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Study of vipac fuel fabrication for FUJI Project

-Literature survey and recent experiment in JNC-

(Technical Document)

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Japan Nuclear Cycle Development Institute

Tokai Works

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Abstract

Vipac fuel pins that are composed of irregular shape fuel granules will be fabricated and irradiated as well as Sphere-pac and pellet fuel pins in the frame of PSI/JNC/NRG collaboration (FUJI project) to compare their performances.

This report describes the outline of the past vipac filling performed at ORNL, RIAR and in Japan and the results of the experiments recently conducted in JNC. Main factors that dominate performance of the vipac filling process are vibration condition and granule size distribution. The effect of vibration condition is significant and large acceleration is necessary to generate high packing fraction. In addition, sweeping frequency is necessary to break the bridging of the powder and it is effective to promote the granules movement to settle in the closely packed arrangement. The effect of granule size distribution was examined. One of the promising mixing ratios was deduced through parametric survey. The packing fraction more than 75% would be possible if granule size less than 45 μm was applied. Though the small granule size is necessary to obtain high packing fraction, the diameter of the granules must be restricted to prevent the fine granules from infiltrating into the insulator sphere region. Therefore the smallest granule diameter must be defined carefully.

Fabrication of vipac pins is one of the most unpredictable processes in this project because both PSI and JNC have quite little vipac experience. Filling test with inactive materials (ZrO_2 and UO_2) and vipac granule fabrication test have been ongoing to overcome this situation and to allow fabricating vipac pins as close as the targeted specifications. Further investigation of filling process should be performed combined with the results of the vipac fabrication test.

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FUJI プロジェクトに関するバイパック燃料製造試験
（文献調査および JNC での最近の実験結果）
（技術報告）

重留　義明

要旨

PSI/JNC/NRG 共同研究（FUJI プロジェクト）では、スフェアパック燃料、ペレット燃料およびバイパック燃料のピン製造を行い、照射試験によってそれらの燃料性能を比較する。ここでのバイパック燃料ピンは不定形な燃料顆粒から製造される。

本報告では ORNL、RIAR および日本で過去に実施されたバイパック充填に関する概要と、最近 JNC で実施された実験結果をまとめた。バイパックの充填挙動における主な要因は振動条件と顆粒サイズ分布である。振動条件の影響は非常に重要で、高い充填率を得るためには高い加速度が必要となり、また与える振動周波数を可変にすることで顆粒のブリッジを崩し、顆粒の配列を動かすことに効果的である。顆粒サイズ分布の影響が検討され、最適な混合条件がパラメトリックな試験により把握された。顆粒サイズに 45μm以下を使用することで 75%以上の充填率が可能である。高い充填率を達成するために微細な顆粒が必要となるが、熱遮蔽粒子の領域へ浸透するのを防ぐために、顆粒サイズは制限される。そのため、最小な顆粒サイズを決めるには十分に検討する必要がある。

バイパック燃料ピンの製造は本プロジェクトにおいて非常に予想し難いプロセスの一つである。なぜなら、PSI および JNC においてバイパック製造の経験が非常に少ないためである。模擬物質（ZrO_2）および UO_2 を用いた充填試験とバイパック顆粒製造試験はこの課題を解決するために進められており、目的とする仕様を満たすように、バイパック燃料ピンを製造する。充填プロセスの研究はバイパック製造試験と共に遂行される。

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Contents

Contents of Figures

Contents of Tables

1. Introduction

Vipac fuel pins that are composed of irregular shape fuel granules will be fabricated and irradiated as well as Sphere-pac and pellet fuel pins in the frame of PSI/JNC/NRG collaboration (FUJI project) to compare their performances.

Vipac fuel developments were mainly conducted in 1960's, however, most of these developments terminated in 1970's. Several literatures [1-10] are available as the results of these works. The program conducted at the Research Institute of Atomic Reactor (RIAR) in Russia is the exceptional case that practical vipac fuel fabrication has been continued until now [11, 12]. The fabrication process in RIAR is combined with pyrochemical process and the electro-deposited fuel materials are supplied to the fuel fabrication process.

In 1990's, development of vipac fuel has been restarted in Japan as a downstream process of the dry reprocessing (oxide pyro process) and now it is conducted at JNC under the frame of the feasibility study on commercialized fast breeder reactor.

One of the main interests of vipac fuel performance is its irradiation behavior. PSI/JNC/NRG collaboration is a golden opportunity to compare it with the performances of pellet and sphere-pac fuels. In this program, from JNC point of view, it is desired that the vipac pins will be prepared to imitate the fuels fabricated in RIAR that are composed of electro deposited granules.

This report describes the summary of the past vipac fuel fabrication tests and of the experiment recently performed in JNC.

2. General outline of Vipac fuel

The outstanding difference of vipac and sphere-pac fuel is shape of the powders that are filled in fuel pins. Not round shape but irregular shape granules are filled in the vipac pins.

First major development program was conducted at ORNL in 1960's[1-5]. In this program, theoretical dense angular particles from sol-gel process were crushed, grinded, classified, mixed with suitable weight ratio, loaded into pins and vibrocompacted. This program has shown the advantages and disadvantages of this process with the fabrication tests at laboratory and pilot plant scale facilities.

A few small studies were also conducted in Japan in 1960's. Naruki[6] and Hirose[7-10] have shown the vibrocompaction characteristics with fused UO_2 particles. Their works were laboratory scale and no actual pin was fabricated.

Though most of vipac programs were terminated in 1970's, the development of vipac fuel development, combined with pyrochemical process,

has been performed in Russia since 1960's[11, 12]. The electro-deposited granules are crushed, classified, mixed with suitable ratio, loaded into pins and vibrocompacted.

