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Design Characteristics of Metallic Fuel Rod on Its In-LMR Performance

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Abstract

Fuel design is a key feature to assure LMR safety goals. To date, a large effort had been devoted to develop metallic fuels at ANL's experimental breeder reactor (EBR-II). The major design and performance parameters investigated include; thermal conductivity and temperature profile; smear density; axial plenum; FCMI and cladding deformation including creep, and fission gas release. In order to evaluate the sensitivity of each parameter, in-LMR performances of metallic fuels are not only reviewed by the experiment results in literatures, but also key design characteristics according to the variation of metallic fuel rod design parameters are analyzed by using the MACSIS code which simulates in-reactor behaviors of metal fuel rod. In this study, key design characteristics and the criteria which must be considered to design metallic fuel rod in LMR, are proposed and discussed.

1. Introduction

In 1983, a concept emerged at Argonne National Laboratory (ANL), called the Integral Fast Reactor concept (IFR), the objective of which was to offer a safe and economical solution to the technical and institutional issues that had inhibited nuclear power from meeting a larger share of the world's energy demands[1]. The IFR fuel cycle is based on pyroprocessing and injection-casting fabrication. The steps in this fuel cycle are few and all processes are extraordinarily compact[2,3]. The technical feasibility of IFR had been demonstrated and the technology database had been established to support its practicality before IFR project was suspended in 1995[4]. Also, metallic fuel properties had provided for the significant breakthroughs achieved by 1994[5]. Metallic fuel appeared to be the most suitable candidate for the integral concept, and the U-Pu-Zr metallic fuel system, which was under development in the late 1960's, was chosen as the candidate fuel because of superior performance characteristics over other metallic fuel systems. By the utilization of small modular fast breeder reactor design concept, the LMFBR power plant with binary (U-Zr) and ternary (U-Pu-Zr) uranium alloy fuel, pool-type reactor configuration, liquid sodium cooling and integral fuel cycle based on pyrometallurogical processing and injection-cast fuel fabrication, has inherent safety and high breeding ratio, and it is also expected to be more economical. Therefore, renewed interest in metallic fuel for FBR has arisen in the USA, Japan, China, and Korea. According to the KALIMER development program, KALIMER with metallic fuel shall be built by the middle of 2010's. KALIMER is to be the first LMR in Korea where a commercial LMR is expected to be operated in 2030's. The base alloy, binary (U-10%Zr) metal fuel is a potential start-up for KALIMER as driver and blanket fuels[6,7]. As mentioned before, metallic fuel properties had provided for the significant breakthroughs achieved by 1994. The good neutron economy of metallic fuel provides for a good neutron economy and effective breeding. This attribute may not appear significant today when energy resources seem plentiful but it does provide a long-term solution if one is needed and no additional development cost[8,9]. The immediate benefit of this property, however, enables minimizing the burnup reactivity swing. This drastically reduces the required control worth such that even with a multiple-rod-runout transient overpower initiator, the passive reactor response limits temperature increase[9,10]. Another metallic fuel property, high thermal conductivity, enables passive response to the loss-of-flow and loss-of-heat sink upset events. Because of the high thermal conductivity, radial temperature gradients in the fuel rod are small and heat stored in fuel slug is small compared to ceramic fuel pellet. In-LMR performances of metallic fuels are reviewed in section 2, by the experiment results in literatures. Also, a sensitivity study on the variation of design parameters for metallic fuel rod is performed by using the MACSIS[7] code in section 3.

2. Irradiation Behavior of Metallic Fuel

Fuel performance issues important to design of advanced LMR systems include fission gas release and swelling, fuel-cladding interaction, axial growth of the fuel and the breach characteristics demonstrated by metallic fuels.

2.1 Swelling and Fission Gas Release

The general swelling behavior for U-Zr and U-Pu-Zr alloys is the increase of fuel pin size versus burnup. Virtually all length increase takes place during a lower burnup interval before the swelling fuel slug contacts the cladding. The leveling-off in axial swelling is thus determined by the fuel-smeared density. The planar smeared density in typically chosen at approximately 75 % to allow sufficient swelling, approximately 30 %, to facilitate fission gas *release from the fuel slug. This much planar swelling world, for isotropic swelling, translate* to a length increase of approximately 5 %[11]. However, the observed length increases are consistently smaller, indicating anisotropic swelling. The main reason for this effect appears to be the difference in swelling behavior between the hotter center of the fuel pin and the colder periphery.

