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Effect of porosity on the manufacturing of U_3O_8-Al dispersion fuel plates

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The pore volume present in the starting fuel meat of dispersion fuel plates influences the behavior of its deformation during the fuel plate fabrication by rolling to a great extent. This study was carried out to investigate the influence of pore content in the starting fuel meat on the manufacturing of aluminum-base dispersion fuel plates. Factors that affect the residual porosity present in the meat of the fuel plate were investigated. Results showed that the residual pore volume of aluminum-base dispersion-type U_3O_8-Al fuel plates depends on the characteristics of the starting fuel meat, which is fabricated by pressing. The residual pore volume depends on the U_3O_8 concentration. For a particular U_3O_8 concentration, the rolling process establishes a constant pore volume, which is called equilibrium porosity. The equilibrium porosity is insensitive to the initial pore volume present in the starting fuel meat. The research showed that fuel meat integrity was greatly influenced by the initial porosity of the fuel meat. U_3O_8-Al dispersion fuel plates were successfully fabricated with uranium loading above 3.0 gU/cm^3. This uranium loading is equivalent to the one used in the U_3Si_2-Al dispersion fuel, currently operating at the IEA-R1 research reactor of the Nuclear and Energy Research Institute – IPEN/CNEN-SP. The U_3O_8-Al dispersion fuel can substitute the silicide fuel with advantages such as lower price and simpler manufacturing process.

1. Introduction

Research reactors are used primarily for the production of radioisotopes and materials testing. The fuel element is formed by assembling a series of spaced fuel plates, which allows the passage of a water flow that serves as coolant and moderator. The fuel element is usually composed of 18–20 flat and parallel fuel plates. The fuel plates consist of a fuel meat containing the fissile material, which is entirely cladded with aluminum. The fuel plates are manufactured by adopting the traditional technique of assembling fuel meat, frame and claddings with subsequent rolling (Durazzo and Riella, 2015; Kaufman, 1962; Cunningham and Boyle, 1955). Powder metallurgy techniques are used in manufacturing the meats for the fuel plates, which are composed of compacts containing U_3O_8 or U_3Si_2 powder enriched to 20% in the ^{235}U isotope (nuclear fuel material) together with aluminum powder (structural material of the fuel meat). The main manufacturing steps of this kind of fuel are the production of fuel meats by pressing and manufacturing of fuel plates by rolling. The method for manufacturing fuel plates by a hot and cold rolling sequence has been well developed and extensively used for the production of fuel elements for many research reactors around the world.

The introduction of fabrication voids into the fuel meat is important to control irradiation-induced swelling in dispersion fuels. The residual porosity accommodates gases generated in the fission. For many years, the control of the residual porosity, or fabrication voids, has been used to explain variations in irradiation performance of dispersion fuels (Weir, 1960; Lambert and Holden, 1968; Graber et al., 1967; Richt et al., 1970).

The residual porosity in the meat of U_3O_8-Al dispersion fuel plates exerts great influence on the corrosion behavior of the fuel meat in the case of cladding failure and exposure to the cooling water (Durazzo and Ramanathan, 1991). If the meat of the fuel plate is exposed to the water due to a cladding failure, the corrosion of the meat is accompanied by hydrogen evolution. The volume of hydrogen evolved increases exponentially with the residual volume

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of porosity present in the fuel meat. Also, it was found that the maximum volume of hydrogen was generated for low water temperature, after an incubation period of about 2 h (Durazzo and Ramanathan, 1991). This situation may be considered in the safety studies regarding the reactor operation once the hydrogen evolution in the case of cladding failure drags out radioactive fission gases stored in the existing porosity in the meat of the fuel plate. So, if the water temperature in the reactor pool is about 30 °C, the radioactivity in the reactor room would increase abruptly and inadvertently within a period of 2 h after exposure of the fuel meat.

For these reasons, it is important to understand the fabrication factors that affect the void concentration of aluminum-base dispersion fuel plates for research reactors. This research was carried out to determine and evaluate these fabrication factors. We studied U_3O_8-Al dispersions at crescent starting porosity contents and different uranium loadings.

Located at the Nuclear and Energy Research Institute – IPEN/CNEN-SP, São Paulo, Brazil, the IEA-R1 research reactor is a swimming pool that operates at 4 MW. Currently, the reactor uses U_3Si_2-Al dispersion fuel plates with uranium loading of 3.0 gU/cm^3. This level of uranium loading can also be achieved by using U_3O_8 as the fissile compound. The U_3O_8 powder is significantly easier to produce. The steps of UF_4 production, subsequent reduction to obtain uranium metal and U_3Si_2 melting are not necessary. To produce U_3O_8, only the precipitation of ammonium diuranate (ADU) and calcination are necessary to get U_3O_8 powder. For these reasons, this research also developed the manufacturing of U_3O_8-Al dispersion fuel plates with minimum uranium loading of 3.0 gU/cm^3, which is equivalent to the one currently being used for the silicide fuel.

2. Experimental procedures

Standard fabrication techniques that simulated the manufacture of fuel plates for the IEA-R1 research reactor were used in preparing the experimental test plates. The general procedures for manufacturing dispersion fuel plates are well established and available in the literature (Durazzo and Riella, 2015; Kucera et al., 1963; Knight et al., 1968; Beaver et al., 1964). These fabrication procedures are almost independent of the uranium compound used in the dispersion. The variations come from the process used for getting the uranium compound powder used; whether UMo alloy, U_3Si_2, or U_3O_8.

In general, the process of manufacturing uranium oxide (U_3O_8) fuel elements involves, firstly, producing ammonium diuranate (ADU) or ammonium uranyl carbonate (AUC) from UF_6 or from a uranyl nitrate solution (NU). U_3O_8 powder is produced from these materials by calcination, pressing, sintering at 1400 °C for 6 h, granulating, and sieving. The U_3O_8-Al dispersion fuel meat is produced by pressing previously weighed and mixed U_3O_8 and aluminium powders. After that, the fabrication procedures are the same as the traditionally used procedures (Durazzo and Riella, 2015; Kaufman, 1962; Cunningham and Boyle, 1955).

In this study, miniature fuel plates were used to evaluate the influence of the porosity (void volume) and U_3O_8 concentration present in the starting fuel meat on its behavior during deformation by rolling. The variables studied were the residual porosity in the meat of the miniature fuel plate after fabrication, elongation of the fuel meat, and the integrity of the meat after rolling. The uranium loading ranged from 0.2 to 4.0 gU/cm^3 (10–90 wt% U_3O_8). The porosity present in the starting fuel meat varied from 5 to 25 vol% for the U_3O_8 concentration of 58 wt%. Table 1 summarizes the main characteristics of the fuel meats used for manufacturing the miniature fuel plates fabricated for this study. Four miniature fuel plates were fabricated for each type of fuel meat studied.

