Design Safety Limits for transients in a metal fuelled reactor

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Abstract. Towards the metal fuel program, a 500 MWe Metal Fast Reactor is planned. The design safety limits for the normal and anticipated transient events are to be arrived at for a metal fuelled reactor which is addressed in this paper. All the design basis events occurring during the lifetime of the components concerned are classified in to four categories based on the frequency of occurrences. The design approach followed in determining the DSL temperature limits for clad is that the pin deemed to have failed if Cumulative Damage Fraction (CDF), based on creep rupture data under operating pressure & temperature conditions, reaches 1.0. This CDF limit is applied uniformly across the categories, viz., CDF of 0.25 is to be respected for each of the category – 1, 2 & 3 events each and the rest 0.25 is allocated for SA during handling & in internal storage. In order to estimate the temperature limits for clad, the time of transient events for which the clad has to withstand the given temperature is considered as 30 minutes for category-2 event and 2 minutes for catergory-3 events which is based on the occurrence of events. The failure mode in a metal fuel pin is primarily due to the fission gas pressure loading and due to the thinning of clad (because of eutectic formation between fuel and clad at high temperature). In order to arrive at the temperature limits, the temperature dependent liquid penetration rate in to the cladding and hence the thinning effect are considered along with the end-of life fission gas pressure loading on the clad. The creep rupture properties of T91 are taken from RCC-MR code after accommodating for irradiation effects. Based on the analysis, for category-2 event, the clad inside hotspot temperature is limited to 993 K and for catergory-3 events, it is restricted to 1043 K and category-4 event, it is restricted to 1243 K. Similarly, the limits for fuel and coolant are also arrived at. These limits will be fine tuned based on the out-pile and in-pile experiments planned in the future.

Key Words: Metal fuel, Transients, Design Safety Limit, T91 Clad.

1. Introduction

Design of components with sufficient margin is the first step towards defence-in-depth principle adopted to ensure reactor safety. This requires considerations of all the loads on the components during normal operation as well as during off normal (transient) events. All the design basis events occurring during the lifetime of the components concerned are classified in to four categories based on the frequency of occurrences [1]. It is essential to define the design safety limits (DSL) for the four categories of events in order to assess that the design provisions of the system/components are adequate to ensure safety.

For the category-1 events i.e. normal operation, the design criteria are as follows ([2]):

1. The centreline temperature of fuel at 115% peak power under hotspot conditions shall not exceed its melting point.
2. The clad inside surface hotspot temperature shall not exceed 923 K (650°C) under normal operating conditions for fuel SA to avoid any fuel-clad eutectic formation.
3. Cumulative Damage Fraction (CDF) under normal operation shall be $\leq$ 0.25 to preserve clad integrity.
4. Sodium (coolant) temperature anywhere in the subassembly shall be less than its boiling point.

Similarly, for the transient events i.e. for categories -2, 3 & 4 events, the temperature limits for fuel, clad and coolant are to be arrived at. This paper recommends the preliminary temperature limits for all the transient events for a metal fuelled reactor based on the literature data and analysis.

2. Transient temperature limits for fuel

The temperature limits for fuel for different categories of events (1, 2 & 3) is that the fuel centerline hotspot temperature should not cross its melting point at 115% peak power. This is followed as a design philosophy. For category-4 event, partial melting is allowed inline with the philosophy adapted for MOX fuel of PFBR [1]. The allowable linear heat rating philosophy followed for a metal fuelled reactor is given in FIG. 1.

