# A CUMULATIVE DAMAGE FRACTION DESIGN APPROACH FOR LMFBR METALLIC FUEL ELEMENTS

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## ABSTRACT

The cumulative damage fraction (CDF) analytical technique is currently being used to analyze the performance of metallic fuel elements for proliferation-resistant LMFBRs. In this technique, the fraction of the total time to rupture of the cladding is calculated as a function of the thermal, stress, and neutronic history. Cladding breach or rupture is implied by CDF = 1. Cladding wastage, caused by interactions with both the fuel and sodium coolant, is assumed to uniformly thin the cladding wall.

The irradiation experience of the EBR-II Mark-II driver fuel with solution-annealed Type 316 stainless steel cladding provides an excellent data base for testing the applicability of the CDF technique to metallic fuel. Mark-II drivers exhibit negligible fuel-cladding mechanical interaction, so the main source of stress is fission-gas pressure, which has been well characterized. The fuel-cladding chemical interaction zone, which has a uniform front and exhibits Arrhenius time-temperature behavior, is considered as cladding wastage in determining the hoop stress. The Mark-II lifetimes provide a lower bound for comparison with the CDF calculations, since the elements breach in a restrainer dimple and not in the cladding proper. At 590°C, the measured lower bound on lifetime, 10.0 at. %, is lower than the calculated CDF lifetime of 14.5 at. %. The measured lifetime at this temperature might be consistent with the CDF calculations if the cold-worked dimple were not present, since it acts as a stress riser. At 670°C, all elements have exceeded 8 at. % burnup, which is greater than the calculated CDF lifetime of 7 at. %. Thus, CDF calculations are conservative at 670°C. With this in mind, the calculations have been extended to other types of metal fuels.

The advanced metal fuels being considered for use in LMFBRs are U-15-Pu-10Zr, Th-20Pu and Th-20U (compositions are given in weight percent). The two cladding alloys being considered are Type 316 stainless steel and a titanium-stabilized Type 316 stainless steel. Both are in the cold-worked condition. The CDF technique was applied to these fuels and claddings under the following assumed steady-state operating conditions, taken from recent system studies: Peak cladding temperature of 640°C, fast fluence of $2.1 \times 10^{23}$ n/cm$^2$, irradiation time of $4.32 \times 10^7$ s, fuel peak burnup of 7 at. %, and linear power of 50 kW/m. Transient events, consisting of six "U-2b" events (15% overpower for 300 s) plus one "E-16" (natural-circulation) event, were assumed to occur at the end of the steady-state exposure.

Calculations for all combinations of the fuel types and claddings under consideration yielded CDF values of less than 0.07. The titanium-stabilized cladding gave lower CDF values than Type 316 stainless steel, owing to its greater strength. CDF values were highest for the Th-20Pu fuel because of its greater interaction (wastage) with the cladding. The very low CDF values indicate that all these designs have substantial margins to accommodate wastage or fuel-cladding stresses in excess of those anticipated.

In summary, the CDF technique gives a conservative estimate of current metal fuel-element lifetimes at 670°C. Further, it predicts satisfactory performance of the advanced fuel designs to which it has been applied.

## Introduction

A renewed interest in metallic fuels for LMFBRs has arisen recently for several reasons. First, the breeding potential of a metallic fuel system is generally superior to that of the corresponding ceramic fuel system because of the greater heavy-metal atom density in the metallic form. Second, reactor-design coolant-outlet temperatures have been decreasing. From a high near 650°C a few years ago, outlet temperatures have decreased to 510°C or lower in many current designs. Finally, the desire to develop workable, proliferation-resistant fuel cycles has given a fresh impetus to metallic fuel development. Metallic fuels are amenable to on-site remote reprocessing in which the fuel is never completely decontaminated, thereby avoiding some of the problems associated with transportation and plutonium separation in spent fuel. Such a reprocessing scheme was successfully demonstrated in the EBR-II Fuel Cycle Facility in the 1960s [1].

A cumulative damage fraction (CDF) analytical method [2] has been adopted to provide a consistent basis for comparison of the expected performance of the various types of fuel elements under consideration in proliferation-resistant core design studies. In the present work, this method was first applied to the EBR-II metallic driver fuel and the results compared with actual irradiation experience. With its validity thus established the method was then applied to the advanced metal fuel systems under consideration. Uranium-plutonium-zirconium (U-Pu-Zr), thorium-plutonium (Th-Pu), and thorium-uranium (Th-U) alloy fuels were evaluated, and all were predicted to meet the goal requirements as specified by recent system-design studies [3] during both steady-state and transient operation.

