THE COMPARISON OF THE PERFORMANCE FOR THE ALLOY FUEL AND THE INTER-METALLIC DISPERSION FUEL BY THE MACSIS-H AND THE DIMAC

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Abstract

Either alloy fuel or inter-metallic dispersion fuel is being considered as the blanket fuel for the HYPER in Korea. The MACSIS-H for an alloy fuel and the DIMAC for a disperison fuel are being developed as the steady-state performance computer code, respectively. Main structures of both codes consist of the temperature profile calculation routine, the swelling/FGR calculation routine, and the deformation calculation routine. Two-types of the alloy fuel meats were considered: U-TRU-Zr and TRU-Zr. And two types of inter-metallic dispersion fuel meats were also considered: (U-TRU-Zr)-Zr and (TRU-Zr)-Zr. The cladding material was the HT9 for each fuel. There were a little fuel characteristics relating with TRU material, so the material data of the Pu-Zr and the U-Pu-Zr were used for those of the TRU-Zr and the U-TRU-Zr, respectively. He production rate was calculated by the other code, and then inserted into the swelling/FGR routine of each code. There was a gap between the fuel meat and the cladding in the alloy fuel, but no gap in the dispersion fuel. The performance and the burn-up limits for the alloy and the inter-metallic fuel were compared by the MACSIS-H and the DIMAC code. Deformation analyses according to the variation of the plenum length and the cladding thickness were also performed for each fuel. If there were no He effects, it appeared that the burn-up limit for the dispersion fuel was relatively higher than that of the alloy fuel. But if there were He effects, the burn-up limit for both fuel types was similar. And it is expected that the burn-up limit for the alloy fuel will be increased depending on the plenum length and the cladding thickness. There are lots of uncertainties on the modelling such as the irradiation growth and the bubble distribution etc., so some experimental tests are needed for clarifying the uncertainties of fuel modelling.

1. Introduction

Either alloy fuel or inter-metallic dispersion fuel is being considered as the blanket fuel for the HYPER (HYbrid Power Extraction Reactor) in Korea. [99 Won] U-TRU-Zr is being considered for the alloy fuel meats, and (U-TRU-Zr)-Zr is being considered for the inter-metallic dispersion fuel meats. The cladding material was the HT9 for each fuel.

Performance analysis in fuel rod design is essential to assure adequate fuel performance and integrity under irradiation conditions. This paper represents an attempt to analyse the fuel performance of the alloy and the inter-metallic fuel rod according to its power history. The MACSIS-H (A Metallic Fuel Performance Analysis Code for Simulating In-reactor behaviour under Steady-state Conditions for HYPER) [99 Woan] for an alloy fuel and the DIMAC (A DIspersion Metallic fuel performance Analysis Code) [01 Byoung] for a disperison fuel are being developed as the steady-state performance computer code, respectively. Main structures of both codes consist of the temperature profile calculation routine, the swelling/FGR calculation routine, and the deformation calculation routine. These codes will be used for simulating operational limits of the alloy and the dispersion metal fuels under steady state conditions, and these codes will also be used as a design tool for the HYPER fuel.

The generation of helium gas during transmutation of ^{241}Am may be a significant issue that must be considered in the design of transmuter fuel. In this paper, He production rates calculated by the other code were inserted into the swelling/FGR routine of each code. The performance and the burn-up limits for the alloy and the inter-metallic fuel were compared by the MACSIS-H and the DIMAC code. Deformation analyses according to the variation of the plenum length and the cladding thickness were also performed for each fuel. The results of this parametric study allow for the selection of nominal design characteristics and operating limits.

There were a little fuel characteristics relating with TRU material, so the material data of the Pu-Zr and the U-Pu-Zr were used for those of the TRU-Zr and the U-TRU-Zr, respectively. There are lots of uncertainties on the modelling such as the irradiation growth and the bubble distribution etc., so some experimental tests are needed for clarifying the uncertainties of fuel modelling.

2. Fuel type and performance analysis codes

Two conceptual fuel forms have been proposed as best suited for use in a HYPER system. Both concepts make use of cylindrical fuel rods in hexagonal assemblies in a manner similar to that employed in developed fast reactor technologies. However, there is little or no experience with the particular fuel composition selected for this application. The fuel forms proposed here for the HYPER concept are believed to be feasible based on experience gained with metallic alloy and dispersion fuel forms; however, it should be realised that much of what is surmised about the expected performance of these fuel forms is speculative, because of the lack of available TRU fuel characteristics.

