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F. Ambrozio Filho and A. Bose

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DEVELOPMENT AND FABRICATION OF FUEL ELEMENTS FOR THE IEA-R-1 REACTOR

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ABSTRACT

Among the engineering activities of the Nuclear Metallurgy, Center of the Instituto de Energia Atômica special importance is given to the fabrication of fuel plates for use in research reactors.

The fabrication procedures developed and adopted for manufacturing fuel elements of the type to be used in the IEA-R-1 reactor are presented in detail.

The general fabrication scheme involves incorporation of an UAl alloy (18 wt % U) core into an aluminium frame, and cladding in with aluminium by a roll bonding technique.

The described procedures were demonstrated by the successful manufacture of 18 fuel elements within the established specifications.

1 - INTRODUCTION

The components containing the nuclear fuel, constituting the fuel elements, are critical parts for the successful performance of nuclear reactors. In all cases they are subjected to rigorous conditions of heat removal, thermal stresses and radiation damage. At the same time they must experience only a very small number of failures.

The need for efficient heat removal from a reactor is one of the principal factors that determines the shape of the fuel element. A high fuel specific power must be achieved, with temperatures compatible with the cooling water. This requires that the fuel element be relatively thin to reduce its interior temperature. It must also have a large surface to volume ratio, since a high heat transfer rate to the coolant is desirable. It is usually thought that high rates of heat transfer make it necessary to have a metallurgical bond between the core and the cladding.

The design of a fuel element to give optimum performance in a given reactor is an extremely complex problem. The important design parameters are interrelated. For example an apparently simple question such as fuel composition cannot be answered without considering neutron energy, neutron economy, type of coolant, operating temperature, neutron flux, rate of burn up, total burn up, start up and shut down behaviour, behaviour in the event of fuel element failure, and finally, fuel element disposal or reprocessing. Similar considerations apply to the size and shape of the elements, composition and thickness of cladding, necessity for a core/cladding bond.

Some parameters and operational data which were important for the development of this work are presented in Table I.

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Table I	
Operational Data of IEA-R1 Reactor (Thermal Output 5 MW)	
Number of plates per assembly	18
Plate Core	UAl alloy (18 wt % U)
U ²³⁵ Content per plate (av.)	76.6 mg
Cladding	1100 aluminium
Nominal distance between two plates	2,9 mm
Power density (av.)	18,8 Kw/l
Specific power density (av.)	0,4 Mw/Kg of U ²³⁵
Heat transfer coefficient	0,186 Cal/cm ² sec °C
Thermal flux (av.)	5,9 . 10 ¹² n/cm ² sec.

UAl alloys clad with aluminium are particularly attractive as fuels for low temperature water cooled and water moderated reactors. They are easily fabricated at temperature below 600°C. They possess relatively good corrosion resistance up to 150°C, and they have good thermal conductivity. Aluminium itself has a low capture cross section for thermal neutrons and is relatively inexpensive.

The initial fuel fabrication parameters for the IEA-R1 reactor were based on similar criteria to those found in the literature⁽¹⁻⁶⁾.

2 – MANUFACTURING PROCEDURE

2.1 – General Requirements:

Satisfactory performance of the reactor and of the fuel components during their operating life requires that special precautions be taken to ensure the following:

- 1) Accurate incorporation of the desired quantity of fissile material into the fuel. An excess quantity than the specified could lead to serious problems.
- 2) Uniform distribution of the fuel in the core of the composite plate. Inhomogeneity in the fuel core could cause undesirable hot spots.
- 3) Proper porosity in the fuel element. Contradictory opinions exist concerning the advantages and disadvantages of the pores. As an advantage the pores can serve as a buffer volume during the radiation induced increase in volume of the fissile material, and provide space for gaseous fission products; whereas their main disadvantages are the associated low thermal conductivity and less irradiation stability of the fuel.
- 4) A good metallurgical bond. This is necessary to protect the fuel from corrosion, promote efficient heat removal, and to avoid leakage of fission by-products.

- 5) Uniformity in thickness of cladding and core materials. This has to be achieved for corrosion protection and for uniform distribution of fuel; and the dimensional specifications should be maintained.
- 6) Ensuring safety measures to prevent criticality incident.
- 7) Safeguarding and accountability for all fissionable materials.

