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SWAGING OF URANIUM DIOXIDE

by

G. FRIGERIO

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Main objective of the work program was to study on a small pilot plant scale the reproducibility of data obtained with the following vibro-swaging process : pneumatical vibration (4 minutes duration) to reach a UO_2 density of approximately 84% of theoretical followed by two passes through the swager without intermediate annealing for a reduction of total area of approx. 18%.

More than one hundred rods of reactor length (125-190 cm) were fabricated. For both stainless steel and Zircaloy-2 rods the reproducibility of the UO_2 average density was $(92.5 \pm 0.5)\%$ T. D. Spread of density values along the rod

length referred to the average density was $(+0.5-1.5)\%$ T. D. or better. Spread of final active length was ± 1.3 cm or better.

In one lot of fused UO_2 the fragmentation behavior was found to be such that it was not possible to obtain densities higher than 90 per cent of theoretical. Therefore, some concern still remains on the constancy of the compacting behavior of different fused UO_2 lots.

From the present work indicative conclusions can be drawn on the fabrication cost of the vibro-swaged UO_2 fuel as compared to the pelletized UO_2 fuel. The estimated figures of 12-14 $/kg U in favour of the swaged fuel seem to be interesting for the problem of decreasing the fuel cost.

A "stationary" technique was chosen for measuring the out-of-pile thermal conductivity of swaged UO_2. Assuming as a comparison base the values reported by Deem and Lucks for UO_2 pellets, the thermal conductivity values for swaged UO_2 seem to remain lower by approx. $(25+0-10)\%$ than the thermal conductivity values for pellets at the same density $(90\%$ T. D.) and at temperatures between $150°$ and $800°C$.

Additional studies have been performed on the fragmentation behavior of fused UO_2 during vibration and swaging, porosimetry of swaged UO_2, roughness of cladding internal surface, and hardness of cladding.

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KEY TO THE FIGURES

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SUMMARY

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Additional studies have been performed on the fragmentation behavior of fused UO_2 during vibration and swaging, porosimetry of swaged UO_2, roughness of cladding internal surface, and hardness of cladding.

1 — INTRODUCTION

The first year program was mainly intended to study the optimum conditions to perform cold swaging of uranium dioxide both with stainless steel and Zircaloy-2 cladding. The problem was to choose a laboratory scale process capable of attaining the maximum swaged density by means of vibratory pre-compaction of the UO_2 powder followed by a relatively small reduction of the fuel rod obtained by a small number of passes through the swager without intermediate annealing.

Main objective of the second year work program has been to demonstrate the feasibility of the fabrication technique set up during the first part of the research on a small pilot plant scale and to check the reproducibility of data obtained.

Additional work has been done on the characterization of the swaged UO_2 rod and on the analysis of economic potentials of the swaged UO_2 fuel.

2 — PRE-COMPACTION AND SWAGING OF REACTOR LENGTH RODS : REPRODUCIBILITY AND UNIFORMITY STUDY

For pneumatic vibration of reactor length rods the apparatus shown in figure 1 was used. It employs two vibrators vertically placed in line with the rod. The upper vibrator (a 2 ″ short stroke vibrator which affords approximately 2500 strokes per minute at 80 p.s.i. air pressure) acts directly on the UO_2 powder through a ram; the lower vibrator (a 2 ″ long stroke vibrator which affords approximately 1600 strokes per minute at 80 p.s.i. air pressure) is rigidly connected to the threaded end plug welded to the tube. With this rather primitive but inexpensive apparatus

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(it costs approximately $ 500) a few minutes of vibration are sufficient to achieve densities of 85-87% T.D., the differences obtained being due to the use of different mixtures of fused UO_2 powders.

A four dies rotary spindle swager was used. The machine has a feeding device with manual advancement of the rod. This semi-automatic device which assures excellent guidance to the bar during swaging is shown in figures 2 and 3. The bar is fixed at one end to a mobile mandrel. This mandrel is connected to a manual crank which when turned advances the bar into the swager at a velocity of 0.3 to 2.5 meters per minute. Between the extremities of the bar, there is a support which prevents the bar from sagging. After the bar is advanced through the swager and the swaging is completed, the bar is extracted backwards in the same direction it was introduced. This was necessary since there was no additional mandrel on the exit side. The mandrel is designed so that the bar may rotate during swaging; however, there is a considerable amount of friction which prevents the bar from rotating at very rapid velocities. Several reactor length bars have been swaged using this semi-automatic feeding device and compared the results obtained by hand feeding. It was found that bars swaged with the feeding device had better surface finish and were straighter.

The following ternary mixture of fused UO_2 powder was used : 67.5% ($-6 + 20$); 12.5% ($-35 + 100$); 20% (-200). This mixture, derived from Hanford report HW-67777, was proved to be the best of the ternary mixtures tested during our previous work, which also demonstrated that a vibrated density of approx. 84% T.D. is quite sufficient to reach the maximum swaged densities with the advantage of a relatively low elongation of the fuel tube.

A first series of 24 stainless steel bars of reactor core length (approx. 125 cm) have been fabricated with the standard vibro-swaging process in order to check the reproducibility of various parameters on a pilot plant scale.

Tubing used for this test were of Italian production (Dalmine), seamless, with commercial tolerances ($\pm$ 0.1 mm ID; $\pm$ 0.1 mm wall).

Data obtained for pre-compaction and swaging of bars of this series are listed in Table I. The results can be summarized as follows :

2.1 — Swaged density (*)

The reproducibility of the average swaged density was (92.5 $\pm$ 0.5)% T.D. for tubes 1 mm thick and (92.0 $\pm$ 0.5)% T.D. for tubes 0.5 mm thick.

The spread of the swaged density referred to the average density, along the tube length was ($+ 1.0 - 2.0$)% T.D. or better for 22 rods out of 24. For the other 2 rods, namely ALC 35 and ALC 37, was ($+ 0.5 - 3.0$) and ($+ 0.5 - 2.5$)% T.D. respectively. Whereas in the 0.5 mm wall rods the variation of density along the tube length was completely random, in the 1.0 mm wall rods it was found that the top of the rod (which entered the swager from the bottom) was in most cases slightly more dense, approx. 1.5% T.D., than the bottom.

2.2 — Vibrated density and active length

A fixed vibration time of a constant weight of UO_2 mixture was used for the two fabrication runs : 6 min and 4 min for rods 1.0 and 0.5 mm thick respectively. These relatively short times were sufficient to achieve with the two vertical vibrators arrangement densities of

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(*) The swaged density was read on the gamma absorptometer recordings. In several samples the results were checked with the "etching" technique.

approx. 84% T.D. With additional horizontal vibration (samples ALC 37, ALC 38, ALC 39 and ALC 40) only 2.5 min were sufficient to reach densities over 84% T.D.

The higher spread of vibrated densities for 1 mm thick rods is mainly due to rods ALC 27 and ALC 30 which bent during vibration without any apparent reason.

With the above mentioned experimental conditions, the final active length of the fuel rods resulted within the ranges (124 ± 2) cm and (126 ± 1) cm for rods 1.0 mm and 0.5 mm thick respectively.

Anyway, both vibrated density and active length could be kept more constant by stopping the vibration when the upper ram acting directly on the UO_2 powder reaches a previously fixed value. This method has the disadvantage of requiring slightly different vibration times and the presence of the operator who stops the vibration at the desired moment.

During the first year of the research, a couple of rods were fabricated with "special dense" UO_2. The densities attainable were lower than for fused UO_2. To confirm this preliminary result, four rods have been prepared having the characteristics of the above mentioned 24 rods. With −70 mesh hi-fired UO_2 vibrated densities of 76-77% T.D. and swaged densities lower than 90% T.D. for a 24% reduction of total area were obtained. This confirms results also obtained by other investigators. For this reason, and because of the high cost of the hi-fired powder, it was decided to continue the reproducibility and uniformity study only with the fused UO_2.

Tubing used for a second series of 24 stainless steel rods of reactor core length (approx. 155 cm) were of American production (Superior), weldrawn, with U.S. standard commercial tolerances (± .001″ ID, ± 10% wall). Data obtained for pre-compaction and swaging of bars of this series are listed in Table II. In Table III are listed the results of a similar test done on 9 Zircaloy-2 rods of reactor core length. Zircaloy-2 tubing of this latter test was also Superior, seamless, with the same tolerances of the Superior stainless steel tubing.

The results of tests reported in Tables II and III can be summarized as follows.

Swaged density

For both stainless steel and Zircaloy-2 tubing the reproducibility of the average swaged density was (92.5 ± 0.5)% T.D.

The uniformity of density was somewhat better than for Dalmine stainless steel tubing. The spread referred to the average density along the tube length was a satisfactory (+ 0.5 − 1.5)% T.D. or better for all of the 33 rods but for 3. For these three rods, namely ALC 62, ALC 98 and ZLC 23, the spread was (+ 0.5 − 2.0), (+ 0.5 − 2.0) and (+ 1.0 − 2.0)% T.D. respectively.

No evidence of systematic differences in density between top and bottom of the rods was observed. The only unexplained anomaly was the presence of "holes" of density in 6 rods, namely ALC 93 (one hole of − 2.5% T.D. (*)), ALC 104 (one hole of − 3.0% T.D.), ALC 105 (one hole of −2.5% T.D.), ALC 106 (two holes of −3.0% T.D.), ZLC 22 (one hole of −5.0% T.D.), and ZLC 23 (four holes of approx. −3.0% T.D.). The length along the rod of these zones of lower density varied between 2 and 4 cm.

(*) The density of the undercompacted zone is obtained by subtracting the % T.D. of the hole to the average density of the rod : in this case one obtains : 92.5 − 2.5 = 90.0% T.D.

Vibrated density and active length

Also in these two tests a 4 min. vibration time was used. The vibrated density values ranged from 83.6 to 84.7% T. D. Spread of initial active length values was ± 1.0 cm whereas for final active length was ± 1.3 cm. This value appears reasonably satisfactory if compared with the case of pellets (± one half of pellet height).

A third series of rod was fabricated for this study. A total of 30 rods of reactor core length (10 rods Superior stainless steel cladded, 10 rods Dalmine stainless steel cladded and 10 rods Superior Zircaloy-2 cladded) were prepared with fused UO_2 of the last 200 pounds lot received by Fiat from Spencer Chemical Company at the beginning of 1962. As explained in detail at paragraph 5.2 of this report, the fragmentation and compacting behavior of this lot resulted to be different from the previously received depleted and natural lots to such an extent that it was not possible to adopt the standard fabrication technique under study. In fact, after 4 min. of vibration the densities obtained with Zircaloy-2 rods were approx. 77% T. D. so that it was decided to increase the vibration time up to 15 min. for the stainless steel rods.

After the standard reduction of total area (18%) the gamma absorptometer recorded UO_2 densities lower than 90% T. D. for all of the rods. In order to see if a further densification was obtainable, the 30 rods were subjected to an additional pass through the swager for a total reduction of 24%. Experimental data are listed in Table IV. The third pass through the swager did not increase the density of the UO_2 which remained as low as 89-90% T. D.

An additional test was done on 10 stainless steel and 6 Zircaloy-2 cladded rods with this lot of very friable powder having in mind of using an initial ternary mixture corrected to compensate somehow the degradation of mesh sizes during the homogenizing treatment (half hour mixing in a ball-mill without balls) and of vibrating the fuel tube as long as necessary to reach a density of 83 per cent of theoretical. It was hoped that the standard reduction of total area of 18% were able to furnish swaged densities higher than 90% T. D. in tubes having a pre-compacted density higher than that of the samples listed in Table IV.

Using the ternary mixture 70% (— 6 + 20); 10% (— 35 + 100); 20% (— 200), the results listed in Table V were obtained with 10 stainless steel and 6 Zircaloy-2 cladded rods. With the actual powder it was not possible to obtain densities significantly higher than 90% T. D. even with the vibrated densities which afforded densities of 92.5 per cent of theoretical with previous lots of fused UO_2.

Apart from the lower densities obtainable with the last lot of fused UO_2, data of Tables IV and V confirm the good reproducibility of the average swaged density (± 0.5% T. D.) and a uniformity of density which is still better than that of the samples listed in Tables I, II and III (in most cases (+ 0.5 — 1.0)% T. D. or better). No "holes" of density or other defects were observable at the gamma absorptometry.

It must be noted that all stainless steel Superior tubing used for samples of Tables II, IV and V were Weldrawn tubing and that their behavior resulted always as satisfactory as the behavior of the seamless tubing previously used for our cold swaging experiments.

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TABLE I — Summary of reproducibility data for vibro-swaging of UO_2 reactor length rods : Stainless Steel Dalmine tubing

Sample	Cladding	Powder	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Initial Active Length (mm)	Final Active Length (mm)	Elongation (%)	Reduction of Total Area (%)	Number of Passes	Vibration Time (min.)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)
ALC 22	SS 304 Dalmine	Fused UO_2 Depleted	12.0	11.0	1.00	0.98	1142	1239	8.5	16.0	2	6	83.2	93.0 (+ 0.5–1.5)
ALC 23	"	"	"	"	"	"	1129	1237	9.6	"	"	"	83.9	93.0 (+0.5–1.5)
ALC 24	"	"	"	"	"	"	1131	1239	9.5	"	"	"	84.0	93.0 (+0.5–1.0)
ALC 25	"	"	"	"	"	"	1140	1241	8.9	"	"	"	83.4	92.5 (+1.0–2.0)
ALC 26	"	"	"	"	"	"	1136	1232	8.5	"	"	"	83.7	93.0 (+0.5–1.5)
ALC 27	"	"	"	"	"	"	1163	1260	8.5	"	"	3	81.8	92.5 (+0.5–1.5)
ALC 28	"	"	"	"	"	"	1138	1237	8.7	"	"	6	83.7	92.5 (+0.5–1.5)
ALC 29	"	"	"	"	"	"	1140	1239	8.7	"	"	"	83.5	92.0 (+1.0–2.0)
ALC 30	"	"	"	"	"	"	1160	1260	8.6	"	"	4	82.0	92.0 (+0.5–1.5)
ALC 31	"	"	"	"	"	"	1136	1235	8.7	"	"	6	83.7	92.5 (+0.5–1.0)
ALC 44	"	"	"	"	"	"	1124	1220	8.5	"	"	"	83.4	92.5 (+0.5–0.5)
ALC 45	"	"	"	"	"	"	1140	1258	9.7	"	"	"	85.2	93.0 (+0.5–2.0)
ALC 32	SS 304 Dalmine	Fused UO_2 Depleted	12.0	11.0	0.50	0.49	1129	1255	11.2	16.0	2	4	84.8	92.0 (+0.5–1.0)
ALC 33	"	"	"	"	"	"	1142	1264	10.7	"	"	"	84.0	92.5 (+0.5–1.0)
ALC 34	"	"	"	"	"	"	1139	1261	10.7	"	"	"	84.2	92.0 (+0.5–1.0)
ALC 35	"	"	"	"	"	"	1139	1259	10.5	"	"	"	84.2	92.0 (+0.5–3.0)
ALC 36	"	"	"	"	"	"	1147	1259	9.8	"	"	"	83.7	92.5 (+0.5–1.0)
ALC 37	"	"	"	"	"	"	1141	1261	10.5	"	"	2.5	84.0	92.0 (+0.5–2.5)
ALC 38	"	"	"	"	"	"	1134	1263	11.4	"	"	"	84.6	91.5 (+1.0–1.0)
ALC 39	"	"	"	"	"	"	1132	1253	10.7	"	"	"	84.7	92.0 (+0.5–0.5)
ALC 40	"	"	"	"	"	"	1139	1263	10.9	"	"	"	84.2	92.0 (+0.5–1.0)
ALC 41	"	"	"	"	"	"	1150	1266	10.1	"	"	4	83.4	92.5 (+0.5–1.5)
ALC 46	"	"	"	"	"	"	1143	1249	9.3	"	"	"	83.9	92.5 (+0.5–0.5)
ALC 47	"	"	"	"	"	"	1145	1255	9.6	"	"	"	83.6	92.5 (+0.5–2.0)