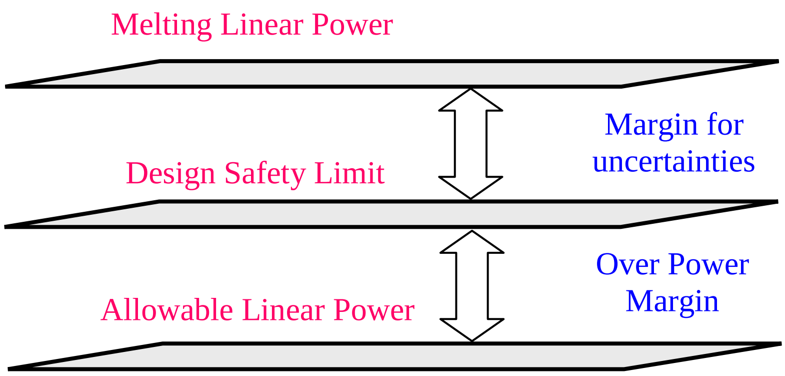

FIG. 1. Linear Heat Rating design philosophy

3. Design approach for determining temperature limits for clad

The design approach followed in determining the DSL temperature limits for clad is that the pin deemed to have failed if Cumulative Damage Fraction (CDF), based on creep rupture data under operating pressure & temperature conditions, reaches 1.0. This CDF limit is apportioned equally and applied uniformly across the categories, viz., CDF of 0.25 is to be respected for each of the category – 1, 2 & 3 events each and the rest 0.25 is allocated for SA during handling & in internal storage.

In order to estimate the temperature limits for clad, the time of transient events is arrived at based on the occurrence of events.

- For a 500 MWe reactor (viz. PFBR), Category 2 events can be classified as two broad categories. Events originating from the primary sodium system (Type 2a) and events originating from secondary & balance of plant (Type 2b). During each Type 2a event, the duration that the clad temperature remains above the normal operating level is ~ 10 s and during each Type 2b events, the same duration is about 60 s [3]. There are about 500 type 2a events and 250 type 2b events envisaged in the reactor life of 40 years [4]. This translates in to 13 number of Type 2a events per year and 6 numbers of Type 2b events per year. Thus, the total duration for which the clad temperature remains above normal operating level during all category 2 events in its life time of 3 years is 25 minutes (((10 s x 13 (events per year) x 3 (year)) + (60 s x 6 (events per year) x 3 (year)))/60 = 24.5 = ~ 25 minutes) only. Considering 20 % margin, this duration can be considered as 30 minutes.

- Maximum duration for which clad temperature remains above normal operating level during category 3 events is 1 minute only and number of occurrence of event in fuel SA of 3years life is only one [3]. Considering margin, this duration can be considered as 2 minutes.

Thus, for metal fuel pin temperature limit estimation, a time limit of 30 minutes and 2 minutes are considered for categories-2 & 3 respectively.

4. Transient temperature limits for clad

The major loading in a fuel pin are due to fission gas pressure and Fuel Clad Mechanical Interaction (FCMI). Besides, clad thickness tends to reduce with the burn-up due to corrosion by fission products or due to sodium. It has been proved by experiments that sodium corrosion is very much less if sodium purity is maintained. The failure mode in a metal fuel pin is mainly due to the fission gas pressure loading and due to the thinning of clad (because of eutectic formation between fuel and clad at high temperature). The irradiation experience of EBR II Mark II driver fuel with 75% smear density shows that negligible Fuel Clad Mechanical Interaction has occurred and hence the main source of stress is fission gas pressure only [5]. In the present design, a smear density of 75% is provided to accommodate the fuel swelling in order to facilitate the interconnection of porosity and hence FCMI is not a major concern in the metal fuel design. The creep rupture properties of the clad material (T91) play a significant role in deciding the temperature limits.

(a) The fission gas pressure at End-of-Life (EOL) for a sodium bonded metal fuel pin is estimated as 6.7 MPa for a peak burn-up of 100 GWd/t (for 100% fission gas release) which is considered for temperature limit estimation. Clad thickness at EOL is arrived at 0.39 mm after taking into consideration of loss of thickness due to FCCI and sodium corrosion and the fabrication tolerance for the clad [1].

(b) At high temperatures, because of the inter diffusion of fission products and clad composition, a low melting eutectics forms at the interface. This penetrates through the clad and reduces the strength of clad by further thinning it. Hence, this is considered in temperature limit estimation [5].

