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PRELIMINARY STUDY OF FREQUENCY-VARIABLE VIBRATION PACKING FABRICATION FOR ATOMIZED METALLIC PARTICULATE FUEL USING SURROGATE SPHERICAL POWDER

An alternative fabrication method for metallic fuel in Gen-IV reactor was introduced with vibration packing of nuclear fuel particles to facilitate remote fabrication in a hot cell and reduce the generation of long-lived radioactive wastes. Vibration packing experiments on metallic particulate fuel using a surrogate 316L stainless steel powder were done to investigate the packing density and the uniformity of the simulated fuel according to the filling method and the vibration condition. Metallic particulate fuel filled with a pre-mixed powder over all particles had the highest packing fraction and the most uniform distribution among the filling methods. The vibration packing method showed that it could fabricate the metallic particulate fuel having uniform distribution of spherical fuel particles through the adjustment of the filling method of the metallic powder and the vibration condition of the metallic particulate fuel.

Keywords: Atomized powder, Injection casting, Metallic particulate fuel, Alternative fabrication method, Vibration packing

1. Introduction

Fast reactor in Gen-IV nuclear systems is an attractive energy source [1-3]. Metallic fuel of U-Zr system for Gen-IV nuclear reactor has been developed in combination with the pyro-electrochemical processing of spent fuel [4-6]. A remote fabrication method in a shielded hot cell needs to be prepared to recycle transuranic (TRU) elements retained in spent nuclear fuel [7-8]. Moreover, the generation of long-lived radioactive wastes and the loss of volatile species need to be minimized during the fuel fabrication process. Innovative fuel concepts, therefore, are necessary to address the fabrication challenges of a conventional injection casting method pertaining to TRU elements while maintaining good performances of metallic fuel [9-10]. Metallic particulate fuel is an innovative form for the injection casting of nuclear fuel slugs [11-12]. Spherical U-Zr system particles can be produced with continuous particle size distribution by centrifugal atomization [13-15]. Metallic particulate fuel has major advantages in the fabrication for remote operation under high radioactive circumstances, any shaped fuels, and the simplification of the process with sodium-free fuel [16-18]. Sphere-packing fuel generally consists of a blend

of spheres of two or three different size fractions contained in the particulate fuel [19-22].

In this study, a metallic particulate fuel for fast reactor in Gen-IV nuclear systems was manufactured by frequency-variable vibration packing using three different size fractions of the spherical atomized particles with continuous size distribution [13-14]. To achieve the required smear density for the metallic fuel, a vibration packing method was applied to the fuel particles prepared by the atomization method. The simulated particulate fuel was fabricated using a surrogate 316L stainless steel powder, and characterized to investigate the feasibility of fabricating a sound fuel with vibro-compaction experiments composed of the filling method of metallic powder and the vibration condition of the particulate fuel.

2. Experimental

The vibration packing apparatus of the particulate fuel was composed of a frequency-variable electrodynamic vibration shaker, a feeding system of metallic powder mounted on a pneumatic vibrator, and a simulated fuel rod jacket with an inner

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diameter of 5.7 mm. Spherical 316L stainless steel powders were prepared by a gas atomization method as a surrogate powder of U-Zr system fuel.

The gas-atomized 316L stainless steel powder was classified with three different size fractions using a vibratory sieve shaker. Fig. 1 showed typical morphology of the gas-atomized 316L stainless steel powder. As the atomized U-Zr system powder has a continuous particle size distribution, some atomized 316L stainless steel particles were prepared by mechanical pre-mixing over all particles. The atomized 316L stainless steel powders were classified with three different size fractions of a coarse powder ranging from 150 to 600 μm , a medium-sized powder ranging from 45 to 150 μm , and a fine powder smaller than 45 μm . The 316L stainless steel powders showed a flowability of 18.8 sec/50g for coarse powder, 12.7 sec/50g for medium-sized powder and 12.8 sec/50g for fine powder, measured according to ASTM-B213. The 316L stainless steel powders also indicated the apparent density of 4.66 g/cm^3 for coarse powder, 4.73 g/cm^3 for medium-sized powder and 4.71 g/cm^3 for fine powder, measured according to ASTM-B329.

Table 1 shows the particle size distributions after sieving of the atomized 316L stainless steel powder. The weight percentage of the particle size range was obtained with the weight ratio in the specific size range divided by the total mass on each sieve, after individual sieving according to type of the atomized powder. A coarse powder ranging from 150 to 600 μm was obtained partly under the process conditions of low melt temperature and gas pressure during gas atomization.

