# Fabrication of Atomized U-Mo Dispersion Rod Type Fuel for Irradiation Test Related to the Qualification Program

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## ABSTRACT

The qualification program of atomized U-Mo dispersion rod type fuel in connection with the spent fuel management is under way using HANARO in Korea. An investigation on the fuel material properties has been carried out. The U-7wt.%Mo and U-9wt.%Mo fuel rods, which have low density equivalent to HANARO fuel of 3.15 g-U/cc and high density of 6 g-U/cc respectively, were planned to be irradiated in HANARO. A neutron physics calculation for the irradiation test in HANARO was done and the fuel center temperatures were estimated. The diameters of fuel meats with low and high uranium densities were decided to be 6.35 mm and 4.5 mm under the condition that the fuel center temperatures do not go up to 250 °C. The fuel meat rods for the irradiation test were successfully fabricated by atomization and extrusion.

## INTRODUCTION

It is known that reprocessing of uranium silicide dispersion fuels is difficult [1]. On the other hand, U-Mo dispersion fuel, which has been developed for the high performance research reactor fuel with a very high uranium density, was investigated to be reprocessable[2]. In connection with the end of the US return policy in May, 2006, an accelerated qualifying program to replace the current uranium silicide fuel with U-Mo dispersion fuel was undertaken by the RERTR program.

In Korea, $U_3Si$ dispersion rod type fuel is used in HANARO, which is a multi-purpose research reactor [3]. In order to get versatility in spent fuel management as well as reactor performance, a qualification program of U-Mo dispersion rod type fuel was established. The fuel rod and bundle irradiation tests as well as an investigation on fuel material properties were planned according to the procedures done for $U_3Si_2$ dispersion fuel qualification and the information from the RERTR program and qualification workshops.

In this paper, the plan for the qualification program is introduced, and the research progress is described.

## QUALIFICATION PLAN

The Mo content of the irradiation test fuel was planned to be 7 wt.% and 9 wt.% from the viewpoint of higher temperature probability due to a longer heat diffusion distance from the center to the surface in rod type fuel than in plate type fuel. In addition, the uranium density of irradiation fuel was chosen to be a low density equivalent to HANARO fuel of 3.15 g-U/cc and a high density of 6 g/U/cc. Under the condition that the fuel center temperature does not go up higher than 250 °C, the fuel meat diameters were calculated to be 6.35 mm and 4.5 mm, respectively. The irradiation tests consist of fuel rod tests for fuel performance evaluation and a bundle test for final demonstration. The fuel rod irradiation tests will be conducted at 40% and 70% burnup.

The test items for the material properties are a tensile test, density and porosity measurements, thermal conductivity measurements, thermal compatibility tests, interaction kinetics, and the determination of interaction heat. The Mo contents of U-Mo dispersion fuels used for property characterization are 6wt.%, 8wt.% and 10 wt.%. The volume fractions of U-Mo fuel powder in the fuel meat are 10%, 30%, 40%, and 50%. All fuel meat specimens are prepared by extruding the mixed powder of atomized U-Mo powder with aluminum powder. The tensile tests are done at two kinds of temperature, room temperature and 150 °C. The temperatures of the thermal compatibility tests are 400 °C, 450 °C, 500 °C and 550 °C. The thermal conductivity measurements are conducted for the longitudinal extrusion direction and the transverse direction close to the actual heat flow direction.

## INVESTIGATION ON FUEL MATERIAL PROPERTIES

12 kinds of fuel meat samples were prepared by extruding the mixed U-Mo and aluminum powders as shown in Table 1. The measured densities showed that the density values were scattered more strongly as the fuel powder volume fraction increased. In general, the ratio of measured density to theoretical density decreased with the fuel powder volume fractions due to the impingement of fuel particles. Tensile test results showed that UTS increased and elongation decreased with the increasing volume fraction of U-Mo fuel powders as shown in Figure 1.

