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by

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ABSTRACT

The feasibility of fabricating UO_2 fuel elements having densities of 90% theoretical by rotary swaging inside a Zircaloy or stainless steel sheath has been demonstrated. The results show that the density achieved in this process is a function both of the type of UO_2 used and the mechanical properties of the sheathing material.

INTRODUCTION

The fabrication of high density uranium dioxide fuel pellets to exacting dimensional tolerances involves a number of critical and expensive manufacturing operations typically shown in Fig. 1. Experiments were conducted at the Mines Branch, Ottawa,[2,3] in which modifications to this fabrication cycle were studied in an effort to reduce manufacturing costs while still maintaining a high degree of quality in the final product. Attention was also directed to alternative methods of fuel fabrication, again with the objective of reducing fuel costs.

One technique of fuel element manufacture, which may be less expensive than the conventional method, is the densification of UO_2 powder directly within its tubular metal sheath by means of rotary swaging operations. A series of experiments, involving over 150 samples, have been conducted in order to demonstrate the feasibility of such a fabrication method for the manufacture of fuel elements. The techniques employed and the results obtained to date are detailed in following portions of this report.

SWAGING EQUIPMENT

Basically, a rotary swaging machine consists of a split die with back-up hammers, which are rotated at high speed within a roll cage by means of a motor-driven spindle.

These components are shown in Fig. 2. As the die sections and hammers revolve within the roll cage they tend to move radially outward by centrifugal force. As the hammers pass each individual roll in the roll cage they are forced inward, thereby closing the die halves and imparting a blow to the work piece as it is fed through the die cavity. This action is repeated a number of times during each revolution of the spindle and causes the work piece to be forged to the shape of the die cavity.

A Fenn Manufacturing Company Model 4F rotary swaging machine (Fig. 3) was used which had a rated capacity of 15/16" diameter in solid rod or 2 1/4" diameter in tubing (based on mild steel). During the initial experiments only two dies were available - 0.500" diameter and 0.428" diameter. The latter size was chosen to correspond to the X-2 loop specimen diameter at the time so as to permit the preparation of specimens for irradiation testing. As the investigation proceeded, additional dies were obtained in order to accommodate larger tubing sizes and also to provide less drastic reductions in each swaging pass.

CHARACTERISTIC DEFORMATION DURING SWAGING

When a solid rod is swaged the reduction in cross-section area is, of course, accompanied by an increase in the length of the rod. Ignoring end effects, it is a simple matter to calculate the amount of elongation which occurs for any given reduction in cross-section area.

In the case of an empty tube being swaged, the net effect of the forces causing deformation is such that extensive wall thickening occurs and the elongation is only a small fraction of that of a solid rod of equal diameter for the same reduction in total cross-section area.

Swaging of a tube filled with a hard, finely divided powder, which is the case of importance in this application, does not appear from the literature to have received attention. Such an assembly might be expected to exhibit behaviour between that of a solid rod and that of an empty tube of the sheathing material employed.

Stages in the reduction by swaging of a UO_2 filled tube are shown in figure 4.

PREPARATION OF SPECIMENS

In this investigation the majority of tests were performed on assemblies in which the UO_2 powder was retained in tubular sheath by means of rubber plugs. The procedure used was to cut a length of tubing and press a rubber plug into one end of the tube. A known weight of UO_2 powder was then poured into the tube and the tube was tapped or vibrated until the powder assumed a minimum volume. By measuring the length of the powder section and the inner diameter of the tube the bulk density of the powder could be calculated and was termed the "tap density" of the powder. A second rubber plug was then pressed into the tube until it contacted the UO_2 powder and effectively sealed the tube.

A limited number of test specimens were also made with welded end plugs. The procedure followed in preparing these specimens was to weld one end plug in place, fill the tube with UO_2 powder to its tap density and weld the second end plug in place making sure that the space between end plugs was filled completely with powder. Stages in the assembly of swaged fuel elements are shown in figs. 5-6.

EXPERIMENTAL

For initial experiments, a series of samples were prepared consisting of lengths of 0.577" O.D. x 0.031" wall Zircaloy-2 tubing each containing one of the 5 different types of UO_2 powder described in Table 1. The oxide was retained in the sheath by means of rubber plugs in each case. The samples were swaged in turn through 0.500" diameter and 0.428" diameter dies thus providing an overall reduction in total cross section area of 44.5%. Sectioned samples from this investigation are shown in Figs. 7 and 8.

The results of these tests, shown in Table II, indicate that for the same amount of swaging reduction (44.5%) certain UO_2 powders attain higher densities than others. The highest swaged densities were obtained with the Norton fused oxide powder which is characterized by a high particle density and a high tap density. For different oxides, the swaged density appeared to be directly related to tap density but slight differences in tap density of samples of the same type of oxide showed no consistent effect on swaged density.

In order to investigate the effect of the extent of swaging reduction on the swaged density obtainable with different types of UO_2 powder, a second series of samples of various starting diameters was prepared. Aluminum-nickel alloy and type 304 stainless steel sheaths were used in some of the samples, to permit observations of the effect of sheathing material on the swaged density of the UO_2 powder.

The results of these tests are summarized in Table III. It will be observed from Table III for fused oxide clad in stainless steel that swaged density increased up to a certain reduction and that additional swaging did not produce an increase in oxide density. At equivalent reductions the Norton fused oxide clad in stainless steel sheaths swaged to a somewhat higher density than similar samples clad in aluminum-nickel alloy.

The results obtained in these two preliminary series of tests led to the following tentative conclusions:

1) UO_2 powders capable of being swaged to high densities exhibit high tap densities.

2) Since tap density is a function of particle density, particle size and particle size distribution, it should be possible to modify tap density within certain limits by varying one or more of these parameters and thus achieve higher swaged densities.

3) Swaged density increases with swaging reduction up to a point (termed the critical reduction) and remains essentially constant for additional swaging reduction beyond this point.

4) The maximum swaged density attainable is dependent on the sheathing material, being somewhat higher for Zircaloy and stainless steel than for the weaker aluminum-nickel alloy.

In the initial tests, highest swaged density was obtained with Norton fused oxide clad in Zircaloy-2 and swaged to 44.5% reduction in area. However, it was thought that the additional cost of the fused oxide would greatly reduce the possible economic advantage of the swaging process over the conventional fabrication method. Efforts were therefore directed toward the production of a sintered oxide which would have characteristics similar to those of the fused oxide.

The Chemical Engineering Branch undertook to supply a number of oxides prepared from different source materials, treated in different ways, and sintered in a standard sintering cycle. The oxides were clad in 0.577" O.D. x 0.031" wall Zircaloy-2 tubing and were evaluated by swaging to 44.5% reduction.

Each of the several batches of powder was subjected to a particle size distribution analysis by screening (see Fig. 9), an oxygen-uranium ratio was determined, and particle and tap densities were measured prior to swaging.

The results of these tests are given in Table IV together with a description of the treatments applied to the various oxides, and are illustrated graphically in Figs. 10, 11. Results showed the following trends:

1) Waxing and/or pressing produced an increase in tap density over that obtained by sintering alone. The particle density of both ADU route and UO_3 route powders was apparently reduced by pressing, indicating that closed porosity was developed.

2) The highest swaged density (expressed as % theoretical for UO_2), apart from fused UO_2 was obtained with ADU route powders, as shown in Fig. 10. However, in Fig. 11 where the tap and swaged densities are plotted as a percentage of particle density, no difference can be detected between samples of UO_3 route and ADU route materials, nor between either of these materials and fused UO_2.

3) Swaged density increases with tap density for both ADU and UO_3 route UO_2.

4) For a given tap density, the swaged density is higher for higher particle density.

Although the swaged density obtained with sintered oxides was not as high as that obtained with fused oxide, density of at least 90% of theoretical could be achieved using this type of swaging feed material. The optimum powder treatment is shown in Fig. 12.

From the results of Tables II and III a critical reduction by swaging appeared to exist beyond which no further densification of the oxide core occurred, the density so achieved for a given oxide being dependent on properties of the sheathing material. In order to investigate the critical reduction and characteristic density for a number of sheath/fuel combinations, a series of different oxides were sheathed in Zircaloy-2, aluminum and type 304 stainless steel, the oxide being confined by end plugs of the appropriate material, welded in place. Each specimen was then swaged in increments to high reductions, the oxide density being calculated from sample dimensions after each swaging pass.

The results are shown in Table V and several are plotted in Fig. 13, and confirmed results previouly obtained on samples using rubber plugs. The critical reduction was found to be related to the sheathing material, being lower for the weaker sheathing material (aluminum) and higher for the stronger sheathing materials. At reductions below the critical reduction, the oxide density was found to be independent of the sheathing material and varied with the tap density of the powder. For a given type of oxide, the highest swaged density was associated with the sheathing material showing the highest critical reduction, in this case Zircaloy-2. No cracking was experienced with aluminum or stainless steel sheaths at reductions up to 80% whereas cracking occurred in certain cases for Zircaloy clad specimens at reductions above 40%.

Some tests were performed in which the oxide was pre-compacted into pellets at 40,000 psi before loading into stainless steel sheaths. These specimens are compared to similar specimens containing loose packed oxide in Fig. 14. For loose sintered UO_2 (type "F"), although the maximum or "characteristic" density is not increased by pre-compaction, the critical reduction required to achieve this density is decreased. For type "A" (as-reduced A.D.U. route UO_2) the swaged density is increased at intermediate reductions by pre-compacting the oxide but the limiting density is not apparently increased.