2.2 Fuel-cladding Interaction

Fuel-cladding interaction that may result in cladding failure can be both mechanical and chemical.

2.2.1 FCMI (Fuel-Cladding Mechanical Interaction)

Since the presence of open (interconnected) fission gas porosity appears to be a key feature in reducing FCMI, the question arises as to what the effect of accumulation of low-density solid fission products on this porosity might be at high burnup. The following discussion shows an approximate calculation of the next volume change due to non-gaseous fission product accumulation. The accommodation of the non-soluble fission products predictably results in a volume expansion as a function of burnup.

However, the U and Pu are depleted from the lattice as they fission, resulting in a volume decrease that partially offsets the volume expansion due to fission products. Further, it can be assumed that all the fission product Zr, Nb, and Mo are soluble in the matrix, which in turn compensates for some of the volume decrease due to the disappearance of U and Pu from fissioning. Thus, non-gaseous fission products contribute to the volume change in three ways[11]:

(1) Volume increase due to non-soluble fission products
(2) Volume decrease due to the fissioning U and Pu
(3) Volume increase due to the increase of the Zr, Mo, and Nb, which are soluble in fuel matrix.

To date, the tests of IFR metallic fuel clad in U-Zr and U-Pu-Zr alloys have shown no definitive evidence for FCMI due to the low levels of total strain measured. Present element design allows the fuel sufficient free swelling due to as-built smeared density of about 75 %[11]. Thus, the gas bubble pressure in fuel slug does not transmitted directly to the cladding. The important point is that no unexpected large cladding strain, which would affect pin reliability, has been observed in as-built smeared density (75-80%) fuel with HT-9 clad. As built 75 % smeared density fuel rod allows free fuel swelling of approximately 30 %, at which point porosity becomes largely interconnected and open to the outside of the fuel, releasing a large fraction of the fission gas to a suitably large plenum at the top of the element.

2.2.2 Fuel-cladding Chemical Interaction(FCCI)

FCCI in an all-metallic fuel element is in essence a complex multi-component diffusion problem. It involves the inter-diffusion of fuel and cladding constituents at operating temperatures[12]. Specifically, the inter-diffusion has been characterized by diffusion of Fe and Ni, when available as cladding constituents into the fuel with corresponding diffusion of lanthanide fission products(La, Ce, Nd, Sm, Pr) into the cladding. The inter-diffusion is also characterized by diffusion of cladding alloying elements into the body of the fuel slug. The potential problem of inter-diffusion of fuel and cladding components in essentially two-fold: weakening of cladding mechanical properties and formation of relatively low melting point compositions in the fuel.

Experimental data[11] on diffusion experiments with uranium also lead the researchers to conclude that Ni played an important role in cladding fuel inter-diffusion. Their findings and conclusions are relevant to the newly developed low-swelling cladding material used for the IFR fuel elements, such as HT-9. In the case of basically Ni-free ferritic steel, HT-9, the U_6Fe and UFe_2 type phases form a single zone without the finger-like structure. There exists a eutectic composition between these two phases the temperature of which depends on the concentration of Pu, Ni and Zr in the phases, as well as U and Fe. The eutectic temperature in the Fe-U-Pu-Zr system drops significantly with Pu concentration, which may be explained the lower melting temperatures for the 26 wt% Pu fuel. The melting in this case is also started in the fuel side of diffusion couple[13]. At very high temperatures of 725-800 °C eutectic melting occurs in a short time. The thickness, uniformity, and rate of formation of the Zr layer appears to be the controlling factor. It seems that a thick and uniform Zr layer retards the formation of molten phases, and that the ample availability of Zr, and N in particular, can assure such a layer[13].

