The 2nd Seminar on the New Fuel Technology Toward the 21st Century,
November 25 - 26, 1997, KAERI, Taejon, Korea

High U-Density Nuclear Fuel Development with Application of Centrifugal Atomization Technology

Chang-Kyu Kim, Ki-Hwan Kim, Don-Bae Lee

Korea Atomic Energy Research Institute,
150 Dukjin-dong, Yusong-gu, Taejon 305-353, Korea

Abstract

In order to simplify the preparation process and improve the properties of uranium silicide fuels prepared by mechanical comminution, a fuel fabrication process applying rotating-disk centrifugal atomization technology was invented in KAERI in 1989. The major characteristic of atomized U_3Si and U_3Si_2 powders have been examined. The out-pile properties, including the thermal compatibility between atomized particle and aluminum matrix in uranium silicide dispersion fuels, have generally showed a superiority to the comminuted fuels. Moreover, the RERTR (reduced enrichment for research and test reactors) program, which recently begins to develop very-high-density uranium alloy fuels, including U-Mo fuels, requires the centrifugal atomization process to overcome the contaminations of impurities and the difficulties of the comminution process. In addition, a cooperation with ANL in the U.S. has been performed to develop high-density fuels with an application of atomization technology since December 1996. If the microplate and miniplate irradiation tests of atomized fuels, which have been performed with ANL, demonstrate the stability and improvement of in-reactor behaviors, nuclear fuel fabrication technology by centrifugal atomization could be most-promising to the production method of very-high-uranium-loading fuels.

Introduction

Research on the intermetallic compounds of uranium was revived in 1978 with the decision by the international research reactor community to develop proliferation-resistant fuels [1]. Although fuel with a uranium density of 4.8 g U/cm^3 is sufficient to convert approximately 90% of all research reactors, conversion of the remaining reactors, which use a significant quantity of HEU, requires fuels with considerably higher densities [2]. Uranium intermetallic compounds, in particular, U_3Si and U_3Si_2, have been preferred choices of fuel materials for high flux research reactors [3-6]. Uranium silicide powders are supplied by the comminution of cast U_3Si_2 or heat-treated U_3Si alloy [7]. The Korea Atomic Energy Research Institute (KAERI) has been

developing uranium silicide fuel for the HANARO of the 30 MW research reactor since 1987. In order to simplify the preparation process and improve the properties of uranium silicide fuel, a centrifugal atomization method has been developed [8]. In addition, centrifugal atomization used for the rapid solidification processing (RSP) of nuclear fuel materials can provide beneficial features which could be not achieved easily by conventional methods. It is known that the powder has several advantages, such as a rapidly solidified microstructure, a relatively narrow particle size distribution, and a spherical shape [9-10]. Spherical particles are especially desirable for improving the plastic flowability and do not have any preferred orientation after extruding or rolling.

There are basically two aspects to the development of high uranium-density LEU dispersion fuels. The first challenge is to discover or develop a uranium compound or alloy with the highest possible uranium density that can be fabricated in a dispersion, and has acceptable irradiation behavior. While the vast majority of reactors can be satisfied with U_3Si_2-Al dispersion fuel, several high performance reactors require high loadings of up to 8~9 g U cm^3. Experience with highly loaded U_3Si_2-Al and UN-Al [11-12] fuels indicates that one is not likely to achieve a fuel volume loading greater than 55% in a commercially viable process; therefore, fuel dispersants with very-high uranium densities, > 15 g U/cm^3, must be used. A series of alloys which maintain uranium in the metastable γ-U phase have shown good irradiation performance in bulk form under fast reactor conditions. The customary technique for making fuel powders for dispersion, which involves crushing and grinding of rather brittle uranium compounds, is not suitable for the uranium alloys with ductility [13-14]. Metallic powders, however, have been routinely made by centrifugal atomization. Hence, spherical powders produced by centrifugal atomization meet the requirements for use in dispersion fuel. In addition, by centrifugal atomization having a rapid cooling effect, it is expected that U alloys with gamma phase stability easily retain this phase in a metastable state. If this metastable gamma phase can be maintained during irradiation, and if the alloy has good compatibility with aluminum matrix, the metastable γ-phase alloy would be a candidate for the dispersion fuel for research reactors.

The second challenge is to improve the maximum volume fraction of fuel particles in the core. To date, the highest density qualified compound is U_3Si_2 used in comminuted powder form. U_3Si_2 fuel has been conventionally prepared by compaction or rolling of blended powder with U_3Si_2 and aluminum. During the rolling for plate type fuel or extrusion for rod or tube type fuel, a certain amount of porosity is formed. This is primarily due to fracturing of the fuel particles in response to the rolling or extrusion force. It seems reasonable to conclude that a reduction or elimination of the fabrication porosity would result in a higher practical maximum fuel loading.

In addition, alloys containing silicon and molybdenum were used to produce the powders, applying the centrifugal technique. Especially, U-Mo powders having high density of above 15 g U cm^{-3} were prepared by rotating-disk centrifugal atomization and were characterized for application as a dispersant for research reactor fuel. The fuel rods were made by extruding the blended powders with atomized U-Mo and aluminum. The major characteristics, including phase stability and thermal compatibility of U-Mo alloy fuels, were examined. The as-fabricated porosity characteristics of the extruded U_3Si_2 fuel cores having atomized and comminuted uranium silicide powders were examined. Thermal compatibility of atomized uranium silicide fuel meats was evaluated, and compared with that of comminuted uranium silicide fuel meats.

The ANL and KAERI entered into a cooperation agreement for the development of a low-enriched uranium (LEU) plate-type research reactor fuel using atomized fuel particles in December 1996. The RERTR program makes efforts to develop high density dispersion fuel using atomized particles.