TABLE II — Summary of reproducibility data for vibro-swaging of UO$_2$ reactor length rods : Stainless Steel Superior tubing

Sample	Cladding	Powder	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Initial Active Length (mm)	Final Active Length (mm)	Elongation (%)	Reduction of Total Area (%)	Number of Passes	Vibration Time (min.)	Vibrated Density (% T.O.)	Swaged Density (% T.O.)
ALC 58	SS 304 Superior	Fused UO$_2$ Depleted	12.7	11.5	0.50	0.49	1360	1538	13.1	18	2	4	84.2	92.0 (+0.5-1.5)
ALC 59	"	"	"	"	"	"	1366	1562	14.3	"	"	"	83.8	92.5 (+0.5-0.5)
ALC 60	"	"	"	"	"	"	1355	1542	13.8	"	"	"	84.5	92.5 (+0.5-1.5)
ALC 61	"	"	"	"	"	"	1360	1539	13.2	"	"	"	84.2	92.5 (+0.5-1.0)
ALC 62	"	"	"	"	"	"	1370	1560	13.9	"	"	"	83.6	92.5 (+0.5-2.0)
ALC 63	"	"	"	"	"	"	1368	1557	13.8	"	"	"	83.7	92.5 (+0.5-1.5)
ALC 64	"	"	"	"	"	"	1352	1541	14.0	"	"	"	84.7	92.5 (+0.5-1.5)
ALC 65	"	"	"	"	"	"	1365	1549	13.5	"	"	"	83.9	92.0 (+0.5-1.5)
ALC 66	"	"	"	"	"	"	1354	1542	13.9	"	"	"	84.5	92.5 (+0.5-1.0)
ALC 67	"	"	"	"	"	"	1364	1551	13.7	"	"	"	83.9	93.0 (+0.5-1.5)
ALC 92	"	"	"	"	"	"	1363	1560	14.0	"	"	"	84.0	92.5 (+0.5-1.0)
ALC 93	"	"	"	"	"	"	1369	1553	13.4	"	"	"	83.6	92.5 (+0.5-1.0)
ALC 96	"	"	"	"	"	"	1368	1538	12.4	"	"	"	83.7	92.5 (+0.5-1.0)
ALC 97	"	"	"	"	"	"	1354	1544	14.0	"	"	"	84.6	92.5 (+0.5-1.5)
ALC 98	"	"	"	"	"	"	1355	1545	14.1	"	"	"	84.5	92.0 (+0.5-2.0)
ALC 99	"	"	"	"	"	"	1362	1552	13.9	"	"	"	84.1	92.0 (+0.5-1.0)
ALC 101	"	Fused UO$_2$ Natural	"	"	"	"	1351	1540	14.0	"	"	"	84.7	93.0 (+0.5-1.5)
ALC 102	"	"	"	"	"	"	1356	1550	13.5	"	"	"	84.4	92.5 (+0.5-1.5)
ALC 103	"	"	"	"	"	"	1365	1538	12.5	"	"	"	83.9	92.5 (+0.5-0.5)
ALC 104	"	"	"	"	"	"	1370	1540	12.2	"	"	"	83.6	92.5 (+0.5-1.0)
ALC 105	"	"	"	"	"	"	1366	1546	13.2	"	"	"	83.8	92.5 (+0.5-1.5)
ALC 106	"	"	"	"	"	"	1352	1544	14.3	"	"	"	84.7	92.0 (+0.5-1.5)
ALC 107	"	"	"	"	"	"	1369	1545	12.9	"	"	"	83.6	92.0 (+0.5-1.0)
ALC 108	"	"	"	"	"	"	1351	1536	13.7	"	"	"	84.7	92.0 (+1.0-1.0)

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TABLE III — Summary of reproducibility data for vibro-swaging of UO_2 reactor length rods : Zircaloy-2 Superior tubing

Sample	Cladding	Powder	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Initial Active Length (mm)	Final Active Length (mm)	Elongation (%)	Reduction of Total Area (%)	Number of Passes	Vibration Time (min.)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)
ZLC 5	Zr-2 Superior	Fused UO₂ Depleted	12.7	11.5	0.50	0.49	1508	1706	13.2	18	2	4	84.2	92.0 (+0.5-1.5)
ZLC 6	"	"	"	"	"	"	1505	1712	13.8	"	"	"	84.3	93.0 (+0.5-0.5)
ZLC 17	"	"	"	"	"	"	1502	1730	15.0	"	"	"	84.5	92.5 (+0.5-1.0)
ZLC 18	"	"	"	"	"	"	1500	1710	14.0	"	"	"	84.5	93.0 (+0.5-0.5)
ZLC 19	"	Fused UO₂ Natural	"	"	0.76	0.74	1657	1872	13.0	"	"	"	83.7	92.0 (+0.5-1.0)
ZLC 20	"	"	"	"	"	"	1649	1863	13.0	"	"	"	84.2	92.0 (+0.5-1.0)
ZLC 21	"	"	"	"	"	"	1657	1880	13.6	"	"	"	83.7	92.0 (+0.5-1.5)
ZLC 22	"	"	"	"	"	"	1657	1881	13.6	"	"	"	83.7	92.0 (+0.5-1.5)
ZLC 23	"	"	"	"	"	"	1656	1878	13.4	"	"	"	83.7	92.5 (+1.0-2.0)

TABLE IV — Summary of reproducibility data for vibro-swaging of UO$_2$ reactor length rods : Last 200 lbs lot received from Spencer

Sample	Cladding	Powder	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Initial Active Length (mm)	Final Active Length (mm)	Elongation (%)	Reduction of Total Area (%)	Number of Passes	Vibration Time (min.)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)
ZLC 7	Zr-2 Superior	Fused UO$_2$ Depleted	12.7	11.1	0.76	0.70	1415	1750	23.8	24	3	4	77.0	90.0 (+0.5-0.5)
ZLC 8	"	"	"	"	"	"	1420	1744	22.7	"	"	"	76.8	90.0 (+0.5-1.0)
ZLC 9	"	"	"	"	"	"	1407	1750	24.3	"	"	"	77.3	90.0 (+0.5-1.0)
ZLC 10	"	"	"	"	"	"	1407	1755	24.7	"	"	"	77.3	89.0 (+0.5-0.5)
ZLC 11	"	"	"	"	"	"	1437	1770	23.1	"	"	"	76.3	90.0 (+0.5-1.0)
ZLC 12	"	"	"	"	"	"	1410	1760	24.7	"	"	"	77.2	90.0 (+0.5-1.5)
ZLC 13	"	"	"	"	"	"	1435	1766	23.1	"	"	"	76.3	90.0 (+0.5-1.0)
ZLC 14	"	"	"	"	"	"	1405	1750	24.5	"	"	"	77.3	90.5 (+0.5-1.0)
ZLC 15	"	"	"	"	"	"	1398	1745	24.8	"	"	"	77.6	89.0 (+0.5-2.0)
ZLC 16	"	"	"	"	"	"	1427	1748	22.5	"	"	"	76.0	89.0 (+0.5-1.0)
ALC 68	SS 304 Superior	"	12.7	11.1	0.50	0.48	1070	1290	20.5	24	3	15	80.4	89.5 (+0.5-0.5)
ALC 69	"	"	"	"	"	"	1052	1270	20.7	"	"	"	81.9	90.0 (+0.5-1.0)
ALC 70	"	"	"	"	"	"	1081	1275	18.0	"	"	"	79.6	90.0 (+0.5-0.5)
ALC 71	"	"	"	"	"	"	1088	1285	18.1	"	"	"	79.1	90.0 (+0.5-0.5)
ALC 72	"	"	"	"	"	"	1085	1268	17.0	"	"	"	79.3	90.0 (+0.5-1.5)
ALC 73	"	"	"	"	"	"	1075	1265	17.8	"	"	"	80.1	89.5 (+0.5-0.5)
ALC 74	"	"	"	"	"	"	1077	1266	17.5	"	"	"	79.8	89.5 (+0.5-1.0
ALC 75	"	"	"	"	"	"	1070	1282	19.8	"	"	"	80.4	89.5 (+0.5-2.0)
ALC 76	"	"	"	"	"	"	1074	1263	17.7	"	"	"	80.1	90.0 (+0.5-0.5)
ALC 77	"	"	"	"	"	"	1065	1278	20.0	"	"	"	80.8	90.0 (+0.5-0.5)

follows : TABLE IV — Summary of reproducibility data for vibro-swaging of UO_2 reactor length rods : Last 200 lbs lot received from Spencer

Sample	Cladding	Powder	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Initial Active Length (mm)	Final Active Length (mm)	Elongation (%)	Reduction of Total Area (%)	Number of Passes	Vibration Time (min.)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)
ALC 78	SS 304 Oalmine	Fused UO_2 Depleted	12.0	10.6	0.50	0.47	990	1240	25.3	22	3	15	82.0	90.0 (+0.5-0.5)
ALC 79	"	"	"	"	"	"	1002	1242	24.0	"	"	"	80.7	89.5 (+0.5-0.5)
ALC 80	"	"	"	"	"	"	1004	1239	23.5	"	"	"	80.5	90.0 (+0.5-1.0)
ALC 81	"	"	"	"	"	"	995	1245	25.1	"	"	"	81.5	90.0 (+0.5-0.5)
ALC 82	"	"	"	"	"	"	998	1250	25.2	"	"	"	81.2	90.0 (+0.5-0.5)
ALC 83	"	"	"	"	"	"	1005	1246	24.1	"	"	"	80.5	90.0 (+0.5-0.5)
ALC 84	"	"	"	"	"	"	999	1252	25.3	"	"	"	81.0	89.5 (+0.5-0.5)
ALC 85	"	"	"	"	"	"	1000	1246	24.6	"	"	"	81.0	90.0 (+0.5-0.5)
ALC 86	"	"	"	"	"	"	1002	1248	24.6	"	"	"	80.7	89.5 (+0.5-0.5)
ALC 87	"	"	"	"	"	"	991	1235	24.6	"	"	"	81.9	90.0 (+1.0-1.0)

TABLE V — Summary of reproducibility data for vibro-swaging of UO_2 reactor lenght rods : Last 200 lbs lot received from Spencer

Sample	Cladding	Powder	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Initial Active Length (mm)	Final Active Length (mm)	Elongation (%)	Reduction of Total Area (%)	Number of Passes	Vibration Time (min.)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)
ALC 109	SS 304 Superior	Fused UO_2 Depleted	12.7	11.5	0.50	0.49	1542	1765	14.4	18	2	23	83.0	89.5 (+0.5-0.5)
ALC 110	"	"	"	"	"	"	"	1767	14.6	"	"	20	"	90.0 (+1.0-1.5)
ALC 111	"	"	"	"	"	"	"	1761	14.2	"	"	16	"	90.8 (+0.5-0.5)
ALC 112	"	"	"	"	"	"	"	1772	14.9	"	"	24	"	89.5 (+0.5-0.5)
ALC 113	"	"	"	"	"	"	"	1756	13.8	"	"	15	"	90.0 (+0.5-1.0)
ALC 114	"	"	"	"	"	"	"	1766	14.5	"	"	13	"	89.5 (+0.5-0.5)
ALC 115	"	"	"	"	"	"	"	1768	14.6	"	"	19	"	89.5 (+0.5-1.0)
ALC 116	"	"	"	"	"	"	"	1767	14.6	"	"	17	"	89.5 (+0.5-0.5)
ALC 117	"	"	"	"	"	"	"	1758	14.0	"	"	13	"	90.0 (+0.5-0.5)
ALC 118	"	"	"	"	"	"	"	1766	14.5	"	"	23	"	90.0 (+0.5-1.0)
ZLC 24	Zr-2 Superior	"	12.7	11.5	0.76	0.74	1510	1732	14.7	18	2	24	83.0	90.0 (+0.5-1.0)
ZLC 25	"	"	"	"	"	"	"	1733	14.8	"	"	26	"	91.0 (+0.5-0.5)
ZLC 26	"	"	"	"	"	"	"	1728	14.4	"	"	16	"	90.5 (+0.5-1.0)
ZLC 27	"	"	"	"	"	"	"	1732	14.7	"	"	12	"	90.0 (+0.5-1.5)
ZLC 28	"	"	"	"	"	"	"	1726	14.3	"	"	15	"	90.5 (+0.5-1.0)
ZLC 29	"	"	"	"	"	"	"	1734	14.8	"	"	17	"	90.5 (+1.0-1.0)

3 — INVESTIGATION ON THE USE OF CERAMIC-GRADE POWDER FOR SWAGING-ANNEALING EXPERIMENTS

The purpose of these experiments was to try to achieve densities higher than 90% of theoretical utilizing ceramic grade UO_2 which is less expensive than fused UO_2 powder.

The process used in a series of preliminary experiments was the following : ceramic grade UO_2 was compacted by swaging and subsequently subjected to a short annealing treatment (sintering) in hydrogen at a temperature of 1100 or 1200 °C followed by a swaging pass to get the cladding in good contact with the UO_2 (during the annealing treatment the UO_2 will pull away from the clad as it sinters).

The experiments used laboratory size stainless steel bars approximately 30 cm long and 1.2 cm in diameter with welded end plugs at both extremities. Data obtained are listed in Table VI (samples from SA1 to SA4).

The very low values obtained for the swaged-annealed densities (50-55% T. D.) are probably due to the low value obtained at the vibratory pre-compaction of the commercial ceramic grade (26% T. D.).

In order to increase the pre-swaged density a mixture was used having the coarse fractions made up of fused UO_2 and ceramic grade powder as the fine fraction. The mixture composition was the following :

— 6 + 8	24.0%
— 8 + 10	6.0%
— 12 + 20	7.5%
— 20 + 30	4.0%
— 30 + 60	2.5%
ceramic grade	56.0% .

A series of 4 swaging-annealing experiments has been performed. Data obtained are listed in Table VI (samples from SA5 to SA8).

With respect to the swaged densities obtained using only ceramic grade powder, the densities afforded by the actual mixture appear to be somewhat more promising but still too far from the desired value (at least 90% T. D.) which could make the swaging-annealing technique competitive with vibro-swaging of fused UO_2 or even hi-fired UO_2.

It is possible that the obtained values could be increased by employing a ceramic grade powder previously fired with an inexpensive treatment. Anyway, the development of this particular kind of powder was not included within the aims of our work. Therefore, the investigation was stopped.

4 — STUDY OF THE DIAMETER-TO-THICKNESS RATIO FOR ZIRCALOY-2 TUBING

During the first year of the research the influence of this parameter on the UO_2 swaged density was studied for stainless steel cladding. The most important result of this study was that the parameter D_0/T is able to influence the shape of the curves obtained by plotting the swaged density as a function of the reduction of fuel area (R.A.). Namely, in the range 0 — 50% R. A., low and intermediate values of D_0/T let the density to increase and level off with increasing reductions while with high values of D_0/T the density reaches a maximum and

TABLE VI — Summary of swaging-annealing experiments with ceramic grade UO_2 powder and with mixture of ceramic grade and fused UO_2 powder cladded in stainless steel.

Sample	Annealing Temperature (°C)	Annealing Time (hrs)	Initial O.D. (mm)	Final O.D. (mm)	Initial Thickness (mm)	Final Thickness (mm)	Number of Passes	Reduction of Fuel Area (%)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)	Grain Size (micron)	O/U Ratio
SA1	1100	1	12.0	9.00	1.00	1.16	4 + 1	55.5	26	54.3	20 (Initial value) 110	2.11
SA2	1100	2	12.0	9.00	0.50	0.58	4 + 1	49.0	26	49.0	140	2.12
SA3	1200	1	12.0	9.00	1.00	1.18	4 + 1	56.0	26	55.6	142	2.11
SA4	1200	2	12.0	9.00	0.50	0.59	4 + 1	49.5	26	50.0	210	2.12
SA5	1100	1	12.0	9.16	1.00	1.26	4 + 1	56	41	73	20 (Initial value) 115	2.02 (Initial value) 2.05
SA6	1100	2	12.0	9.16	1.00	1.24	4 + 1	55	41	76	150	2.05
SA7	1200	1	12.0	9.16	1.00	1.24	4 + 1	55	41	75	160	2.05
SA8	1200	2	12.0	9.16	1.00	1.20	4 + 1	54	41	80	200	2.06

then actually decreases with further reductions in area. In addition, it was found that tubes with higher D_0/T ratios ruptured with fewer passes through the swaging machine.