The alloy fuel consists of a U-TRU-Zr metallic alloy slug and liquid metal thermal bond clad in ferritic/martensitic steel, much like Experimental Breeder Reactor II (EBR-ll) fuel or fuel developed for the Integral Fast Reactor (IFR) concept. The fuel cladding material is HT9. This ferritic stainless steel is chosen for its low irradiation swelling characteristics. A fission gas plenum is located above the fuel slug and sodium bond. At the bottom of each fuel and blanket pin is a solid rod end plug for axial shielding. This fuel form offers a greatly simplified fuel fabrication route that lends itself well to remote hot cell techniques, but requires fabrication at elevated temperatures where retention of volatile TRU elements may be difficult. The key design parameter for the alloy fuel is shown in Table 1.

Table 1. **The key design parameter for the alloy and dispersion fuel**

	Alloy	Dispersion
Fuel Slug	TRU-60Zr or U-TRU-60Zr	45(U-TRU-10Zr)-Zr or 45(TRU-10Zr)-Zr
Fuel Slug Diameter (mm)	4.57	5.28
Smeared Density (%)	75	–
Fuel Cladding Gap (mm)	0.35	–
Cladding Material	HT9	HT9
Pin Outer Diameter (mm)	6.68	6.68
Integrated Gap Between Fuel and Clad (mm)	0.7	–
Pin Inner Diameter (mm)	5.28	5.28
Cladding Thickness (mm)	0.7	0.7
Pin Overall Length (mm)	3462.5	3462.5
Upper End Plug (mm)	25.5	25.5
Lower End Plug and Shielding (mm)	637	637
Upper Gas Plenum Length (mm)	1600	1600
Sodium Filler Height (mm)	250	–
Net Gas Plenum Length (mm)	1350	1600
Fuel Slug Length (mm)	1200	1200
Bond Material	Na	–

The intermetallic dispersion fuel comprises of U-TRU-Zr metallic alloy fuel particles imbedded in a Zr matrix and clad in ferritic/martensitic steel. This form is expected to have good high-burn-up irradiation performance, excellent thermal shock resistance in the event of accelerator beam interruption, and offers a potential fabrication route that may not require high-temperature processing, thus enhancing the retention of volatile TRU elements during fabrication. This fuel form may or may not require a liquid metal thermal bond between fuel and cladding. The disadvantage of this fuel form is a fabrication process that may be relatively complex for remote implementation. The key design parameter for the alloy fuel is also shown in Table 1.

The MACSIS-H is a computer code to analyse the in-reactor behaviour of metallic fuel under steady state conditions. MACSIS-H calculates thermal performance characteristics and dimensional changes of the fuel rods. It is comprised of a series of subroutines which model in-reactor fuel phenomena. The fuel rod is divided into a specified number of axial nodes, and then one-dimentional calculations are performed in each axial node. DIMAC is being developed for simulating operational limits of dispersion metal fuels under steady state conditions, based on DIFAIR code for silicide dispersion fuel of the research reactor DIMAC analyses one-dimensional in-reactor performance of the dispersion fuel under steady-state condition.

3. He generation effects

The generation of helium gas during transmutation of ^{241}Am may be a significant issue that must be considered in the design of transmuter fuel. [01 Meyer] Helium is generated due to neutron capture by ^{241}Am and subsequent alpha decay of ^{242}Cm to ^{238}Pu. Some data on helium generation is calculated by the other codes. [01 Meyer] A rule-of-thumb for estimating helium production rates from 6-40wt% ^{241}Am is 50 ml He per gram of transmuted americium. ^{241}Am weights and the He generation rates in each fuel design of Table 1 for HYPER according to above He generation assumption are given in the Table 2.

Table 2. **^{241}Am weights and the He generation rates in each fuel for HYPER**

Fuel type	**Density** (g/Cm^3)	**^{241}Am weight**	**He generation rate**
U-TRU-60Zr alloy	9.042	1.7g	85ml/165day
TRU-60Zr alloy	8.95	2.12g	106ml/165day
(U-TRU-10Zr)-55ZR dispersion	8.92	2.27g	113.5ml/165day
(TRU-10Zr)-55Zr dispersion	8.91	2.26g	113ml/165day

In the MACSIS-H, the number of fission events based on the average energy released per fission are calculated, and then effective fission gas yield (atoms/fission) are calculated, and the volume of fission gas generated are calculated including the he generation rate.