Table 1
Characteristics of the fuel meats used for manufacturing miniature fuel plates.

U_3O_8 Concentration (wt%)	Uranium Loading (gU/cm^3)	Void Content (vol%)
10	0.24	15
20	0.50	15
30	0.80	15
40	1.18	15
50	1.59	15
	1.29	25
	1.64	20
58	1,99	15
	2.34	10
	2.69	5
70	2.65	15
75	2.95	15
80	3.21	15
85	3.51	15
90	3.95	15

The U_3O_8 powder used in the manufacture of fuel meats was previously sieved using a sieve of between 125 μm and 44 μm. A maximum of 20 wt% fines smaller than 44 μm was allowed. The aluminum powder was also sieved and the fraction above 44 μm was rejected. The U_3O_8 and aluminum powders were weighed and mixed in the desired proportions.

The pressing operation for fabricating the fuel meats was carried out using a manual hydraulic press with a 23 mm diameter double-effect cylindrical die. The weight of the sample and the pressing pressure were varied so as to obtain a constant thickness of 4.2 mm for the meats and 15 vol% of porosity (green density of 85% of the theoretical density of the dispersion). Fuel meats with fixed composition of 58 wt% U_3O_8 were prepared with porosity varying from 5 to 25 vol% (75–95% of theoretical density) to study the influence of the initial porosity of the starting fuel meat on the final residual porosity of the rolled fuel meat. The porosity of the pressed samples varied in the range of ±0.25 vol%. The homogeneity of the samples was verified by analyzing the radiographs of the pressed fuel meats.

Frame and cladding plates used for manufacturing the miniature fuel plates had dimensions of 120 mm × 190 mm. The thickness of the frame was 4.2 mm. The thickness of the cladding plates was 2.5 mm. Due to the high number of required samples, twelve miniature fuel plates were manufactured in a single rolling operation. Five plates with multiple meats were manufactured, containing a total of 60 miniature fuel plates. For that, the aluminum plates used as frames were drilled in 12 positions for fitting in the fuel meats. Fig. 1 schematically illustrates the frame plate showing the positions of holes.

After the fitting of the meats, the picture-frame set was

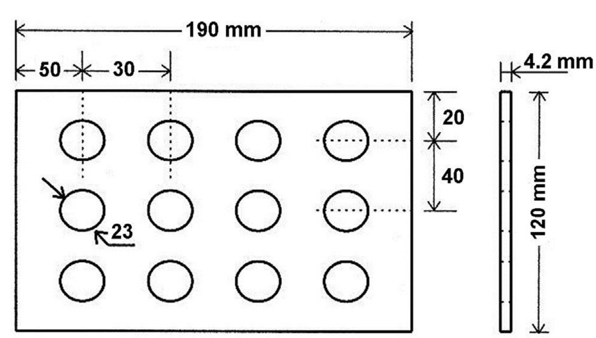

Fig. 1. Frame plate used for manufacturing miniature fuel plates.

assembled and TIG-welded. Welding was performed by means of continuous weld beads applied to the edges of the assembly. The ends of the edges were not welded to allow the escape of gases during the first hot-rolling passes. Each picture-frame set was identified in order to know the position at which the meats were inserted. Fig. 2 shows the assembling scheme of the sets.

Before the first hot-rolling pass, the sets were heated for 60 min at 440 °C. Hot-rolling was performed in nine rolling passes, according to the rolling schedule shown in Table 2. The thickness reduction was 81% in hot-rolling and 13% in cold-rolling. The total reduction in thickness was 83.5%. After hot-rolling, the plates were heated for 60 min for the blister test, which was used for testing the bonding between fuel meats, frame and claddings.

After rolling, the length, the integrity, and the uranium homogeneity of the fuel meats were assessed by means of radiography. Radiography also allowed the cutting of individual miniature fuel plates from each rolled plate. The samples were identified and the residual porosity present in the meats was determined by using the hydrostatic method with water as liquid. Metallography was used to study the microstructure of the fabricated fuel meats.

3. Results and discussion

3.1. Residual porosity and elongation of the fuel meats

As shown in Table 1, in order to evaluate the influence of the initial porosity and uranium density (U_3O_8 concentration) of the starting fuel meat on the residual porosity and elongation of the meat after rolling, fuel meats were fabricated containing increasing concentrations of U_3O_8 (uranium loadings) and starting porosity of 15 vol%. Fuel meats with U_3O_8 concentration of 58 wt% and starting porosity varying from 5 to 25 vol% were prepared to analyze the influence of the starting porosity on the rolling operation.

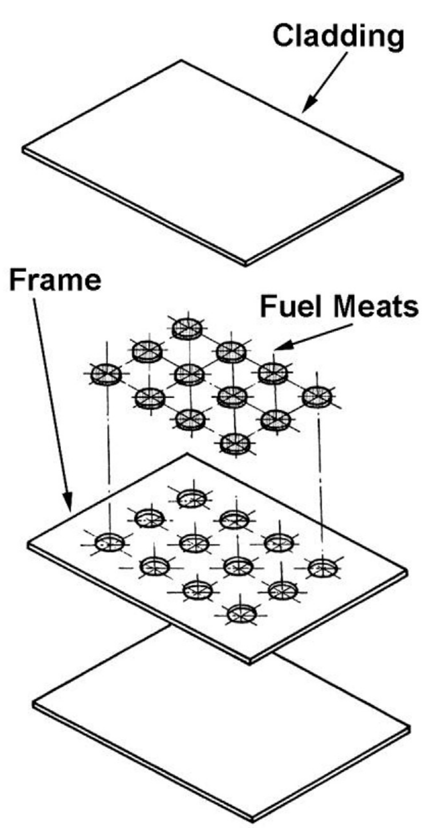

Fig. 2. Assembly diagram of the sets for rolling.