This co-operation will be valuable both in comparing the irradiation performance of atomized and comminuted dispersion fuels and in developing higher-density fuels using other fuel alloys, where atomization may be the most-practical fuel particle production method. In addition, in order to develop dispersion fuels having densities in the range of 8 to 9 g-U/cm^3, a microplate irradiation experiment was initiated at the Advanced Test Reactor (ATR) located in Idaho in August of this year [15]. This experiment is scoping in nature, attempting to obtain performance data on the (12) different uranium alloy dispersion fuels. U-10wt.%Mo and U_3Si_2 samples prepared by the centrifugal atomization method in KAERI were included in this test. CERCA in France decided to purchase U_3Si_2 and U-10wt.%Mo powders, in April this year, to examine the potential benefits of such powders to the highly loaded fuel plates. BWXT in the U.S. also requested to supply U_3Si_2 powder recently, in order to compare to the characteristic of the comminuted powder and to test the benefits such a powder to the high loaded fuel plates. On the other hand, in order to localize HANARO fuel, an irradiation test has been aimed at evaluating the in-reactor performance and the integrity of both atomized and comminuted LEU U_3Si dispersion fuel developed by KAERI.

Major Characteristics of Atomized Powders

The typical morphology and size distribution of atomized U_3Si, U_3Si_2, and U-Mo particles are shown in Fig. 1. Most of the particles have nearly perfect spherical shapes with smooth surfaces and

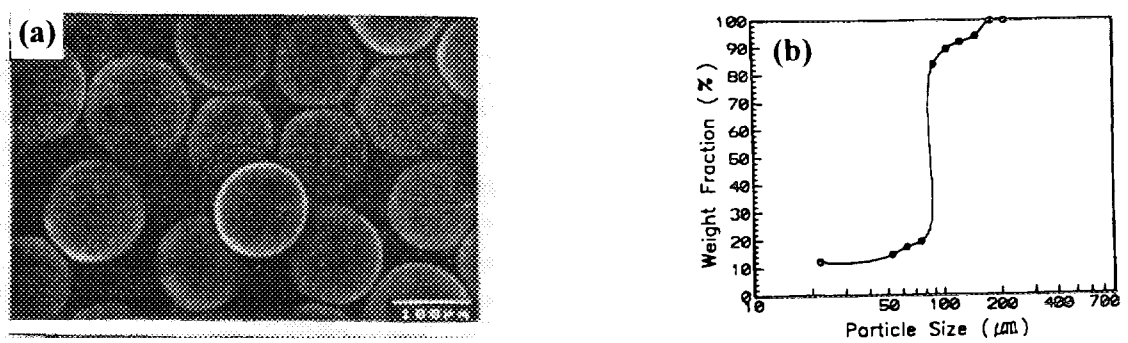

Fig. 1. Typical morphology (a) and size distribution (b) of the atomized particles.

few attached satellites, regardless of the sort of alloys. The fragment from the melt-drop becomes spherical due to the surface tension force before it begins to solidify. In addition, the size distribution of the powder is relatively narrow, and the median particle size is about 80 μm. The size distribution for nuclear fuel powder can be controlled through the adjustment of the atomization parameters such as the feeding rate of the melt and the revolution speed of the disk. The atomized U_3Si_2 powder yield below 125 μm in size was about 95%, compared to the totally produced U_3Si_2 powder weight.

Scanning electron micrographs of atomized U_3Si and U_3Si_2 powders are illustrated in Fig. 2. The

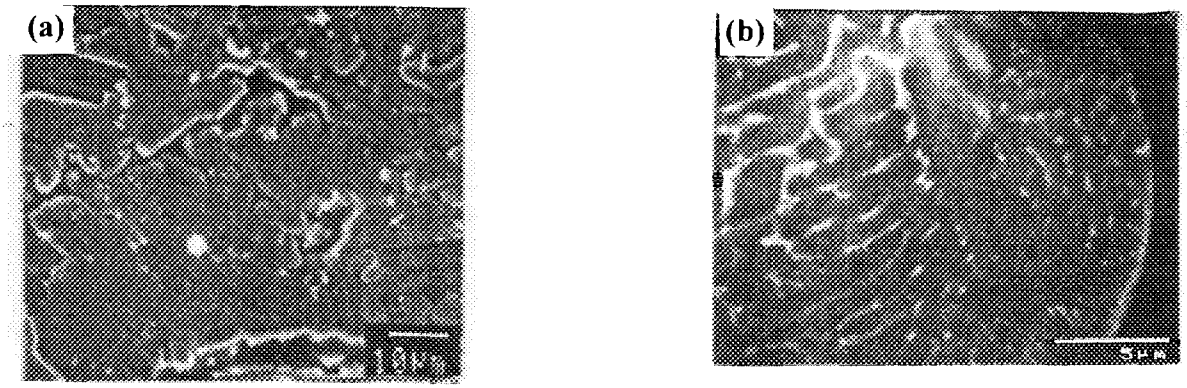

Fig. 2. Scanning electron micrographs of atomized U_3Si (a) and U_3Si_2 (b) powders.

centrifugally atomized U_3Si powder shows a dendritic microstructure with primary precipitates having non-faceted growth morphology independent of the particle size [16]. The arm thickness of primary U_3Si_2 precipitates in the atomized U_3Si powder was found to be fine; about 2 ㎛ due to the rapid solidification effect, compared with the conventionally frozen ingot [17]. On the other hand, the U_3Si_2 particles consist of a cellular structure with fine U_3Si_2 grains below 5 ㎛ in size and finely dispersed silicon-rich precipitates at grain boundaries. The formation of a fine cellular structure generally originates from the great cooling rate before the solidification [18]. The X-ray diffraction patterns of atomized uranium silicide powders show the formation of crystalline phases. The major phases of atomized powders are α-U and U_3Si_2 in the U_3Si powder, and U_3Si_2 in the U_3Si_2 powder. A shorter time for a peritectoid reaction of atomized U_3Si powder, compared with comminuted U_3Si powder, results from the small secondary arm spacing of primary U_3Si_2 precipitates and the rapid nucleation of the U_3Si_2 phase, and the grain size of atomized powder decreases to below 3 ㎛ after the peritectoid reaction, much finer than the 20 ㎛ in size of comminuted powder. The completed transformation in the centrifugally atomized specimens needs after 6 hours, which is one-twelfth of that for the conventionally frozen specimens [17].