The manufacturing procedure for the fuel plates is presented in Figure 1.

2.2 – Preparation of the Core:

The starting materials used to prepare the melt were pure aluminium and pure uranium. Some of the impurities present in high concentrations are given in Table II.

	Si (ppm)	Fe (ppm)	Mg (ppm)	Cu (ppm)	Mn (ppm)	Cr (ppm)	Ni (ppm)
Uranium	220	150	100	38	12	10	12
Aluminium	70	165	30	15	10	—	—

2.2.1 – Melting and Casting

The melting was done in air in a graphite crucible and the alloys were cast into graphite slab molds. The following steps were used for melting and casting:

- 1) Melt down the aluminium metal.
- 2) Increase the temperature to 800°C and add uranium metal with constant stirring with a graphite rod.
- 3) Raise the temperature to 1000°C and allow the melt to freeze in order to retain dissolved gases.
- 4) Remelt two to three times and add degassing material during the last melting.
- 5) Pour at a temperature of 800°C into a graphite mold preheated to 300°C.

2.2.2 – Examination of the Core

The casting were oversized to permit machining off their faces and sides. Excess lengths were provided for removing shrinkage pipe and taking samples for determining the composition by a density method and for metallographic examinations.

After inspecting visually the as cast samples for porosity and soundness the samples were degreased, rinsed in distilled water followed by alcohol, dried and stored.

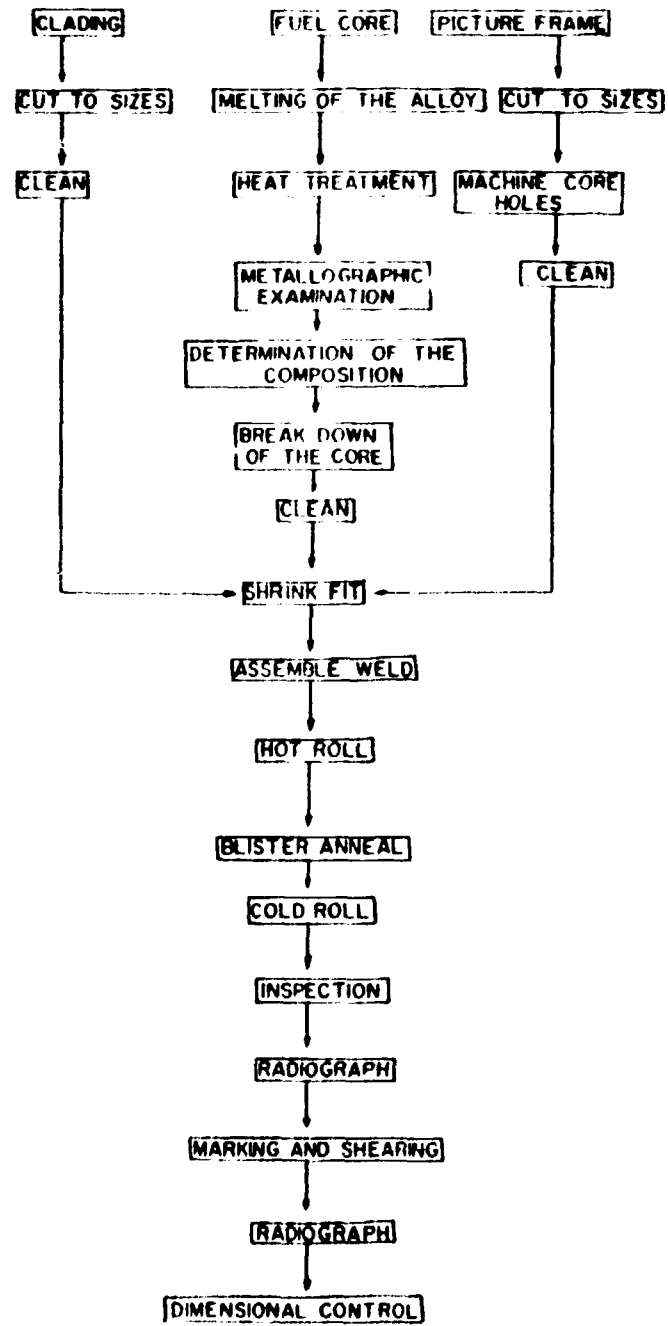


Figure 1 - Schematic Representation of the Manufacturing Procedure

For metallographic examination, the specimen was polished with emery paper (600 μm) and given a final polish with magnesia. The specimen was then etched with 2N KOH solution for about 3 minutes before being examined under microscope.

