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**A STUDY ON DENSITY, POROSITY AND GRAIN SIZE
OF
UNIRRADIATED ROX FUELS AND SIMULATED ROX FUELS**

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A Study on Density, Porosity and Grain Size
of
Unirradiated ROX Fuels and Simulated ROX Fuels

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The unirradiated ROX fuels made of (1) 23wt%PuO₂-17wt%SZR-56wt%Al₂O₃-4wt%MgO (ROX-SZR) and (2) 20wt%PuO₂-29wt%ThO₂-48wt%Al₂O₃-3wt%MgO (ROX-ThO₂) were fabricated by JAERI. Additionally, 9 simulated ROX fuels (used UO₂ instead of PuO₂) were fabricated by NFI. Densities, porosity and grain sizes of those were studied. Obtained results are:

(1) ROX fuels:

The estimated theoretical density (TD) was 5.6g/cc for the ROX-SZR and 6.2g/cc for the ROX-ThO₂. Those were about half of that in UO₂ (10.96g/cc). As-fabricated density determined was 4.6g/cc (82%TD) for the former and 5.2g/cc (83%TD) for the latter. The %TD of those was low than that of UO₂ (95%TD). One of main reason is that the ROX fuels were sintered at temperature of 1,400°C while UO₂ was sintered at temperature of 1,700°C.

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The average pore diameter was about $3 \mu\text{m}$ and the porosity was 17-18%, implying that the ROX fuels were resulted in containing a lot of small pores $< 10 \mu\text{m}$. Grain size was about $2 \mu\text{m}$.

(2) **Simulated ROX fuels:**

The estimated TD was about 5.0-5.7g/cc. Those were about half of that in UO_2 . As-fabricated density determined in the present study was about 4.5-5.5g/cc. The %TD of the simulated ROX fuels ranged about 94-98%TD. They were in the same as that of UO_2 because as high sintering temperature of $1,750^\circ\text{C}$ as UO_2 . The average pore diameter was about $4-8 \mu\text{m}$ and the porosity was $< 6\%$. Grain size was revealed to be about $1-4 \mu\text{m}$.

Keywords: Density, Porosity, Grain Size, Unirradiated ROX Fuel, Simulated ROX Fuel, Densification, Swelling, Grain Growth

未照射岩石型(ROX)燃料及び模擬岩石型燃料の
密度、気孔率及び結晶粒径に関する研究

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未照射岩石型 (ROX) 燃料として次のような組成を持つ燃料を原研で2種類作製した。すなわち、(1) 23wt%PuO₂-17wt%SZR-56wt%Al₂O₃-4wt%MgO(以下、ROX-SZR)及び(2) 20wt%PuO₂-29wt%ThO₂-48wt%Al₂O₃-3wt%MgO(以下、ROX-ThO₂)。続いて、未照射岩石型燃料のプルトニウムをウランで置き換えた模擬岩石型燃料を原子燃料工業で9種類作製した。これら未照射燃料について、密度、気孔率及び結晶粒度に関する研究を実施した。得られた結論は以下のとおり。

(1) 岩石燃料：

推定理論密度 (TD) 値は、ROX-SZR で 5.6g/cc, ROX-ThO₂ で 6.2g/cc であった。岩石燃料の理論密度値は UO₂ (10.96g/cc) の約半分であった。本研究から得られた焼結 (製造) 密度は、ROX-SZR で 4.6g/cc (82%TD)、ROX-ThO₂ で 5.2g/cc (83%TD) であった。%TD は UO₂ のそれ (通常 95%TD) よりかなり小さかったが、その理由は、模擬 ROX 燃料が 1,400°C で焼結されたのに UO₂ は約 1,700°C 程度で焼結されるためである。平均気孔径は約 3μm、気孔率は 17-18% の範囲にあったことから、当該 ROX 燃料は沢山の小径気孔 < 10μm を含むことが示唆された。結晶粒径は約 2μm であった。

(2) 模擬岩石燃料：

推定理論密度値は約 5.0-5.7g/cc の範囲にあった。模擬岩石燃料の理論密度値は UO₂ の約半分であった。本研究から得られた焼結密度は約 4.5-5.5g/cc の範囲にあった。焼結温度が 1,750°C と比較的高かったため、模擬岩石燃料の %TD は 94-98%TD と現行の UO₂ 並になった。平均気孔径は約 4-8μm、気孔率は 6% 以下であった。結晶粒径は約 1-4μm であった。

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1. Introduction

From a viewpoint of fuel reliability, a density of nuclear fuel material is considered to be one of key design parameters. When an oxide type of ceramic fuel pellet such as UO_2 is sintered enough with high temperature and time, then its density becomes very close to 10.96g/cc, where no internal pores are existed. The density is known as the theoretical density (TD). Practically, by some limitations a conventional UO_2 is sintered as temperature as about 1,700°C, then its density becomes about 10.41g/cc (95%TD), where internal pores of about 5% are born.

The behavior of internal pores under irradiation will be of importance from the viewpoint of fuel performance. For example, a partial annihilation of those pores at the beginning-of-life (BOL) will occur and make a shrink of fuel pellet, that is, an increase of fuel density. This phenomenon is known as "fuel densification". While, at the end-of-life (EOL) as the result of formation of FP gas bubbles at grain boundaries, the decrease of fuel density will occur and make a fuel swell. This phenomenon is known as "fuel swelling" and it accompanies with an expansion of volume of fuel pellet ⁽¹⁾.

A change of density in the course of irradiation is very influential to the thermal performance of the fuel rod. If a densification occurs, a resultant increase of fuel-to-cladding gap will degrade a thermal conductivity of fuel rod and make the fuel pellet hot. This increases a potential risk for fuel melt which is strictly prohibited to occur from the viewpoint of licensing. On the other hand, if a swelling occurs, a resultant decrease of fuel-to-cladding gap will enhance a fuel pellet-to-cladding mechanical interaction (PCMI). This increases the potential risk for fuel failure ⁽²⁾.

In the Japan Atomic Energy Research Institute (JAERI), a new type of ceramic fuel is under development for a future use in the conventional light water reactors (LWRs). Because the fuel consists of many kinds of minerals so it is denoted as "the rock-like oxide (ROX)" fuels ⁽³⁾. The ROX fuel consisted mainly of PuO_2 as the fissile material and ZrO_2 - MgAl_2O_4 - Al_2O_3 of the geology stable mineral components as the inert matrices. As an alternation, a use of ThO_2 instead of ZrO_2 is also taken into consideration,

not only because of its excellent physical property as the neutron resonance material against a Pu fissile but also because of one of valuable minerals having very high resistance against the reprocessing ⁽¹⁾.

Additionally, the authors prepared the simulated ROX fuels consisted of UO_2 instead of PuO_2 as the fissile material and $\text{ZrO}_2\text{-MgAl}_2\text{O}_4$ of mineral components as the inert matrices. The use of UO_2 instead of PuO_2 was according to an idea that physical characteristics between PuO_2 and UO_2 might be resembled much. It is known that a handling of UO_2 in the laboratory is rather easy than that of PuO_2 . By using the simulated ROX fuels, well-characterized database for the ROX fuels are expected. A result obtained from out-of-pile tests carried out on the simulated ROX fuels is described elsewhere ⁽⁴⁾.

To date, there exists poor database regarding as-fabricated density, porosity and grain size of the ROX fuels as well as simulated ROX fuels. These parameters are known to be of importance because they have a strong relation to an in-core fuel densification and swelling. Therefore, these parameters are studied in the present study by experiment. In parallel, one is aimed at estimating the theoretical density (TD) and the percent TD (%TD) from these parameters.

2. Experiment

2.1 Fabrication of the Test Specimens

(1) ROX fuels

As the ROX fuel, (1) 20 weight percent (wt%) of plutonium dioxide (PuO_2) powder as a fissile material was combined mechanically with 29wt% ThO_2 -48wt% Al_2O_3 -3wt%MgO powders known as the inert matrices, was prepared. Additionally, (2) 23wt% of PuO_2 powder combined with 17wt% $\text{ZrO}_2(\text{Y})$ -56wt% Al_2O_3 -4wt%MgO powders known as the inert matrices, was also prepared. The two were co-precipitated by HNO_3 and dried at JAERI. In both cases, Pu isotopes were 94.3at%²³⁹Pu-5.3at%²⁴⁰Pu-0.4at%²⁴¹Pu and others in very small magnitude. A component of ZrO_2 (Y) mentioned in the latter is the

stabilized zirconia containing ternary components of 88.8mol%ZrO₂-11.0mol%Y₂O₃-0.2mol%Gd₂O₃, and hereinafter denoted as SZR. Addition of alkaline rare earth material of Y₂O₃ to ZrO₂ is necessary to prevent the ZrO₂ from a cracking induced by structural change at around temperature of 1,000°C.

In JAERI, these powders were pressed into a form of pellets, then provided for the preliminary sintering as green pellets at the temperature of 1,400°C for 14 hours under atmospheric (air) condition. Subsequently, sintered green pellets were fractured mechanically into small pieces to make accurate weighing of the Pu content of 40mg in each specimen. After weighing, fragmented green pellets were pressed again into a form of disk fuel and sintered finally at the temperature of 1,400°C for 8 hours under reduced (8%H₂+92%Ar gas) condition. The dimension of each disk was 3mm in outer diameter (O.D.) and 1mm in thickness. Sintered disks had PuO₂ as a fissile and either ThO₂-Al₂O₃ (corundum)-MgAl₂O₄ (spinel) or SZR-Al₂O₃-MgAl₂O₄ as the inert matrices.

Regarding the ternary phase diagram of the ROX fuels, a result of study was reported ⁽³⁾. In the documents it is mentioned that with a presence of excess corundum (Al₂O₃), the alkali- and alkaline earth elements were to be solidified by the formation of hibonite phase (SrO·6 Al₂O₃), where the spinel of MgO·Al₂O₃ would be a host phase. X-ray diffraction study (XRD) made on the present test specimen by Yamashita ⁽⁵⁾, revealed that hibonite (PuAl₁₁O₁₈) phase was surely formed during the final sintering stage not only in ROX-ThO₂ but also in ROX-SZR. A volumetric ratio of PuAl₁₁O₁₈: PuO₂-ThO₂ (fluorite host phase) was estimated to be 0.25:0.75, while that of PuAl₁₁O₁₈ : PuO₂-SZR (fluorite host phase) was 0.70:0.30. The hibonite in the host fluorite phase was very significant in the latter. The hibonite formation was out of scope in original design, hence its influence on the ROX fuels is not known yet.

(2) Simulated ROX fuels

Original fuel powders were co-precipitated and dried at JAERI then transported to the Nuclear Fuel Industries (NFI), Ltd. for pressing into a form of pellet, followed by sintering ⁽⁴⁾. The pellet was sintered at the temperature of 1,750°C for 4h under the reduced (3H₂+N₂ gas) condition.

Three kinds of simulated ROX fuel, namely the specimen No.12, No.13 and No.16 were fabricated. Hereinafter they are abbreviated as the sp.#12, sp.#13 and sp.#16. They contained UO_2 as a fissile material and SZR- MgAl_2O_4 as the inert matrices.

At the same time, additional 6 kinds of simulated ROX fuels- sp.#01, sp.#02, sp.#03, sp.#04, sp.#05 and sp.#06 were sintered. They only consisted of SZR- MgAl_2O_4 as the inert matrices and used as references of sp.#12, #13 and #16. Strictly speaking, they were not the simulated ROX fuels because none of UO_2 was included. Subsequently, however, they are frequently denoted as the simulated ROX fuels without any notation for the readers..

Now, 2 ROX fuels and 9 (3 simulated ROX fuels and 6 inert matrices) simulated ROX fuels are prepared for the study. As-fabricated characteristics of the ROX fuels are summed up in Table 1, while, those of the simulated ROX fuels are separately summed up in Table 2, respectively. As seen from the latter, amounts of SZR in the simulated ROX fuels are gradually increased from the sp.#1 to the sp.#5. The composition between the sp.#2 and the sp.#6 is resembled much. Fabricating details of the simulated ROX fuels were described elsewhere ⁽⁴⁾.

2.2 Density Measurement

2.2.1 Methods

Principally, a density ρ of either ROX fuel or UO_2 fuel is defined by the equation; $\rho = \text{mass} / \text{volume}$. In the present, the geometrical density and the gas or liquid immersed density were studied. The former is the density determined by as-sintered dimensions taking into no consideration of pores really existing in the fuel. The latter is the density taking into consideration of pores inside of fuel. It is more realistic density than the former.

(1) Geometrical density

The geometrical density, ρ_g or GD (g/cc or Mg/m^3) is given by

$$\rho_g = W/0.25 \pi d^2 h \quad \text{for a fuel in pellet form.....(1)}$$

or

$$\rho_g = W / 0.25 \pi d^2 t \quad \text{for a fuel in disk form.....(2)}$$

where, W is the weight (g) of the test specimen, d the O.D. (cm), h the height of pellet (cm) and t the thickness of disk (cm), respectively.

(2) Immersed density

The immersed density, ρ_i or ID (g/cc) is given by

$$\rho_i = W \rho_l / \{W - (W_1 - W_2)\} \dots \dots \dots (3)$$

where, W (g) is the sum of the weight of fuel and the suspending wire, ρ_l the density(g/cc) of the liquid used for the measurement, W_1 (g) the sum of the weight of fuel and the suspending wire in the liquid and W_2 (g) the weight of the suspending wire, respectively. In this equation, the density of air, ρ_{air} of 0.0012g/cc at the room temperature was neglected as it was so small compared with that of water (0.9982g/cc at 20°C) and meta-xylene (0.8628g/cc at 20°C). If one has the theoretical density of ρ_{th} (g/cc), the percent theoretical density(%TD) is given by

$$\%TD = \rho_i / \rho_{th} \times 100 \quad \dots \dots \dots (4)$$

and

$$\%TD = \rho_i / 10.96 \times 100 \quad \dots \dots \dots (5)$$

for the case of UO_2 ⁽⁶⁾. Here, pure water, water with driwel (a kind of goods used as surface active agency) and meta-xylene were used basically as a liquid. For the simulated ROX fuels, a helium (He) gas was used.

(3) Relationship between GD and ID in UO_2

According to the author's previous study^(6,7), it was led that there existed a relationship between GD and ID by the water (abbreviated here as WD), as shown in Fig. 1. As to the case for GD and ID by meta-xylene (abbreviated here as MID) as shown in Fig. 2, an almost linear relationship was built up.

However, some exceptions such as the specimen A are still being. The specimen A had much small pores $< 1 \mu\text{m}$ and small grain size diameter of $5 \mu\text{m}$. As shown in Fig. 3, an influence of design parameters on the density of UO_2 was studied. A comparison between sample 1 (sintered at $1,400^\circ\text{C}$) and sample 3 (sintered at $1,600^\circ\text{C}$) led that the sintering temperature was very influential to as-sintered density. This is repeatedly observed between sample 4 (sintered at $1,400^\circ\text{C}$) and sample 6 (sintered at $1,600^\circ\text{C}$). While, a comparison between sample 1 and sample 6 led that the increase of grain size was most effective to increase the UO_2 pellet density. The important remark obtained from this was that sintering temperature should be selected carefully prior to start an experiment.

2.2.2 Mock-up Test

A density measurement was performed at the Department of Hot Laboratories, JAERI. Places used were (1) the hot cell no.1 usually utilized for a density measurement of a spent UO_2 fuel pellet from LWR and (2) the cold $\beta \gamma$ cell newly prepared for a density measurement of disk type small fuel. The overview of the former is shown in Photo.1. At place (1), measurements of GD and ID were carried out. For ID, water, diwiel and meta-xylene were used. At place (2), a measurement of ID by water and meta-xylene was carried out. Measurement made at place (2) was just like commissioning test.

In mock-up tests, (i) bearing balls made of stainless steel, (ii) metal disks made of nickel (Ni) and (iii) as-sintered UO_2 were provided as test specimens. The bearing balls had the O.D. of 2mm with a very fine surface, that is, no porosity inside and outside. The original metal density was 7.76 g/cc . Densities were measured at place (1) and (2). Nickel disks having a very fine surface had the O.D. of 3mm and thickness of 1mm. The original metal density was 8.88 g/cc . Density was measured at place (2) alone. As-sintered UO_2 fuel pellet was sliced by a thickness of about 1mm prior to fragmentation into pieces. Densities were measured at place (1) due to a hot material.

2.2.3 Simulated ROX Fuels

Regarding 6 inert matrices (sp.#01-sp.#06) and 3 simulated ROX fuels (sp.#12, sp.#13 and sp.#16), not only GD but also He gas immersion density (GID) were measured.