3. Parametric Study

3.1 Design tool

MACSIS code is used for present parametric study. MACSIS is metallic fuel performance computer code, which calculates the thermal performance characteristics and dimensional changes of the fuel rods in a fast neutron environment. MACSIS is comprised of a series of subroutines, which model certain liquid metal reactor fuels phenomena. MACSIS code calculates the temperature distribution, thermal expansion, axial growth, and gas release, and the radial redistribution of the fuel alloying elements during irradiation in the metallic fuel slug assuming that the fuel slug is an infinitely long rod concentric with an infinitely long clad. This assumption, together with the assumption of axisymmetry, makes the analysis one-dimensional. The other major assumption is that the conditions of the fuel and its environment are at steady state once an element power is specified. A detailed thermo-mechanical analysis is performed in the radial direction with provisions to specify up to 10 radial rings for the fuel-cladding system. Axial variations in operating conditions are accounted for by inputting powers and fast fluxes for up to 20 fuel axial nodes and one plenum node. Thermally, the axial nodes are coupled through the calculated coolant temperatures. However, axial heat conduction is ignored, and there are no provisions for mechanical coupling between axial nodes, except for calculating rod internal pressure. The heat generated in each segment and released fission gas is accumulated over the segments for calculation of coolant temperatures and plenum pressure.

3.2 Temperature profile calculation

Axial temperature distributions for KALIMER fuel, cladding, and coolant are plotted in Fig. 1 for fresh fuel. The inlet and outlet coolant temperatures of KALIMER are 360 °C and 530 °C, respectively. The outlet temperatures of fuel assemblies are maintained homogeneously by orificing the flow rate through each assembly. Since axial power profile of the pin has a chopped cosine shape, the coolant and cladding temperatures are S-shaped curves and their shapes hardly change during the irradiation. The temperature difference between coolant and cladding is small due to high heat removal rate of the sodium coolant. The temperature drop across the fuel-cladding gap is also small because sodium with high thermal conductivity is filled in the gap. Furthermore, the high thermal conductivity of the metallic fuel slug gives very low thermal gradient in radial direction. Therefore overall operating temperature of metallic fuel pin is very lowly maintained during normal operation of the reactor, and it has a comparatively low stored energy. This facet implies that metallic fuel gives a little thermal shock in the flow channel during RBCB (run beyond cladding breach) operation. Because of high heat removal characteristic of metallic fuel pin, the peak temperature of fuel centerline appears near to the top of the fuel pin. Should the accident sequence proceed to fuel melting, the melting initiates at the top of fuel pin so that molten fuel easily expand into plenum region, this provide a significant source of negative reactivity feedback.