(c) The creep rupture correlation of T91 material for transient events is not available. Hence, in the present analysis, the steady state peak temperature is used for the time to rupture estimation which is conservative in nature [6]. The creep rupture properties of T91 are taken from RCC-MR code after accommodating for irradiation effects.

4.1. Temperature dependent cladding penetration rate

Literature data reveals that for ternary metal fuel (U-Pu-10%Zr) with HT9 cladding and other fuel-cladding pairs; the rate of liquid-phase penetration is given by [7],

$$S = \exp\,[A+Q/RT]$$

Where S = rate of liquid-phase penetration, µm/s

A = constant = 11.65

Q = activation energy, -31.13 kcal/mole

R = gas constant, 1.987 cal/mole-K

T = Temperature, K

Though the above equation is applicable for HT9 alloy, the same is used for T91 material in the analysis. Both the steels are ferritic steel with difference in Cr (12% Cr in HT9 & 9% Cr in T91) & other minor element composition. As the relevant data is not available on T91, the above correlation is used in the analysis which will be subsequently confirmed by irradiation experiments.

4.2. T91 creep rupture properties

As already mentioned, since time to rupture correlation under transients is not available for T91, the steady state temperature rupture correlation is used in the analysis. The creep data is taken from RCC-MR code [8] after accommodating for the irradiation effects (10%). The data provided in RCC-MR gives the rupture stress up to a temperature of 675°C only whereas the transient temperatures may be allowed to reach up to ~800°C. Hence, extrapolation of data is carried out using Larson-Miller Parameter (LMP). Since the ferritic to austenitic transition temperature is more than 800°C, it is assumed that there is no structural change takes place in the T91 material up to 800°C. Also, the life of pin inside reactor is limited to 3 years and the time of transient events is only in the order of few seconds, the extrapolation of creep data up to 800°C as a first approximation is justified.

4.2.1. Developing LMP Master curve for T91

T (log tr + C1) = LMP = constant

where T is clad mid-wall temperature in K

Tr is the rupture time in hours

C1 is the material constant for T91.

Based on the RCC-MR rupture data, the material constant is estimated as C1 = 26.45. With this material constant, a master curve for T91 material is generated i.e. LMP Vs stress to rupture as shown in FIG. 2. The correlation for LMP as a function of rupture stress is arrived at.

The LMP correlation arrived at is given by,

$$LMP = a \times \sigma^5 + b \times \sigma^4 + c \times \sigma^3 + d \times \sigma^3 + e \times \sigma + f$$

Where, σ in MPa

$a = -5.28 \times 10^{-9}$
$b = 6.09 \times 10^{-6}$
$c = -2.71 \times 10^{-3}$
$d = 0.593$
$e = -85.6368$
$f = 31064.816$