2.2.4 ROX Fuels

The ROX fuel of 20wt%PuO₂-29wt%ThO₂-corundum-spinel is hereinafter abbreviated as the ROX-ThO₂. While, the ROX fuel of 23wt%PuO₂-17wt%SZR-corundum-spinel is hereinafter abbreviated as the ROX-SZR. Regarding the two, GD, ID by water, diwiel and meta-xylene were used. The O.D. and thickness of the two specimens were 2.8mm and 1mm, respectively. All measurements were done at the place (1).

2.3 Porosity Measurement

(1) Simulated ROX fuels

At the Nuclear Fuel Industries, Ltd. (NFI), test specimens were mounted on cylindrical epoxy resins for grinding by the emery papers made of SiC (#320, #800 and #1,200) for a few minutes each, then fine polishing by the diamond pastes (5-10min.) and the aluminum buff up to the particle size of 0.05 μm (5-10 min.) were carried out. After washing, pictures were taken from 9 simulated ROX fuels with a magnification by x100. As-polished fuel microstructures for the simulated ROX fuels are shown in Photo. 2(a) and those for the inert matrices are shown in Photo. 2(b), respectively. The magnification of those were chosen to cover all pores having diameter at least from 1 to 100 μm at observations. Numbers of pores (N_i) were optically counted by an image analyzer together with their diameter, d_p. Then, one obtained a set of data (N_i, d_p). For simplification, sub-micron pores having diameter d_p < 1 μm were tried to count as small as possible and obtained data sets were put into (N_i, 1). In other words, all sub-micron pores having a diameter < 1 μm were postulated as pores having a diameter of 1 μm irrespective to its intrinsic size. This will be denoted as the "normalization of sub-micron pores". While, all pore particles having diameter d_p > 1 μm were set as (N_i, d_p). Then average pore diameter d_a (μm) and porosity p (%) were determined after this treatment in statistical manner. The latter is defined

as

$$p (\%) = \left\{ \frac{\text{Area occupied by all counted pores (m}^2\text{) in the picture}}{\text{Total area of the picture (m}^2\text{)}} \right\} \times 100 \dots \dots \dots (6)$$

(2) ROX fuels

The grinding was the same as used in the simulated ROX fuels. The typical pictures taken were shown in Photo. 3. More details are addressed to the author's separate paper ⁽⁴⁾. Numbers of pore particles as a function of their diameter were counted by the same manner as described above.

Normalization of sub-micron pores were also done. Then, the average pore diameter and the porosity of each specimen were obtained statistically.

2.4 Grain Size Measurement

Two-dimensional intercept method ⁽⁸⁾ was used for determining the grain size diameter.

(1) Simulated ROX fuels

As-polished fuel microstructures taken by the scanning electron microscopy (SEM) ^(4,9) were used. In which, grain boundaries between SZR-UO₂ and MgAl₂O₄ were observed clearly among the test specimens, except sp.#1 and sp.#5 having a single phase only.

(2) ROX fuels

As-polished pictures taken from SEM were prepared for determination of grain size. The method was the same as mentioned in the above. As shown in Photo. 3, for example, all pictures with magnification of x1,000-3,500 had clear grain boundaries.

2.5 Estimation of Theoretical Density

Generally, a prediction of ρ_{th} (g/cc) by theoretical approach is difficult not only for the simulated ROX fuels but also for the ROX fuels, because ROX fuels had multi-components and they contained pores inside. Hence, accurate estimation of a lattice constant is hard to obtain, especially by the existence of lots of pores.

As described in the section 2.3, the porosity; p (%) was succeeded to obtain from the measurement, where a relationship between p (%) and ρ_{th} (g/cc) was given by

$$p(\%) = \{1 - (\rho_i / \rho_{th})\} \dots \dots \dots (7)$$

where ρ_i (g/cc) is the density of ROX or the simulated ROX fuels measured by immersion method. From this, the ρ_{th} is given by

$$\rho_{th} = \rho_i / \{1 - 0.01p\} \dots \dots \dots (8)$$

3. Results and Discussion

3.1 Density

(1) Mock-up test

Results of the mock-up test are summed up in Table 3. The density of bearing balls is shown in Fig. 4. The followings are revealed:

- The measured density was about 7.78g/cc in average irrespective of methods, where the original metal density was 7.76g/cc. Hence, if the specimen had no pores, the measured density was independent on methods and fallen into the almost same data band.
- The density by water immersion method caused a maximum error band of ± 0.21 g/cc. It was one order of magnitude greater than the others.
- The difference in MID measured between at the place (1) and the place (2) was insignificant only to the magnitude of 0.05g/cc. This implies that for the case of specimen without pores the accuracy of data obtained from the two places was almost in the same magnitude.

The water immersion density (WID) of nickel disks is plotted in Fig. 5. The density measured at the place (1) was relatively low than that (8.88g/cc) of pure metal. Hence, WID data had an error band of ± 0.16 g/cc. It implies that measurement of disk type specimen at the place (1) using for the density of spent UO₂ fuel pellet may not be suitable.

The densities of reference UO_2 pellet is plotted in Fig. 6. The MID measured at the place (1) was 10.49g/cc, slightly higher than that of conventional UO_2 with a density of 10.41g/cc. Here, WID data also had an relative large error band of ± 0.11 g/cc.

(2) Simulated ROX fuels

Results of the density measurements on simulated ROX fuels are summed up in Table 4. GD and GID as a function of amounts of SZR are shown in Fig. 7. From this, followings are revealed.

- Densities of the simulated ROX fuels and those of matrices increased with increased amounts of SZR. Data ranged from 3.0g/cc (100wt% MgAl_2O_4) to 6.0g/cc (100wt%SZR).
- Densities of the simulated ROX fuels were large than those of the inert matrices. Densities in the former ranged 4.9-5.4g/cc, those were approximately half of the UO_2 fuels using in LWRs.
- The difference between GD and GID was within 0.5g/cc, except sp.#5 and sp.#6 where the two had large porosity as described later on. It was revealed that a deviation between GD and GID became large when one made a fuel having a large porosity.

(3) ROX fuels

Results of the density measurements are summed up in Table 5. The density depending on measuring method is shown in Fig. 8. The followings are revealed.

- An increase of density occurred in the order of 1) GD, 2) ID by water and 3) ID by meta-xylene and 4) ID by driwel. The difference was small between 3) and 4). The interaction between the pores existed inside fuels and immersed liquid was a cause of the ordering.
- Densities of the ROX-SZR varied from 4.3g/cc to 4.6g/cc. The maximum case was addressed to ID by meta-xylene. The water immersion density showed a large error band among the data. Densities of the ROX- ThO_2 varied from 4.8g/cc to about 5.2g/cc.
- The density of ROX- ThO_2 (5.2g/cc) was greater than that of ROX-SZR (4.6g/cc) .

In Fig. 9, densities of (1) the ROX fuels and those of (2) the simulated ROX

fuels are plotted together as a function of amounts of SZR. Densities of the inert matrices were less than those of ROX fuels and simulated ones. Direct comparison between the ROX fuels and the simulated ROX fuels should not make because the two had a different sintering process, hence resultant porosity was about 18% for the former and about 5% for the latter.

3.2 Porosity

Results of the simulated ROX fuels and those of the ROX fuels are respectively shown in Table 6 and Table 7. By using the two tables, (1) d_a and (2) p are plotted as a function of amounts of SZR. They are shown respectively in Fig. 10 and Fig. 11.

(1) ROX fuels

The d_a in the ROX fuels was small to the magnitude of $3 \mu\text{m}$, and the p was large to the magnitude of 17-18%. It is worthy of mentioning that the ROX fuels contained a lot of small pores.

It is clear from Fig. 12 that the ROX fuels contained a lot of small pores $< 10 \mu\text{m}$. For comparison, a typical UO_2 data ^(10,11) was included. The UO_2 pellet (enrichment:10wt%) was sintered at $1,400^\circ\text{C}$ in NFI to have the GD of 90%TD. Grain size and average pore diameter were $3 \mu\text{m}$ and $9 \mu\text{m}$, respectively. Hence the UO_2 was fabricated similarly to that of the ROX fuels. The pores contained in UO_2 were, however, greater than those of the ROX fuels. The UO_2 was loaded into the capsule and irradiated in the Japan Materials Testing Reactor (JMTR) to the burn-up of 3.4MWd/kgU. Post-irradiation examination (PIE) revealed that the UO_2 was stable and only densified to the magnitude of 0.5%TD. According to this experimental fact, we may say that the pore distribution of the ROX fuels in the present study may be stable against densification.

(2) Simulated ROX fuels

The d_a in the simulated ROX fuels (sp.#12, #13 and #16) ranged approximately $4-8 \mu\text{m}$. The p in the simulated ROX fuels was $< 6\%$. Therefore, as shown in Fig. 13, the pore distributions among those were resembled consisting of pores $< 30 \mu\text{m}$.

For comparison, a typical UO_2 data ^(10,11) was included in the figure. The UO_2 pellet (enrichment:10wt%) was sintered at $1,600^\circ\text{C}$ in NFI to have the GD of

95%TD. Grain size and average pore diameter were $5 \mu\text{m}$ and $4 \mu\text{m}$, respectively. Hence the UO_2 was fabricated similarly to that of the simulated ROX fuels. The pores contained in UO_2 were relatively smaller than those of the simulated ROX fuels. The UO_2 was loaded into the capsule and irradiated in JMTR to the burn-up of 3.4MWd/kgU. PIE revealed that the UO_2 was stable and densified to the magnitude of 1.8%TD. According to this experimental fact, we may say that the pore distribution of the simulated ROX fuels is rather stable against densification

(3) Inert matrices

The d_a in the inert matrices ranged approximately between 6 and $11 \mu\text{m}$. While, the p of those was classified into two groups, one had about 5% (sp.#1, sp.#2 and sp.#3) and the other had about 8-19% (sp.#4, sp.#5 and sp.#6), irrelevant to amounts of SZR. The worst one against densification stability was the sp.#6 having d_a of $11 \mu\text{m}$ and p of 19%. As shown in Fig. 14, the significant difference between the two groups was addressed to the large pores having a diameter $>20 \mu\text{m}$.

It is worthy of mentioning that UO_2 pellet in LWRs are well controlled the sintering conditions in order to prevent those from densification at BOL and the swelling at EOL. Usually it is known that the small pores $<1 \mu\text{m}$ (sub-micron pores) will be annihilated easily by irradiation and make the fuel pellet shrinkage, while the large pores will be agglomerated easily by irradiation and enhance the expansion of fuel pellet by capturing the fission product gas.

3.3 Grain size

Grain size of the simulated ROX fuels and that of the ROX fuels are respectively shown in Table 8 and Table 9. They are plotted together as a function of amounts of SZR and shown in Fig. 15. The followings are revealed:

(1) ROX fuels

Grain size of the ROX fuels were small of the order of $2 \mu\text{m}$. The value was roughly the same between ROX-SZR and ROX- ThO_2 irrespective to amounts

of SZR. With respect to the porosity and grain size, therefore, there is no significant difference between the ROX fuels. However, a difference was observed in the as-fabricated density.

(2) Simulated ROX fuels

Grain size of the simulated ROX fuels shown in the figure was $1-4 \mu\text{m}$, irrespective to the amounts of SZR. With respect to the grain size, there is no significant difference among simulated ROX fuels and their inert matrices. However, a difference was observed in the as-fabricated density and the porosity.

3.4 Theoretical Density (TD) and %TD

According to Eqn.(6), the $\rho(\%)$ of simulated ROX fuels and ROX ones were estimated and shown in each third column of Table 6 and Table 7. The TD or ρ_{th} and %TD were estimated by Eqn.(8) and Eqn.(4) and shown in Table 10.

3.4.1 TD

The immersed density ρ_i and ρ_{th} are plotted together as a function of amounts of SZR(%) and shown in Fig. 16. The followings are revealed:

(1) Simulated ROX fuels

- TD (ρ_{th}) of the simulated ROX fuels ranged from 5.0-5.7 g/cc, while TD of the inert matrices ranged from 3.7-6.9 g/cc. In two cases, TD was increased with the increased amounts of SZR.
- TD of the conventional UO_2 is 10.96 g/cc so that TD of the simulated ROX fuels is of order of 46-52% of that of UO_2 .

(2) ROX fuels

- TD of the ROX fuels was 5.6 g/cc for ROX-SZR and 6.2 g/cc for ROX- ThO_2 , respectively.
- TD of the ROX-SZR is of order of 51% of that of UO_2 , while TD of the ROX- ThO_2 is of order of 57% of that of UO_2 .
- It is worthy of mentioning that the TD between the simulated ROX fuels and the ROX-SZR had no significant difference. It was 5.0-5.7 g/cc for the

former and 5.6 g/cc for the latter.

3.4.2 %TD

Percent TD in Table 10 was plotted as a function of amounts of SZR (%) and shown in Fig. 17. In LWRs, the ρ_i of the UO_2 pellet is well controlled to have the value of 10.41 g/cc. Therefore, UO_2 has the value of 95%TD as given by Eqn. (5). UO_2 data line is also included in the figure. The followings are revealed:

(1) Simulated ROX fuels

- The simulated ROX fuels and their inert matrices were sintered in NFI to have the %TD of approximately 95. They were sintered at 1,750°C for 4h under the reduced gas of $3\text{H}_2+\text{N}_2$. Due to large amounts of porosity observed in sp.#4, #5 and #6, %TD of them ranged 81-92. The remainders including three simulated ROX fuels ranged from 94 to 98%TD, the same level as that of conventional UO_2 .
- Two inert matrices (sp.#4 and #5) had large amounts of SZR (> 90%) and gave low %TD. One inert matrix (sp.#6), however, had less SZR (30%) but showed the lowest %TD. It is notable that sintering condition was common among all specimens. The reason for this discrepancy is not clarified.

(2) ROX fuels

- The ROX fuels were sintered in JAERI. Sintering temperature was 1,400°C for 8h under the reduced gas of $8\%\text{H}_2+92\%\text{Ar}$. The temperature level as high as 1,400°C was the technical limit usable in the laboratory. The resultant %TD for ROX-SZR and ROX- ThO_2 was 82 and 83, as shown in Fig. 17.
- In addition to the density of 82%TD, the ROX fuels had the p to the magnitude of 18% and a grain size to the magnitude of $2\ \mu\text{m}$. According to the author's previous report ⁽¹²⁾, the fuel with low %TD generally has a potential for a significant densification. However, we found that the ROX had a stable distribution of pore despite of relative large magnitude of porosity. There is little possibility to have a large magnitude of swelling because there exists great many pores

inside which can accommodate lots of gas bubbles at EOL. A swelling rate revealed was $1\% \Delta V/V$ per 1%FIMA at EOL⁽¹³⁾. The corresponded swelling rate of UO_2 was the same.

4. Conclusion

The ROX fuels made of (1) 23wt%PuO₂-17wt%SZR-56wt%Al₂O₃-4wt%MgO (ROX-SZR) and (2) 20wt%PuO₂-29wt%ThO₂-48wt%Al₂O₃-3wt%MgO (ROX-ThO₂) were fabricated by JAERI. Additionally, three simulated ROX fuels and six their inert matrices were fabricated by NFI. Density, porosity and grain size measurements of those were carried out and obtained results are:

1. Density

- (1) At mock-up test, geometrical density (GD), water immersion (WID), meta-xylene immersion (MID) and driwel immersion density (DID) were used. Irrespective of those four methods, obtained density of bearing ball was fallen into about 7.78g/cc in average, while an original metal density was about 7.7.6g/cc. This is attributed the fact that bearing ball had no pores at all.
- (2) As-sintered density measured by MID was 4.6 and 5.2g/cc for ROX-SZR and ROX-ThO₂, respectively. The estimated TD of those was 5.6 and 6.2g/cc. The estimated TD was about half of that of UO_2 . Because of pores existed in these fuels, densities were changed depending on measuring methods such as WID, MID and so on.
- (3) As-fabricated densities of the simulated ROX fuels were in the range of 4.5-5.5g/cc, while those of the inert matrices were 3.0-6.0g/cc. The estimated TD of the former was 5.0-5.7g/cc, while that of the latter was 3.7-6.9g/cc, respectively. The density of simulated ROX fuels is also about half of that of UO_2 . Their densities were increased with the increased amounts of SZR contained in the fuel.
- (4) Due to the low sintering temperature of 1,400°C, the %TD of the ROX fuels was in the range of 82-83%TD. While, the simulated ROX fuels sintered at 1,750°C was in the range of 94-98%TD.

2. Porosity

- (1) The d_p of ROX fuels was about 3 μ m and the p of those was 17-18%. The ROX fuels contained a lot of small pores <10 μ m. It is notable that the d_p

in UO_2 was $<10 \mu\text{m}$ and p was about 5%.