Fig. 3 shows the effect of starting porosity of the fuel meat on the residual porosity of the meat after rolling the miniature fuel plate. During the deformation, densification was observed in the fuel meats with starting porosities greater than 10.3 vol%. On the other hand, the effect was contrary for fuel meats with starting porosities below this value. This result showed that regardless of the initial porosity of the starting fuel meat, the porosity of the rolled fuel meats tend to equalize, reaching equilibrium. The value of this equilibrium porosity for U_3O_8 concentration of 58 wt%, and under the manufacturing conditions used is 10.3 vol%, as shown in Fig. 3. The deviation from this value for starting fuel meats with high porosities (20 and 25 vol%) is possibly due to the irregularities observed in these meats after rolling, as will be discussed in the next section.

These results are in agreement with the results obtained by Martin and Martin (Martin and Martin, 1970; Martin, 1969). Their work which studied the fabrication of fuel plates with U_3O_8-Al and UAl_x-Al dispersions showed that the porosity of the fuel meat reached equilibrium after the first hot-rolling pass. This equilibrium porosity remained constant at 7 vol% during all the hot-rolling process. Later, during the cold-rolling, this equilibrium porosity increased linearly with the reduction in thickness. According to these authors, the increase in porosity during cold-rolling was the result of the fragmentation of the U_3O_8 particles with subsequent alignment of the fragments ("stringering"). The research found that after fabrication, the main factor that determined the final porosity of the fuel meat for a given U_3O_8 concentration is not the starting porosity of the fuel meat, but the cold-rolling conditions and resistance to fragmentation of the U_3O_8 particles.

Fig. 4 shows the effect of uranium concentration on the residual porosity present in U_3O_8-Al fuel meat after cold-rolling for uranium loadings from 0.24 to 3.95 gU/cm^3 (10–90 wt% U_3O_8). The starting porosity, prior to rolling, was kept at 15 vol%. It can be seen from Fig. 4 that the equilibrium achieved in the porosity of the fuel meat after fabrication (cold-rolled meats) increased linearly with the uranium loading (U_3O_8 concentration). Fig. 4 also shows that for uranium loadings above 2.45 gU/cm^3, this effect became more pronounced. Note that, depending on the uranium loading of the fuel meat, there may be a decrease in porosity during rolling (below 2.87 gU/cm^3) or an increase relative to the initial porosity of the starting fuel meat (uranium loadings above this value). This suggested that voids are formed and eliminated at the same time during the deformation of the aluminum metal matrix in the fuel meat. If the formation of voids is predominant, there would be an increasing porosity during rolling. Otherwise, it would result in a decreased porosity.

According Hobson and Leitten (Hobson and Leiten, 1967), the fragmentation of U_3O_8 particles during rolling depends on the fragmentation resistance of the particle, which is related to its density and shape. The fragmentation also depends on the rolling temperature, reduction per pass and spacing between particles. Since the characteristics of the U_3O_8 powder used to manufacture all samples and the rolling process were kept constant, the fragmentation of the particles was dependent only on the spacing between them, which, in turn, depended on the uranium loading of the sample, or its U_3O_8 concentration.

These results were confirmed by a qualitative analysis of the microstructures as shown in Fig. 5 wherein a gradual increase in the residual porosity of the fuel meat with the increased uranium loading was observed. This increase was accentuated at uranium loadings above 2.65 gU/cm^3 (70 wt% U_3O_8), confirming the results shown by the curve presented in Fig. 4. In spite of the inevitable pullout of some U_3O_8 particles during the metallographic preparation, an increase was observed in the void fraction with the

Table 2
Rolling schedule used for manufacturing miniature fuel plates.

Pass	Reduction Thickness (%)	Gage (mm)	Accumulated Reduction (%)	Heating Time (min)
hot-rolling				
0	0	9.20		Preheating (60 min)
1	25	6.93	24.7	15
2	25	5.20	43.5	15
3	15	4.42	52.0	15
4	15	3.76	59.1	15
5	15	3.20	65.2	15
6	15	2.72	70.4	15
7	15	2.31	74.9	15
8	13	2.01	78.2	15
9	13	1.75	81.0	blister test (60 min)
cold-rolling				
1	7	1.63	82.3	no heating
2	7	1.52	83.5	no heating

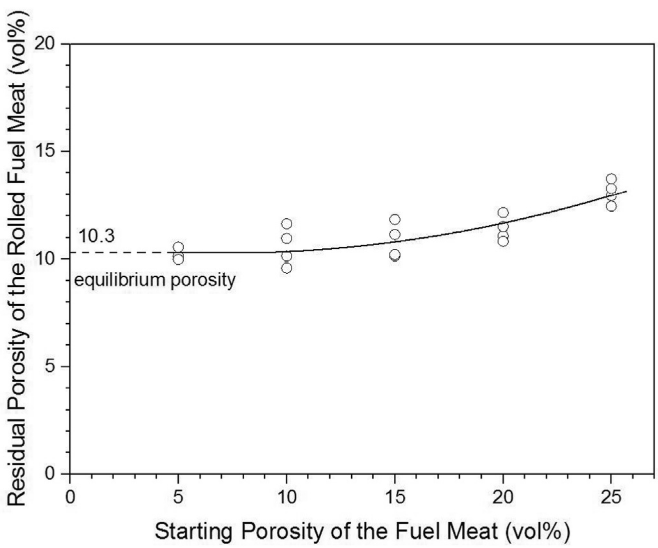

Fig. 3. Effect of the starting porosity on the residual porosity of the fuel meat after rolling.

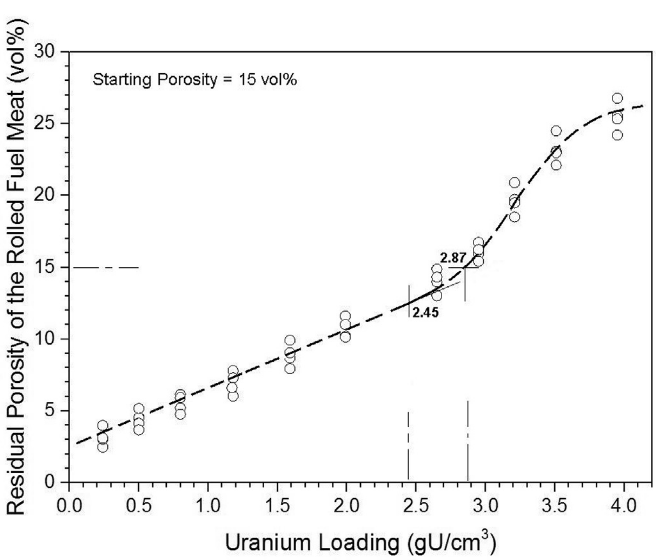

Fig. 4. Effect of the uranium loading on the residual porosity of the fuel meat after rolling.

uranium loading.

