Effect of Inlet Temperature and Operating Linear Heat Rating (LHR) on the Maximum Achievable Burnup of MK-1 Carbide Fuel in FBTR

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Abstract. India has been operating Fast Breeder Test Reactor (FBTR) with Mixed Carbide Fuel as the driver fuel since 1985. Mixed Carbide was chosen as the fuel due to its high stability with Pu rich fuel, compatibility with coolant and for its better thermal performance. Being a unique fuel of its kind without any irradiation data, it was decided to use the reactor itself as the test bed for this driver fuel. The fuel has performed extremely well, with the peak burn-up reaching 165 GWd/t. The Linear Heat Rating (LHR) and burnup of the fuel was initially set at 250 W/cm and 25 GWd/t respectively. Based on rigorous theoretical analysis and Post Irradiation Examination (PIE) done at 25 GWd/t, 50 GWd/t and 100 GWd/t burnup intervals, the LHR limit was raised to 400 W/cm and allowable burn-up was raised to 165 GWd/t. The burnup limit of the fuel SA comes from the following factors: Wrapper dilation; Wrapper residual ductility; Fission gas pressure and Fuel Clad Mechanical Interaction (FCMI) induced stress in pin; Clad strains; Clad residual ductility; Clad Cumulative Damage Fraction (CDF); coolant flow reduction through subassembly, etc. For major part of the FBTR operation, the peak LHR was maintained at 320 W/cm at a lower inlet temperature. Presently, the operating parameters like inlet temperature and the peak LHR of the FBTR of MK-1 fuel SA are raised to 400°C and 400 W/cm respectively which would result in different limits on the achievable burnups. In this work, the effect of LHR & inlet temperature has been comprehensively studied on the achievable burnup of the MK- 1 fuel SA. From the analysis, it is observed that the two enveloping parameters that govern the SA life are wrapper dilation and pin CDF. The maximum burnup achievable with an operating LHR of 400 W/cm is 85 GWd/t and 114 GWd/t for inlet temperatures of 400°C and 380 ° C respectively. The reduction in the inlet temperature by 20 °C not only decreases the fuel swelling but also helps in increasing the free swelling phase without FCMI. Thus, this study gives an insight on the behaviour of the MK-1 carbide fuel in FBTR for the present operating conditions of the FBTR and the influence of inlet temperature and operating LHR on the achievable burnup.

Key Words: Mixed Carbide fuel, Burnup limit, Fuel pin life, Wrapper dilation.

1. Introduction

Fast Breeder Test Reactor (FBTR) at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam is a 40 MWt / 13.2 MWe, sodium cooled, loop type fast reactor fuelled with unique plutonium rich mixed carbide. FBTR was conceived as a test-bed for the irradiation of fuels and materials for the fast reactors and a training ground for mastering the challenges of sodium technology. FBTR was made critical on 18th October 1985.

The Linear Heat Rating (LHR) and burnup of the fuel was initially set at 250 W/cm and 25 GWd/t respectively. Subsequently LHR and coolant inlet temperature was gradually raised to 400 W/cm and 400°C. The peak burnup was also gradually increased to 165 GWd/t by carrying out analysis coupled with the verification of its behaviour by Post Irradiation Examination (PIE) on the subassemblies (SA) which were discharged at 25, 50, 100 & 155 GWd/t burnup. The peak burnup of 165 GWd/t could be achieved due to moderate LHR & inlet temperature of operation in the initial stages. Since it is desired to operate FBTR at its rated conditions of 400°C inlet with LHR of 400 W/ cm, the behaviour of the fuel is expected to be different. This warrants a new estimate on the allowable burnup. For determining the burnup limit, it is required to know the various life limiting phenomena for the FBTR MK-1 fuel. These aspects have been analysed with the indigenously developed codes, which are validated against the PIE results, and the burnup limit is determined. The details of the analysis carried out and approach to fix the achievable burnup is discussed in this paper. The schematic of the FBTR MK-1 fuel SA is shown in FIG. 1. The geometrical parameters and operating conditions of FBTR are indicated in the FIG. 1 and TABLE I respectively.