In the DIMAC, it is assumed that there are no fission gas release in the dispersion fuel. Therefore, fractional swelling due to the formation of fission gas bubbles, per unit fuel meat volume, is given by:

$$\Delta V_{uc}/V_{uc} = (V_{sp} + V_b)N_{tp} + VT_{zr} + V_{ip} + V_{He} - 1 \qquad (1)$$

where, V_{uc} is the unit volume of the fuel meat;

V_{sp} is the volume of a fuel particle which is treated as an equivalent sphere of uniform size characterised by a single equivalent radius;

V_b is the volume increase per fuel particle due to the accumulation of gas bubble considering the bubble size distribution;

N_{tp} is the number of TRU-Zr fuel particles per unit volume of fuel;

VT_{zr} is the volume of Zr-matrix per unit fuel meat volume;

V_{ip} is the initial porosity per unit volume of the fuel;

V_{He} is the volume increase per 1 g of ^{241}Am.

4. Performance analysis of HYPER fuel

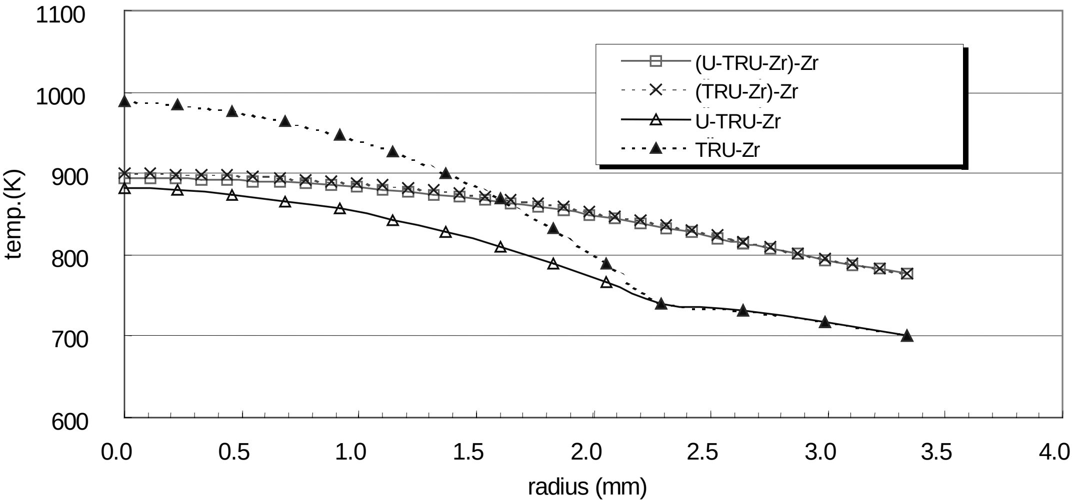
4.1 Radial temperature distribution of the alloy and dispersion fuel

Since there is no thermal conductivity data available for Pu-Zr alloys, a correlation was developed based on the change in thermal conductivity of U-Zr alloys with the addition of zirconium. [01 Byo] It is also assumed that the trends of the thermal conductivity for U-TRU-Zr alloys is similar to those of U-Zr alloys. And the Bruggeman equation [35 Bru] is adapted for the thermal conductivity model for the dispersion fuel. Based on the thermal properties of each fuel, the radial temperature distribution analysis was performed for a fuel element design that shown in Table 1.

Figure 1 shows the radial temperature distribution for each fuel at a linear power density of 28.8 kW/m, as calculated by the MACSIS-H and the DIMAC code. The temperature difference for both dispersion fuels from the fuel vertical centerline to the cladding outer surface is about 140 K at an assumed coolant temperature of 713 K for both dispersion fuel. The centerline temperature of the fuel is 900 K for both dispersion fuels. The temperature difference for U-TRU-60ZR alloy fuel from the fuel vertical centre-line to the cladding outer surface is 180 K, but 29l K for TRU-60ZR alloy fuel, because the thermal conductivity of U-TRU-60Zr alloy is higher than that of TRU-60Zr alloy.

