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भारत सरकार
GOVERNMENT OF INDIA
परमाणु ऊर्जा आयोग
ATOMIC ENERGY COMMISSION

FABRICATION OF MOX FUEL ELEMENT CLUSTERS FOR IRRADIATION IN PWL, CIRUS

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Radiometallurgy Division

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BHABHA ATOMIC RESEARCH CENTRE
बंबई, भारत
BOMBAY, INDIA
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INIS Subject Category : E31; E23

Descriptors

TARAPUR-1 REACTOR
TARAPUR-2 REACTOR
NUCLEAR FUELS

FUEL PELLETS
FUEL ELEMENT CLUSTERS
PLUTONIUM DIOXIDE
URANIUM DIOXIDE
POWDERS
MIXING
COMPACTING
SINTERING
CRUSHING
GRINDING
CLEANING
DRYING
DEGASSING
ZIRCALOY - 2
WELDING
FUEL CANS
CANNING
SPECIFICATIONS
OPTIMIZATION
CHEMICAL COMPOSITION
FLOWSHEETS

ABSTRACT

Three clusters, each containing 6 Zircaloy-2 clad short length fuel elements of either MOX or UO_2 fuel pellets were fabricated for irradiation in pressurized water loop of CIRUS. The major objectives of the programme were (a) to optimize the various fabrication parameters for developing a flow sheet for MOX fuel element fabrication; (b) to study the performance of the MOX fuel elements at a peak heat flux of 110 w/cm^2; and (c) to study the effect of various fuel pellet design changes on the behaviour of the fuel element under irradiation.

Two clusters, one each of UO_2 and MOX, have been successfully irradiated to the required burn-up level and are now awaiting post irradiation examinations. The third MOX cluster is still undergoing irradiation.

Fabrication of these fuel elements involved considerable amount of development work related to the fabrication of the MOX fuel pellets and the element welding technique and is reported in detail in this report.

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1. INTRODUCTION

Three clusters, each having 6 zircaloy-2 clad short length fuel elements conforming in general to Tarapur Atomic Power Station (TAPS) fuel specifications [1] were fabricated for irradiation in pressurised water loop of CIRUS.

The major objectives of the campaign were -

(a) to optimise various fabrication parameters and develop a flow sheet for mixed oxide (MOX) fuel element fabrication,

(b) to study the performance of MOX fuel elements at the peak heat flux of 110W/cm^2,

(c) to study the performance of chamfered fuel pellets under irradiation, and

(d) to study the controlled porosity fuel pellet behaviour under irradiation.

The first cluster (A-C-1) contained elements having natural UO_2 pellets. One of the elements had controlled porosity fuel pellets. This cluster was fabricated and irradiated to qualify the fuel fabrication procedure and to streamline the fuel handling arrangements.

The second cluster (A-C-2) contained one element of natural UO_2 and the remaining five of natural UO_2-4wt% PuO_2 fuel pellets. One of the MOX elements contained controlled porosity fuel pellets. The basic design concepts of this cluster has been described elsewhere [2].

The third cluster (A-C-3) consisted of three MOX and three Helium filled elements. These three Helium filled elements were incorporated in

the cluster to enable irradiation of MOX elements at increased heat flux [3].

The first and second cluster (A-C-1 and A-C-2) underwent successful irradiation upto a burn up level of approximately 500 MWD/T and 16,500 MWD/T respectively and are now awaiting post irradiation examination.

The third cluster (A-C-3) is currently undergoing irradiation at the heat flux of 110 W/cm^2 compared to 92 W/cm^2 attained in the cluster A-C-2.

Fabrication of these fuel elements involved considerable amount of development work related to the fabrication of MOX fuel pellets and the element welding technique. These are discussed in this report.

2. SPECIFICATION OF SINTERED FUEL PELLET AND ELEMENT

In view of presence of PuO_2 in the fuel, the existing Low Enriched Uranium (LEU) oxide TAPS fuel specifications had been modified. Table 1 gives some of the major deviations in the specification for MOX fuel/fuel elements over the existing TAPS UO_2 fuels.

3. ELEMENT AND CLUSTER DETAILS

The details of the fuel elements and their arrangement in the clusters are shown in Fig. 1, 2 & 3.

The top and the bottom end plugs were welded to the fuel tubes by TIG welding technique under Helium and Argon respectively. The filler gas used in all the elements was Helium.

4. ESTABLISHMENT OF VARIOUS FABRICATION PARAMETERS

4.1 Fabrication of fuel pellets

In general the conventional route consisting of cold compaction and sintering was followed for the fabrication of fuel pellets. However, each process step needed considerable developmental effort for fixing the actual parameters as described in the next paragraphs.

4.1.1 Feed material

The feed material for the pellet fabrication were (a) natural UO_2 powder produced by ADU route at Nuclear Fuel Complex (NFC), Hyderabad, and (b) PuO_2 powder produced via oxalate route and air-calcined at a temperature of 823K at fuel reprocessing division (FRD), Bombay. The UO_2 and PuO_2 powder characteristics were analysed and are given in table 2. Apart from these characterization tests, UO_2 powder was also subjected to sinterability test at 1973K under A-8 v/o H_2 for 8 hrs. Powder lots which resulted in a sintered pellet density of above 94% Theoretical Density (T.D) were only accepted for this work.