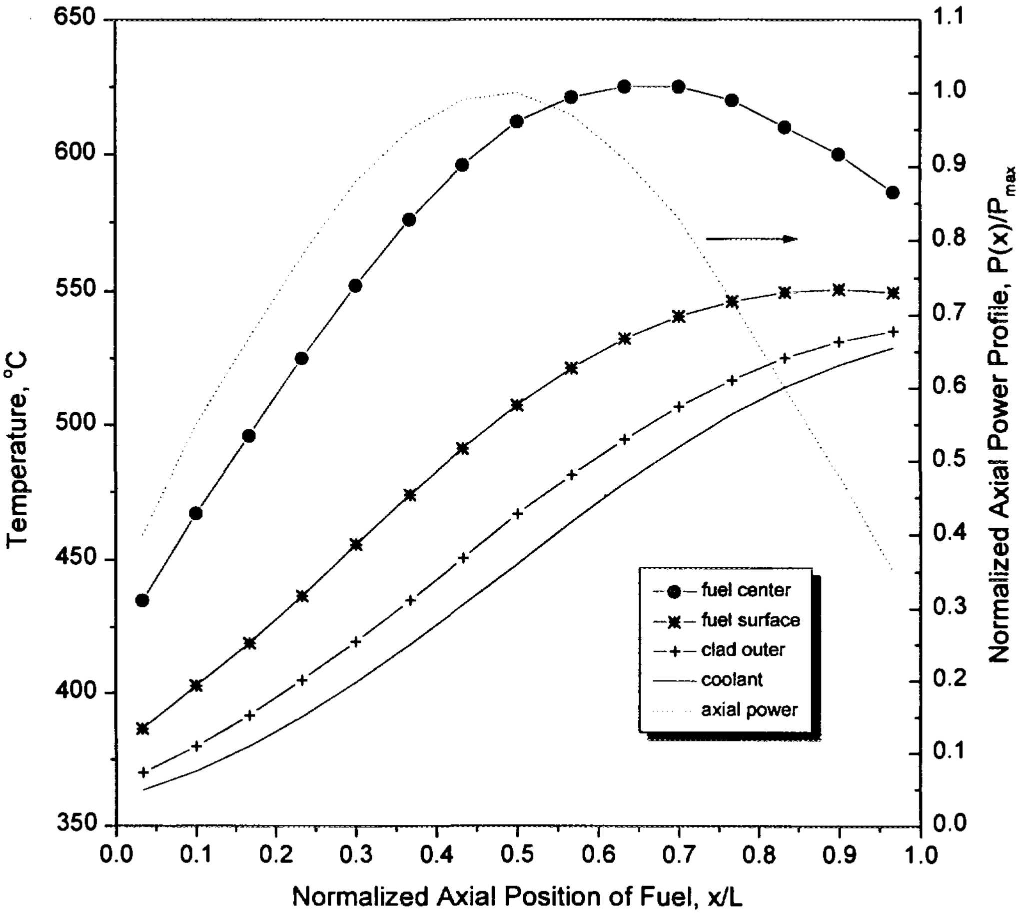

Fig. 1 Axial Temperature Distribution of KALIMER Fuel Pin at Beginning of Life (peak linear heat = 330 W/cm)

Fig. 2 shows several cases of temperature variation with respect to linear heat generation of a typical KALIMER fuel pin. In the design of metallic fuel pin, fuel temperature limits on fuel melting and eutectic/liquid-phase formation should be considered in the temperature point of view. Based on the aggregate of TREAT tests, ANL concluded that centerline fuel melting, even extensive melting exceeding 80 % of a given radial cross-section, is not a problem and does not result in pin failures[14]. However, the prevention of centerline fuel melting is regarded as a design limit of KALIMER fuel pin for conservatism. The solidus temperature of U-10Zr metallic fuel is known as 1240 °C so that the linear power-to-melt for BOL (beginning of life) is around 1240 W/cm by the calculation of MACSIS code. As irradiation proceeds, the thermal conductivity of metallic fuel is degraded down to approximately 50 % of initial condition at around 1.5 at.% burnup. For the further irradiation, the conductivity is restored with bond sodium infiltration into fuel slug. In the case of 50 %

degraded thermal conductivity, which is the worst condition of fuel temperature, the calculated power-to-melt is about 970 W/cm. These levels of power-to-melt are very high compared to those of mixed oxide fuel, and this means metallic fuel has a large safety margin in the reactivity related accidents such as UTOP (unprotected transient overpower).

