JAERI-M
6904

DENSIFICATION OF URANIUM DIOXIDE FUEL PELLETS (I)

February 1977

M. UCHIDA, K. YANAGISAWA, M. ICHIKAWA

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-M 6904

Densification of Uranium Dioxide Fuel Pellets (I)

Masaaki UCHIDA, Kazuaki YANAGISAWA, Michio ICHIKAWA

Division of Reactor Safety, Tokai, JAERI

(Received January 7, 1977)

Eitht kinds of UO_2 pellets with varying density, grain size and pore size distributions were irradiated to burnups of 8,000 to 11,000 MWD/t-UO_2 in JMTR. Pre-irradiation density measurements were made by different methods, and post-irradiation ones only by an immersion method in meta-xylene. The results were compared with pre-irradiation ones.

Densifications in the initially 95 %TD pellet groups showed remarkable dependence upon the grain size; densification was large in pellets with small grain size. In the initially 90 %TD pellet groups, densifications were much smaller. Post-irradiation pore size distributions also supported the results.

No significant grain growth was observed dueing irradiation. On the other hand, remarkable grain growth was observed in pellets in out-pile heating, at 1700 ^{o}C for 24 hrs, as well as density increase.

JAERI－M 6904

二酸化ウラン燃料ペレットの焼きしまり(1)

日本原子力研究所東海研究所安全工学部
内田　正明・柳澤　和章・市川　達生

（１９７７年１月７日受理）

密度，粒径，ポア径分布の異なる８種のUO_2ペレットをＪＭＴＲにおいて8000～11000 MwD／t－UO_2までの燃焼度で照射した。照射前の密度測定には数種類の測定法を，照射後のそれはメタキシレン－液浸法を用い照射前後のデータ比較を行った。

初期密度９５％ＴＤのペレットの焼きしまりは粒径に著しく依存した。即ち微細粒径のペレットは著しく焼きしまった。しかし初期密度９０％ＴＤのそれでは焼きしまりは一般にかなり小であった。照射後のポア分布の解析もこの結果を裏づけた。

照射中に顕著な結晶粒の成長は見られなかった。しかし炉外加熱後のペレットでは相当な結晶粒成長と密度の増加が見られた。

Contents

1. Introduction

Since irradiation-induced densification of uranium dioxide fuel pellet was found to cause a detrimental effect on fuel rod integrity in 1972, a number of studies have been made both in order to avoid the adverse effect itself, and to investigate in depth the nature of the phenomenon. The practical goal of the study would be achieved with fabrication of fuel pellet with densification-stability. In these few years, this goal is considered to have already been achieved. It has been reported from various organizations[1]-[4] that UO_2 pellets with large grain size showed excellent stability against densification. In PWRs, an additional measure was taken; fuel ords were prepressurized with helium to prevent colapse of the cladding.

Despite these circumstances, detailed study of the phenomenon itself would not lose its meaning because densification is one of irradiation-induced deformation mechanisms of fuel pellet, hence fundamental understanding of the phenomenon would contribute to those of other mechanisms like swelling and creep. In addition, it is doubtful that fuel pellet with maximum densification-stability is the most desirable one because densification would also work to lessen the adverse effects of pellet-clad interaction and swelling. Remarkable grain size dependency of densification is agreed upon by many investigators, but quantitative agreement have not been achieved between different investigators.

Different densification mechanisms have also been proposed; Marlowe[5] explained the phenomenon in terms of the thermal sintering mechanism substituting the thermally-activated diffusion with irradiation-induced one. On the other hand, Stehle and Assmann[6] proposed a fission-product knock-out mechanism and stressed the importance of the size of fabrication porosity as well as grain size. MacEwen and Hastings[7] have made a more comprehensive calculation including diffusions of both interstitials and vacancies. No evidence is as yet available to quantify the validity of either mechanism.

The authors performed an irradiation experiment to study densification in 1973, in JMTR. The present report aims at reporting the results from fundamental parametric studies.

2. Description of the Irradiation Program

The irradiation program primarily consisted of comparison in densification behavior among eight kinds of UO_2 pellets. The specifications of the eight kinds are briefly shown in Table 1. Main parameters are the density and sintering temperature. These pellets are marked in relatively high enrichment and very small dimensions. It is for the purpose of studying the irradiation-induced phenomena excluding thermal effects; i.e. increasing power density without elevating fuel center temperature.

The specific purposes and features of the capsules used in this experiment are shown in Table 2. Two capsules: 73F94A and 11A aimed at serving for general purpose; simple comparison of density change among maximum number of pellets. In 73F8A, variation in fuel center temperature was measured and compared between two kinds of pellets Types H and G which were expected to be the most liable to, and the most stable to densification respectively. In 73F6A, axial load was applied to the fuel stack throughout the irradiation via diaphram. As no fuel center temperature measurements were made in 73F9A and 11A, the measurements in 8A also served as temperature monitor to the two capsules.

The structure of the capsules 73F9A and 11A is illustrated to Fig. 1. The six kinds of UO_2 pellets, total of 36 in number per capsule, were distributed one pellet by one in the stack so as to equalize the effect of flux variation among the six groups. As different kinds of pellets come adjacent to each other, tungsten spacers were inserted between pellets in order to avoid mixing of different kinds of pellets. Tungsten spacers were not used in 8A, in which two ordinary fuel stacks were formed using each single kind of pellets, and center temperature measurement was made.

3. Fabrication of UO_2 Pellets

UO_2 pellets used in the present experiments were all fabricated in the Nuclear Fuel Industries, Ltd., Yokosuka, Japan. As stated before, the groups of pellets were specified in terms of density and sintering temperature. Characteristics of powder and green density of pressed compacts were changed to achieve the specified density at specified temperature. In pellet types C, F and G, fine grains of naphthalene were added during cold pressing, which evaporated during sintering to leave coarse sintering pores. The objective of this treatment was to reject fine porosities to realize stable pellets.

Fig. 2 shows sintering curves of the six groups of pellets. Pellets with density of 90%TD were taken from somewhat unstable (not saturated) state compared with those with 95%TD. But it must be noted that 90%TD and 95%TD pellets were taken from the different sintering curves.

Impurity chemical analysis was made on powder of UO_2. The results are shown in Table 3. Four kinds of density measurements; 1) geometrical, 2) immersion into meta-xylene, 3) immersion into water (under evacuation), and 4) mercury pychnometry were performed on the eight kinds of sintered pellets. Numerical results of these measurements are summarized in Table 4 together with post-irradiation results. Mercury pychnometry was introduced as an alternative to the geometrical method in the post-irradiation samples with cracks. There was an excellent agreement between the two method above 10.0 g/cc.

As-sintered pellets were also examined metallographically and characterized by grain size and pore size distribution, but the results are shown in the later parts together with the post-irradiation ones.

4. Irradiation Conditions

Rough estimate of the power density, hence burnup is obtained from the readings of the two C/A thermocouples which were inserted into the aluminum cooling blocks around the fuel pins of 73F8A. This is shown in Table. The measured temperature was compared with the calculated one and the power density was proportionally obtained. Although other capsules had also thermocouples in cooling blocks, burnups in them were obtained assuming the same power density as 73F8A, because the structures of the other capsules were more complex and the power density obtained in this way is no more than a rough estimate. Burnup variation within a single capsule was obtained from the profiles of post-irradiation gamma scanning for 73F8A and 11A.

Fuel center temperature measurement was performed on the two stacks of 73F8A. Two sets of W/Re thermocouples were inserted to each stack from the opposite direction to ensure the accuracy. They produced consistant signals. The highest temperature measured during irradiation was 1170°C.