The pyrochemical process can be applied as a dry fuel reprocessing method. Several utility companies in Japan have paid attention to this combined process of dry reprocessing and vipac fuel because it could potentially be more economical process than the conventional wet reprocessing and pellet route. They started investigation on this process early in the 1990's and this work has been taken over by JNC. Since then, JNC has investigated the vipac fuel performance as a candidate process of the future FBR fuel cycle system.

3. Literatures survey of vipac fuel fabrication

3.1 Vipac fuel production at ORNL

Vipac fuel research had been considered as a candidate fuel system for Th-U-233 fuel cycle and years of research program was conducted at ORNL in 1960's[1-5]. Pin filling methods with vibrating energy was investigated as a part of this research.

The shards fuels were prepared by crushing, grinding, classifying the sol-gel derived product which consisted of theoretical dense angular particles, roughly 1.2×1.2×0.6 cm. The pin size was 1.09 cm ID and 117 cm long.

The particles were consisted of two size fractions: 55 wt % of coarse fraction (3327 to 1981 μm) and 45 wt % of fine fraction. The coarse fraction was obtained by jaw crushing the so-gel products. The fine fraction was obtained by ball-milling the materials under 3327 μm for a specified period of time. The obtained fine particle distribution is shown in Table 1.

After weighting each fraction, material was dumped into a V-type blender. A vibratory feeder was used to load the blended shards to a pin. Interruption of the loading must not occur, because it generates a low density region in the finished pin. The rate of loading had to be slow and constant (500 g/min was the feed rate at ORNL).

Vibration energy was selected to be 20,000G in order to compact powders up to approximately 90 % theoretical density. The frequency was approximately 300 Hz. The pin was connected to the vibrator by a chucking anvil. The chuck must grasp the rod tightly and any detectable looseness caused reduction of final packing fraction from 5 to 7 %. Placing a weight on the top of column was necessary, because it was effective to prevent the generation of low density region in upper part. The weight was 1 kg.

The packing fraction was specified that (1) the rods have a fuel density of ±2 % of this determined average density and, (2) the density within a fuel rod of ±2 % of the average for that fuel rod. During production, an average

density of 90 % theoretical was obtained. The axial density distribution of each pin was determined by gamma absorption scanning method.

Table 1 Particle size distribution for fine fraction obtained from ball-milling –6 mesh material

Mesh Size	Particle Size (μm)	Amount (wt %)
-6 + 10	3327 - 1981	20
-10 + 16	1981 - 1168	13
-16 + 50	1168 – 295	9
-50 + 140	295 – 105	9
-140 + 200	105 – 73	6
-200 + 270	73 – 53	5
- 270	< 53	38

3.2 Vipac compaction experiments in Japan

(1) Experiments by Naruki [6]

Naruki (Atomic Fuel Corporation (former JNC)) investigated the effect of vibration conditions with fused UO_2 shards.

The size of the pins was 40" length, 0.5" outer diameter, and 0.035" wall thickness (that means inner diameter is 10.92 mm). The average specific gravity of the powders are 99 %T.D. and granule size distribution was -6+12 mesh (3.327-1.4 mm) 67.5%, -40+70 mesh (375-212 μm) 20 %, -200 mesh (73 μm) 12.5 %.

The powder of each fraction was well blended in a glass bottle. The blended powder was slowly tapped out of the bottle in to the pins through a funnel that was connected to the pin. While loading the powders, the pin was vibrated at 8 G of 300 Hz. 800 g of powder was loaded in about 2 minutes.

The packing fraction obtained with several frequencies and accelerations are shown in Fig. 1. In this case higher packing fraction was obtained by larger acceleration. The frequency, which gave the highest packing fraction, was 300 Hz.

The packing fraction at several accelerations with fused MgO and ThO_2 are shown in Fig. 2. Their granule size distributions were different from that of UO_2, as shown in Table 2. This result shows some difference in the packing fraction between MgO and ThO_2. This could be attributed to the granule characteristics that are granule shape, density, etc.

The effect of frequency was investigated by following steps. The powder blend was loaded into the pins in about 2 minutes with vibrating the pins at a chosen frequency of 8G. After loading, acceleration was controlled to be 20 G for 2 minutes, 40G for 2 minutes and 60 G without interruption. The result is

shown in Fig. 3.

This result indicates the frequency has large effect on the packing fraction and the highest density was obtained at around 300 Hz. This frequency is same as the one that was used in the vipac compaction at ORNL.

The effect of sweeping frequency was also investigated in this paper. Naruki has explained that sweeping frequency is effective because a combination of high and low frequency gives both large and small amplitudes to the powders and large amplitudes give effective agitation to coarse granules and small ones do the same to fine granules.

The packing fraction obtained under several sweeping condition is shown in Tables 3 and 4. These results show broad frequency range and high sweeping rate generally produce high packing fraction. However the difference of the packing fraction attributed to the sweeping rate is relatively small. As indicated in Table 4, low sweeping rate caused powder loss by pulse ejection from the pin. This occurred at resonance frequency of 650 Hz. This means low sweeping rate gives long duration of resonance vibration and provides excessive violent vibration to the powders.

According to these results, vibration with wide frequency range and short cycle sweeping at large acceleration is desirable to obtain high packing fraction.