4.1.2 Mixing of UO_2 and PuO_2 powder

Proportionate quantities of UO_2 and PuO_2 powders were milled together in a planetary ball-mill in bowls of 250 gms capacity. Four batches (each of 250 gms) of the milled material were blended in a ribbon blender for obtaining a 1 Kg. homogenized blend. During blending, 0.3wt% Methyl cellulose (pore former) was added to the powder to make controlled porosity fuel pellets. The parameters which needed study during the milling operation were -

(a) Choice of proper bowl & ball materials

(b) Optimum milling time, and

(c) Mode of addition of UO_2 to PuO_2.

Table 3 shows the impurity pick-up in UO_2-PuO_2 mixture after 2 hrs milling with various bowl and ball combinations. It can be seen from the table that agate bowl and ball combination gave the minimum impurity in the blend. It was also found that this combination could be used even for 16 hrs milling without exceeding the impurity levels beyond specification.

A milling time of 2 hrs, which was found sufficient to give homogeneous blend, was fixed on the basis of chemical analysis on random samples from the blended lots after different milling times. An overall variation of ± 0.03 wt% of plutonium was observed in the blend and was found to give plutonium content in the sintered pellets well within the specification.

Incremental addition of UO_2 to PuO_2 was found to be very effective in avoiding presence of plutonium-rich clusters in the pellets. When UO_2 was incrementally added to PuO_2, alpha-autoradiograph of the sintered MOX pellets always showed uniform distribution of PuO_2 in UO_2 (fig. 4). This was further confirmed by neutron radiography. Typical neutron radiograph is shown in fig. 5.

4.1.3 Precompaction, granulation and final compaction

Non-free flowing characteristics of the UO_2-PuO_2 Powder blend necessitated precompaction followed by granulation for obtaining free flowing granules to facilitate automatic pellet compaction.

The parameters which were studied here were the effect of pre-compaction pressure and granule size on the acceptability of sintered and ground pellets.

Keeping the final compaction pressure fixed at 300 MPa, two precompaction pressures of 75 MPa and 150 MPa were tried and the granule sizes were varied between -8 to -85 mesh. Acceptance rate of sintered pellets were found to be much higher when precompaction to final compaction pressure ratio (Rp) was maintained at 0.25 (i. e. precompaction press. of 75 MPa). Higher Rp value produced pellets with pitting defects and undulations on the flat surfaces.[4] It was also observed that finer the granule size, better was the surface finish of the pellets. However, an optimum granule size of -20 mesh was chosen for practical reasons. Granulation was done in an oscillatory granulator fixed with a screen. Use of a screen finer than 20 mesh often led to metallic inclusion in the pellets due to wear and tear of the screen. Moreover, finer the granules, the more would be the die-fill length necessitating accommodation of bigger compaction tooling in the press.

Ejection of green pellets under pressure was found to improve the pellet acceptability by reducing end flaking defects.

4.1.4 Sintering of Mixed Oxide (MOX) pellets

Sintering parameters have an important bearing on the characteristics of the sintered pellets such as density, grain size, O/M ratio and the

interdiffusion between uranium and plutonium. Parameters such as heating rate, time and temperature at the intermediate and final soaks and atmosphere of sintering all had to be optimised for getting good quality pellets with high acceptance rate. After a large number of experiments, the sintering time temperature cycle was finalised as given below:

(1) Heat from room temperature to 423 K at the rate of 3-4 K/min and soak at 423 K for 1 - 2 hrs.

(2) Heat from 423 K to 673 K at the rate of 2 - 3 K/min and soak at 673 K for 1 - 2 hrs.

(3) Heat from 673 K to 973 K at the rate of 3 - 4 K/min and soak at 973 K for 1 - 2 hrs.

(4) Heat from 973 K to the final sintering temperature at the rate of 3 - 4 K/min and final soak at sintering temperature for 8 hrs.

(5) Cool at the rate of 4 - 5 K/min.

Three intermediate soaks of 1 - 2 hrs each were chosen for the following reasons:

(a) The first soak at 423 K was chosen for removal of all adsorbed moisture from the green pellets.

(b) The second soak at 673 K was given for the removal of the surface lubricant and the volatile pore-formers (used for making controlled porosity pellets) from the green pellets.

(c) The third soak at 973 K was given for reducing hyperstoichiometric UO_{2+x} to $UO_{2.00}$ and subsequent removal of moisture generated by the reaction.

A sintering soak at 1923 K for 4 hrs was found sufficient to obtain uniform solid solution between UO_2 and PuO_2 and also a sintered density above 94% T.D. However, a sintering temperature of 1953 K for 8 hrs was preferred for producing pellets with higher grain size and increased resistance to thermal redensification. Moreover, it was observed that MOX pellets always

had a lower grain size compared to UO_2 pellets, when sintered in similar conditions. Typical microstructure of MOX and UO_2 pellets are shown in fig. 6. Results of the thermal redensification test carried out at 1973 K for 24 hrs in A-8v% H_2 cover gas are given in table 4. Typical as polished microstructures of controlled porosity and normal fuel pellets are shown in fig. 7.