Although one of the purposes of the center temperature measurement in 73F8A was monitoring for other capsules, it is difficult to estimate the center temperature of other capsules from it. Absence of centerhole in the pellet groups A to F in 73F11A would bring about somewhat higher center temperature, but the existence of cooling effect by tungsten spacers would suffice to cancel out this effect. Therefore the measured center temperature in 73F8A would be taken to show the upper limit in all four capsules.

Another purpose of fuel center temperature measurement was to examine the effect of densification. The pellet types G and H selected for this purpose were expected to show the minimum, and the maximum densification, respectively. Fig. 3 shows the variation of fuel center temperature in the two stacks for five reactor cycles under constant cooling block temperature, hence constant power density.

In order to compare densification with thermally activated process, all kinds of pellets were heated out-pile at 1700°C for 24 hrs. Heating was performed in vacuum instead of dry hydrogen, so that some extent of oxidation and vaporization occurred at the surfaces. All these pellets, two per each group, were subjected to meta-xylene density measurement, grain size measurement and pore analysis just like irradiated ones. From the metallographs after heating, the interior of the pellets seemed not affected by surface oxidation. But the observation stated in the latter parts of the report should be viewed with some care.

5. Post-Irradiation Examinations of 73F8A and 11A, and Related Test Results

The main items of post-irradiation examinations on the two capsules comprised of; gamma scanning on fuel stack, dismantling and visual observation of pellets, density measurement. Metallographic observations were also performed on the pellets of 73F11A.

(1) Dismantling and Visual Observation

Pellet stacks of the two capsules had been clad with two halves of split stainless tubes during irradiation. Thanks to this precaution, pellets were successfully removed from the capsule in 73F11A. In 73F8A, however, adhesion of pellets to the stainless tube had occurred to some extent and some mixing of adjacent pellets occurred during removal. But in the case of 73F8A, pellet stacks were composed of a single group of pellets, therefore it did not cause no serious problem.

Fig. 4 shows outlooks of dismantled pellets, or cracked pieces of pellets of 73F11A. It was noted that in the pellet types A to C with initial density of 95 %TD, cracking was not so extensive and some pellets retained the original cylindrical geometry. The initially 90 %TD pellets generally cracked to fine pieces.

(2) Density Measurement

With the two capsules 73F8A and 11A, only immersion density measurement in meta-xylene was performed after irradiation. Before irradiation, on the other hand, density measurement by several methods were performed which comprises of: geometrical density on all the pellets (33 to 43 per group), immersion density measurement in water under evacuation (8 to 12 pellets per group), immersion density in meta-xylene (8 pellets per group) and mercury pychnometry (3 pellets per group). These pre-irradiation measurements form references not only to the two capsulles but also to 73F6A and 9A whose post-irradiation examinations will be performed later.

Meta-xylene immersion density was adopted as post-irradiation measurement because of its easiness to carry out in the cave, and all of the irradiated pellets were subjected to this measurement. Results are summarized in Table 4. Though power density, hence burnup changed pellet to pellet, no significant burnup dependency of post-irradiation density was observed in a single group. Therefore comparison of pre-, and post-irradiation density was made not only individual pellet, but groupwise. Density changes due to irradiation are shown in the second row from the

bottom in Table 4. Among the groups of 95% initial geometrical density, group A with 1400°C sintering showed markedly large density increase. Groups C and G with naphthalene addition prior to sintering showed small density increase. On the other hand, groups D and H with 1400°C sintering showed only small increases among the groups with 90%TD initial geometrical density. It must however be recalled that in these pellets major part of porosity is formed by open pores and the change of open porosity cannot be observed by immersion density measurement.

Immersion density measurements in meta-xylene were also performed on UO_2 pellets after out-pile heating at 1700°C for 24 hours (2 pellets per group) and the observed density changes are listed in the last row of Table 4. Changes were generally smaller than those due to irradiation, but the order among different groups is similar.

(3) Metallography — Grain Size Measurement

Grain size measurement was performed by intercept procedure on all groups of UO_2 pellets pre/post irradiation, and post out-pile heating. Results are shown in Table 6. It is observed that the specification of UO_2 pellets in terms of sintering temperature had realized fairly different grain sizes; pellet groups A, D and H sintered at 1400°C having extremely small grain sizes. It is noted that irradiation had caused no significant grain growth in every group of pellets. It is no doubt the result of the measures taken to lower fuel center temperature during irradiation. On the other hand, out-pile heating at 1700°C caused significant grain growth.

(4) Pore size and pore size distribution measurement.

Pore size distributions were analyzed quantitatively both pre- and post irradiation. QTM-720 type image analyser was used for this purpose. Pre-irradiation pore size distribution could be analyzed directly from the optical microscope with the magnification of 1000.

The results are shown in Figs. 5 to 7. In these figures, pore size was defined as the diameter of a circle whose area is equivalent to the cross-section of a pore on the polished plane. Types C, F and G pellets had large shperical pores which were introduced by the addition of naphthalene into the powder before cold pressing. To cover wide range of pore size due to the treatment above, two magnifications, 100 and 1000 were adopted for these three types of pellets and separate data were connected.

Total porosities, hence densities of pellets determined by this method agreed well with those determined from geometry and weight with a few exceptions. One of the exceptions, type A pellet showed smaller porosity value

than predicted from density measurement. It is considered to be caused by, first rounding of the edges of small pores during polishing and second, limited resolution of the optical microscope. Therefore type A pellets were considered to contain the maximum amount of sub-micron pores. It is also noted that pore size distributions in 90%TD pellets are generally shifted to the larger side compared with 95 %TD pellets.

On the other hand, post-irradiation pore size distribution could be analyzed only with microphotographs taken in the hot-cave. Therefore photographic measurements were performed on pre-irradiation pellets too and compared with post-irradiation ones. Results on four types of pellets are shown in Figs. 8(a) to (c). Number of pores countable on x 1000 photographs was so limited that the data contain considerable statistical error, so the results were plotted in the Figures as cumulative curves. Porosity decrease in type A and B pellet is remarkable. On the other hand total porosity in type D pellet appears as if it has increased with irradiation. (see Fig. 8(c)) Considering large uncertainties it should be concluded that porosity change due to irradiation was small in type D pellets, because increase of total porosity is unlikely.

Examples of original photographs subjected to these measurements are shown in Figs. 9.

6. Discussions

The present article sims at interim reporting of the test results from the first half of the densification capsules. Thus in this discussion, it is only tried to examine the validity of the data and topics, without making in-depth considerations on the densification mechanism.

In the various reports issued until now, both experimental and analytical, attempts were all made to correlate densification with grain size and pore size distribution. In the present experiment too, the main parameters were the above two, although the different sintering conditions may have caused changes in other unknown microstructural factors and have affected densification. Therefore, first of all, densifications observed in the present eight kinds of pellets were plotted against grain size in Fig. 10, and against sub-micron porosity in Fig. 11. In these figures, densification was expressed not as per cent density increase, but as fracticnal decrease of porosity. It is for the purpose of comparing densifications in different initial density pellets.

In Fig. 10, a remarkable dependency of densification exists on grain size with initially 95 %TD pellets. It is also in a good agreement with Chubb et al[2]'s data on initially 89 %TD pellets. That the pellets with smaller grain size densify more is also in agreement with all other experimental reports and predictions. But the pellet groups with initial densities of about 90 %TD did not show evident grain size dependency in the present experiment. They generally showed far smaller densification compared with 95 %TD groups. It seems somewhat peculiar when compared with Chubb et al's data[2], which are also on low density (89 %TD) pellets. This problem is discussed in the later part of this section.