The effect of particle size was investigated briefly by preparing Norton fused oxide in three distinctly different size ranges and graded so as to obtain the same tap density for each size range. The results are shown in figure 15 and tend to indicate that maximum swaged density for a given oxide powder can be increased by the use of large particle sizes graded to give high tap density.

During the course of the investigation numerous miscellaneous samples were prepared to evaluate particular grades of oxide, as loop samples, or as control samples with oxides of known characteristics. The results of these tests are summarized in Table Vl. While it is difficult to draw conclusions from such a heterogeneous set of results, no effect of tube size on the density achieved for a given reduction during swaging is apparent. The total range of diameters covered is, of course, within a factor of two.

DISCUSSION AND CONCLUSIONS

1) The manufacture of fuel elements by rotary swaging of uranium dioxide powder within a tubular metal sheath appears to be quite feasible. In practice the fuel could be prepared in approximate multiples of the desired length with the oxide retained within the sheath by means of rubber plugs. Following swaging, the elements would be cut and machined to the exact length desired and excess oxide removed by machining to permit the insertion of permanent metal end plugs. The alternative method whereby the fuel elements are welded individually before swaging cannot be recommended until more information is available

on end plug design and on the length variation which can occur on swaging nominally identical elements.

2) Best results are obtained with uranium dioxide powders having a particle density approaching theoretical density, a low specific surface area, and a high bulk density. These characteristics are best obtained with a fused oxide, which has been adjusted to the required particle size distribution by comminution and screening. Characteristics approaching those of fused uranium oxide may be obtained with oxide initially prepared by the A.D.U. route and subsequently agglomerated and loose sintered in a hydrogen or steam/hydrogen cycle.

3) Aluminum, austenitic stainless steel and Zircaloy-2 sheaths were tested in this investigation. Best results were obtained using Zircaloy-2, although results using stainless steel were nearly as good. Some cracking of Zircaloy sheathed elements was noted at reductions only slightly over the critical reduction. However, it is thought that this problem could be circumvented by precompaction of the powder so as to reduce the critical reduction value or, alternatively, by introducing an intermediate annealing treatment so as to restore the ductility of the sheath.

4) During the initial stages of swaging the sheathing behaves as an empty tube and undergoes extensive wall thickening, and the oxide density increases markedly. Above a certain critical

reduction, which is dependent upon the properties of both the sheathing material and the oxide powder, the oxide cannot be densified any further and additional swaging merely causes the tubing wall to thin and the assembly to lengthen markedly. In this stage the tubing reacts as though it were being swaged over a mandrel. These changes are shown diagrammatically in Figure 16. It may be possible to use this characteristic deformation to advantage in producing thin-walled fuel elements.

5) The results of this investigation indicate no effect of starting diameter on swaged density.

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TABLE I

Sources of Materials Employed in Initial Experiments

Type of UO_2	Supplier	Raw Material	Treatment
'used oxide	Norton Co. Chippawa, Ont.	"Moving bed" UO_2	Smothered carbon arc fusion, product crushed and milled
:.G.E. Sintered	Carboloy Division of Canadian General Electric	A.D.U.* route UO_2.	Agglomerated, sintered at 1700°C in H_2, milled as required
..E.C.L. Sintered	--	A.D.U. route UO_2	Pressed 40,000 p.s.i., granulated -20 mesh, sintered in H_2 4 hrs. 1700°C, milled as required.
'High temperature" ..E.C.L. UO_3 route	--	UO_3	Reduced in H_2 at temperature up to 1200°C, used as received
:ldorado "moving bed"	Eldorado Mining and Refining Ltd.	UO_3	Reduced in pellet form by H_2 in a moving bed reactor. Milled as required.

* A.D.U. ≡ ammonium diuranate

TABLE II

SWAGING RESULTS FOR A NUMBER OF TYPES OF URANIUM DIOXIDE CLAD IN ZIRCALOY-2

Sample No.	Uranium Oxide Type & Batch Number	Grade USS Sieve No.	O/U Ratio	Density of UO_2 g/cm^3 Particle	Tap	Swaged
18		-165 mesh	1.96	10.97	7.4	10.5
22		-170 mesh	1.96	10.97	7.4	10.2
51	Fused oxide	-14	1.96	10.97	7.4	10.3
57		-30	1.96	10.97	7.8	10.2
1		As received	2.01	10.75	6.8	9.9
2		As received	nd	nd	6.8	9.7
20		-165 mesh	nd	nd	nd	10.1
27		-170 mesh	nd	nd	6.9	10.1
33	CGE Sintered	-170 mesh	nd	nd	6.3	10.1
36		-170 mesh	nd	nd	6.4	9.7
26		-170 mesh	nd	nd	6.0	10.0
34		60%-70 mesh + 100 mesh 40%-270 mesh + 325 mesh	nd	nd	7.0	10.0
35		60%-35 mesh + 50 mesh 40%-270 mesh + 325 mesh	nd	nd	7.2	9.9
37	AECL Sintered (P72)	-170 mesh	2.02	nd	7.0	9.8
38		-170 mesh	2.02	nd	6.6	9.8
24	AECL Sintered (P67)	-170 mesh	nd	nd	5.6	9.4
48	Eldorado "moving bed" 6038B	As received	nd	nd	4.1	7.7
49	Eldorado "moving bed" 6040B	As received	nd	nd	4.0	7.9

Note: (1) All results are for specimens clad in tubes initially 0.577 O.D. x 0.031" wall, and reduced 45% in area by swaging.

(2) nd = not determined.

TABLE III

THE EFFECT OF SHEATHING MATERIAL, ELEMENT DIAMETER AND SWAGING REDUCTION IN AREA ON THE SWAGED DENSITY OF THREE TYPES OF URANIUM DIOXIDE

Sample No.	Uranium Oxide Type	Grade (USS sieve)	Sheath Material	Initial diameter of sheath (in.)	Reduction in area on Swaging (%)	Density of UO_2 g/cm^3 Particle	Tap	Swaged
42	Fused oxide	-170	Aluminum/nickel	0.505	28.5	10.97	6.9	9.5
44	" "	-170		0.508	28.5	10.97	7.0	9.5
67	Fused oxide	-170	Stainless steel	0.631	15.0	10.97	7.3	8.9
68		-170		0.749	22.0	10.97	6.9	9.1
66		-170		0.503	28.0	10.97	7.0	10.0
71		-170		0.503	28.0	10.97	7.1	9.8
69		-170		0.631	37.0	10.97	6.7	9.7
72		-170		0.632	37.0	10.97	7.1	9.8
73		-170		0.743	41.0	10.97	6.9	9.8
85		-170		0.876	42.0	10.97	6.8	9.5
25	C.G.E.sintered	-170	Zircaloy-2	0.600	39.0	10.75	6.0	9.2
23	" "	-170		0.750	41.5	10.75	6.0	9.8
7	High temperature	*	Zircaloy-2	0.500	26.5	10.24	4.9	7.0
8	AECL UO_3 route	*		0.500	26.5	10.24	4.9	6.6

* nd = not determined.

TABLE IV

THE EFFECT OF VARIOUS TREATMENTS ON THE SWAGED DENSITY OBTAINED FOR SEVERAL TYPES OF URANIUM DIOXIDE

Sample No.	Starting Material	Treatment [2,5]	O/U Ratio After Treatment	Density g/cm^3 Particle	Tap	Swaged
52		Reduced only	2.03	10.45	3.9	7.8
62		Waxed and slurried[3] before sintering	2.02	10.78	4.2	8.5
50	E-20 UO_3	Sintered	2.08	10.33	4.3	8.5
53		Sintered	2.01	10.51	4.8	8.7
60		Sintered	2.02	10.32	5.5	9.0
65		Sintered	2.02	10.36	5.5	8.9
61		Waxed and slurried[3] before sintering	2.02	10.76	6.1	9.1
58		Waxed and pressed[4] before sintering	2.02	10.31	6.8	9.7
76	E-44 UO_3	Sintered	2.02	10.44	5.9	9.3
77		Waxed and pressed before sintering	2.02	10.29	5.7	9.4
63		Sintered	2.02	10.90	5.4	9.0
64		Waxed and tumbled before sintering	2.02	10.80	6.2	9.1
75	"Micronised" UO_3	Pressed before sintering	2.01	10.43	6.8	9.6
74		Waxed and pressed before sintering	2.01	10.48	7.0	9.7
56	P163 ADU	Sintered	2.02	10.74	5.6	9.4
55	P164 ADU	Reduced before sintering	2.02	10.97	6.0	9.3
54	P164 ADU	Reduced before sintering	2.02	10.94	6.0	9.5
81	E45 ADU	Reduced before sintering	2.01	10.81	5.8	9.4
80		Waxed and pressed before sintering	2.01	10.76	7.0	9.8
79		Reduced, waxed & pressed before sintering	2.01	10.61	7.2	9.9

Notes:

(1) All specimens were clad in Zircaloy-2 tubing, initially 0.577" diameter and reduced 44.5% in area during swaging.