## 2. CDF Method

Analysis using the CDF method assumes that the damage to the fuel-element cladding depends on the stress $\sigma$, temperature T, and fast-neutron fluence $\phi t$, such that when the cumulative damage fraction reaches unity, the cladding is breached. This is formulated as

$$\text{CDF} = \int_0^t \frac{dt}{t_R(\sigma, T, \phi t)} \tag{1}$$

where the time to rupture, $t_R$, reflects the stress-rupture behavior of the cladding [4]. The reduction in element lifetime due to irradiation is greatly overestimated by the post-irradiation fluence-dependent correlations. The recommendation [2] followed in the present work assumes the use of unirradiated-material correlations for the steady-state portion of the irradiation and postirradiation correlations during transient events. Two cladding materials were considered for use with the metal fuels. They are Type 316 stainless steel, in both the solution-annealed and 20% cold-worked conditions, and a stronger,

titanium-stabilized Type 316 stainless steel, also in the cold-worked condition. The stress-rupture correlations for these cladding materials at 640°C are shown in Fig. 1 [5-6]. The principle source of stress on the cladding was assumed to be the pressure of fission gas released from the fuel [7]. Little, if any, contribution from fuel-cladding mechanical interaction (FCMI) is expected. The stress is enhanced by the loss of cladding wall thickness as a result of sodium corrosion on the outside and interdiffusion of fuel and cladding constituents on the inside.

## 3. Systems Analysis

### 3.1 Materials Considerations

Four fuel alloys were evaluated using the CDF method. The first was the EBR-II Mark-II driver fuel, a uranium-fissium* alloy which has been extensively studied [7-11]. The other three alloys evaluated were uranium-plutonium-zirconium, thorium-plutonium, and thorium-uranium. Although these systems have not been as extensively investigated as the EBR-II driver fuel, some data are available [12-13]. All the fuel-element designs were based on the present EBR-II Mark-II driver design [7]; i.e., sodium-bonded with a fuel smear density of 75%. As the fuel swells during irradiation, the fission-gas bubble porosity in the fuel becomes interconnected just before fuel-cladding contact is established. Up to about 80% of the fission gas generated is released to the element plenum. The weak fuel produces little if any FCMI [7]. The main source of stress in the cladding is, therefore, the fission gas pressure in the plenum, which is a function of plenum-to-fuel volume ratio, temperature, and the amount of gas released from the fuel. Gas release from the Mark-II fuel has been well characterized as a function of burnup [7-9]; a constant release fraction of 80% from beginning of life was assumed for the other fuel types.

With uranium and plutonium metallic fuel systems, after fuel/cladding contact is made, the cladding diffuses into the fuel, leaving a weakened, depleted zone in the cladding. This zone has a uniform front parallel to the fuel-cladding interface and shows no penetration stringers along the grain boundaries [7,8]. The depth of this zone can be described by

$$\Delta = [D_o \; t \; \exp \; (-Q/RT)]^{\frac{1}{2}}$$

where $\Delta$ is the depth in cm,

$D_o$ is a diffusion constant in $cm^2/s$,

t is the irradiation time in seconds,

Q is the activation energy,

R is the gas constant, and

T is the maximum cladding temperature in °K.

*Fissium is the term used to denote an alloy which represents the approximate equilibrium concentration of metallic fission products.

The constants $D_o$ and Q are dependent on the fuel and cladding alloys. The values of $D_o$ and Q for the alloys under consideration are given in Table I [7,11-13]. The fuel-cladding compatibility in the titanium-stabilized cladding was assumed to be the same as in Type 316 stainless steel.

An additional type of cladding wastage to be considered was sodium corrosion on the cladding OD, given by [14]

$$R = 3.31 \times 10^{-38} T^{9.494} \quad (3)$$

where R is the corrosion rate in mm/s and T is the absolute temperature. In addition, an arbitrary 0.025-mm as-fabricated tolerance was assumed for the wall thickness. The fission-gas pressure was converted to cladding hoop stress by means of the equation

$$\sigma = P[OD^2 + ID^2)/(OD^2 - ID^2] \quad (4)$$

where $\sigma$ is the hoop stress, and P is the plenum pressure. The OD and ID were adjusted for the assumed wastages and tolerance. Changes in dimensions due to cladding creep and swelling were not considered, nor was stress relaxation in the cladding due to these mechanisms. The effect of a low melting phase ($\sim$ 700°C) in the Th-Pu alloy at $\sim$2% uranium has also not been considered, but poses a potentially significant problem for this system.