Table 1. Measured density of samples used for material property investigation.

| Sample No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mo content | 6wt.% | | | | 8wt.% | | | | 10wt.% | | | |
| Fuel vol.% | 10 | 30 | 40 | 50 | 10 | 30 | 40 | 50 | 10 | 30 | 40 | 50 |
| Measured Density | 4.21 ±0.02 | 7.16 ±0.19 | 8.45 ±0.40 | 9.83 ±0.81 | 4.17 ±0.01 | 7.05 ±0.26 | 8.48 ±0.81 | 9.51 ±0.61 | 4.37 ±0.35 | 7.076 ±0.17 | 7.78 ±1.68 | 9.58 ±0.64 |
| Theoretical Density | 4.20 | 7.20 | 8.70 | 10.21 | 4.17 | 7.10 | 8.56 | 10.03 | 4.13 | 7.00 | 8.43 | 9.86 |

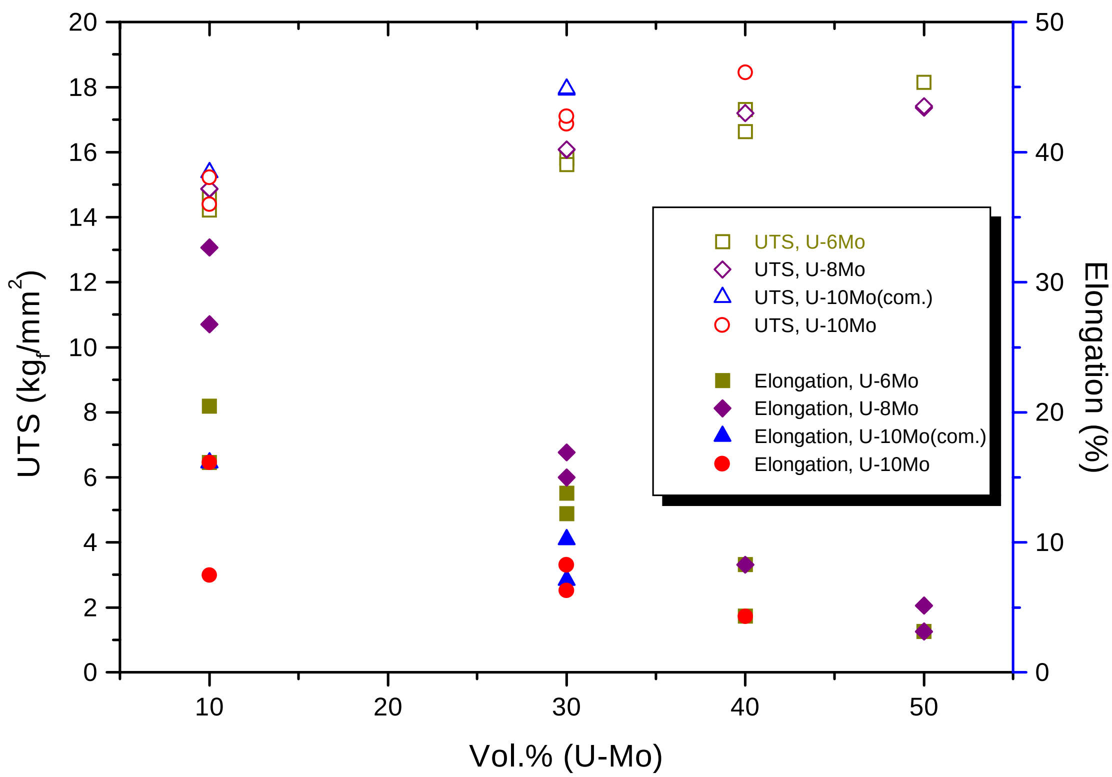



Figure 1. The variation of UTS and elongation of U-Mo/Al dispersion fuel meat with the volume fraction of U-Mo fuel powders.

The thermal compatibility tests show a considerable difference between the U-6wt.%Mo and U-8wt.%Mo dispersion fuel meats as shown in Figure 2. U-8wt.%Mo dispersion fuel meat annealed at 400 °C for 500 hours did not show detectable interacted layers, while the U-6wt.%Mo dispersion fuel meat showed interacted layers 6 to 10 μm in thickness, as shown in Figure 3 and the decomposed cellular structures in the remaining areas of fuel particles as shown in Figure 4. In general, the fuel meat with a higher Mo content was revealed to have more stability in thermal compatibility tests. However, the low limit of Mo content having the thermal stability is presumed to be between 6wt.% and 8wt.%. Therefore an additional thermal compatibility test for