The suitability of high purity A-8v% H_2 and N_2-8v%H_2 gas mixtures were evaluated as sintering atmosphere. Except a marginal difference in the density, all other physical characteristics were identical in the pellets sintered in either of the atmospheres. However, nitrogen content in the sintered MOX pellets were found to be on the limiting side of the specification when N_2-8v% H_2 was used. Table 5 shows the nitrogen analysis results in UO_2 and MOX pellets sintered with A-8v% H_2 and N_2-8v% H_2 gas mixtures. Based on this observation, A-8v% H_2 gas mixture was chosen as the cover gas for MOX pellet sintering. No difficulty was observed in meeting the O/M specification of the pellets when high purity gas mixture was used as the sintering gas.

4.1.5 Grinding and washing of pellets

The variation in the diameter over the length of the sintered pellets was found to be within $\pm$ 0.04 mm, although the specification calls for pellet diameter variation not exceeding $\pm$ 0.02 mm. Due to this, pellets were always sintered to oversize and subsequantly ground to the specified diameter.

During centreless grinding 2v% mineral oil - water mixture was used as cooling medium. This medium was chosen over plain water to avoid corrosion of the grinding machine components. However, the mineral oil/ water medium leaves oil stains over the ground surface of the pellets. Ground pellets were cleaned using a three-stage washing treatment; first a demineralised water jet, second an ultrasonic cleaning in 5v% detergent-water solution at 333 K and finally ultrasonic cleaning in 20v% Alcohol-water mixture at room temperature.

4.1.6 Drying/outgassing of ground pellets

Hot air drying of ground pellets was initially tried but was not found suitable for hypostoichiometric MOX pellets. A hot vacuum-drying cum outgassing treatment was developed to outgas the pellets to reduce the total equivalent hydrogen content. The method has been described in detail elsewhere [5].

4.2 Fabrication of fuel elements

Zircaloy-2 is a chemically very active material and reacts easily with oxygen, nitrogen and moisture at elevated temperature, affecting its corrosion and mechanical properties. Therefore, proper cleaning and handling of the Zircaloy-2 clad is a must for fuel element fabrication. During welding maintenance of pure protective atmosphere has to be assured to meet the various specifications. Considering these, Zircaloy-2 clad tubes and other hardwares were cleaned ultrasonically and degassed at 473 K for 2 hrs in vacuum.

Initially, the first end plug (bottom) welding was tried in a once through argon glove box. However, this required a lot of time for flushing to stabilise the purity of the atmosphere. Moreover, any bagging in or bagging out operation was found to disturb the purity of the atmosphere to a large extent. Considering these difficulties, an evacuable chamber was attached to the welding machine, which could house the weld joint and could be evacuated and filled back with high purity argon/helium.

The second end plug (Top) welding was carried out in a special glove box having two compartments by partitioning the box with analuminium panel having an opening with fixtures for pellet loading. One compartment was used for Plutonium active operations, viz. handling the outgassed mixed oxide fuel pellet stacks and pushing the fuel stacks in the bottom end plug welded tubes held in the second compartment through the opening in the partition panel. Proper care was taken to avoid the contamination of the clad tube mouth during loading. After loading the fuel stack, the other components like plenum spring, Zircaloy-2 pellets etc. were loaded in the

tube. The loaded tube was withdrawn to the inactive compartment and then fixed in the welding chamber along with the second end plug. After evacuation and flushing of the chamber and the element with Helium, welding was performed in comparatively plutonium inactive condition.

The second end plug (Top) welding involved development of the TIG helium arc welding technique. Striking the arc in helium atmosphere required a high voltage D.C. superimposition in addition to the high frequency normally used for starting the arc. [6] Many trial welds were done before the welding parameters were fixed. Weld samples were examined both radiographically and metallographically for checking the soundness of the welds, the degree of penetration, amount of heat affected zone and the presence of any weld defect like porosity, root pocket, wall thinning etc. Weld sections were autoclaved to check the corrosion rate and chemically analysed for checking oxygen, nitrogen and hydrogen content.

All the welds were critically examined visually for colour and metrologically for weld bead dimensions.

5. CLUSTER FORMATION

After the top end plug welding, the fuel elements were decontaminated and inspected. Full element X-ray radiography was done to establish that all components had been sequentially introduced in the element. Metrological check for element bowing was done. Overall integrity of the welded elements were checked by Helium leak testing. Accepted elements were assembled into clusters using the other assembly hardwares like tie plates, hanging rod etc. The overall flow-sheet for the fabrication of cluster is shown in fig. 8. Characteristics of a typical fuel element used in the cluster are given in Annexure 1.

6. DISCUSSION

Pitting (fig. 9) and end-claking (fig. 10) defects were the two major causes for sintered pellet rejection. Pitting defect in the pellets was

almost eliminated by choosing a precompaction to final compaction ratio of 0.25 and use of -20 mesh granules for final compaction. Considerable reduction in end flaking defect was obtained by ejecting the green compacts from the die, under load. Compared to right cylindrical pellets, incidence of end flaking defect was found higher in chamfered pellets. The reason was presumed to be the non-uniform pressure distribution within the powder mass below the chamfer. The problem substantially reduced by changing the chamfer angle from 35° to a value between 45 to 55° [4].