(2) The standard sintering cycle consisted of heating in hydrogen to 1000°C, steam from 1000° to 1400°C, holding in steam for 30 mins. at 1400°C before cooling to room temperature in steam. The resulting oxide powder was then reduced to $UO_{2.0}$ in hydrogen at 900°C.

(3) Slurried samples were dried and granulated through a 20 mesh screen before sintering.

(4) Pressed samples were pressed at 20,000 psi then granulated through a 20 mesh screen before sintering

(5) Unless stated otherwise, treatment was done on the source material which was then reduced in the sintering cycle.

TABLE V

Results of Swaging Experiments on Welded Assemblies

Sheath Material	Oxide Type & Batch No.	Grade U.S. Sieve	UO_2 Tap Density g/cm^3	Starting Diam. (in)	Total Reduction in area %	Final Diam. (in.)	UO_2 Swaged Density g/cm^3
Aluminum	Fused UO_2	-30	7.3	1.000	44	.749	9.1
	Fused UO_2	-30	7.4	.626	53	.425	9.4
	(AECL Sint)F79	-20	7.6	.750	28	.636	9.0
	HTR UO_2	AR	4.5	.999	81	.427	7.2
	ADU (as reduced)	AR	1.9	.626	54	.426	5.4
Stainless Steel	Fused UO_2	-400	6.7	.748	47.5	.541	9.9
	Fused UO_2	-30	7.6	.753	48	.542	10.0
	Fused UO_2	-6 + 18	6.3	.626	52	.434	10.3
	Fused UO_2	-30 + 170	6.6	.626	51	.438	10.1
	Fused UO_2	-400	6.6	.626	51	.438	9.8
	(AECL Sint)F88	-20	7.0	.748	47	.543	9.8
	C.G.E. Sintered	-170 (compacted 40,000 psi)	8.4	.629	51	.437	9.6
	Eldorado moving bed (PMB)	AR	4.2	1.000	54.5	.675	7.7
	" " (MB6040B)	AR	4.2	.630	52	.437	7.8
	" " (MB6040B)	AR	4.2	.753	54	.512	7.6
	HTR U02	(compacted 40,000 psi)	6.2	.630	51	.437	8.6
	ADU (p68) route (as reduced)	AR	1.8	.748	66	.435	7.7
	ADU route (as reduced)	-170 (compacted 40,000 psi)	5.2	.627	51	.437	7.8
Zircaloy	Fused UO_2	-30	7.6	.750	35	.603	9.9
	Fused UO_2	-30	7.6	.751	35	.605	9.9
	Fused UO_2 *	-30	7.4	.577	45	.428	10.2
	Fused UO_2	-30	7.7	.751	40.5	.580	9.8
	HTR UO_2	AR	4.4	.750	40	.582	7.6
	Eldo. Moving Bed (MB6040B)	AR	4.6	.600	47	.436	7.7
	ADU route P68 (as reduced)	AR	2.0	.600	49	.428	4.5

AR = as received   * Rubber end plugs

HTR = High temperature AECL UO_3 route.

TABLE VI

THE EFFECT OF SHEATHING MATERIAL, ELEMENT DIAMETER AND SWAGING REDUCTION ON THE SWAGED DENSITY OF MISCELLANEOUS SAMPLES OF URANIUM DIOXIDE

Sample No.	Oxide Type[1] and Batch No.	Grade USS Sieve	O/U Ratio	Sheath Material	Initial Sheath Diameter (ins.)	Swaging Reduction % Area	Density of UO_2 g/cm^3 Tap	Swaged
95	P78 sintered ADU route	nd[2]	nd	Stainless Steel	1.000	80.0	7.6	9.7
125	CGE sintered ADU route	-18	nd	" "	0.917	38.0	7.9	9.3
126	CGE sintered ADU route	-18	nd	" "	0.922	26.0	7.9	9.1
127	CGE sintered ADU route	-18	nd	" "	1.048	41.0	7.5	9.6
128	CGE sintered ADU route	-18	nd	" "	1.183	55.0	8.1	9.4
129	P87B sintered ADU route	As rec'd	2.02	" "	1.164	53	6.3	9.3
130	P85B sintered ADU route	As rec'd	2.02	" "	1.165	61	6.9	9.5
132	P87B sintered ADU route	-16	2.02	" "	1.165	53	7.2	9.1
136	P83B sintered ADU route	As rec'd	2.02	" "	1.165	61	6.6	9.2
137	P83B " " "	+ 100	2.02	" "	1.165	61	6.1	9.4
138	P84B " " "	+ 70	2.02	" "	1.165	61	6.1	9.4
139	P86B " " "	+ 70	2.02	" "	0.924	40	6.0	9.2
142	P96 tumbled, sintered, ADU route	As rec'd	nd	" "	0.626	51.5	5.1	9.3
143	P96 " "	+ 170	nd	" "	0.626	51.5	5.2	9.2
144	P97 Pressed, sintered, ADU route	As rec'd	nd	" "	0.626	51.5	6.6	9.6
145	P97 " "	+ 170	nd	" "	0.626	51.5	5.9	9.6
146	P87C sintered ADU route	+ 70	nd	" "	0.753	68.0	nd	9.7
149	P88D " " "	As rec'd	nd	" "	0.753	50.0	6.5	9.1
150	P88D " " "	-170	nd	" "	0.753	50.0	5.8	9.2
96	Fused UO_2	nd	nd	" "	1.000	80.0	7.8	9.7
131	Fused UO_2	-16	1.96	" "	1.164	53	nd	9.9
135	Fused UO_2	-16	1.96	Zircaloy-2	0.600	39	7.3	9.8
141	Fused UO_2	+ 170	1.96	"	0.599	39	7.6	9.8
147	Fused UO_2	-18	nd	Stainless Steel	0.753	68.0	nd	9.7
148	Fused UO2	-18	nd	" "	0.753	68.0	nd	9.8
134	P67 crushed, sintered pellets	nd	2.01	Zircaloy-2	0.600	30	7.7	9.4
133	UK Electrolytic UO_2[3]	As rec'd	2.02	Zircaloy-2	0.600	40	5.9	9.9
99	High Temp. UO_3 route	As rec'd	nd	Stainless Steel	1.000	81.0	4.7	8.9
97	Eldorado moving bed(6038B)	As rec'd	nd	" "	1.000	81.0	4.0	8.3
112A	" " " "	As rec'd	nd	" "	0.630	52.0	4.2	7.8
113	" " " "	As rec'd	nd	" "	0.630	52.0	4.1	7.7
98	P68 as reduced ADU route	As rec'd	nd	" "	1.000	81.0	1.8	8.5

NOTES: (1) The term "sintered" indicates the as-reduced powder was pressed into pellets at 20,000 psi using 2 w/o wax binder, the pellets granulated through a 20 mesh screen and sintered in hydrogen at 1650-1725°C, before grinding to the grade specified in column 3. "Tumbled" material was tumbled in a mixer to provide agglomerates prior to sintering, as opposed to the pressing and granulating treatments decribed above. Routes "ADU" and "UO_3" refer to the parent compound from which the UO_2 was produced.

(2) nd = not determined.

(3) Supplied by AERE, Harwell, England. Preparation route not known.

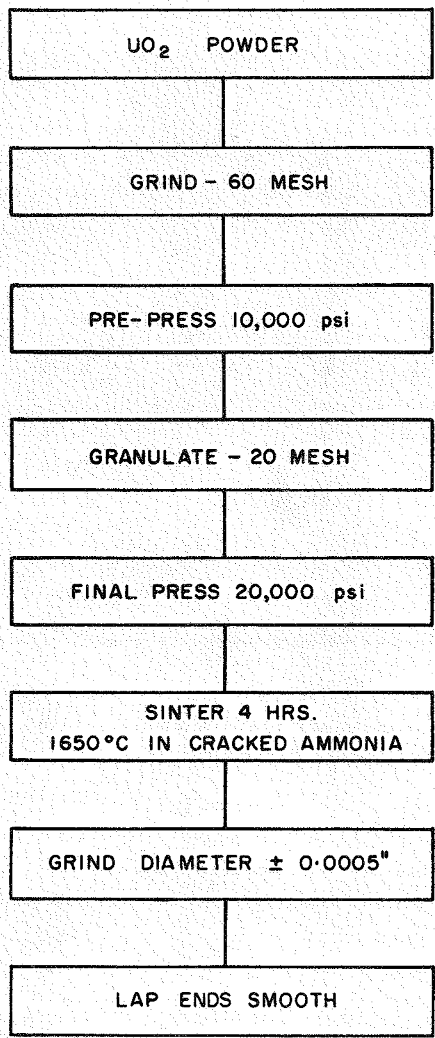

Figure 1 Typical flowsheet for UO_2 pellet fabrication

(Photo No. CT-1894A)