Table 2 Granule distribution of Naruki's experiment

	Fused UO_2		Fused ThO_2, Fused MgO	
Coarse	-6, +12 (3327-1400 μm)	67.5%	-10, +16 (1700-1000 μm)	60.0%
Medium	-40+70 (375-212 μm)	20%	-70, +100 (212-150 μm)	15 %
Fine	-200 (73 μm)	12.5%	-200 (73 μm)	20 %

Table 3 Effect of sweeping frequency range

Frequency range (Hz)	Weight of load (kg)	8 G	20 G	40 G	60 G		
		After loading	(2 min)	(2 min)	(5 min)	(10 min)	(15 min)
300	1.0	-	-	-	84.4		
300- 500	1.0	78.1	81.3	83.4	85.2	85.7	86.4
300- 500	4.0	78.6	80.9	85.0	86.3	86.5	86.7
300-1000	1.0	-	81.1	83.5	86.5	86.9	87.0
300-1000	4.0	-	81.6	85.3	87.4	87.6	87.7
300-1500	1.0	-	-	85.3	86.2	87.2	-
300-1500	4.0	-	81.6	84.9	87.1	87.5	87.8
300-3000	1.0	-	82.0	85.2	86.7	86.9	87.0
300-3000	4.0	-	81.5	84.4	86.9	87.6	87.7
150	1.0	-	-	-	83.0	-	
150- 500	1.0	78.4	81.4	84.5	85.2	85.6	85.7
150- 500	4.0	79.1	81.4	85.2	86.0	86.4	87.0
150-3000	1.0	79.1	81.8	84.4	86.8	86.9	86.8
150-3000	4.0	79.6	82.0	85.0	87.0	87.5	87.5

Table 4 Effect of sweeping speed (Figures in parentheses are quantity of powder loss in g-unit)

Frequency Range (Hz)	Sweep rate (cycle/min)		
	0.43	1.4	4.4
300-1000	86.5 (0)	86.9 (0)	87.5 (0.7)
300-1000	85.8 (4.3)	88.0 (16.2)	87.2 (0)
300-3000	87.3 (0)	86.7 (11.0)	88.0 (0)
300-3000	87.2 (0)	86.9 (0)	87.8 (0)

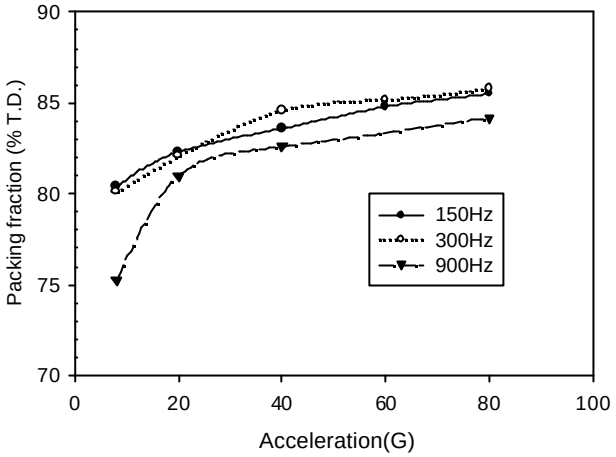

Fig.1 Effect of the acceleration on the compaction density

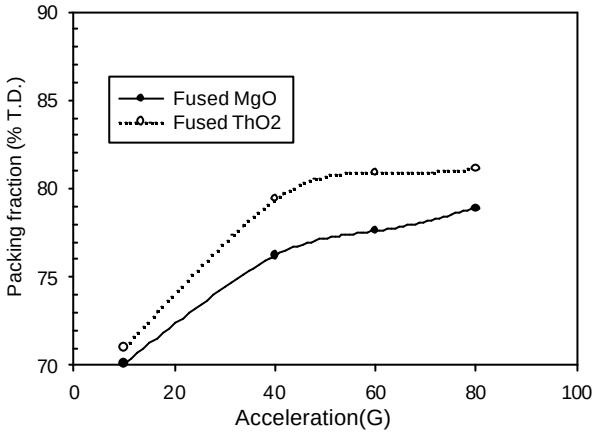

Fig.2 Effect of acceleration on packing fraction
(Fused MgO,ThO2)

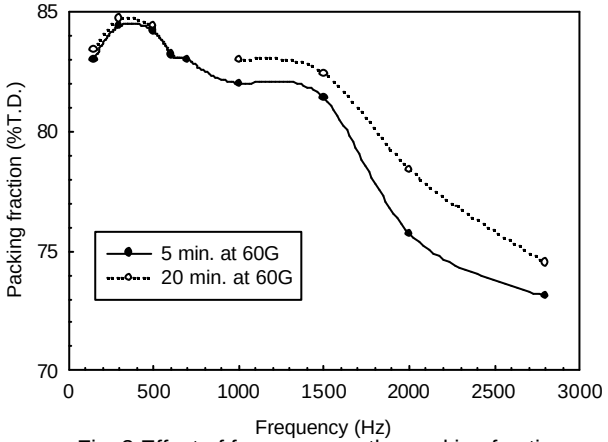

Fig. 3 Effect of frequency on the packing fraction
* Vibration was not continued for 20 min at 600 and 700 Hz because of resonance vibration

(2) Experiments by Hirose [7]-[10]

Hirose conducted vipac compaction experiment with fused UO_2 to investigate the vibration conditions [7]. The granule was ternary mixture and the granule distribution was -6+8 mesh (3.33-2.18 mm) 60 %, -48+65 mesh (320-225 μm) 20 %, -325 mesh (50 μm) 20 %.

The obtained packing fraction is shown in Table 5. By processing this result and arranging figure of displacement versus packing fraction as shown in Fig.4, the effect of displacement came to be appeared. Fig. 4 shows that high acceleration with the displacement between 10 and 30 μm is effective to produces high packing fraction.

Table 5 Packing fraction obtained by Hirose (%. T.D.)