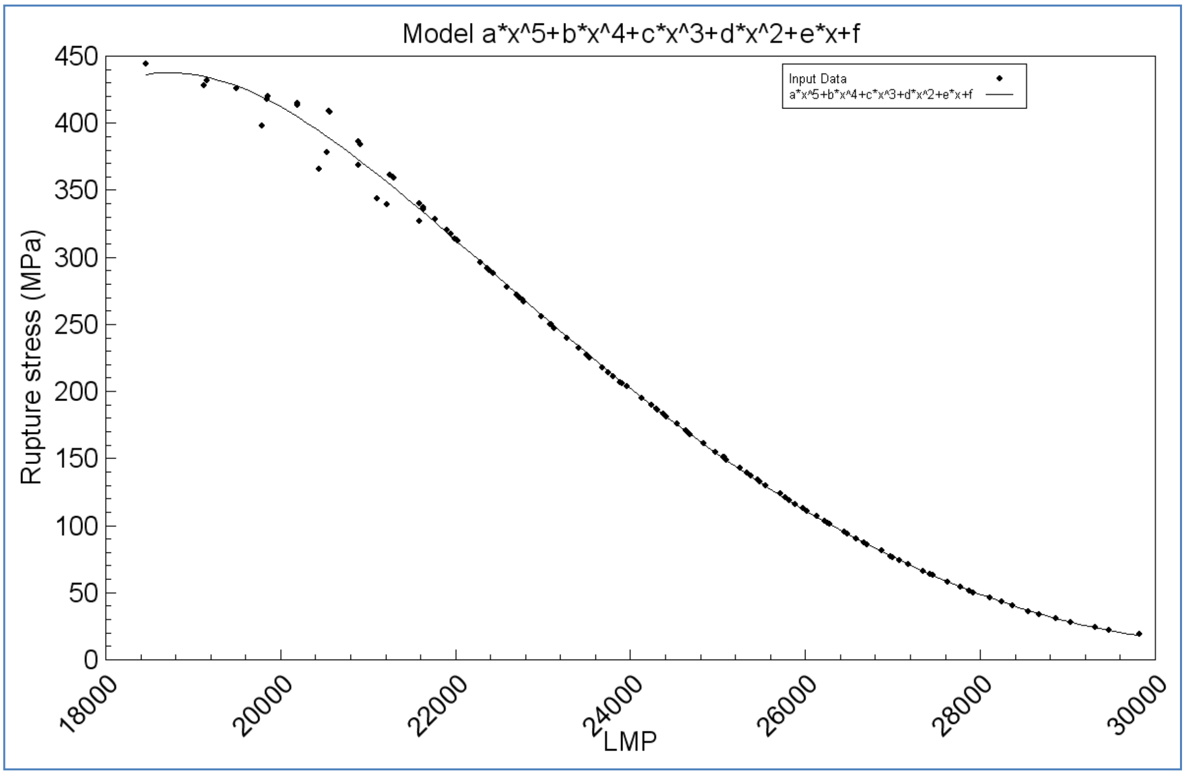

FIG. 2. Master curve for T91 material with C1 = 26.45

4.3. Category -2 temperature limit for clad

For category-2 events, the time of operation is considered as 30 minutes as discussed earlier. For this time period, the clad inside hotspot temperature is incremented (and the corresponding clad mid-wall temperature is determined) till target CDF of 0.25 is reached. For this estimation, reduction in clad thickness due to liquid phase penetration is considered and also appropriate factor of safety is used in the rupture stress estimation. Based on the analysis, for a CDF of 0.25, the clad inside hotpot temperature needs to be limited to 720°C (993 K) for category – 2 transient events.

4.4. Category -3 temperature limit for clad

For category-2 events, the time of operation is considered as 30 minutes. For these 30 minutes with category -2 temperature limit of 993 K, the clad thinning is found out as 28.6 microns. Hence, for a category-3 event after passing through Category-2 event, the starting clad thickness is 0.39-0.0286 = 0.361 mm.

For category-3 events, the time of operation is considered as 2 minutes as discussed earlier. For this time period, the clad inside hotspot temperature is incremented (and the corresponding clad mid-wall temperature is determined) till target CDF of 0.25 is reached. For this estimation, reduced clad thickness due to liquid phase penetration is considered and also appropriate factor of safety is used in the rupture stress estimation. Thus for a CDF of 0.25, the clad inside hotpot temperature needs to be restricted to 770°C (1043 K) for category – 3 transient events.

Literature data [9] also reveals that the onset of fuel-cladding eutectic formation starts at 700-725°C range, depending on the fuel alloy and cladding types. However, at this onset temperature, not much fuel-clad interaction occurs. In fact, even at 100°C above the eutectic temperature, the eutectic penetration in to the cladding is only minimal for an hour. Only at much higher temperatures, close to the fuel melting point, the eutectic penetration in to the cladding becomes rapid. Therefore, eutectic formation is not a primary safety concern during transient overpower conditions. Thus, the choice of transient temperature limit of 770°C for category -3 event is justified.

4.5. Category-4 event temperature limit for clad

For category-4 events, the clad temperatures will be very high and the liquid phase penetration rate is very high which will cause clad to fail. Hence, CDF is not allotted for this event. For this event, fuel pin failure is allowed but the fuel pin geometry should be maintained for cool-ability. A similar philosophy was adopted in the case of MOX fuelled PFBR [1].