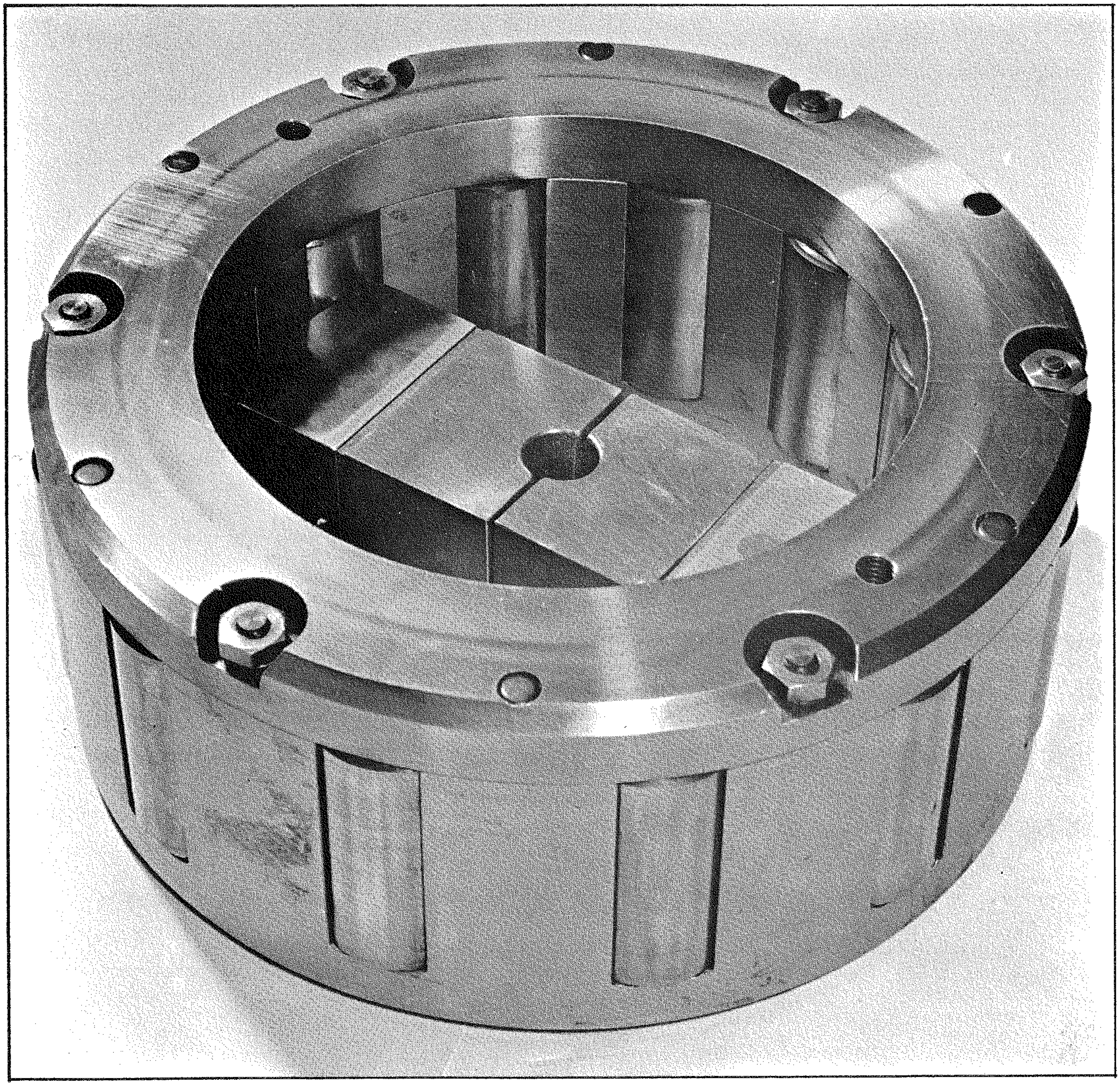

Figure 2 Roll cage, hammers and dies of swaging machine

(Photo No. 1702-2)

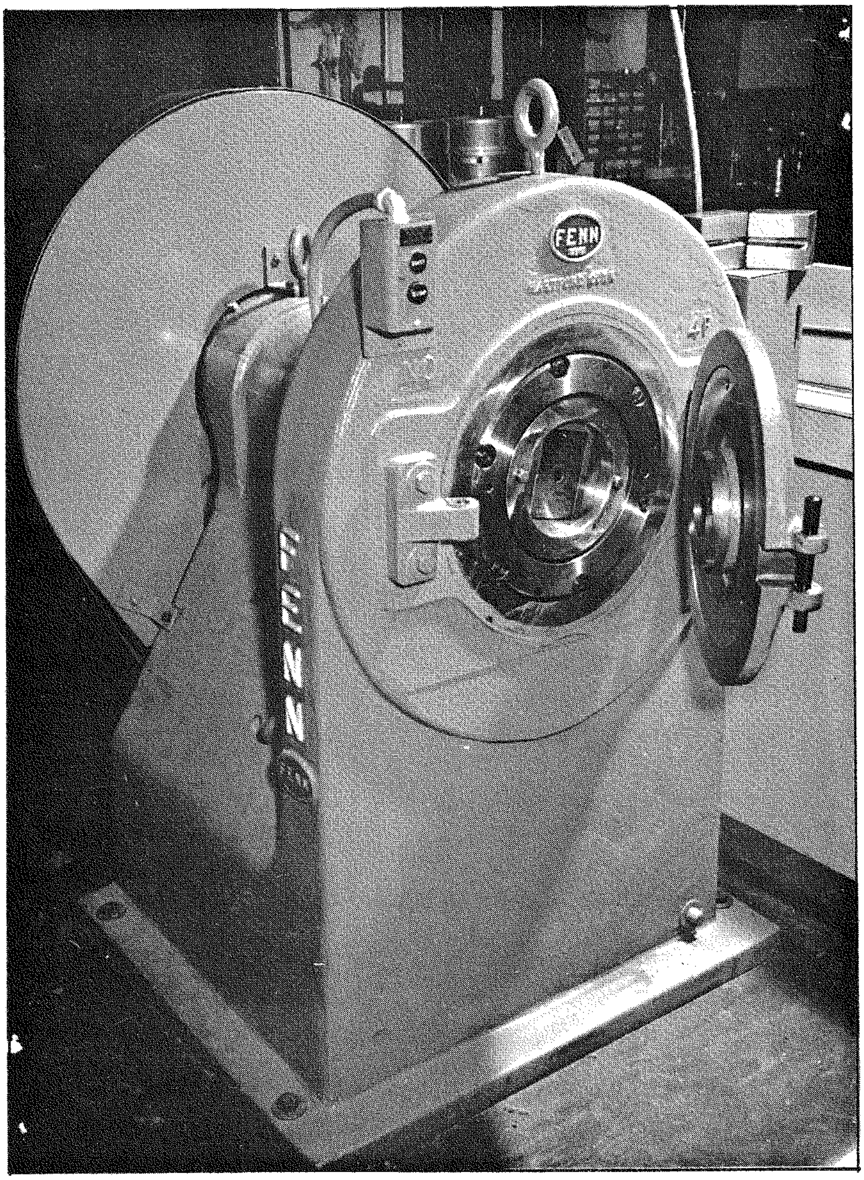

Figure 3 Fenn model 4F swaging machine

(Photo No. 1210-3)

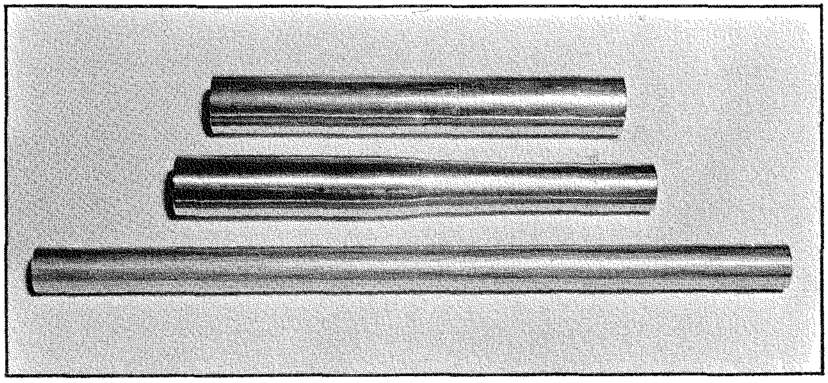

Figure 4 Stages in the reduction of a filled tube by rotary swaging

(Photo No. 1450-2)

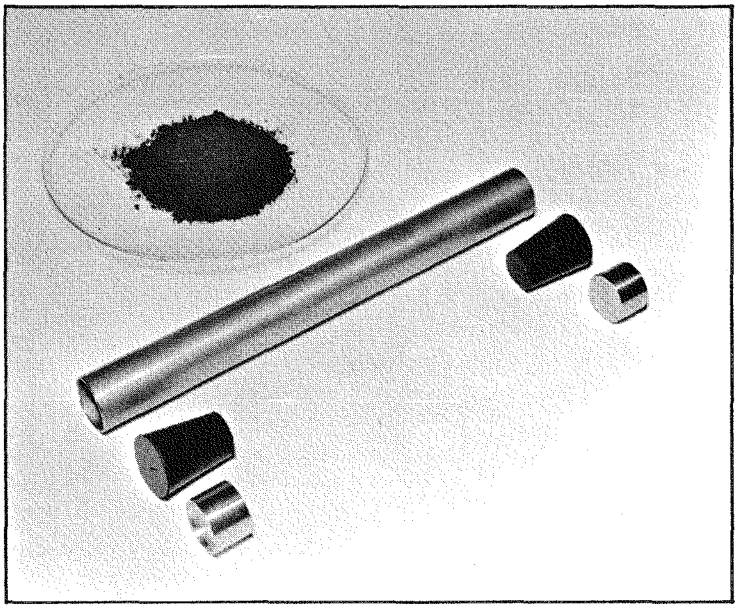

Figure 5 Uranium dioxide powder, sheath, rubber plugs and welded plugs used in fuel element assembly.

