Design of Pseudo Fuel Debris Fabrication Equipment for Critical Experiment in converted STACY

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Abstract

Towards the decommissioning of the Fukushima Daiichi Nuclear Power Station (1F), Japan Atomic Energy Agency (JAEA) has designed fabrication equipment of a pseudo fuel debris for the evaluation of the criticality characteristics of 1F fuel debris. In order to confirm the feasibility of the fabrication-method in designing, some fuel pellets mixed with uranium oxide and structural materials (Fe, Si, Zr, etc.) were manufactured. The properties such as pressing and sintering condition were obtained by the prototyped fuel debris. The pseudo fuel debris fabricating equipment reflecting these properties is designed in 2016 and now constructed. The equipment will be installed in 2018 to start the fabrication.

1. Introduction

In 1F decommissioning project including defueling, the fuel debris needs to be treated with great care from the standpoint of criticality safety, due to the uncertainty of its chemical composition and physical state. In the accident at 1F, it is speculated that uranium, zirconium and iron solid solution is one of the major materials of fuel debris, according to the review and analysis of information released from Tokyo Electric Power Company and government authorities. In addition, porous structure of the fuel debris may form with the concrete composition by molten-core-concrete-interaction.

For development of criticality control of the fuel debris, JAEA has been planning to perform critical experiments using a pseudo fuel debris, at the Static Experiment Critical Facility (STACY). Also the core of STACY is being converted from a uranyl-nitrate-solution-fuel type to a UO_2-fuel-rod-and-water-moderator type. The critical experiments using the modified STACY require the pseudo fuel debris with simulating the criticality characteristics of 1F fuel debris. And high dimensional accuracy is required for the pseudo fuel debris to evaluate the criticality characteristics of the fuel debris with high accuracy. JAEA designed new equipment to fabricate the pseudo fuel debris. In designing, in order to confirm the feasibility of the fabrication-method, some fuel pellets mixed with uranium oxide and structural materials (Fe, Si, Zr, etc.) were manufactured. The properties such as pressing and sintering condition were obtained by the prototyped fuel debris. The pseudo fuel debris fabricating equipment reflecting these properties is designed in 2016 and now constructed. The equipment will be installed to start the fabrication in 2018.

2. Critical experiments for fuel debris

In the accident at 1F, it is conceivable that fuel debris may have formed from the solidified melted including the fuel assemblies, control rods, and some other reactor materials [1].Therefore the fuel debris may include zirconium from the clad, boron from the control rod, iron from the reactor structure, and light elements such as silicon contained in concrete. According to the phase composition as a function of composition and temperature, debris have various composition distributions [2]. Some effects such as deceleration, diffusion distance, and thermal neutron absorption by these elements affect nuclear criticality safety for the fuel debris in 1F.

For development of criticality control of the fuel debris, JAEA has been planning to perform critical experiments at the STACY using a pseudo fuel debris which have various chemical compositions (Fe, Si, Zr, etc.) [3]. As shown in Fig.1, the pseudo fuel debris will be located in the center of the sample loading device. And the sample loading device will be located in the core tank of the modified STACY. The use of a pellet-shaped sample as the pseudo fuel debris is most preferable from the view point of safety, stability, handling convenience.