For uranium loadings up to 1.18 gU/cm^3 in the fuel meat (40 wt% U_3O_8), few voids were observed in the micrographs, indicating a low porosity. For fuel meats containing 1.59 to 2.65 gU/cm^3 (50–70 wt% U_3O_8), there was a gradual increase in the void fraction. Comparing the micrographs of samples containing 2.65 and 2.95 gU/cm^3 (70 and 75 wt% U_3O_8, respectively), one could see a sharp increase in the fraction of voids present in the fuel meat, which continued to increase with increasing uranium density to 3.95 gU/cm^3, equivalent to the U_3O_8 concentration of 90 wt%.

The presence of fragmentation of U_3O_8 particles, with the subsequent alignment of the fragments ("stringering"), can be observed by analysing the micrographs presented in Fig. 5, which were obtained by a longitudinal cutting of the samples in the rolling direction. Elongated voids in the rolling direction could be observed at high uranium loadings. These elongated voids may have been formed by the drag of U_3O_8 particles through the flow of the aluminum matrix during deformation. In view of this, it can be assumed that particles of U_3O_8 fragment and are dragged during rolling, creating voids, while the aluminum metal matrix deforms plastically, eliminating or closing the voids.

As the uranium loading increased, the formation of voids also increased (both due to fragmentation as dragging) at the same time that the volume fraction of aluminum matrix decreased. This hindered the removal of the voids formed and resulted in an increase of the final porosity of the rolled fuel meat. Above 2.65 gU/cm^3 (70 wt% U_3O_8), when the fraction of aluminium in the meat was less than 50 vol%, fragmentation increased markedly because of the high probability of collision between particles, at the same time that there is no longer more continuous aluminium metal matrix responsible for eliminating voids. This explains the behavior observed in the curves shown in Fig. 4.

According to Martin and Richt (1969), these voids formed during manufacturing are significantly related to the performance of the fuel during irradiation. Their research compared the performance of miniature UAl_3-Al and U_3O_8-Al dispersion fuel plates in irradiation tests. They attributed the better stability (less swelling) of U_3O_8-Al dispersions to its higher porosity after fabrication, which enabled an accommodation of fission gases. Also, additional irradiation testing of dispersion based fuel plates indicated that the residual porosity present in the fuel meat reduced the swelling of the fuel plate for a given burnup rate to less than half (Martin et al., 1969).

Considering the fact that the effect of higher residual porosity in fuel meats with high uranium loading is beneficial for the performance of the fuel under irradiation, the limiting factor of the increase in uranium loading should not be the residual porosity of the

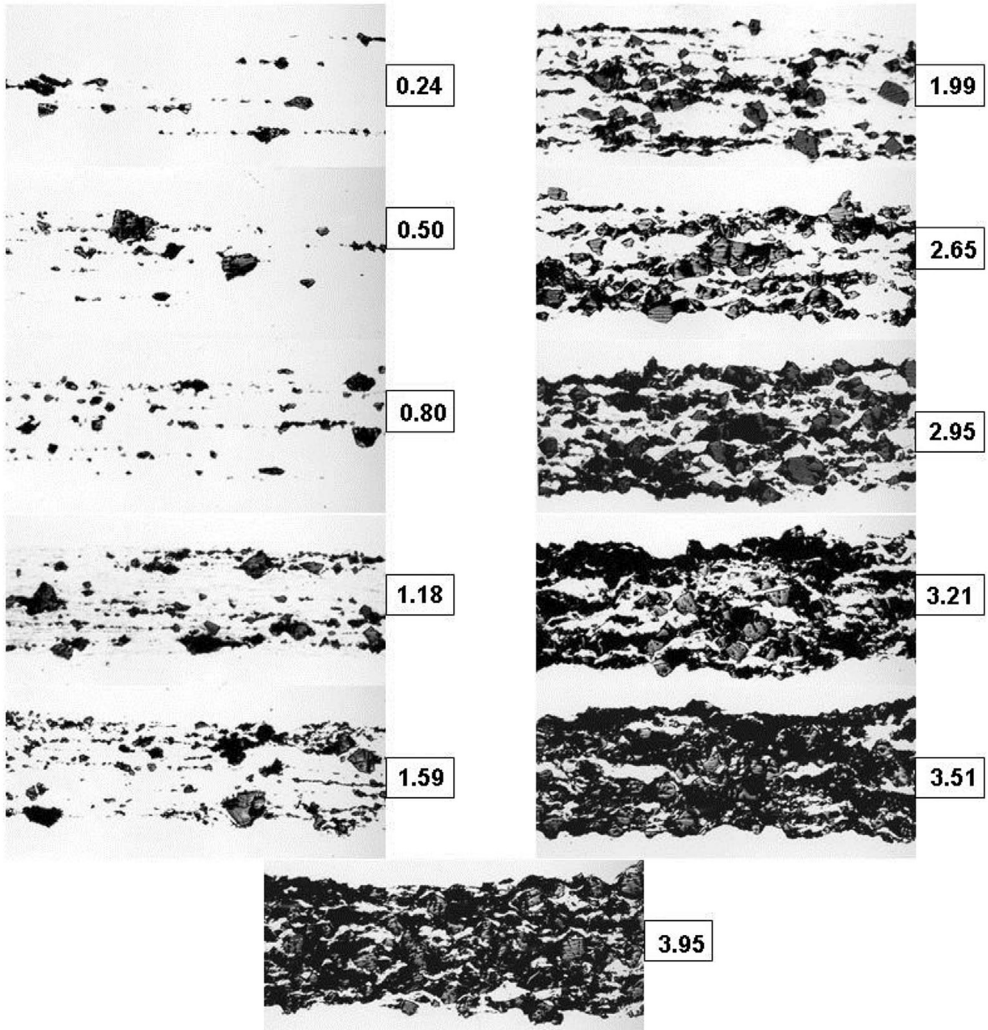

Fig. 5. Micrographs of U_3O_8-Al fuel meats with increasing uranium loadings (in gU/cm^3).

fuel meat but its mechanical integrity, as will be discussed in the next section.

The knowledge of the fuel meat elongation is important for proper design of the dimensions of the assembly components for rolling, since the final length of the meat of the finished fuel plate is a specification that must be met. Based on this, the relationship between the length of the meat of the finished fuel plate and the starting porosity of the fuel meat was determined. The length of the cores of the miniatures fuel plates was determined by X-ray, using a metric scale with accuracy of 0.5 mm. The results are shown in Fig. 6. The elongation was calculated as the ratio between the length of finished fuel meat (L) (after rolling) and the length of the starting fuel meat (Lo) (before rolling).