Nitrogen pick-up in hypostoichiometric MOX pellet when sintered in N_2-H_2 atmosphere has been reported by others [7,8]. In hypostoichiometric MOX pellets containing trace quantity of H_2 or moisture, a compound like $(U,Pu)O_{2-x}\ H_x$ is expected to be present [9]. The presence of trace quantity of H_2 and moisture in MOX pellet is always possible, firstly due to sintering atmosphere which contains 6 to 8 volume % of H_2 and also because PuO_2 gets reduced at high temperature to Pu_2O_3 in presence of hydrogen and the moisture formed may get trapped in the pellet. [10] From the liberature [8] a reaction between plutonium hydride and nitrogen is known to occur. This may be the reason for marginally higher nitrogen content in MOX pellets. The hydrogen containing mixed oxide compound is reported to evolve hydrogen at temperatures above 653 K. [8,9]. This is also confirmed by our experiments. An outgassing treatment in the temperature range of 773 K to 823 K for 2 hrs or at 673 K for 8 hrs was found to bring down the hydrogen content in the MOX pellets to a value in the range of 0.3 to 0.5 μgm/gm. This is comparable to the hydrogen content obtained in UO_2 pellets degassed at 473 K for 2 hrs.

LEU oxide fuel elements are outgassed in loaded (one end welded) condition at 473 K. This type of treatment is not suitable for MOX elements because as has been explained in the preceding paragraph MOX fuel pellets have to be outgassed at a temperature in the range of 673 to 873 K to ensure low total equivalent hydrogen content. This high temperature may alter the mechanical properties of the clad tube. Considering this constraint, MOX fuel pellets and Zircaloy-2 hardwares were outgassed seperately.

Welding of the second end plug (Top Plug) to the loaded tube initially posed some problem even after all the welding parameters were fixed. Many times the welding could not be successfully completed due to the expulsion of the plug by the pressure of the expanding hot Helium gas present inside. The problem could be solved by introducing two Zircaloy pellets at the end of the fuel column to act as heat sink.

7. SUMMARY

A high yield was achieved in the fabrication of MOX fuel pellets meeting 'Class A', TAPS pellet specification by the control of -

(i) Precompaction pressure/compaction pressure ratio (0.25)

(ii) Granule size (-20 mesh)

(iii) Ejection of green pellets under load.

In the case of chamfered pellets an angle of chamfering in the range of 45 to 55° was found to be very effective in reducing the end flaking defect.

Use of N_2-8v% H_2 gas mixture as sintering atmosphere gave rise to marginally higher nitrogen content in the pellets. Hence, A+8v% H_2 gas mixture was used to take into account any uncertainties in the nitrogen analysis.

Plutonium rich cluster size was effectively controlled by incremental addition of UO_2 during milling. Sintering the pellets at 1953 K for 8 hrs achieved complete solid solubility (as detected by XRD), apart from meeting other desired physical and chemical specifications including dissolution behaviour.

Pellets and the clad materials were given separate outgassing treatment. This type of treatment also avoids necessity of long plutonium active furnace inside glove boxes for outgassing of loaded elements.

Welding of second end plug to the loaded tube by TIG Helium arc needed a high voltage D.C. superimposition in addition to the high frequency normally used for starting the arc.

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T A B L E - 1

Major Deviations in the MOX fuel specifications compared to TAPS LEU oxide fuel specifications

S.No.	Property	MOX	LEU Oxide
1.	Chemical composition of sintered pellets	4 ± 0.1wt% PuO_2 + natural UO_2 (including permissible impurities)	100% UO_2 (including permissible impurities)
2.	Oxygen to Metal ratio of sintered pellets	2.00 ± 0.02	1.99 to 2.03
3.	Equivalent Hydrogen content of sintered pellets	Less than 1 PPm	Only moisture in element specified
4.	Homogeneity (Macro) of Pu distribution in sintered pellets	i) Dissolution in 10 M Nitric Acid under reflux condition for 6 hrs. Maximum residue in this test shall be less than 0.1 wt%. ii) Extent of solid solution formation between UO_2 & PuO_2 to be tested by XRD. The sample shall not show presence of any second phase.	No such specification applicable
5.	Homogeneity (Micro) in sintered pellets	Maximum size of Pu rich cluster shall be less than 400 microns as measured by alpha autoradiography.	No such specification applicable.
6.	Fuel element surface contamination	Loose contemination less than 30 dpm/100 cm^2 and fixed contamination less than 300 dpm/100 cm^2	Uranium surface contemination to be less than 1.4×10^{-8} gm/cm^2

TABLE - 2

Characteristics of UO_2 and PuO_2 powders

	Characteristics	UO_2	PuO_2
1.	Apparent Density (g/cm^3)	1.68	1.36
2.	Tap Density (g/cm^3)	2.60	2.10
3.	Specific Surface area (m^2/g)	2.60	23.5
4.	Oxygen to metal ratio	2.06	2.00
5.	Total impurities (ppm)	less than 1000	less than 2500

TABLE - 3

Impurity Pick-up During Milling of Powders

Milling condition			Impurities in PPm			
Bowl material	Ball material	Time of milling	Chromium	Silicon	Tungsten	Iron
Agate	Agate	2 hrs.	20	60	50	-
	Tungsten carbide	2 hrs.	9	56	132	-
	Tempered chrome steel	2 hrs.	3.9	52	75	197
Tempered chrome steel	Agate	2 hrs.	13	90	130	70
	Tungsten carbide	2 hrs.	20	110	64	46
	Tempered chrome steel	2 hrs.	7	95	50	375
As received powder			6	60	25	61
Maximum acceptable in sintered pellet			400	200	100	400

TABLE -4

Results of Thermal Redensification Test on MOX pellets

Initial sintering temperature (kelvin)	Sintering time (hrs.)	Initial sintered density of pellets (% T.D)	Density increase after reintering at 1973K for 24 hrs (% T.D)
1923	4	93.5 to 95.0	1.1 to 1.5
1923	8	94 to 95.5	0.8 to 1.0
1953	8	95.5 to 97	less than 1
1953 *	8	94 to 94.5	0.2 to 0.5

* Pellets with pore formers.