TABLE I: OPERATING CONDITIONS

Coolant Temperature	Reactor Inlet	400 ºC
Peak LHR	At core center	400 W/ cm
Flux ($n/cm^2/s$)	Active core bottom	$1.25*10^{15}$
	Active core center	$1.71*10^{15}$
	Active core top	$0.98*10^{15}$
Peak Fluence at (E>0.1 Mev) , (n/cm^2)/(dpa)	100 GWd/t	$0.783*10^{23}$ / (56)
	150 GWd/t	$1.17*10^{23}$ / (84)

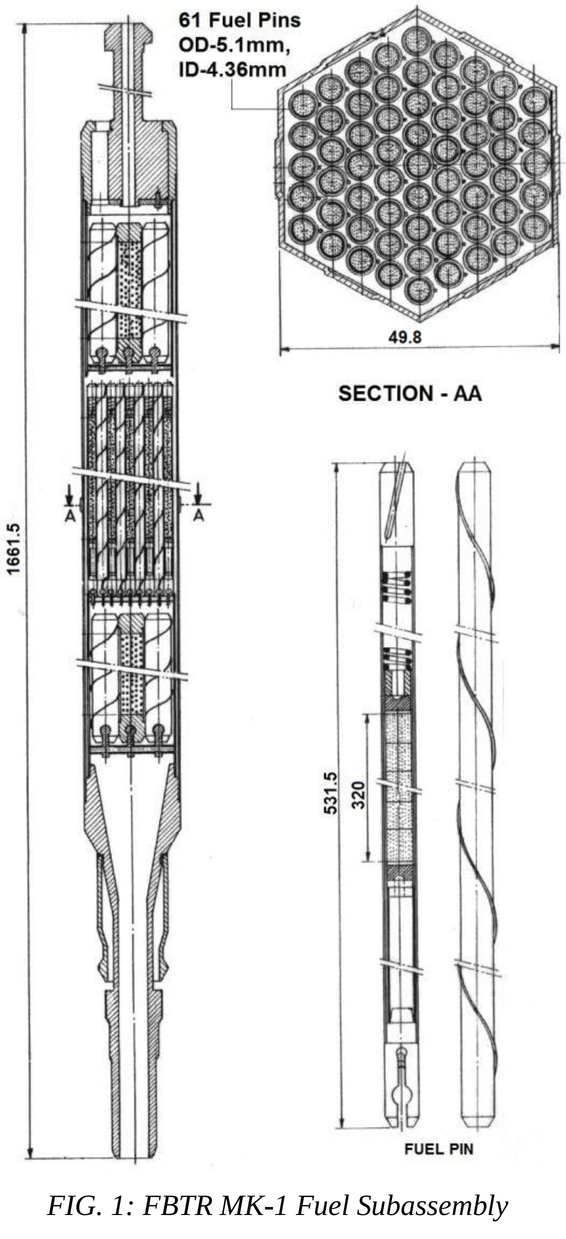

FIG. 1: FBTR MK-1 Fuel Subassembly

2. Analysis Details

The burnup limit of the fuel SA is restricted from the following factors:

- Wrapper dilation;
- Wrapper ductility;
- Fission gas pressure & FCMI induced stress in pin;
- Clad strains and subassembly flow reduction;
- Clad ductility;
- Clad Cumulative Damage Fraction (CDF);

Effect of each factor on limiting the burnup of the SA is evaluated and discussed in the following sections.