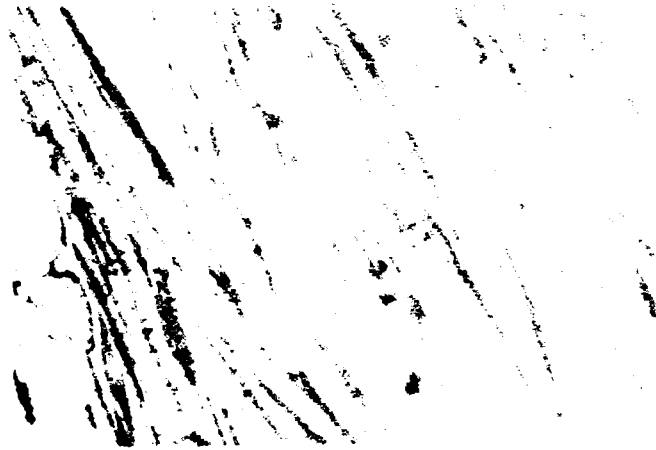


Figure 2a -- Sample as-cast (x 1000)

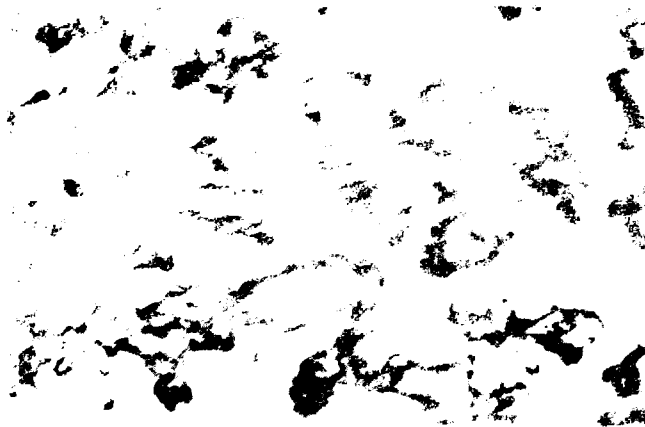


Figure 2b -- Sample After Heat Treatment at 600°C for 6 hrs. (x 1000)

Figure 2a and 2b show the photomicrographs of an as-cast sample and a sample heat treated at 600°C for 6 hours respectively. Primary long needle like morphology of UAl_4 crystals which can be seen in as-cast sample (Figure 2a) changes after heat treatment (Figure 2b). The compound UAl_4 coalesces into nodules which make the rolling easier.

2.2.3 -- Break Down of the Core

The 12.7 mm thick castings were then preheated for six hours at 600°C and hot rolled at 600°C to a final thickness of 3.2 mm. The rolling sequence reductions were never exceeded more than

20%, as can be seen in Table III. The very first pass without any reductions was given to acquire an uniformity in flatness of the fuel plate. The samples were rotated about their longitudinal and transverse axes between two passes, and 5 – 10 minutes tempering at 600°C between two consecutive passes were allowed.

Pass n ^o	Draft (mm)	Reduction (%)
1	12,7	—
2	10,79	15,0
3	9,20	14,7
4	7,93	13,8
5	6,66	16,0
6	5,37	19,3
7	4,45	17,1
8	3,70	16,8
9	3,20	13,5

During the plastic flow the structure of the alloy changes which could lead to anisotropy in the properties, but can be repaired by annealing. Heat treatment also improves the brittle structure of the alloy which leads to improved bonding character. The alloy was heated at 600°C for 30 hours for these purposes.

2.3 – Framing and Cladding

2.3.1 – Choice of Material

Generally the choice of material for framing and cladding depends on many factors which are summarized as follows:

- 1) High material strength and plasticity.
- 2) Change of properties, if produced by irradiation, should be under well specified limits.
- 3) High corrosion resistance.
- 4) High fatigue limit imposed by the existence of cyclic temperature changes.
- 5) Need for high thermal conductivity.
- 6) The material should have a coefficient of thermal expansion close to that corresponding to the core.