TABLE - 5

Nitrogen in Sintered Pellets

Pellet composition	Sintering atmosphere	Nitrogen content in pellet (ppm)
UO_2	N_2 - 8 v/o H_2	60 ± 8
UO_2 - 4wt% PuO_2	N_2 - 8 v/o H_2	100 ± 5
UO_2	A - 8 v/o H_2	55 ± 5
UO_2 - 4wt% PuO_2	A - 8 v/o H_2	60 ± 3

Maximum nitrogen content acceptable in sintered pellet : less than 100 ppm.

Annexure 1

MOX Fuel Element Characteristics

A. Fuel Pellet:

	Chemical Characteristics	Typical value	Specified value
1)	Plutonium content (Wt%)	3.53 ± 0.02	3.53 ± 0.09
2)	(Uranium + Plutonium) content (Wt%)	88.07	87.5 Min.
3)	Oxygen/U+Pu ratio	1.996 ± 0.002	2.00 ± 0.02
4)	Carbon content (PPm)	25 ± 3	200 Max.
5)	Chlorine content (PPm)	3	15 "
6)	Florine content (PPm)	1	25 "
7)	Nitrogen content (PPm)	16 ± 2	100 "
8)	Total equivalent Hydrogen content(PPm)	0.5	1 "
9)	Total impurities (PPm)	450	2500 "
10)	Equivalent Boron content (PPm)	0.66	2.5 "
	Homogeneity		
1)	Residue left after dissolution test (wt%)	0.06	0.10 Max.
2)	Solid solubility (XRD analysis)	Single phase solid solution	Single phase solid solution
3)	Pu rich cluster size (Alpha-autoradiographic analysis) in microns	Maximum size of Pu rich cluster 100	400 Max.
	Physical Characteristics		
1)	Density (% T.D.)	95.92	93.3 to 96
2)	Length (mm)	15.352	14.09 ± 1.77
3)	Diameter (mm)	12.359	12.37 ± 0.02
4)	Grain size (microns)	6 - 11	5 to 50

B. Fuel Element:

1)	Length of the fuel column including insulating UO_2 and Zircaloy-2 pellets (mm)	459.945	457.708-462.788
2)	Total length of Zircaloy-2 pellets(mm)	25.04	25.6 ± 3
3)	Weld to Weld distance (mm)	487.5	487.5 ± 1.5

..2/-

4)	Length of the plenum spring (mm)	17.5	17.8 $\pm$ 1.5
5)	Fuel/clad diametral gap (mm)	0.291 to 0.309	0.241 to 0.368
6)	He leak rate (Std. cc/Sec)	less than 10^{-8}	Less than 10^{-8}
7)	Fixed contamination (dpm/100 cm^2)	Nil	300
8)	Loose contamination (dpm/100 cm^2)	Nil	30