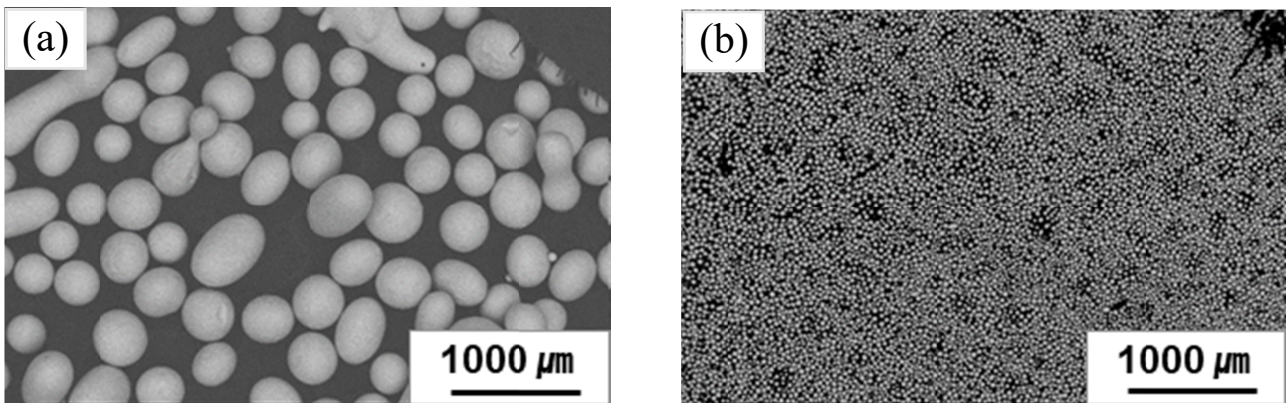


Fig. 1. Typical morphology of the gas-atomized 316L stainless steel powder classified using vibratory sieve shaker; (a) coarse powder (<50 mesh), (b) fine powder <325 mesh

The vibration packing experiments were conducted to investigate the packing density, that is, the smear density, and the uniformity of the simulated fuel with adjustment of the fabrication process parameters [23]. The packing density of the simulated fuel rod was evaluated by weighing the mass of the surrogate spherical powder after the vibro-compaction and the calculation of the space volume in the particulate fuel.

$$\emptyset = \frac{V_t}{V_b} = \frac{W}{V_b \rho_t} \quad (1)$$

in which \emptyset is the packing fraction of the vibratory compacted fuel, V_t is the true volume of the spherical 316L stainless steel powder, V_b is the bulk volume of the vibratory compacted fuel, that is, V_t + intraparticle pore volume (ϵ_{intra}) + interparticle pore volume (ϵ_{inter}), and W is the weight of the feeding 316L stainless steel powder [24]. The homogeneity of the vibratory compacted particulate fuels was examined by nondestructive techniques of X-ray radiography and micro-computed tomography.

3. Results and discussion

The effect of the average vibration frequency on the packing fractions of the sphere-packed particulate fuel with the error bars showing standard deviation is shown in Fig. 2. The particulate fuel packed with a pre-mixed powder over all particles showed the highest packing fraction of 77.5% in weight in the particulate fuel. The particulate fuel infiltrated with the continuous sequence

TABLE 1

The particle size distributions after sieving of the atomized 316L stainless steel powder

Type of powder Particle size (μm)	Pre-mixed powder over entire particle size (wt.%)	Pre-mixed powder with coarse and medium-sized powder (wt.%)	Coarse powder (150-600 μm , wt.%)	Medium-sized powder (45-150 μm , wt.%)	Fine powder (<45 μm , wt.%)
425-600	12.0	12.7	16.9	—	—
300-425	59.7	61.8	83.1	—	—
90-150	8.3	6.6	—	13.8	—
63-90	7.4	5.2	—	19.9	—
45-63	5.8	13.7	—	66.3	—
45 >	6.8	—	—	—	100