- 7) The material should not have very high vapor pressure, to preclude their significant vaporization which would contaminate the reactor loop.
- 8) The material should have low enough neutron cross section for neutron economy.
- 9) It should be easy to handle and inexpensive.

2.3.2 – The Billet Assembly

In all existing high or average power reactors except those using fluid fuel, the fuel is entirely enclosed in a cladding of non-fissionable material. There are two compelling reasons for that, namely prevention of corrosion by the coolant and retention of fission products. A third reason is that cladding may exert restraining forces that help to prevent distortion of the fuel during operations. Under some conditions the cladding assists in restraining the dimensional changes of the fuel core during irradiation.

Manufacture of fuel elements by rolling involves two opposing factors: a high degree of reduction is necessary in order to provide adequate bonding between the components of the rolled assembly but the degree of reductions should be limited in order to obtain a core of satisfactory structure.

As illustrated in Figure 3 each fuel plate billet requires two cover plates and one picture frame, in addition to a fuel compact. The cover plates were fabricated from aluminium 1100 by shearing. The frame was fabricated first by shearing a plate from aluminium 1100 and then the core opening of 96,0 x 60,1 mm was made in the center of the plate. Attention is called to the dimensions of the fuel core and the opening in the frame. The core-width and the length were designed to be identical to the dimensions of the opening in the frame, as shown in Table IV, in order to obtain an interference fit between core and frame.

Table IV

Dimensions of Core, Cladding and Frame

	Thickness (mm)	Width (mm)	Length (mm)
Core	3,2	60,7	96,9
Cladding	3,2	115,0	150,0
Frame	3,2	60,1	96,0
Cladding	3,2	115,0	150,0

The picture frame together with the two plates on its two sides were then flat pressed in a pressing machine with a pressure of 20 tons.

Immediately prior to billet assembly, the picture frame and the two cover plates were thoroughly cleaned first by sodium hydroxide in 10% aqueous solution at a temperature of 80°C and then in a neutralizing aqueous solution of 50% nitric acid.

The billet was then assembled by heating the frame at 600°C, seeping the deep freeze core into the expanded hole, then allowing the frame to cool to room temperature.

The cover plates were welded to the picture frame by the inert gas arc melted method. The four