FUEL ELEMENT WITH COMPONENTS

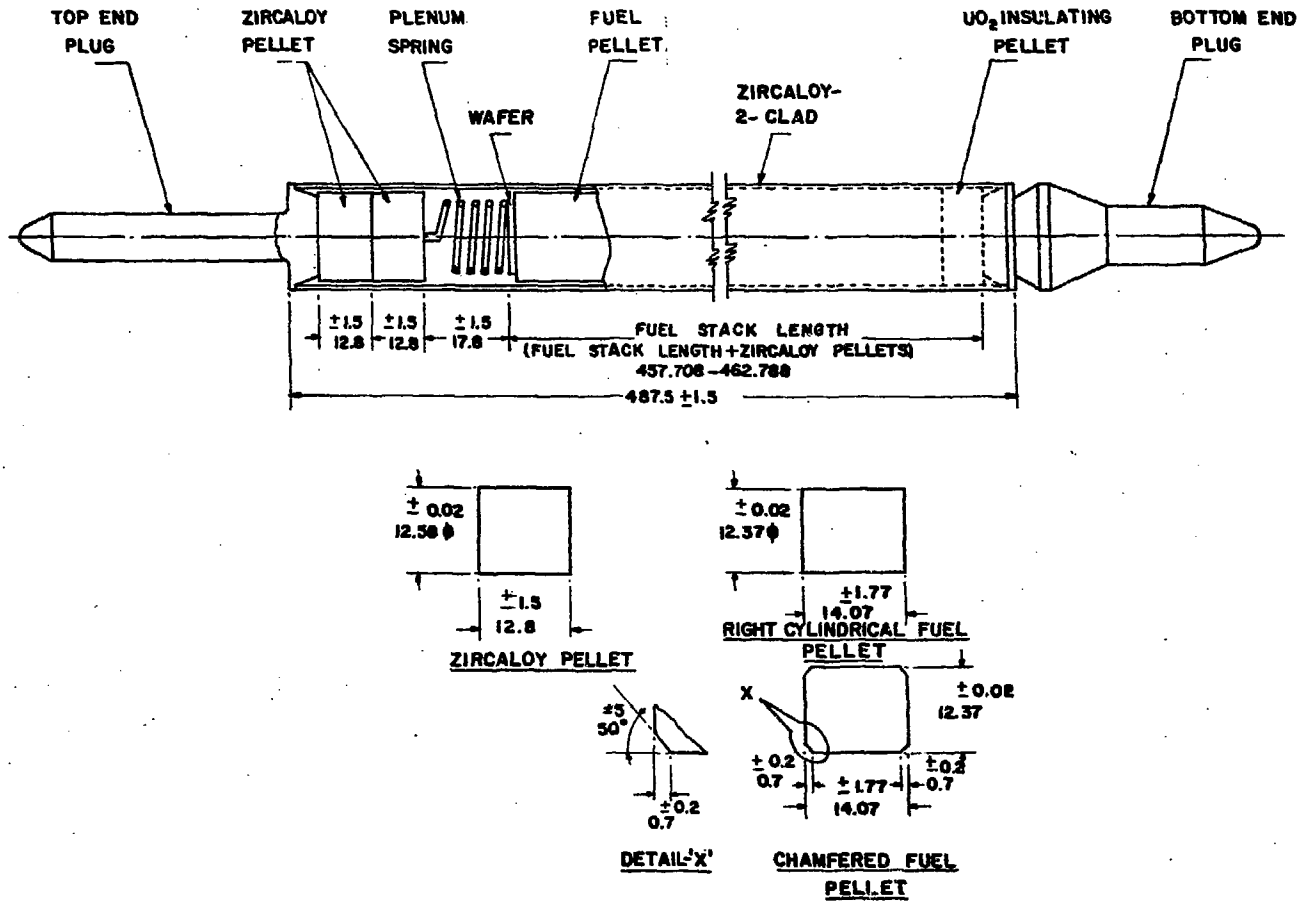
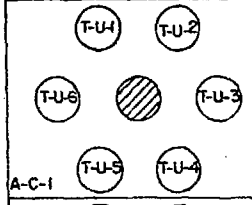
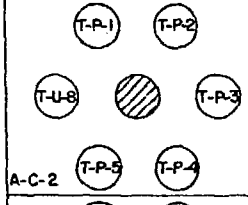
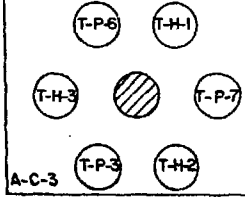


Fig.—1.

FUEL ELEMENT AND CLUSTER DETAILS

CLUSTER	ELEMENT NO	FUEL PELLETS			FILLER GAS (He) PRESSURE	REMARKS
		COMPOSITION	AVERAGE DENSITY (% T.D.)	SHAPE		
	T-U-1	NATURAL-UO_2	95.94	RIGHT CYLINDRICAL	1 Atm	
	T-U-2	-do-	96.01	-do-	1 "	
	T-U-3	-do-	96.08	-do-	1 "	
	T-U-4	-do-	94.23	-do-	1 "	CONTROLLED POROSITY PELLETS
	T-U-5	-do-	95.16	-do-	1 "	
	T-U-6	-do-	96.08	-do-	1 "	
	T-P-1	4% PuO_2-UO_2	96.27	-do-	1 "	
	T-P-2	-do-	96.34	-do-	1 "	
	T-P-3	-do-	94.33	-do-	1 "	CONTROLLED POROSITY PELLETS
	T-P-4	-do-	96.26	-do-	1 "	
	T-P-5	-do-	96.20	-do-	1 "	
	T-U-8	NATURAL UO_2	94.53	-do-	1 "	
	T-P-6	4% PuO_2-UO_2	95.92	CHAMFERED	1.5 Atm	
	T-H-1	—		—	1.5 "	FILLER GAS HELIUM ONLY
	T-P-7	4% PuO_2-UO_2	95.57	CHAMFERED	1.5 "	
	T-H-2	—		—	1.5 "	FILLER GAS HELIUM ONLY
	T-P-8	4% PuO_2-UO_2	95.83	CHAMFERED	1.5 "	
	T-H-3	—		—	1.5 "	FILLER GAS HELIUM ONLY

STRUCTURAL ROD

Fig.-2.