	300cps	420	580	800	1100	1500	2100	2880
11.5 G	83.5	83.7	83.5	82.7	81.4			
21.5	84.1	84.2	84.6	84.6	83.5	82.0		
40	84.8	85.0	85.4	85.7	85.5	84.4	82.5	75.8
55			85.8	86.1	86.0	85.7		
74	85.2	85.3	86.1	86.5	86.5	86.2	85.2	82.5
96			85.8	86.8	86.8	87.0	86.4	84.0
125			85.6	86.7	86.7	87.2	87.1	86.4

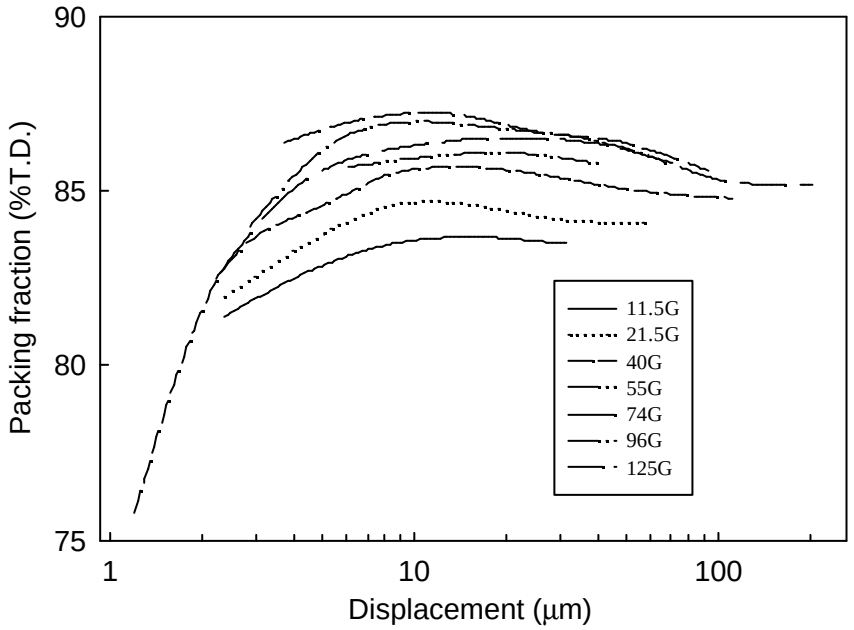

Fig. 4 Effect of displacement

3.3 Vipac compaction in Russia

Vipac fuel fabrication has been practically conducted at Research Institute of Atomic Reactor (RIAR) in Russia. The fuel material is prepared by the pyrochemical process. The electro-deposited fuel granules are crushed by a jaw crusher and classified into each fraction. According to the reports published by RIAR [11, 12], fuel powders consist of six different size fractions; 800-1000 μm 1.4-3 %, 630-800 μm 14.4-22.5 %, 400-630 μm 18-25.5 %, 250-400 μm 15-24 %, 100-250 μm 19-25 %, <100 μm 14.4-22.5 %.

The powders of each fraction are poured into a small container and mixed in it. After mixing, the powders are loaded into a pin through a funnel at one burst. A rod follower is placed on the fuel column and fuel powders are vibrocompacted. During the vibrocompaction, frequency is swept from 300 to 2000 Hz at 40 G. The vibrocompaction is completed in 8 minutes. The fuel pins with over 80%T. D. packing fraction are produced by these conditions.

Table 6 summarizes the vipac fabrication processes in each institute.

Institute	ORNL	Atomic Fuel Corporation	RIAR
Raw fuel material	Sol-gel product (theoretical dense angular particles, roughly 1.2×1.2×0.6 cm)	Fused UO_2	Electro-deposited powders (Theoretical dense granules)
Particle size distribution	3327-1981 μm 64% 1981-1168 5.9 1168-295 4.1 295-105 4.1 105-73 2.7 73-53 2.3 <53 17.1	3327-1400 67.5% μm 20 375-212 12.5 <73	800-1000 1.4-3% μm 14.4-22.5 630-800 18-25.5 400-630 15-24 250-400 19-25 100-250 14.4-22.5 <100 μm
Powder preparation	Jaw-crushing of raw material and ball milling of –6 mesh materials		Jaw-crushing of raw material and grinding (with ball mill?)
Blending	V-blender	Blending in a glass bottle	Blending in a small container
Loading method	Loading by vibrating feeder without interrupting	Tapping out the powders from the bottle into the pins with vibrating the pin	Loading the powders into a pin through a funnel at one burst
Vibration conditions	20,000G, 300Hz with 1kg weight on the fuel column	1) 8G 300Hz (while loading), 2) 20G 300Hz for 2min 3) 40G 300-3000Hz with sweeping cycle 4.4 cycle/min for 4 min 4) same as 3) but 60G for 10-15 min.	Sweeping frequency from 300 to 2000 Hz at 40G with a rod follower
Cladding	I. D.: 10.9mm Column length: 107 cm	I. D.: 10.9mm	I. D.: 5.4mm Column length: 45 cm

4. Recent experiments in JNC

JNC has performed vipac filling experiments to establish the filling procedure. The conditions of the experiments have been set as same as the process in RIAR. However, demonstrative experiment of vipac filling for FUJI project is necessary, because the size of the pin, fuel material, vibrator performance, etc are different from the process in RIAR. Both experiments under RIAR conditions and preliminary experiments for the fabrication in FUJI project are described in this report.

4.1 Vipac filling experiment under RIAR conditions

The experiments consist of 1) optimization of mixing ratio by inactive experiments with ZrO_2 and 2) demonstration of vibrocompaction with elector-deposited UO_2. The inactive tests were performed to verify the effect of size distribution, which necessitate the labor some trial and error method. After narrowing down the parameters, the demonstrative experiments with UO_2 granules were performed.