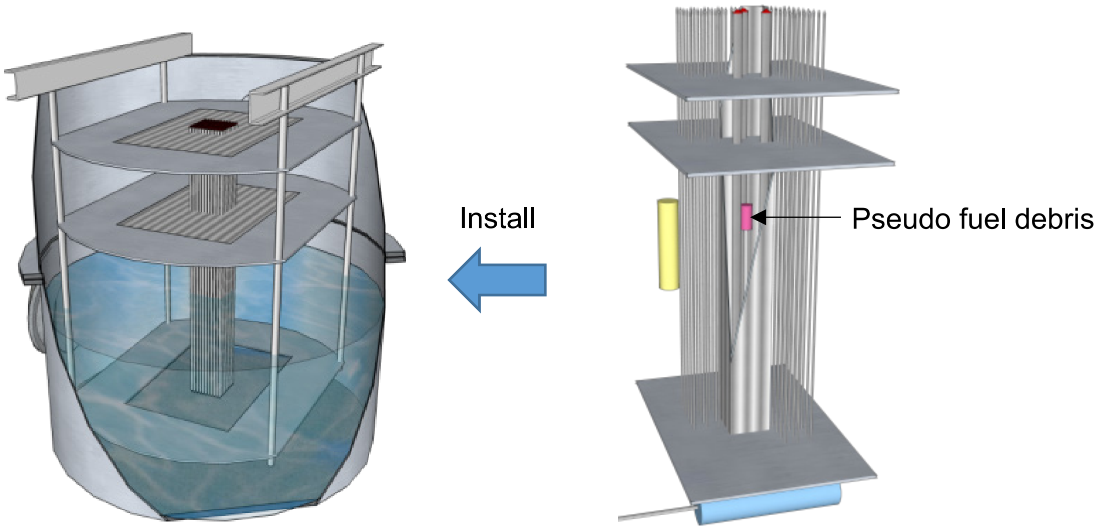

Fig.1 Overview of the modified STACY

3. Prototype of pseudo fuel debris

The pseudo fuel debris pellets are to be manufactured by mixing UO_2 and reactor structural materials (Fe, Si, Zr, etc.) with various chemical compositions. The debris materials will be mixed in the form of oxide powders. Fabrication of the pseudo fuel debris pellet requires to understand molding conditions, sintering conditions, and shape stability of the pellet. Furthermore, uniform outer diameter dimensions are required for the pseudo fuel debris pellet used in critical experiments for STACY. However, research on the fabrication method of UO_2 pellets containing a large amount of impurities has not been done sufficiently. Therefore, in order to confirm the feasibility of the pseudo fuel debris fabrication method, some fuel pellets mixed with uranium oxide and structural materials (Fe, Si, Zr, etc.) were manufactured. The conditions of molding and sintering were obtained by the trial manufacture, and the shape stability was examined by the prototyped fuel debris.

3.1 Specification of the prototyped fuel debris

The prototyped fuel debris with various chemical compositions listed in Table 1 were tried to manufacture. Specification of the prototyped fuel debris is as follows.

Pellet size after sintering : ϕ8 mm in diameter and 10 mm in height (target size)
Powder particle size : 125 μm or less
Uranium enrichment : Depleted uranium

Table 1 Chemical compositions of the prototyped fuel debris

Lot No.	Chemical compositions (wt.%)					
	U	Zr	Si	Fe	Ca	Al
1	100					
2	90	10				
3	75	25				
4	59	41				
5	44	56				
6	34	66				
7	23	77				
8	12	88				
9		100				
10	94		6			
11	88		12			
12	80		20			
13	73		27			
14	65		35			
15	43		57			
16	32		68			
17			100			
18	55	28		9	9	
19	80					20

3.2 Manufactural procedure

(1) Powder preparation
Weighed UO_2 powder and metal oxide powder (Zr, Si, Fe, Ca, and Al) are mixed by means of a planetary ball mill. Then the resultant mixture are sieved using an sieve 125 μm in mesh size, and uniformly mixed with a die lubricant and a binder by a mixing machine.

(2) Pellet molding
Conditioned powder of 3 ~ 5g is fed into dies and pressed biaxially using a load of several hundred MPa such that after sintering pellet size is ϕ8 mm in diameter and 10 mm in height.

(3) Sintering
These green pellets are sintered by heating in a furnace under a reducing atmosphere using a gas containing hydrogen (4% H_2-Ar balanced). The sintering and holding temperature are 1650°C, and the time spent is 4 hours.

3.3 Result and discussion

(1) Pellet molding
The results of the pellet molding test are shown in Table 2. Figure 2 shows photographs of the green pellet pressed under the predetermined molding condition. Under the present molding condition, Lot No.15 (U43:Si57), No.16 (U32:Si68), No.17 (Si100) pellets were not possible to

mold. Lot No.14 (U65:Si35) pellet was possible to mold, therefor it is considered that the threshold of additive amount of Si is 35wt.% ~ 57wt.% in the present condition of molding. As the results of the U - Zr pellets (Lot No. 1 to 9), it was possible to mold within the range of 0 wt.% to 100 wt.% for the Zr.

Table 2 Results of the pellet molding

Lot No.	Chemical compositions (wt.%)						Remarks
	U	Zr	Si	Fe	Ca	Al	
1	100						
2	90	10					
3	75	25					
4	59	41					
5	44	56					
6	34	66					
7	23	77					
8	12	88					
9		100					
10	94		6				
11	88		12				
12	80		20				
13	73		27				
14	65		35				
15	43		57				Unmoldable
16	32		68				Unmoldable
17			100				Unmoldable
18	55	28		9	9		
19	80					20	

Lot No.1 (U = 100) 	Lot No.2 (U:Zr=90:10) 	Lot No.3 (U:Zr=75:25) 	Lot No.4 (U:Zr=59:41) 
Lot No.5 (U:Zr=44:56) 	Lot No.6 (U:Zr=34:66) 	Lot No.7 (U:Zr=23:77) 	Lot No.8 (U:Zr=12:88) 
Lot No.9 (Zr = 100) 	Lot No.10 (U:Si=94:6) 	Lot No.11 (U:Si=88:12) 	Lot No.12 (U:Si=80:20) 
Lot No.13 (U:Si=73:27) 	Lot No.14 (U:Si=65:35) 	Lot No.18 (U:Zr:Fe:Ca=55:28:9:9) 	Lot No.19 (U:Al=80:20) 