(Photo No. 1450-1)

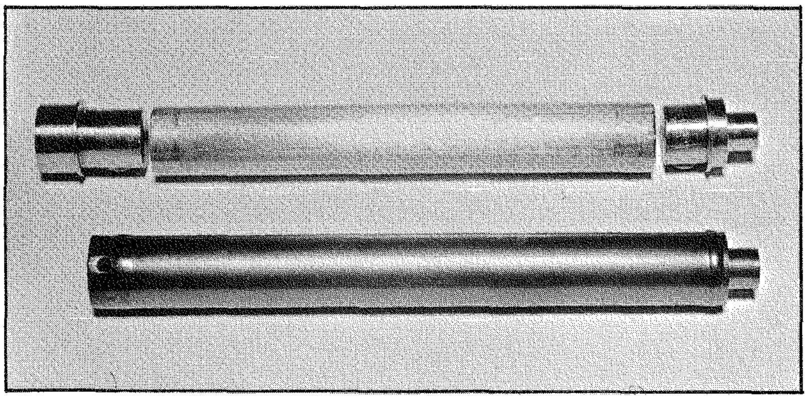

Figure 6 Swaged element of UO_2 in Zircaloy before installing final welded end plugs, and a similar element after welding and autoclave testing

(Photo No. 1450-3)

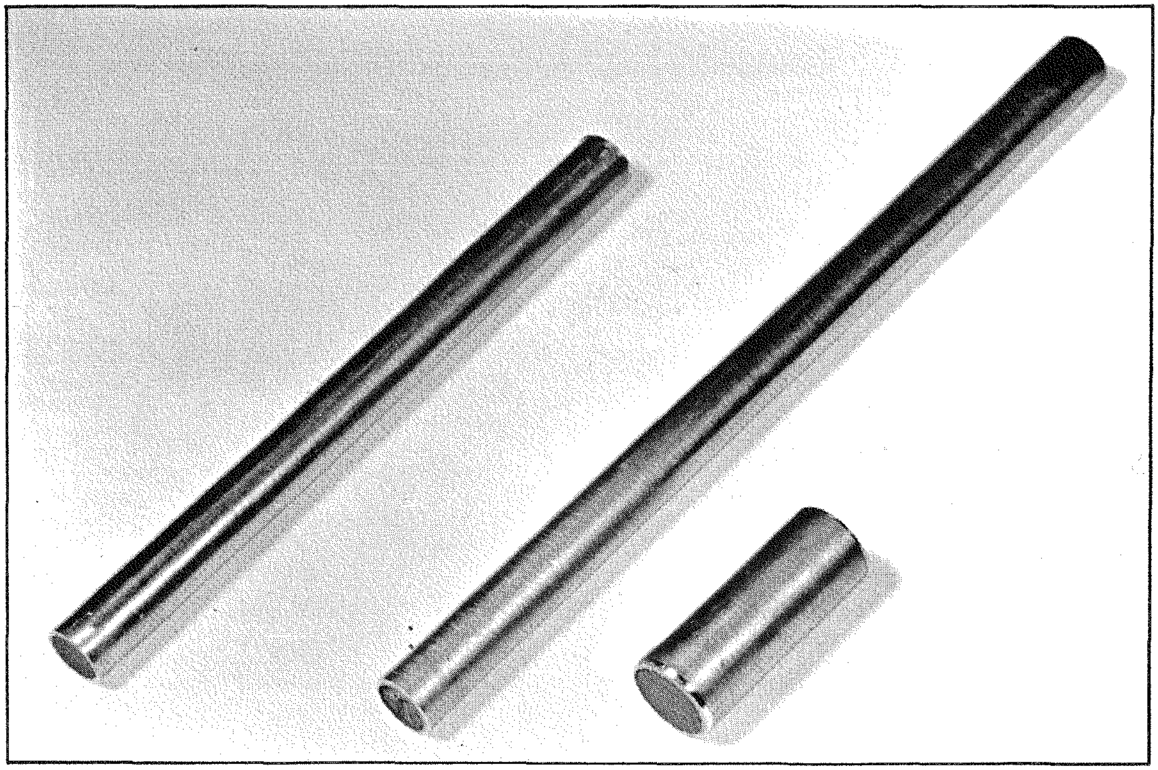

Figure 7 Swaged sections of UO_2 clad in Zircaloy

(Photo No. 1210-8)

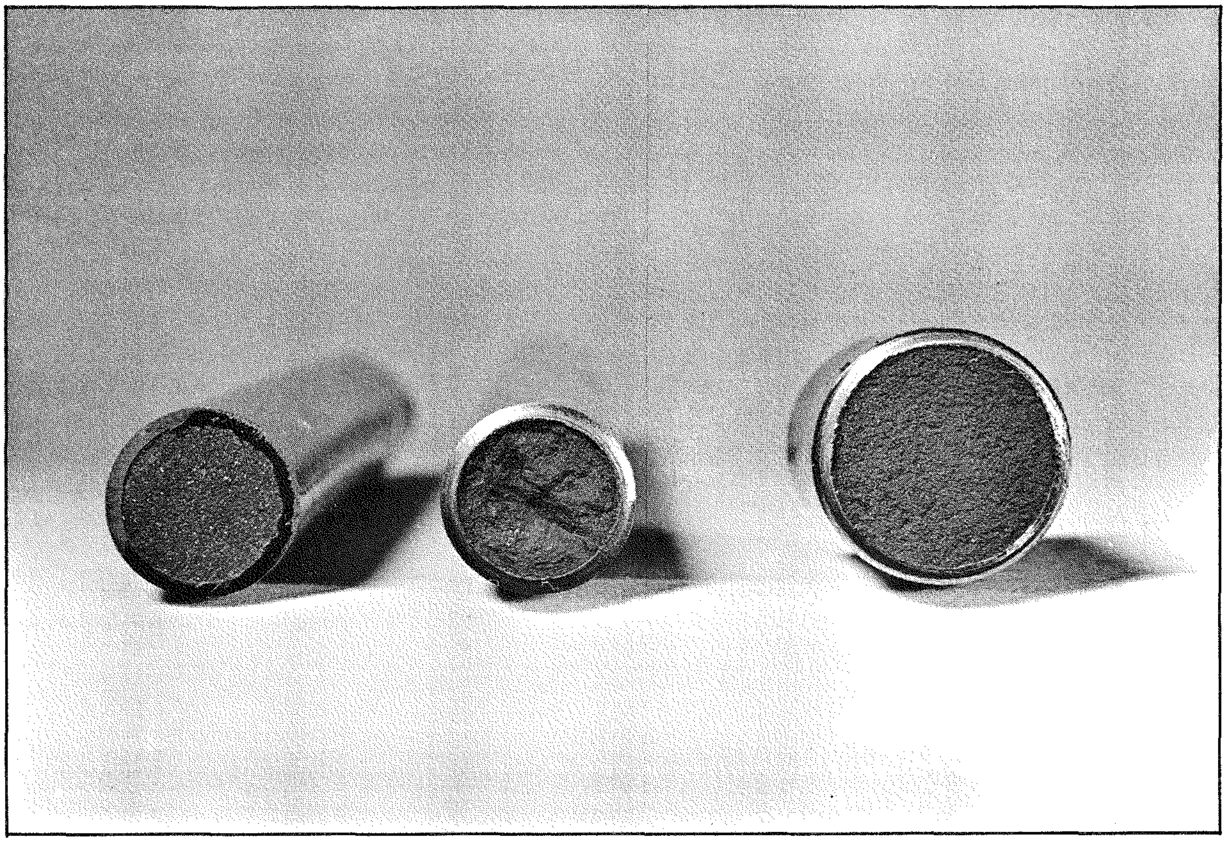

Figure 8 Swaged sections of UO_2 clad in Zircaloy showing the appearance of the fuel. Left to right:

(i) Norton fused UO_2 45% reduction, density 94%

(ii) Sintered UO_2 45% reduction, density 90%

(iii) Sintered UO_2 42% reduction - density 89%

(Photo No. 1210-9)