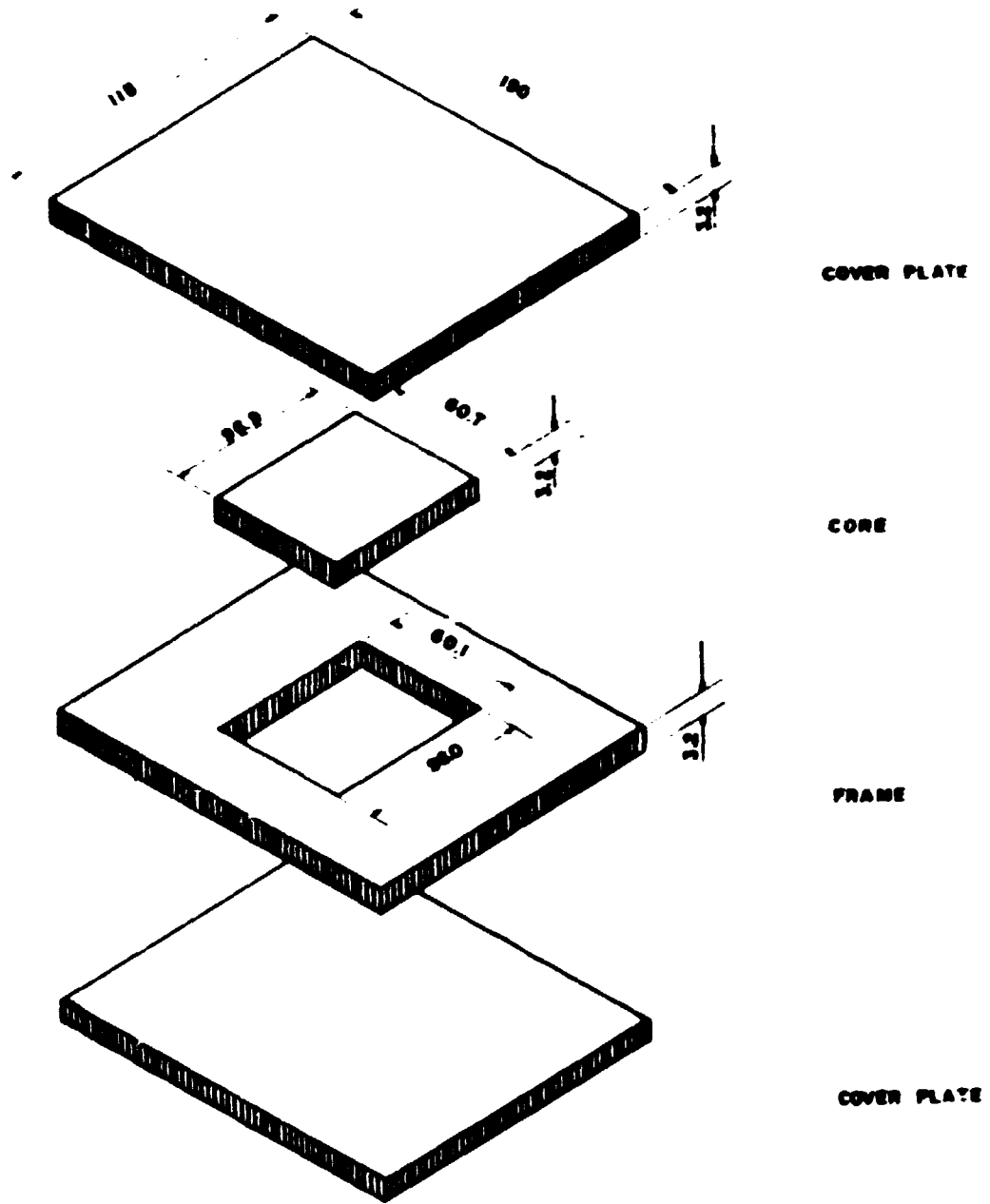


Figure 3 - Design of Billet Assembly

corners were left unwelded for a nominal distance of 1,5 cm to permit escape of entrapped air during the initial stages of hot rolling.

2.4 – Composite Plate Fabrication

The billets were heated in a furnace at 600°C for one hour prior to the first pass and reheated for at least 5 minutes between passes. The reduction degree corresponding to each phase was very carefully selected. The experience showed that the first few (3 to 4) sequences should have reductions under 10% for a homogeneous flow of material into the existing gap, if any, between the core and the frame. The reduction degree from the next phase onwards should be raised as it is shown in a typical reduction sequence in Table V. As before the very first pass without any reduction was given to acquire an uniformity in flatness of the plate.

Table V
Rolling Sequence for the Composite Plate

Pass no.	Draft (mm)	Reduction (%)
1	9,84	—
2	9,20	6,5
3	8,57	6,9
4	7,30	14,8
5	4,76	34,8
6	3,65	23,3
7	3,00	17,8
8	2,70	10,0
9	2,38	11,8
10	2,06	13,4
11	1,81	12,1
12	1,65	8,8
13	1,45	12,1

The billets were rotated about their longitudinal and transverse axes between passes. Special precautions were taken during rolling to minimize cambering or "rainbowing" of the plates. Cambering of the plates could possibly be corrected, if not too serious, by passing the plates through the mill at a slight angle where as gross rainbowing occurring during hot rolling could not be corrected. A level mill and proper feeding were maintained to diminish this difficulty.

After hot rolling, the plates were measured with a micrometer and were annealed for one hour at 500°C to remove stresses induced in the hot rolling process. The hot worked plates were then

annealed for one hour at 500°C for blister testing. Blisters were checked for visually; the plates with blisters were rejected and the others were numbered consecutively.

The annealed fuel plates were then cold rolled to obtain accurately the final thickness, using the same mill that was used for hot rolling. Total cold reduction in thickness were approximately 4 to 6% with approximately 2% in reduction for each sequence. The plates were rotated about their transverse and longitudinal directions between each rolling.

2.5 – Radiographic Examination, Marking and Shearing

The acceptable plates were radiographed to locate internal defects, determine straightness, and delineate the fuel bearing core section of the composite plate. The active fuel core within the fuel plate was located by comparing its radiographic outlines positioned over the plate. As illustrated in Figure 4a, the plates were numbered before radiography to permit positioning of the fuel section, symmetrically with respect to the subsequent shear edges and ends of the plates, and to ensure sufficient aluminium at the edges and ends to meet the dimensional specifications.