2.1. Wrapper Dilation

Dilation of the hexcan duct (increase in width across flats) is caused by creep due to internal coolant pressure and also due to neutron induced void swelling. The dilation of hexcan reduces the inter SA gap and thus dictates the force required to retract the SA from the core during fuel handling operations. Since the temperatures of the wrapper is in the negligible thermal creep regime, only irradiation induced creep is considered in this analysis. The increase in width across flat due to dilation is adopted from Charak et. al. [1], which is given as follows:

$$\Delta W = \frac{W_i \chi}{W_i + 5\chi} + \frac{(W_i + 2t)}{300}\left[\frac{\Delta V}{V}\%\right]$$

Where, $\chi = 0.00695 * P * \frac{W_i^4}{t^3} k$

P = Internal coolant pressure, MPa
t = Thickness of the wrapper, mm
k = Creep Compliance = ε/σ, MPa^{-1}
W_i =Wrapper inside width across flat, mm
% $\Delta V/V$= Percentage volumetric swelling

The above equation is derived from the fixed beam theory which is subjected to uniform load. The coolant pressure inside the SA induces a bending stress on the wall of hexcan duct and makes it to bend outward. Each side of the duct is assumed as a fixed wall with supports at corners. The coolant pressure decreases from active core bottom to top due to pressure drop in the pin bundle during flow. Hence, the bending stresses are maximum on the duct wall at core bottom and decreases almost linearly to the top of the core. The neutron dose follows the flux profile and is maximum at the core center. The correlations to calculate void swelling and irradiation creep based on neutron dose and stress for the 20% cold worked material is adopted from the references [2,3,4,5,6]. Though the nominal gap between the SAs is 1 mm, the minimum gap is only 0.7 mm taking into consideration of the tolerances. For the permissible dilation estimation, minimum gap of 0.7 is only considered. The dilation pattern of wrapper depends on local wall temperature of the duct, stress and dose which in turn depends on the inlet temperature of the Reactor, mass flow rate and operating LHR. The dependence of the inlet temperature and LHR on the achievable burnup is shown in FIG. 2 and FIG. 3 respectively. The analysis indicates that for a case of 400°C inlet and 400 W/cm LHR, the minimum gap of 0.7 mm is getting closed at 103 GWd/t. The dilation pattern of the wrapper along with its components at the 103 GWd/t burnup is shown in FIG. 4.

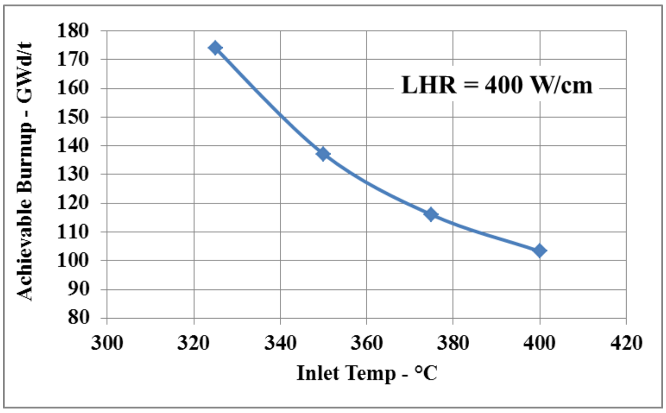

Fig. 2: Variation of achievable peak burnup from wrapper dilation as a function of inlet temperature

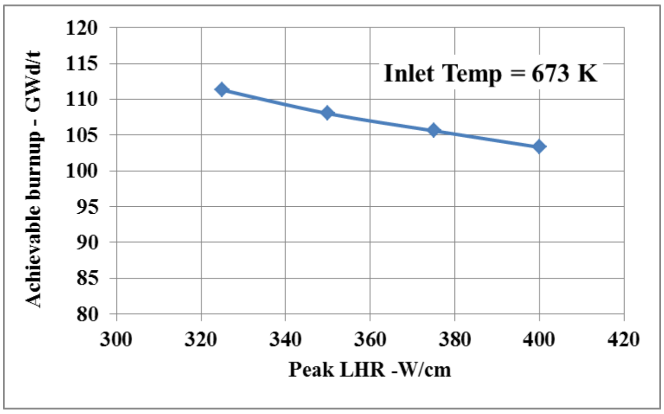

Fig. 3: Variation of achievable peak burnup from wrapper dilation as a function of LHR