### 3.2 Design and Operating Parameters

The design and operating parameters of the fuel elements used in the analyses are shown in Table II. The Mark-II values are typical of the EBR-II design and operating parameters. The values for the advanced metal fuels reflect the recommended, optimized design from recent studies [3]. The 640°C peak cladding temperature is the $2\sigma$ temperature (the highest temperature expected, including uncertainties).

## 4. Results and Discussion

### 4.1 Mark-II Fuel Elements

A substantial number of Mark-II fuel elements have achieved high burnup at two temperatures. At 590°C, the normal peak cladding temperature for row 6 elements, 588 elements have achieved at least 10 at. % burnup. Thirteen of these incurred cladding breaches at 10 at. % burnup. At this temperature, above 10 at. % burnup, the probability of cladding breach increases very rapidly. The breaches all occurred, however, at a dimple in the cladding, initially 12 mm above the top of the fuel, which serves as a restraint to axial fuel growth. The dimple probably acts as a stress riser and, if not present, would allow the elements to achieve even higher burnup before cladding breach occurred. At 590°C, the 10 at. % burnup breach threshold is, therefore, a lower limit. No cladding breaches occurred among nineteen elements irradiated to 8 at. % burnup at 675°C, the peak temperature in a subassembly intentionally operated with reduced flow.

The calculated CDF for Mark-II elements at 590°C and 675°C is shown as a function of burnup in Fig. 2. The rather steep slopes of these semilogarithmic plots indicate that most of the damage accrues in a short time late in life. This characteristic is in good qualitative agreement with Weibull statistical analyses, which indicate essentially no breaching below the threshold and a high breaching rate above it [8]. At 590°C, the CDF analysis predicts a lifetime of 14.5 at. %. Although this is greater than the observed lifetime of 10 at. %, the analysis does not consider the effect of the cladding dimples, where the breach actually occurs. Were the dimples not present, 14.5 at. % would not be an unrealistic estimate of element life expectancy.

At 675°C, CDF analysis predicts breaching at 7 at. % burnup. The most probable source of this discrepancy is that at 675°C, significant carbide precipitation occurs in the cladding. The now relatively low-carbon matrix has a lower creep strength, allowing greater stress relaxation in the cladding. The lower cladding stress which would be reflected as a longer lifetime. At this higher temperature, the CDF calculation apparently is conservative.

### 4.2 Advanced Metal Fuels

CDF analyses were performed on the U-Pu-Zr, Th-Pu, and Th-U alloy fuels at the specified system design conditions given in Table II. Steady-state operation for 12,250 h (510 days) at the peak temperature [3] was assumed to be followed by typical design-basis transients; this is a conservative approach, since the cladding properties are more degraded and damage rates correspondingly greater at end of life. The transients considered were six 15%-overpower events of five minutes' duration each, followed by one natural-circulation event resulting in a peak power/flow of ~175% for ~50 s. Peak cladding temperatures achieved during these events were 725°C and 875°C, respectively, compared with a nominal $2\sigma$ temperature of 640°C. For comparison, the fuel-cladding eutectic temperatures for U-Pu-Zr, Th-Pu, and Th-U with stainless steel are approximately 825, 875, and 875°C, respectively. Enhanced fuel-cladding reaction rates and fluence-degraded cladding stress-rupture properties were assumed during the transients. The results of the calculations are given in Table III. All the calculated CDF values are well below 1.0. The CDF increment due to the transients is about 30% of the total in the Type 316 stainless steel cladding but only 5-10% of the total in the titanium-stabilized cladding. The CDF values in the titanium-stabilized cladding are about an order of magnitude lower than in Type 316. Because of the very low values and conservative nature of the calculation, as evidenced by the 675°C Mark-II results, cladding breaching is not expected until much beyond 7 at. % burnup. Addi-

tional calculations were made to determine the expected breach burnup; these results are also given in Table III. Breach burnups fall within the 14-16 at. % range in Type 316 and the 20-25 at. % range in the titanium-stabilized cladding. These are all well beyond the 7 at. % goal burnup.