1) Optimization of mixing ratio by inactive experiments (with ZrO_2)

To begin the parametric survey on the size distribution, the base granule distribution that is the first trial should be determined. The base distribution was determined through preliminary trial-and-error experiments and is shown in Table 7. The influence of each fraction ratio was examined by varying its fraction slightly. The vibration conditions were 25G with sweeping frequency from 500 to 1000Hz. Vibration time was 5 minutes and sweeping rate was 100 Hz/sec.

The mixing ratio of fine granule fractions was investigated by varying the mixing ratio of F61(106-45 μm) and F62(<45 μm). The mixing ratios of other fractions were fixed. It should be mentioned that the total of mixing ratio is not 100 and unit of mixing ratio corresponds to 0.24 g ZrO_2, hereafter.

Table 8 shows the matrix that describes the effect of the mixing ratio combination. According to this table, the highest packing fraction has been obtained when the weight fractions of F61 and F62 are 20, 15 respectively.

The effect of mixing ratio of each fraction was investigated by similar way. The packing fractions obtained with varying mixing ratio are shown in Table 9. As shown in this result, the packing fraction higher than that of the base distribution was not realized.

Table 10 shows the packing fractions with the distributions that are slightly deviated from the base distribution. The difference of packing fractions from the base distribution is small although all of packing fractions indicated less value than that of the base distribution. Therefore, the packing fraction is

insensitive to the small deviation of the mixing ratio, this means weighing granules does not have to be controlled strictly.

The ratio of the largest granule size fraction of F1 (1000-850 μm) was large in the above mentioned experiments, though the mixing ratio of this fraction is quite small (1.4-3.0 %) at RIAR. If we follow the distribution of RIAR, the largest fraction should be F2 (850-600 μm). Therefore, the packing fraction without the fraction F1 was investigated and the result is shown in Table 11. According to this table, the obtained packing fractions are slightly smaller than that of base distribution, however, the difference is insignificant. It is concluded that the high packing fraction is possible without F1.

Table 7 Test condition and granule size distribution of the base distribution

	Granule size (μm)	Weight fraction
F1	1000-850	45
F2	850-600	10
F3	600-425	10
F4	425-250	5
F5	250-106	5
F6 (F61, F62)	<106 (106-45, <45)	35
Cladding : ID 6mm, OD 8mm, 400mm length Column length : 160-240mm Vibration : 500-1000Hz, 25G Vibration time : 5 min.		

Table 8 Effect of granule size distribution of small granules

Mixing ratio of F61 \ Mixing ratio of F62	0	5	10	15	20	25	30	35	40	45
0										
5				81.32	80.73	81.72	81.85	81.61	81.37	80.52
10				81.49	82.26	82.39	81.7			
15			81.6	82.53	82.6					
20			83.26	83.71	83.69					
25	81.19	82.85	82.93	83.24	83.14	82.92				
30			82.6	82.39	82.89					
35				82.27						

Table 9 Effect of granule size distribution

No.	Granule size (μm)							Packing fraction (%)
	1000-850	850-600	600-425	425-250	250-106	106-45	45-	
	F1	F2	F3	F4	F5	F61	F62	
1	8	8	8	18	18	20	15	79.42
2	18	8	8	8	8	20	15	80.90
3	8	18	8	8	18	20	15	80.70
4	18	18	8	18	8	20	15	81.43
5	8	8	18	18	8	20	15	80.10
6	18	8	18	8	18	20	15	80.97
7	8	18	18	8	8	20	15	80.95
8	18	18	18	18	18	20	15	81.09
9	13	13	13	13	13	20	15	80.03
11	20	20	5	5	5	15	15	82.38
12	20	20	5	15	5	15	25	82.00
13	20	20	5	5	15	15	25	81.44
14	20	20	5	15	15	15	15	83.24
15	20	20	5	5	5	25	25	80.56
16	20	20	5	15	5	25	15	81.39
17	20	20	5	5	15	25	15	81.39
18	20	20	5	15	15	25	25	81.17
19	20	20	5	10	10	20	20	81.33
21	25	25	10	10	10	5	5	78.43
22	35	25	10	10	10	5	15	79.87
23	25	35	10	10	10	5	15	80.05
24	35	35	10	10	10	5	5	77.83
25	25	25	10	10	10	15	15	81.59
26	35	25	10	10	10	15	5	81.63
27	25	35	10	10	10	15	5	81.42
28	35	35	10	10	10	15	15	81.40
29	30	30	10	10	10	10	10	81.20
base	45	10	10	5	5	20	15	83.71

Table 10 Effect of small deviation from the base distribution

No.	Granule size (μm)							Packing fraction (%)
	1000-850	850-600	600-425	425-250	250-106	106-45	45-	
	F1	F2	F3	F4	F5	F61	F62	
31	40	10	10	5	5	20	15	83.48
32	50	10	10	5	5	20	15	82.88
33	45	15	10	5	5	20	15	83.30
34	45	20	10	5	5	20	15	83.60
35	45	25	10	5	5	20	15	82.40
36	45	10	5	5	5	20	15	83.09
37	45	10	15	5	5	20	15	83.31
38	45	10	20	5	5	20	15	83.03
39	45	10	10	10	5	20	15	83.12
40	45	10	10	15	5	20	15	82.29
41	45	10	10	5	10	20	15	82.85
base	45	10	10	5	5	20	15	83.71

Table 11 Effect of removal of F1

No.	Granule size (μm)							Packing fraction (%)
	1000-850	850-600	600-425	425-250	250-106	106-45	45-	
	F1	F2	F3	F4	F5	F61	F62	
51	-	40	10	5	5	20	15	81.85
52	-	45	10	5	5	20	15	82.37
53	-	45	10	5	5	20	15	83.31
54	-	55	10	5	5	20	15	82.39
55	-	60	10	5	5	20	15	82.69
base	45	10	10	5	5	20	15	83.71

2) Demonstration of vibrocompaction with elector-deposited UO_2

The vibrocompaction with the electro-deposited UO_2 was conducted to demonstrate the compaction behavior. The deposited UO_2 granules were milled by a mortar and classified into six fractions with vibration sieves. The F4 and F5 fractions were treated as one fraction in the UO_2 experiments because of experimental convenience.