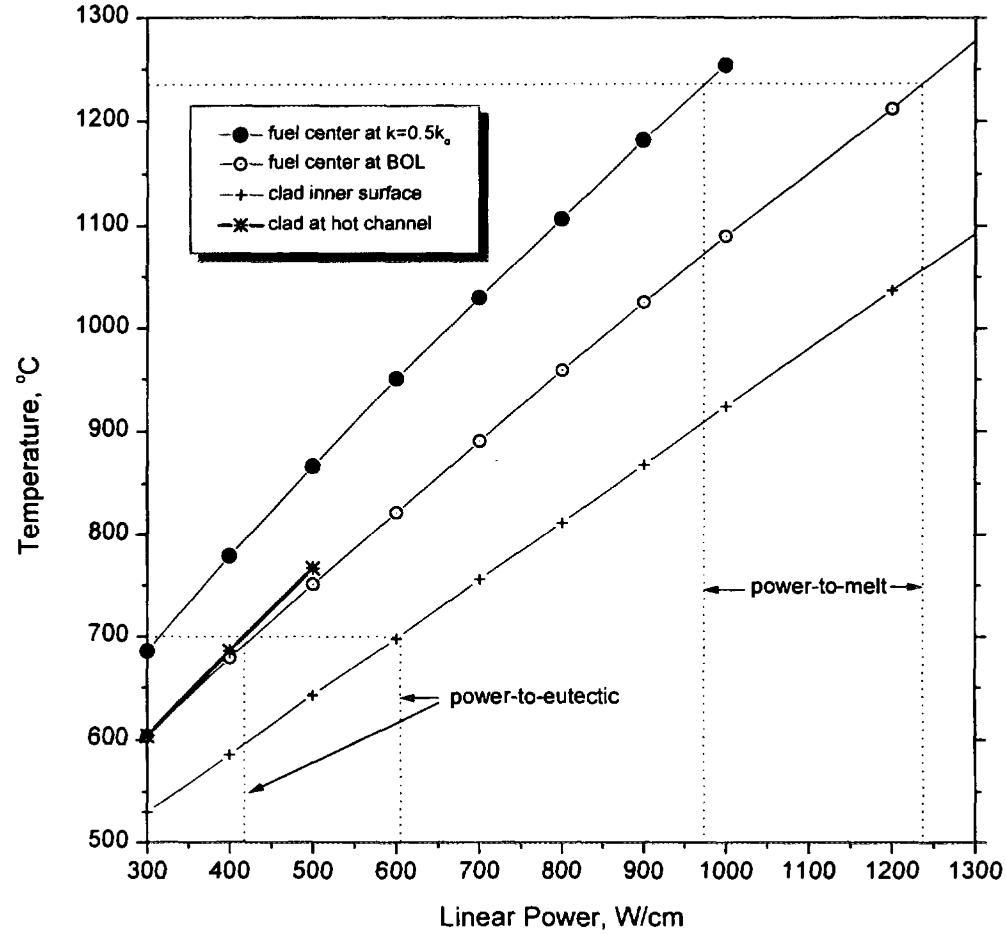

Fig. 2 The Operating Limits on Linear Power Rate for Metallic Fuel Pin in KALIMER.

During irradiation, complicated multi-element metal mixture including fission product is formed at the fuel-cladding interface of a metallic fuel pin. According to the experimental results, no liquid phase has been observed at temperature below 700 °C. Above this temperature, liquid phase is formed at the interface and its penetration reduces cladding thickness. Although the detail mechanism of this behavior is not known yet, it is being revealed that the penetration does not cause an instantaneous failure but proceeds at a certain rate that depends on the composition and temperature of the mixture. Considering this indication, the most conservative criterion that prevents any eutectic reaction during steady state operation is considering in KALIMER fuel pin design. Using the nominal irradiation temperature of KALIMER fuel pin, the calculated power-to-eutectic is about 600 W/cm. If we consider the hot channel temperature of 150MWe KALIMER core, the coolant temperature at top-end of the fuel including +2σ uncertainty reaches 593 °C. In this case, the power-to-eutectic is decreases to about 420 W/cm. The linear power of KALIMER fuel pin is not determined yet, but the limiting pin power including overpower rate will be around 420 W/cm based on above analysis.

3.3 FGR and rod internal gas pressure

The cladding strain of fuel pin with the high-smeared density is primarily creep strain due to FCMI. The cladding strain of the low-smeared density can be accounted for by the plenum pressure stress alone, which confirms[11] that FCMI is virtually nonexistent in suitably designed metallic fuel rods and that cladding stress is determined by the fission gas pressure in the interconnected porosity.