The calculation indicate that the fuel temperature remain well below the solidus temperature of each fuel. The temperature calculation shown are based on estimated thermal conductivities, thus the uncertainty associated with these temperature are unknown, and these calculations are for BOL conditions. However, each fuel has a sufficient margin to the slug centre-line melting, so no thermal operational concerns are expected for these fuels.

Figure 1. **Radial temperature distribution for the alloy and dispersion fuel**



4.2 Fuel deformation for each fuel

Figure 2 shows the fission gas generation according to He effect in the alloy fuel. Even though ^{241}Am weight is much smaller than other heavy metal, but the amount of fission gas generation of the Am is about 1/3-1/2 of those of heavy metal. Helium production is likely to be the most important fuel design consideration for transmutation scenarios with high MA content.

Figure 3 shows the creep rate comparison according to He effects as a function of the plenum-to-fuel ratio for alloy fuel. In case of the 0.5 plenum-to-fuel ratio, the difference of creep rate due to He effect is largest. The differences of creep rate due to He effect decrease as a function of the plenum-to-fuel ratio. So far, a lot of model such as the eutectic melting and the transient behaviour have not been established, it is estimated that 1.5 times of the plenum-to-fuel ratio is conservative for the fuel integrity. The plenum lengths for the 0.5, 1.0, and 1.5 plenum-to-fuel ratio are 450, 900, and 1 350 mm, respectively.

Figure 4 shows the strain rate comparison with He effects as a function of the burn-up for U-TRU-60Zr alloy fuel. The values of cladding strain are about 3.3, 3.1, and 3.01% at 30at% for the 0.5, 1.0, and 1.5 the plenum-to-fuel ratio, respectively. A shorter plenum length gives a larger total diametric strain and increases rod internal gas pressure. The values of cladding strain for the TRU-60Zr alloy fuel are very similar to those for the U-TRU-60Zr alloy fuel, because the strain in the alloy fuel strongly depends on the smear density, and the smear density for both fuels is the same. As the design requirement for cladding is assumed to be about 3% of cladding strain, the 1.5 times of the plenum-to-fuel ratio is recommended to satisfy the fuel integrity at the higher burn-up.

Figure 2. **Fission gas generation for U-TRU-60Zr**

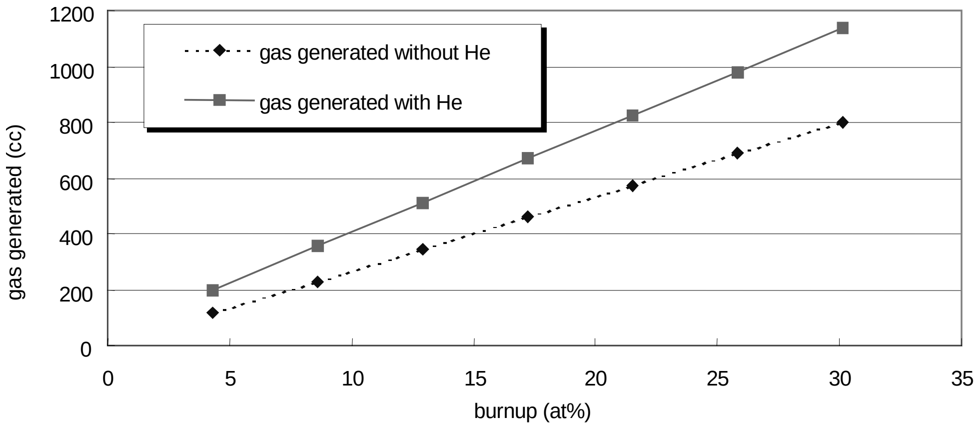


Figure 3. **Creep rate comparison He effects as a function of the according to plenum-to-fuel ratio for alloy fuel**