In Fig. 11, it was tried to correlate densification with the amount of sub-micron porosity obtained from the quantitative pore analysis on the pre-irradiation pellets (direct counting; Figs. 5 to 8). In fact, the amount of sub-micron porosity cannot be directly obtained by this method because such small pores are missed either by limited resolution of optical microscope, or by polishing process. Therefore, based on the idea that the analysis reproduces correctly the pore distribution above 1 microns, the difference between porosity determined from geometrical density measurement and 'super-micron porosity' by pore analysis was defined as sub-micron porosity

$P_f = P - \sum_{d>1\mu} pi = 1 - \rho - \sum_{d>1\mu} pi$ where P_f; sub-micron porosity, P; total

porosity, pi; porosity due to size group i, ρ ; density (determined by geometrical method). In this case again, some degree of correlation was obtained with 95 %TD pellets. This method could not be carried out with 90%TD pellets because of large uncertainty in pore-analysis data with these pellets. This correlation is of cource less reliable compared with grain size dependency because of the indirect nature of the method.

Care must be paid to the fact that meta-xylene was used as the liquid to measure immersion density in the present experiment. Meta-xylene, because of its large permeability, has a tendency to neglect open porosity in the immersion density measurement. With high-density UO_2 pellets abcve 95 %TD, it does not cause a problem because in those pellets porcsity is mostly composed of closed pores[8], which is also seen in the density table (Table 4). But with the lower density pellets around 90 %TD, the circumstances are different; considerable part of porosity is formed by open pores. Therefcre in these pellets, comparison of meta-xylene immersion density between pre-, and post-irradiation gives, strictly speaking, the change of closed part of the porosity due to irradiation. Hence there is a possibility that types D, E, F and H pellets, especially types D and H pellets with small grain sizes had in fact densified more than observed. These pellets may have shown much greater porosity decrease if mercury pychnometer method was used like in Chubb et al's 89 %TD pellets[2] as stated before. By this assumption, a plausible and consistent explanation seems to become possible.

But there is a strong counter-evidence to this assumption. In Chubb et al's case, comparison of microphotographs between pre-, and post-irradiation states revealed nearly complete disappearance of pores due to irradiation in unstable pellets. On the other hand, the type D pellet in the present experiment showed quite similar pore structure both in nonirradiated, and irradiated states, see Figs. 9(c) and (d). This evidence supports the results of meta-xylene immersion density measurements, that is, densification was actually small in the 90 %TD pellets especially in types D and H.

This problem will be further examined applying mercury pychnometry to the pellets in the remaining twc capsules. But even now, it is possible to make some discussions on the observed 'stability' of types D and H pellets despite extremely small grain size. In MacEwen and Hastings' model[7], intra-, and inter-granular pores were separately dealt with, and the relative stability of the latter is predicted to some extent. In fact the most part of porosity is inter-granular in those pellets like D and H, or more properly expressing, large pores are surrounded each by a number of smaller grains.

Suppose an extreme case in which two large pores are separated by several layers of small grains. Even applying the volume diffusion model with grain boundary working as a sink of defects, it is readily understood that 'active' grains serving for pore annihilation are only those just adjacent to the two large pores, those in the interior layers not serving for densification at all. These layers would form a solid framework throughout a pellet, showing resistance to macroscopic shrinkage of the pellet. Hence it is even possible that, in an extreme case, densification is smaller and smaller the grain size. The effect of grain size on densification should be considered not independently but in relation to the size and form of pores.

In the present experiment, densification had occurred independently of grain growth; all types of pellets showed no grain growth to any observable extent, nor densifying types of pellets like A showed any different behavior as to grain size. This fact conflicts with the assumption of Marlowe type model[5], in which proportional progress of densification and grain growth is built in, by analogy to the thermal sintering model by Coble[9]. This implies that irradiation-induced densification should be treated differently from thermal sintering, not only in the origin of lattice defects, but even in the diffusion modes.

7. Conclusions

1) Eight kinds of UO_2 pellets with varying density, grain size and pore size distribution were irradiated to burnups of 8000 to 11000 MWD/t-UO_2, and density changes were measured with meta-xylene immersion method.
2) Densification in initially 95 %TD pellets showed intensive dependency on grain size; densification was greater in the pellets with smaller grain size.
3) Initially 90 %TD pellets showed much smaller densification compared with 95 %TD ones of similar grain size. 90 %TD pellets had generally coarser pore size distributions than 95 %TD pellets. With 90 %TD pellets most of the pores were larger than grains.
4) No grain growth was observed due to irradiation.

Acknowledgement

The authors gratefully acknowlege the careful PIE works performed by the staffs of JMTR Hot Laboratory and management of irradiation by Mr. T. Ishii, JMTR. Thanks are also due to Prof. T. Kirihara of Nagoya University and Mr. A. Morishima for their useful discussions and encouragements.

7. Conclusions

1) Eight kinds of UO_2 pellets with varying density, grain size and pore size distribution were irradiated to burnups of 8000 to 11000 MWD/t-UO_2, and density changes were measured with meta-xylene immersion method.
2) Densification in initially 95 %TD pellets showed intensive dependency on grain size; densification was greater in the pellets with smaller grain size.
3) Initially 90 %TD pellets showed much smaller densification compared with 95 %TD ones of similar grain size. 90 %TD pellets had generally coarser pore size distributions than 95 %TD pellets. With 90 %TD pellets most of the pores were larger than grains.
4) No grain growth was observed due to irradiation.

Acknowledgement

The authors gratefully acknowlege the careful PIE works performed by the staffs of JMTR Hot Laboratory and management of irradiation by Mr. T. Ishii, JMTR. Thanks are also due to Prof. T. Kirihara of Nagoya University and Mr. A. Morishima for their useful discussions and encouragements.

References

1) W.R. Yario et al., "In-Pile Densification Characteristics of Uranium Dioxide", Trans. ANS 18: 123 (June 1974)

2) W. Chubb, A.C. Hott, B.M. Argall, and G.R. Kilp, "The Influence of Fuel Microstructure on In-Pile Densification" Nucl. Technol. 26 (1975). 486

3) A. Hanevik, P. Arnesen and K.D. Knudsen, "In-Reactor Measurements of Fuel Stack Shortening" BNES Inter. Conf. Nucleat Fuel Performance, London, (1973)

4) H. Stehle, H. Assmann and F. Wunderlich, "Uranium Dicxide Properties for LWR Fuel Rods", Nucl. Eng. Des. 33 (1975) 230.

5) M.O. Marlowe, "In-Reactor Densification Behavior of UO_2" NEDO-12440 (1973)

6) H. Stehle and H. Assmann, "The Dependence of In-Reactor UO_2 Densification on Temperature and Microstructure", J. Nucl. Mater. 52 (1974) 303

7) S.R. MacEwen and I.J. Hastings, "A Model for In-Reactor Densification of UO_2" Phil. Mag. 31 (1975) 135

8) J. Belle, "Uranium Dioxide: Properties and Nuclear Applications" publication from USAEC (1961) 333.