The cross-sectional micrograph and the X-ray diffraction pattern of atomized U-10wt.%Mo alloy particles are illustrated in Fig. 3. It is seen that the microstructure of atomized particles is polycrystalline, with many γ-U grains below 5 ㎛ in size. Despite the rapid solidification, the SEM images reveal some Mo segregation, or cored microstructure, characteristic of an alloy with a substantial liquidus-solidus gap, such as U-Mo alloy [18]. All phases of atomized alloy powders below 150 ㎛ are found to be the isotopic-metastable γ-U (bcc) phase. It is known that U-10wt.%Mo alloys frozen slowly consist of α-U phase and γ'-U_2Mo intermetallic compound with lamellar structure [19], however γ-U (bcc) phase, which is the equilibrium phase above about 560℃, can be retained in a metastable state at room temperature by rapid solidification. Scanning electron micrograph for the U-10wt.%Mo powder annealed at 400℃ for 100 hours illustrates that U-10wt.%Mo powder still reveals fine grain structure below 5 ㎛ in size with microsegregation of Mo. It is thought that these results originated from the supersaturation of Mo in the metastable γ-U solid solution of U-10wt.%Mo alloy. Large substitution of Mo atom within the U matrix causes U atoms to become immobile due to Mo with low diffusivity [20]. This therefore confirms that the γ-U phase of atomized U-10wt.%Mo powder can be retained for extended times, presumably because the diffusion- controlled transformation is retarded at increased

Mo content.

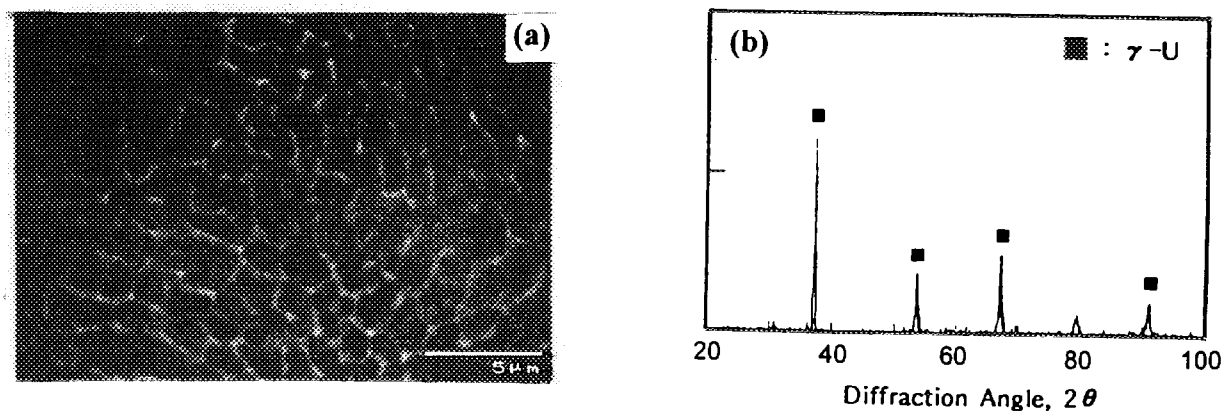

Fig. 3. The cross-sectional micrograph (a) and the X-ray diffraction pattern (b) of atomized U-10wt.%Mo alloy particles.

Major Characteristics of Atomized Fuels

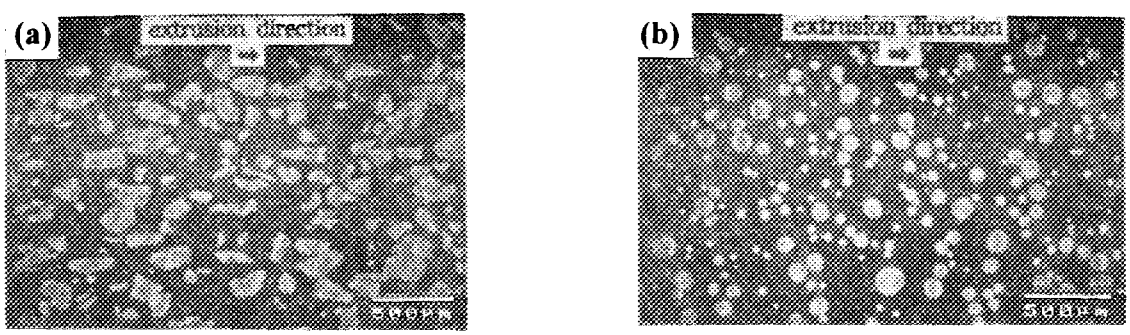

Fig. 4. The cross-sections of the U_3Si fuel meat with comminuted particles (a) and atomized particles (b).