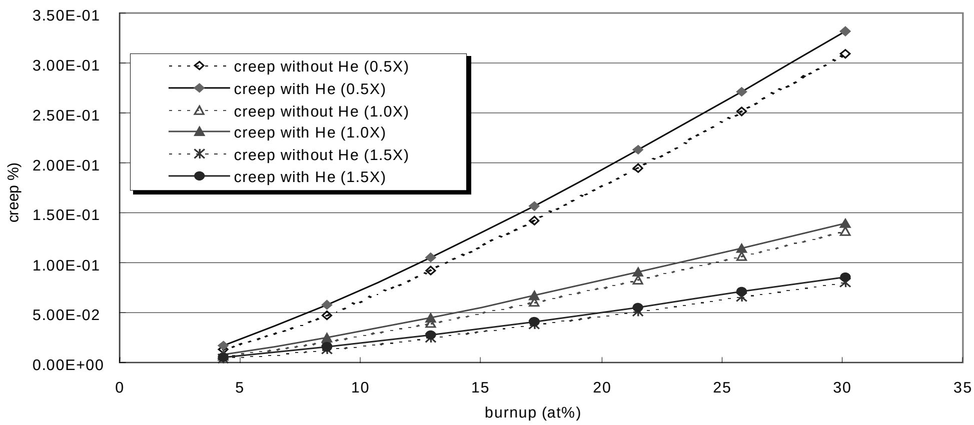


Figure 4. **Cladding strain according to plenum-to-fuel ratio for the alloy fuel**

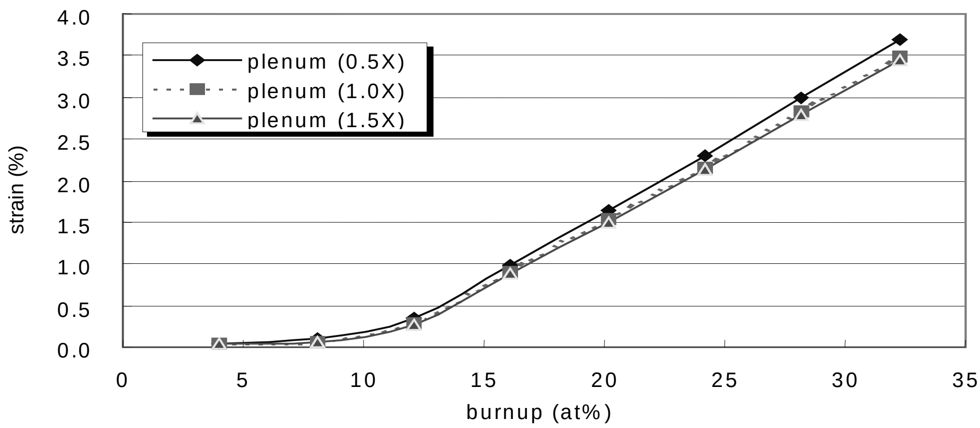


Figure 5 shows the strain rate comparison with He effects as a function of the cladding thickness for alloy fuel. As expected, the burn-up limit increases with increasing cladding thickness. The values of cladding strain are about 3.01, 2.95, and 2.8% at 30at% for the 0.7, 0.85, and 1.0 mms of the cladding thickness, respectively. But a lot of factors such as the core size, the economics and the other cladding material properties should be also considered, so the cladding thickness will be determined in the future, and the cladding thickness set to 0.7 mm in this design.