9) R.L. Coble "Sintering Crystalline Solids. I. Intermediate and Final State Diffusion Models" J. Appl. Phys., 32 (1961) 787

Table 1 Specifications of UO_2 Pellets

fuel type	A	B	C	D	E	F	G	H
enrichment (w/o)	10.0							
dia. & height (mm)	5.55 ± 0.02ϕ x 6.0 ± 0.3							
geometrical density (%TD)	95 ± 1.5			90 ± 2			95 ± 1.5	90 ± 2
center hole dia. (mm)							1.8	
sintering temperature (°C)	1400	1600	1600	1400	1600	1600	1600	1400
additive to powder			naphthalene			naphthalene		

Table 2 Summary of Densification Capsules

item capsule name	73F6A	73F8A	73F9A	73F11A
specific objective	effect of axial loading	center-temp.. change due to densification	parametric survey	
instrumentations & control	bellows system	4 center T/C 2 T/C 2 SPD	4 T/C	
number of stacks	1	2	2	
number of UO_2 pellets	9 (A,B,C each 3)	40 (G and H each 20)	36 (A to F each 6)	
reactor cycles	1	5	1	4

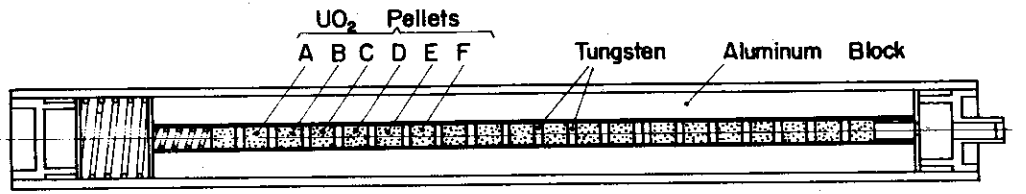


Fig. 1 Schematic drawing of the capsule 73F11A
(Only one half of the capsule is shown, two such tubes are mounted in an outer tube)

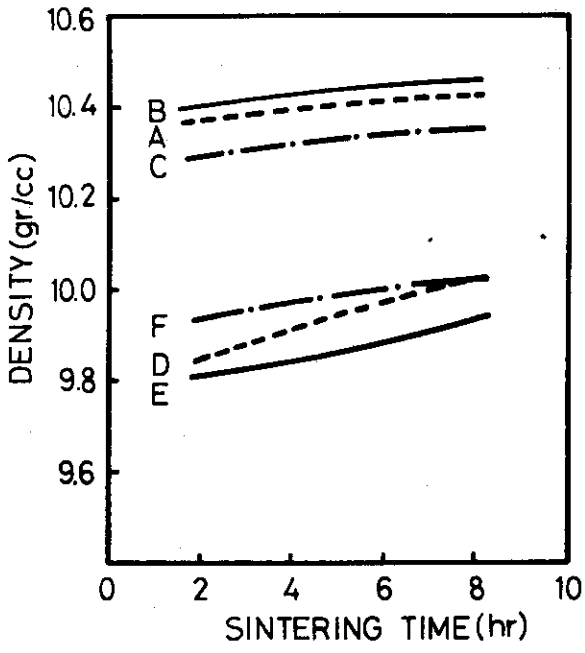


Fig. 2 Sintering curves of six groups of pellets

Table 3 Chemical Analysis on UO_2 Powders

Element	Content (ppm)	
	Powder I	Powder II
Al	5.0	7.0
Ag	0.3	0.3
B	0.1	0.1
Ca	13	27
Cd	0.1	0.1
C	24	22
Cl	11	9
Cr	0.4	0.4
N	8	15
Cu	0.4	0.8
F	1.0	1.0
Fe	7	8
Pb	0.2	0.3
Mg	9	10
Mo	0.1	0.1
Ni	2.1	2.1
Si	5.0	5.0
Sn	0.4	0.8
Total	87.1	109.0

Table 4 Summary of Density Measurement

Capsule		73F11A						73F8A	
Pellet Group		A	B	C	D	E	F	G	H
Spec.	geomet. density	95	95	95	90	90	90	95	90
	sinter temp. (°C)	1400	1600	1600	1400	1600	1600	1600	1400
	additive			naphtha.			naphtha.	naphtha.	
Pre-Irrad.	geomet. density	94.64	94.91	94.64	90.31	91.25	90.57	94.69	90.89
	density in water	95.91	96.14	96.27	97.33	96.38	94.62	96.03	94.31
	density in m-xylene	94.72 ±0.39	94.97 ±0.42	94.94 ±0.36	95.58 ±0.21	92.63 ±1.62	92.32 ±1.41	95.06 ±0.45	96.68 ±0.57
Post-Irrad.	density in m-xylene	98.25 ±0.39	96.73 ±0.85	95.72 ±0.66	96.39 ±1.35	94.40 ±0.79	93.16 ±0.59	96.01 ±0.24	96.39 ±0.20
Density Increase	by irradiation	3.53	1.76	0.78	0.81	1.77	0.84	0.95	-0.29
	by out-pile heating	2.21	0.75	-0.06	0.16	0.85	0.10	0.11	-1.35

All density values are in %TD.

Values with ± denotes confidence limits of 30.

Table 5 Estimated Burnups of Four Capsules

Capsule	Burnup (MWD/t-UO_2)	Max./Avg.
73F6A	3000	
73F8A	11000	
73F9A	3000	
73F11A	8000	1.18

Table 6 Results of Grain-Size Measurement

type		A	B	C	D	E	F	G	H
Spec.	geometrical density (%TD)	95	95	95	90	90	90	95	90
	sintering temperature (°C)	1400	1600	1600	1400	1600	1600	1600	1400
Grain size (m)	as-sintered	2.6	4.6	6.5	2.5	4.2	4.9	6.1	2.5
	post-irrad.	2.0	4.8	5.5	2.3	4.9	4.3		
	post-re-sintering	13.7	13.4	13.7	9.4	13.7	13.4		

Grain sizes here are obtained by multiplying a mean intercept diameter by 1.2

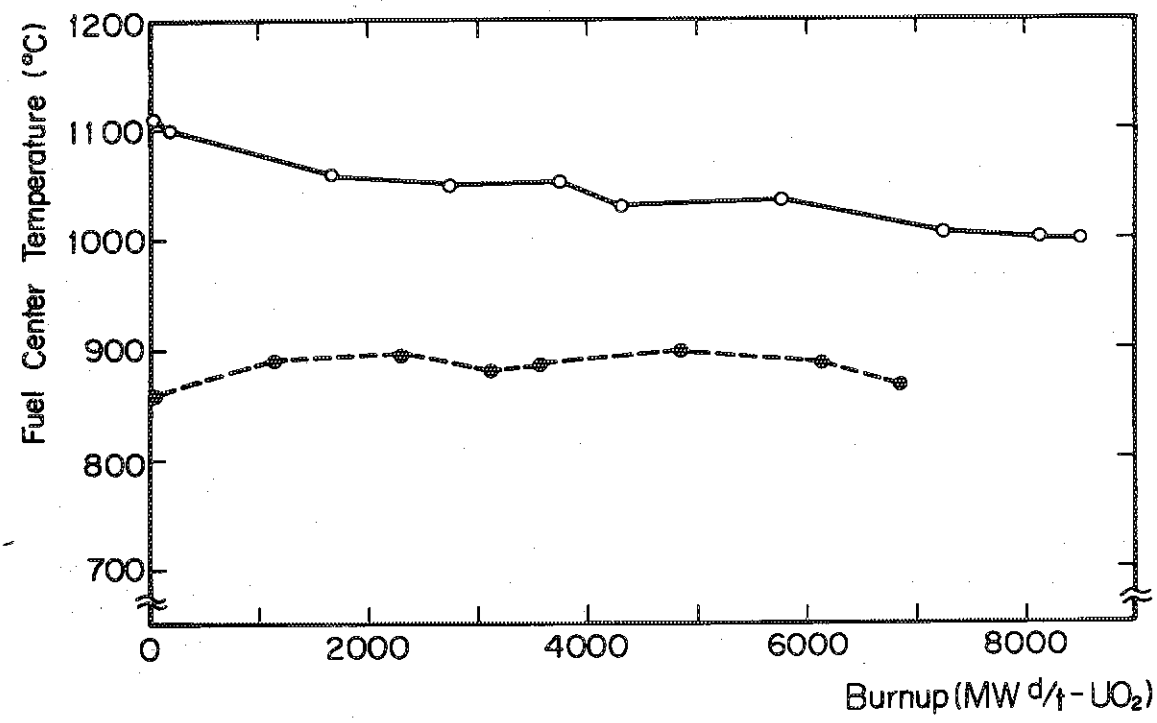


Fig. 3 Variation of fuel center temperature with burnup in 73F8A (, upper stack with type G pellet, , lower stack with type H pellet)