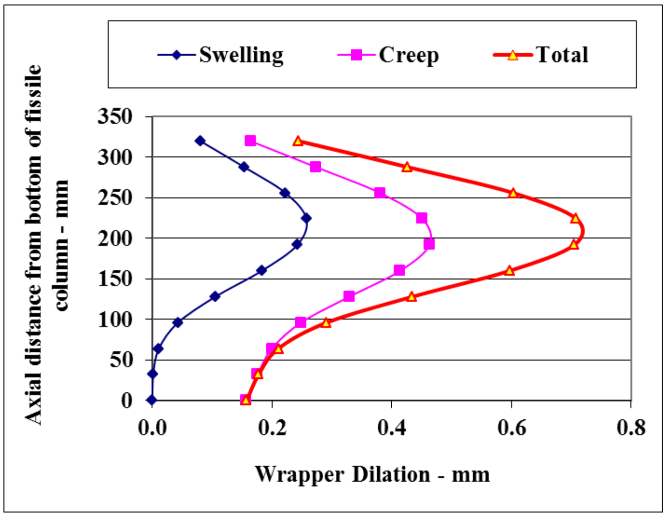

FIG. 4: Estimated dilation pattern for FBTR MK-1 wrapper at 400 °C inlet and 400 W/cm LHR at 103 GWd/t burnup

2.2.Residual Ductility

The ductility of the wrapper decreases due to embrittlement and irradiation hardening. Since the material is already cold worked, and at wrapper irradiation temperature, the irradiation hardening is not much expected to be pronounced. Whereas, reduction in wrapper ductility due to embrittlement is a concern. Ductility loss can be correlated with the observable parameters like void swelling. Based on the various tests carried out on the structural materials for the prediction of ductility as a function of burnup [7], it is observed that at volumetric swelling of ~6 %, the total and uniform elongations converge. Even after 6% void swelling, sufficient ductility is reported in PIE. Nil ductility may result between 10% to 16% void swelling depending up on the compositional variations and irradiation conditions for 316 grade steel.   For MK-1 SA wrapper, which was irradiated initially at an average LHR of 320 W/cm and 320 ^{0}C inlet temperature, the peak volumetric swelling was 3.5 % and the reported uniform elongation as 9.8 ± 2.5% [8] which is in line with the respective literature values. The peak dose and burnup corresponding to the above values is 83 dpa and 155 GWd/t. The estimated maximum achievable burnup at higher operating conditions with the above limit of 6% on swelling is 141 GWd/t. Hence, based on residual ductility limit, 141 GWd/t burnup is achievable.

2.3.Fission Gas Pressure, FCMI and Hoop Stress

The fission gas release and its pressure are highly dependent on the operating temperature and local burnup of the pellet. In general, fission gas release increases with the temperature and burnup. At a threshold burnup of around 2 at %, fission gas accumulated in the pellet releases in to the plenum once a saturation of fission gas in the fuel matrix has been reached. The breaking of the grain boundaries due to bubbles joining leads to a sudden increase in the release rate. A typical average fission gas release at 400 W/cm LHR and 400°C inlet temperature as a function of burnup is shown in FIG. 5. The estimated release starts around 20 GWd/t burnup and reaches maximum of 25 % at 60 GWd/t burnup but decreases to 22 % due to decrease in the fuel temperature because of the pellet-clad gap closure. The maximum pin pressure under hot condition is 4.5 MPa at the end of 100 GWd/t and 6.2 MPa at the end of 150 GWd/t. The clad is stressed by the internal gas pressure right from BOL. Whereas FCMI starts only after the interaction load exceeds the gas pressure inside the pin. Hence,while calculating the FCMI stress, fission gas pressure component is also included in that. For the stress calculation, only fission gas pressure is considered till the onset of FCMI and after that fission gas pressure or FCMI whichever is higher is considered. The maximum hoop stress on the clad due to fission gas induced pressure (primary stress) or FCMI induced stress (secondary stress) is 100 MPa which is lesser than the allowable limit. Hence, the stress induced from the fission gas pressure or FCMI does not dictate the achievable burnup.