Fig. 6 shows that when the starting fuel meats have high initial porosity (above 15 vol%), the elongation was not very sensitive to porosity. On the contrary, when the porosity present in the starting fuel meat was small (equal to or less than 10 vol%), the elongation considerably increased with the decrease of the porosity of the starting fuel meat. These results were consistent with the porosities of the fuel meats measured after rolling, as shown in Fig. 3. The starting fuel meats with high porosity, above the equilibrium porosity, exhibited lower elongation during rolling, since there was a reduction of the initial porosity present in the starting fuel meat,

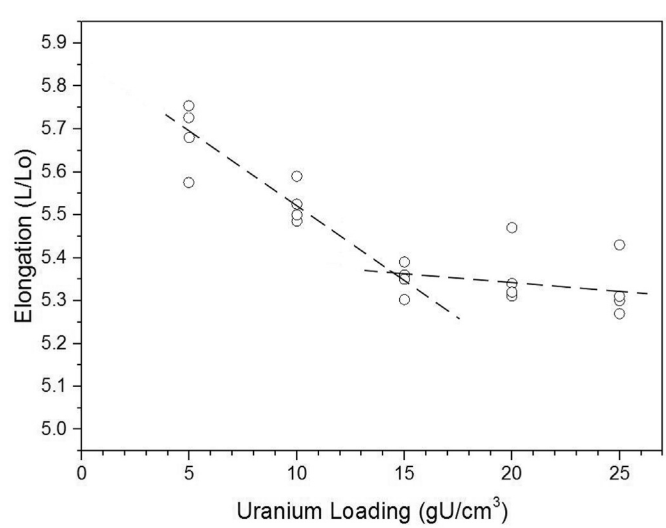

Fig. 6. Effect of the initial porosity of the starting fuel meat on the elongation after rolling.

or a decrease in its volume. On the contrary, when the porosity of the starting fuel meat was small, below the equilibrium porosity, porosity was formed during rolling, which increased the core volume and resulted in an elongation which was greater the smaller is the initial porosity of the starting fuel meat.

The relationship between the elongation of the fuel meat during rolling and uranium loading can be observed in Fig. 7. The results were consistent with the porosities of the fuel meats measured after rolling, as shown in Fig. 4. The elongation during rolling increased with uranium loading (or U_3O_8 concentration), very similar to the increase observed in the equilibrium porosity after rolling. This behavior was expected since the increased porosity led to an increase in the volume of fuel meat, which was reflected in the increase of their length, since its thickness was predetermined. This increase was almost linear, up to a uranium loading of about 2.45 gU/cm^3, when a sharp increase occured as in the case of the equilibrium porosity (Fig. 4).

3.2. Integrity and uranium distribution of the fuel meats

The presence of structural defects in rolled fuel meats, such as inclusions with high uranium concentration and irregular distribution of fuel, were verified by radiography. The radiographies also allowed the cutting of various individual samples.

Fig. 8 presents the radiographs of the rolled fuel meats containing 58 wt% U_3O_8 manufactured from starting meats with porosities ranging from 5 to 25 vol%. Fig. 9 presents the radiographs of the rolled fuel meats containing from 10 to 90 wt% of U_3O_8 (uranium loading varying from 0.24 to 3,95 gU/cm^3) manufactured from starting meats with fixed porosity of 15 vol%.

In fuel meats manufactured from starting meats with low densities (porosities of 25 and 20 vol%), light spots aligning perpendicularly to the rolling direction can be observed on radiographs of Fig. 8. Such spots could also be observed, but to a lesser degree, on the radiographs of rolled fuel meats manufactured from starting meats with high U_3O_8 concentration (over 75 wt%) shown in Fig. 9.

Through metallographic observation of the longitudinal section of the samples, it was found that the spots observed on the radiographs were due to pronounced changes in the thickness of the fuel meat, in the form of constrictions. This thickness was much reduced and in some areas, there were extreme situations where the

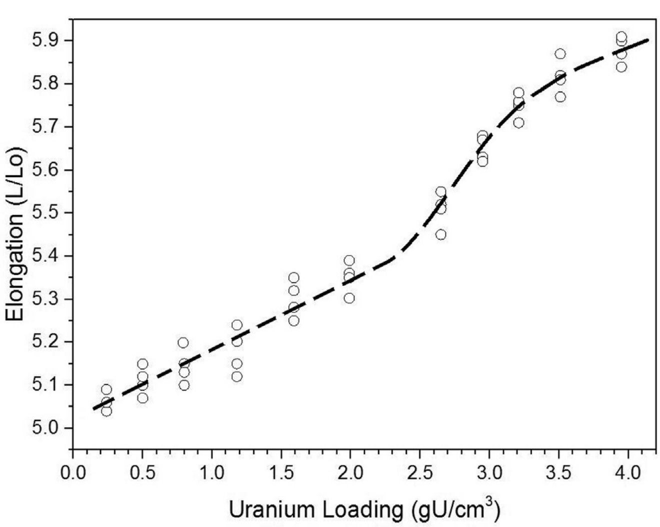

Fig. 7. Effect of the uranium loading on the elongation of the fuel meat after rolling.

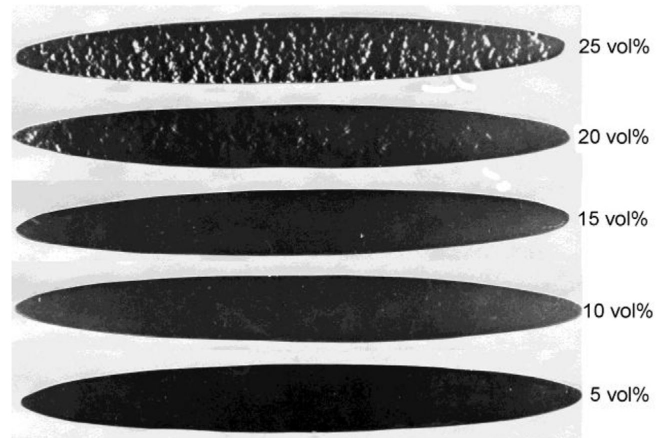

Fig. 8. Printing from radiographs of miniature fuel plates manufactured from meats with 58 wt% U_3O_8 and different levels of porosity.