4.3 Sensitivity Studies

To determine the sensitivity of the results to variations in some of the important fuel and cladding parameters, the uranium-plutonium-zirconium alloy in the titanium-stabilized cladding was chosen as a base case, since it has been given the most consideration in system-design studies and, therefore, may be considered as the prime candidate system. The parameters varied were temperature, fission-gas release, fuel-cladding mechanical interaction, and cladding wastage from fuel-cladding reaction. The figure of merit used in the sensitivity studies was the burnup to breach, i.e., CDF = 1. The results of the sensitivity studies are shown in Table IV. The maximum decrease in burnup to breach that can be achieved by varying a single parameter is less than 4 at. %, which is relatively insignificant with respect to the goal burnup of 7 at. %. It is especially interesting to note that if all the parametric variations in Table IV that resulted in decreased lifetime are taken together in one case, the resulting calculated burnup to breach is 15.3 at. %, still a factor of two greater than the 7 at. % goal burnup.

## 5. Conclusions

The following conclusions may be drawn from this study:

1. CDF lifetime calculations for EBR-II Mark-II elements are conservative at high temperatures and probably conservative or consistent with breach observations in Mark-II elements at lower temperatures.

2. Based on CDF calculations, the U-Pu-Zr, Th-Pu, and Th-U advanced metal alloy fuel systems considered may be expected to reach their goal burnups with no cladding breaches.

3. The greater strength of the titanium-stabilized cladding relative to Type 316 stainless steel provides a greater margin between goal burnup and burnup to breach but is not required to reach a goal burnup of 7 at. %.

4. The burnup to breach is not significantly affected by slight to moderate variations in temperature, fission-gas release, fuel-cladding mechanical interaction, or cladding wastage.

## 6. Acknowledgments

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Table I. Constants for Compatibility of Metal Fuels with Type 316 Stainless Steel Cladding

| Fuel Alloy | $D_o$, $cm^2/s$ | Q, kcal/mole |
|---|---|---|
| U-Fs | $3.45 \times 10^{2}$ | 62.35 |
| U-Pu-Zr | $2.56 \times 10^{2}$ | 62.5 |
| Th-Pu | $2.69 \times 10^{-1}$ | 45.6 |
| Th-U | $2.51 \times 10^{-2}$ | 44.0 |

Table II. Design and Operating Parameters for Metal Fuels

| | Mk-II | Advanced Fuels[a] |
|---|---|---|
| Cladding Alloy | SA 316 SS | CW 316 SS, CW 316 SS + Ti |
| Cladding OD, mm | 4.4 | 7.1 |
| Cladding ID, mm | 3.8 | 6.1 |
| Plenum/Fuel Volume Ratio | 0.8 | 1.0 |
| Peak Cladding Temperature | 675 | 640 |
| Peak Fuel Burnup, at. % | 10 | 7 |
| Peak Linear Power, kW/m | 30 | 66 |
| Irradiation Time, days | -- | 510 |

[a] U-Pu-Zr, Th-Pu, Th-U

Table III. Summary of Advanced Metal Fuel CDF Calculations

| Fuel | Cladding | CDF at 7 at. % burnup | | Burnup for Steady-state CDF = 1 |
|---|---|---|---|---|
| | | Steady State | Steady State + Transient | |
| U-Pu-Zr | CW 316 SS | $4.2 \times 10^{-2}$ | $5.8 \times 10^{-2}$ | 16 |
| | CW 316 SS + Ti | $3.0 \times 10^{-3}$ | $3.2 \times 10^{-3}$ | 26 |
| Th-Pu | CW 316 SS | $4.8 \times 10^{-2}$ | $7.0 \times 10^{-2}$ | 14 |
| | CW 316 SS + Ti | $3.5 \times 10^{-3}$ | $3.8 \times 10^{-3}$ | 20 |
| Th-U | CW 316 SS | $3.7 \times 10^{-2}$ | $5.2 \times 10^{-2}$ | 16 |
| | CW 316 SS + Ti | $2.7 \times 10^{-3}$ | $2.9 \times 10^{-3}$ | 25 |