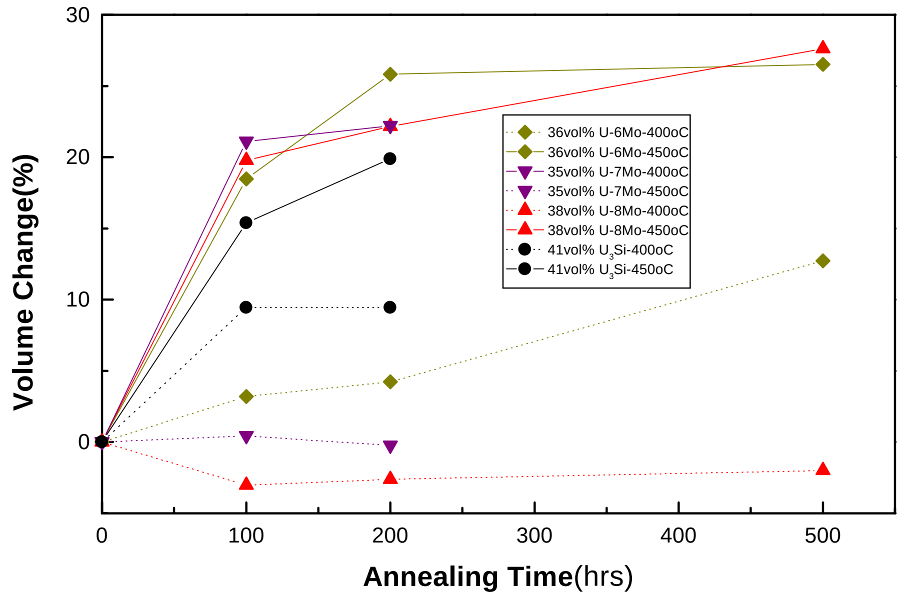
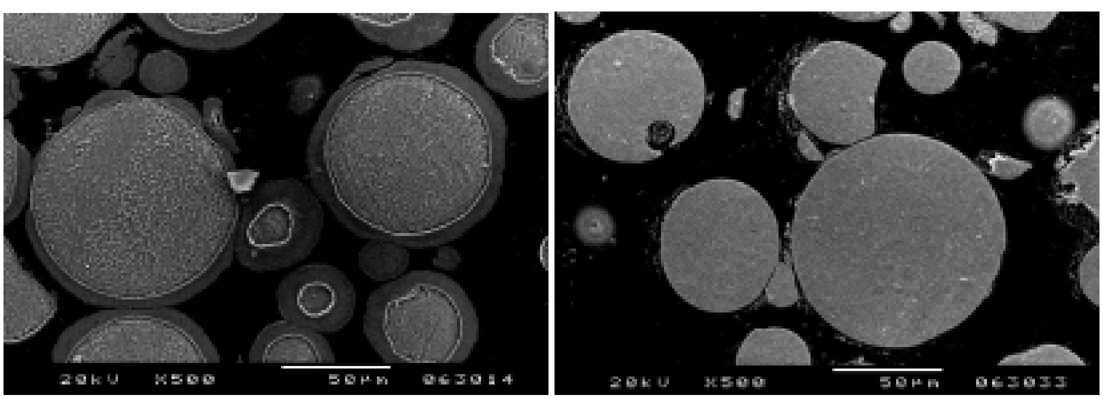
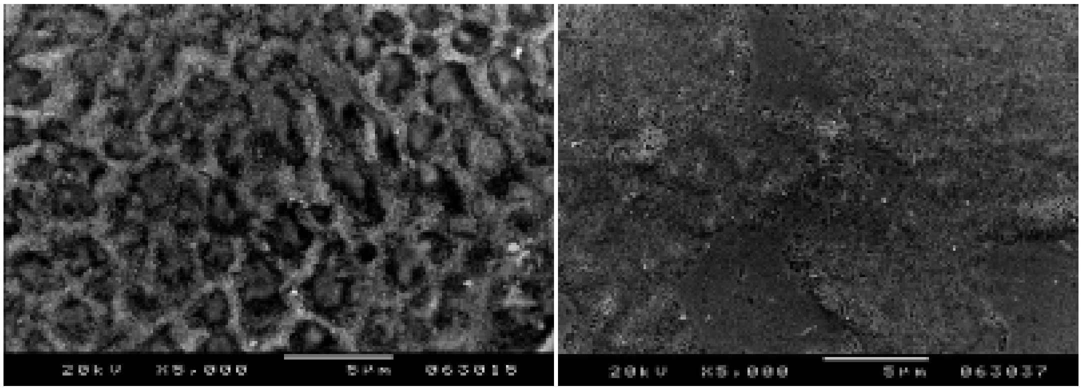



Figure 2. The thermal compatibility test results for various fuel meats.



(a) U-6wt.%Mo fuel meat, (b) U-8wt.%Mo fuel meat

Figure 3. The swelling behavior of the annealed fuel meats at 400 °C for 500 hours.



