requirements as well as for safety. In PGSFR fuel design, events are classified into four groups according to their severity as shown in Table II. During normal operation (NO) and anticipated operational occurrences (AOO), cladding integrity shall be guaranteed by limiting cladding strain and CDF. During design base accident (DBA)-1, a small fraction of fuel pin failure is allowed in principle but the limit is conservatively established not to allow a fuel failure for a single most-damaging event. The acceptance criteria for DBA-2 is that fuel rod keeps a coolable geometry with no fuel pin failure propagation which is limited with fuel and cladding temperatures.

Table II: PGSFR fuel acceptance criteria and limits.

	Acceptance Criteria	Specified Limits
NO and AOO	No fuel pin failure	CDF<0.05 Strain<1%
DBA-1	A small fraction of fuel pin failure	CDF <0.05 (Single most-damaging DBA-1) Strain <1% (Single most-damaging DBA-1)
DBA-2	Fuel pin coolable geometry, with no fuel pin failure propagation	Fuel temperature<Solidus Cladding temperature < 1,075°C
DEC	Core coolability with in-vessel retention	Coolant temperature < Sodium boiling

4.2. Remarks on CDF for SFR Fuel Design

Under a high temperature condition, cladding strain and CDF increases are caused mainly by thermal creep. Thus the criteria for cladding strain and CDF are interrelated through the Monkman-Grant relationship.

$$\dot{\varepsilon} \cdot t_r = \text{constant} \quad (2)$$

where $\dot{\varepsilon}$ is the secondary creep strain rate.

Although CDF limit is around 0.1 as shown in Table I, it is mostly found that CDF value is less than 10^{-3} at best-estimated condition of previous SFR fuel design as well as in irradiation tests where fuel pin did not breach.

The variation of CDF with time for fuel rod is quite peculiar compared to structural components. When stress increases with time as in the case of fuel rod design, CDF begins to increase significantly beyond a certain time, i. e. in the form of a power function as shown in Fig. 1. It is caused that thermal creep strain is accelerated due to tertiary creep and most of CDF increase occurs when time approaches the end of life. Fuel rod shall be designed to avoid tertiary creep region. Thus it is impractical that the difference of CDF is interpreted as a fuel design margin. In contrast the evolution of CDF during the creep deformation of a structural component is different. When a thermomechanical load is nearly constant with time and stress varies a little, a design margin could be stated with the magnitude of CDF.

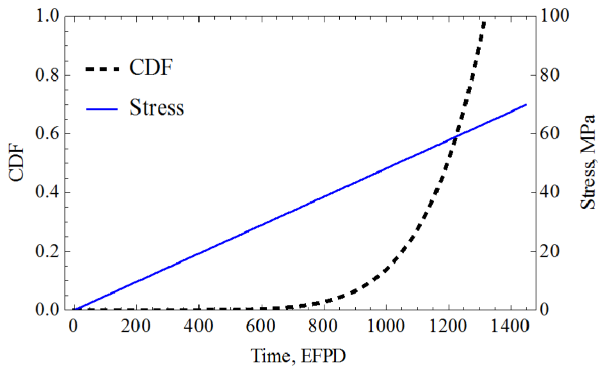

Fig. 1. CDF increase under monotonic increase of stress

It is important to have proper knowledge on what are implicitly included in CDF limit and calculation procedure. For example the CDF limit of 0.05 for the PGSFR fuel which is lower than other cases is employed in combination with the best-estimated time-to-rupture curve. Moreover the validity of its usage and the degree of its conservatism have to be proved against experimental data during establishing a fuel design methodology.

5. Conclusions

CDF is introduced as a measure to protect against rupture due to thermal creep. It is no doubt that CDF has been employed as a fuel acceptance criterion in SFR fuel designs. A combination of temperature and duration limits is accepted as a design guideline in the sense that it is derived from CDF equation which is a function of time, temperature, and stress.

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