Figure 5. **Cladding strain according to the clad thickness for the alloy fuel**

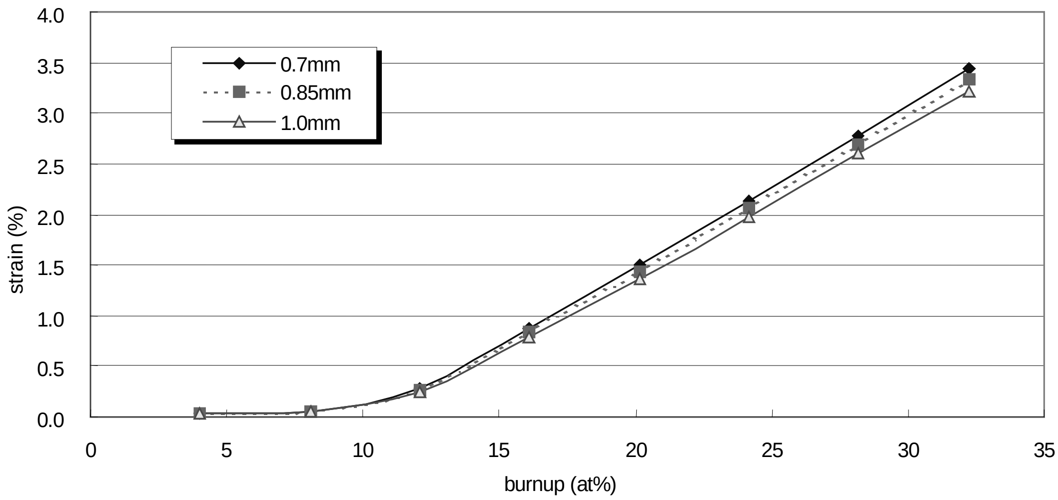


Figure 6 shows the strain rate comparison with He effects as a function of the burn-up for (U-TRU-10Zr)-45Zr dispersion fuel at a linear power density of 21.6 and 28.8 kW/m, respectively. The values of cladding strain without He effects are about 2.65%, 2.85% at 30at% at a linear power density of 21.6 and 28.8 kW/m, respectively. But the values of cladding strain with He effects are about 3.1%, 3.3%. It is assumed that there is no gap, and no fission gas release in the dispersion fuel, so the He effects of the dispersion fuel will be larger than those of the metallic fuel. So the need for the gap in the dispersion fuel will be analysed in the future.

Figure 7 shows the strain rate comparison with He effects as a function of the burn-up for (TRU-10Zr)-45Zr dispersion fuel at a linear power density of 21.6 and 28.8 kW/m, respectively. The values of cladding strain for the TRU-60Zr dispersion fuel are a little smaller than those for the U-TRU-60Zr dispersion fuel, because of the higher TRU amounts, the smaller thermal conductivity, the higher He generation. Because the strain in the dispersion fuel strongly depends on the gas generation rate and the swelling rate, the gap may be needed to satisfy the fuel integrity at the higher burn-up.

Figure 8 shows the strain rate comparison with He effects as a function of the cladding thickness for dispersion fuel. The burn-up limit also increases with increasing cladding thickness, but the increasing rates of dispersion are larger than that of alloy fuel. The values of cladding strain are about 3.1, 2.85, and 2.64% at 30at% for the 0.7, 0.85, and 1.0 mm of the cladding thickness, respectively. So it is estimated that the increasing of the cladding thickness and the gap installation will improve significantly the burn-up limits of the dispersion fuel.