Comminuted U_3Si fuel particles with a certain aspect ratio lie along the working direction during forming, i. e., in the extrusion or rolling direction. Fig. 4-(a) shows a cross-section of the fuel meat with comminuted particles in which the fuel particles are reoriented along the working direction of the fuel meat. In contrast, the atomized particles shall never have an aspect ratio since they are spherical. Regardless rolling or extruding, they have no chance of developing anisotropic orientation along the working direction during forming. Fig. 4-(b) shows the atomized particles without anisotropic orientation in the fuel meat in comparison with the comminuted particles aligned in the working direction. The shape of the fuel particles greatly effects the fuel properties in relation with the orientation in the fuel meat. The direction of heat transfer in the fuel meat of

reactor operation is perpendicular to the plate, which means a heat is dissipated perpendicular to the working orientation of the fuel particles in the meat with the comminuted powder. Fig. 5 shows the difference in thermal conductivity between the fuel meats with comminuted powder and atomized one. The meat with the atomized particles has about 23% higher thermal conductivity in the heat-transfer direction of reactor operation than the one with the comminuted particles does. These data of conductivity, which show the great difference, say that thermal conductivity increases by a sufficient amount using atomized powder.

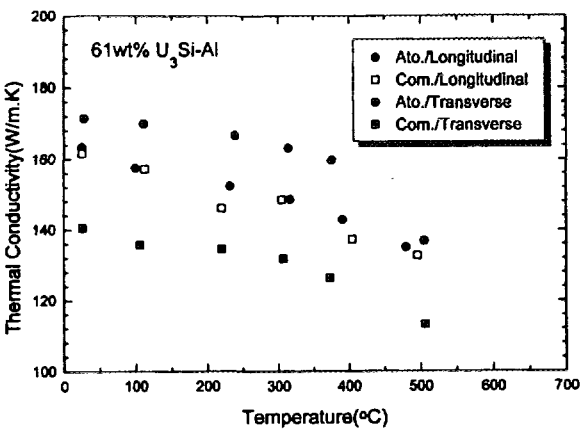

Fig. 5. Thermal conductivity of 61wt.%U_3Si-Al fuel.

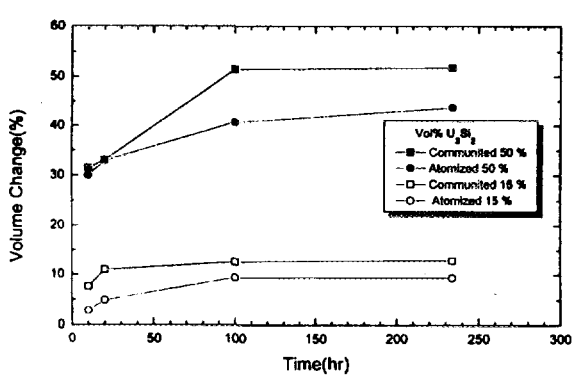

Fig. 6. Volume changes of fuel meats as a function of annealing time at 500 °C.

The annealing time versus the dimension percent increases for the heat treatment of the Al-15vol.% U_3Si_2 and the Al-50vol.% U_3Si_2 fuel samples at 500°C are shown in Fig. 6. U_3Si_2 fuel samples with the comminuted powder showed a larger volume increase compared with those prepared with the atomized powder after annealing at 500°C. As the aluminum reacts with the fuel,

the fuel's volume increases due to the difference between densities of the original particle and reaction product, and to the pores produced by the Kirkendall effect [21]. It is supposed that the smaller surface area of atomized spherical powder compared to the irregular comminuted powder is also related to the reduction of volume change in terms of the diffusion-controlled process. In addition, comminuted fuel samples have a higher porosity than atomized fuel samples, as illustrated Fig. 7. Lots of pores in the fuel samples are stabilized by trace impurity gases such as hydrogen, due to the formation of the intermediate phase without dissolution of the gases [22]. It is thought that higher porosity contributes to reducing a restraint force on the swelling.

Dimensional changes in the samples are given in Table 1. The U-2wt.%Mo sample exhibits a rather steep volume increase, reaching 26% after 2,000 hours. The volume of the U-10wt.%Mo sample, on the other hand, remains the same, except for a temporary decrease after the 1,000 hour anneal. The U-10wt.%Mo/aluminum dispersion, however, increased in volume by 31% after 215 hours at 500°C, similar to the volume increase in the U_3Si_2/aluminum dispersion. The retarded diffusion behavior is primarily due to the fact that U-10wt.%Mo is not liable to decompose from an as-atomized metastable γ-phase (bcc) solid solution into the equilibrium α-U and U_2Mo two-phase structure, still leaving some γ-U phase, despite thermal annealing at 500°C for 215 hours. In addition, the substitutional molybdenum supersaturated in the unreacted U-10wt.%Mo island along

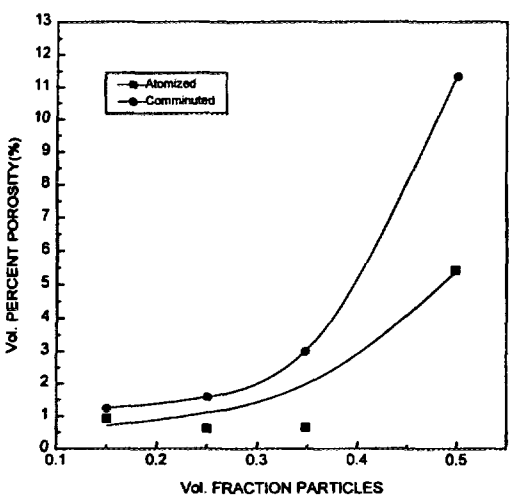

Fig. 7. The void content of fuel cores in extruded dispersion cores with comminuted and atomized U_3Si_2 particles.

the cell boundary inhibits the diffusion of aluminum atoms into the particle. Consequently, the atomized U-10wt.%Mo powder showed good γ-U phase stability at elevated temperatures, and the U-10wt.%Mo fuel meat with the rapidly solidified powder displays superior thermal compatibility

with aluminum compared to U_3Si_2 [Fig. 8].