(2) The d_a of simulated ROX fuels was about $4-8 \mu\text{m}$ and the p of those was $<6\%$. Despite of the same fabricating condition, the d_a and p among the inert matrices were not fallen into the same data band.

3. Grain size

Grain size of the ROX fuels was about $2 \mu\text{m}$ while that of the simulated ROX fuels was $1-4 \mu\text{m}$.

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Table 1 As-fabricated Characteristics of the ROX Fuels

Composition of Pu isotopes (at%)	²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu
ROX-SZR Powder After sintering	<0.01	94.3	5.3	0.4	<0.01
	23wt%PuO ₂ -17wt%SZR ⁽¹⁾ -56wt%Al ₂ O ₃ -4wt%MgO PuO ₂ -PuAl ₁₁ O ₁₈ (hibonite)-SZR-Al ₂ O ₃ (corundum)-MgAl ₂ O ₄ (spinel) ⁽²⁾				
ROX-ThO₂ Powder After sintering	20wt%PuO ₂ -29wt%ThO ₂ -48wt%Al ₂ O ₃ -3wt%MgO PuO ₂ -PuAl ₁₁ O ₁₈ (hibonite)-ThO ₂ -Al ₂ O ₃ (corundum)-MgAl ₂ O ₄ (spinel)				
Specifications:					
<i>(i) Fuel</i>	<i>(ii) Sheath</i>		<i>(iii) Fuel Pin</i>		
Fuel form	Disk	State	Zr-1wt%Nb	Enriched fuel column	5 mm
Outer diameter (O.D.)	3 mm	O.D.	6 mm	Diametral gap	1 mm
Length	1 mm	Inner Diameter	4 mm	Fill gas pressure	0.1MPa
End form	Flat			Gas composition	100% He
L/D ⁽³⁾	0.3			Plenum volume	about 0.4 ml

Note

- (1) SZR: Stabilized ZrO₂ composed of 88.8%ZrO₂-11.0%Y₂O₃-0.2%Gd₂O₃(mole percent)
- (2) Spinel, the resultant compound of Al₂O₃ and MgO powder. In the text, this was denoted conventionally as "MgAl₂O₄".
- (3) L/D: Ratio of disk thickness to diameter

**Table 2 As-fabricated Characteristics of
the Simulated ROX Fuels**

(1) Simulated ROX fuel

Specimen No.	Composition (wt%)		
	UO ₂	SZR	MgAl ₂ O ₄
Sp.#12:	26	24	50
Sp.#13:	24	43	33
Sp.#16:	24	23	53

(2) Inert Matrices

Specimen No.	Composition (wt%)		
	UO ₂	SZR	MgAl ₂ O ₄
Sp.#1:	0	0	100
Sp.#2:	0	32	68
Sp.#3:	0	56	44
Sp.#4:	0	88	12
Sp.#5:	0	100	0
Sp.#6:	0	30	70

(3) Pellet Characterization

Enrichment	Natural U
O.D.	9.1mm
Inner diameter:	None
Length:	9.6mm
End form:	Flat

Table 3 Summary of Mock-up Test

1.1 Material: bearing balls (O.D.=2mm)				
No.	Method	Density(g/cc)	Deviation	Liquid density(g/cc)
1	Original bearing metal	7.76		0.0012 ⁽¹⁾
2	Geometrical	7.79		0.0012
3	Water immersion	7.81	0.21	0.9973
4	Driwel immersion	7.78	0.02	0.9969
5	M-xylene immersion ⁽²⁾	7.75	0.02	0.8597
6	M-xylene immersion ⁽³⁾	7.80	0.00	0.8554
	Ave.	7.78	0.02	
1.2 Material: Nickel disks (O.D.=3mm, Thickness=1mm)				
No.	Method	Density(g/cc)	Deviation	Liquid density(g/cc)
1	Density by pure metal	8.88		0.0012
2	Water immersion ⁽⁴⁾	8.76	0.16	0.9973
1.3 Reference UO ₂ pellet (Fragmented) ⁽⁵⁾				
No.	Method	Density(g/cc)	Deviation	Liquid density(g/cc)
1	Water immersion	9.63	0.11	0.9973
2	Driwel immersion	10.53	0.03	0.9969
3	M-xylene immersion	10.49	0.00	0.8597

Note:

- (1) A density of air at measurement.
- (2) Measurements from no.3 to no.5 were done at newly installed $\beta \cdot \gamma$ equipment built up for density measurement of a disk-type small piece of fuel. The present study was the first trial of density measurement by this equipment. The trial was carried out at the cold area.
- (3) Measurement no.6 was done at the hot cell no.1. The place was once used for density measurement of a spent UO₂ fuel pellet.
- (4) Water immersion measurement was done at newly installed $\beta \cdot \gamma$ equipment.
- (5) Measurement was done at the hot cell no.1. UO₂ pellet was sliced first and fragmented into pieces prior to measurement so that geometrical density data were not obtained.

Table 4 As-fabricated Density(GD, GID) of the Simulated ROX Fuels

Sp.# ⁽¹⁾	Material(wt%)	Density (g/cc)		
		GD ⁽²⁾	σ ⁽³⁾	GID ⁽⁴⁾
1	100MgAl ₂ O ₄	3.21	0.08	3.52
2	32SZR ⁽⁵⁾ -68MgAl ₂ O ₄ ⁽⁶⁾	3.96	0.02	4.09
3	56SZR-44MgAl ₂ O ₄	4.47	0.04	4.60
4	88SZR-12MgAl ₂ O ₄	5.12	0.01	5.49
5	100SZR	5.19	0.02	5.89
6	30SZR-70MgAl ₂ O ₄	2.89	-	4.02
12	26UO ₂ ⁽⁷⁾ -24SZR-50MgAl ₂ O ₄	4.74	0.07	4.91
13	24UO ₂ -43SZR-33MgAl ₂ O ₄	5.07	0.01	5.37
16	24UO ₂ -23SZR-53MgAl ₂ O ₄	4.77	0.01	4.85

Note:

- (1) No.1-No.6 were the inert matrices and No.12,13 and16 were the simulated ROX fuels.
- (2) GD : the geometrical density, determined by as-fabricated pellet dimensions.
- (3) Standard deviation of GD.
- (4) GID : the helium gas immersion density obtained without deviation.
- (5) SZR means stabilized zirconia (ZrO₂) in form of 88.8mol%ZrO₂-11mol%Y₂O₃-.2mol%Gd₂O₃
- (6) MgAl₂O₄ is the spinel consisted of Al₂O₃ and MgO.
- (7) Fuel material: natural U, O.D.=9.1mm, Length=9.6mm

Table 5 Density of Disk-type ROX Fuels

1.1	ROX-SZR				
	O.D.=2.8mm, Thickness=1mm				
	No.	Method	Density(g/cc)	$\sigma^{(1)}$	Liquid density (g/cc)
	1	Geometrical	4.27	0.01	0.0012 ⁽²⁾
	2	Water immersion	4.38	0.12	0.9969
	3	M-xylene	4.57	0.01	0.8568
	4	Drivel immersion	4.60	0.03	0.9968
1.2	ROX-ThO ₂				
	O.D.=2.8mm, Thickness=1mm				
	No.	Method	Density(g/cc)	σ	Liquid density (g/cc)
	1	Geometrical	4.79	-	0.0012
	2	Water immersion	5.11	0.03	0.9969
	3	M-xylene	5.15	0.01	0.8558
	4	Drivel immersion	5.13	0.02	0.9968

Note:

(1) Standard deviation(\pm) for a density

(2) A density of air at measurement

Table 6 Results of Porosity Measurement on the Simulated ROX Fuels

Sp.#	Material (wt%)	(i)	(ii)	(iii)
1	100MgAl ₂ O ₄	5.9	5.8	5.0
2	32SZR-68MgAl ₂ O ₄	6.7	5.6	5.6
3	56SZR-44MgAl ₂ O ₄	6.7	4.8	4.3
4	88SZR-12MgAl ₂ O ₄	9.2	7.5	7.9
5	100SZR	9.6	9.3	14.1
6	30SZR-70MgAl ₂ O ₄	10.6	12.9	19.1
12	26UO ₂ -24SZR-50MgAl ₂ O ₄	6.6	4.4	5.0
13	24UO ₂ -43SZR-33MgAl ₂ O ₄	7.5	5.4	6.4
16	24UO ₂ -23SZR-53MgAl ₂ O ₄	4.2	2.7	2.4

Note:

(i) Average pore diameter (μ m)

(ii) Standard deviation(\pm) of pore diameter

(iii) Porosity (%)

Table 7 Results of Porosity Measurement on the ROX Fuels

1.	ROX-SZR:			
	(i)	(ii)	(iii)	
	2.9	5.1	18.4	
2.	ROX-ThO ₂ :			
	(i)	(ii)	(iii)	
	2.7	3.7	17.4	

Note:

(i) Average pore diameter (μ m)

(ii) Standard deviation(\pm) of pore diameter

(iii) Porosity (%)

Table 8 Results of Grain Size Measurement on the Simulated ROX Fuels

Sp.#	Material(wt%)	Grain size μm	$\sigma^{(1)}$
1	100MgAl ₂ O ₄	-(2)	-
2	32SZR-68MgAl ₂ O ₄	1.8	0.2
3	56SZR-44MgAl ₂ O ₄	1.7	0.3
4	88SZR-12MgAl ₂ O ₄	3.0	0.4
5	100SZR	-	-
6	30SZR-70MgAl ₂ O ₄	3.6	0.5
12	26UO ₂ -24SZR-50MgAl ₂ O ₄	4.0	0.6
13	24UO ₂ -43SZR-33MgAl ₂ O ₄	2.7	0.4
16	24UO ₂ -23SZR-53MgAl ₂ O ₄	3.2	0.2
	Average	2.9	0.9

Note:

- (1) Standard deviation(\pm) of grain size
 (2) Grain size of sp.#1 and #5 could not be determined because these consisted of a single phase material.

Table 9 Results of Grain Size Measurement on the ROX Fuels

1	ROX-SZR		
	Grain size(μm)	$\sigma^{(1)}$	
	2.0	0.1	
2	ROX-ThO ₂		
	Grain size(μm)	σ	
	2.1	0.1	

Note: (1)Standard deviation(\pm) of grain size

Table 10 Summary of Measurement on Theoretical Density (TD) and %TD of ROX Fuels and Simulated ROX Fuels

1. Simulated ROX Fuels:				
	(i)	(ii)	(iii)	(iv)
Specimen	$p(\%)$	$\rho_1(\text{g/cc})$	$\rho_{\text{th}}(\text{g/cc})$	%TD
#1	5.0	3.52	3.71	95.0
#2	5.6	4.09	4.33	94.4
#3	4.3	4.60	4.81	95.7
#4	7.9	5.49	5.96	92.1
#5	14.1	5.89	6.86	85.9
#6	19.1	4.02	4.97	80.9
#12	5.0	4.91	5.17	95.0
#13	6.4	5.37	5.74	93.6
#16	2.4	4.85	4.97	97.6
2. ROX Fuels				
Specimen	$p(\%)$	$\rho_1(\text{g/cc})$	$\rho_{\text{th}}(\text{g/cc})$	%TD
ROX-SZR	18.4	4.57	5.60	81.6
ROX-ThO ₂	17.4	5.15	6.23	82.7

Note:

(i): Porosity determined by image analyzer.

(ii): Density determined by He gas immersion for the simulated ROX fuels and that determined by meta-xylene immersion for the ROX fuels

(iii): Theoretical density(g/cc) estimated by equation (8) given in the text

(iv): Percent TD obtained from equation (4) in the text or (ii)/(iii) x 100

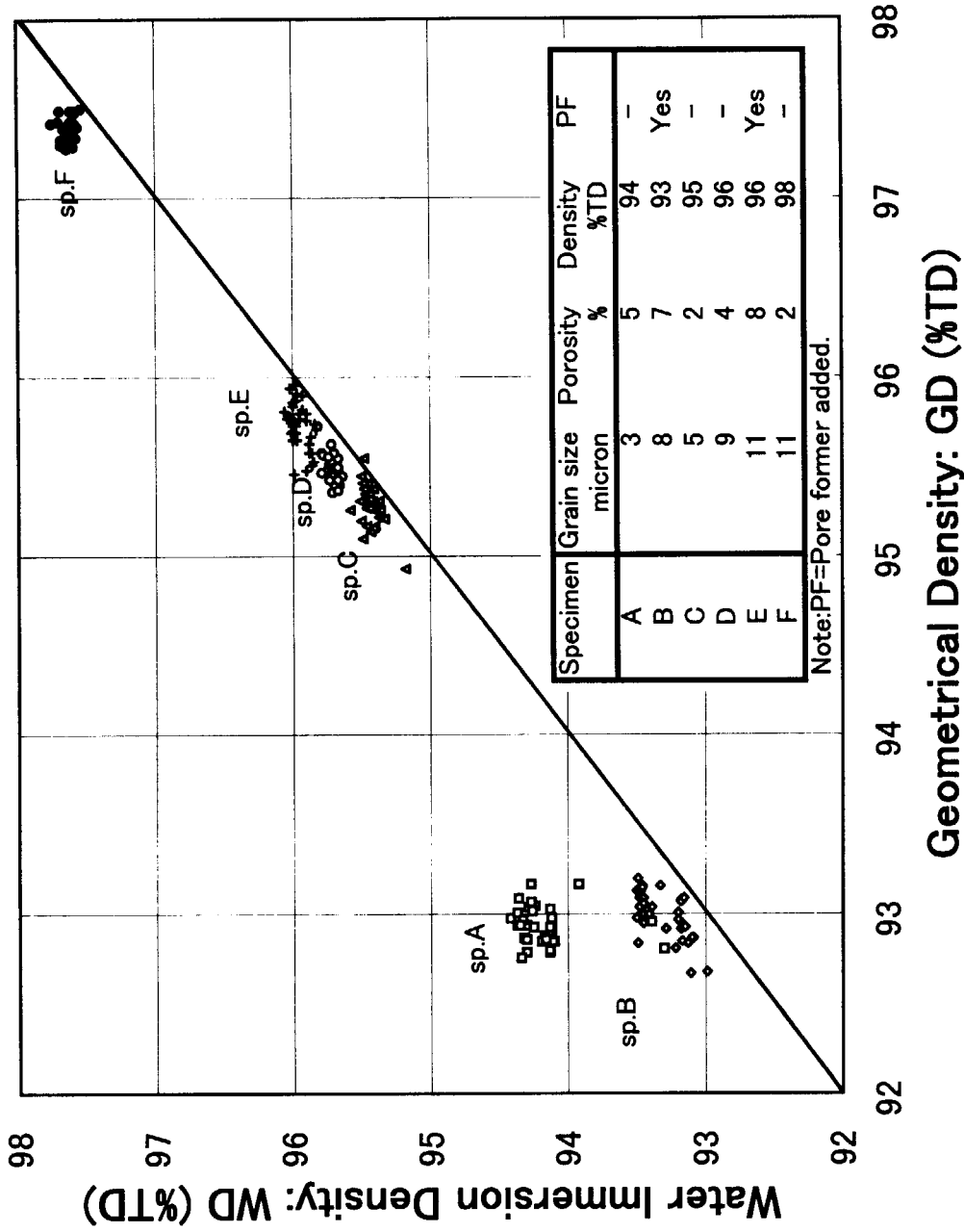


Fig. 1 Relationship between GD and WD in UO₂ fuel.
Data are referred from ref. (6).