In order to check if this behavior could be observed also for the cold swaging of UO_2 in Zircaloy-2, over 35 bars with various diameters and wall thicknesses were prepared (*). The samples were 30-60 cm in length and were all vibrated to the same fused UO_2 density of 80% T.D. The samples were cold swaged to varying reductions in area with no intermediate annealing. The swaged density of UO_2 was determined by means of the "etching" technique.

A series of results obtained for Zircaloy-2 tubes having low (15), intermediate (25) and high (30 and 50) diameter-to-thickness ratios respectively, is shown in figure 4.

An additional series of results obtained for Zircaloy-2 tubes filled with the UO_2 fused powder of the last lot received from Spencer which presents a different compacting behavior, as already mentioned at paragraph 2, is shown in figure 5.

No conclusions of the type above mentioned for stainless steel can be drawn from data obtained for Zr-2. However, some indication can be obtained from these tests on the rupture behavior of tubes having different D_0/T ratios. As expected, tubes with higher D_0/T ratios ruptured with fewer passes through the swaging machine. The results presented in Table VII illustrate that at low D_0/T ratio ruptures occurred after 40% R.A., but for high D_0/T ratios ruptures occurred in almost all samples after only 28% R.A.

Table VII — Rupture behavior of Zircaloy-2 tubes having different D_0/T ratios

a. Samples of figure 4.

D_0/T	Rupture behavior
15	1 sample in 2 ruptured at 40% R.A.
25	1 sample in 2 ruptured at 25% R.A.
30	2 samples in 3 ruptured at 28% R.A.
50	3 samples in 3 ruptured at 28% R.A.

b. Samples of figure 5.

D^3/T	Rupture behavior
15	No sample ruptured up to 50% R.A.
21.4	1 sample in 2 ruptured at 30% R.A.
25	1 sample in 2 ruptured at 32% R.A.
30	2 samples in 3 ruptured at 28% R.A.

No cracks in Zircaloy-2 tubes were observed for reductions of area lower than 20%.

(*) The average grain sizes of Zircaloy-2 tubes were in the range 21-23 microns.

5 — SWAGED UO₂ BAR TESTING

5.1 — Gamma absorptometer for UO₂ density determination (*)

A semi-automatic apparatus for non-destructive determination of the UO_2 swaged density and uniformity of density along the rods has been designed, constructed and put into operation.

An overall view of the experimental setup is shown in figure 6. A 1 curie source of Cs-137 is utilized. The vertical gamma beam, having a diameter of approximately 14 mm, which is slightly larger than the rod O.D., traverses the rod which is centered on it. The rod is moved horizontally step by step of a constant distance equal to 0.5″ every 25 seconds which is also the speed of the strip chart of the recorder. The intensity of emergent radiation is measured by a phototube connected to a high quality electronic chain and recorded. The time constant of the electronic apparatus has been appropriately chosen in accord with the speed of strip chart.

The calibration of the density scale was done by preparing standard pieces approx. 8 cm long taken from swaged rods previously tested for uniformity of density. The UO_2 density of these rods is measured by means of the usual etching technique.

The sensitivity of the absorptometer resulted to be such that differences in UO_2 density as low as 0.5% T.D. could be detected.

5.2 — Fragmentation of UO₂ during vibration and swaging

During the first year of the research granulometric analysis of swaged UO_2 contained in two bars showed that considerable fragmentation occurs during swaging.

In order to check this preliminary result and to study more completely this effect, four bars having the characteristics listed below were cut open and all of the UO_2 was recovered and subjected to sieve analysis.

Sample	Cladding	UO₂	Reduction of Fuel Area (%)	Vibrated Density (% T.D.)	Swaged Density (% T.D.)
ALC 20	SS304	Fused	18.6	81	92.0
ALC 21	SS304	Fused	26.5	80	93.0
ŻLC 3	Zr-2	Fused	18.6	80.5	92.4
ZLC 4	Zr-2	Fused	26.5	80	92.9

The results of the sieve analysis were as follows :

Mesh	− 4 + 12	− 12 + 20	− 20 + 150	− 150
Initial mixture (Weight %)	45	20	—	35
ALC 20	0.5	4	39	56.5
ALC 21	0.5	2.5	35.5	61.5
ZLC 3	1	4	38	57
ZLC 4	0.5	2	36.5	61

(*) Work done in co-operation with the Radiochemistry Group of Fiat-Sezione Energia Nucleare.

Considerable fragmentation occurred in all samples, as expected. No significative difference was observable between UO_2 powders recovered from stainless steel and Zircaloy cladded bars, at least in the grain size ranges considered.

Further work was done to study separately the fragmentation during vibratory pre-compaction and during swaging.

Two bars vibrationally compacted to 84% T.D. were cut open and all of the fused UO_2 was removed and subjected to sieve analysis. The same thing was done for two identical bars which were compacted to 84% T.D. and swaged according to our standard process. The characteristics of the four bars are listed below.

Sample	Cladding	Initial O.D.	Initial Thickness	Reduction of Fuel Area	Vibrated Density	Swaged Density
ALC 42	SS 304	12.0 mm	1.0 mm	—	83.9% T.D.	—
ALC 43	SS 304	12.0 mm	0.5 mm	—	84.0% T.D.	—
ALC 42 bis	SS 304	12.0 mm	1.0 mm	18%	83.7% T.D.	92.6% T.D.
ALC 43 bis	SS 304	12.0 mm	0.5 mm	17%	84.0% T.D.	92.6% T.D.

The results of the sieve analysis were as follows :

Mesh	− 6 + 20	− 20 + 35	− 35 + 100	− 100 − 200	− 200
Initial mixture (Weight %)	67.5	—	12.5	—	20
After vibration ALC 42	65.5	2	7	3	22
ALC 43	64.5	2.5	7.5	2.5	23
After swaging ALC 42 bis	7.5	12	32.5	16	32
ALC 43 bis	6.5	11	31	15	36.5

The heaviest fragmentation occurs during swaging, as expected.

The final grain size distribution comes out to be as if the coarsest fraction disappears giving a contribution roughly equal (10-15%) to finer fractions. A check of the − 200 mesh fraction variation in grain size after vibration and swaging has been done with the following results :

	− 200 + 230	− 230 + 270	− 270 + 320	− 320 + 400	− 400
Initial distribution (Weight %)	47.5	16	6.5	7	23
After vibration and swaging	11	8	9	10	62

The above mentioned results were obtained from depleted and natural fused UO₂ lots received from Spencer during 1960 and 1961. However, the last lot received from the same vendor at the beginning of 1962 (a 200 pounds lot of depleted fused UO_2) did not behave as the previous ones as far as degradation of particle size is concerned. As already mentioned at paragraph 2, this phenomenon was proved to be such as to make impossible the adoption of our standard fabrication technique.

The 200 pounds lot was ordered specifying the following granulometry :

67.5%	— 6 + 20
12.5%	— 35 + 100
20.0%	— 200

The powder was received in three different packages, one for each nominal composition. The granulometry of the powder, as received, resulted to be the following (after 1/2 hour screening of the standard mixture) :

54.5%	— 6 + 20
12.0%	— 20 + 35
12.5%	— 35 + 100
1.0%	— 100 + 200
20.0%	— 200 .

The change between the two compositions showed that the lot of powder received was quite friable. This might explain the difference between the nominal requested grain size and that actually received, as due to degradation of particle size during transportation and screening.

The granulometry of the powder ready for tube loading, i.e. after 3 hrs milling in a mill without balls, resulted to be the following (after 1/2 hr screening) :

42.0%	— 6 + 20
17.0%	— 20 + 35
15.0%	— 35 + 100
4.0%	— 100 + 200
22.0%	— 200 .

With this mixture we did not obtain, as usually, a packed density of approx. 84% of theoretical after 4 minutes of pneumatic vibration but only approx. 82% after 30-40 minutes.

It was noted that the friability of the powder was very marked for the coarse grain size only. It was thought that only a certain fraction of the coarse grain size could be friable, for example the fraction coming from the external layer of the original fused UO₂ body. To check this possibility 1000 grams of the — 6 + 20 powder were subjected to a 1/2 hour milling in a mill without balls followed by screening analysis; the remaining — 6 + 20 powder was again subjected to a 1/2 hour milling followed by screening analysis; and so forth for a total of six milling-screening cycles. The results were as follows :

Mesh	$-6 + 20$	$-20 + 35$	$-35 \div 100$	$-100 - 200$	-200
Initial weight (g)	1000	—	—	—	—
After 1st 1/2 hr. milling (g) (% decrease)	857 (14%)	114	18	6	5
After 2nd 1/2 hr. milling	803 (6.5%)	43	8	2	1
After 3rd 1/2 hr. milling	767 (4.5%)	28.5	5	1.5	1
After 4th 1/2 hr. milling	739 (4%)	23	3	1	1
After 5th 1/2 hr. milling	714 (3.5%)	20	3	1	1
After 6th 1/2 hr. milling	700 (2%)	11	2	0.5	0.5

The hypothesis of the existence of grains of fused UO_2 more friable than the others seems supported by this experiment.

Additional work was done to study separately the fragmentation of the friable lot of UO_2 powder during vibratory pre-compaction and during swaging. One bar vibrationally compacted to 82.3% T.D. was cut open and all of the fused UO_2 was removed and subjected to sieve analysis. The same thing was done for one identical bar which was compacted to 82.3% T.D. and swaged according to our standard process.

The characteristics of the two bars are listed below.

Sample	Cladding	Initial O.D.	Reduction of Total Area	Vibrated Density	Swaged Density
ALC 100	SS 304	12.7 mm	—	82.3% T.D.	—
ALC 90	SS 304	12.7 mm	18%	82.3% T.D.	90.5% T.D.

The results of the sieve analysis were as follows :

Mesh	$-6 + 20$	$-20 - 35$	$-35 - 100$	$-100 - 200$	-200
Initial mixture (*) (w/o)	53.0	12	13.5	1.5	20.0
After vibration ALC 100	50.0	12.5	14.5	2.0	21.0
After swaging ALC 90	9.0	14.0	26.5	14	36.5

(*) Nominal mixture (67.5% $-$ 6 + 20; 12.5% $-$ 35 + 100; 20% $-$ 200) of the as received powder homogenized by a 1/2 hour milling in a mill without balls.

Comparing these data with the data reported at the beginning of this paragraph for the samples ALC 42 bis and ALC 43 bis after swaging, one can observe that the final grain size composition of the swaged UO_2 is not very different for the two powders. However, it must be noted that with the friable powder of the last lot received it was not possible to obtain densities higher than 90,5% T. D. even with higher reductions of area, as already described at paragraph 2.

The above discussed fragmentation behavior of the 200 pounds lot was the argument of a letter exchange between the vendor and us. In particular, the vendor was asked if the cost of the fused UO_2 would not increase if it was requested by the purchaser that the fused UO_2 should meet the following test procedure :

"A sample of 50 lbs of the nominal mixture shall be subjected to a homogenizing treatment for 3 hours in an approx. 15 dm^3 ball mill without balls turning at a speed of approx. 50 rpm. After this treatment the degradation of the $- 6 + 20$ mesh size shall be limited within the values 67.5% $- 65\%$ ".

In fact, it seems from our tests that the lots we received from Spencer before the last one meet the above mentioned specification.

The reply of Spencer was the following :

"Your comments concerning the granulometry of our fused and ground UO_2 powder are extremely interesting. The degradation of the mesh sizes compares roughly with our previous experience in long-haul transportation. The only way we know for you to be able to use a specific granulometry is for you to do the grinding and separation at the geographical point where you intend to load the fuel element tubes.

This problem has existed here in the U.S. for some time, and the users of our fused and ground material now have standardized on purchasing $- 3 + 20$ mesh, and screening the material after receipt. They inform us that approximately 10-15% of the material is all that they have to size after screening.

We would like to note, of course, that we deliberately manufacture friability into this powder so that it will attain high tube densities under vibratory compaction.

It is our rough estimate that it would be cheaper for you to do your own screening and sizing of $- 3 + 20$ mesh than it would be for us to attempt to meet the test procedures shown at the bottom of page 2 of your letter (*). Inasmuch as this is crystalline material, it is quite easy to screen, and large amounts can be handled in very short times by a limited number of personnel.

For your comparison, should you desire to purchase $- 3 + 20$ mesh size material, our quotation of April 3, 1962 (**) will be reduced 7.6 % in price".

5.3 — Thermal conductivity of swaged UO_2

The same technique used during the first year of the contract was adopted. This "stationary" method was based on the radial heat flux in an infinitely long cylinder and required a known heat source situated in an axial position along the center of the swaged bar to insure a radial heat flux. Thermocouple measurements at various known distances from the center of the rod make it possible to calculate the thermal conductivity.

(*) The test procedure is the one mentioned above.
(**) Conversion of UF_6 to fused and ground UO_2, 3.5% enriched, quantity 50,000 lbs for $ 4.35 per pound. This quotation was used by us for the cost evaluation reported at paragraph 6.

The sample preparation for measuring thermal conductivity consisted of placing the heater assembly centrally in a stainless steel tube, filling the tube with UO_2 and swaging the composite. The heater assembly consisted of a fine Nichrome heating element insulated by MgO in a copper tube having outside diameter of 3 mm.

After swaging, a fine hole of 0.4-0.5 mm diameter is carefully drilled forming a chord for the thermocouple. Iron-constantan thermocouples of 0.2 mm diameter were soldered with the two wires coming from directions 180° apart. The bead was reduced to a maximum value of 0.4 mm.

In order to avoid oxidation of UO_2 at elevated temperatures, the sample was placed in a Vycor tube through which inert atmosphere was continuously passed. The copper tube which was wrapped around the swaged UO_2 samples was for water cooling so as to yield a higher temperature drop trom the center to the outside of the UO_2.

During the first year of the research the thermal conductivity of swaged UO_2 was determined at temperatures up to 500 °C. Subsequently, attempts to modify the experimental setup were made so that measurements may be performed to higher temperatures.

An alternate current circuit was prepared in order to increase the power dissipated by the heater. The heater assembly was modified by replacing the Nichrome heating element with a kanthal A1 wire insulated by Al_2O_3 in a stainless steel tube having outside diameter of 4 mm. Chromel-alumel thermocouples were used.

In order to avoid oxidation of UO_2 at elevated temperatures, the nitrogen gas stream passes through a purification tube where oxigen and water impurities are trapped before entering the Vycor tube encasing the sample.

A device (shown in figure 7) moves horizontally the thermocouple junction inside the UO_2 by means of a lead screw.

Measurements have been performed up to 825 °C on swaged UO_2 samples of 90-91% T.D. Results are presented in figure 8 together with values obtained during the first year of the research at temperatures lower than 500 °C.

Assuming as a comparison base the values reported by Deem and Lucks (*) for UO_2 pellets, the thermal conductivity values for swaged UO_2 seems to remain lower by approx. 25% than the thermal conductivity values for pellets at the same density (90% T.D.) and temperatures between 150 and 800 °C.

In order to ascertain whether reasonably correct values of thermal conductivity could be obtained with the experimental setup, it was necessary during the first year of the research to perform experiments on a material of known conductivity. A stainless steel sample was prepared identical with the swaged UO_2 sample with the one exception that a 1 mm hole was drilled to accomodate a thermocouple insulated by an extremely small alumina tube. Data obtained resulted approx. 8% lower than the published data. Since stainless steel has a thermal conductivity considerably higher than UO_2, the ΔT's which were measured were very small and, therefore, subject to considerable error. Since the temperature differences between consecutive measurements were considerably larger for UO_2, it was expected that the measurements would be somewhat more accurate.