Figure 6. **Cladding strain for the (U-TRU-Zr)-Zr dispersion fuel**

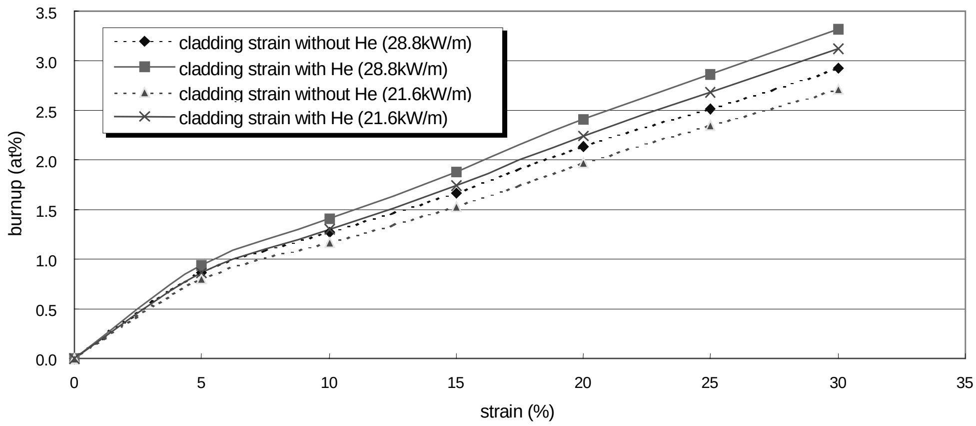


Figure 7. **Cladding strain for the (TRU-Zr)-Zr dispersion fuel**

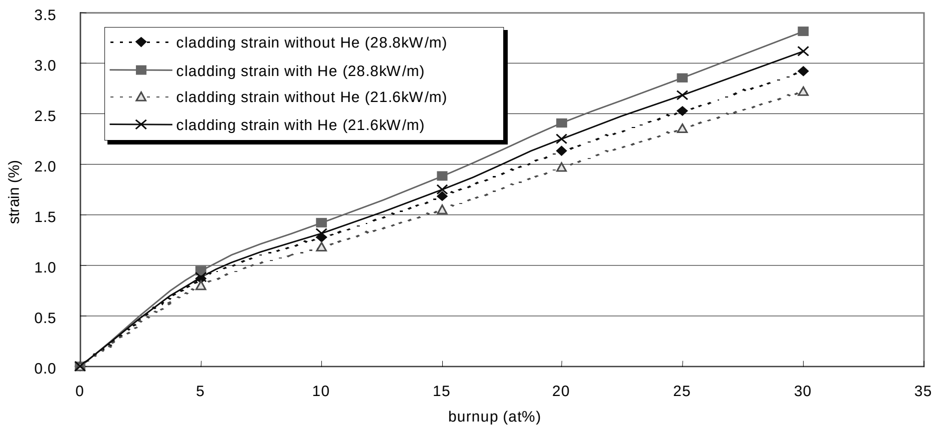
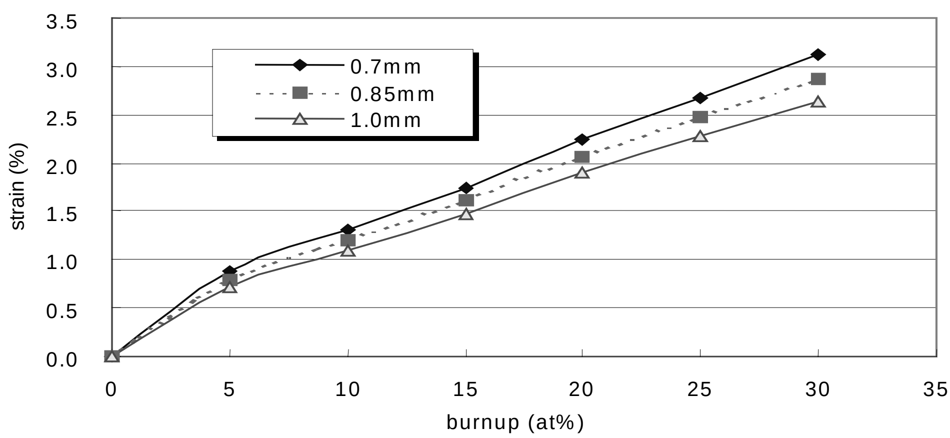


Figure 8. **Cladding strain due to the clad thickness for the (U-TRU-Zr)-Zr dispersion fuel**



5. Conclusion

Either alloy fuel or inter-metallic dispersion fuel is being considered as the blanket fuel for the HYPER (HYbrid Power Extraction Reactor) in Korea. Performance analysis in fuel rod design is essential to assure adequate fuel performance and integrity under irradiation conditions. The MACSIS-H for an alloy fuel and the DIMAC for a disperison fuel are being developed as the steady-state performance computer code, respectively. He production rate was calculated by the other code, and then inserted into the swelling/FGR routine of each code. This paper represents an attempt to analyse the fuel performance the alloy and the inter-metallic fuel rod according to its power history.

The performance and the burn-up limits for the alloy and the inter-metallic fuel were compared by the MACSIS-H and the DIMAC code. Deformation analyses according to the variation of the plenum length and the cladding thickness were also performed for each fuel. It is estimated that each fuel for HYPER has a sufficient margin to the slug centre-line melting, so no thermal operational concerns are expected for these fuels. In the U-TRU-60Zr alloy fuel, the values of cladding strain are about 3.01% at 30at% for the 1.5 the plenum-to-fuel ratio. In the dispersion fuel, if there was no He effect, the values of cladding strain is about 2.85% at 30at%. But there was He effects, the values of cladding strain is about 3.3% at 30at%; i.e. if there was no He effects, it appeared that the burn-up limit for the dispersion fuel was relatively higher than that of the alloy fuel. But if there was He effects, the burn-up limit for both fuel types was similar. Because there is no gap, and no fission gas release in the dispersion fuel, it is appeared that the He effects of the dispersion fuel will be larger than those of the metallic fuel.

And it is expected that the burn-up limit for the alloy fuel will be increased depending on the plenum length and the cladding thickness. As the design requirement for cladding is assumed to be about 3% of cladding strain, a detailed review for cladding strain is needed. There are also lots of uncertainties on the modelling such as the irradiation growth and the bubble distribution etc., so some experimental tests are needed for clarifying the uncertainties of fuel modelling.

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