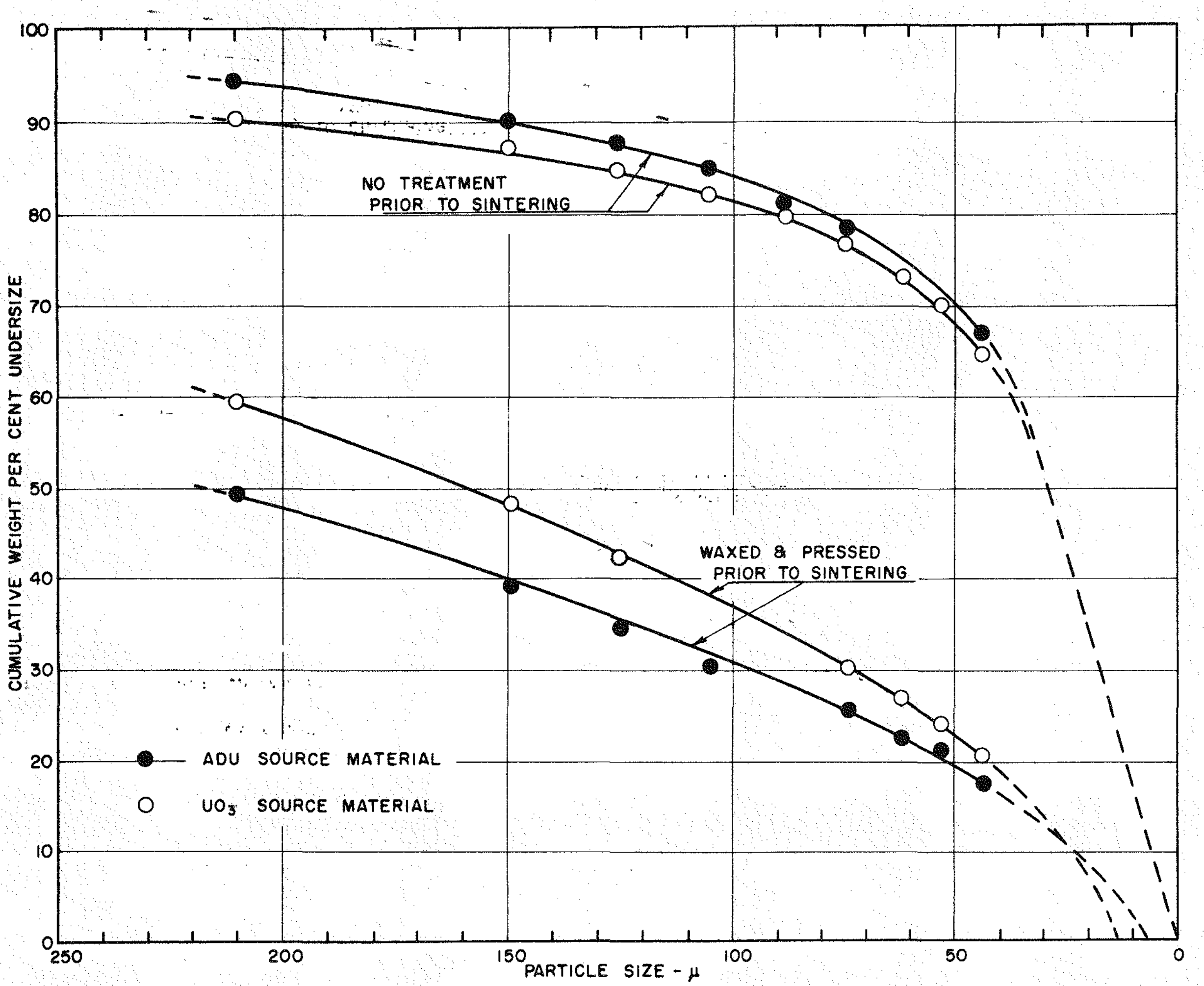

Figure 9 The effect of prior treatment on the particle size distribution of UO_2 powder obtained after sintering

(Photo No. CT-1471A)

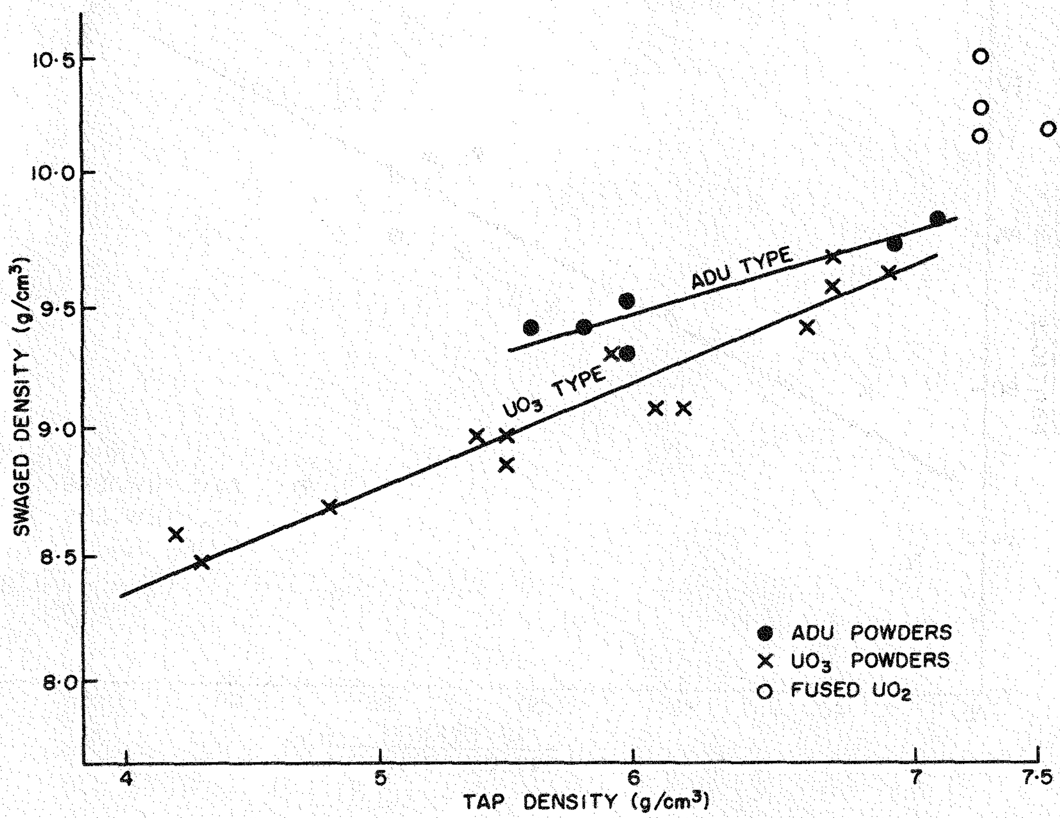

Figure 10 The relation of tap density and swaged density for three types of UO_2 powders

(Photo No. CT-1894C)

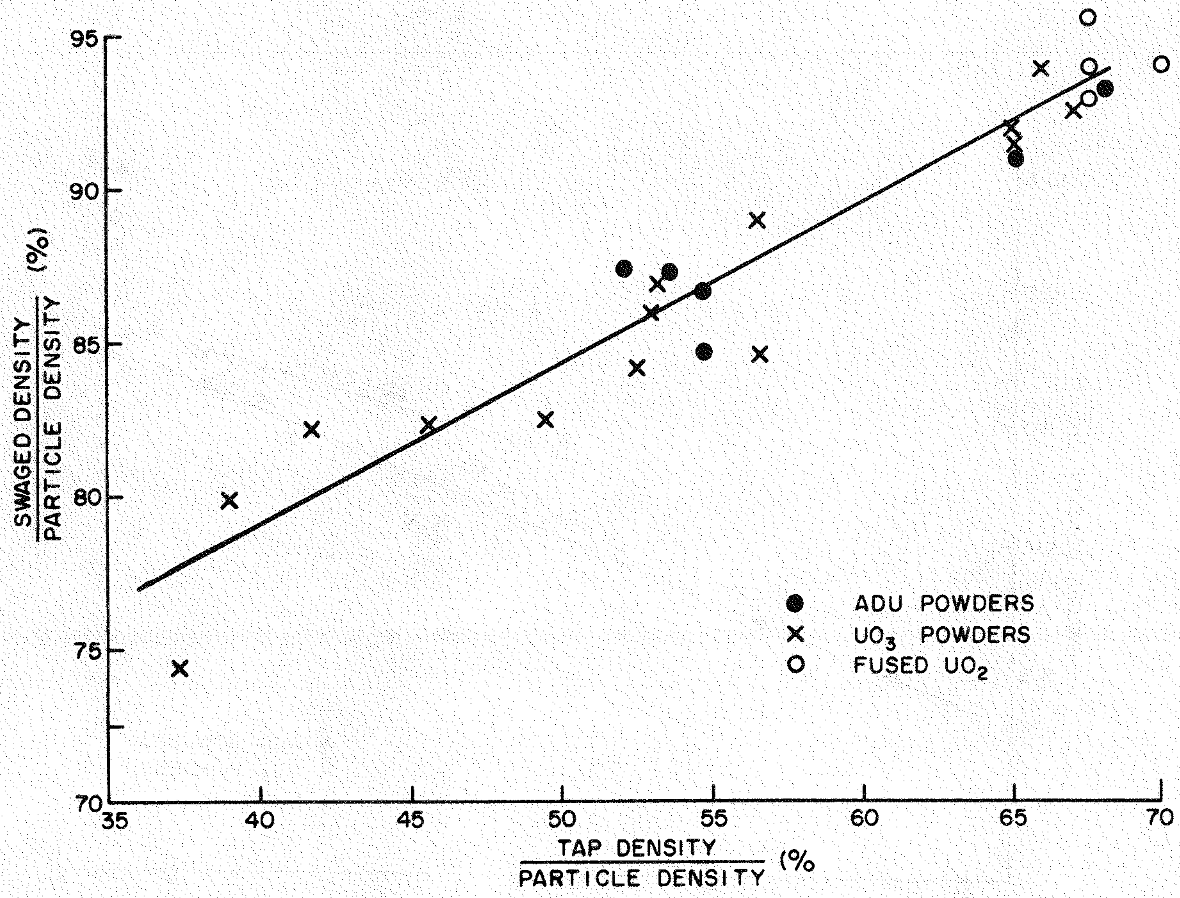

Figure 11 Tap density/swaged density relationships for three types of UO_2 powder, corrected for particle density variations.