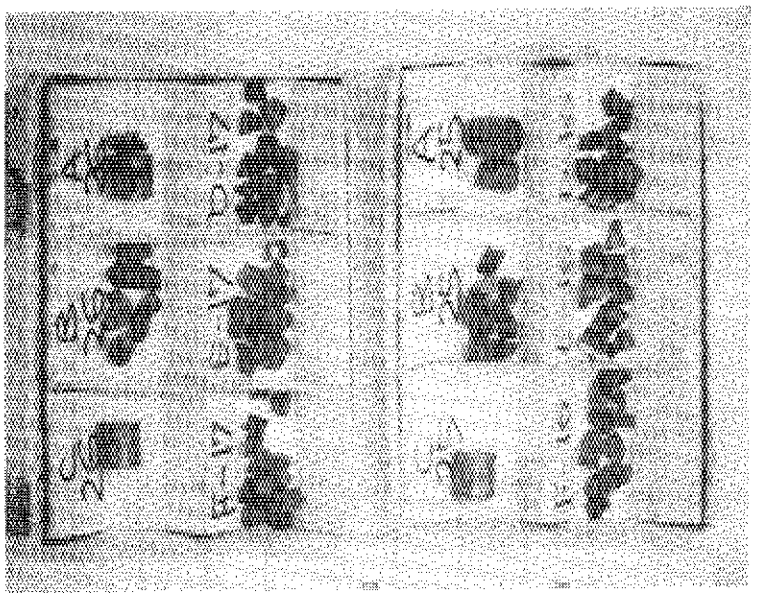


Fig. 4 UO_2 pellets dismounted from the capsule

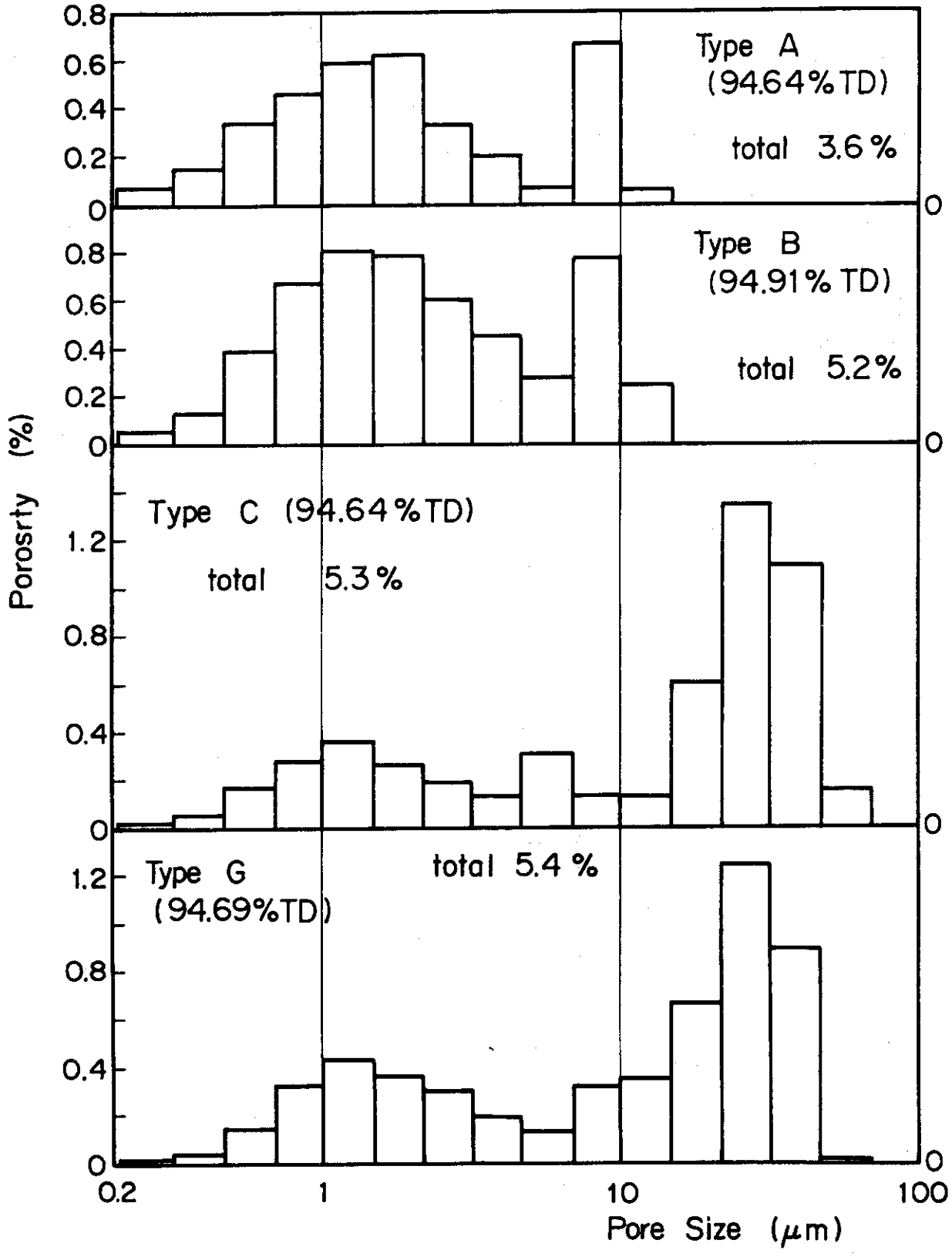


Fig. 5 Pore size distribution in 95 %TD pellets befcre irradiation (direct analyzed with QT™ micrc analyzer)