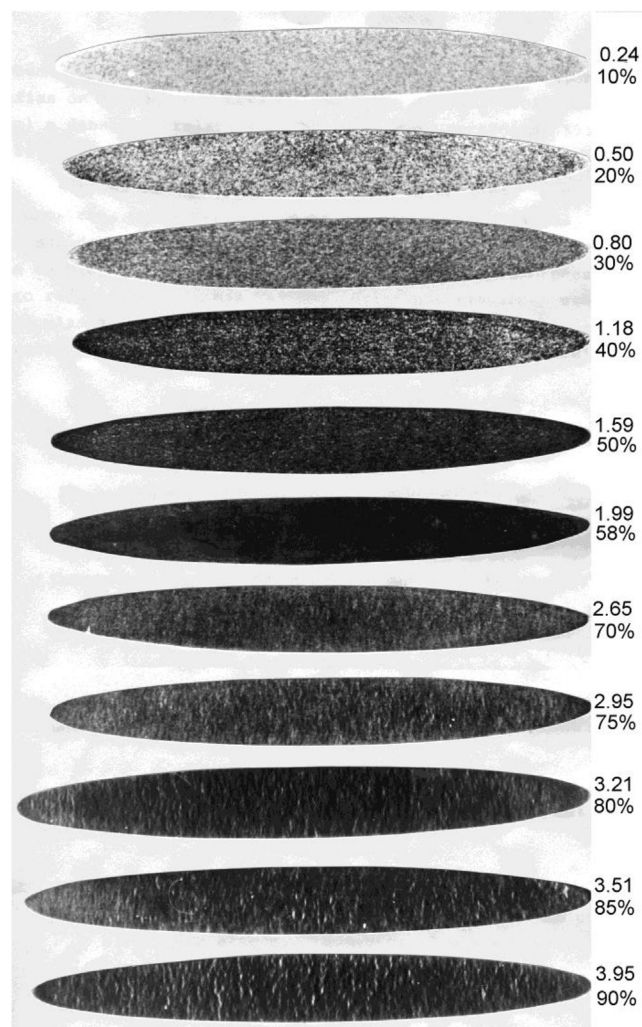

Fig. 9. Printing from radiographs of miniature fuel plates manufactured from meats with different uranium loadings and 15 vol% of porosity.

claddings virtually touch or where there was a void between them. Figs. 10 and 11 illustrate this effect.

Samples containing meats with 58 wt% U_3O_8 and porosity in the

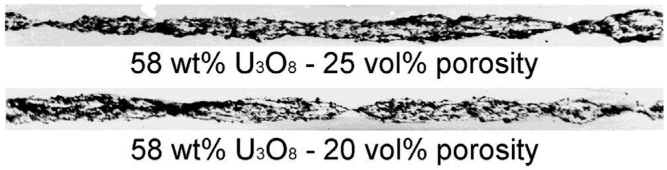

Fig. 10. –Macrographs of the longitudinal section of miniature fuel plates illustrating defects that are seen on the radiographs presented in Fig. 9.

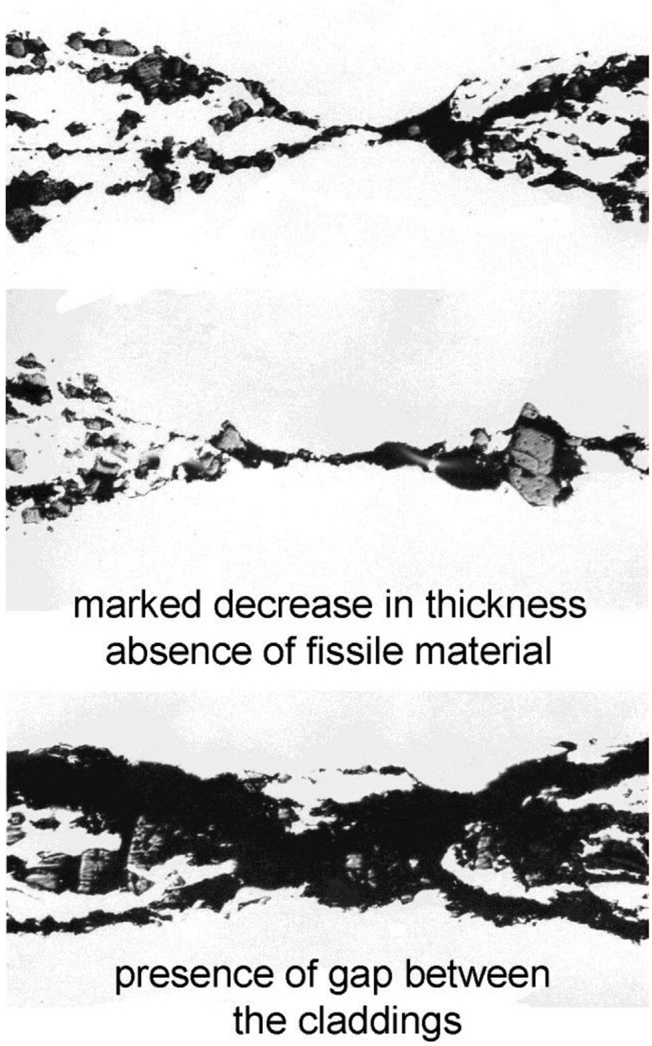

Fig. 11. Micrographs detailing the causes of stains observed on the radiographs of Fig. 8 and 9.

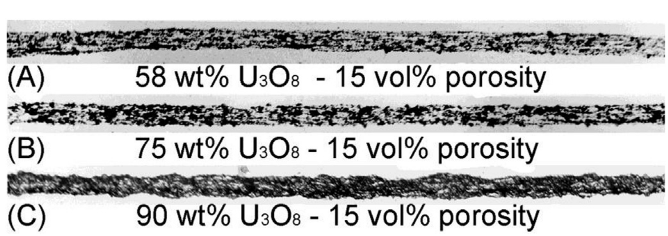

Fig. 12. –Macrographs of the longitudinal section of miniature fuel plates.

starting fuel meat below 20 vol% did not show this type of irregularity, and their thickness was uniform, as can be seen in Fig. 12(A). Samples containing meats with U_3O_8 concentrations above 75 wt% also showed these irregularities. Fig. 12 (B) shows the longitudinal section of a sample with the meat containing 75 wt% U_3O_8 where the uniformity of the thickness of the fuel meat can be observed. On the other hand, Fig. 12 (C) shows the meat of the sample containing 90 wt% U_3O_8, where pronounced variations can be observed in the thickness of the fuel meat, resulting in bright spots on the radiographs.