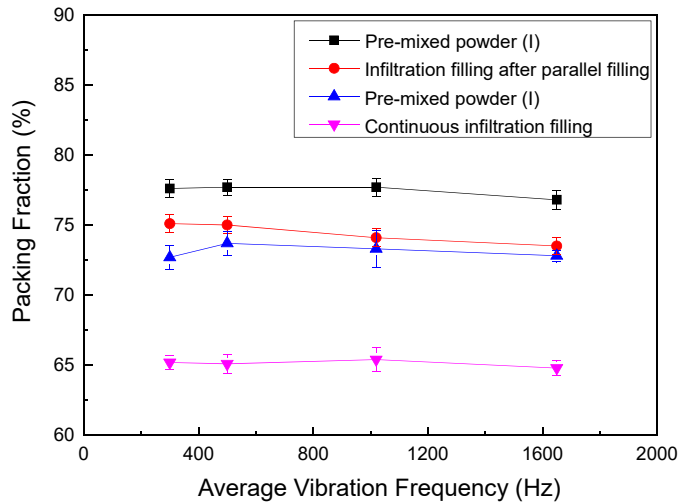


Fig. 2. The effect of the average vibration frequency on the packing fractions of the sphere-packed particulate fuel with the error bars showing standard deviation of the vibration packing experiments

of a coarse powder, a medium-sized powder, and a fine powder generally had the lowest packing fraction of 65.1% in weight with the particulate fuel. The packing fraction of the simulated particulate fuels was widely distributed ranging from 65.1% to 77.5% up to 12.4% in the maximum difference according to the filling method. The filling method of the pre-mixed powder (I) was the most suitable method in the particulate fuels manufactured with packing fraction corresponding to 75% of the theoretical density. However, the packing fractions according to the average vibration frequency in the same filling conditions indicated small differences ranging from 0.6% in weight in continuous infiltration filling to 1.5% in weight in infiltration filling after parallel filling. Thus, the maximum difference in average packing fraction was smaller than 0.9% in weight in spite of the variation of vibration frequency. This means that the vibration conditions did not have a large effect on the packing fraction in the same packing method of the simulated particulate fuels. The spherical

atomized fuel powder had a continuous size distribution over all particles [13-14]. It is so difficult for fine particles to infiltrate in small pores surrounded with coarse particles and medium-sized particles, because the diameter of the spherical particle fractions needs to differ at least by a factor of 7 for optimum packing [19-20]. Blending of spherical particles with smaller diameter ratios generally results in difficult blending, non-uniform loading, and lower packing fractions. It is assumed that the filling method had a larger effect on the packing fraction of the simulated particulate fuels compared with the vibration conditions.

X-ray radiographic results and micro-computed tomography of the sphere-packed particulate fuels according to the filling method are shown in Fig. 3 and Fig. 4, respectively. The particulate fuel filled with the pre-mixed powder over all particles generally exhibited a relatively homogeneous state as shown in Fig. 3(a), except for the top end of the particulate fuel with low-density distribution. It is thought that the movement of the fine particles toward the lower part would result in the slight lack of fine particles in the upper end. The distribution state of the fuel particles was generally uniform in the filling of the pre-mixed powder (I) as shown in Fig. 4(a). The diameter ratio of the spherical particle fractions must be much larger by a factor of 7 for dense packing; however, the average diameter ratio of three different particle fractions is less than 4, as the spherical atomized powder had a continuous size distribution over all particles [13-14]. We believe that the pre-mixing method of all particles before vibro-compaction would be necessary to overcome the difficulty in infiltration of medium-sized and fine particles in the simulated particulate fuel.

The particulate fuel packed with the infiltration filling after feeding of a pre-mixed powder with a coarse powder and a medium-sized powder, shown in Fig. 3(b), caused an extensive low-density segregation in both fuel ends ranging from 65 mm to 95 mm over the entire length. It is thought that it was somewhat difficult to infiltrate the fine particles through medium-sized particles towards the lower part due to the interruption of the