(Photo No. CT-1860C)

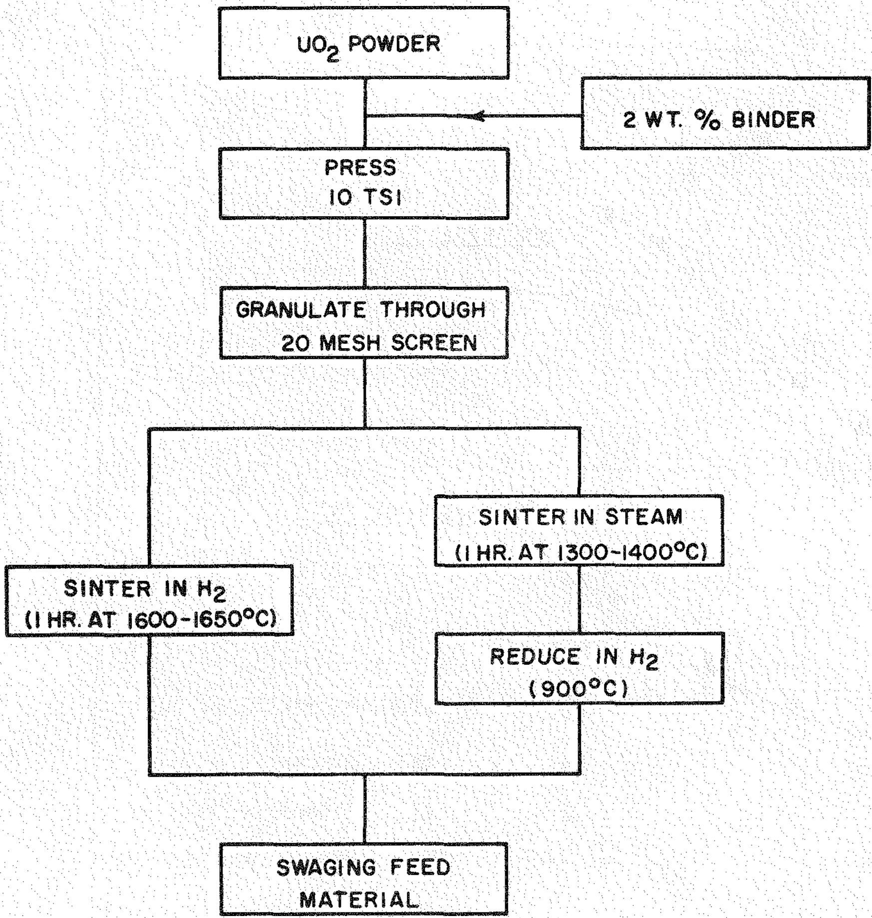

Figure 12 Flowsheet for the preparation of UO_2 swaging feed (Photo No. CT-1860D)

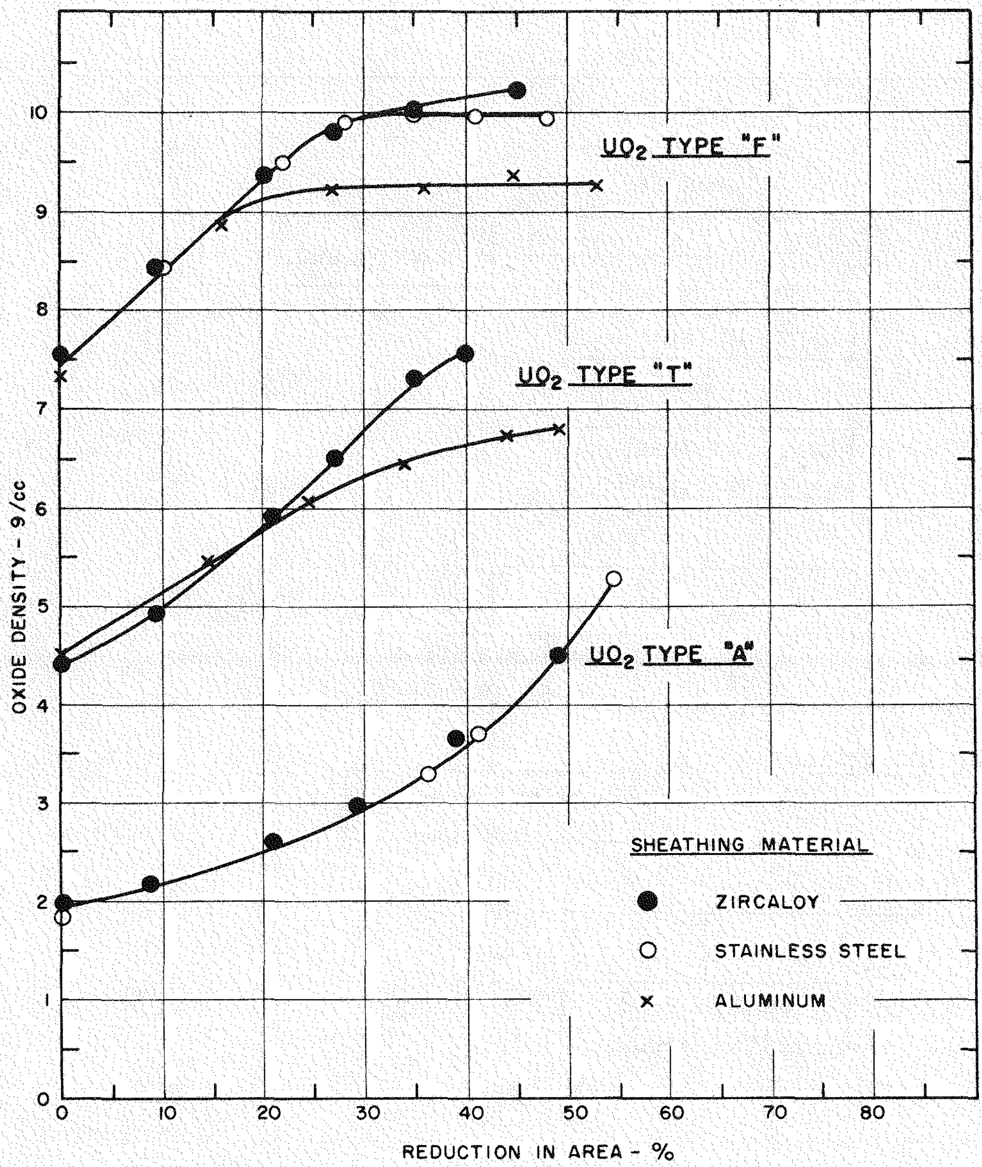

Figure 13 The effect of reduction in area by swaging on the density of three types of UO_2 clad in three sheathing materials.

UO_2 type F: Fused UO_2

type T: UO_2 reduced at 1200°C

type A: ADU reduced at 900°C

(Photo No. CT-1471D)

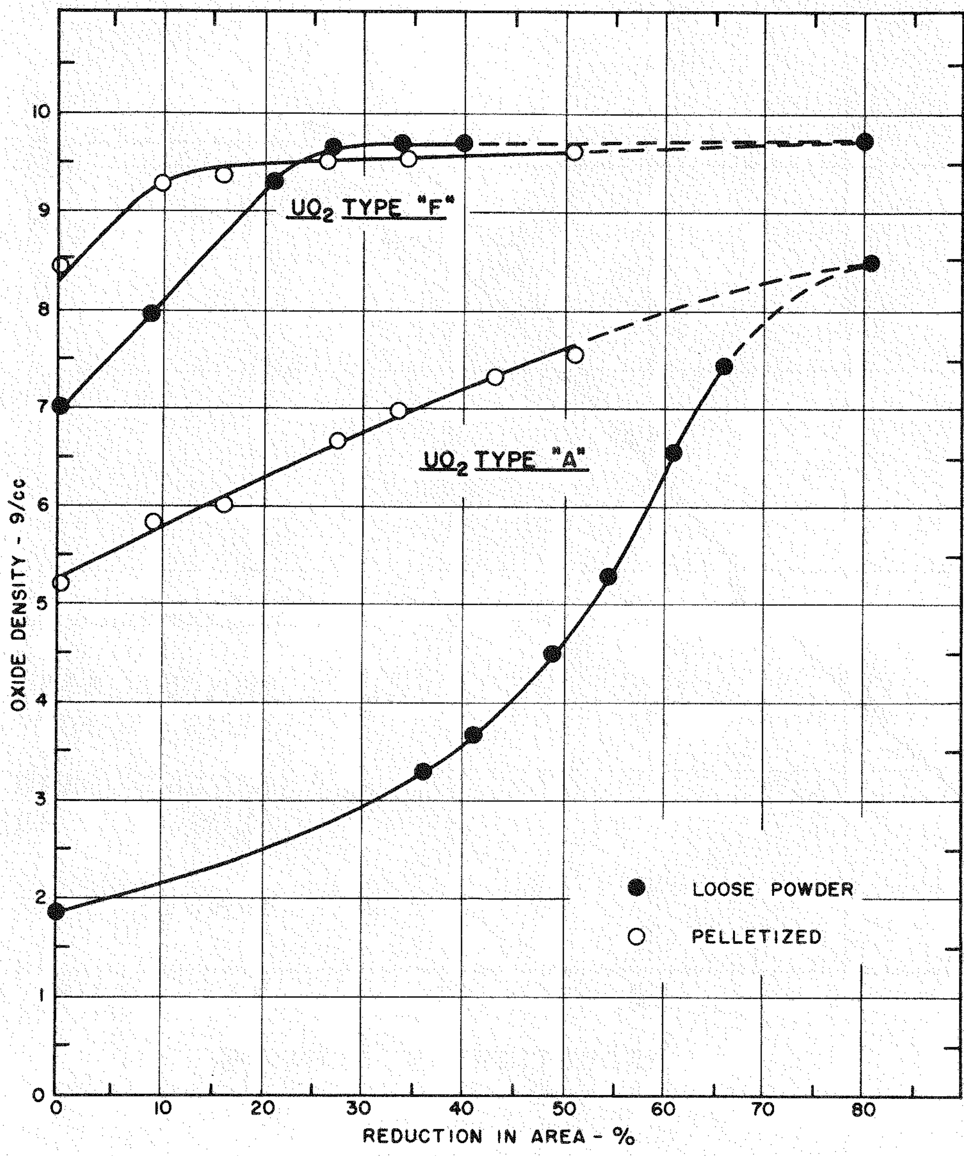

Figure 14 The effect of pre-compacting UO_2 powder on the density obtained by swaging.