Such defects, in the form of fuel meat constriction, suggest the appearance of cracks perpendicular to the rolling direction in the first rolling passes, which are filled with aluminum from the claddings on the subsequent rolling passes. This behavior can be explained by the compression stress field to which the deformation zone during rolling is submitted. Depending of the reduction in thickness, this field has a certain depth which, under certain conditions, may cover the whole thickness of the fuel meat, resulting in a homogeneous deformation. On the other hand, if the applied reductions are small, the stress field would change and a tensile stress zone would be formed in the central region of the fuel plate (meat region). This tensile stress zone would be responsible for the cracking of the fuel meat and the appearance of these constrictions. Therefore, this type of defect can be controlled with an appropriate rolling passes scheme.

The uniformity in thickness of the U_3O_8-Al fuel meat should be considered for two reasons. First, the reduction in thickness of the cladding in areas where an increase in the meat thickness occurs must be considered. Secondly, the non-uniformity in the distribution of uranium caused by changes in the core thickness should be considered. The presence of localized regions where there is an excessive concentration of fuel (large thickness of the meat) can result in excessively high temperatures in these regions during irradiation. Qualitatively, the radiographs did not indicate occurrence of U_3O_8 segregation due to homogenization problems, even at high U_3O_8 concentrations (90 wt%), which could also result in heterogeneous distribution of uranium.

The micrographs shown in Fig. 5 indicated that the threshold for obtaining cores with a continuous matrix of aluminum was 75 wt% of U_3O_8, or uranium density of 2.95 gU/cm^3. The appearance of the microstructure of these samples was very similar to the fuel meats obtained by Copeland and Martin (1980) also containing 75 wt% of U_3O_8. These authors imposed this concentration as a limit for the production of fuel plates for irradiation testing. The continuity of the aluminum matrix, the uniformity of thickness and homogeneous distribution of voids in the fuel meat are important to the performance of the fuel. In regions where the void concentration is too high, the aluminum matrix is discontinued and the cladding thickness, small; the tensile strength in the thickness direction is compromised. These areas can accumulate fission gases during irradiation enabling the appearance of a bubble ("blister") due to increased pressure.

3.3. Fabrication of full-sized U_3O_8-Al dispersion fuel plates

The experience acquired from the previously presented studies on miniplate fabrication was applied in the manufacture of full-sized U_3O_8-Al dispersion fuel plates. The uranium loading goal was 3.2 gU/cm^3, which was higher than the loading currently used in the standard silicide fuel operating at the IEA-R1 research reactor. This uranium loading was equivalent to 45 vol% of U_3O_8, 50 vol% aluminum and 5 vol% porosity in the starting fuel meat. This loading was considered the technological limit for the U_3O_8-Al dispersion fuel, once the amount of aluminum used is the minimum that ensures the continuity of the metal matrix in the meat of

Table 3
Specifications adopted for qualifying the full-sized U_3O_8-Al fuel plates.

Length of fuel meat	590–610 mm	
Width of fuel meat	60.35–64.85 mm	
	Zone 1 (central)	Zone 2 (defect zone)
Thickness of fuel meat	0.71–0.81 mm	1.07 mm (maximum)
Thickness of claddings	0.30 mm (minimum)	0.25 mm (minimum)

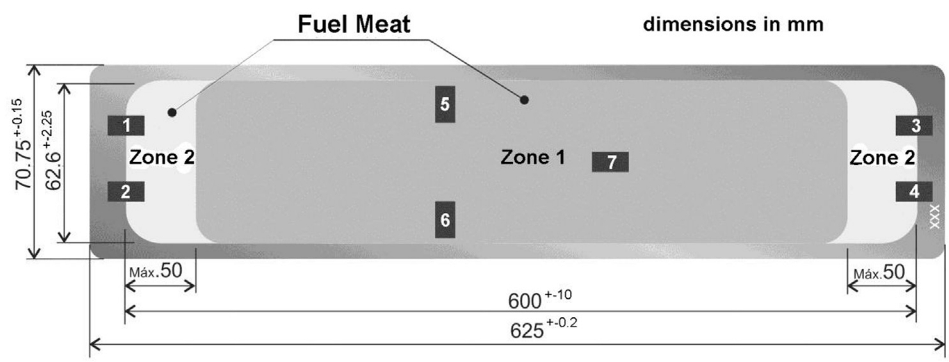

Fig. 13. –Specifications and sampling scheme for thickness measurements of fuel meats.

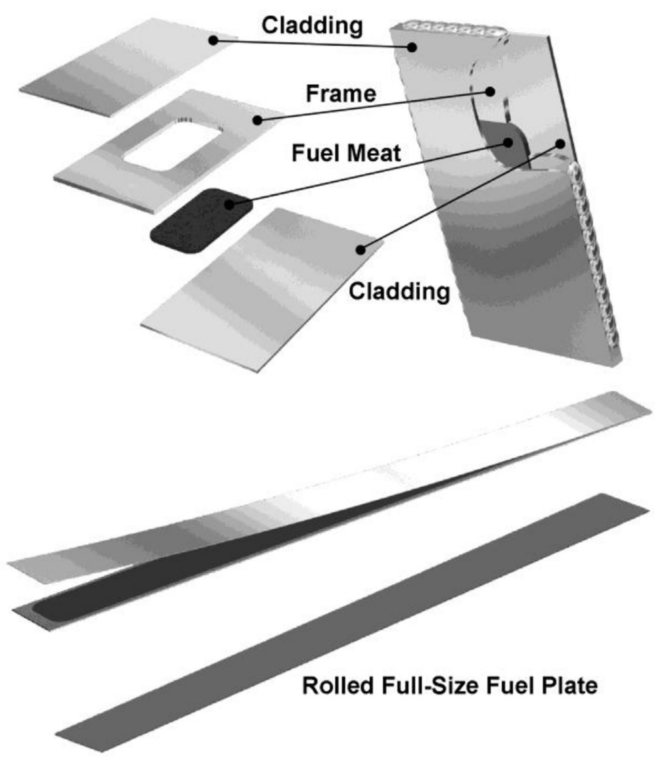

Fig. 14. Steps for manufacturing full-sized U_3O_8-Al dispersion fuel plates.

the finished fuel plate. The specifications used in the manufacture of the full-sized fuel plates were those valid for manufacturing the fuel plates for IEA-R1 reactor, which are summarized in Table 3 and Fig. 13. Fig. 13 shows the sampling scheme for measuring the meat thickness by using metallographic techniques. Four full-size fuel plates were fabricated. Seven samples were extracted from one of the fabricated full-size fuel plate for measurement of meat and cladding thicknesses.