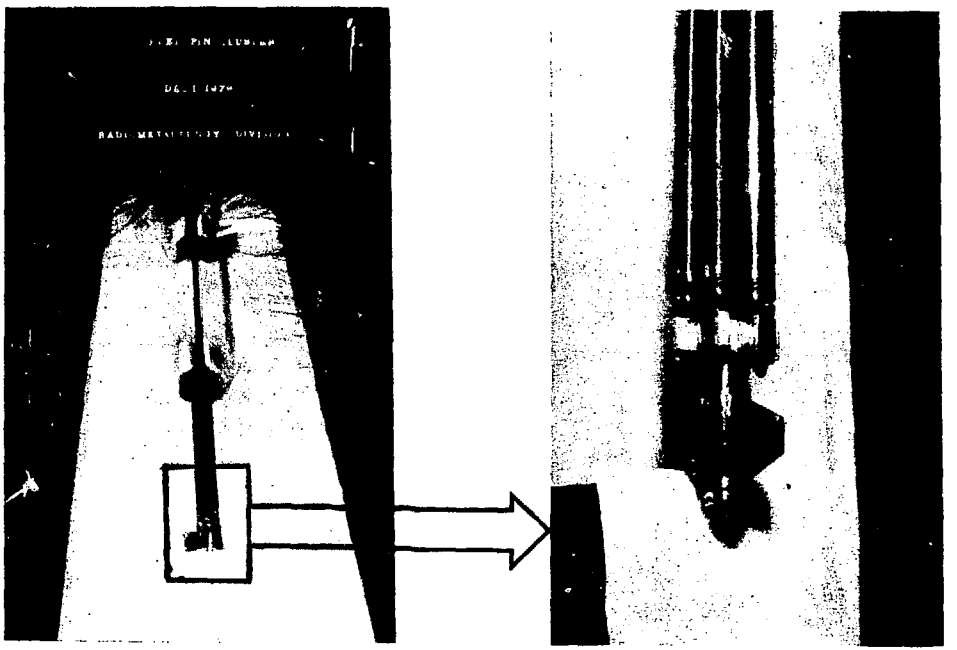
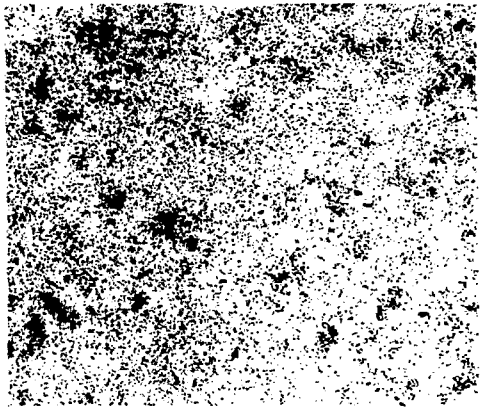
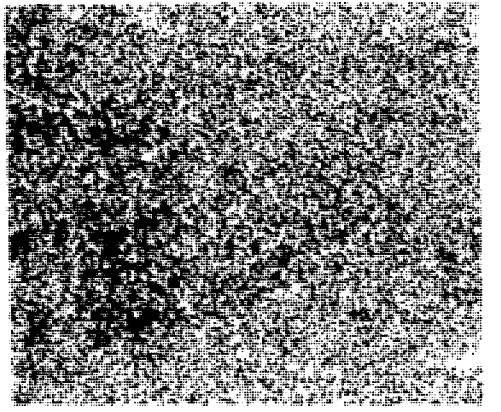


Fig. 3. : MOX FUEL PIN CLUSTER

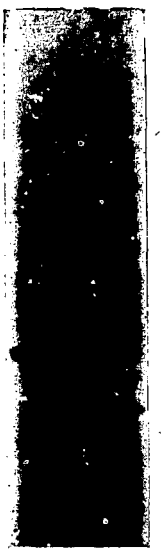


A. Non-uniform distribution of PuO_2 in UO_2
(UO_2 added in bulk)



B. Uniform distribution of PuO_2 in UO_2
(UO_2 added incrementally)

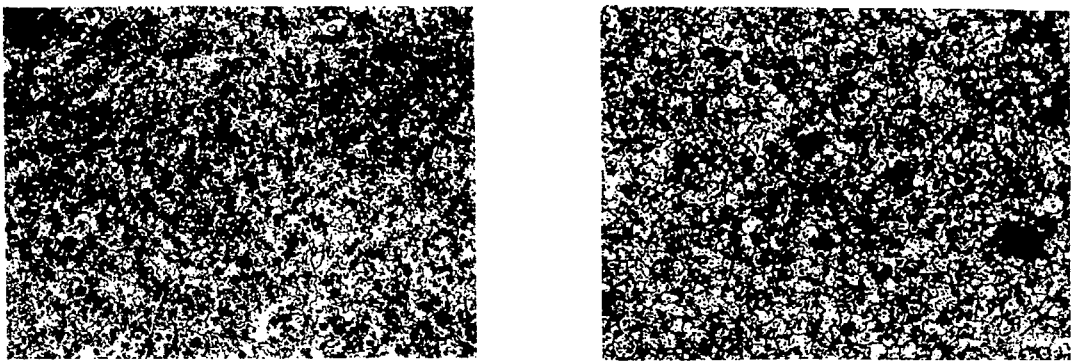
Fig. 4. : ALPHA AUTORADIOGRAPH OF MOX PELLETS



A. Pellets having PuO_2 clusters of different sizes (specially fabricated as a defect standard)

B. Pellets having uniform distribution of PuO_2 (as obtained in this campaign)

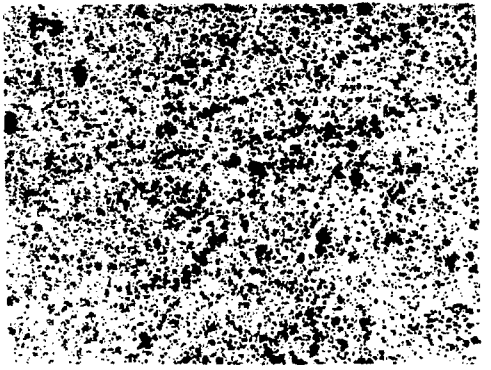
Fig. 5. : NEUTRON RADIOGRAPHS OF MOX PELLETS