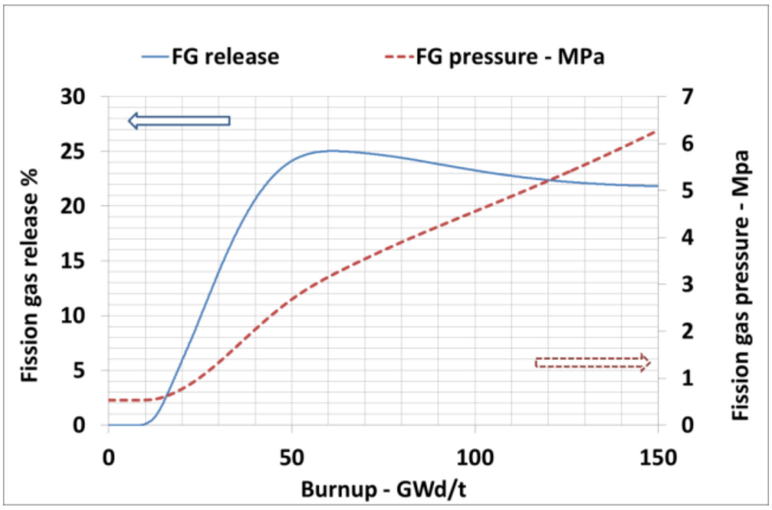

FIG 5: Average fission gas release in the pin at 400 W/cm and 400°C inlet

2.4.Clad Strains and Flow Reduction

Clad strain consist of thermal strain, creep strain and swelling strain. Thermal strain becomes zero after shutdown of the reactor. Whereas, creep and swelling strains are permanent. Hence, the total permanent strain is the summation of creep and swelling strains. The total permanent strain computed at the end of 103 GWd/t is 2.5 % and 0.1 % at core mid and core top respectively. At the end of 150 GWd/t burnup, the computed permanent strains on the clad are 7.4 % and 0.65% at core mid and top respectively. The above clad strains can be able to accommodate in the dilated wrapper without bundle wrapper interaction. The results are shown in FIG. 6. At the burnup of 103 GWd/t, the flow reduction is 2.1 % and at the end of 150 GWd/t, the flow reduction is 5% which is well within the margins. Thus, the clad strains and consequent flow reduction is unlikely to restrict the FBTR MK-1 SA burnup.

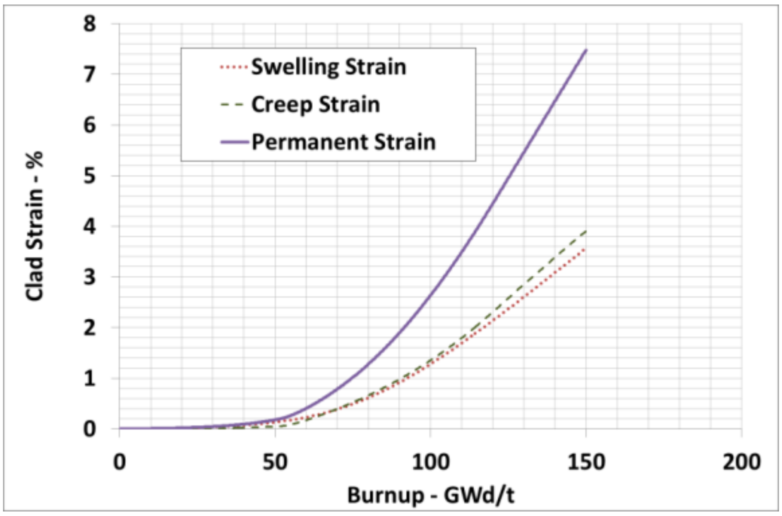

FIG. 6: Clad strains at middle of the active core

2.5.Clad Ductility

Ductility variation in the clad can be estimated by the measure of volumetric swelling which is similar to that of wrapper discussed in section 2.2. For FBTR MK-1 SA which undergone a burnup of 155 GWd/t, the peak clad swelling observed is 11.4 % at 160 mm from the active core bottom. It is reported that at ~16 % void swelling, nil ductility may result. Taking a limit of 10 % as swelling limit on the conservative side, from ductility exhaustion point of view, the pin can be allowed up to 140 GWd/t for the new operating conditions.