(Unit: %)

Time (hr)	U-2wt.%Mo Alloy			U-10wt.%Mo Alloy		
	△ ℓ	△ d	△ V	△ ℓ	△ d	△ V
11	-0.15	-0.17	-0.49	-0.09	-0.18	-0.45
40	-0.03	-0.30	-0.63	-0.02	-0.06	-0.14
107	0	-0.23	-0.46	-0.14	-0.05	-0.24
350	+0.19	+0.06	+0.31	-0.07	0	-0.07
1000	+1.83	+0.39	+2.61	-1.04	-1.52	-4.08
2000	+4.28	+10.86	+26.00	-0.12	-0.11	-0.34

Table 1 Dimensional changes of Al-24vol.% U-Mo fuel meats after annealing at 400°C for various times.

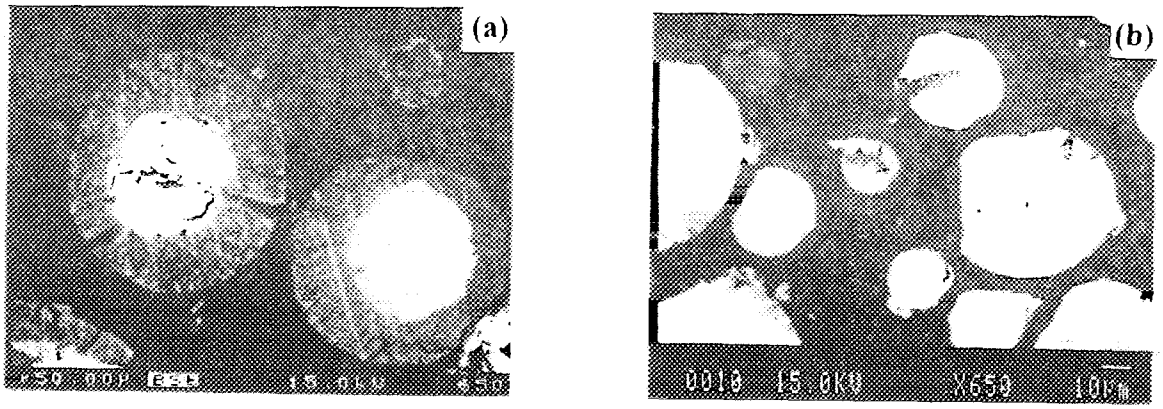

Fig. 8. Backscattered electron images of atomized fuel meat after annealing at 500°C for 20 hours; (a) U_3Si_2, (b) U-10wt.%Mo.

In-pile Irradiation of Atomized U_3Si Fuel in HANARO

The HANARO fuel which is U_3Si dispersion fuel in Al matrix has only been supplied by AECL in Canada. This irradiation examination has aimed at identifying the in-reactor performance and the integrity of both atomized and comminuted U_3Si dispersion fuel for the localization of the

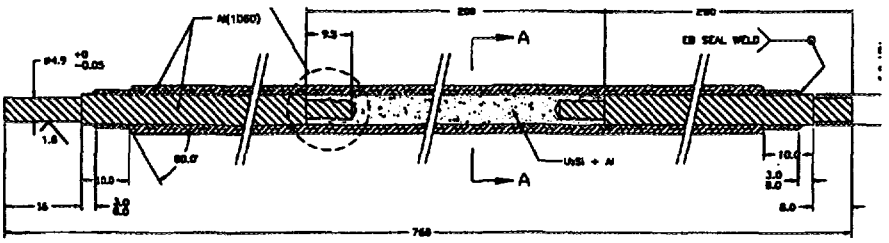

Fig. 9. The design draft of the irradiation LEU fuel rods.

reactor operation, optical inspection, and examination post irradiation, were established. The irradiation fuel rods are the same as the standard HANARO fuel rods except that the fuel meat length of irradiation rod is 20 cm (Fig. 9). The irradiation fuel assembly consisted of 3 atomized fuel rods, 3 comminuted fuel rods, and 12 dummy fuel rods. The irradiation fuel rods were fabricted using LEU metal. The end plugs were inserted at both ends of fuel meats technically. The co-extrusion then put the cladding on the fuel rods. All fabrication steps followed the quality control system which was developed by referring to the CANDU fuel Q/A system. The fuel meat homogeneity was inspected using a gamma scanning method and the soundness of the welding part was inspected using a real time radiography method. In addition, the defects of the cladding were inspected using an eddy current detection method. Safety analysis of the irradiation fuel assembly was performed using the MCNP4A code supposing the linear power to be 27.5 MW. The results calculated for all parts divided by the 5 cm interval showed that the maximum linear power was 101.06 W/m. According to the results calculated using the DIFAIR code, the maximum centerline temperature on the linear power 120 KW/m was expected to be 267°C. Also, for the linear power of 110 KW/m, the temperature was 262°C. The expecting linear power of the irradiation fuel rod is lower than the supposing temperature used for calculation. Accordingly the centerline temperature of irradiation fuel rod would be lower than 262°C. The temperature is lower than the breakaway swelling temperature 350°C and much lower than the blistering temperature 640°C. In addition, the swelling was calculated to be about 9.3% at 95 at% burnup using the DIFAIR computer code. This swelling value is much lower than the HANARO requirement of 20%. Consequently, the irradiation fuel rods were evaluated to maintain a soundness and a safety. The quality assurance system was established by applying the Q/A system of CANDU fuel fabrication. The Q/A assurance plan was worked out first of all. And then the other Q/A documents, specially, material specification, product specification, process specification, procurement manual, flowsheet, work ordering sheet, test and inspection plan, quality inspection instruction, technical qualifying report, and drawings were prepared. The quality inspection technologies of the Gamma Scanning System, Real Time Radiography System, and Eddy Current System were developed. The established Q/A system was applied to the fabrications of dummy fuels, hydraulic test fuels, and irradiation test fuels.