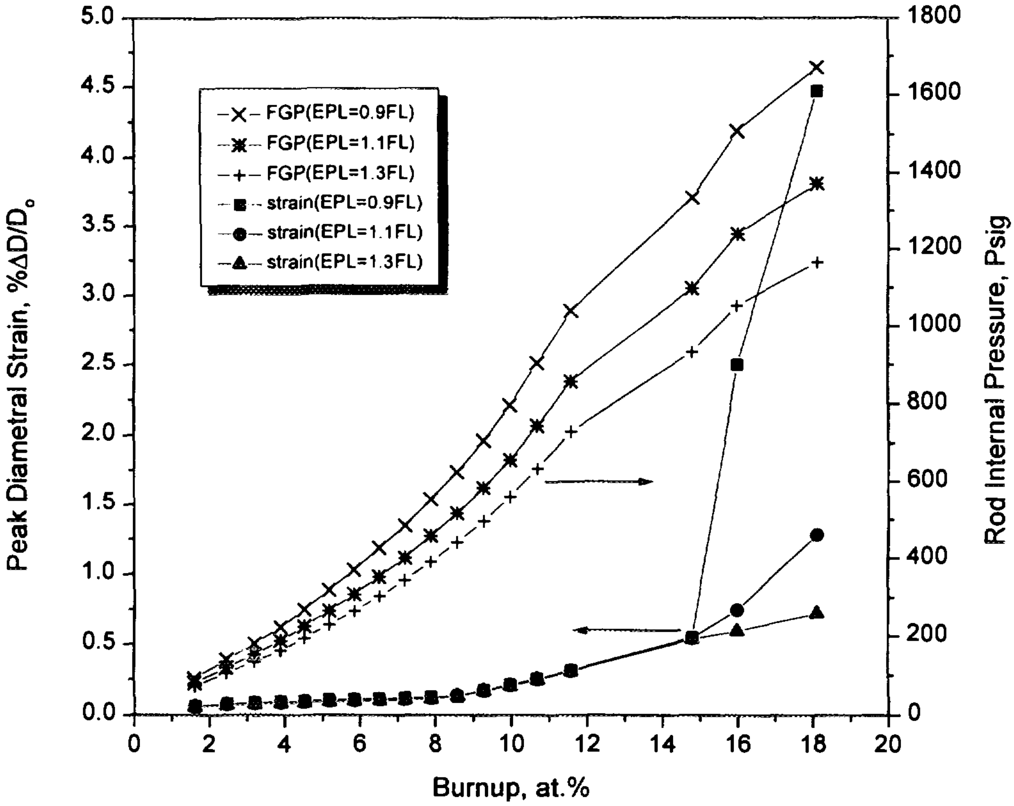

Fig. 3 The Evolution of Total Strain and Rod Internal Gas Pressure with Burnup According to the Variation of Different Plenum Sizes

The effects on total diametric strain and rod internal gas pressure with different plenum sizes were analyzed by MACSIS code. Fig. 3 shows that the evolution of total strain and rod internal gas pressure with burnup according to the variation of different plenum sizes, under very high operation condition with peak clad mid-wall temperature of 653 °C. As shown in Fig. 3, the deformations at below range of 14 at.% burnup are less than approximately 0.5 % in every cases. Apparently little diametric strain has occurred in case of 1.3 times plenum as the length of fuel core, which shows that the deformations at below range of 18 at.% burnup are only approximately 1 % or less. Less plenum length gives larger total diametric strain and rod internal gas pressure. However, in case of 0.9 times plenum as the length of fuel core, total diametric strain was largely increased up to 4.5 % at 18.1 at.% burnup.

3.4 Smear density and cladding strain

The effects on total diametric strain with different smeared-densities were analyzed by MACSIS code, to evaluate the effective smeared-density value at which significant FCMI does occur. Because the five types of different smeared densities differ mainly in the clad strains behaviors. Fig. 4 shows that the evolution of total strain with burnup for different smeared densities, under very high operation condition with peak clad mid-wall temperature of 659 °C. Peak fuel surface and clad-inside temperatures were 668 and 667 °C, respectively. Total diametric strain is generally increased as the smeared density increases.

Apparently little FCMI has occurred in both cases of 72 % and 76 % smeared-densities, which shows that the deformations at below range of 18 at.% burnup are only approximately 1.7 % or less. This means no FCMI is occurred in the fuel pin with high-smeared density. Maximum total diametric strain in case of 80 % smeared-density is approximately 3 %, the level of this strain is acceptable by a narrow margin. However, in cases of 84 % and 88 % smeared-densities, total diametric strains were largely increased up to approximately 5 % at 9.8 at.% at the burnup of 17.5 at.%, respectively. It may conclude that total diametric strains are largely increased when the smeared densities are over than 80 %.

Below 550 °C of cladding temperature at normal operating conditions, it appeared that there were no big differences of total diametric strain with burnup for different smeared densities for which were analyzed in this study. In all cases of these, the integrity criteria of clad are largely satisfied.