2.6.Cumulative Damage Fraction

For pin life estimation CDF approach is being followed in this work. CDF is a life fraction rule for the estimation of the damage in case of varied operating conditions. Damage is estimated cumulatively with the ratio of time of operation and time to rupture. The time to rupture of the clad is a function of clad stress and clad temperature which has been synthesized from the irradiation data. The hoop stress in a clad is caused by fission gas induced pressure or FCMI induced pressure. FG pressure is a primary stress while FCMI is a secondary stress as it relaxes with clad strain. Due to operation of the fuel pin at higher LHR and inlet temperature, the swelling of the fuel is more. Hence, considerable FCMI is noticed on the clad after the gap closure. The hotspot clad temperature for higher operating conditions at the top of the active core is 956 K and at core mid it is 867 K.

The variation of CDF at 400°C inlet and 400 W/cm LHR as a function of burnup and axial locations is shown in FIG. 7. The CDF reaches 1 at 240 mm axial location at a burnup of 85 GWd/t under hotspot conditions. While at nominal temperature conditions, the damage is only 0.32 at the end of 150 GWd/t burnup. At active core top, the CDF reaches 1 at 110 GWd/t burnup in hotspot and 121 GWd/t in nominal temperature conditions. The rapid increase in the CDF at certain locations is due to the onset of FCMI. The FCMI on the clad is a strong function of the relative swelling and creep between fuel & clad. Clad swelling relaxes out the FCMI whereas fuel swelling increases the FCMI. Clad swelling is expected to be low at top of the core due to low dose as well as high temperature. But fuel swells typically high in between the core mid and top and thus leading to more interaction and CDF.

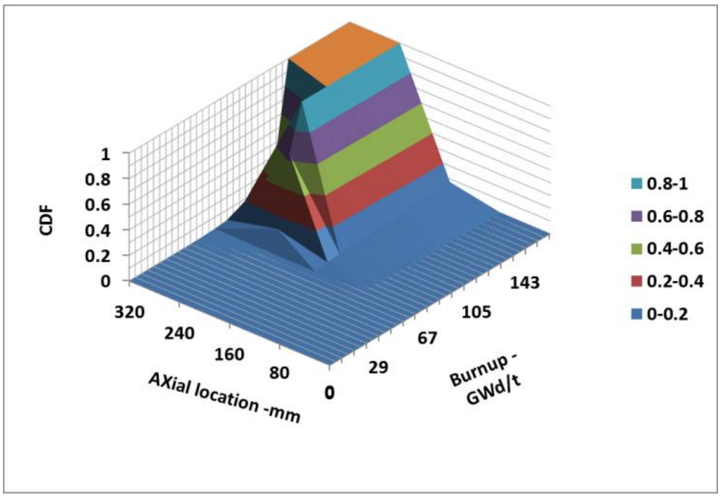

Fig. 7: Variation of CDF along the axial length as a function of burnup

In the current FBTR core, the operating history of many of the SAs was varying with time history (burnup). A parametric study has been carried out to find out the achievable burnup from CDF point of view for different conditions. A possible matrix of LHR and core inlet temperatures for various reactor operation conditions from BOL till its EOL was worked out wherein CDF=1. The allowable burnup from pin point of view with inlet temperature of 350, 380 and 400 °C at a constant LHR of 325, 350, 375 and 400 W/cm are shown in FIG. 8. From FIG 8, it is observed that, as expected at lower operating conditions, the achievable burnups are higher than 150 GWd/t. The analysis is limited to 150 GWd/t as the performance validation of the code needs further confirmation from PIE results beyond that. At 400 W/cm LHR and 400 °C inlet temperature, CDF reaches unity at 85 GWd/t burnup under hotspot temperature conditions.