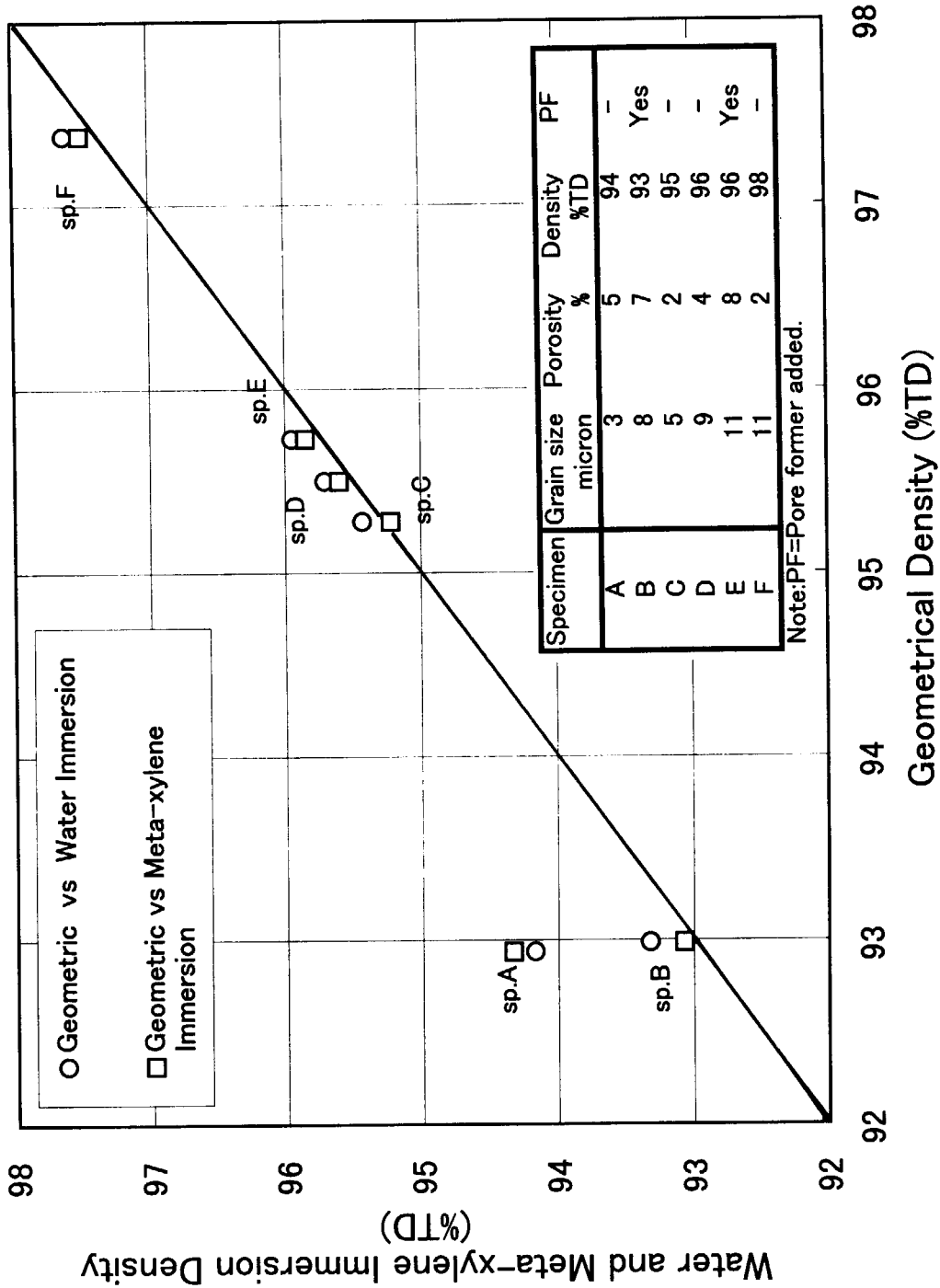


Fig. 2 Immersion densities by water and meta-xylene as a function of geometrical density. Data are referred from ref. (6).

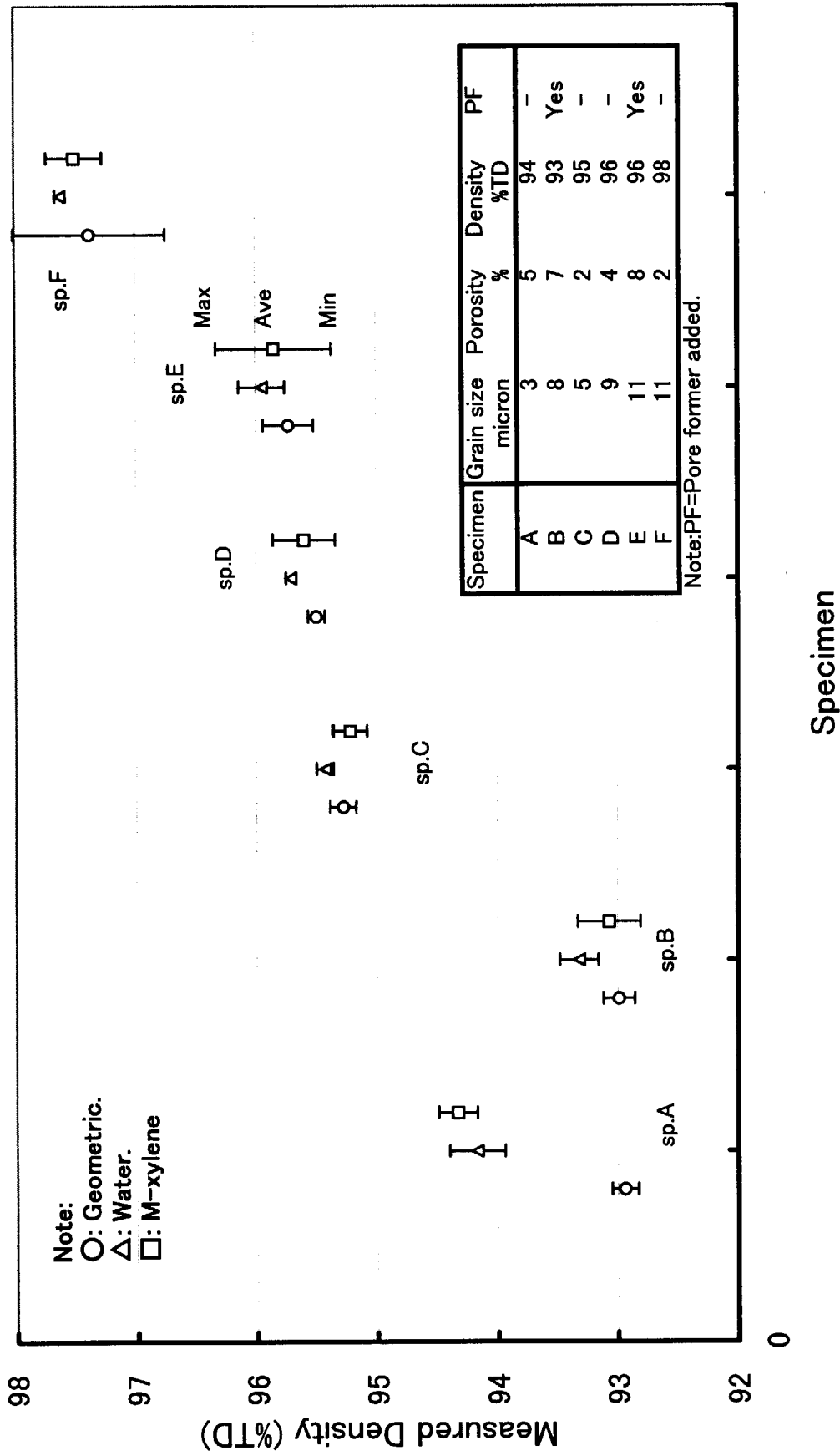


Fig. 3 Geometrical density, immersion densities by water and meta-xylene plotted according to the specimens. Data are referred from ref. (6).

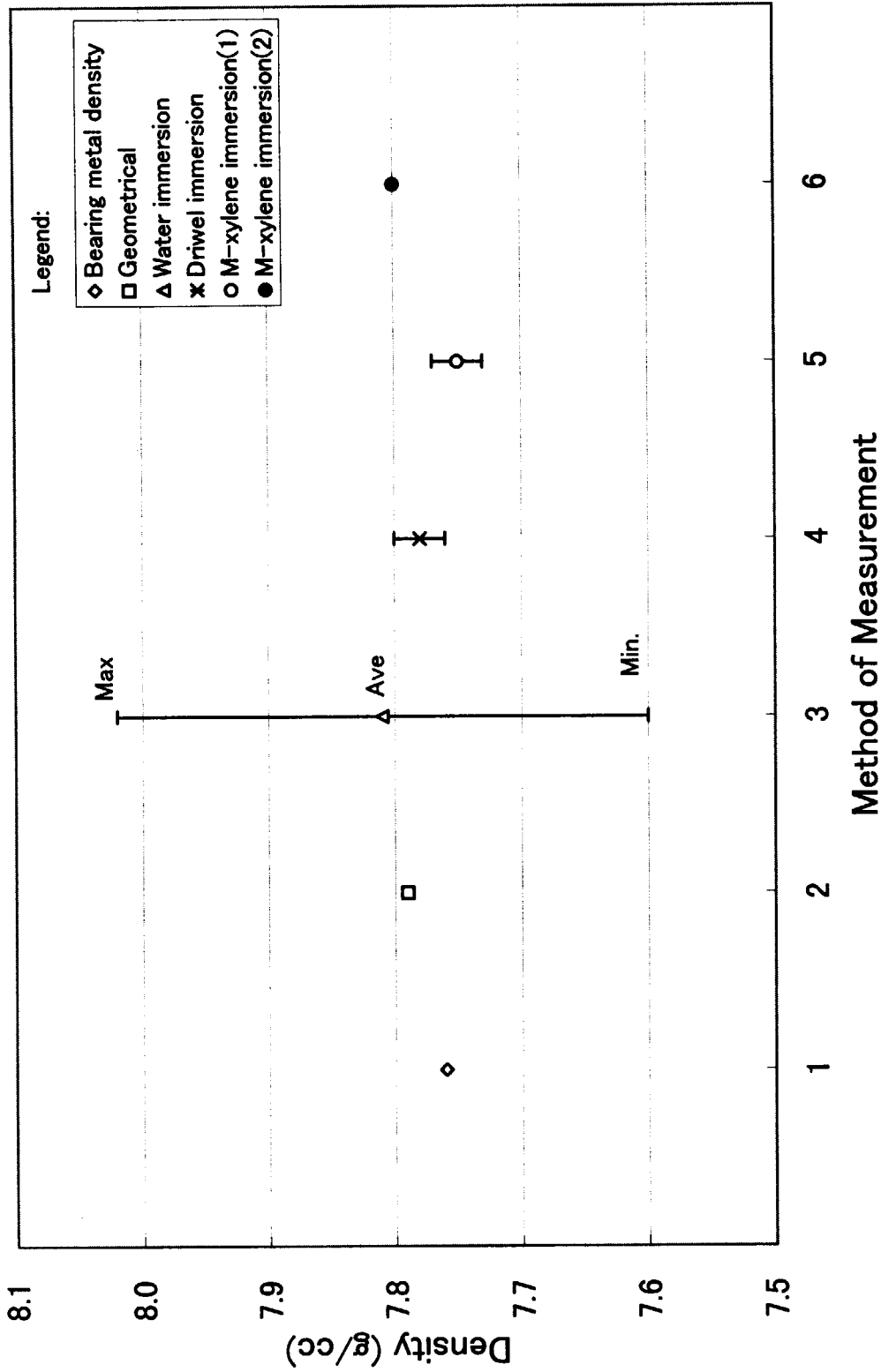


Fig. 4 Results of mock-up test for density measurements performed by bearing balls.

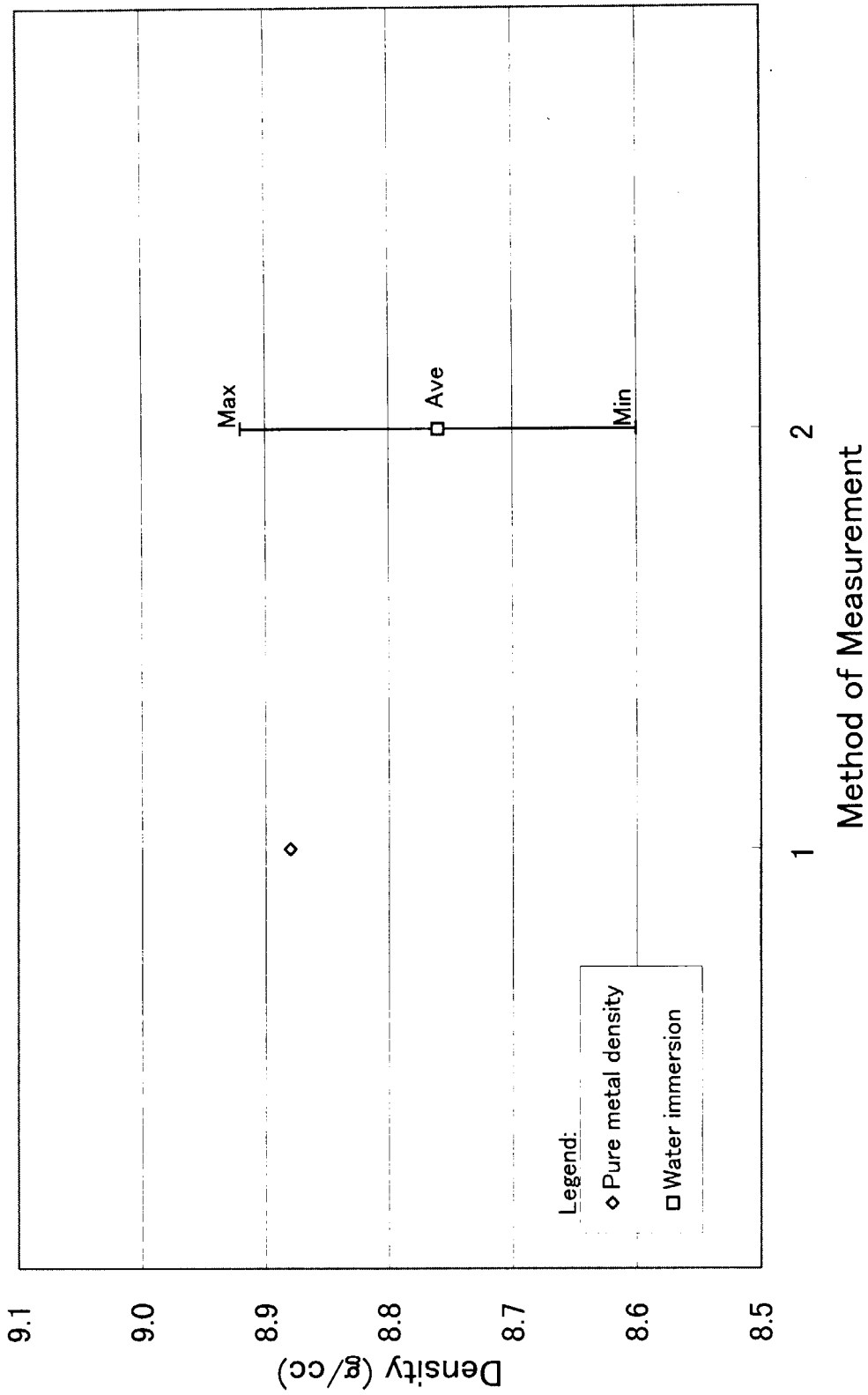


Fig. 5 Results of mock-up test for density measurements performed by nickel disks.

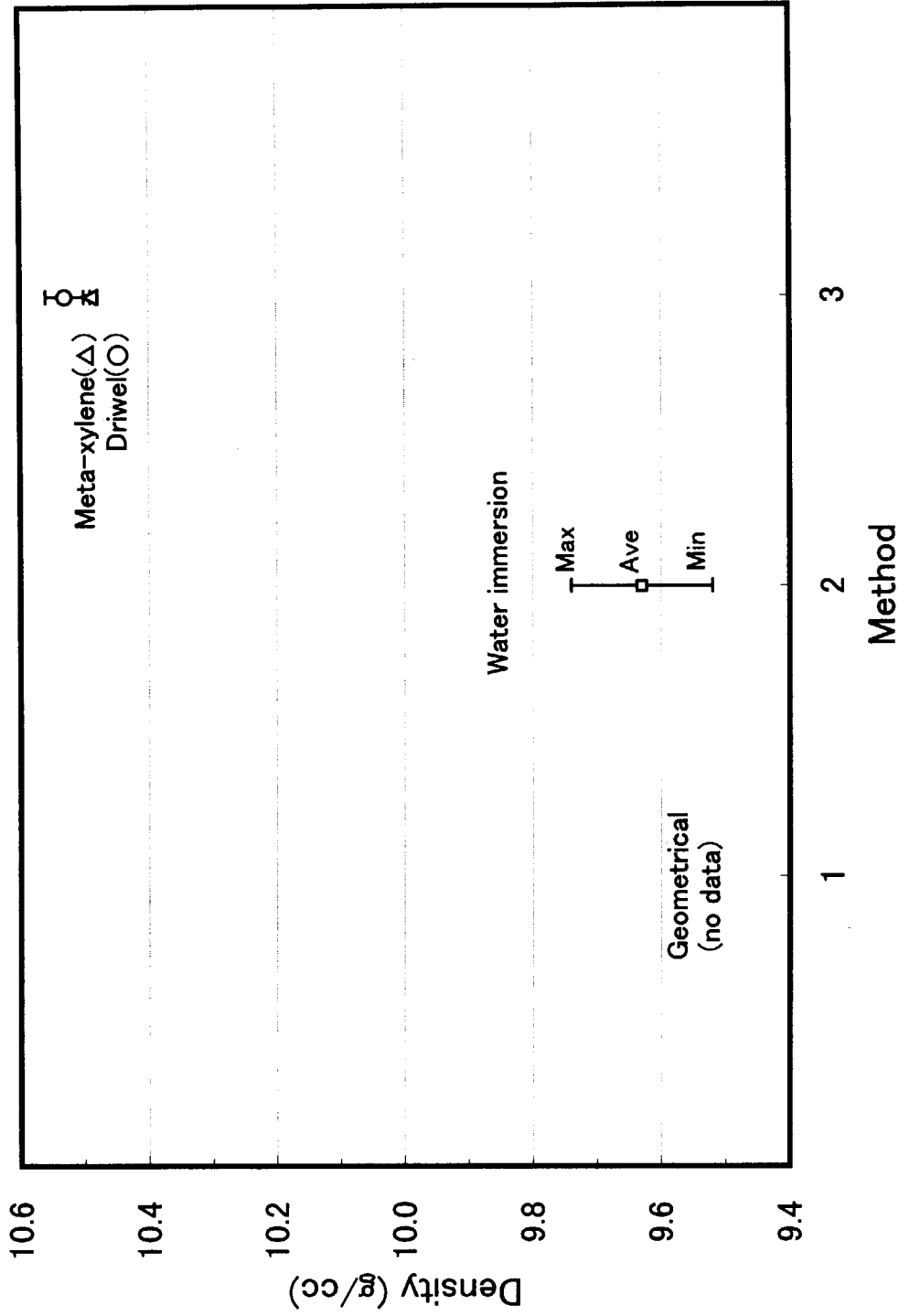


Fig. 6 Results of mock-up test for density measurements performed by Reference UO_2 fuels.