Prior to shearing the fuel plate numbers were again inscribed and the plates were marked according to dimensional specifications to establish reference lines for shearing. The plates were then sheared from inscribed lines.

The fuel plate was machined to the final width, using a machining fixture. The fixture consisted of two parallel rectangular plane slabs inside which the plate could be inserted. The plate was inserted and clamped in such a way that the width of the plate which was to be filed laid outside the edges of the slabs. After aligning each plate edge with reference to the parallel slabs, the edges were hand filed. The corners of the plates were then deburred and rounded by hand filing.



Figure 4a – Radiography of a Plate Before Shearing



Figure 4b – Radiography of the Same Plate After Shearing

All fuel plates were again radiographically inspected to ensure that the specified dimensions had been met (Figure 4b). Minimum and maximum core width, core length, minimum and maximum inactive edge width, edge length as well the thickness of the plates were checked.

Table VI
Dimension of the Fabricated Fuel Plates

Plate N°	Active Part		Active + Inactive Part		
	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Thickness (mm)
1	605.5	63.6	635.0	71.2	1.64
2	595.4	64.2	626.2	71.0	1.63
3	606.8	63.0	624.9	71.1	1.65
4	603.3	63.1	625.1	71.5	1.64
5	602.1	63.3	624.1	71.0	1.60
6	596.0	62.5	620.4	71.0	1.64
7	604.6	62.9	625.2	71.3	1.65
8	611.4	63.0	624.8	71.0	1.60
9	591.8	63.3	625.1	71.0	1.63
10	592.1	63.1	625.5	71.2	1.60
11	609.2	62.5	624.1	71.3	1.62
13	590.0	63.0	636.4	70.9	1.65
14	592.3	62.9	635.8	70.9	1.65
15	588.6	62.9	633.0	71.0	1.62
16	595.6	63.0	634.7	70.8	1.60
18	596.3	63.1	632.0	70.9	1.63
19	596.1	63.3	632.8	70.8	1.60
20	603.6	63.2	632.0	71.2	1.65

Average dimension of the plates and their standard deviations:

$$599.26 \pm 6.57 \quad 53.01 \pm 0.30 \quad 628.73 \pm 4.93 \quad 71.06 \pm .18 \quad 1.63 \pm .02$$

Table VI presents the dimensions of all the 18 fuel plates. Each value corresponds to average of three measurements taken at three different places of each plate (two at the two ends and one at the middle). The average dimensions of the 18 plates and their standard deviations were calculated and also presented in Table VI. The deviations from the average show it clearly that the fuel element dimensions can indeed be controlled precisely.

3 – CONCLUSIONS

This work describes the basic manufacturing procedures for the fabrication of 18 fuel plates of the type to be used in IEA-R1 reactor. The results obtained in manufacturing these elements demonstrate that:

- 1) The fuel element can be manufactured within the established specifications and tolerances by using the conventional picture frame technique.
- 2) A good metallurgical bonding can be achieved by roll bonding technique.
- 3) The technique is reproducible and by making some fine adjustments it can indeed be used for high quality fuel plates manufacture.

RESUMO

Entre as atividades de engenharia do Centro de Metalurgia Nuclear do Instituto de Pesquisas Energéticas e Nucleares destaca-se a fabricação de combustíveis tipo placa para uso em reatores de pesquisa.

São apresentadas, em pormenores, a marcha desenvolvida e adotada na fabricação dos elementos combustíveis do tipo usado no Reator IEAR-1.

O processo usado é o da co-laminação, a quente, de um conjunto constituído por duas placas de revestimento e uma moldura em cujo interior é colocado um núcleo de uma liga de AlU (18% U, em peso).

Este trabalho descreve os métodos usados no processo de fabricação de 18 placas de elementos combustíveis planos obtidos dentro das especificações requeridas.

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INSTITUTO DE PESQUISAS ENERGÉTICAS E NUCLEARES

Caixa Postal, 11 049 -- Pinheiros

CEP 05508

01000 -- São Paulo -- SP

Telefone: 211-6011

Endereço Telegráfico -- IPENUCLEAR

Telex -- (011) 23592 - IPEN - BR