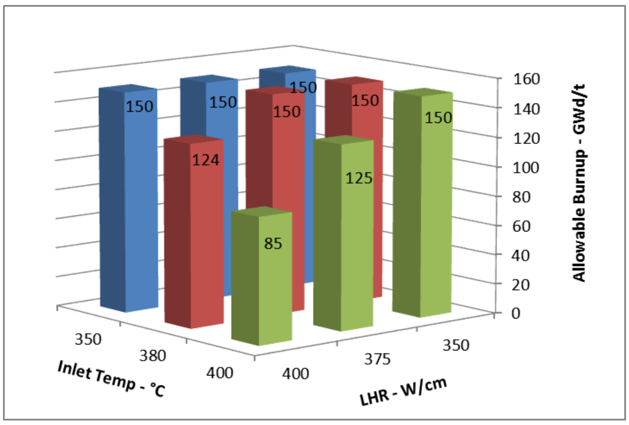

FIG. 8: Allowable burnup as a function of burnup and LHR

3. Effect of inlet temperature and LHR on the achievable burnup

It is observed in the FIG. 8 that decrease in LHR or inlet temperature increases the achievable burnup. Further to quantify the sensitivity of the achievable burnup based on the individual parameters like wrapper dilation and pin CDF, an analysis was carried out by varying LHR at constant inlet temperature and vice versa.

The achievable burnup as a function of inlet temperature and LHR are shown in FIG. 9 and FIG. 10 respectively. From the figures it is observed that, with increase in LHR or inlet temperature, the decrease in the pin life is of comparable order. But, in case of wrapper dilation, increase in inlet temperature has dominant effect than increase in LHR. This is because of increase in LHR, the proportional increase in wrapper temperature at core mid is not observed.

It is also found out that at lower inlet temperatures, the achievable burnup is dictated by wrapper dilation limit and at higher inlet temperature, pin life dictates the achievable burnup. Hence, up to 380°C inlet temperature, wrapper dictates the SA life and beyond that pin dictates the SA life. Hence, decrease in the inlet temperature to 380 °C and operate at LHR of 400 W/ cm maximizes both the power and burnup of the SA.

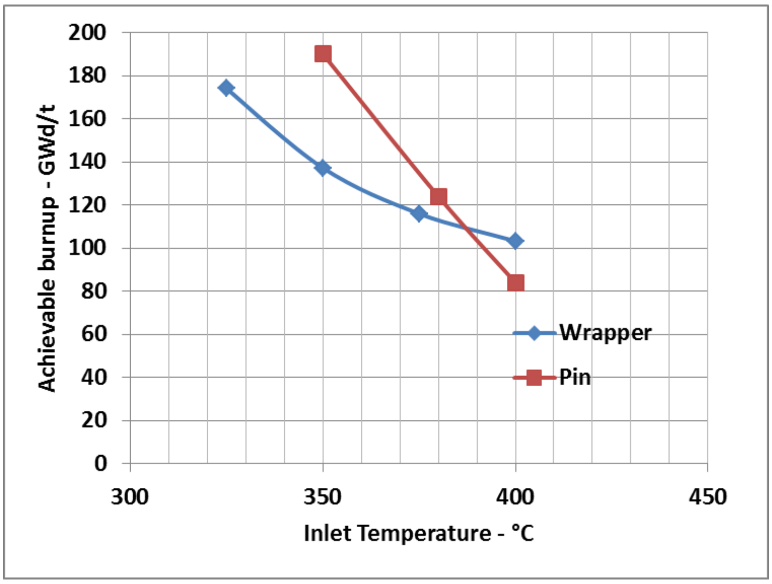

FIG. 9:Achievable burnup from wrapper and pin point of view at different inlet temperatures (LHR= 400 W/cm)