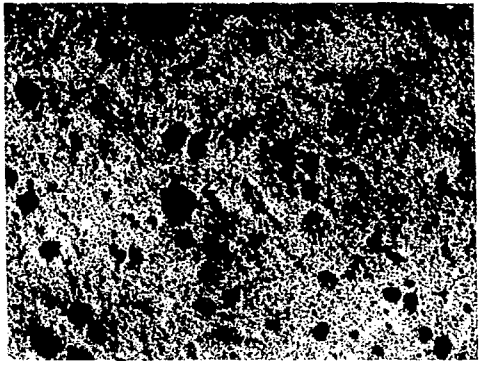
A. Mox

B. UO_2

Fig. 6. : MICROSTRUCTURE OF SINTERED MOX & UO_2 PELLETS SHOWING DIFFERENCE IN GRAIN SIZE
(MAGNIFICATION 350 *X*)



A. Normal pellet (Magnification 225 *X*)



B. Controlled porosity pellet (Magnification 75 *X*)

Fig. 7. : AS POLISHED MICROSTRUCTURE OF CONTROLLED PORGSITY & NORMAL PELLETS

FABRICATION FLOWSHEET

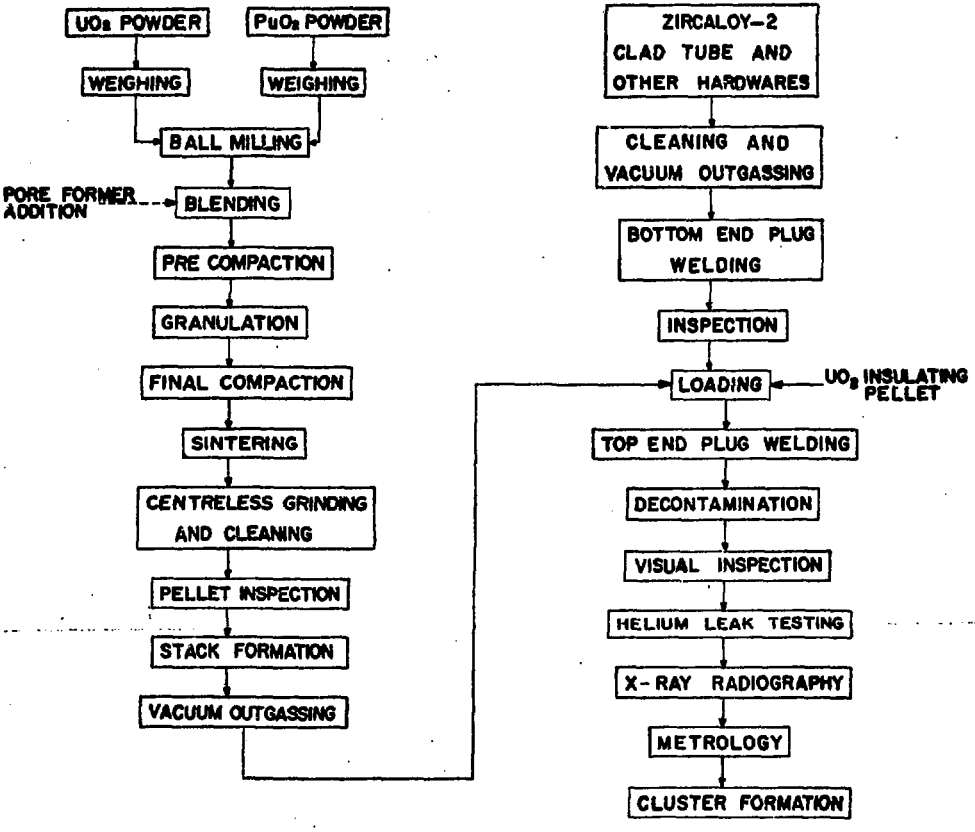


Fig.-8.

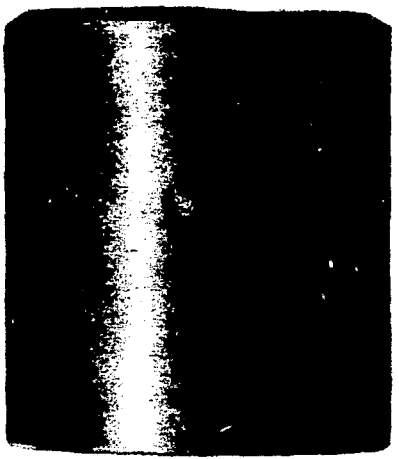


Fig. 9. : PITTING DEFECT IN PELLET

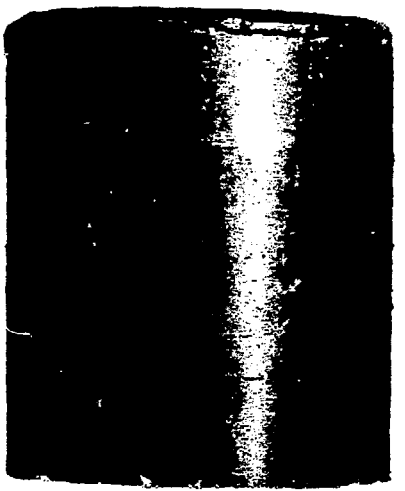


Fig. 10. : END FLAKING DEFECT IN PELLET