During the last period of the research, measurements of the thermal conductivity of UO_2 pellets were performed with the same experimental technique used for the swaged UO_2. Data

(*) BMI-1448, Section J, June 1960. As shown in figure 8, the values reported by Deem and Lucks lay between the high values reported by Kingery (J. Am. Ceram. Soc. 42, 617, 1959) and the lower values reported by Hedge and Fieldhouse (AECU-3381, 1956).

obtained at four different temperatures are reported in figure 8. They are approx. 12% lower than the values reported by Deem and Lucks. However, it must be noted that these values are to be considered only roughly indicative because the technique used by us for measuring the thermal conductivity is much more suitable for swaged UO₂ samples which have the UO₂ in strict contact with the axial heater assembly, whereas this contact with the inside of the drilled holes of the pellets is certainly not as satisfactory.

5.4 — Porosimetry of swaged UO₂

In order to obtain some information on the open porosity of swaged UO₂, three samples have been subjected to the pressurized mercury analysis up to 5,000 psi. The apparatus used was the Aminco-Winslow Porosimeter Cat. No 5-7107 produced by the American Instrument Company.

The three samples were obtained by cutting a piece approximately 10 mm long from three different swaged rods. The characteristics of the three samples are listed below :

Sample	Cladding	UO₂	Reduction of Fuel Area	Swaged Density
P 1	SS 304	Fused	19.4%	89% T. D.
P 2	SS 304	Fused	27.2%	92% T. D.
P 3	SS 304	Special Dense (Hi-fired)	26.5%	89% T. D.

The results of the analyses for these three samples and two reference pellets are shown in figure 9. They can be summarized as follows.

i. A difference in the pore distribution has been noted between swaged UO₂ of the same density but different type of powder even though the minimum measurable diameters of open pores are very close (460 Å and 480 Å for "fused" and "hi-fired" powders respectively).

ii. The minimum measurable pore diameter is increasing with increasing density for both swaged UO₂ and pellets.

iii. Open porosity of swaged UO₂ has higher values than the open porosity of pellets having the same density, as expected.

5.5 — Roughness of cladding internal surface (*)

The inner surface of the swaged tube in contact with the UO₂ powder shows evidence of engravings left by the UO₂ grains compacted and fragmented during swaging.

A series of roughness measurements has been done on the inner surface of the 2 cm long samples used for the UO₂ "etched" density determination of the reactor length rods with stainless steel and Zircaloy-2 cladding.

The surface measuring instrument was the Taylor-Hobson Model 3 "Talysurf" apparatus with pick-up 0,0005 " in radius.

(*) Work done in co-operation with Fiat   L.R.C.A.A.

The value obtained for the C. L. A. Index (cut-off 0.1 ") were the following :

— Stainless steel tubes .020" wall as received from Dalmine :   110   microinches
— Same after swaging of hi-fired UO_2 to 89.6% T. D.   150   microinches
— Same after swaging of fused UO_2 to 93% T. D.   250-420   microinches
— Zircaloy-2 tubes .020" wall as received from Superior :   40   microinches
— Same after swaging of fused UO_2 to 93% T. D. :   200-440   microinches .

Figure 10 shows typical profiles of the inner surface of Zircaloy-2 tubes as received and after swaging of fused UO_2.

5.6 — Hardness of cladding

The adopted vibro-swaging process does not affect heavily the mechanical properties of the cladding. Total reductions of area of approximately 18% cause a very slight reduction of the tube-wall thickness (approx. 2%).

A series of hardness measurements has been done on the cladding surface of the rods fabricated for the reproducibility and uniformity study. The apparatus used was the Rockwell Superficial-Hardness Tester Galileo Mod. SA-200. The following hardness numbers were measured (average of 10 values) :

— Superior Stainless 304
     as received   :   15 T — 77
     after swaging :   15 T — 85.5
— Dalmine Stainless 304
     as received   :   15 T — 74
     after swaging :   15 T — 84
— Superior Zircaloy-2
     as received   :   15 T — 81
     after swaging :   15 T — 84

5.7 — Thickness testing of cladding

An apparatus has been set up to measure the average thickness of cladding. The technique is based on the measure of the voltage drop between two points along the tube length. The two contacts are obtained by means of two blades fixed at a distance of 2.99 cm. The measuring instrument is a Leeds & Northrup Universal Potentiometer Type K3.

The thickness is furnished by the expression

$$T = \frac{1}{2}\left(D_0 - \sqrt{D_0^2 - \frac{4}{\pi}\rho\, l\, \frac{1}{V}} \right)$$

where   V = voltage drop between contacts
    I = current intensity
    D_0 = outside diameter
    ρ = resistivity of tube material
    l = distance between contacts.

The error of the measurements on swaged rods has been evaluated to be approx. $\pm 4\%$ of the thickness value.

This technique was set up in order to measure the variation of thickness along the swaged rods. Several stainless steel rods have been tested. None of them showed any preferential thickness variation larger than the tolerance values spread.

5.8 — Thermal cycling of swaged UO_2 rod samples

Four samples taken from swaged UO_2 rods were subjected to thermal cycling in air between room temperature and 600°C. Cycle time : 10 min. The samples, 11.5 mm in diameter and approx. 15 cm long, were stainless steel cladded with wall thickness of approx. 0.5 mm. The fused UO_2 densities were in the range 92-93 per cent of theoretical.

The cycle numbers for the four tests were 350-700-1000 and 1000 respectively.

No dimensional changes were measured after the thermal cycling in the four samples.

6 — ANALYSIS OF ECONOMIC POTENTIALS OF SWAGED UO_2 FUEL

The work done under the present contract has dealt only with the development of a suitable process for fabricating vibro-swaged fuel rods. From this work conclusions can be drawn on the fabrication cost of vibro-swaged UO_2 fuel as compared to pelletized UO_2 fuel. No definite answer however can be reached on potentials of swaged as compared to pelletized fuel, until more information would be available on behavior of swaged fuel under irradiation. From this point of view the maximum attainable effective UO_2 thermal conductivity (or linear specific power) and burn-up level should be known.

On the first quantity, preliminary results have been published; they show, for the specific samples considered, a 20-30% lower effective thermal conductivity in swaged rods then in pelletized rods; not much information seems available instead to the writer best knowledge, on the maximum attainable burn-up.

Another point of view to be considered when trying to compare swaged to pelletized fuel is that of neutron economy. In this respect fuel density is not very important by itself; the most important quantity is instead the cladding-to-fuel weight ratio. As it has been shown during the development of the present work, current pelletized fuel fabrication process can be matched on this respect by the vibro-swaging technique. One has to take into consideration however that pelletized fuels are making some progress in the directions of increasing the fuel density and decreasing the cladding thickness. Both, tend to decrease the cladding-to-fuel weight ratio. Anyway, a definite answer on the minimum cladding-to-fuel weight ratio attainable both in improved pelletized and swaged fuels could be given only by actual irradiation behaviour experience.

The fabrication cost of swaged fuel rods, as will be shown later, are lower than that of pelletized fuel. So it seems that, to a certain extent, a lower linear specific power and burn-up level and a greater cladding-to-fuel weight ratio could be permissible in swaged fuels.

To have some indication on the breakeven points, a preliminary economic investigation has been done to compare for a typical power plant a core made up of UO_2 pelletized fuel with different swaged cores. The swaged cores considered have been obtained varying, into certain ranges, the values of the three most important parameters mentioned above, compared to that of the reference pelletized core.

The reference case considered is similar to the Yankee reactor. Changing from pelletized to swaged cores, the power rating, the core radius and height, the core lifetime, have not been

changed in order not to have to consider variations in cost due to different refueling time, or different pressure vessel size. The same hot channel factor has been assumed to be valid for all the cases.

The parameters characterizing the several cores considered are given in Table 8. In determining such parameters the following four relationship between the reference case and the swaged cases have been imposed.

$$a) \quad \frac{\text{linear specific power of swaged fuel (kw/cm)}}{\text{linear specific power of reference pellet fuel (kw/cm)}} = \alpha$$

$$b) \quad \frac{\text{burn-up level of swaged fuel (MWD/t)}}{\text{burn-up level of reference pellet fuel (MWD/t)}} = \beta$$

$$c) \quad \frac{\text{cladding-to-fuel weight ratio in swaged fuel}}{\text{cladding-to-fuel weight ratio in reference pellet fuel}} = \gamma$$

$$d) \quad \frac{\text{density of swaged fuel}}{\text{density of reference pellet fuel}} = \delta .$$

The cases considered are 10 and they result from partial combination of :

— 2 values of α : 0.75, 1
— 3 values of β : 0.75-0.875, 1
— 2 values of γ : 1, 1.25

The effect of variation of δ is not very important (in the range of interest for the present investigation), when α, β, γ are fixed; such effect is in between the limit of errors of the used method of calculation to determine core reactivity and lifetime. In fact when α, β, γ are fixed, if furthermore the core dimensions and power are fixed, a slight change in fuel density means only a slight change (inversely proportional to square root of density) in fuel rod radius, with material number densities, number of fuel rods, weight of fuel, and lattice pitch unchanged.

For the present investigation a density of :

— 95 % T.D. for reference pellet core,
— 92.4% T.D. for swaged core,
have been assumed.

For each core for a fixed lifetime of 20.000 hrs at 392 MW (full power operation), values of initial and final U-235 enrichment and Pu produced have been calculated, using a rapid calculation code developed in FIAT for the Remington UTC computer (*). Owing to the roughness of the computation used, all the analysis here given has only an indicative value. A cost analysis for the entire core has then been done, using a Remington UTC code. Such a code computes the fuel cycle cost according to Euratom procedures (**).

(*) Such a code is divided in two parts : the first part called FN-Rapido calculates initial reactivity and enrichment using semiempirical corrected four factor formula; the second part is called VITA-1 and calculates, with uniform burn-up approximation, the core lifetime as a function of enrichment with automatic search of initial enrichment for a given lifetime.

(**) The code is called CICLO COMBUSTIBILE-2. For the accounting method used reference should be made to the Euratom document EUR/C/3851/61 f : "Coût du cycle de combustible des réacteurs de puissance". A reprocessing cost of 19500 $/day has been used instead of 17240 $/day as indicated in the document. The interest rate during fabrication has been assumed to be 7%. The fabrication time varies according to the fuel enrichment as indicated in line 23 of Table VIII. A loading factor of 80%, a 10% spare fuel elements, a transportation time of fresh fuel of 0.17 years, a decay and transportation time of irradiated fuel of 0.4 years have also been used.

The difference in fabrication cost between pelletized and swaged fuel has been analyzed in detail, as reported in Appendix I. Such difference in cost is in favour of the swaged fuel and amounts to approx. 14 $/kg U for the cores with the same number of fuel rods as the reference pelletized core, and to 12 $/kg U for the cores with higher number of fuel rods (cases 4, 5, 6 of Table VIII). To this figure an estimated 0.5% of non recoverable UO_2 losses has to be added for the swaged cores. Since the comparison in fabrication cost between pelletized and swaged fuel starts from loading of fuel tubes with pellets on one part and loading of fuel tubes with swageable grade powder on the other part, such non recoverable losses have been considered to be zero in the case of pellets.

The cost for the remaining part of fuel element fabrication have been assumed to be the same for the pelletized and swaged cores. Such a cost has been assumed to be 83 $/kg, which added to the cost evaluated in Appendix I gives a total fabrication cost, as indicated in line 22 of Table VIII. For the reference pellets case, such a cost is of 115 $/kg.

The results of cost comparison between the reference pelletized core and the swaged cores are given in line 28 of Table VIII. The maximum net saving, among the cases considered, amounts to $ 265,000 for the entire core cost. This results for case n° 1, which is identical to the reference case as far as fuel geometry, linear specific power and burn-up is concerned. Furthermore the same amount of UO_2 per rod results in the two cases, the gap existing in the pellets case compensating for the higher density.

Decreasing the value of α and β and increasing the value of γ, the savings tend to diminuish and become negative after certain points.

The breakeven points have been estimated interpolating between the computed cases. Such breakeven points are :

— with β and γ held fixed at value 1, α can be lowered to 0,55;
— with α and γ held fixed at value 1, β can be lowered to 0,95;
— with α and β held fixed at value 1, γ can be increased to 1,25.

These results show clearly that the burn-up level is a much more important variable than the linear specific power. Enough variation seems to be permitted also for the cladding-to-uranium weight ratio. If these conclusions are correct the effort on studying the irradiation behavior should be concentrated on demonstrating the ability of the swaged fuel elements to withstand the same fuel burn-ups as the pelletized fuel.

A word of explication should be given for the last three lines of Table VIII. In comparing different cores to be put in the same reactor, one has to be sure that not only the same geometrical core dimension and the same power and lifetime is obtained. One has to check also that no variation is required to the primary pumps and that no significative variations in safety have occurred. For the first item, the pressure drops across the core have been evaluated and are reported in line 30 of Table VIII. For the Yankee plant a variation of pressure drop from 16 psi to 20-25 psi would be permissible without any change in primary pumps. The interesting cases in Table VIII respect this limitation.

From the point of view of safety two parameters are of importance : the ratio between burn-out heat flux and maximum heat flux (DNBR), and the specific power generated in the core per unit coolant volume. Assuming the same hot channel factors, the DNBR do not vary very much from one case to the other, as shown in line 31 of Table VIII. For a plant like the one here considered a maximum specific power of 120 kw/liter of coolant should be chosen in order to

TABLE VIII - PARAMETERS CHARACTERIZING THE SWAGED FUEL CORES AND THE PELLETIZED REFERENCE CORE

1		Pelletized reference core	Swaged fuel cores								
1	Identification number	A	1	2	3	4	5	6	1a	2a	3a
2	Thermal Power (MW) $\equiv$ P	392				392					
3	Equivalent Core Radius (cm) $\equiv$ R	99.0				99.0					
4	Active core height (cm) $\equiv$ H	228.6				228.6					
5	$\dfrac{\text{Linear specific power of swaged fuel}}{\text{Linear specific power of pellet fuel}} \equiv \alpha$	1	1	1	1	0.75	0.75	0.75	1	1	1
6	$\dfrac{\text{Burnup level of swaged fuel}}{\text{Burnup level of pellet fuel}} \equiv \beta$	1	1	0.875	0.75	1	0.875	0.75	1	0.875	0.75
7	$\dfrac{\text{Cladding to fuel weight ratio-swaged}}{\text{Cladding to fuel weight ratio-pellet}} \equiv \gamma$	1	1	1	1	1	1	1	1.25	1.25	1.25
8	$\dfrac{\text{Density of swaged fuel}}{\text{Density of pellet fuel}} \equiv \delta$	1				0.973					
9	Linear specific power $(\frac{kW}{cm}) \equiv q'$	73.5	73.5	73.5	73.5	55.1	55.1	55.1	73.5	73.5	73.5
10	Burnup level $(\frac{MWD}{t}) \equiv$ E	15,400	15,400	13,475	11,550	15,400	13,475	11,550	15,400	13,475	11,550
11	Fuel density (% T.D.) $\equiv \rho$	95				92.4					
12	Core total uranium weight at beginning of life (kg) $\equiv Pu^i$	21,260	21,260	24,297	28,347	21,260	24,297	28,347	21,260	24,297	28,347
13	Core total number of fuel rods $\equiv$ N	23,142	23,142	23,142	23,142	30,856	30,856	30,856	23,142	23,142	23,142
14	Fuel radius (cm) $\equiv r_o$	0.3734	0.3786	0.4048	0.4372	0.3278	0.3505	0.3786	0.3786	0.4048	0.4372
15	Internal cladding radius (cm) $\equiv r_1$	0.3786	0.3786	0.4048	0.4372	0.3278	0.3505	0.3786	0.3786	0.4048	0.4372
16	External cladding radius (cm) $\equiv r_2$	0.4318	0.4318	0.462	0.499	0.374	0.400	0.432	0.445	0.476	0.516

FOLLOWS : TABLE VIII - PARAMETERS CHARACTERIZING THE SWAGED FUEL CORES AND THE PELLETIZED REFERENCE CORE

		Pelletized reference core	Swaged fuel cores								
	Identification number	A	1	2	3	4	5	6	1a	2a	3a
17	Cladding thickness / fuel radius $\equiv \dfrac{s}{r_0}$	0,142	0,142	0,142	0,142	0,142	0,142	0,142	0,175	0,175	0,175
18	Lattice half-pitch (cm) $\equiv l/2$	0,5765	0,5765	0,5765	0,5765	0,499	0,499	0,499	0,5765	0,5765	0,5765
19	Initial U-235 fuel enrichment (%) $\equiv w_i$	3,24	3,24	3,65	4,41	3,40.	3,90	4,87	3,75	4,35	5,47
20	Final U-235 fuel enrichment (%) $\equiv w_f$	1,83	1,83	2,50	3,63	2,04	2,70	4,10	2,32	3,05	4,72
21	$\dfrac{g \text{ of Pu produced}}{\text{kg of initial U}}$ (g/kg) $\equiv g$	3,78	3,78	4,44	5,96	4,16	5,02	6,49	4,07	4,98	6,81
22	Fuel fabrication cost ($/kg U)	115	102,5	102,5	103,0	104,5	104,5	105,5	102,5	103,0	103,5
23	Fabrication time (years)	0,5	0,5	0,5	0,6	0,5	0,5	0,6	0,5	0,5	0,6
24	Full power core lifetime (hrs)	20.000				20.000					
25	Actual core lifetime (years)	2,85				2,85					
26	Total core fabrication cost ($)	2.437.000	2.172.000	2.482.000	2.910.000	2.214.000	2.508.000	2.981.000	2.172.000	2.494.000	2.924.000
27	Total core cost ($)	7.453.000	7.188.000	7.703.000	8.182.000	7.401.000	7.923.000	8.436.000	7.450.000	8.419.000	8.564.000
28	Net savings ($)	-	+ 265.000	- 250.000	- 729.000	+ 52.000	- 470.000	- 983.000	+ 3.000	- 966.000	-1.111.000
29	Specific power per moderator unit volume (kw/l)	99,6	99,6	117,9	136,3	100,1	118,7	136,3	105,4	130,6	155,9
30	Pressure drop across the core (psi)	16,0	16,0	23,3	30,6	16,5	23,5	30,6	18,3	29,1	40,0
31	$\dfrac{\text{Burnout heat flux}}{\text{Maximum heat flux}} \equiv$ DNBR	2,8	2,8	2,7	2,6	2,6	2,7	2,8	2,8	2,7	2,5

be safe from the point of view of loss of coolant flow accident. Line 29 of Table VIII shows that only the case 3, 6, 3*a* have a higher specific power than permitted. Such cases are ruled out anyway from the core cost comparison.