While arriving at the clad temperature limit for category-4 event, it is necessary to respect the condition that the bond sodium inside the metal fuel pin should not cross its boiling point at the corresponding bond gas pressure. For the category-4 events, the clad temperature limit is arrived at as 970°C which has a 200°C margin over the category-3 temperature limit. For a fresh pin, the fill gas pressure at BOL at operating temperature is ~ 0.4 MPa and hence it is assumed that the bond sodium will not reach its boiling point (1057°C) for a clad temperature limit of 970°C. Also, this limit on clad will also not allow the coolant boiling in the SA as the boiling point of flowing sodium is ~ 942°C (at a static pressure head of 0.17 MPa prevailing at the active core top). Based on the above facts, the clad temperature limit for category-4 event is arrived at as 970°C.

5. Transient temperature limit for coolant

As a design philosophy, bulk coolant boiling is not allowed for all categories of events. For category-3 event, the clad inside hotspot temperature is restricted to 770°C which will automatically restrict the sodium temperature to less than its boiling point. For category-4 event, even though the clad temperature limit of 970°C will restrict the flowing coolant boiling in the SA (at the corresponding pressure head), there can be local boiling (hotspots) but the bulk coolant temperature should be less than its boiling point.

6. Discussion

Based on the above analysis, the design safety limits for the metal fuelled reactor has been arrived at for various categories of events for fuel, clad and sodium and are tabulated in Table I.

TABLE I: DESIGN SAFETY LIMITS FOR A METAL FUELLED REACTOR

Parameter	**Category -1 event**	**Category -2 event**	**Category -3 event**	**Category -4 event**
Fuel centerline hotspot temperature	$< T_{melt}$			Partial fuel melting is allowed but coolable geometry shall be preserved
Clad inside hotspot temperature, °C (K)	650 (923)	720 (993)	770 (1043)	970 (1243)
CDF	0.25	0.25	0.25	-
CDF of 0.25 is assigned for storage and handling				
Sodium (Coolant) temperature	No Bulk Coolant Boiling No burnout in local hotspots			Local boiling may occur but the bulk coolant temperature should not cross its boiling point

The fuel temperature limits are respected when the clad temperature limits are strictly followed i.e. for category-3 event, the clad inside hotspot temperature is restricted to 770°C which will automatically restrict the fuel centerline hotspot temperature to less than its melting point since the temperature drop in bond medium (sodium) and in fuel (high thermal conductivity) is minimum. For category -4 event, clad temperature limit is specified as 970°C. For this event, partial fuel melting is allowed. This is allowed based on the fact the clad melting point is higher than that of fuel and hence coolable geometry will be maintained.

The preliminary design safety limits for metal fuelled reactor are arrived at based on certain assumptions as given below:

- Rate of liquid phase penetration correlation used is for HT9 alloy and not for T91.
- Irradiated creep rupture properties for T91 are not available. Hence, 10% reduction in rupture properties is considered for analysis which will be confirmed by irradiation experiments.
- Creep properties for T91 are available up to 675°C only and extrapolation using LMP is done for temperatures up to 800°C with an assumption that there are no structural changes in T91 material up to 800°C.

These assumptions will be confirmed with out-of-pile and in-pile experiments.

7. Conclusion

Towards the metal fuel program, a 500 MWe Fast Reactor with metal fuel is planned. The design safety limits for the normal and anticipated transient events have been arrived at for a metal fuelled reactor and is addressed in this paper. In this paper, preliminary temperature limits for various categories of events are determined based on the literature and analysis. For category-2 event, the clad inside hotspot temperature is limited to 993 K, for catergory-3 events, it is restricted to 1043 K and category-4 event, it is restricted to 1243 K. Similarly, the limits for fuel and coolant are specified. These limits will be fine tuned based on the out of pile and in-pile experiments planned in the future.

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