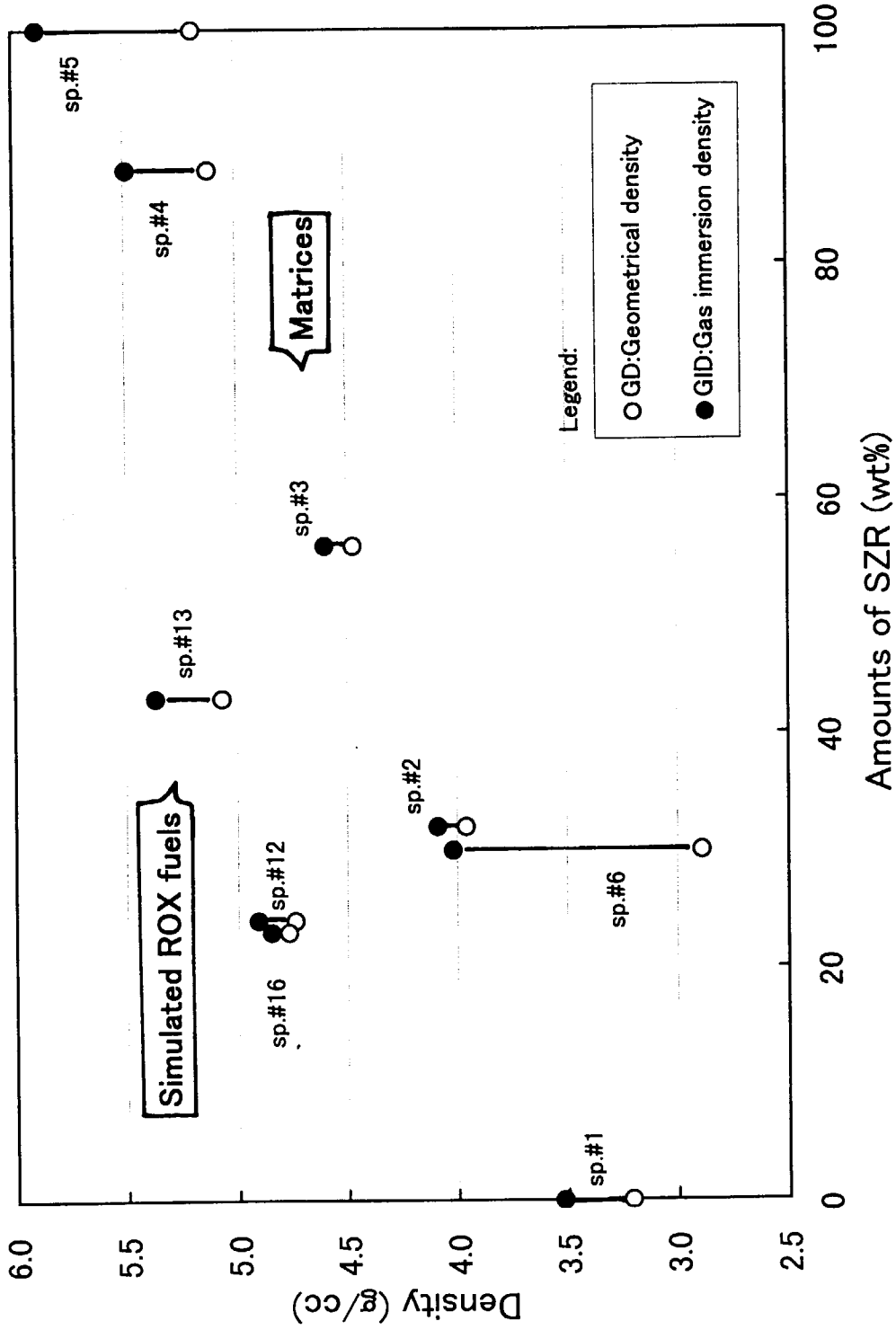


Fig. 7 Densities of the simulated ROX fuels and their matrices: GD and GID are plotted as a function of amounts of SZR.

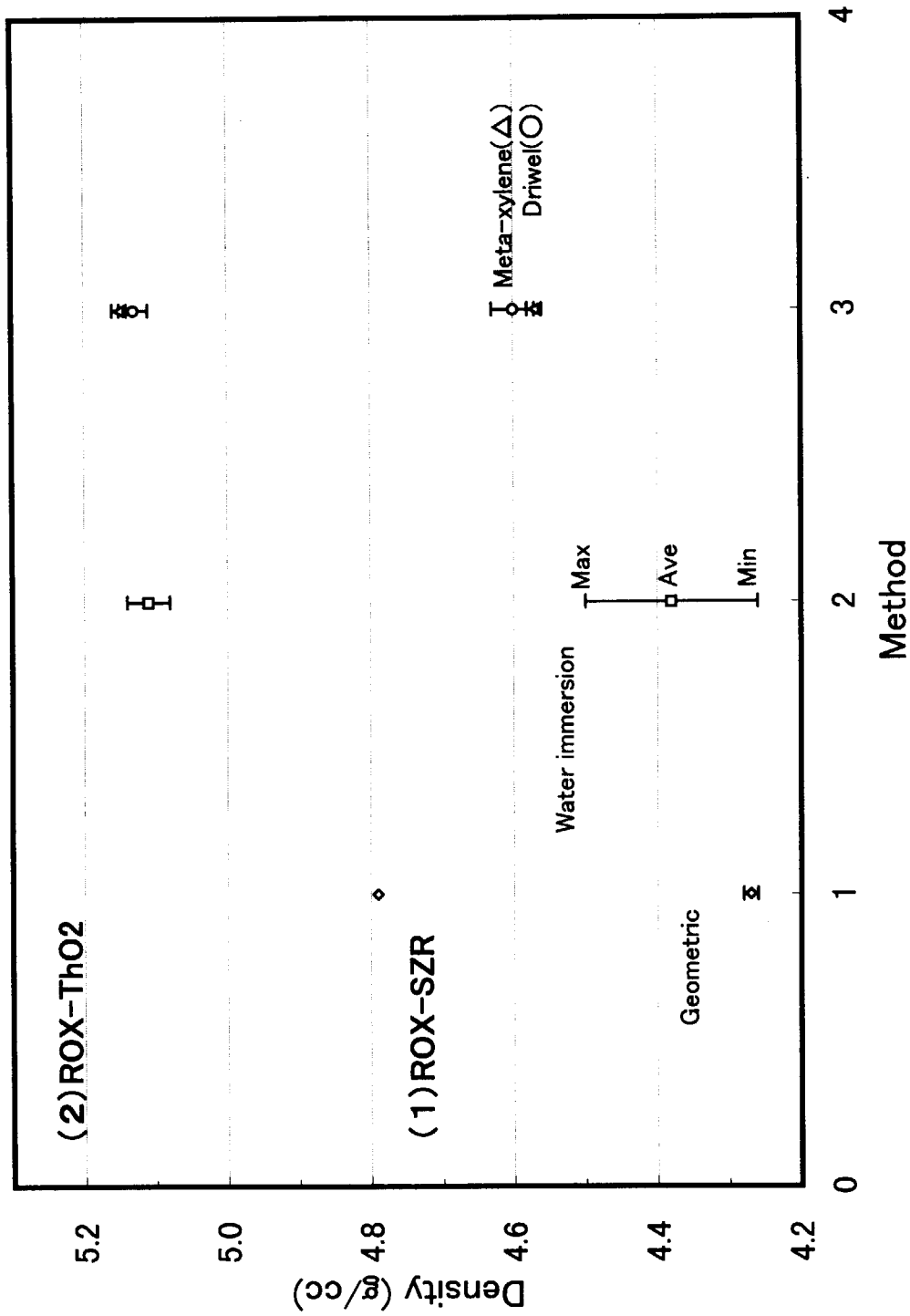


Fig. 8 Densities of the ROX fuels. Liquid for the immersion was exchanged each.

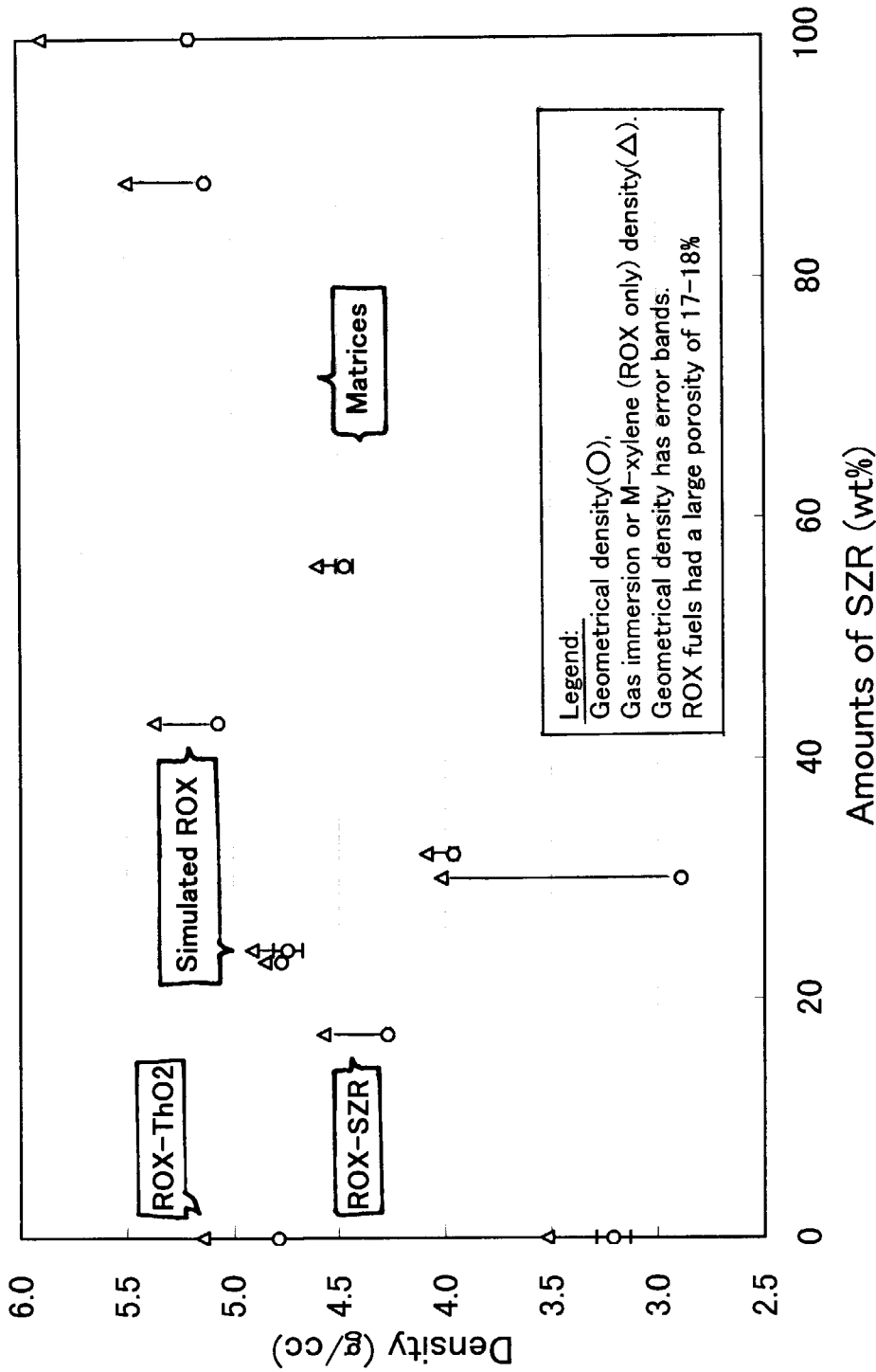


Fig. 9 Densities of the ROX fuels, the simulated ROX fuels and their matrices as a function of amounts of SZR contained in each specimen.

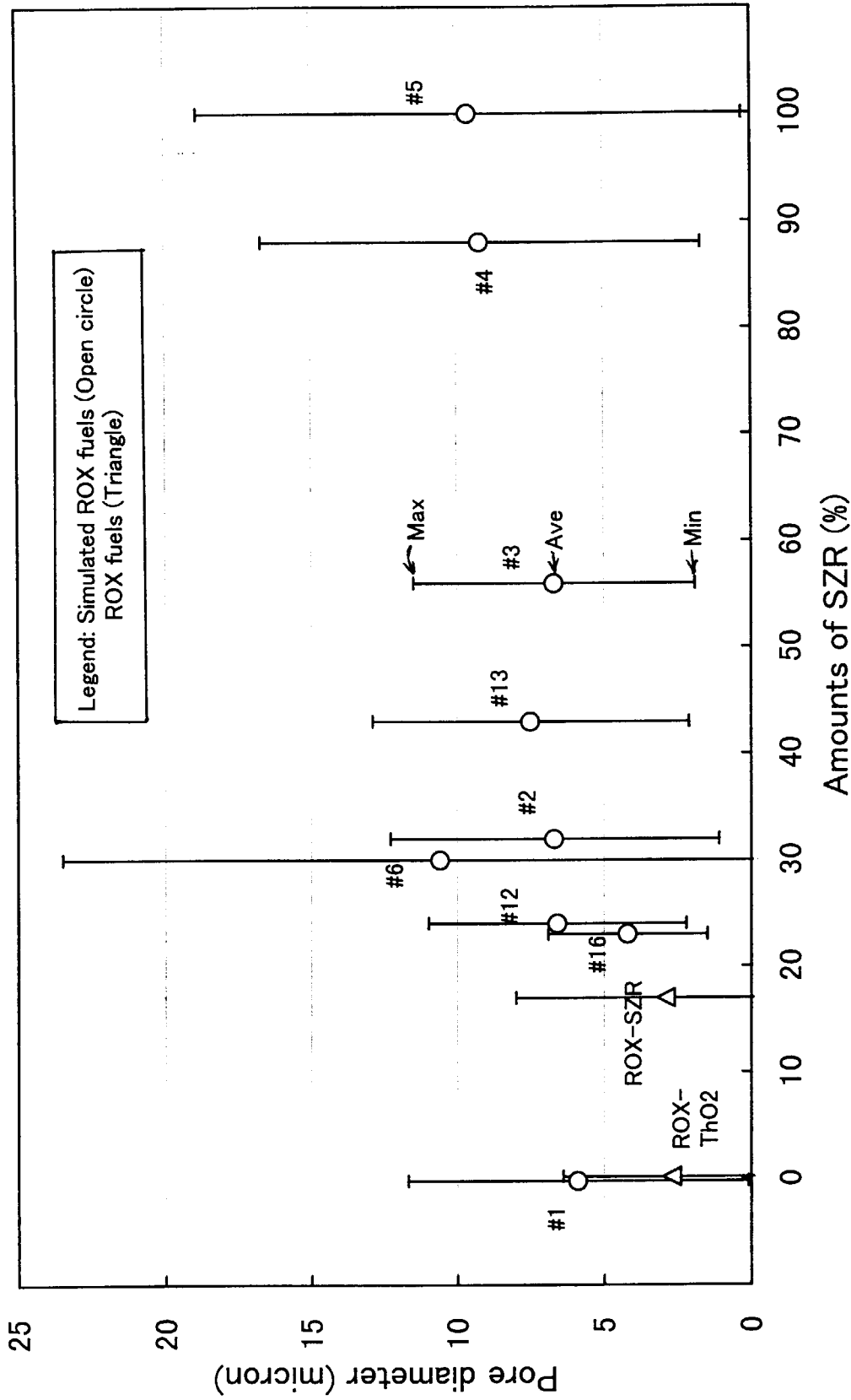


Fig. 10 Pore diameter of the ROX and the simulated ROX fuels as a function of amounts of SZR contained in each specimen.