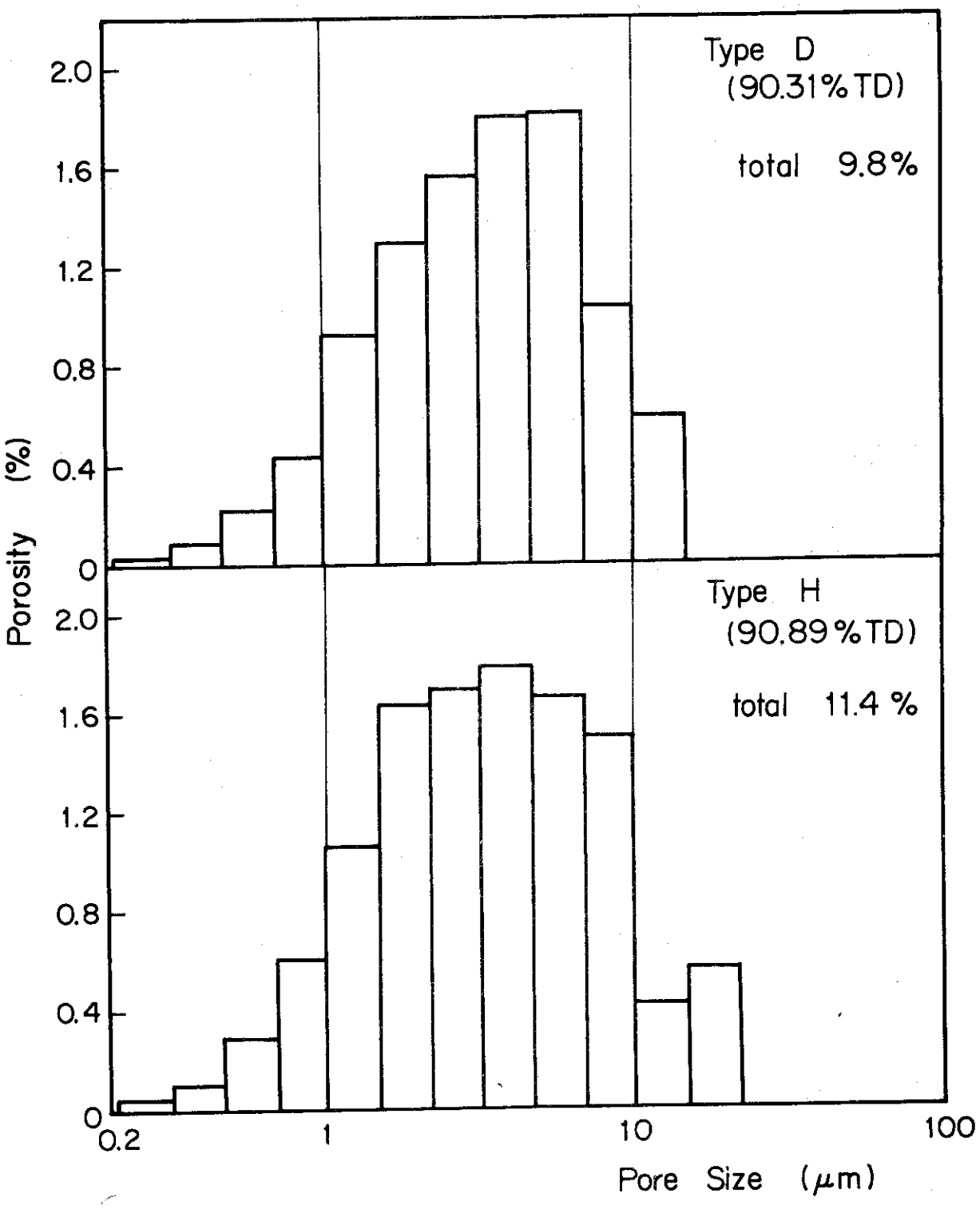


Fig. 6 Pore size distribution in 90 %TD pellets before irradiation (1) (direct analyzed with QTM micro analyzer)

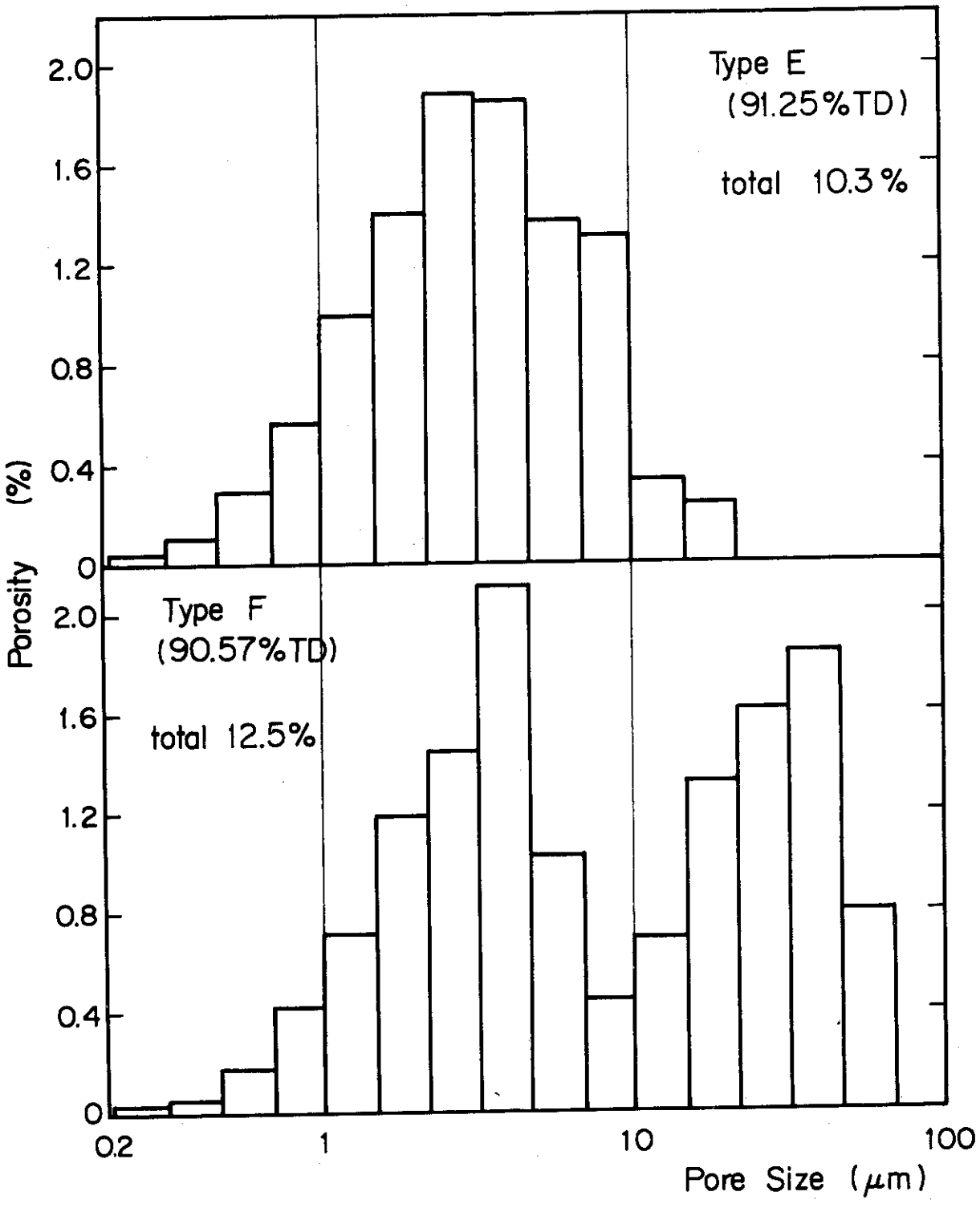


Fig. 7 Pore size distribution in 90 %TD pellets before irradiation (2) (direct analyzed with QTM micro analyzer)