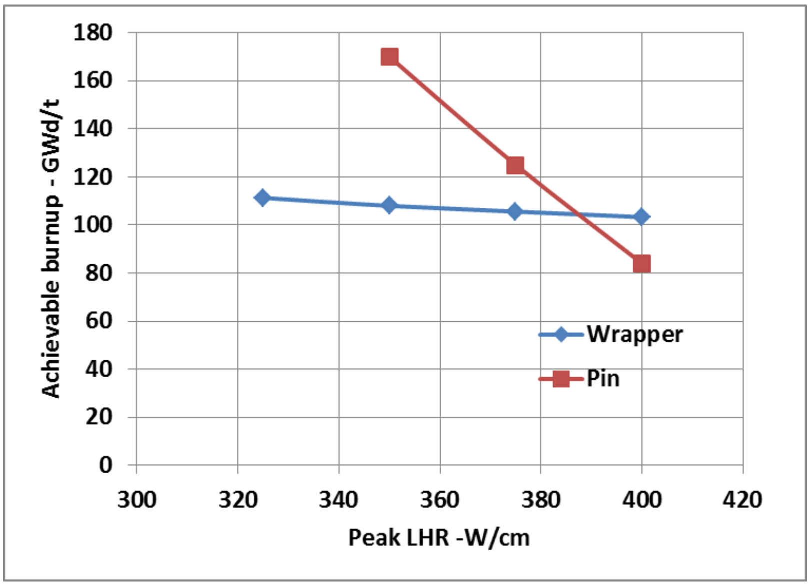

Fig. 10: Achievable burnup from wrapper and pin at different LHR (Inlet temperature = 400°C)

4. Burnup Limit for operation at 400 W/cm LHR and 400°C inlet temperature

From the analysis, the burn up limit for SAs operating constantly at an LHR of 400 W/cm with a SA inlet temperature of 400°C from different considerations like wrapper dilation & residual ductility, clad ductility exhaustion & CDF are given in Table II. It may be observed that the minimum burnup limit is determined by the creep damage of the clad due to fission gas pressure and FCMI in excess of fission gas pressure under hotspot conditions. The actual burnup potential of the fuel SA is however much higher under nominal conditions where the temperature substantially influences the fuel swelling. The next burnup limit comes at 103 GWd/t is dictated by the wrapper dilation where sufficient ductility would still be available. Hence, going by the experience obtained so far and also keeping reasonable conservatism, it is planned to irradiate the MK-1 SA operating at constant LHR of 400 W/cm and 400°C right from BOL to a maximum of 103 GWd/t.

TABLE II: BURNUP LIMIT ON MK-1 FUEL FROM DIFFERENT PARAMETERS AT 400 W/CM LHR AND 400°C INLET TEMPERATURE

Parameter	Allowable burnup value, GWd/t
Wrapper dilation	103
Wrapper residual ductility	141
Fission gas pressure and FCMI stress	> 150
Clad residual ductility	140
CDF – Hotspot	85
CDF – Nominal	>150

5. Summary

FBTR MK-1 carbide fuel has been operating so far at various LHR & sodium inlet temperature levels which were lower than the target levels of 400 W/ cm & 400°C respectively. To increase the FBTR power, core is constantly expanded towards its maximum level. Besides, LHR & sodium inlet temperature are planned to be increased to its rated levels.

An analysis was carried out to find out the burnup limit for operating the reactor at an LHR (400 W/ cm) and high inlet temperature (400°C). The minimum burnup limit of 85 GWd/t is arrived at in a conservative manner for a MK-1 fuel pin operating at constant LHR of 400 W/ cm and 400°C right from BOL based on clad hotspot temperatures. This is important in establishing the safety margin. However, It is seen that the MK- 1 fuel pin has the capability to achieve a burnup of 103 GWd/t based on nominal clad temperature and wrapper dilation considerations. Taking into account the various limiting parameters and their influences and the experience obtained so far, it is planned to irradiate the MK-1 SA operating at constant LHR of 400 W/cm and 400°C right from BOL to a maximum of 103 GWd/t. This would give valuable data on the behaviour of mixed carbide fuel at a higher LHR and inlet temperatures from which the potential for carbide fuel operation at higher operating conditions can be ascertained in addition to the confirmation of safety margins.

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