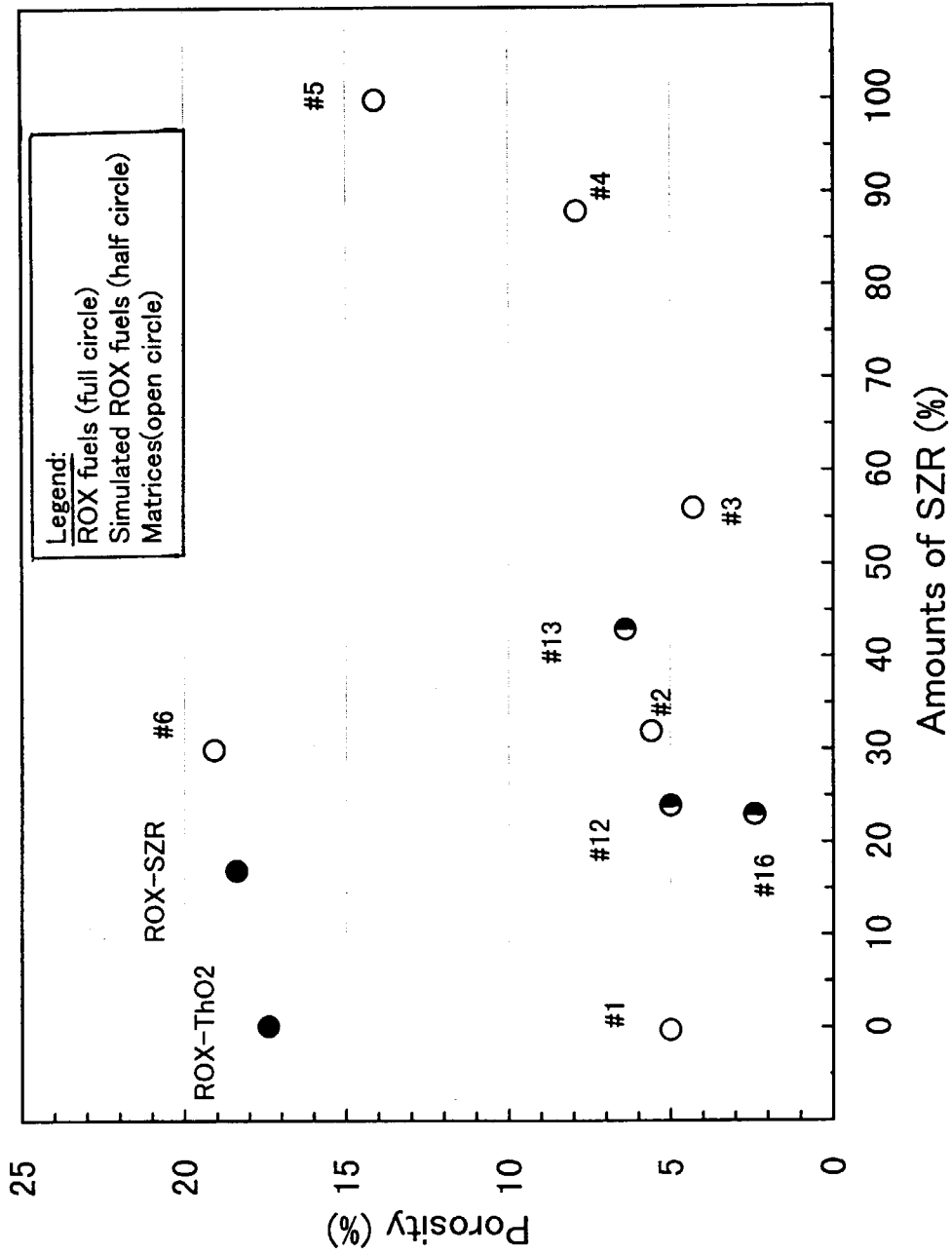


Fig. 11 Porosity of the ROX and the simulated ROX fuels as a function of amounts of SZR contained in each specimen.

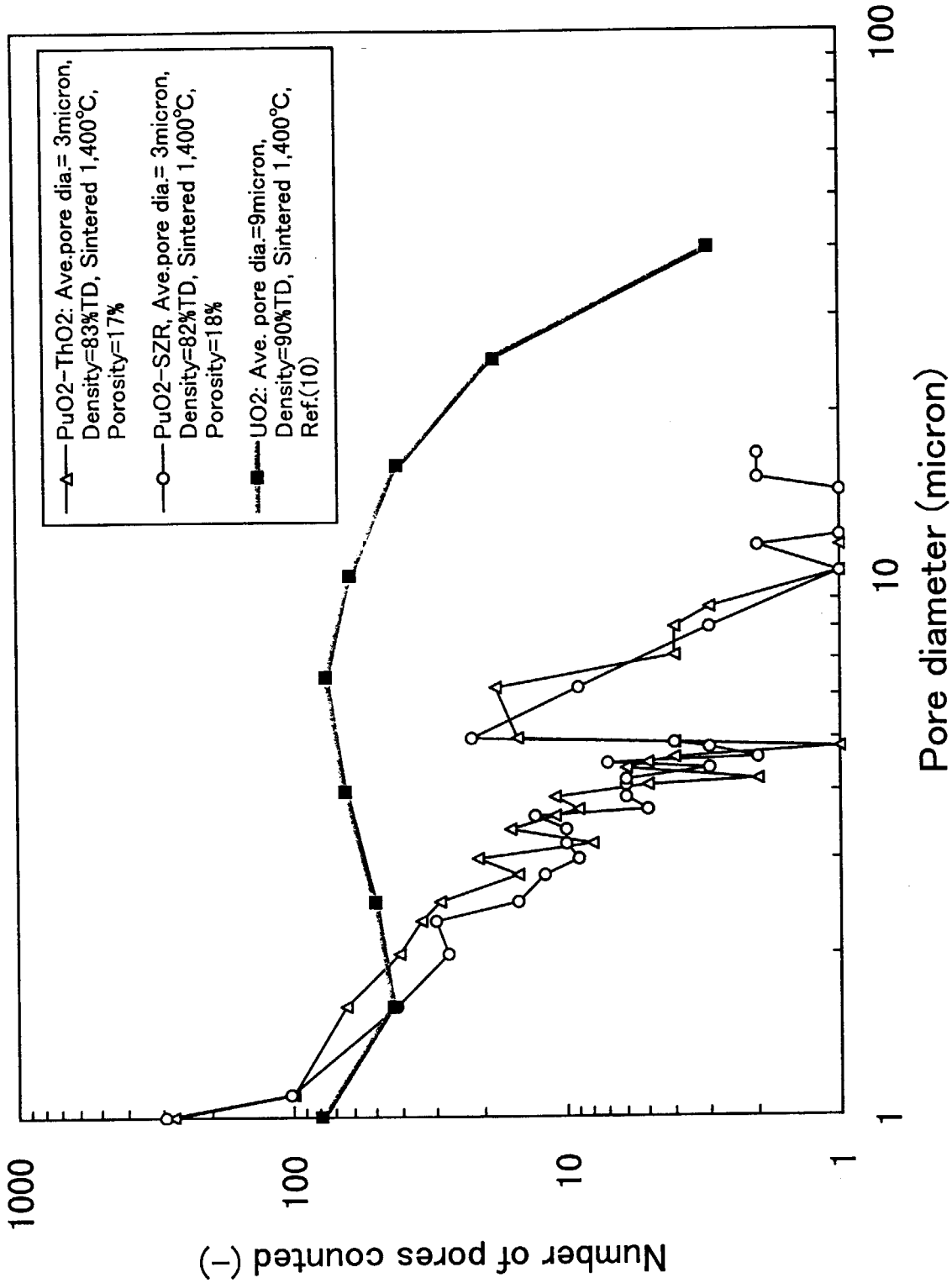


Fig. 12 Number of pores counted from the ROX fuels and UO₂ pellet (ref. (10)) as a function of pore diameter.

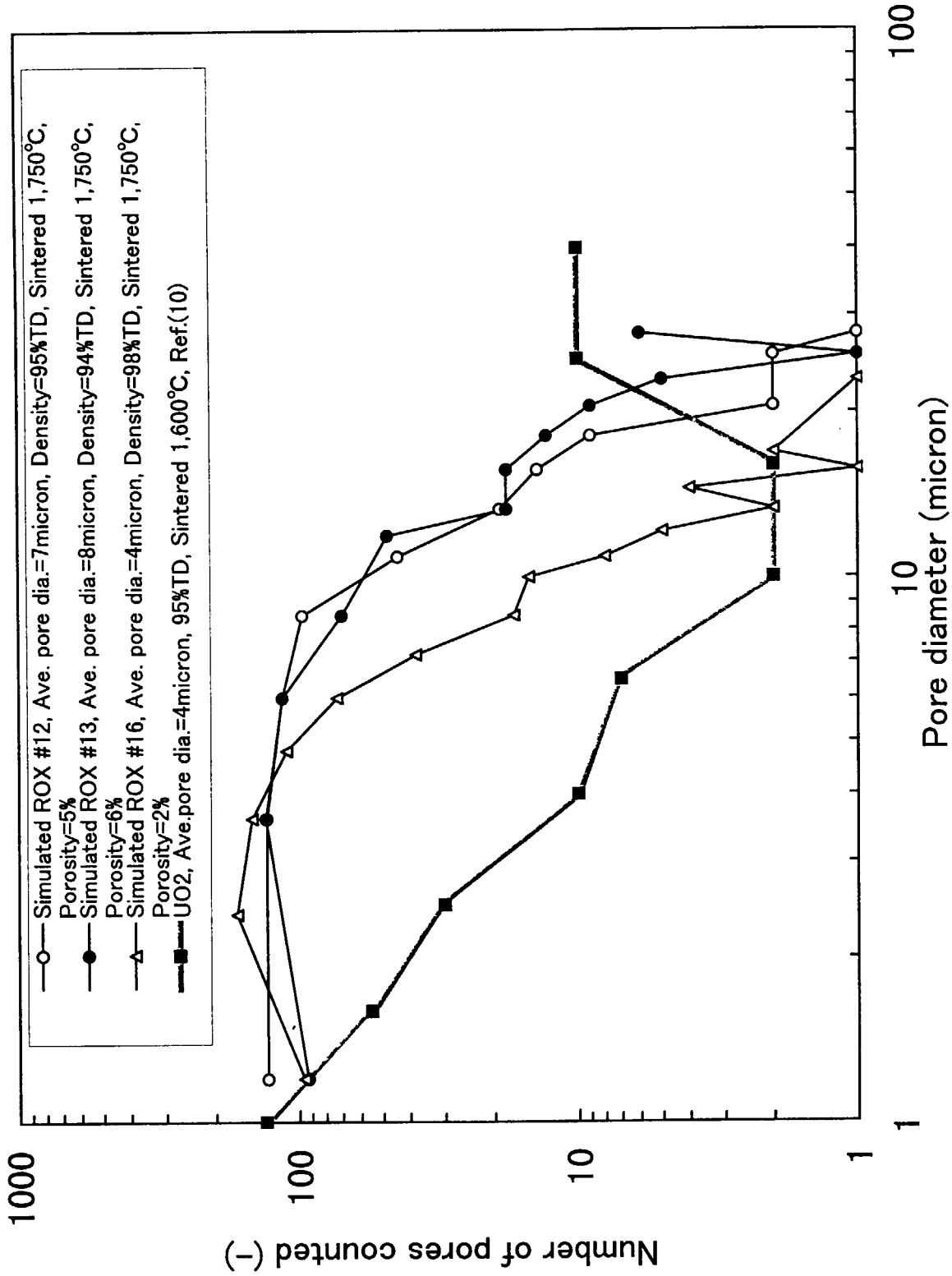


Fig. 13 Number of pores counted from the simulated ROX fuels and UO₂ pellet (ref. (10)) as a function of pore diameter.

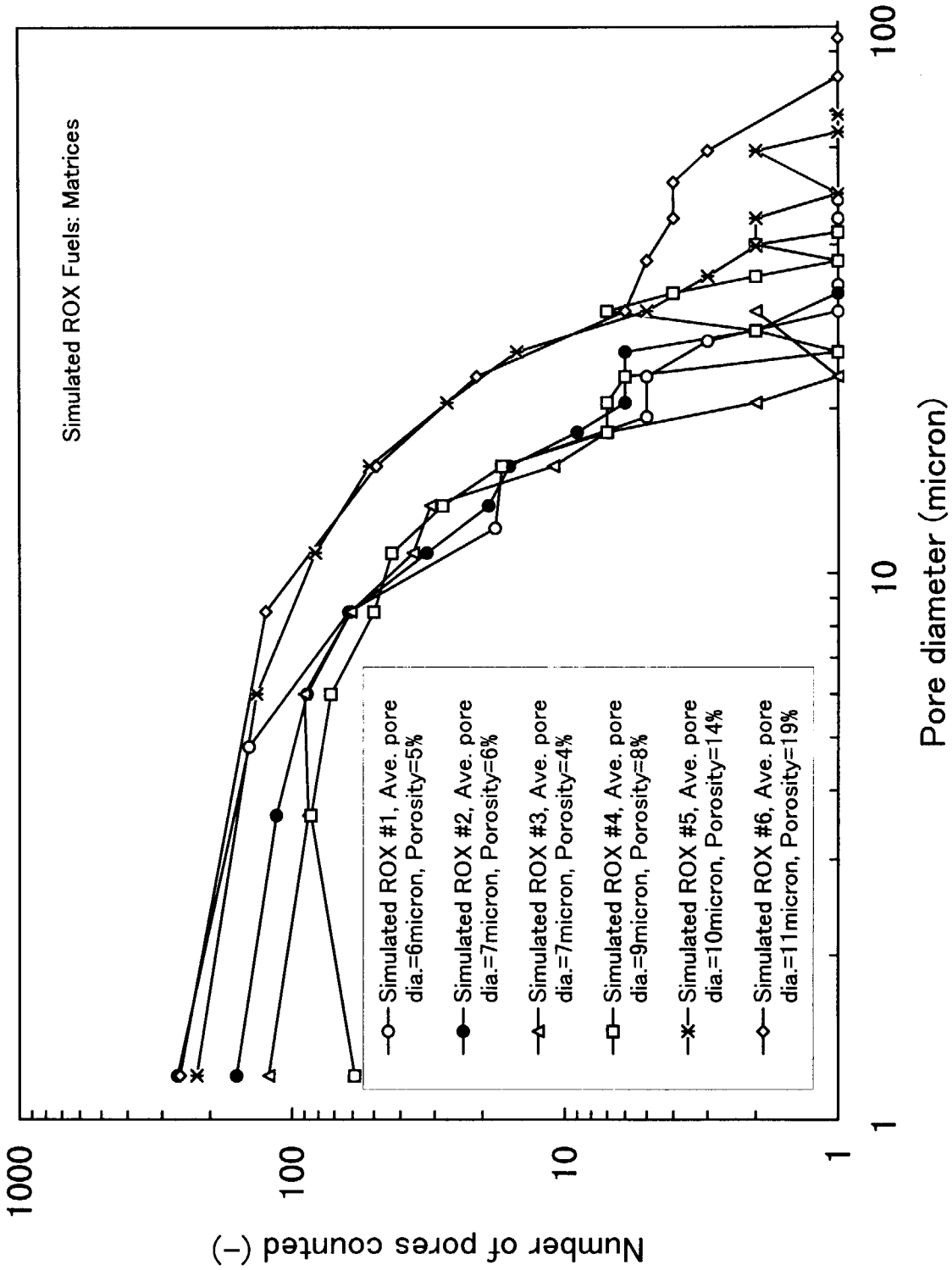


Fig. 14 Number of pores counted from the inert matrices of simulated ROX fuels as a function of pore diameter.