(a) U-6wt.%Mo fuel meat, (b) U-8wt.%Mo fuel meat

Figure 4. SEM observations on U-6wt.Mo and U-8wt.%Mo dispersion fuel meats thermally annealed at 400 °C for 500 hours.

U-7wt.Mo fuel meat is under way.

It is known that the thermal interaction increases with annealing temperature. The fuel meats containing more than 7wt.% Mo content showed that relatively considerable interactions occurred at 450 °C for 500 hours. The maximum stable temperature for the U-Mo fuel meat is considered to be somewhere between 400 °C and 450 °C.

When heat treatment for coarsening the grains was done, the growth rate of the layers was slowed. In the compatibility test for fuel meats with various fuel powder volume fractions, the interaction rates were examined to be higher for smaller fuel powder volume fractions. The reason is presumed to be due to the higher probability for aluminum atoms to be provided in fuel meats with a lower volume fraction of fuel particles.

An investigation on interaction kinetics, reaction heats, and thermal conductivities of fuel meats was done. The results are reported separately by Ki-Hwan Kim and Sang-Hyun Lee at this meeting.

## NEUTRONICS STUDY FOR LOADING

Calculations were done to find the uranium loading density in U-Mo dispersion fuel having the same value of affective multiplication as the current uranium silicide dispersion fuel in HANARO. The uranium loading densities for U-7wt.%Mo and U-9wt.%Mo equivalent to current HANARO fuel were obtained as 3.41 g-U/cc and 3.36 g-U/cc, respectively.

An effort was made to estimate the fuel center line temperature for all kinds of the irradiation fuels. The thermal conductivity of fuel was taken to be 104 W/m·K from the obtained information. The irradiation bundle consists of 6 aluminum dummy rods and 12 various fuel rods, which are 3 low (3.15 g-U/cc) and 3 high (6 g-U/cc) density fuel rods of U-7wt.Mo and U-9wt.%Mo, respectively. It will be loaded in the OR hole of HANARO. The operating power of HANARO was assumed to be 24 MW. The linear power calculation for each fuel rod was done using the MCNP code and the fuel center temperature was then estimated. Supposing the fuel rod diameter to be the same as the standard size of HANARO fuel, 6.35 mm, the center temperature of high density fuel was calculated to be much higher than 250 °C. Therefore, it was decided the diameter to reduce to 4.5 mm under the condition that the maximum center temperature does not go up higher than 250 °C. Using the final fixed diameter, the maximum fuel center temperatures were estimated as shown in Table 2.

Table 2. The estimated maximum center temperatures for various fuels

| | U-7wt.%Mo fuels | | U-9wt.%fuels | |
|---|---|---|---|---|
| | Low density | High density | Low density | High density |
| Linear Power (kW/m) | 76.8 | 61.1 | 76.8 | 61.1 |
| Center Temp. (°C) | 243.1 | 219.7 | 243.1 | 219.7 |

## FUEL FABRICATION FOR IRRAIATION TESTS

Fuel powders of U-7wt.%Mo and U-9wt.%Mo were produced by rotating disk centrifugal atomization. The chemical compositions were obtained as shown in Table 3. Mo contents were analyzed to be a little more than the expected value based on the experiments using depleted uranium metal. This difference is assumed to originate from oxidation on the surface of LEU metal pieces. The most likely impurity incorporated during the atomizing process would be carbon because graphite assembly is used as susceptors for induction heating. The carbon content appeared to be relatively low. The particle size distribution was obtained as shown in Figure 5. The fraction of smaller sized particles less than 325 mesh is around 20%, which is almost same as the fraction of fuel powders used in the USA. The particle size can be controlled by the atomizing parameters such as rotating speed, melt feeding rate and temperature, and disk size. In the case of fuels not requiring a very high density, fuel powder with small fraction of fine particles would be better from the viewpoint of the interaction between fuel particles and the matrix

The densities of atomized fuel powders were measured as shown in Table 4. The differences with the theoretical densities are assumed to be induced from the internal

Table 3. Chemical Analysis Results of Atomized U-Mo powders

| | U-7wt.%Mo | U-9wt.%Mo |
|---|---|---|
| U | 92.29±0.06% | 90.20±0.09% |
| Mo | 7.3% | 9.1% |
| Si | 130 ppm | 110 ppm |
| C | 400 ppm | 400 ppm |