Parametric survey was conducted to deduce the optimum mixing ratio, which gives the highest packing fraction. The result of the experiment is shown in Table 12. The vibration conditions were 35 G with sweeping frequency from 500 to 1000 Hz. Vibration time was 10 minutes except No.13 - 16. It should be mentioned that the total of mixing ratio is not 100 and unit of mixing ratio corresponds to 0.48 g UO_2, hereafter.

According to the results, the packing fraction higher than 75 % was

produced if F62 that is the fraction smaller than 45 μm was used. The packing fraction close to 80 % is produced when the vibration time was extended to 30 minutes. The uniformity of the axial profile was checked only for No. 16 and it showed quite large heterogeneity through the fuel column. The heterogeneity was generated because of the inconstant granule pouring and granule segregation caused by the long time vibration.

Further experiments and improvement are necessary to produce uniform axial profile.

Table 12 Packing fraction with electro deposited UO_2

No.	Granule size (μm)						Packing fraction (%)	Vibration time (min)
	1000-850	850-600	600-425	425-106	106-45	45-		
	F1	F2	F3	F4+F5	F61	F62		
1	45	10	10	10	25	0	74.8	10
2	45	10	10	10	25	5	76.7	10
3	45	10	10	10	25	10	78.8	10
4	45	10	10	10	25	15	78.2	10
5	45	10	10	10	15	10	77.6	10
6	45	10	10	10	15	15	77.4	10
7	45	10	10	10	20	15	78.4	10
8	45	10	10	15	20	15	76.8	10
9	45	10	10	10	10	15	76.5	10
10	45	10	10	10	20	20	77.6	10
11	45	10	10	10	25	20	77.9	10
12	45	10	10	10	20	10	77.1	10
13	45	10	10	10	30	10	79.4	30
14	45	10	10	10	30	10	79.1	30
15	45	10	10	10	30	15	78.0	30
16	45	20	10	10	35	15	80.0	75
17	-	50	10	10	25	15	77.62	10
18	-	50	10	10	10	30	76.91	10
19	-	50	10	10	5	25	76.47	10
20	-	50	10	10	15	35	76.90	10

4.2 Preliminary experiment of vipac filling for FUJI project

JNC has conducted inactive filling test with ZrO_2 to contribute the vipac fabrication in FUJI project. The experiment was performed based on the results of the experiments under the RIAR conditions. The experiments described in this report were quite rough parametric survey to obtain the tendency, because the performance of the vibrator to be used I the project had not been clear. More practical experiment is supposed to be performed later.

1) Powder characterization

Powder characteristics have been known to be key parameters to produce vipac pins with high packing fraction. The powder characteristics were measured to judge which parameters would be influential and dominating to obtain high packing fraction. The measured characteristics and the methods are described as follows.

(1) Pour density

Pour density was measured by pouring the powders into a cylinder with 20 cc volume.

(2) Flow rate

Flow rate was measured by the “Flow rate measurement for fine ceramics (JIS R 1639-4)”.

(3) Packing fraction of the mono-fraction granules

Packing fraction of mono-fraction granules reflects the compactability of the blended multi-fraction granules when the fraction is blended in them. The packing fraction was measured after the 10 minutes vibrocompaction. The vibration conditions were 25 G, 500-1000 Hz (sweeping 6 cycles/min).

Table 13 shows the results of the measurements. At the moment the data of grinding effect is available only for F1. As seen in F1 data, all of the pour density, flow density, and mono-fraction packing fraction were increased by grinding. The effect of grinding process and shape factor should be investigated further to allow more accurate prediction of the packing fraction of MOX granules.

Table 13 Results of the powder characterizations

			Pour density		Flow rate	Mono-fraction packing fraction	
Fraction	Range (μm)	Finishing	g/cm3	vol %	g/sec	before vibration	after vibration
F1	850-600	unground	2.86	48.9	4.52	48.9	54.7
		ground	5.85	57.3	5.01	55.3	60.7
F2	600-425	unground	2.78	47.6	4.79		
F3	425-250	unground	2.73	46.6	5.76		
F4	250-106	unground	2.66	45.4	6.55		
F5	106-45	unground	2.53	43.2	6.74	44.2	54.3

2) Preliminary vibration test

The preliminary experiments were necessary to decide initial experimental conditions. In this case the weight and the rate of frequency sweeping were examined. The main experimental conditions are shown in Table 14.

Table 14 Experimental conditions

Granule condition			Cladding
Fraction	Range (μm)	Mixing fraction (%)	: SUS 410mm length, 6.7mm I.D.
F1	850-600	50	
F2	600-425	10	
F3	425-250	5	
F4	250-106	5	
F5	106-45	30	

(1) Weight

The report by ORNL [1-5] mentioned that it is necessary to place a weight on top of the fuel column. To check the necessity of it, vibrocompaction tests with and without a weight were conducted. The weight of 250 g was applied. It should be mentioned that the experiments without the weight does not mean the fuel column was completely free, but only a rod follower (30 g) was placed on the column.

Table 15 shows the results. The packing fractions without the weight show higher packing fractions than the ones with the weight contrary to the ORNL reports.

The reason is explained as followings. The granules with high fluidity show high packing fraction, that is, the granule flow while vibrating is the driving force to move the granules to closely packed arrangement. In this case the weight probably functioned to lower the effective powder fluidity and the powder flow was disturbed.