As mentioned above, two test fuel assemblies designated HFT B1 and HFT-B2, including both atomized and comminuted U_3Si dispersion fuel, are supposed to be charged in HANARO. The HFT B2 assembly, which will begin to irradiate in the end of 1997 as the first step, is going to examine to the integrity of developed U_3Si fuels under the normal linear power condition of 30~108 KW/m. It is planned to be discharged from the reactor after fuel burnup of ~ 30% and ~60%, respectively, in order to examine the in-reactor behavior and the appearance integrity with the naked eye. The target fuel burnup at this HFT B2 assembly will be ~60 at.%. After the HFT B2 assembly shows sound in-reactor behaviors similar to that produced by the AECL in Canada, the next HFT B1 assembly, which is going to irradiate from the middle of 1998 as the second step, will examine to the integrity of developed U_3Si fuels under the high linear power condition of 113 KW/m. The target fuel burnup at this HFT B1 assembly will be ~85 at.%. These irradiation tests for the HFT B2 and the HFT B1 assemblies are expected to be finished by the end of 1998. Thereafter, the HTF B3 assembly for the actual proofs of the developed fuels will begin to charge and irradiate so that the in-pile integrity of the U_3Si fuels may be examined, and compared with that of the actual driver fuel for HANARO.

Miniplate and Microplate Irradiation of Atomized Fuels with ANL

In order to examine the in-reactor performance of atomized LEU U_3Si_2 fuel miniplate in the HANARO, the miniplate fuel assembly has been in the progress of design and fabrication in co-operation with the ANL and the BWXT in United States. An miniplate irradiation test rig of atomized U_3Si_2 fuel was already designed and preliminarily manufactured (Fig. 10). Thermal hydraulic and linear power calculations were performed by using the PLTEMP and the MCNP4A computer codes respectively. The results obtained from hydraulic test for the preliminarily manufactured rig showed that the pressure drop was 327 kPa at flowrate 9 kg/sec and met the HANARO requirement. The vibration measurement revealed that vibration amplitude is very low. For the development of U_3Si_2 atomization technology, an atomization system was modified from outside-coil-type to inside-coil-type. The disk rotation motor was improved using electric pulse motor. The crucible and nozzle material was changed from ceramic-coated graphite to ZrO_2 ceramic. Hence, a higher temperature could be applied to U_3Si_2 atomization. As the result, the atomized LEU U_3Si_2 powder has successfully been prepared in spring this year. The U_3Si_2 powder yield below 125 ㎛ in size was 94%, compared to the totally produced U_3Si_2 powder weight. The carbon contamination was about 580 ppm and the powder generally had a spherical shape with a smooth surface, and also showed a narrow size distribution with the median size of 51 ㎛. The LEU atomized U_3Si_2 fuel powder will be shipped from the KAERI to the ANL, as soon as the container arrives at KAERI. So to mention of the following plan, miniature test plates containing the atomized fuel powder will be produced or otherwise procured in ANL. KAERI will assemble the irradiation bundle and install it in the test rig. The test plates will be irradiated in the HANARO, and then the post-irradiation examinations of the test plates will be performed.

The U.S. RERTR program is currently attempting to develop dispersion fuels having densities in the range of 8 to 9 g-U/cm^3. To gain initial fuel performance data on a sample of such γ-stabilized uranium alloy dispersion fuels, a microplate irradiation experiment has been initiated in the Advanced Test Reactor (ATR) located in Idaho [15]. This experiment is scoping in nature, attempting to gain performance data on the following ten (10) different uranium alloy dispersion

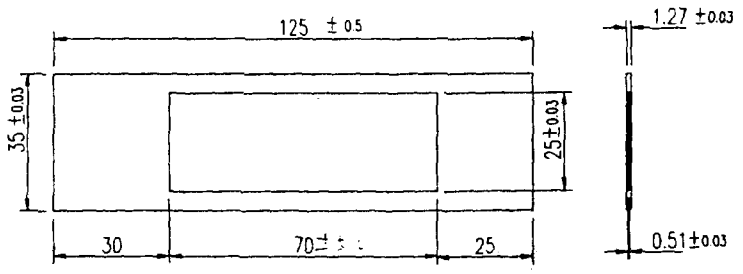

Fig. 10. An atomized U_3Si_2 miniplate irradiation test rig.

fuels: U-10Mo, U-8Mo, U-6Mo, U-4Mo, U-9Nb-3Zr, U-6Nb-4Zr, U-5Nb-3Zr, U-6Mo-1Pt, U-6Mo-0.6Ru and U-10Mo-0.05Sn. In addition, U-10Mo and U_3Si_2 samples prepared by the centrifugal atomization method in KAERI are included in this test. All fuels in this test are in an aluminum matrix and aluminum cladding. These fuel types are contained in two irradiation vehicles, designated RERTR-1 and RERTR-2. Each of two irradiation vehicles contains 32 "microplates". Both irradiation vehicles contain all fuel; types except two; the U-4Mo and U-5Nb-3Zr fuel types are not included in RERTR-2. The fuels employed in this test were fabricated in plate form. Due to small size of the fuel plates, they are referred to as "microplates". The external dimensions of the microplates are 3.000-in. in length, 0.875-in. in width, and 0.05-in. thickness (76 mm x 22 mm x 1.3 mm) (Fig. 11).