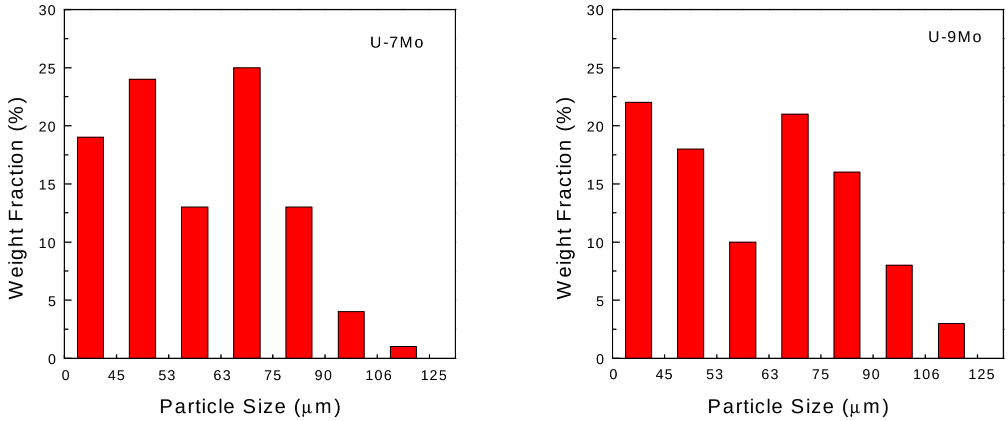



Figure 5. Particle sized distributions of atomized U-7wt.%Mo and U-9wt.%Mo.

porosity in the particles and the measurement error in the alcohol immersion method. X-ray diffraction analysis results are shown in Figure 6. All powders were found to be have a typical gamma structure due to the rapid cooling effect of the atomization process

After the mixing work was done as usual, the mixed fuel powders were extruded into fuel meat rods at 400 $^{o}$C with an extrusion ratio of 40:1 for 6.35 mm in diameter and 80:1 for 4.5 mm in diameter. The fuel meat densities were measured as shown in Table 4. The measured densities for all kinds of fuel meats appeared to be close to the theoretical densities. The fraction of the measured density to the theoretical density was calculated to be higher than 98%. The porosities are considered to be very small, presumably less than 3 %. The gamma phase of fuel particle was analyzed to maintain in extruding as shown in Figure 7. It is assumed that the extruding temperature of 400 $^{o}$C is too low to decompose the gamma phase and the time taken for extruding is too short.

The fuel meat rods were cladded with 1060Al by co-extrusion at 510$^{o}$C. The thickness of the cladding was set to be 0.76mm for 6.35 mm diameter fuel meat.

Table 4. Density Measurements of Atomized U-Mo powders

| | U-7wt.%Mo | U-9wt.%Mo |
|---|---|---|
| Measured Density | 17.06 g/cm$^3$ | 16.97 g/cm$^3$ |
| Standard Deviation | 0.11 g/cm$^3$ | 0.05 g/cm$^3$ |
| Theoretical Density | 17.53 g/cm$^3$ | 17.19 ppm |

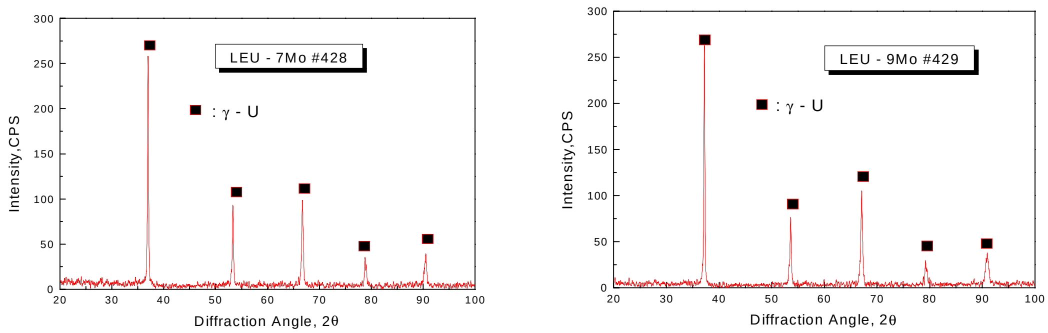



Figure 6. X-ray diffraction results of atomized U-7wt.%Mo and U-9wt.%Mo fuel powders.