Hereafter the vibrocompaction was performed without the weight. However, it is necessary to check the axial distribution of packing fraction to decide to remove the weight completely.

Table 15 Effect of the weight on the fuel column

	Packing fraction (%)	
	25G, 500-1000Hz	50G, 1000-2000Hz
With weight	69.1	72.7
Without weight	72.1	76.6

(2) Rate of frequency sweeping

It is commonly known that sweeping frequency is effective to produce high packing fraction in the vipac filling. The experiment was conducted to examine the effect of frequency sweeping rate. Vibrocompaction with three sweeping rates at 25 G of 500-1000 Hz were performed. The packing fractions are shown in Table 16.

From this result no significant difference caused by the difference of the sweeping rate was observed. This result is consistent with Naruki's results. It can be concluded that the sweeping rate has small effect on the packing fraction.

Hereafter sweeping rate of 6 cycles/min are applied because make it consistent with the experiments under the RIAR conditions.

Table 16 Effect of sweeping rate

Cycles/min	Packing fraction (%)	
	Before vibration	After Vibration
3	62.0	74.6
6	61.8	73.2
12	62.1	74.2

3) Vibrocompaction test

(1) Effect of vibration conditions

The performance of the vibrator had not been clear when the experiments described in this report were performed. Therefore, vibrocompaction experiments were performed with wide range of vibration conditions. Almost all vibrocompaction tests were performed for twice. The parameters of vibration conditions were acceleration (3 to 50 G) and frequency (50 to 1000 Hz; constant frequency, 50 – 100 to 1000 – 2000 Hz; swept). Fig.s 5 and 6 show the results. The each result of twice measurements is plotted in the figures.

These results show the tendency that high packing fraction is generated with higher acceleration in both constant frequency and sweeping frequency cases. Frequency sweeping produced higher packing fractions and smaller difference between twice measurements than the result of the constant frequency.

The causes of the difference in packing fractions of twice measurements seem to be the difference of initial packing fraction before vibration and the bridging of granules during the vibration. The former one has effect on both constant and sweeping frequency vibration and later one has effect only on the

constant frequency vibration. This means sweeping frequency is effective to break the bridging of granules and promotes the granules movement to settle in to the closely packed arrangement.

The difference of the initial packing fraction is probably generated by the inconstant loading of the granules and this defect is not possible to be modified by vibration. Therefore uniform loading of granules is necessary.

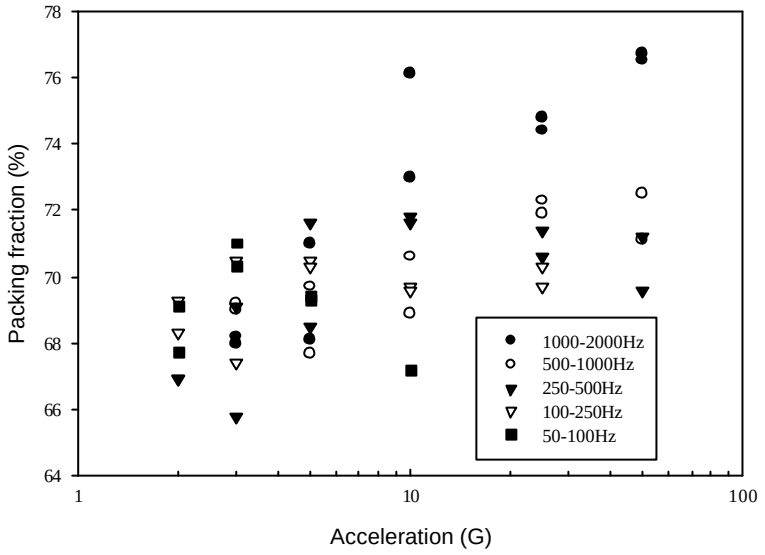

Fig. 5 The Effect of the acceleration on packing fraction
(Sweeping frequency)

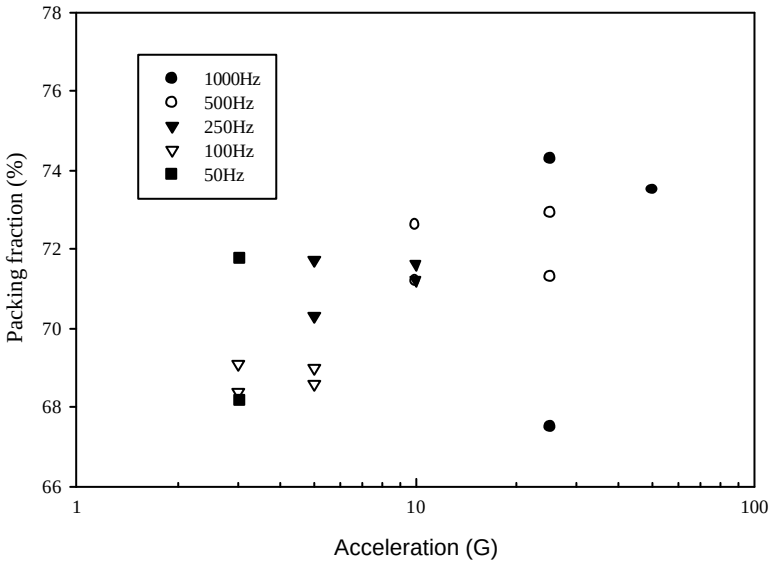

Fig. 6 The Effect of the acceleration on packing fraction
(Fixed frequency)

(2) Effect of mixing ratio

The mixing ratio of the fractions is another important factor for vipac fabrication. The optimum mixing ratio is theoretically evolved for sphere-pac, on the other hand, the theory of the mixing ratio for vipac has not yet established and optimization must be done by trial-and error method.