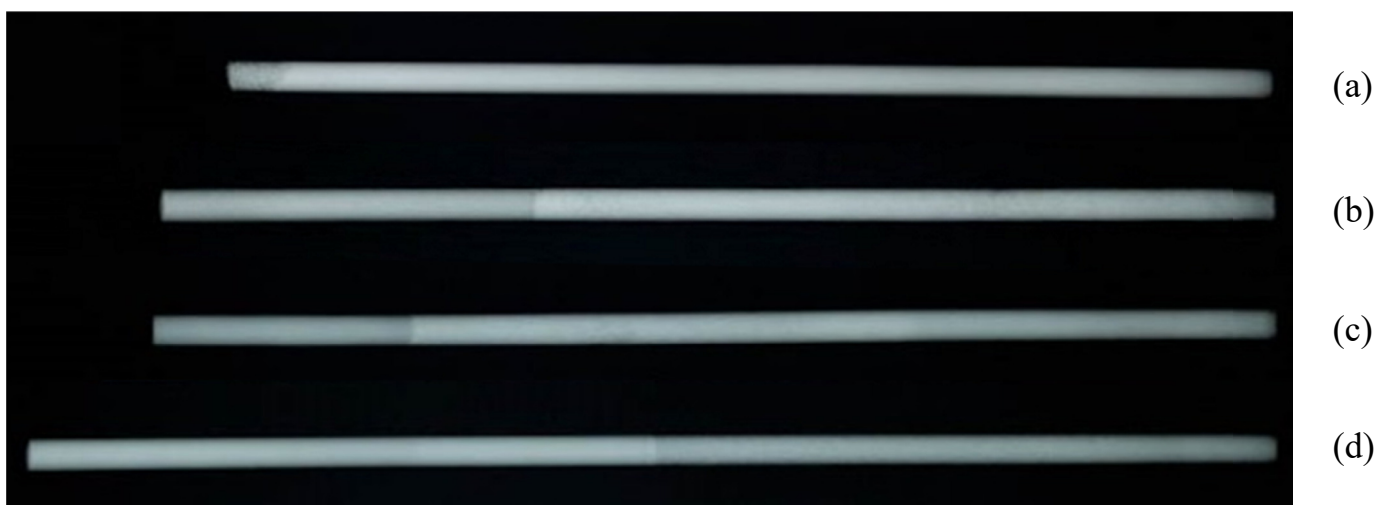


Fig. 3. X-ray radiographic results of the sphere-packed particulate fuels according to the filling method; (a) filling of premixed powder (I), (b) infiltration filling after filling of premixed powder (II), (c) infiltration filling after parallel filling of coarse and medium-sized powder, (d) continuous infiltration filling