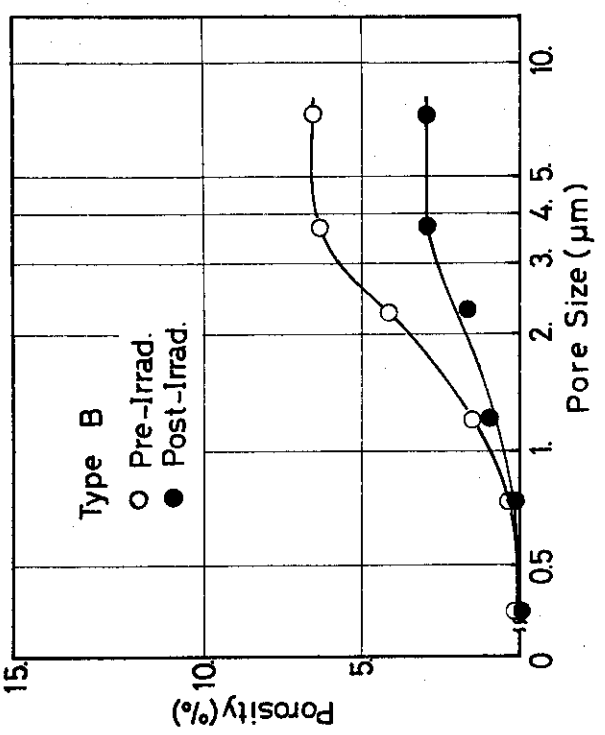


Fig. 8(b) Photographic analysis of pore size distribution in Type B pellet

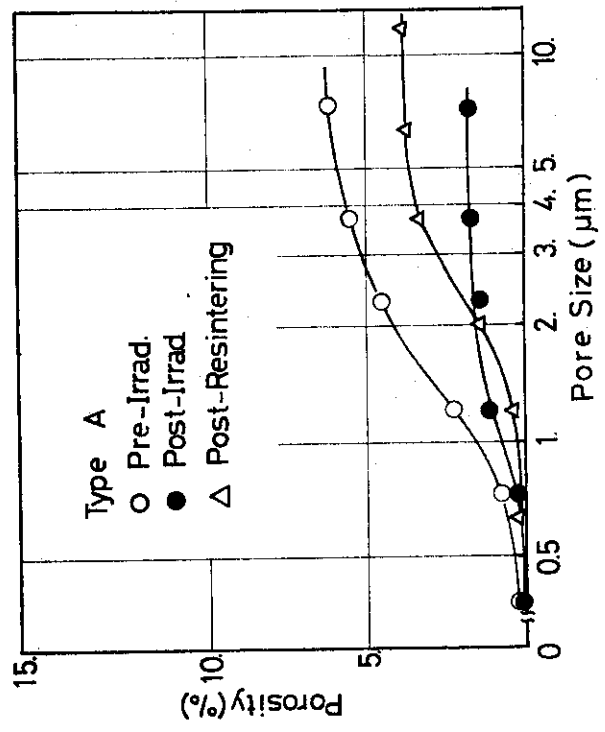


Fig. 8(a) Photographic analysis of pore size distribution in Type A pellet

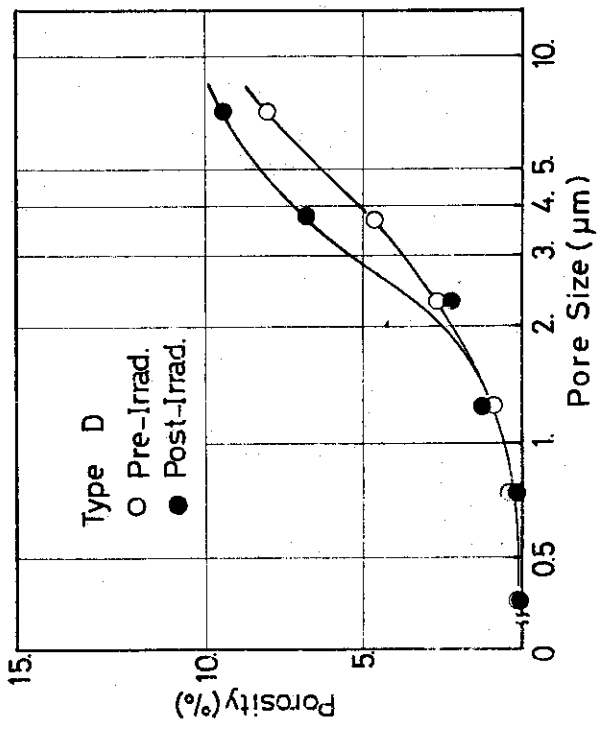
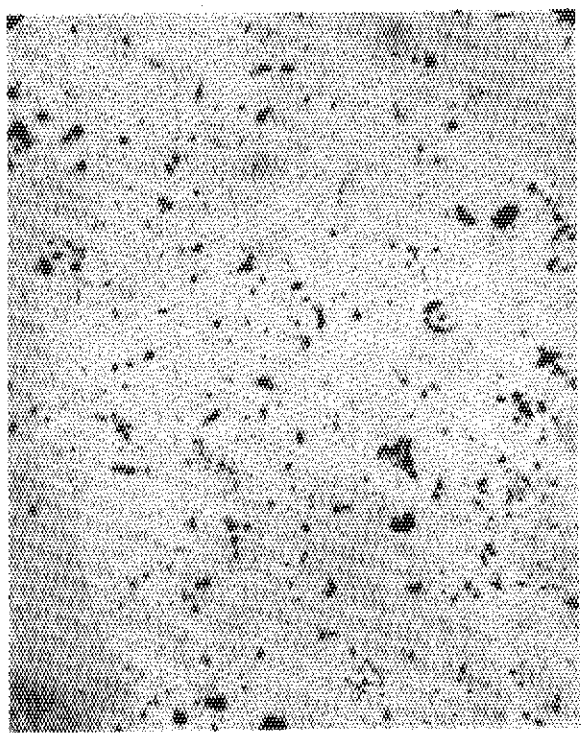
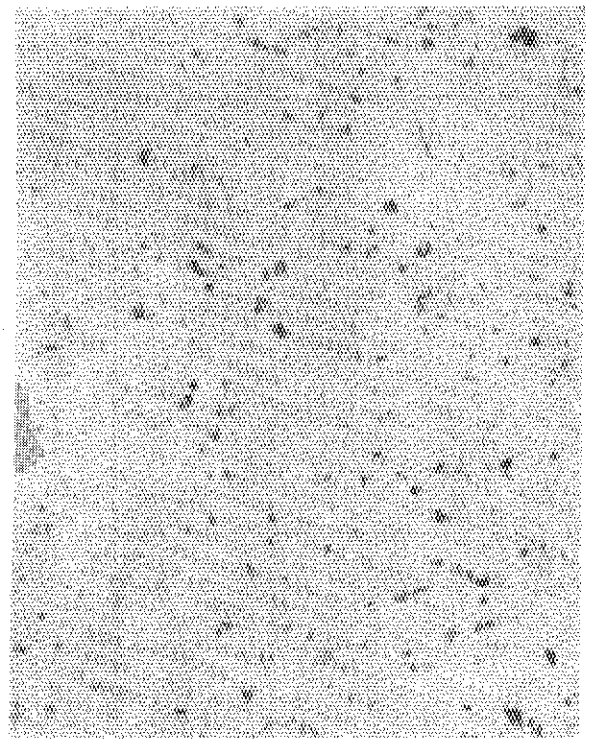