The U_3Si_2 powder yield below 125 ㎛ in size was 96%, compared to the totally produced U_3Si_2 powder weight. The carbon contamination was low below 1,000 ppm and the powder generally had a spherical shape, and showed a narrow size distribution with the median size of 51 ㎛. In addition, the cross-section of Al-25vol.%U_3Si_2 fuel meat prepared with atomized powder exhibited a uniform distribution of the particles, sometimes with cracked particles (Fig. 12-(a)). The U-10wt.%Mo powder yield below 125 ㎛ in size was 97%, compared to the totally produced U_3Si_2 powder weight. The carbon contamination was below 500 ppm and the powder had a spherical shape with a smooth surface, and showed a narrow size distribution with the median size of 53 ㎛. Also, the cross-section of Al-25vol.%U-10wt.%Mo fuel meat prepared with the atomized powder exhibited a uniform distribution of the particles, none of which were cracked (Fig. 12-(b)). Consequently, good quality of U_3Si_2, and U-10wt.%Mo fuel cores could be obtained. By using the developed atomization technology, microplates which were loaded in the ATR reactor have been fabricated and shipped successfully. Two irradiation test vehicles have been fabricated and inserted into the ATR in Idaho. Irradiation of these experiments began in August 1997. The experimental vehicle RERTR-1 is scheduled to undergo two reactor cycles totaling 91 days of irradiation (38 effective full power days), being discharged from the reactor following a shutdown scheduled for November 30, 1997. The peak fuel burnup at this time is expected to be ~43 at.%. the RERTR-2 will undergo six reactor cycles totaling 245 days of irradiation (108 effective full power days). Discharge of RERTR-2 is anticipated to occur following the reactor shut down in June of 1998 at a peak fuel burnup of ~79 at.%. Of particular interest are the extent of reaction of the fuel and matrix

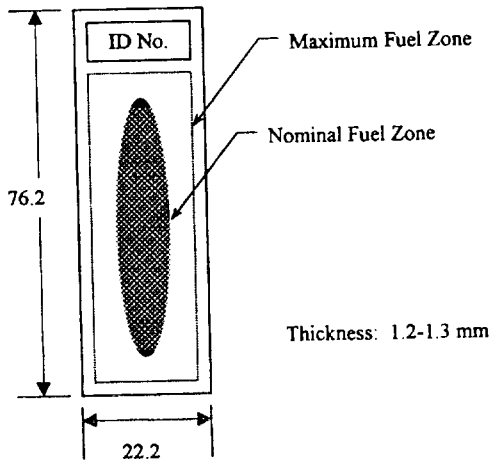

Fig. 11. The microplate.

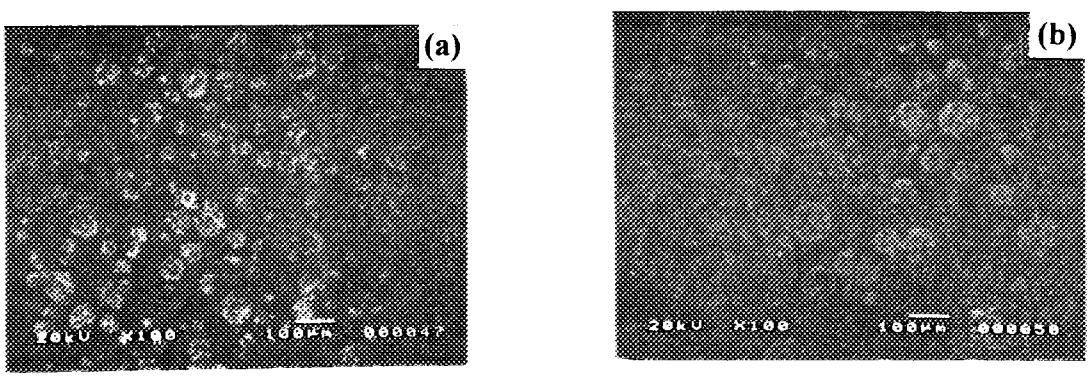

Fig. 12. The cross-section of Al-25vol.% U_3Si_2 (a) and Al-25vol.% U-10wt.%Mo(b) fuel meat with the atomized powder.

phases and the fission gas retention/swelling characteristics of these fuel alloys.

If in cooperation with ANL in U.S. the irradiation test of atomization fuel is performed and the improvement of fuel performance is proven, the atomization process would disseminate world-wide and a considerable profit could be achieved through the technology export. In addition, uranium high loading fuel for high performance research reactors would be hopefully developed with application of atomization process. This result would be contributed to the development of advanced nuclear material.

Foreign Supply of Atomized Powders

Atomized U_3Si_2 and U-10wt.%Mo powders for CERCA were already prepared last month and currently are being packed for shipment now. Depleted uranium lumps with no trace of fission products or transuranian elements were used to fabricate the atomized powders. The U_3Si_2 and U-10wt.%Mo powders had about 20% of the powders below 45 ㎛ against the powders below 125 ㎛ in limited size. The chemical compositions of as-atomized powders in this preparation are shown in Table 2. The metallurgical phases of the powders had almost pure U_3Si_2 in the U_3Si_2 powder and γ-U in the U-10wt.%Mo powder. In addition, the atomized U_3Si_2 powder for BWXT are being prepared now.

Tabel 2 The chemical compositions of as-atomized powders for CERCA
(Unit: wt.% in alloying element, ppm in impurity element).