Fig.2 Photographs of the green pellet

(2) Result of the pellet density measurement

In the process of pellet manufacturing, the correlation between green density and sintered density was investigated from the viewpoint of the design of manufacturing equipment. The pellet densities before and after sintering are shown in the Table 3. Figure 3 shows photographs of the pellet sintered under a predetermined sintering condition. The outer diameter and the height after sintering were set to ϕ 8 mm in diameter and 10 mm in height respectively as the target values, but it can be seen that they are largely different depending on the composition of each pellet.

As a result, in order to optimize the outer diameter of the objective pellet, it is necessary to adjust the inner diameter of the mold and the press pressure. Also, in order to optimize the target pellet height, it is necessary to adjust the press pressure and the amount of powder charged into the dais. Based on these results, equipment that can manufacture the pellets for the critical experiments in STACY was designed.

Table 3 Pellet densities before and after sintering

Lot No.	Before sintering			After sintering		
	Outer diameter (mm)	Height (mm)	Density (g/cm^3)	Outer diameter (mm)	Height (mm)	Density (g/cm^3)
1	10.09	12.02	5.34	8.01	9.57	10.43
2	10.06	12.23	5.27	8.26	10.05	9.37
3	10.07	12.02	5.23	8.54	10.27	8.39
4	10.07	12.00	5.05	8.74	10.65	7.46
5	10.07	11.96	4.31	8.75	10.69	6.32
6	10.07	12.06	4.11	8.98	11.08	5.59
7	10.07	12.71	3.99	9.01	11.77	5.35
8	10.07	12.16	3.83	9.07	11.32	5.05
9	10.09	12.23	3.49	8.92	11.15	4.88
10	10.10	11.97	5.18	8.84	10.82	7.22
11	10.11	12.61	4.16	8.85	11.21	5.88
12	10.26	12.34	3.78	9.34	11.57	4.65
13	10.29	11.56	3.39	9.45	10.91	4.03
14	10.31	11.11	3.02	9.46	10.53	3.54
15*	-	-	-	-	-	-
16*	-	-	-	-	-	-
17*	-	-	-	-	-	-
18	10.06	12.00	3.89	9.22	11.09	4.75
19	10.07	12.34	4.12	8.30	10.33	7.12

*Lot No.15, 16, 17 pellet was not possible to mold.