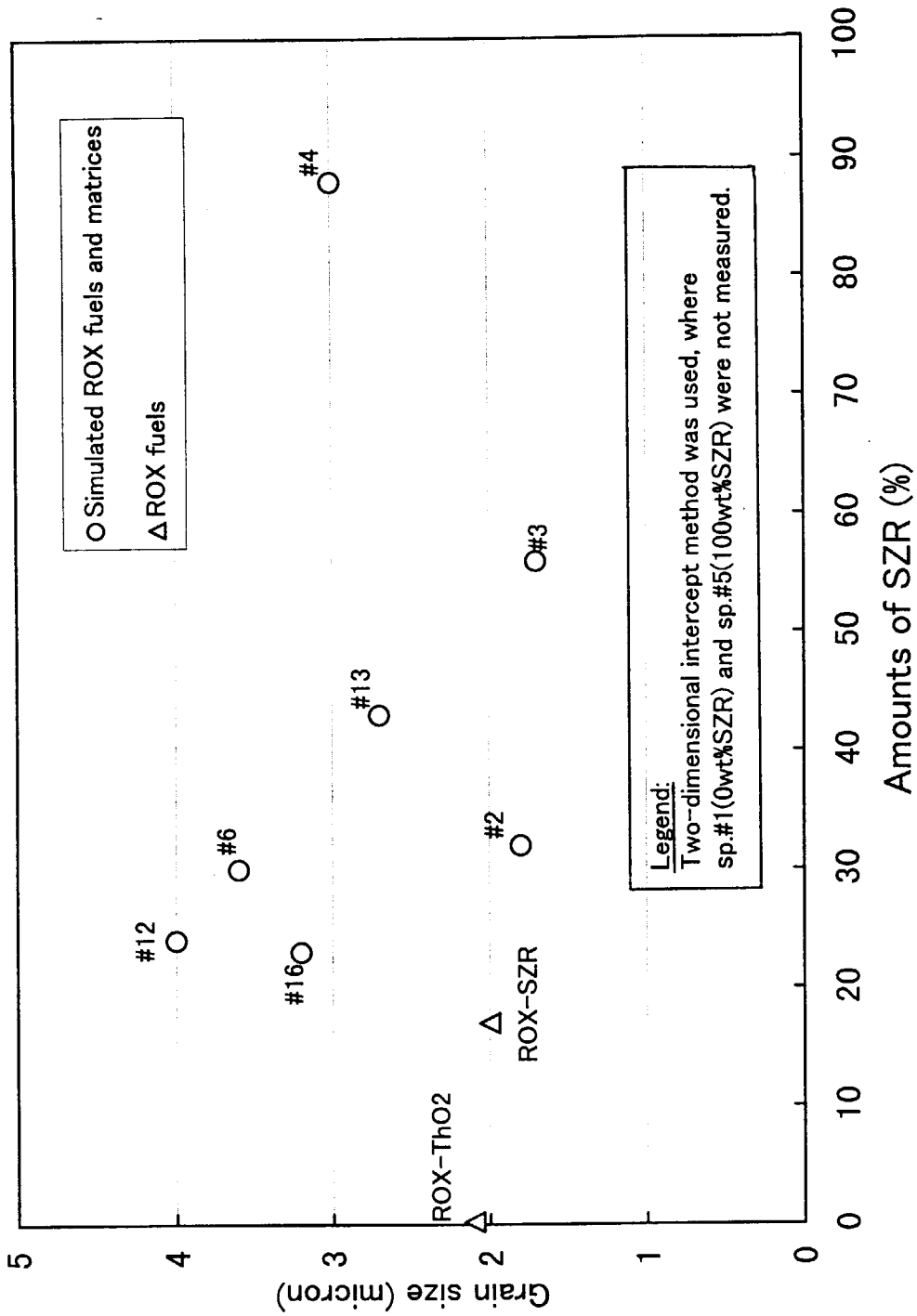


Fig. 15 Grain size diameter of the ROX and the simulated ROX fuels as a function of amounts of SZR contained in each specimen.

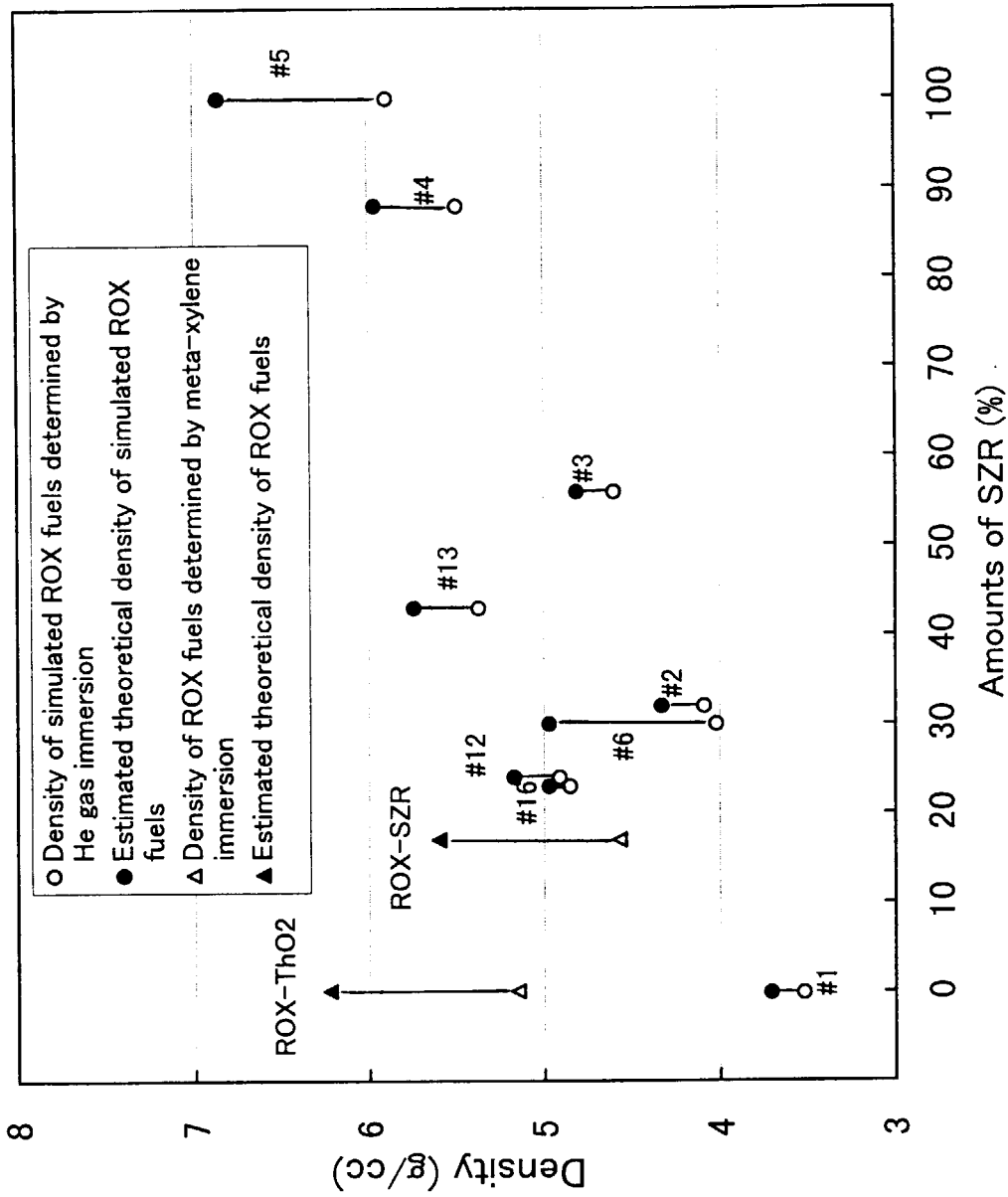


Fig. 16 Theoretical density of the ROX and the simulated ROX fuels as a function of amounts of SZR contained in each specimen. Immersed densities by He gas for the ROX fuels and by meta-xylene for the simulated ROX fuels are included for comparison.

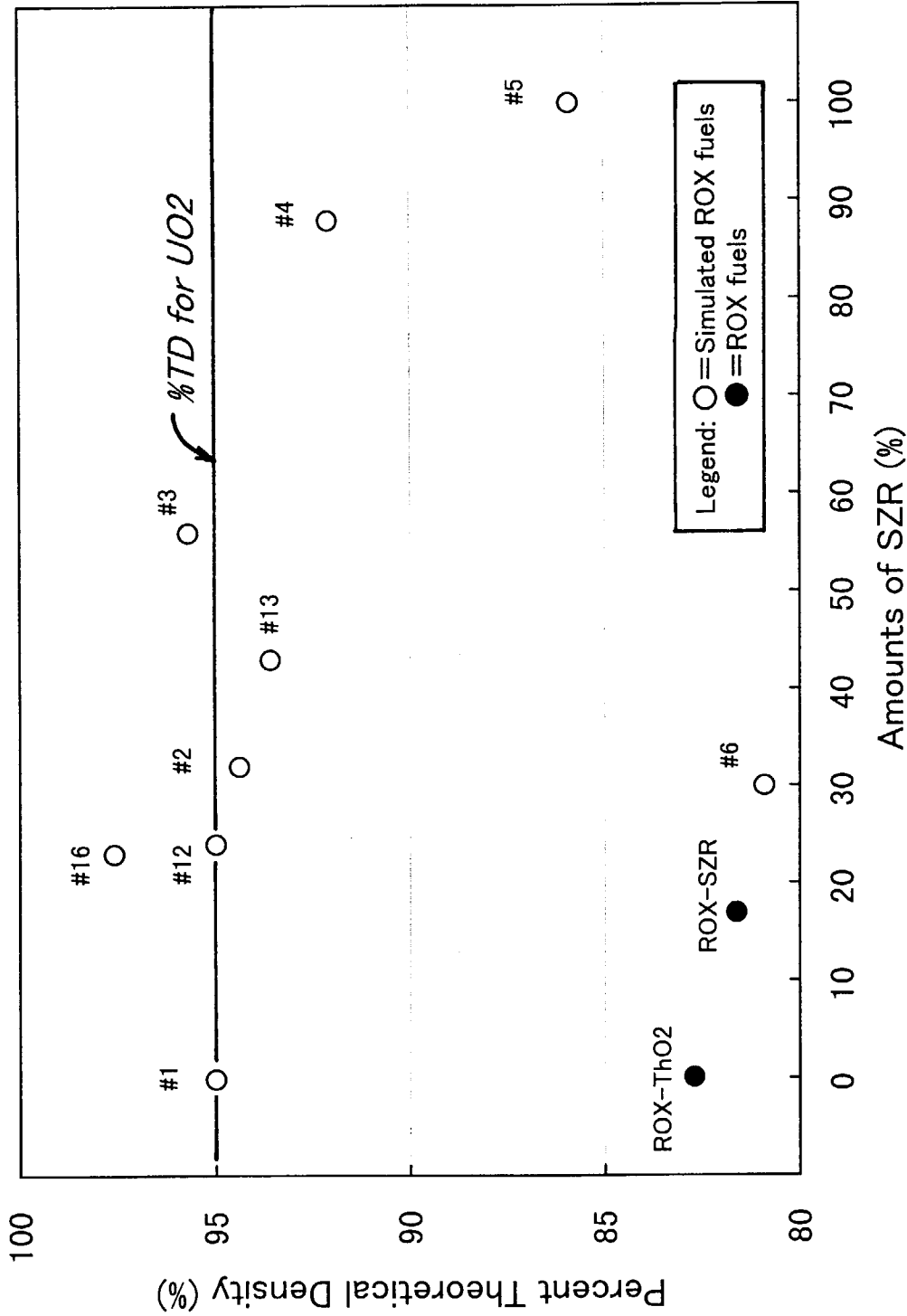


Fig. 17 Percent theoretical densities (%TDs) of the ROX and the simulated ROX fuels as a function of amounts of SZR contained in each specimen. %TD of UO₂ is included for comparison.

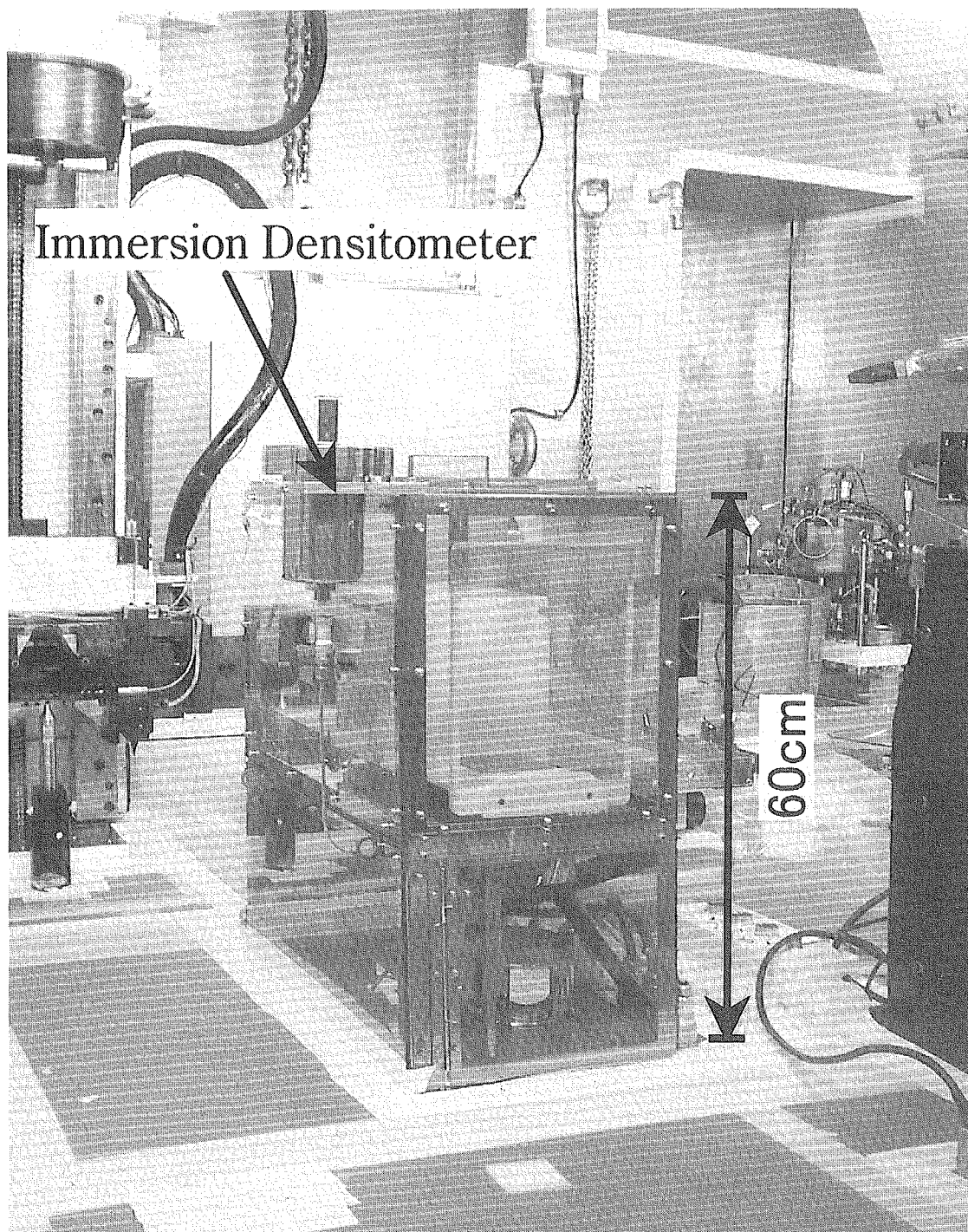


Photo. 1 Overview of the equipment installed at hot cell No.1 Belonged to the Department of Hot Laboratories, JAERI, usually a density of spent UO_2 fuel from LWR was measured.