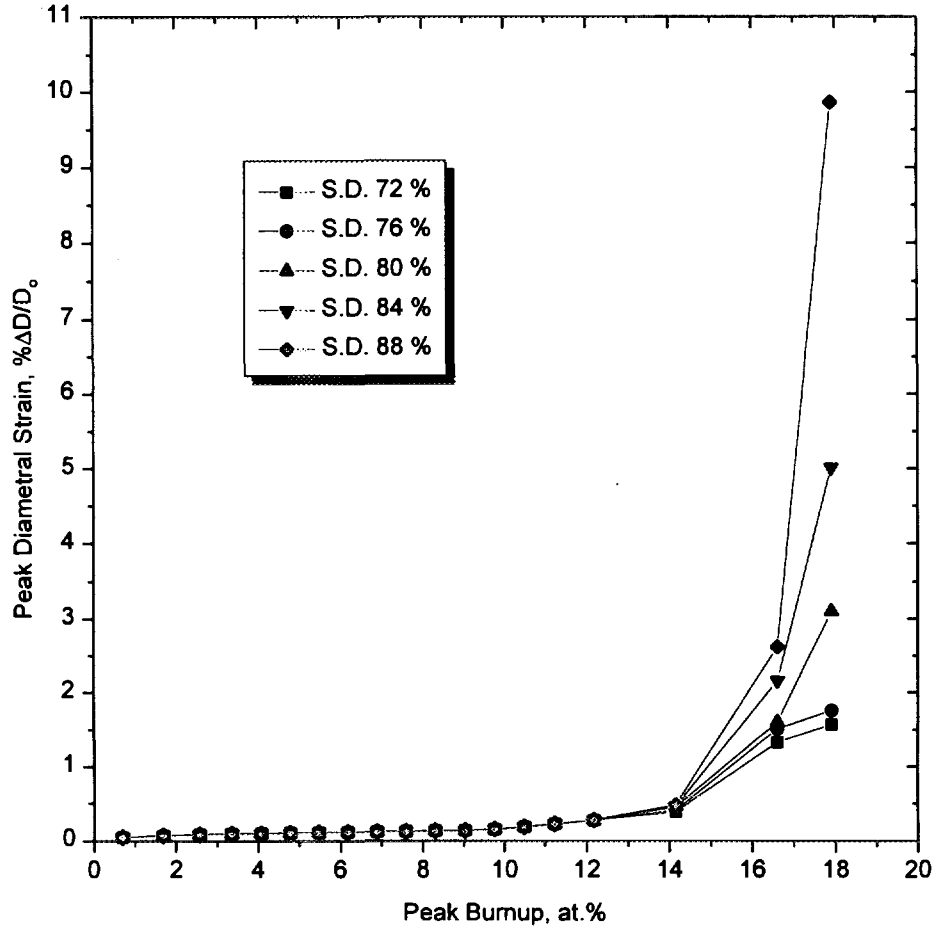

Fig. 4 Evolution of Total ΔD/D with Burnup for Different Smeared Densities

4. Conclusion

Key performance issues important to the design of metallic fuel system for advanced LMR include fission gas release and swelling, fuel-cladding interaction, axial growth of the fuel and the breach characteristics demonstrated by metallic fuels. It is appeared that metallic fuel gives a little thermal shock in the flow channel during RBCB operation.

Parametric study is performed using the MACSIS code. For the worst case of 50 % degraded thermal conductivity, calculated power-to-melt is about 970 W/cm, which is very high comparing with that of MOX fuel. Considering the hot channel temperature of KALIMER core, the power-to-eutectic is decreased to about 420 W/cm. Less plenum length gives larger total diametric strain and rod internal gas pressure. However, in case of 0.9 times plenum as the length of fuel core, total diametric strain was largely increased up to 4.5 % at 18.1 at.% burnup. Apparently little FCMI has occurred in both cases of 72 % and 76 % smeared-densities, which shows that the deformations at below range of 18 at.% burnup are only approximately 1.7 % or less. It appeared that total diametric strains are largely increased when the smeared densities are over than 80 %. Below 550 °C of cladding temperature at normal operating conditions, it appeared that there were no big differences of total diametric strain with burnup for different smeared densities so that the integrity criteria of clad are largely satisfied.

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