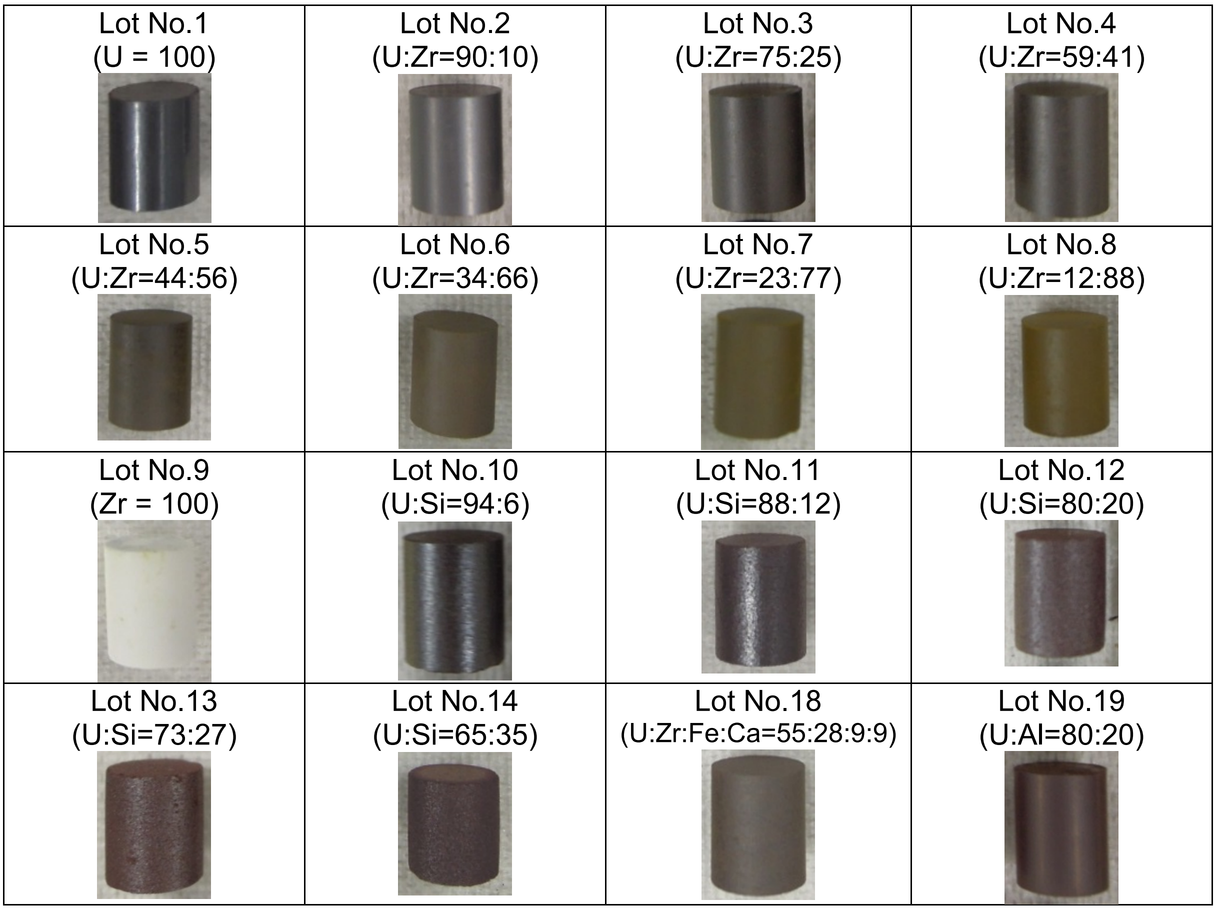

Fig.3 Photographs of the sintered pellet

4. Design of pseudo fuel debris fabrication equipment

The equipment for fabricating of the pseudo fuel debris is composed of a ball mill, molding machine, and sintering furnace, and so on. The manufacturing equipment is to be installed in two glove boxes in the experimental building adjoining the modified STACY. The molding machine is composed in one glove box. The other one is composed of the ball mill and the sintering furnace. The manufacturing ability is to be 300 pellets a month.
The outline of specifications of each component is as follows. And Figures 4 and 5 show photographs of the molding machine and sintering furnace.

(1) Ball mill
The reactor structural materials (Fe, Si, Zr, etc.) and UO_2 powder are uniformly mixed by a ball mill.

Model:	Fritsch P-5/4 (off the shelf)
Final particle size:	less than 1 micrometer
Grinding bowls:	Zirconia, 250 mL
Grinding balls:	Zirconia, 20 mm

(2) Molding machine
The mixed oxide powder is molded into green pellets by a molding machine. The molding machine has an automatic stop sensor to prevent a part such as a finger and a hand of a worker from being caught.

Cylindrical molding:	SKS3, ϕ8.5, 9.0, 9.5 mm in diameter
Maximum load:	50 kN
Upper stroke:	95 mm

(3) Sintering furnace
The green pellets are sintered by a sintering machine. Due to the temperature limitation of the grove box, the outer surface temperature of the sintering furnace is kept below 60 °C.

Maximum temperature:	1800 °C
Temperature distribution	±10 °C
Sintered capacity:	92 pellets (23 pellets × 4 stage) in a day
Sintering atmosphere	Argon or argon + 4 % hydrogen gas

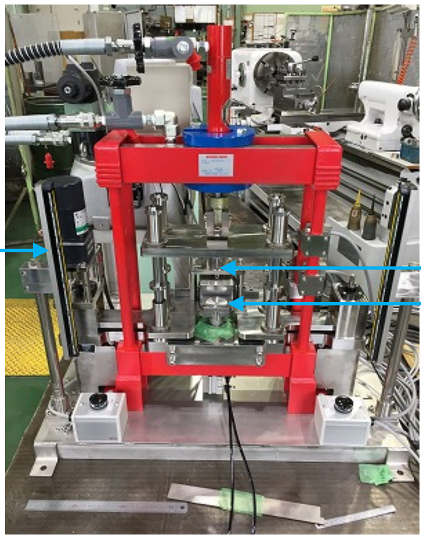

Fig.4 Molding machine

Outer Inner

Fig.5 Sintering furnace

5. Conclusions

As a result of prototyping, molding conditions, sintering conditions, and shape stability were confirmed within the range of 0 wt.% to 100 wt.% for the Zr content and 0 wt.% to 35 wt.% for the Si content. The pseudo fuel debris fabricating equipment is designed in 2016 and now constructed. And the equipment will be installed to start the fabrication in 2018.

Acknowledgment

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