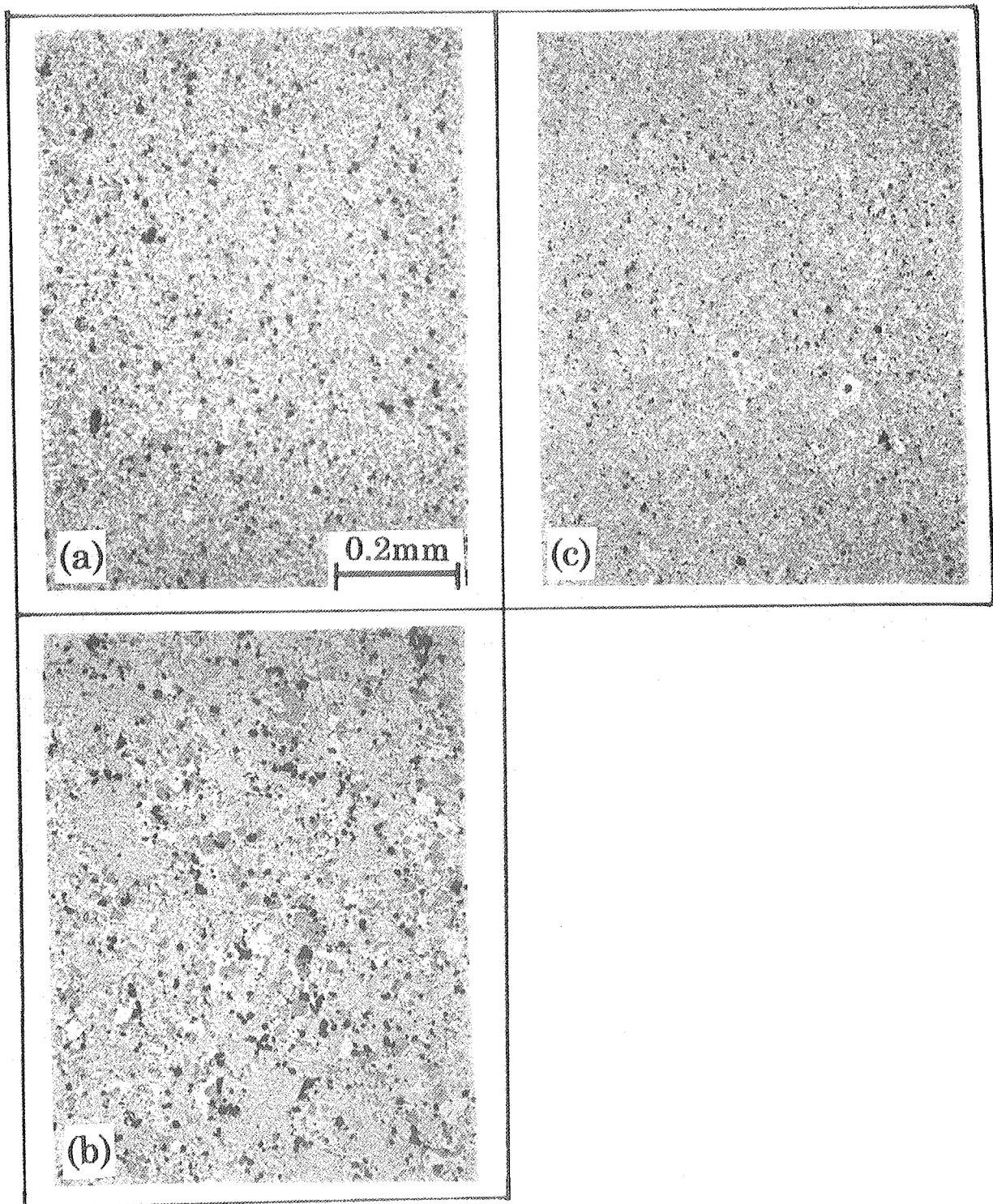


Photo. 2(a) As-polished fuel microstructures of the simulated ROX fuels:

- (a) sp.#12; 26wt% UO_2 -24wt%SZR-50wt% MgAl_2O_4 ,
- (b) sp.#13; 24wt% UO_2 -43wt%SZR-33wt% MgAl_2O_4 ,
- (c) sp.#16; 24wt% UO_2 -23wt%SZR-53wt% MgAl_2O_4 .

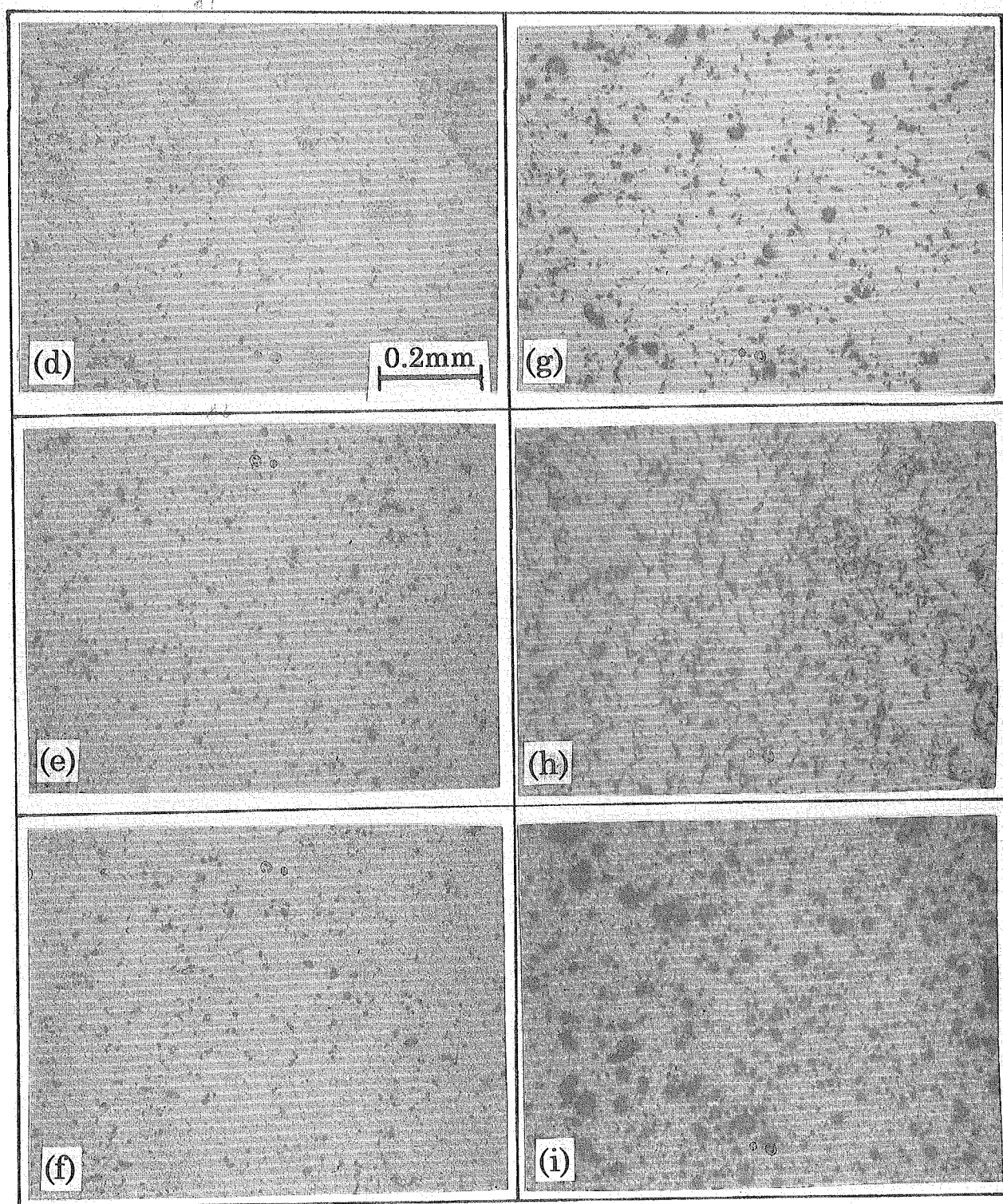


Photo. 2(b) As-polished fuel microstructures of the inert matrices of simulated ROX fuels:
 (d) sp.#01;100wt%MgAl₂O₄, (e) sp.#02;32wt%SZR-68wt%MgAl₂O₄,
 (f) sp.#03;56wt%SZR-44wt%MgAl₂O₄,
 (g) sp.#04;88wt%SZR-12wt%MgAl₂O₄, (h)sp.#05;100wt%SZR,
 (i) sp.#06;30wt%SZR-70wt%MgAl₂O₄.

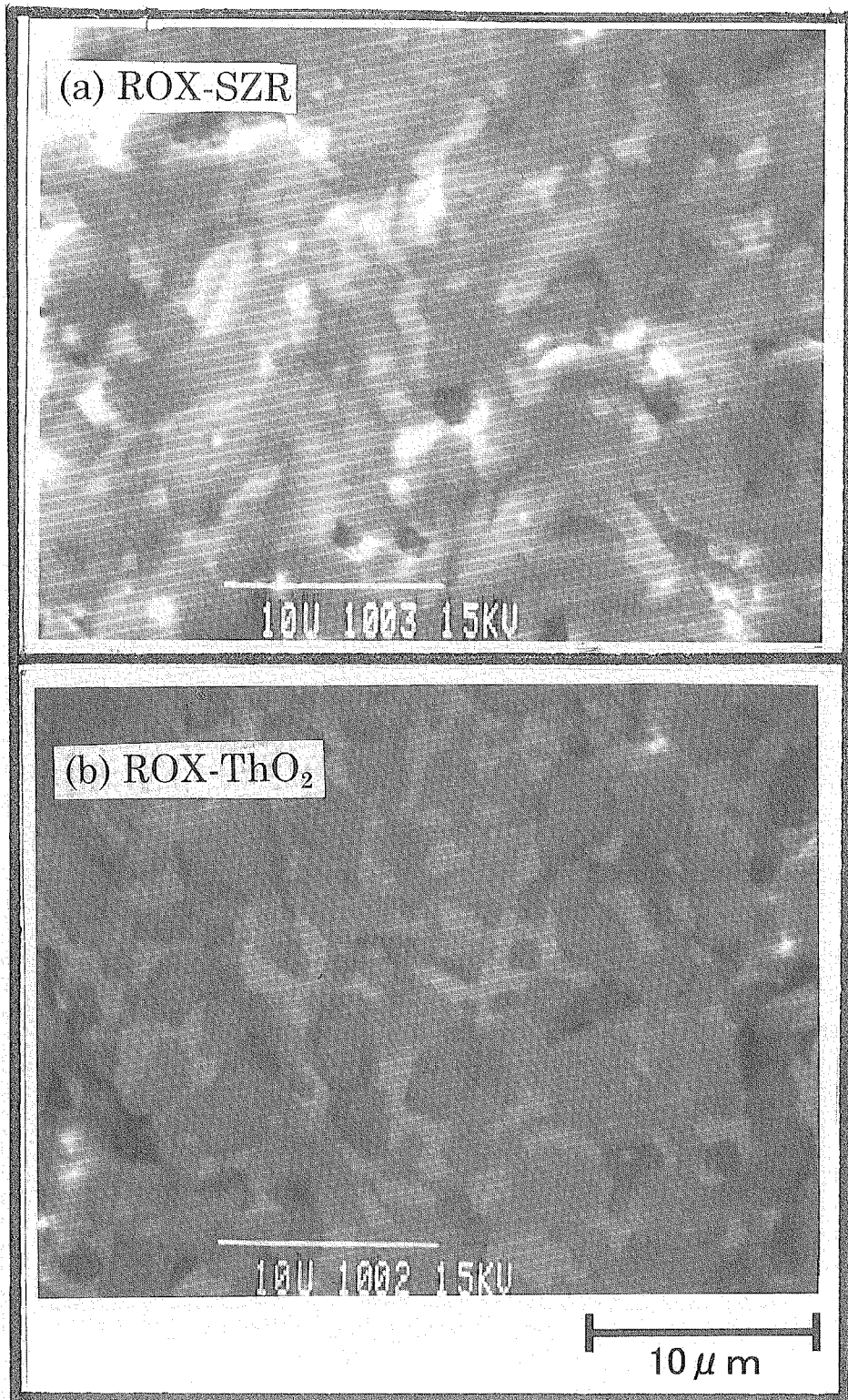


Photo. 3 As-fabricated/as-polished ROX fuels taken by the scanning electron microscope:
(a) ROX-SZR and (b) ROX-ThO₂

国際単位系 (SI) と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s ⁻¹
力	ニュートン	N	m·kg/s ²
圧力, 応力	パスカル	Pa	N/m ²
エネルギー, 仕事, 熱量	ジュール	J	N·m
工率, 放射束	ワット	W	J/s
電気量, 電荷	クーロン	C	A·s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m ²
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	°C	
光束度	ルーメン	lm	cd·sr
照射度	ルクス	lx	lm/m ²
放射線量当量	ベクレル	Bq	s ⁻¹
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表2 SIと併用される単位

名称	記号
分, 時, 日	min, h, d
度, 分, 秒	°, ', "
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218 × 10⁻¹⁹ J

1 u = 1.66054 × 10⁻²⁷ kg

表4 SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バ - ン	b
バ - ル	bar
ガ - ル	Gal
キュ - リ	Ci
レントゲン	R
ラ - ド	rad
レ - ム	rem

1 Å = 0.1 nm = 10⁻¹⁰ m

1 b = 100 fm = 10⁻²⁸ m²

1 bar = 0.1 MPa = 10⁵ Pa

1 Gal = 1 cm/s² = 10⁻² m/s²

1 Ci = 3.7 × 10¹⁰ Bq

1 R = 2.58 × 10⁻⁴ C/kg

1 rad = 1 cGy = 10⁻² Gy

1 rem = 1 cSv = 10⁻² Sv

表5 SI接頭語

倍数	接頭語	記号
10 ¹⁸	エクサ	E
10 ¹⁵	ペタ	P
10 ¹²	テラ	T
10 ⁹	ギガ	G
10 ⁶	メガ	M
10 ³	キロ	k
10 ²	ヘクト	h
10 ¹	デカ	da
10 ⁻¹	デシ	d
10 ⁻²	センチ	c
10 ⁻³	ミリ	m
10 ⁻⁶	マイクロ	μ
10 ⁻⁹	ナノ	n
10 ⁻¹²	ピコ	p
10 ⁻¹⁵	フェムト	f
10 ⁻¹⁸	アト	a

(注)

- 表1-5は「国際単位系」第5版, 国際度量衡局 1985年刊行による。ただし, 1 eV および 1 uの値はCODATAの1986年推奨値によった。
- 表4には海里, ノット, アール, ヘクトールも含まれているが日常の単位なのでここでは省略した。
- barは, JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
- EC閣僚理事会指令ではbar, barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N (=10 ⁵ dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度 1 Pa·s (N·s/m²) = 10 P (ポアズ) (g/(cm·s))

動粘度 1 m²/s = 10⁴ St (ストークス) (cm²/s)

圧	MPa (=10 bar)	kgf/cm ²	atm	mmHg (Torr)	lbf/in ² (psi)
	1	10.1972	9.86923	7.50062 × 10 ³	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322 × 10 ⁻⁴	1.35951 × 10 ⁻³	1.31579 × 10 ⁻³	1	1.93368 × 10 ⁻²
	6.89476 × 10 ⁻³	7.03070 × 10 ⁻²	6.80460 × 10 ⁻²	51.7149	1

エネルギー・仕事・熱量	J (=10 ⁷ erg)	kgf·m	kW·h	cal (計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778 × 10 ⁻⁷	0.238889	9.47813 × 10 ⁻⁴	0.737562	6.24150 × 10 ¹⁸
	9.80665	1	2.72407 × 10 ⁻⁶	2.34270	9.29487 × 10 ⁻³	7.23301	6.12082 × 10 ¹⁹
	3.6 × 10 ⁶	3.67098 × 10 ⁵	1	8.59999 × 10 ⁵	3412.13	2.65522 × 10 ⁶	2.24694 × 10 ²⁵
	4.18605	0.426858	1.16279 × 10 ⁻⁶	1	3.96759 × 10 ⁻³	3.08747	2.61272 × 10 ¹⁹
	1055.06	107.586	2.93072 × 10 ⁻⁴	252.042	1	778.172	6.58515 × 10 ²¹
	1.35582	0.138255	3.76616 × 10 ⁻⁷	0.323890	1.28506 × 10 ⁻³	1	8.46233 × 10 ¹⁸
	1.60218 × 10 ⁻¹⁹	1.63377 × 10 ⁻²⁰	4.45050 × 10 ⁻²⁶	3.82743 × 10 ⁻²⁰	1.51857 × 10 ⁻²²	1.18171 × 10 ⁻¹⁹	1

1 cal = 4.18605 J (計量法)

= 4.184 J (熱化学)

= 4.1855 J (15 °C)

= 4.1868 J (国際蒸気表)

仕事率 1 PS (仏馬力)

= 75 kgf·m/s

= 735.499 W

放射能	Bq	Ci
	1	2.70270 × 10 ⁻¹¹
	3.7 × 10 ¹⁰	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58 × 10 ⁻⁴	1

線量当量	Sv	rem
	1	100
	0.01	1

A STUDY ON DENSITY, POROSITY AND GRAIN SIZE OF UNIRRADIATED ROX FUELS AND SIMULATED ROX FUELS