	U	Si	Mo	Cd	Al	Cu	Li	B	C
U_3Si_2	92.0	7.78	-	<10	37	10	<10	< 0.3	400
U-10Mo	90.8	-	9.7	<10	86	20	<10	< 0.5	120

Conclusion

In order to simplify the preparation process and improve the properties of the uranium alloy fuels, a rotating-disk centrifugal atomization technique has been applied to the production of the fuel powders of uranium-silicide and uranium-molybdenum alloys. Most of the nuisances in the fabrication process of uranium-silicide and uranium-molybdenum fuels could be eliminated by obtaining the powders directly from the molten alloys, which enhances the production economy and results in product powders with less impurities.

The characteristics, specially, morphology, size distribution, alloy phase and microstructure of high-density U_3Si, U_3Si_2, and U-10wt.%Mo alloy powders have been examined. The out-pile properties, including the thermal compatibility between atomized particles and the aluminum matrix in U_3Si, U_3Si_2, and U-10wt.%Mo fuel meats, have been studied. The particle size distribution of atomized U_3Si, U_3Si_2, and U-10wt.%Mo powders could be controlled by adjusting the atomization parameters irrespective of alloy composition. The resulting particle shapes of most powders are near perfectly spherical with relatively narrow distribution, giving no chance of anisotropic alignment of the particles along the working direction. Thermal conductivity of the atomized U_3Si fuel core increases in the radial direction due to the isotropic distribution of particles in the fuel rod, compared with that of comminuted U_3Si fuel core. Formability increases in the extruded U_3Si_2 fuel rod using spherical powders, which improves the U-loading drastically. U-10wt.%Mo powder has a fine grain structure with an isotropic γ-U phase. In addition, U-10wt.%Mo fuel meats, show a excellent thermal compatibility with the Al matrix and maintain a relatively good phase stability.

Moreover, the RERTR (reduced enrichment for research and test reactors) program, which recently begin to develop very-high-density uranium alloy fuels, including U-Mo fuels, further requires the centrifugal atomization process to overcome the contamination of impurities and the difficulties of comminution. A cooperation with ANL in U.S. was established to develop high-density fuels with application of atomization technology for RERTR since December1996. The microplate and miniplate irradiation tests of atomized fuels have been performed with ANL. If these results demonstrate the stability and improvement of in-reactor behaviors, nuclear fuel fabrication technology with centrifugal atomization could be most-promising to the production methods of very-high-uranium-loading fuels for RERTR, and the atomization technology would disseminate world-wide.

References

[1] J. L. Snelgrove, et. al., Pro. of 19th International Meeting on Reduced Enrichment for Research and Test Reactors, Seoul, Korea, 1996.

[2] A. Travelli, Pro. of 19th International Meeting on Reduced Enrichment for Research and Test Reactors, Seoul, Korea, October 6-10, 1996.

[3] G. L. Copeland, G. L. Hofman, J. L. Snelgrove, ANL/RERTR/TM-9, (1986).

[4] R. F. Domagala, T. C. Wiencek, H. R. Tresh, Nucl. Technology, 62 (1983) 353.

[5] G. L. Hofman and J. Rest, ANL/RERTR/TM-18.

[6] U.S. Nuclear Regulatory Commission: "Safety Evaluation Report Related to the Evaluation of Low-Enriched Uranium Silicide-Aluminum Dispersion Fuel for Use in Non-Power Reactors," U.S. Nuclear Regulatory Commission Report NUREG-1313 (July 1988).

[7] D. F. Sears, L. C. Berthiaume, L. N. Herbert, ANL/RERTR/TM-9, 1986.

[8] C. K. Kim, K. H. Kim, C. T. Lee, I. H. Kuk, Pro. of 14th International Reduced Enrichment for Research and Test Reactors, 1991.

[9] T. Kato, K. Kusaka, Materials Transactions, JIM. 31 (1990) 362.

[10] T. Kato, K. Kusaka, H. Horata, and J. Ichikawa, Tetsuto-Hagane, 6 (1985) 719.

[11] J. P. Durand and Y. Fanjas, Pro. of 16th International Meeting on Reduced Enrichment for Research and Test Reactors, Oarai, Japan, October 4-7, 1993.

[12] J. P. Durand and P. Laudamy and K. Richter, Pro. of 17th International Meeting on Reduced Enrichment for Research and Test Reactors, Williamsburg, Virginia, USA, September 18-23, 1994.

[13] J. P. Durand, Y. Lavastre, M. Grasse, Pro. of 20th International Meeting on Reduced Enrichment for Research and Test Reactors (to be published), Jackson-Hole, Wyoming, USA, October 5-10, 1994.

[14] C. L. Trybus, T. C. Wiencek, M. K. Meyer, D. J. McGam, and C. R. Clark, Pro. of 20th International Meeting on Reduced Enrichment for Research and Test Reactors (to be published), Jackson-Hole, Wyoming, USA, October 5-10, 1994.

[15] S. Hayes, C. L. Trybus, and M. K. Meyer, Proc. of 20th International Meeting on Reduced Enrichment for Research and Test Reactors (to be published), Jackson-Hole, Wyoming, USA, October 5-10, 1994.

[16] R. Mehrabian, Int. Metall. Rev., 27 (1982)184.

[17] R. West, H. Fredrikson, J. Mater. Sci., 20 (1985) 1061.

[18] R. R. Anantatmula, A. A. Johnson, R. S. Vatne, Pro. of the International Meeting of the International Metallographic Society, 217 (1975).
[19] Konobeevskin et al, Proc. of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1958.
[20] K. H. Eckelmeyer, Microstructural Structure, Vol. 7, eds. McCall (Fallen, 1977).
[21] J. Burke: The Kinetics of Phase Transformation in Metals (Pergamon Press, Oxford, 1965) pp 184-195.
[22] T. C. Wiencek, R. F. Domagala, H. R. Tresh, Nucl. Tech., 71 (1985) 608.