Table IV. Sensitivity Studies on U-Pu-Zr Fuel in Titanium-stabilized Type 316 Stainless Steel Cladding

| Parameter Variation | Burnup to Breach, at. % |
|---|---|
| Base Case | 25.7 |
| Cladding Temp. Increased from 640 to 650°C | 23.3 |
| Fission-gas Release Increased from 80 to 100% | 22.2 |
| Fuel-cladding Mechanical Interaction Increased from 0 to 20 MPa | 22.7 |
| End-of-life Cladding Wastage Decreased from 0.07 to 0 mm | 31.4 |
| End-of-life Cladding Wastage Increased from 0.07 to 0.16 mm | 22.7 |

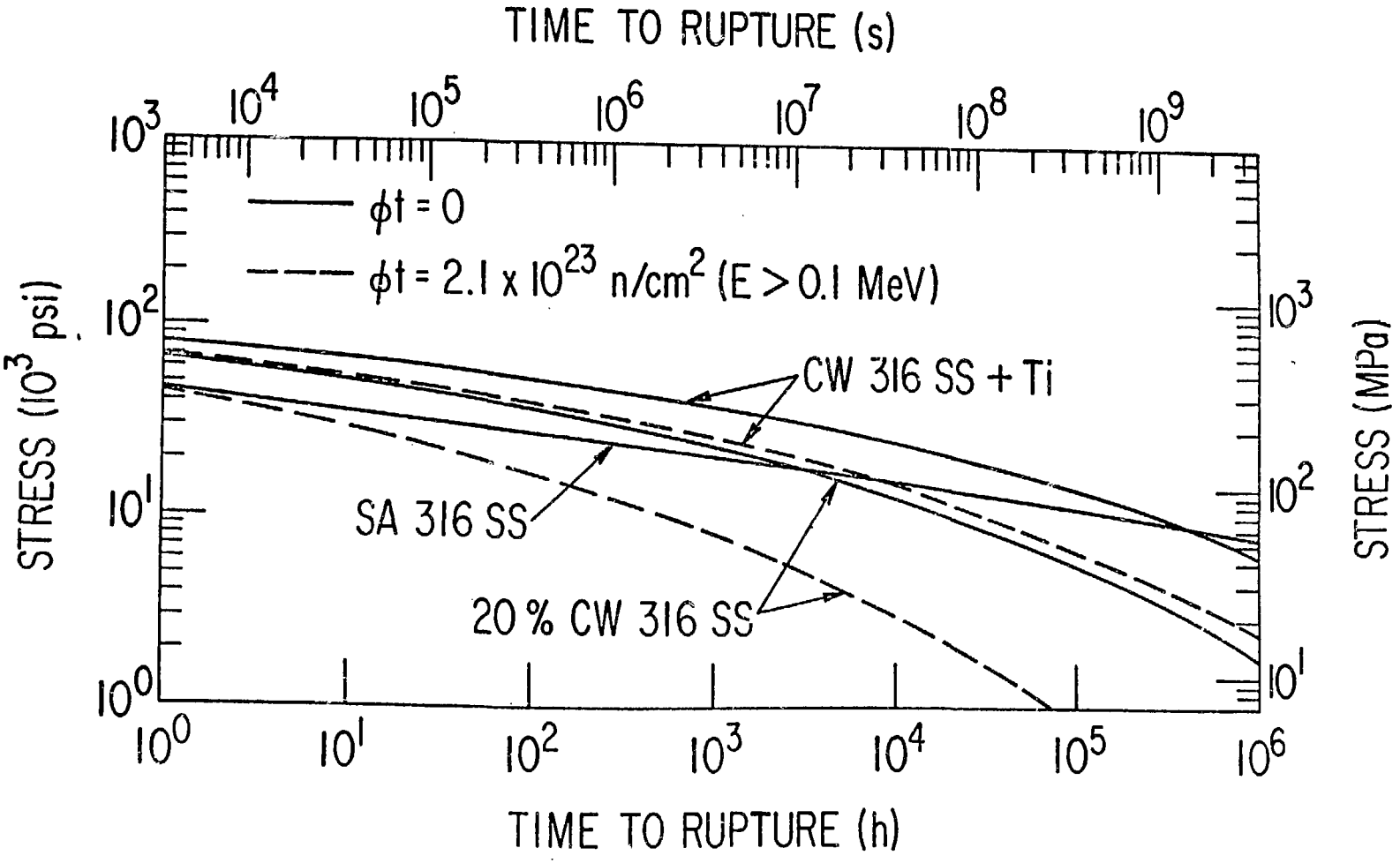


Fig. 1. Stress-rupture Correlations Used for Type 316 Stainless Steel and Titanium-stabilized Type 316 Stainless Steel at 640°C.