Table 5. Measured densities of fuel the meat with U-7wt.Mo and U-9wt.%Mo.

| Alloy | Uranium Loading Density | Measured Densities | Theoretical Density |
|---|---|---|---|
| U-7wt.%Mo | 3.15 g-U/cm$^{3*}$ | 5.77±0.07 | 5.80 |
| | 6 g-U/ cm$^3$ | 8.04±0.12 | 8.16 |
| U-9wt.%Mo | 3.15 g-U/ cm$^{3*}$ | 5.82±0.09 | 5.82 |
| | 6 g-U/ cm$^3$ | 8.15±0.08 | 8.26 |

* Uranium loading density equivalent to current HANARO fuel

**FUTURE PLAN RELATED TO U-Mo FUEL QUALIFICATION**

The fuels for the irradiation tests are expected to be fabricated by the end of October. The 1st irradiation test is scheduled to start from the end of November until the end of May, 2001 with the condition of a low burnup of about 40 at.%. After the 1st irradiation test is confirmed to be conducted without problems up to around 30at.% burnup, the

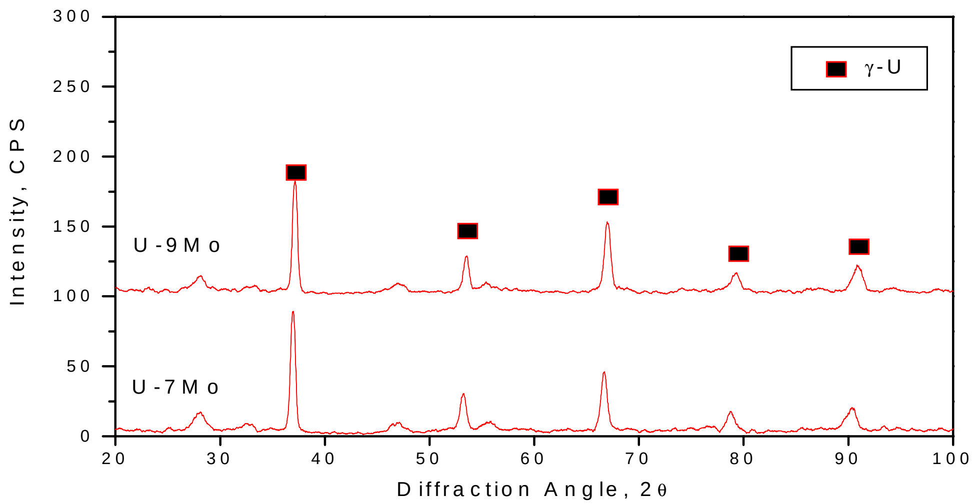



Figure 7. X-ray diffractions of the fuel powders taken from extruded fuel meats by NaOH leaching.

2nd irradiation test for a high burnup of 70 at.% will be launched in the OR hole in HANARO around March, 2001 and is expected to take about 12 months. After the evaluation of the 1st and 2nd tests, the last fuel bundle irradiation test for the demonstration of fuel performance is planned to be done at about 60 at.% burnup for about 10 months from around January, 2003. The final report for the qualification program is expected to be issued by the end of 2004. A study for the application of high uranium loading fuel to HANARO will be carried out separately.

## SUMMARY

In order to get versatility in spent fuel management as well as the fuel performance in HANARO, qualification of U-Mo dispersion rod type fuel has been carried out. Achievements and future plans are summarized as follows:

1) Investigation on material properties
   - The low limit of Mo content having thermal stability is presumed to be between 6wt.% and 8wt.%.
   - The maximum stable temperature for the U-Mo fuel meat is considered to be somewhere between 400 °C and 450 °C.

2) Neutronics study
   - The uranium loading density for U-7wt.%Mo equivalent to $U_3Si$ fuel with 3.15 g-U/cc in HANAO was calculated to 3.41 g-U/cc.
   - It was decided to reduce the diameter for high U density fuel meat to 4.5 mm for the maximum center temperature to not go up higher than 250 °C.

3) Fuel fabrication
   - Fuel meats of U-7wt.%Mo and U-9wt.%Mo were successfully produced by rotating disk centrifugal atomization and extrusion.
   - The measured density for the fuel meats appeared to be close to the theoretical density. The porosities are very small, less than 3 %.

4) Future plan for U-Mo fuel qualification
   - The 1st irradiation test is scheduled to start from the end of November until the end of May, 2001 with a low burnup of about 40 at.%.
   - The final report for the qualification program is expected to be issued by the end of 2004 through the 2nd irradiation test with a higher burnup of 70at.% and the last fuel bundle irradiation test for the demonstration of fuel performance.

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