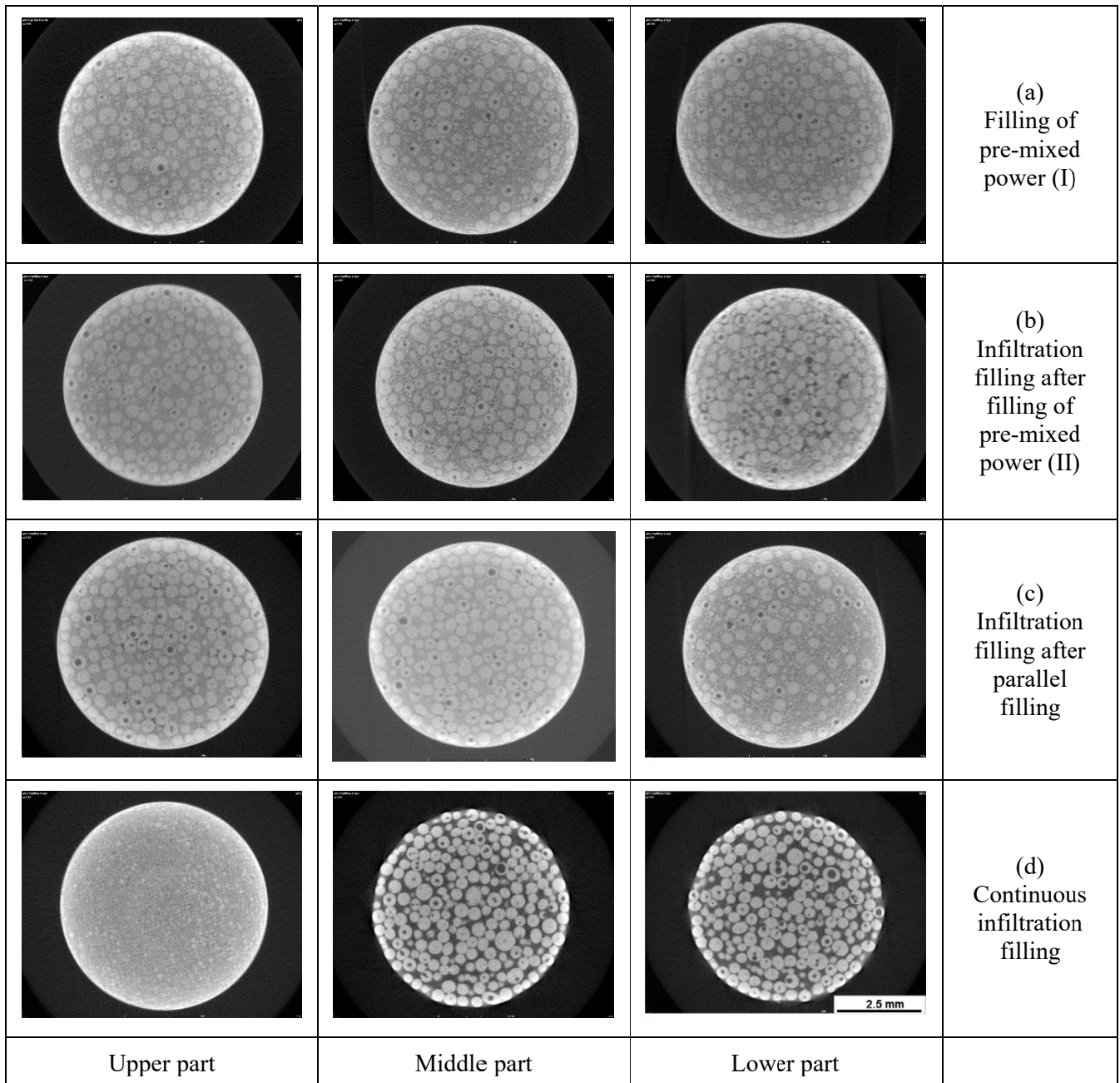


Fig. 4. Micro-computed tomography of radial cross-sections for the sphere-packed particulate fuel according to the filling method and position of the particulate fuel

medium-sized particles, which led to considerable residual of fine particles in the top part and some lack of fine particles in the lower part. The distribution state of the fuel particles prepared by the feeding of pre-mixed powder (II) and the infiltration filling, as shown in Fig. 4(b), was not uniformly arranged differently with the position of the particulate fuel. The fuel particles were uniformly packed in the middle part, but there was low-density segregation by fine particles in the upper part and a considerable number of large pores among coarse particles in the lower part. We assumed that it would be difficult for the fine particles to take up empty space among medium-sized and coarse particles densely and uniformly due to the continuous size distribution of the atomized powder.

The particulate fuel infiltrated with fine powder after parallel filling of coarse and medium-sized powder as shown in Fig. 3(c) generally revealed a homogeneous state with some low-density segregations in the upper part of the particulate fuel in a length of about 30 mm. It is assumed that it was difficult to infiltrate the fine particles in the top fuel part through coarse and medium-sized powder up to the bottom region due to the interruption of the medium-sized particles having a small diameter ratio with fine particles. Medium-sized and coarse particles fed by parallel filling were simultaneously packed before the infiltration filling of the fine particles, which resulted in low-density segregation by fine particles in the top region due to the interruption of the medium-sized particles, similar with the infiltration

filling after feeding of a pre-mixed powder with a coarse powder and a medium-sized powder. The distribution state of the fuel particles prepared by the filling of coarse and medium-sized powder and the parallel infiltration with fine powder, as shown in Fig. 4(c), exhibited some large pores among coarse particles in the upper part, but they were generally uniform in the middle part and the lower part. We assumed that it was difficult for the fine particles to occupy empty space among medium-sized and coarse particles densely and uniformly due to continuous size distribution of the atomized powder because medium-sized and coarse particles fed with parallel filling were arranged in advance before the infiltration filling of the fine particles [19-20].

The particulate fuel infiltrated with the continuous sequence of coarse powder, medium-sized powder, and fine powder exhibited an entire low-density segregation in the particulate fuel overall as shown in Fig. 3(d). The distribution state of the fuel particles after continuous infiltration indicated segregation by the fine particles in the upper part and with high porosity by coarse particles in the middle and the lower part as shown in Fig. 4(d), resulting in the lowest packing fraction of in the particulate fuels. It is assumed that it was very difficult for the fine particles in the upper part to infiltrate through medium-sized particles and coarse particles due to a continuous size distribution of the atomized powder, which caused to significant segregation of the fine particles in the upper part, as shown in Fig. 4(d). It is thought that it was so difficult for the fine particles in the upper part of the particulate fuel to move downward in the lower part during continuous infiltration, which resulted in lot of large pores among medium-sized particles and coarse particles in the middle part and the lower part, as shown in Fig. 4(d).