7 — CONCLUSIONS

The work done under this contract has demonstrated the suitability of the cold swaging technique for fabricating full size swaged fuel elements for nuclear power reactors having densities of the uranium dioxide as high as 92.5 per cent of theoretical.

When starting a normal production of these kind of fuel elements a few minor problems could still arise as, for example, the problem focused by our work on the changes in compacting behavior of different lots of the fused UO_2 powder. In fact, this problem was quite troublesome during several years for people in charge of UO_2 pellet fabrication who had to run preliminary tests on the just received lots of ceramic grade powder in order to adjust the sintering cycle to the sintering behavior of the new lot. Anyway, should fused UO_2 substitute the pellet fuel, it seems reasonable to assume that this problem will be solved with a better control of the fabrication conditions of the fused UO_2 powder.

The vibro-swaging with no annealings is certainly very attractive for stainless steel cladded rod fabrication. As far as Zircaloy-2 cladding is concerned, the amount of work done under the present contract cannot be considered as sufficient to assert the suitability of the cold swaging. Even though it was not observed any crack in Zircaloy-2 rods fabricated with reductions of area lower than 20%, it must be noted that cracks were observed in two rods at only 25% R. A. and that several rods ruptured at 28% R. A. The visual and Zyglo test examinations on these rods as received had not shown any defect.

From the present work indicative conclusions can be drawn on the fabrication cost of the vibro-swaged UO_2 fuel as compared to the pelletized UO_2 fuel. The estimated figures of 12-14 \$/KgU seem to be interesting for the problem of decreasing the fuel cycle cost. However, no conclusive answer can be given on economic potentials of swaged as compared to pelletized fuel, until more informations will be available on behavior of swaged fuel under irradiation and in operative conditions. The preliminary and very conservative analysis of economic potentials of swaged UO_2 fuel performed under this contract has shown for a typical reactor plant a maximum net saving of approx. 4% of the entire core cost. On the other part, the estimation of breakeven points showed that the burn-up level is a much more important variable than the linear specific power of the fuel rod. If this conclusion is correct, the effort on studying the irradiation behavior should be concentrated on demonstrating the ability of the swaged fuel elements to withstand the same fuel burn-ups as the pelletized fuel.

APPENDIX I

Evaluation of difference in cost between vibro-swaged and pellet-filled fuel elements (*)

The cost evaluation which follows is limited to the economic influence of various materials and fabrication steps requested by the vibro-swaging process as developed on a pilot plant stage during our research compared to the conventional pellet-filling tube process.

The Yankee first core design was used as the basis for this study. The comparison between vibratory packed rods and pelletized rods must take into consideration that more of the powder type rods have to be fabricated because of the lower fuel content per rod unit length. With vibro-swaged rods it seems reasonable to assume the same number of pelletized rods because the somewhat lower fuel density is compensated by the absence of the gap existing between the pellets and clad. In the Yankee fuel rod there is a cold nominal clearance of 0.004 inch. With this clearance the equivalent densities (same quantity of fuel per rod unit length) are 90.5 and 92.5 % of theoretical for 93 and 95 % T. D. pellets respectively. Anyway, for the study reported in paragraph 6, two different numbers of rods have been considered for the vibro-swaged cores, i.e. 23,142, which is also the number of Yankee fuel rods, and 30,856. For each of these two numbers, three different fuel loading have been considered, i.e., 21,260, 24,297 and 28,347 Kg of Uranium.

Typical processes for fabricating fuel rods by vibro-swaging and pellet-filling tube are shown in figure 11. Dotted line encloses materials and steps significant for cost comparison,

The following features need some words of explanation :

1. Labor estimate was done on a production scale facility designed by FIAT-Sezione Grandi Motori. The capacity of this facility was 100 rods per working day which means roughly one Yankee core per year. Figure 12 shows the tube loading and vibration cycle : 1. Homogenizing of ternary mixture; 2. Weighing and loading of the four reservoirs; 3. Fixturing of the four tubes; 4. One fourth loading of tube length; 5. First vibration of the four tubes (one single tube is vibrated each time); 6. Reloading of one fourth of tube length; 7. Second vibration of the four tubes, etc. The cycle ends with the fourth vibration of the fuel rod.

2. No difference in cost is expected for end cap material, end cap welding, placing tube in fixture, removing tube from fixture and cutting tube to length, inspection.

3. For comparison reasons, and because the cost of materials is derived from recent quotations of U.S. vendors, the $ 9 per hour labor rate was adopted as the average of the U.S. industry labor costs.

4. A typical scrap allowance of a 1 % total loss at the end of the process has been assumed in the recent Combustion Engineering study (**) for both the pellet process and the vibratory packing process. It has been observed (***) that perhaps the most promising potential advantage of vibratory compaction as a means of producing powder loaded fuel elements is that the manufacturing losses through rejection should be very low. This is not likely to be true of the swaging process where the tube wall is mechanically deformed to decrease the initial cross-section. We think that this deformation through the swager will not be a problem for the stainless steel cladding; however, it might slightly increase the rejection rate at the helium leak test of the welded caps. Anyway, bearing in mind the relatively small reduction of the initial cross-section as necessary for the vibro-swaging here considered (approx. 18 % R.A.), it is our feeling that a 2 % scrap allowance should be a reasonable assumption.
   A conservative 0.5 % of non recoverable losses has been assumed for the calculations reported at paragraph VI.

5. The comparison between tubing costs for the two processes was done on a very conservative basis. For the vibro-swaging process quotations were on completely commercial quality weldrawn stainless steel tube with standard commercial tolerances. For the pellet-filling tube process quotations were also on commercial quality tube with one-half of standard commercial tolerances to allow for the pellet stack loading but with no special testing to be performed. The length of tubing requested for one finished fuel rod is expected to be about equivalent for the two processes because the approx. 13 % tube elongation during swaging is roughly compensated by the piece of tube which remains empty after the last loading and vibration and is lost at the tube cutting to length.

6. A larger overage of fuel in the pellet process (2 % against 0.5 % in the vibratory packing process) has been considered necessary in the Combustion Engineering study (**) to allow for the time required for pelletizing and the rework of pellets which are damaged in handling. In our estimate the overage was conservatively taken equal to 2 % also for vibro-swaging process because it is our feeling that changes in the fragmentation behavior of different lots of fused UO_2 mixtures might make necessary some rework of the standard mixture or the performing of preliminary runs to check the behavior of as received lots of fused UO_2 powder.

(*)   Work done in co-operation with Fiat - Sezione Grandi Motori.

(**)   B.E. Murtha and W.P. Chernock, "Economics of Powder Packed Fuel Elements", CEND-153, Vol. 1 December 1, 1961.

(***) "The Development and Testing of the UO_2 Fuel Element System", CEND-88, VI-C-2, June 1, 1960.

Details of labor and materials estimate follow. The final cost difference is in favour of the swaged fuel and has been assumed to be approx. $32 - 18 = 14$ \$/KgU for the cores with the same number of fuel rods as the reference pelletized core and approx. $32 - 20 (*) = 12$ \$/KgU for the cores with higher number of fuel rods.

Labor Estimate	Vibro-swaging		Pellet-filling tube
1. Fuel loading :			
Pellet weighing and loading; MH (")	—		0.20
Powder mixing and weighing; MH	0.08		—
Powder loading and pre-compaction; MH	0.18		—
Pre-compacted bar swaging; MH	0.08		—
Subtotal; MH/Fuel rod	0.34		0.20
2. Numbers of rods per core	23,142 —	30,856	23,142
3. Scrap allowance (% of loading)	2%	2%	1%
4. Total number of rods required	23,605	31,474	23,374
5. Total MH for core loading	8,026	10,702	4,675
Total for labor ($ 9/Hour)	$ 72,200	$ 96,300	$ 42,100

(") MH = Man-Hours

Materials Estimate	Vibro-swaging			Pellet-filling tube
	21,260 — 24,297 — 28,347 (Kg U)			21,260 (Kg U)
1. UO$_2$ Fuel; lbs.	55,800	63,700	74,200	55,000
Cost per pound; $	4.35	4.35	4.35	10.20
Subtotal for fuel	$ 243,000	$ 278,00	$ 323,000	$ 560,000
Conversion cost of excess				
UO$_2$ to U$_3$O$_8$ ($ 2.00/lb)	$ 4,300	$ 4,900	$ 5,700	$ 3,200
Total for fuel	$ 247,300	$ 282,900	$ 328,700	$ 563,200
2. Tubing				
Number of rods	23,605	31,474		23,374
Quantity; ft.	189,000	245,000		187,000
Cost per foot; $	0.35	0.35		0.45
Total for tubing	$ 66,000	$ 86,000		$ 84,000

Summary	Vibro-swaging						Pellet-filling tube
Number of rods	23,142			30,856			23,142
Fuel loading							
(Kg U)	21,260 —	24,297 —	28,347	— 21,260 —	24,297 —	28,347	21,260
Labor	$ 72,200	$ 72,200	$ 72,200	$ 96,300	$ 96,300	$ 96,300	$ 42,100
Fuel	$ 247,300	$ 282,900	$ 328,700	$ 247,300	$ 282,900	$ 328,700	$ 563,200
Tubing	$ 66,000	$ 66,000	$ 66,000	$ 86,000	$ 86,000	$ 86,000	$ 84,000
Totals	$ 385,500	$ 421,100	$ 466,900	$ 429,600	$ 465,200	$ 511,000	$ 689,300
$/Kg U	18.10	17.30	16.50	20.20	19.10	18.00	32.40

(*) This figure has been slightly increased to account for the extra cost due to handling of a larger number of rods.
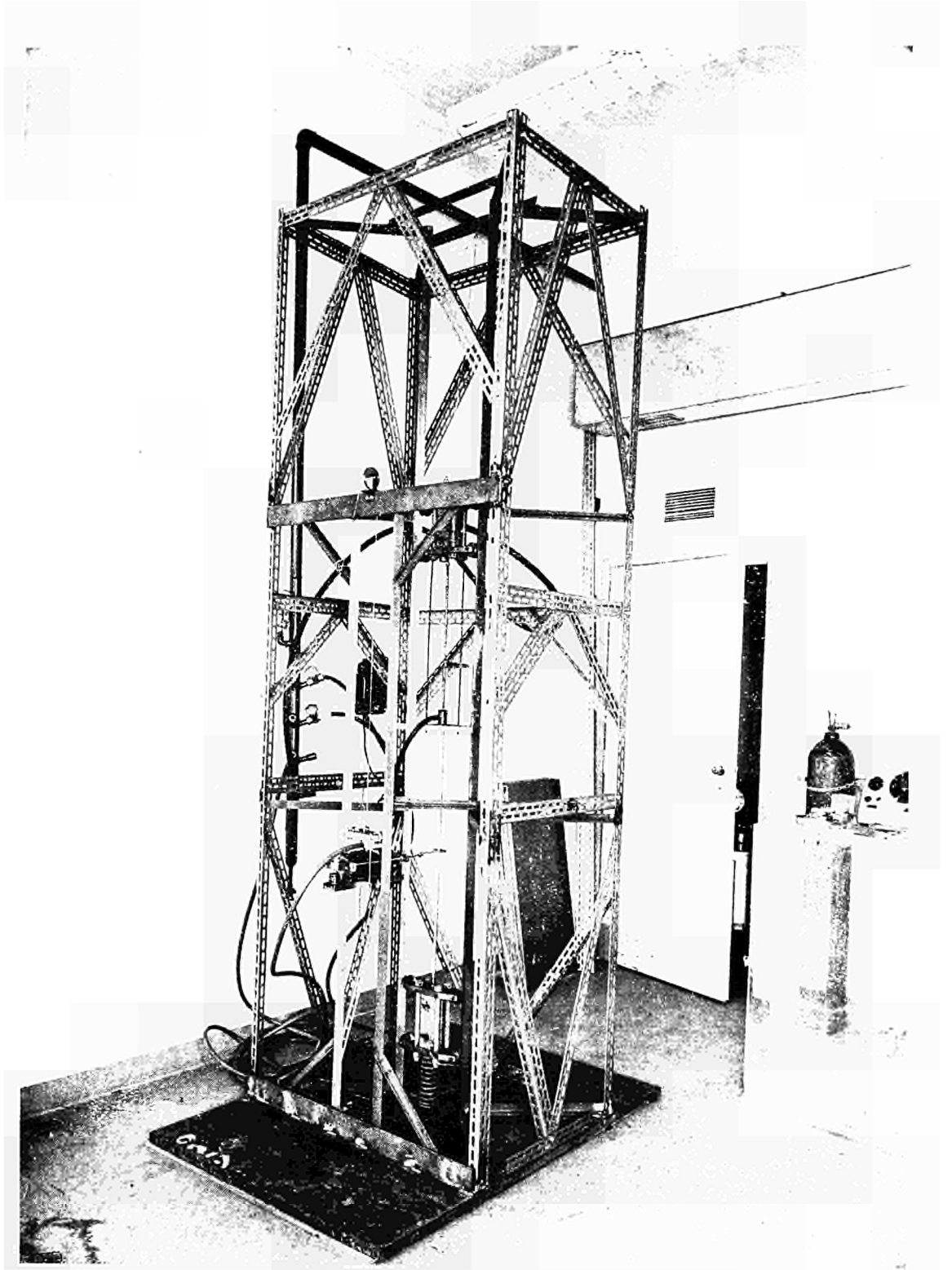
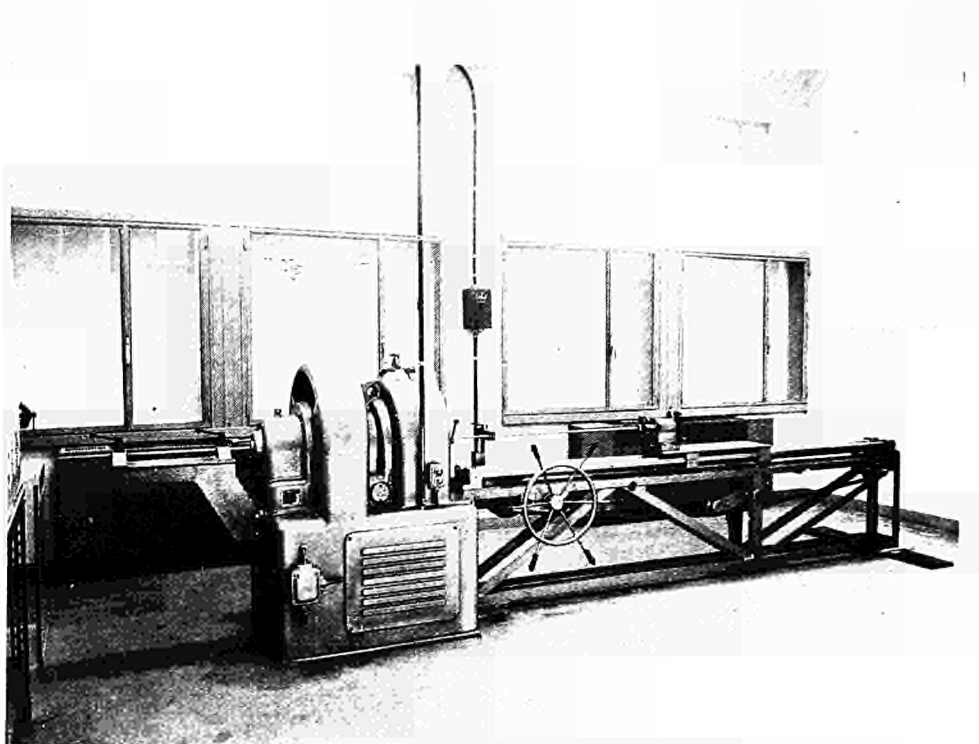Fig. 1 — Apparatus for the pneumatic vibration of reactor length rods.