UO_2 type F: Sintered UO_2

type A: ADU reduced at 900°C

(Photo No. CT-1471E)

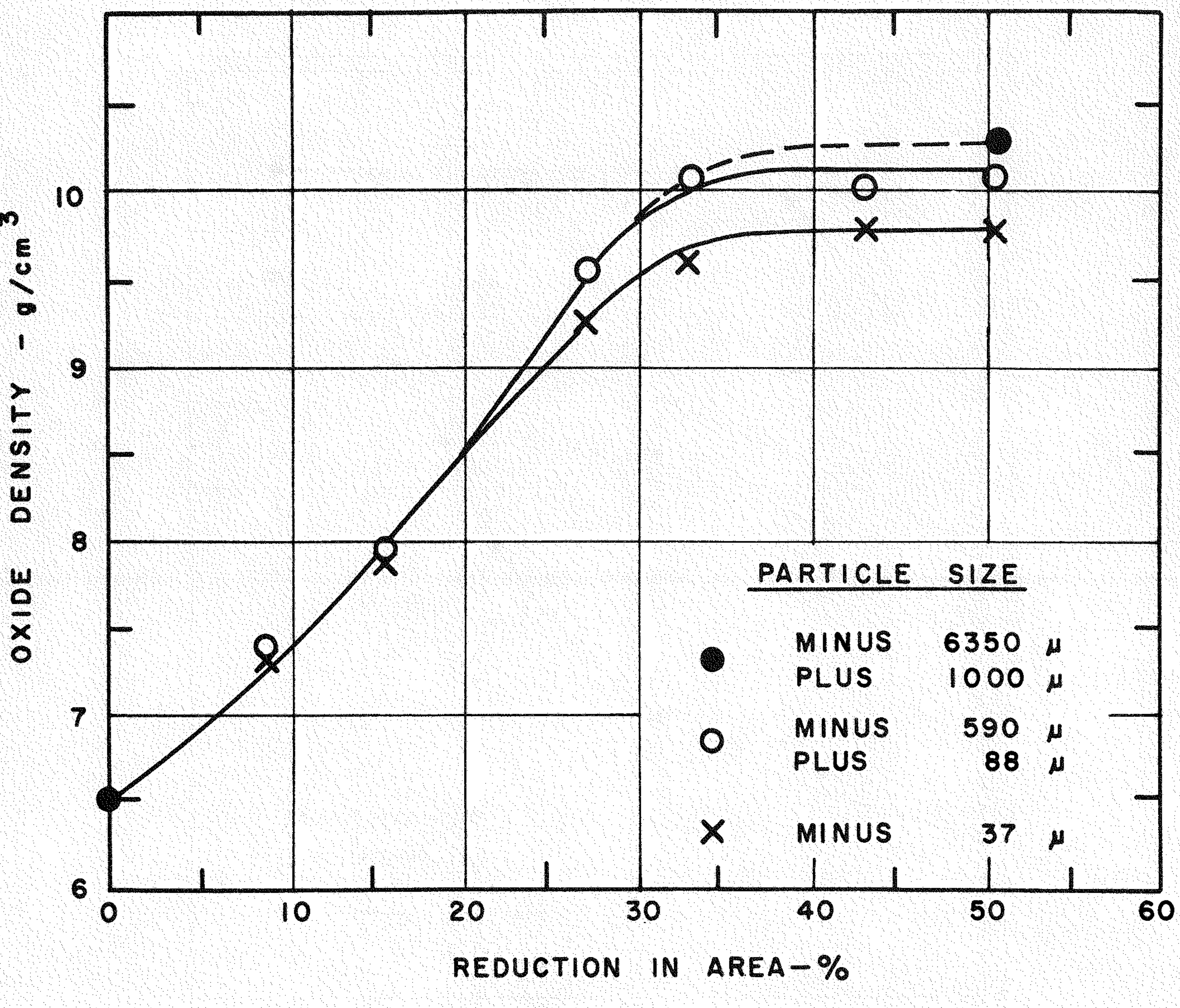

Figure 15 The effect of particle size on the density obtained by swaging fused UO_2 in stainless steel sheathing.

(Photo No. CT-1924A)

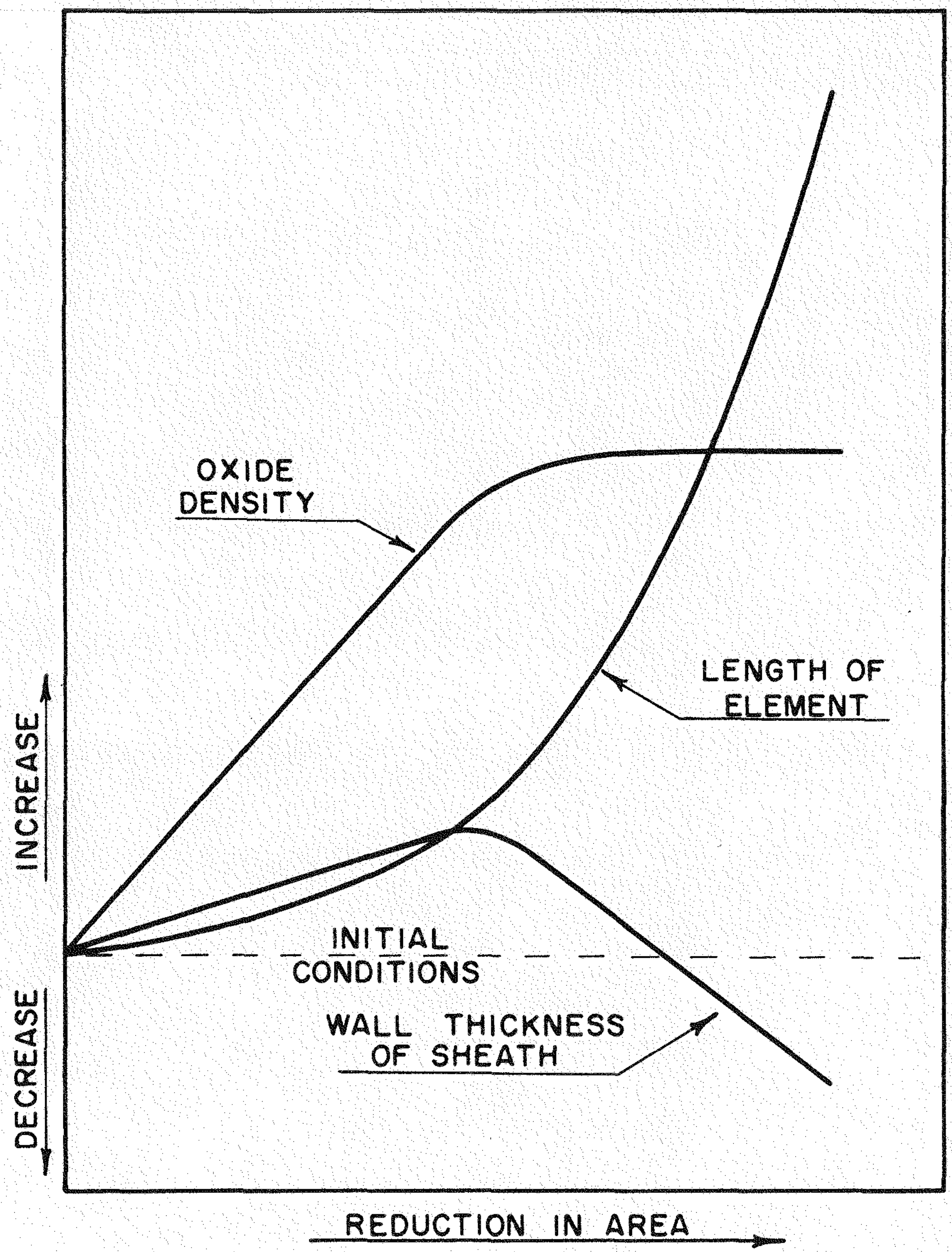

Figure 16 Typical changes in UO_2 density and in sheathing dimensions during swaging

(Photo No. CT-1471B)