According to the results presented in Fig. 7, the expected elongation for uranium loading of 3.2 gU/cm^3 was 5.77 (L/Lo). Then, the length of the starting fuel meat was calculated to be 104 mm for the thickness of 4.2 mm. The width of the starting fuel meat was defined as 59 mm, assuming that the fuel meat widened around 5% after rolling, as shown in the experimental observation on mini-plates. The initial porosity of the starting fuel meat was around 6.5 vol%. The initial porosity was kept as low as possible in order to ensure the best possible homogeneity (meat thickness and uranium distribution) in the rolled fuel meat.

The starting fuel meats were pressed under 5.5 Tf/cm^2 with nominal dimensions of 104 × 59 × 4.2 mm. These meats were assembled with frames and claddings according to the picture-frame technique (Durazzo and Riella, 2015; Kaufman, 1962; Cunningham and Boyle, 1955). The thickness of the frame plate was 4.2 mm. The thickness of the cladding plates was 2.5 mm. The assemblies were rolled according to the rolling schedule presented in Table 2. Fig. 14 illustrates the steps of the manufacturing process.

Table 4 presents the main characteristics of the pressed fuel meats. Table 5 presents the characteristics of the meats of the finished fuel plates. The desired uranium load was achieved. The dimensional specifications for the fuel plate and the meat were fulfilled.

The meat thickness was measured in the central zone of the meat (3 samples) and in the end regions (4 samples). The samples were embedded, ground and polished. The measurements were made with a bright field metallurgical optical microscope. Table 6 presents the results from cladding and meat thicknesses measurements.

The fuel meat integrity and the homogeneity of uranium distribution were evaluated by means of radiography. No defects were detected. The uranium distribution in the meats was very homogeneous, as illustrated in Fig. 15. The thickness of the meat was uniform. No defects in the form of fuel meat constriction were observed, as illustrated in Fig. 16.

4. Conclusions

The results of this study showed that the residual porosity of the meat of the fuel plate after rolling was independent of the initial

Table 4
Main characteristics of the starting meats used to produce full-size fuel plates.

Meat	Mass (g)	Width (mm)	Length (mm)	Thickness (mm)		Volume (cm^3)	Porosity (vol%)	Uranium Loading (gU/cm^3)
				Min	Max			
1	129.26	59.11	104.24	4.10	4.15	25.45	6.83	3.24
2	129.27	59.12	104.25	4.15	4.22	25.82	6.47	3.20
3	129.31	59.20	104.38	4.12	4.27	25.95	6.47	3.19
4	129.26	59.13	104.24	4.10	4.22	25.70	6.47	3.21

Table 5
Main characteristics of the meats of full-size fuel plates.

Fuel Plate	Plate Thickness (mm)	Fuel Meat Length (mm)	Fuel Meat Width (mm)	Meat Volume (cm^3)	Meat Porosity (vol%)	Uranium Loading (gU/cm^3)
1	1.53	595.0	61.47	27.10	14.39	3.05
2	1.51	601.5	61.54	27.35	14.93	3.02
3	1.50	607.5	61.70	27.31	14.75	3.02
4	1.50	606.0	61.75	27.25	14.75	3.04

Table 6
Meat and cladding thicknesses of full-size U_3O_8-Al dispersion fuel plates.

	Zone 1		Zone 2	
	Meat (mm)	Cladding (mm)	Meat (mm)	Cladding (mm)
Fuel Plate 3	0.78–0.81	0.32–0.38	0.80–0.98	0.26–0.35

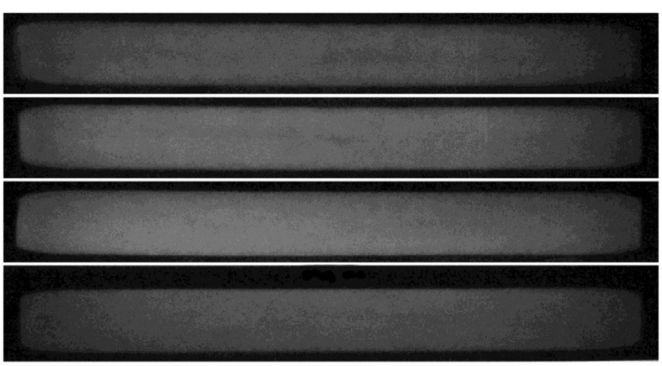

Fig. 15. Radiographies illustrating the meats of the four full-size plates fabricated.

Fig. 16. Micrograph illustrating homogeneous thickness of the meat and the end defect.

porosity of the starting fuel meat, reaching an equilibrium value which depended on the uranium loading (U_3O_8 concentration). If the porosity of the starting fuel meat was too large (above 15 vol%), the meat would undergo cracking to achieve the equilibrium porosity. In the course of rolling, the cladding fills the cracks formed and causes non-uniformity in the thickness of the fuel meat, in the form of constrictions. These results confirmed the results obtained by other researchers (Martin and Martin, 1970; Martin, 1969).

Qualitatively, the results indicated that by using starting fuel meats with maximum porosity of 15 vol%, fuel plates with U_3O_8 concentration up to 75 wt% (equivalent to uranium loading of 3.0 gU/cm^3) can be manufactured with a thickness of acceptable uniformity. Furthermore, the results indicated that fuel plates with uniform thickness in the meats can be manufactured even for U_3O_8 concentrations above 75 wt% by decreasing the porosity of the starting fuel meat to below 10 vol%. The decrease of the porosity of the starting fuel meat and the use of an appropriate rolling pass design enabled the use of high uranium loadings, indicating an experimental limit between 3.0 and 3.2 gU/cm^3.

The findings were confirmed experimentally by manufacturing full-sized U_3O_8-Al dispersion fuel plates. Four full-size fuel plates were successfully fabricated with uranium load higher than 3.0 gU/cm^3. All the dimensional specifications for the fuel meat were met. The thicknesses of the fuel meat was uniform and comfortably met the specification. High degree of uranium distribution homogeneity was achieved for the fuel meats. The silicide fuel with 3.0 gU/cm^3 currently produced for the IEA-R1 research reactor can be replaced by the U_3O_8-Al dispersion fuel developed in this work, keeping the uranium loading.

The findings relating to the effect of porosity on the manufacturing process should also be valid for the U_3Si_2-Al dispersion fuel, considering the volume fraction of the fissile compound.

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