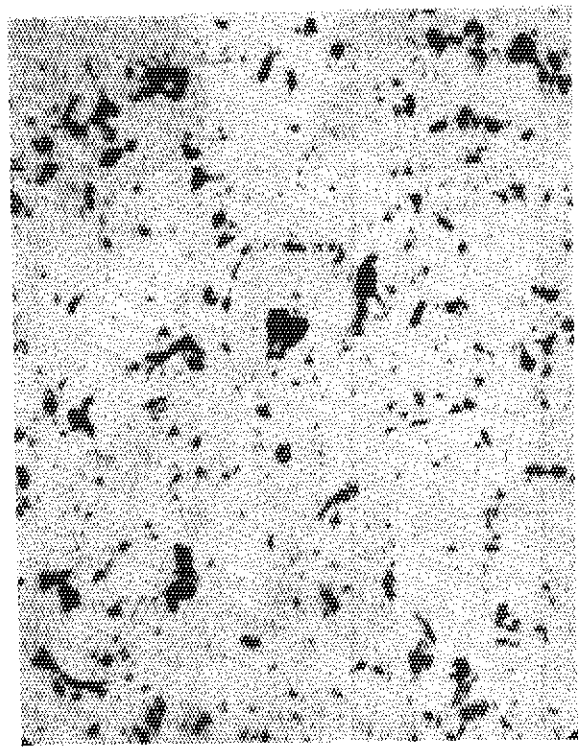
Fig. 8(c) Photographic analysis of pore size distribution in Type D pellet



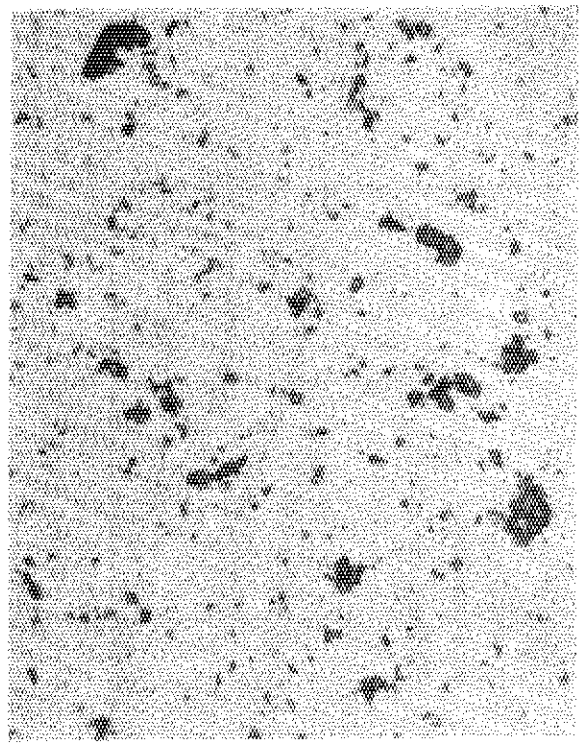
(a) Type A, Pre-Irradiation



(b) Type A, Post-Irradiation



(c) Type D, Pre-Irradiation



(d) Type D, Post-Irradiation

Fig. 9 Photomicrographs of the polished surfaces of UO_2 pellets (1000)

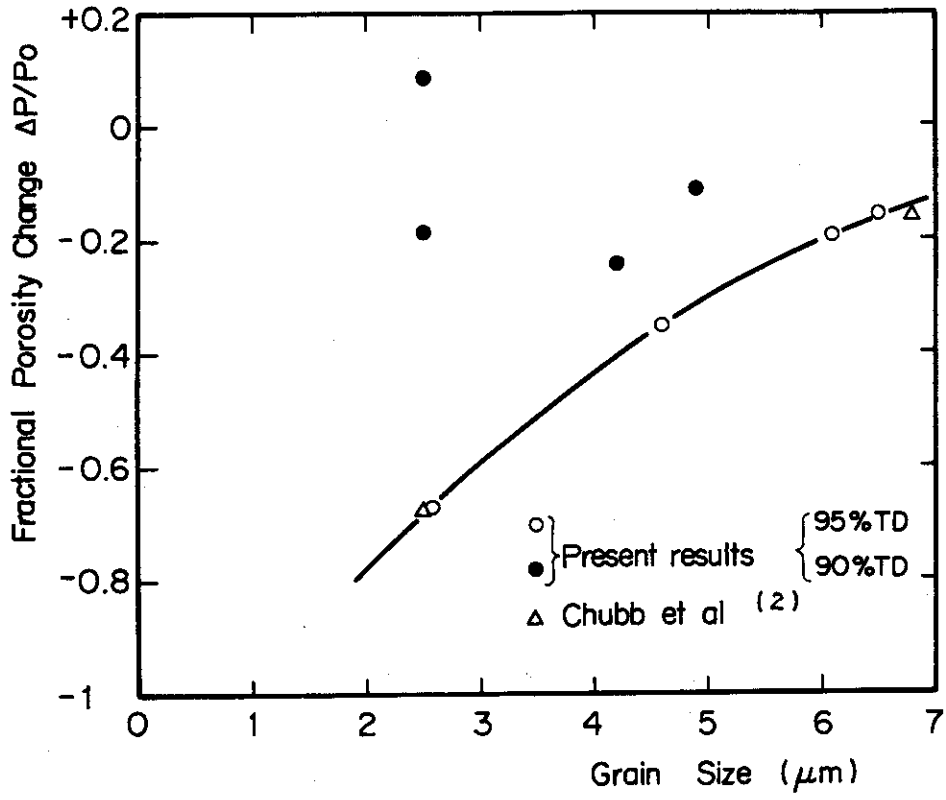


Fig. 10 Density increase (fractional porosity decrease) as a function of grain size

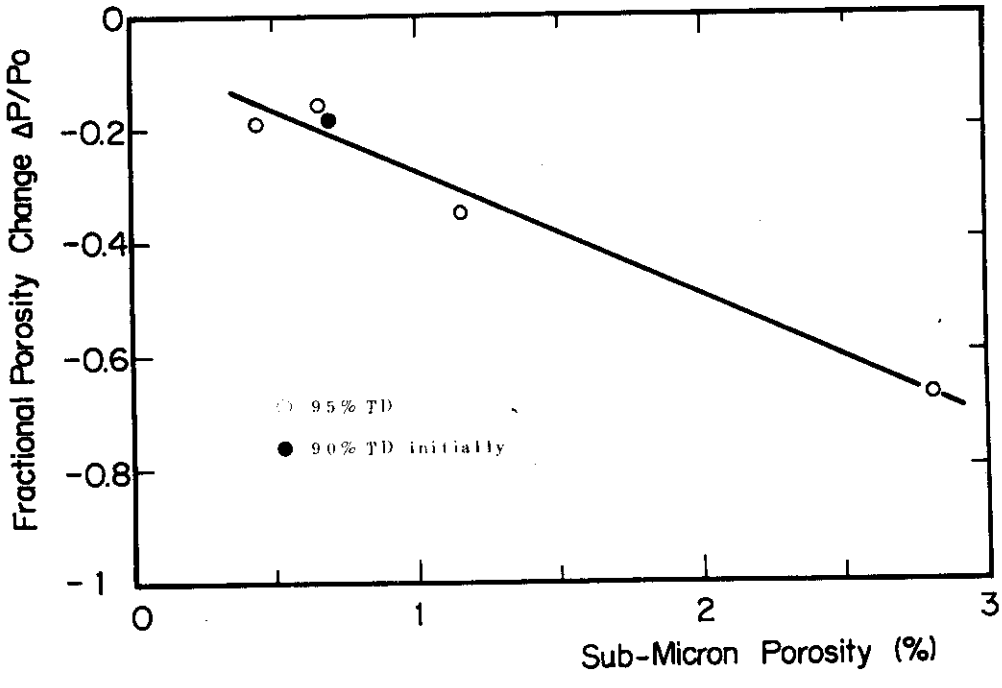


Fig. 11 Density increase (fractional porosity decrease) as a function of sub-micron porosity