4. Conclusions

The simulated particulate fuel was fabricated using a surrogate 316L stainless steel powder with a vibration packing method and characterized it to investigate the feasibility of the alternative fabrication method. The filling method had a larger effect on the packing fraction of the simulated particulate fuels compared with the vibration condition due to continuous size distribution of the atomized powder. The metallic particulate fuel prepared by the filling method of the pre-mixed powder over all particles had the highest packing fraction and the most uniform distribution among the filling methods.

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REFERENCES

- [1] T. Abram, S. Ion, *Energy Policy* **36**, 4323-4330 (2008).
- [2] Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems*, 2002.
- [3] H.S. Lee, G.I. Park, I.J. Cho, *Sci. Technol. Nucl. Install.* **2013**, 1-11 (2013).
- [4] H. Lee, G.I. Park, E.H. Kim, *Nucl. Eng. Technol.* **43**, (317-328) 2011.
- [5] J.I. Jang, *Nucl. Eng. Technol.* **43**, 161-170 (2007).
- [6] J.H. Jang, H.S. Kang, Y.S. Lee, H.S. Lee, J.D. Kim, *J. Radioanal. Nucl. Chem.* **295**, 1743-1751 (2013).
- [7] C.E. Stevenson, *The EBR-II Fuel Cycle Story*, American Nuclear Society, La Grange Park, Ill, USA, 1987.
- [8] H. Lee, G.I. Park, I.J. Cho, *Sci. & Technol. Nucl. Install.* **2013**, 1-11 (2013).
- [9] J.H. Kim, H. Song, H.T. Kim, K.H. Kim, C.B. Lee, R.S. Fielding, *J. Radioanal. Nucl. Chem.* **299**, 103-109 (2014).
- [10] M.A. Pouchon, G. Ledergerber, F. Ingold, K. Bakker, *J. Nucl. Mater.* **3**, 275-312 (2012).
- [11] G. Ledergerber, F. Ingold, R.W. Stratton et al., *Nucl. Tech.* **114**, 194-203 (1996).
- [12] G. Bart, F.B. Botta, C.W. Hoth, G. Ledergerber, R.E. Mason, R.W. Stratton, *J. Nucl. Mater.* **376**, 47-59 (2008).
- [13] K.H. Kim, D.B. Lee, C.K. Kim, I.H. Kuk, K.W. Paik, *J. Nucl. Sci. & Tech.* **34**, 1127-1132 (1997).
- [14] J.H. Kim, J.W. Lee, K.H. Kim, C.B. Lee, *Sci. and Tech. Nucl. Install.* **2016**, 1-7 (2016).
- [15] K.H. Kim, S.J. Oh, S.K. Kim, C.T. Lee, C.B. Lee, *Surf. Interface Anal.* **44**, 1515-1518 (2012).
- [16] R. Herbig, K. Rudolph, B. Lindau, *J. Nucl. Mater.* **204**, 93-101 (1993).
- [17] K.L. Peddicord, R.W. Stratton, J.K. Thomas, *Prog. Nucl. Energy* **18**, 265-299 (1986).
- [18] G. Ledergerber, F. Ingold, R.W. Stratton, H.P. Alder, *Nucl. Technol.* **114**, 194-204 (1996).
- [19] A.S. Icenhour, D.F. Williams, *Sphere-Pac Evaluation for Transmutation*, ORNL/TM-2005/41, 2005.
- [20] G.D. Del Cul, C.H. Mattus, A.S. Icenhour, L.K. Felker, *Fuel Fabrication Development for the Surrogate Sphere-Pac Rodlet*, ORNL/TM-2005/108, 2005.
- [21] A.L. Lotts et al., *Fast Breeder Reactor Oxide Fuels Development*, ORNL-4901, 1973.
- [22] Ch. Hellwig, K. Bakker, M. Nakamura, F. Ingold, L.A. Nordstro, Y. Kihara, *Nucl. Sci. Eng.* **153**, 233-244 (2006).
- [23] H.A.C.K. Hettiarachchi, W.K. Mamppearachchi, *Powder Technology* **336**, 150-160 (2018).
- [24] J.G. Jeon et al., *Korean J. Met. Mater.* **54**, 322-331 (2016).