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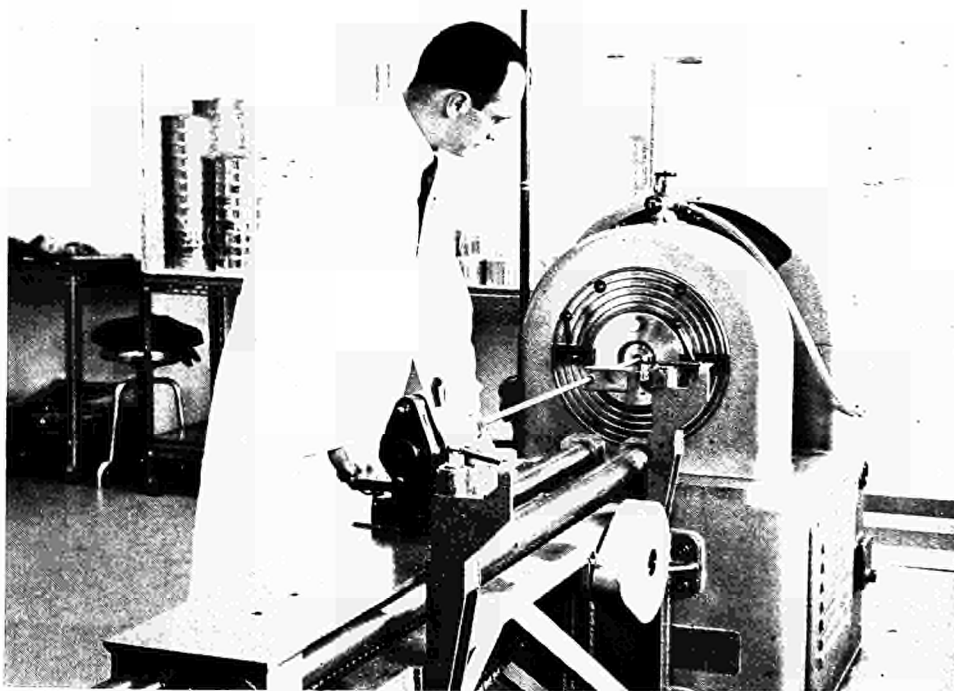Fig. 2 — Swaging machine and semi-automatic feeding device.

Fig. 3 — Swaging of a UO₂ bar using the semi-automatic feeding device.

Fig. 1 — Apparatus for the pneumatic vibration of reactor length rods.

Fig. 2 — Swaging machine and semi-automatic feeding device.