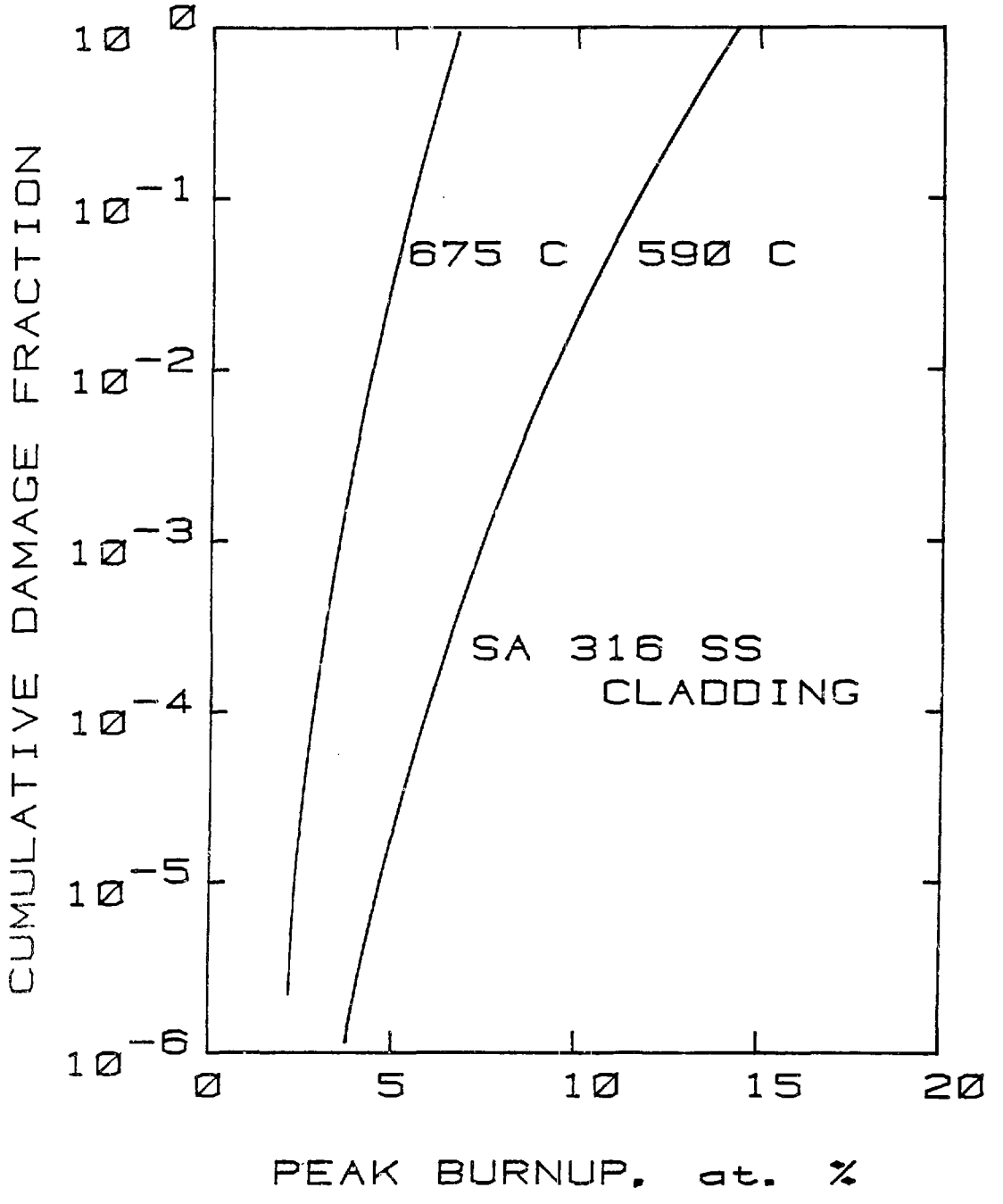


Fig. 2. Calculated CDF in Mark-II Fuel Elements.