The preliminary survey of mixing ratio was performed. In this test effect of the mixing ratios of the large and small fractions were investigated while the mixing ratios of the medium sizes were kept constant. Table 17 and Fig. 7 show the results. The optimum mixing ratio of large and small granules was found to be around 50:30. Both packing fraction before and after the vibration show same tendency by the mixing ratio.

The effect of fine granule distribution within 0–106 μm was investigated. The smallest fraction was divided into further three fractions (106-75, 75-45, 45-0 μm) and packing fractions were measured at several mixing ratio of these three fractions. The mixing ratios of other fractions were kept constant during this test.

Table 18 shows the results. It is obvious that the packing fractions with larger amount of small granules shows higher value than those of others. It can be mentioned the presence of small size granules is quite effective to produce higher packing fraction.

Though the small granule size is necessary to obtain high packing fraction, the diameter of the granules must be restricted to prevent the fine granules from infiltrating into the insulator sphere region. Therefore the smallest granule diameter must be defined carefully.

Table 17 Effect of mixing ratio on packing fraction

Test No.	Mixing ratio					Packing fraction (%)	
	850-600	600-425	425-250	250-106	106-45	Before vibration	After vibration
1	70	5	10	5	10	57.0	65.3
2a	60	5	10	5	20	60.9	70.9
2b						60.6	70.1
3a	50	5	10	5	30	62.0	73.3
3b						63.1	72.0
4a	40	5	10	5	40	60.1	71.1
4b						61.3	70.3
5	30	5	10	5	50	58.1	67.9
6	20	5	10	5	60	54.3	65.2
7	10	5	10	5	70	52.5	62.9

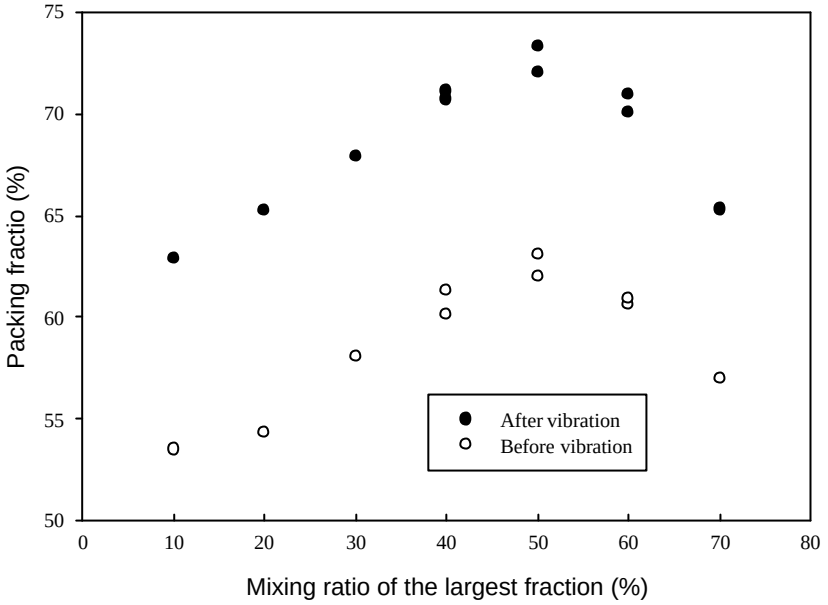

Fig. 7 Effect of the mixing ratio (the largest and smallest fractions). The ratios of medium fractions are kept constant. (500-1000Hz(6times/min), 25G)

Table 18 Effect of the granule size distribution within the smallest fraction on packing fraction

Size distribution of the smallest fraction			Packing fraction	
106-75	75-45	45-	Before vibration	After vibration
30	0	0	61.9	71.8
15	15	0	62.6	74.1
0	30	0	63.5	74.5
20	5	5	62.5	73.6
5	20	5	61.7	73.7
10	10	10	61.2	73.9
15	0	15	62.0	74.5
0	15	15	61.9	75.6
5	5	20	62.0	76.3
0	0	30	61.5	77.4

Mixing ratio of each fraction
850-600:600-425:425-250:250-106:106-=50:10:5:5:30
Vibration conditions
Frequency: 500-1000Hz
Sweeping rate: 6cycles/min
Acceleration: 25G
Vibration time: 10min.

5. Conclusion

This reports describes the outline of the past vipac filling performed at ORNL, RIAR and in Japan and, additionally, the results of the experiments recently conducted by JNC.

According to these results, the main factors that should be paid attention in vipac filling are vibration conditions and granule size distribution.

The effect of vibration conditions is significant and large acceleration is necessary to produce high packing fraction. In addition, sweeping frequency is necessary to break the bridging of the powder and effective to promote the granules to settle in the closely packed arrangement during vibration.

The only way to optimize the granule size distribution is a trial-and-error method at this stage. One of the promising mixing ratios was deduced through parametric survey in JNC. The packing fraction more than 75% would be possible if granule size less than 45 μm was applied. Though the small granule size is necessary to obtain high packing fraction, since the insulator region that is adjacent to the vipac fuel column will be filled with sphere material in this project, the lower limit of the granule size should be restricted to prevent the fine granules from infiltrating into the insulator sphere region. Therefore the smallest granule diameter must be defined carefully.

Fabrication of vipac pins is one of the most unpredictable processes in this project because both PSI and JNC have quite little vipac experience. Filling test with inactive materials (ZrO_2 and UO_2) and vipac granule fabrication test have been ongoing to overcome this situation and to allow fabricating vipac pins as close as the targeted specifications. Further investigation of filling process should be performed combined with the results of the vipac fabrication test.

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