Fig. 3 — Swaging of a UO_2 bar using the semi-automatic feeding device.
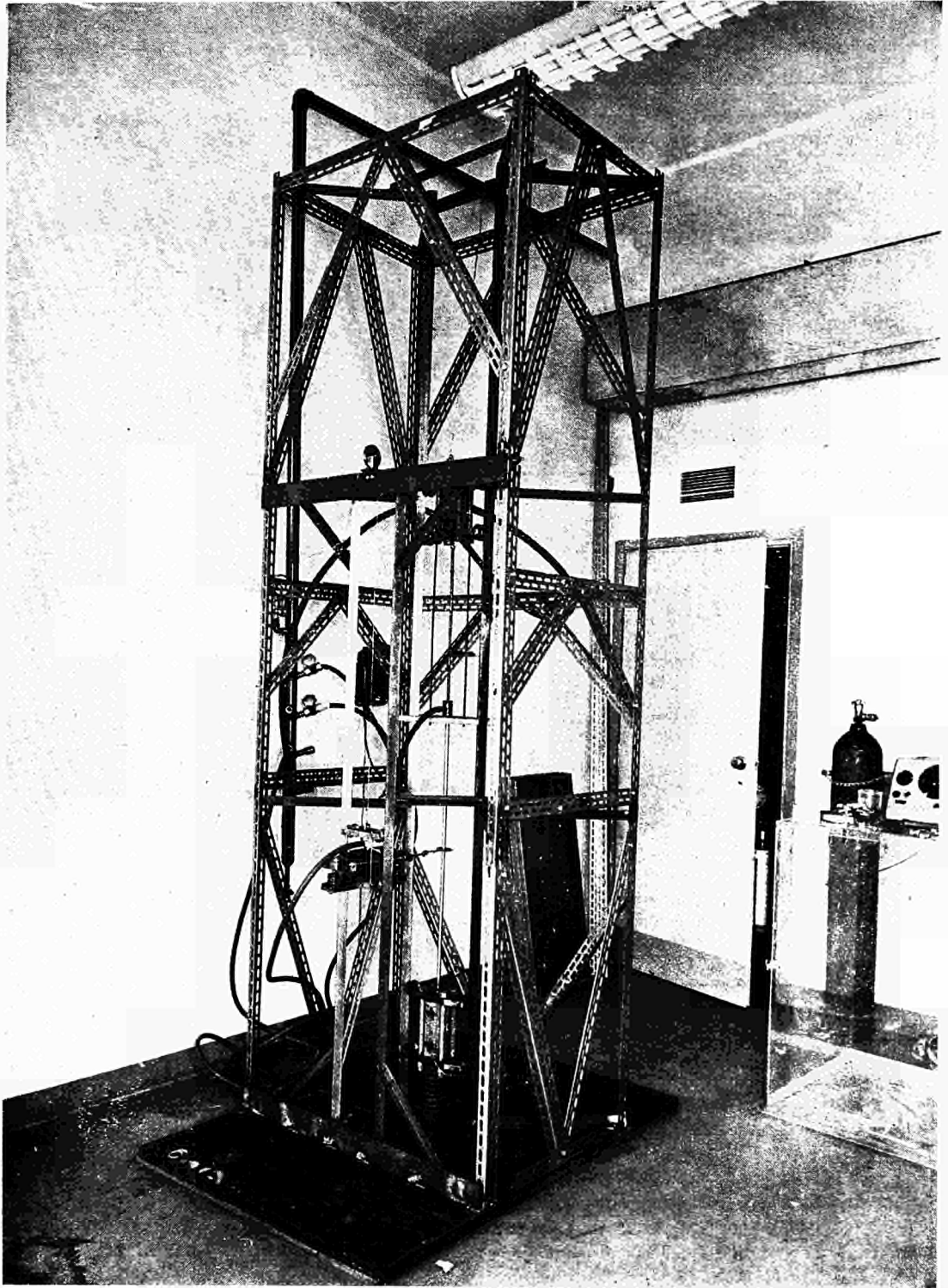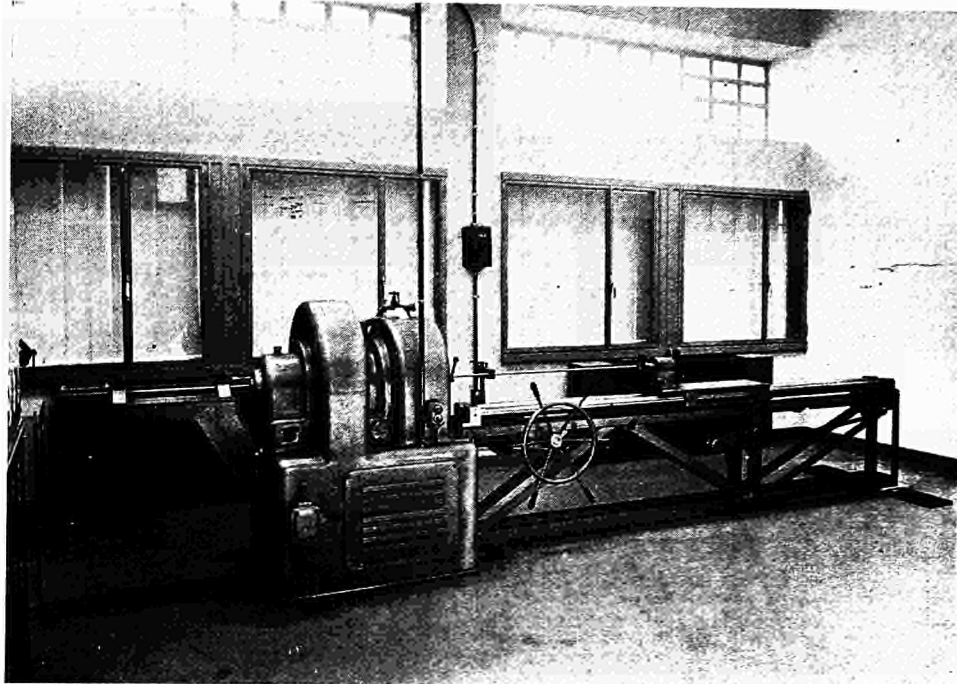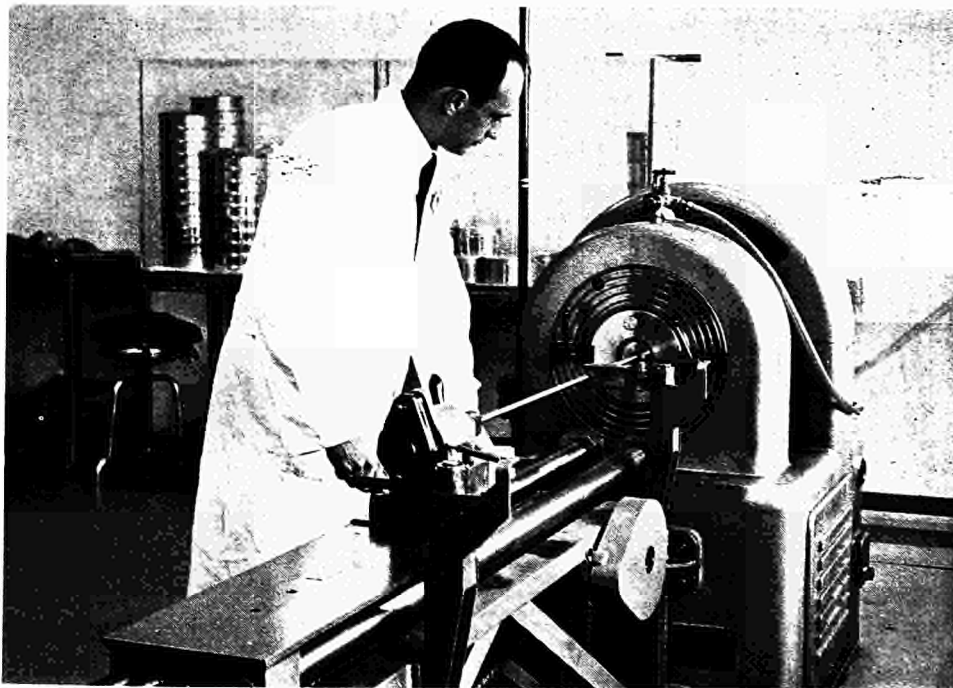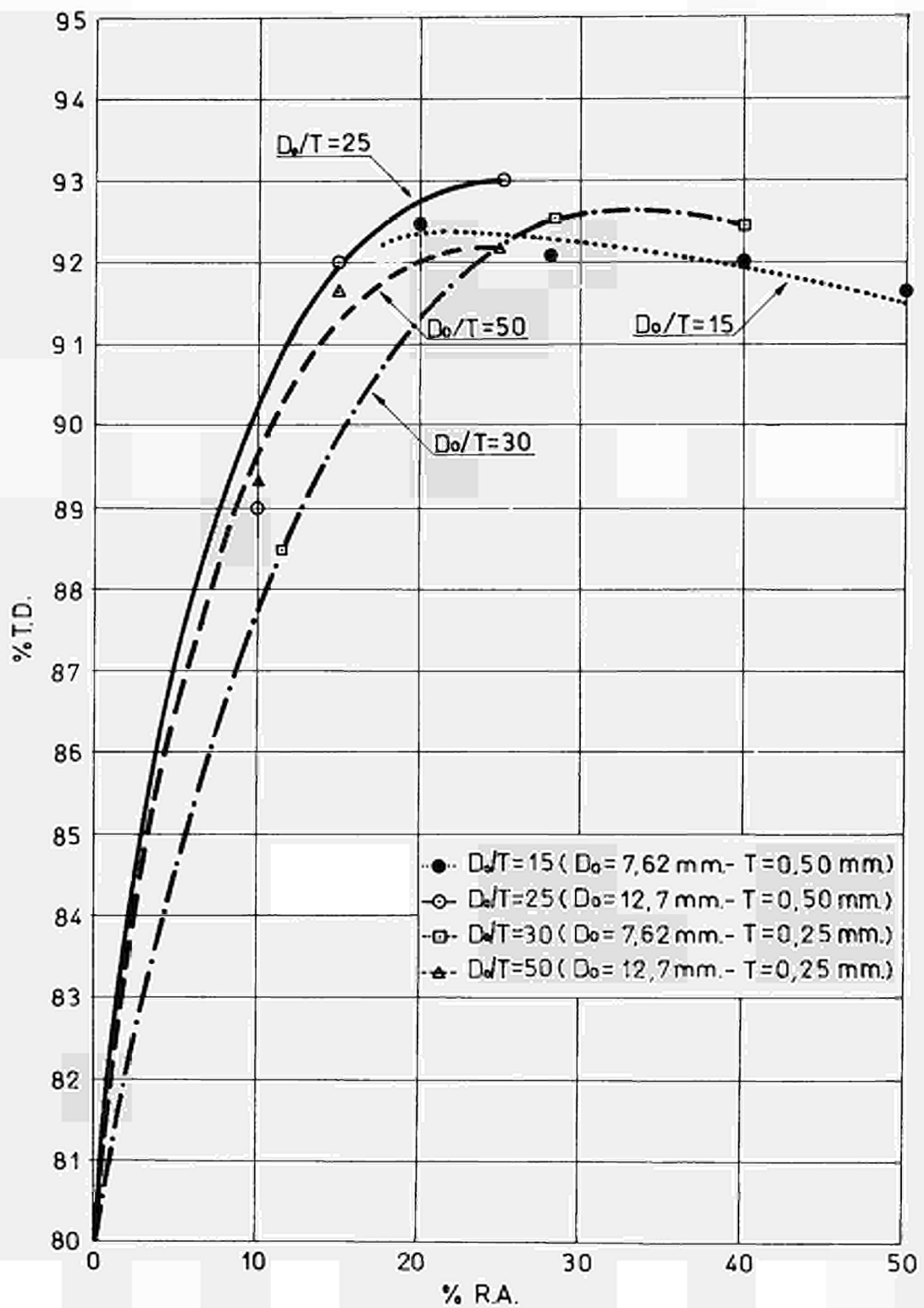
Fig. 4 — Swaged density of UO₂ plotted as a function of reduction of area for Zircaloy-2 bars having different diameter-to-thickness ratios.
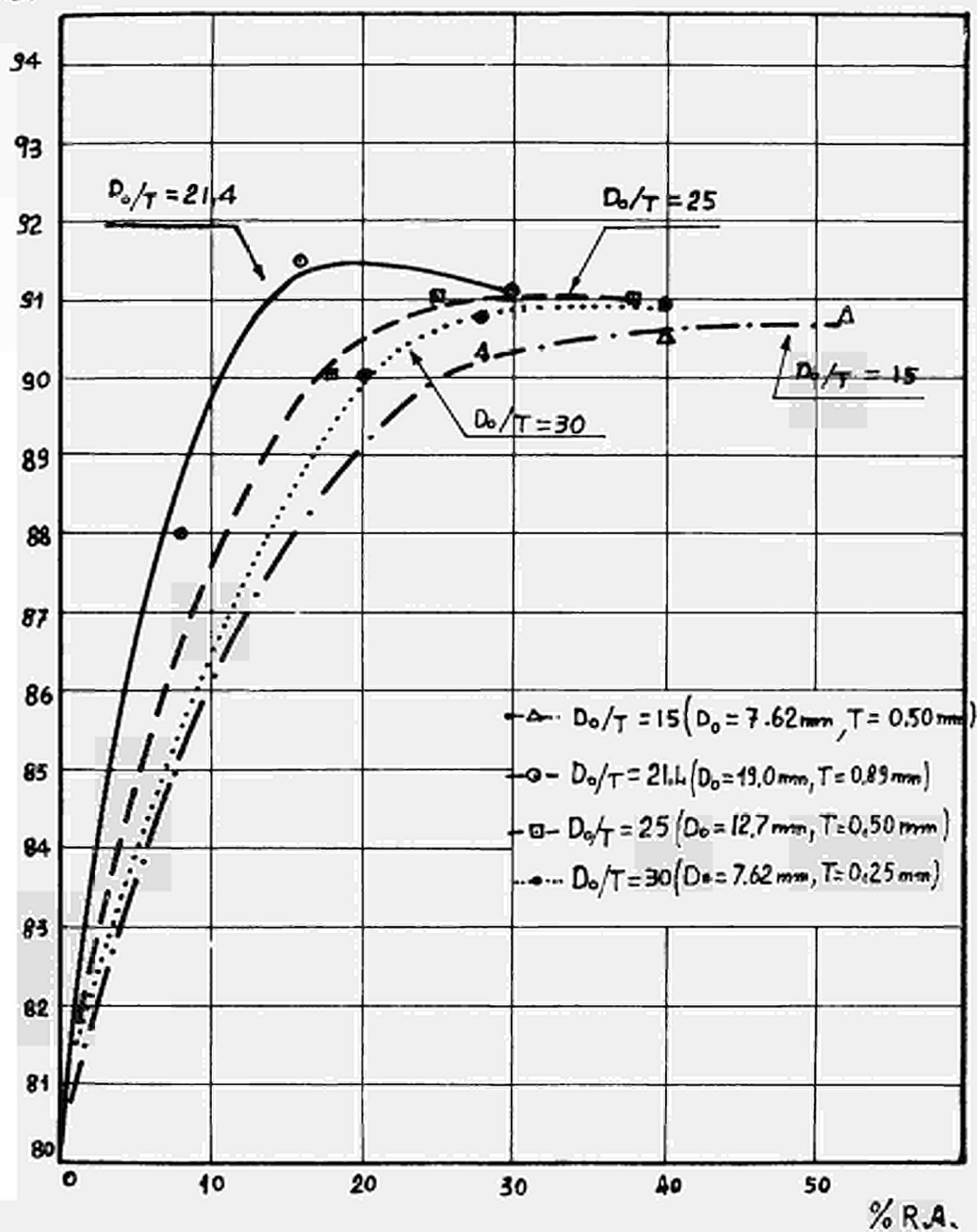
Fig. 5 — Swaged density of UO₂ plotted as a function of reduction of area for Zircaloy-2 bars having different diameter-to-thickness ratios. Very friable fused UO₂ lot.
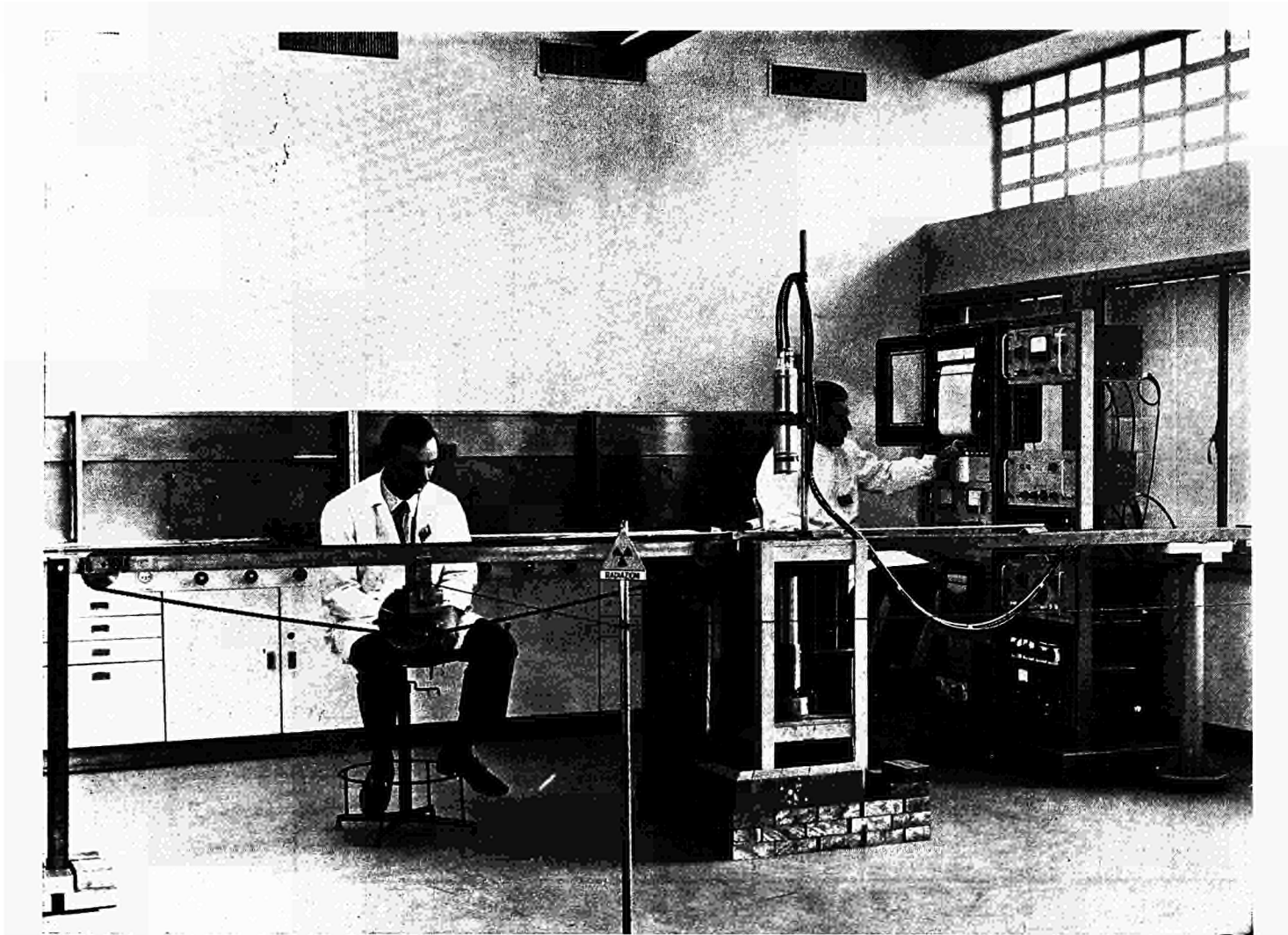
Fig. 6 — Gamma absorptometer for UO₂ density determination. Overall view of the experimental setup.
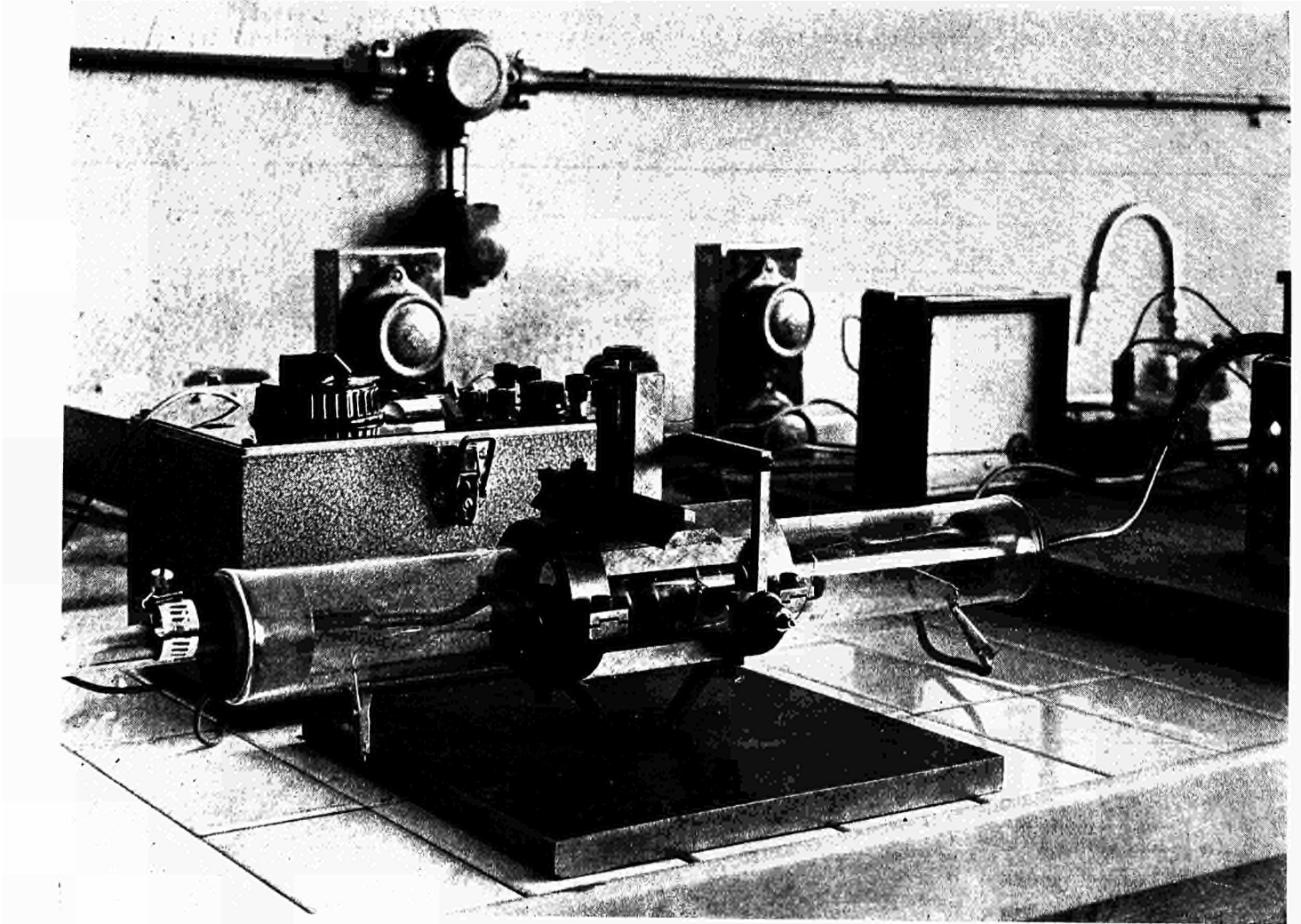
Fig. 7 — Experimental setup for the measurement of the thermal conductivity of swaged UO₂. Detailed view of sample.
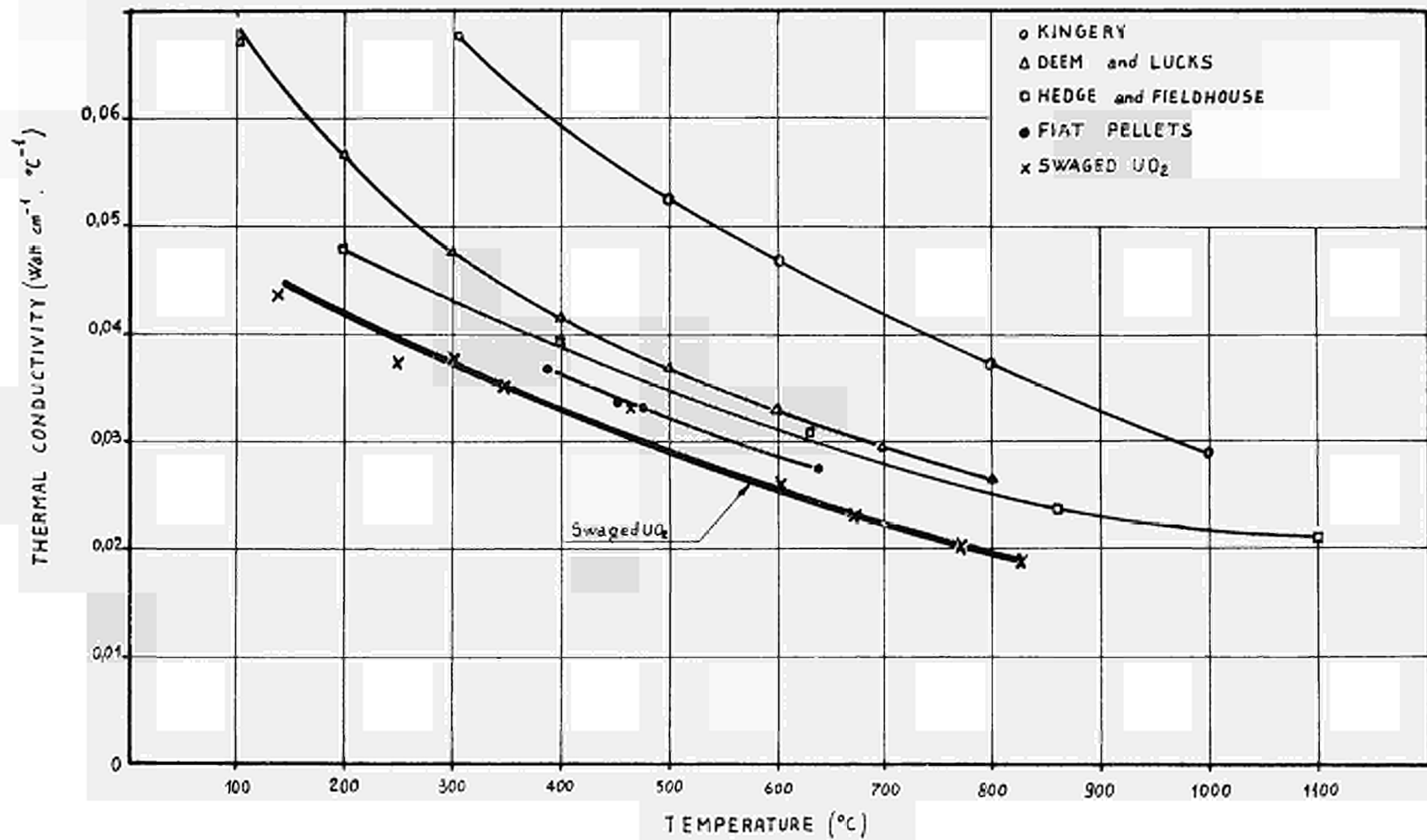
Fig. 8 — Thermal conductivity vs. temperature of swaged UO₂ of 90-91 per cent of theoretical density. Reference values for pellets are adjusted to UO₂ of 90 % T. D.
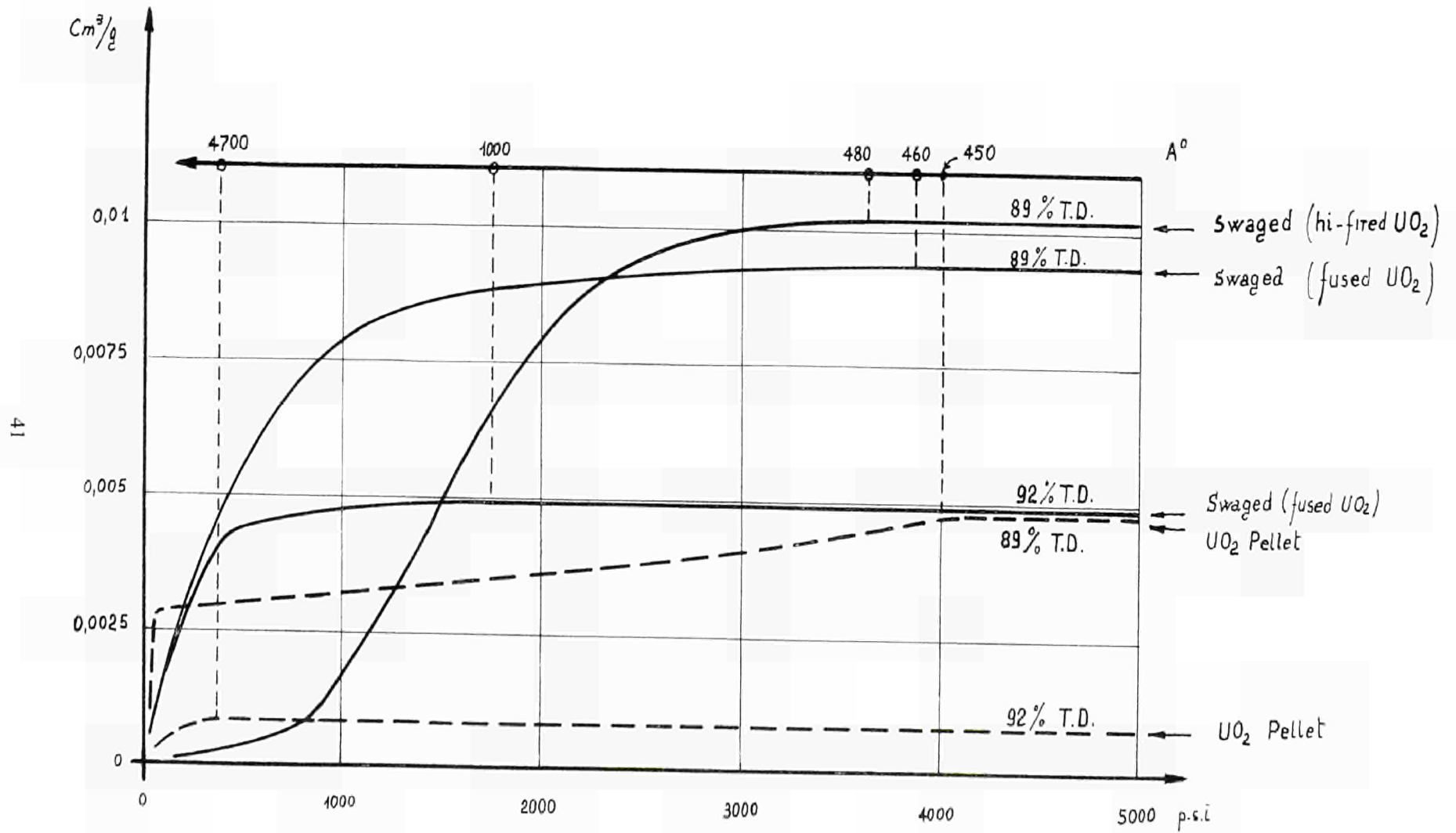
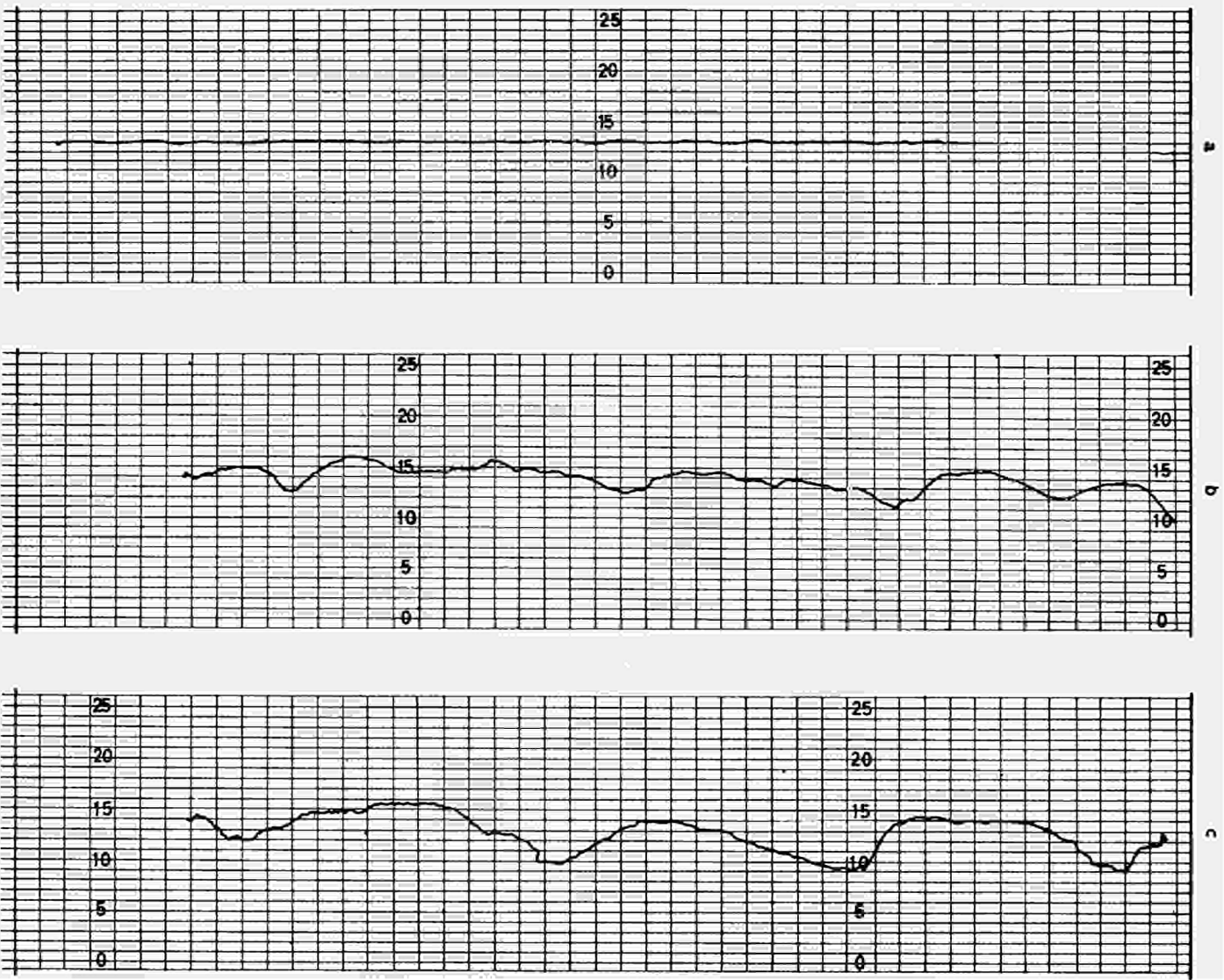Fig. 9 — Open porosity curves from pressurized mercury technique for swaged UO₂ and pellet samples.

Fig. 10 — Typical profiles of the inner surface of Zircaloy-2 tubes as received (a) and after swaging of fused UO₂
(b, c). Abscissae 20 x; ordinates 200 x; C.L.A. Index: $a = 40$ μin; $b = 200$ μin; $c = 440$ μin.
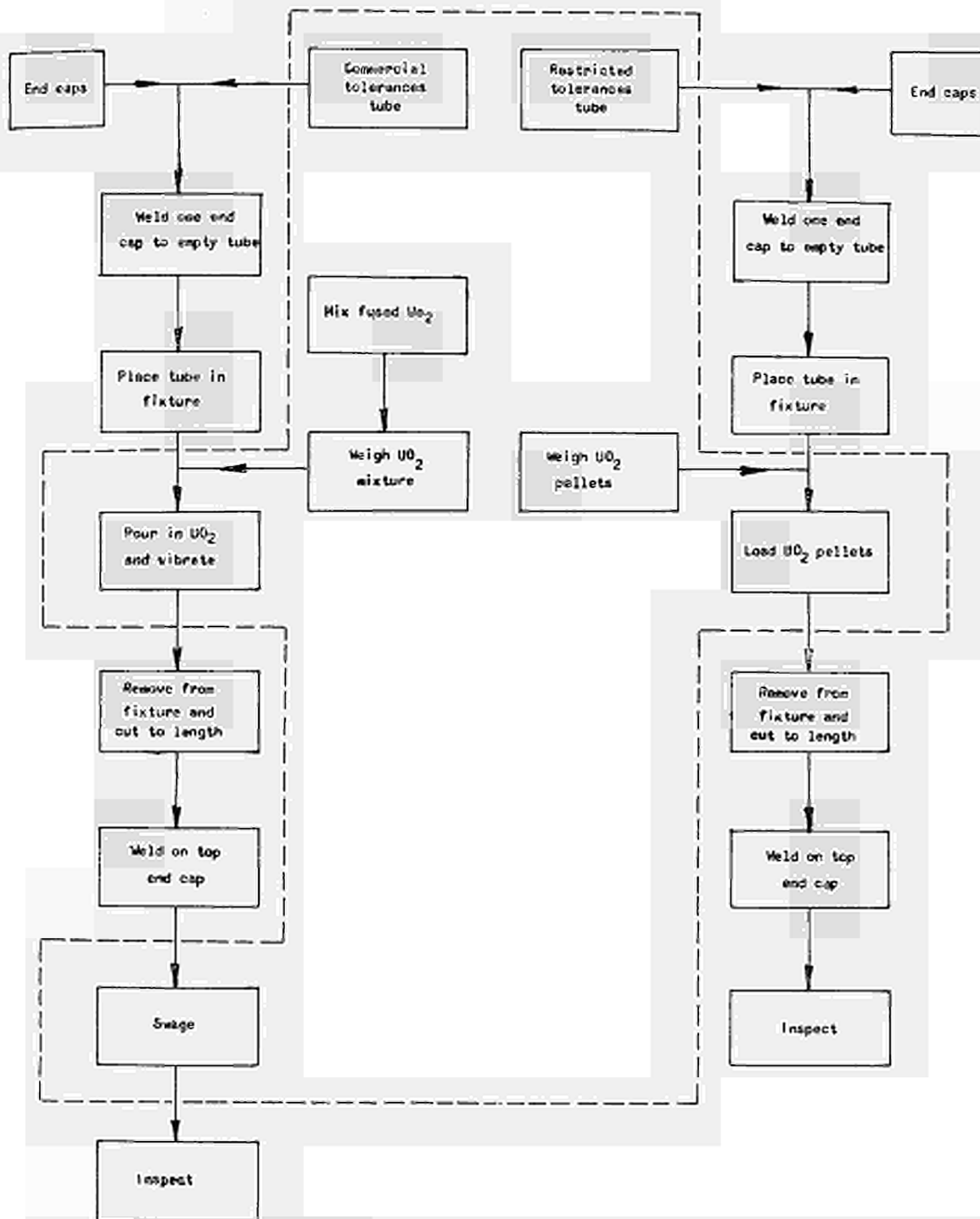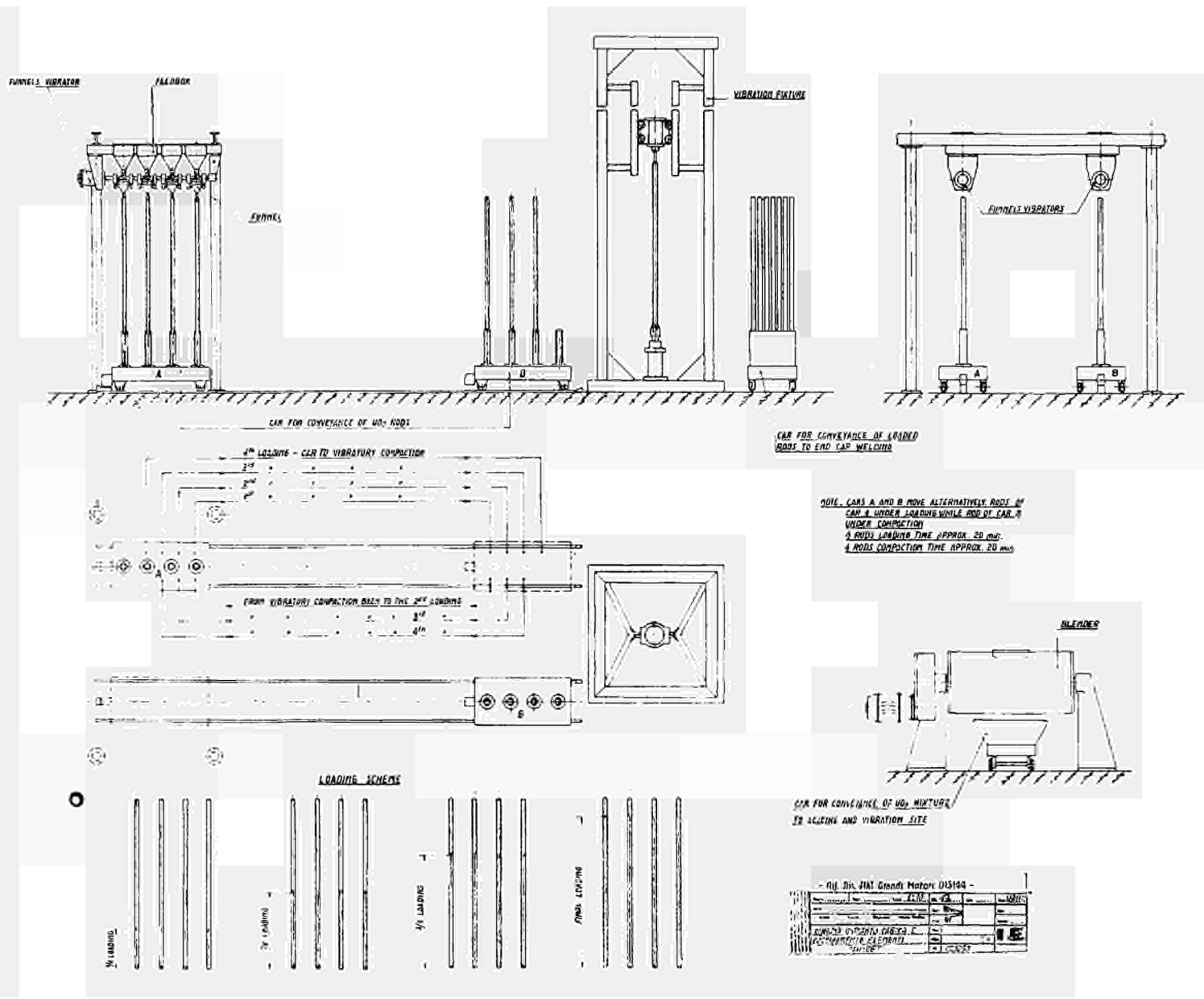
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Fig. 11 — Typical process for fabricating fuel rods by vibro-swaging and pellet-filling tube. Dotted line encloses materials and steps significative for cost comparisons.

Fig. 12 — Production scale facility having a capacity of 100 swaged rods per day; tube loading and vibration cycle.