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A PRELIMINARY STUDY OF FUEL FABRICATION COSTS FOR LARGE HEAVY-WATER-MODERATED REACTORS

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METALS AND CERAMICS DIVISION

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A. L. Lotts and D. A. Douglas, Jr.

APRIL 1964

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ABSTRACT

The purpose of this limited study was to estimate the cost of fabricating fuel elements for very large process heat reactors intended for desalination of seawater. In concept, the reactor would be moderated by heavy water, cooled by light water, and fueled by natural uranium. The special case of using plutonium and depleted uranium as the fuel was also considered.

The fuel elements were envisaged as being of the concentric-tube, Zircaloy-clad type, containing either vibratorily compacted natural UO_2 or 99.4% depleted UO_2 spiked with 0.6% PuO_2; costs were estimated for three reactor sizes: 3500, 25,000, and 100,000 Mw(t). Fabrication plants were conceived, operational methods were established, processing times and labor were estimated, and the future cost of Zircaloy was predicted.

From this analysis the cost of natural-uranium fuel fabrication, not including uranium or UO_3 costs, was estimated to be \$15.55, \$9.62, and \$5.35 per kilogram of uranium for 3500-, 25,000-, and 100,000-Mw(t) reactors, respectively. The cost of PuO_2-UO_2 fuel fabrication, including all operations from sol-gel—produced oxide to finished elements but not including plutonium, uranium, or PuO_2-UO_2 costs, was estimated, per kilogram of uranium plus plutonium, to be \$19.83, \$12.15, and \$6.30, respectively.

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INTRODUCTION

A study of nuclear-powered, seawater distilling plants is being conducted by the Oak Ridge National Laboratory. This study has already shown that plants which use very large reactors to supply heat to evaporators can probably produce fresh water from the sea more inexpensively than any other proposed means.

Nuclear and conventional power plants of today appear to have promise for saline-water conversion for municipal and industrial use. However, the cost must be appreciably reduced to supply economically large quantities of agricultural water. A cost reduction of the magnitude required appears to be possible for very large stations with inexpensive fuel cycles. Recently, Hammond and co-workers[1] observed that large reactor stations in the range of 25,000 Mw(t) may be capable of producing heat at low enough cost to make distillative desalination of seawater economically feasible for irrigation use. Only reactor types related to current technology have been considered in the present ORNL study.

As a part of the overall economic study, an analysis was made by the Metals and Ceramics Division to determine the fabrication costs of the fuel elements and, primarily, to estimate the effect of production rate on the fuel element cost. The D_2O-moderated and boiling H_2O-cooled reactor fueled with natural uranium, which appears to have the lowest heat cost, was selected as the reference reactor for this study. (A fuel cycle based on depleted uranium spiked with 6 g of Pu per kg of fuel was

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[1]R. P. Hammond, I. Spiewak, and G. Young, Prospects for Sea-Water Desalination with Nuclear Energy, An Evaluation Program, ORNL TM-465 (January 1963).

also considered in the study.) Fuel element costs are predicted for three sizes of reactor plants: 3500, 25,000, and 100,000 Mw(t).

DESCRIPTION OF REACTOR

The conceptual design of the reference reactor is very similar to that being developed at the Savannah River Laboratory (SRL) as part of the Atomic Energy Commission's ten-year program for obtaining economical power reactors. Since SRL's design work is within the framework of current technology, reactors of this type can be considerable as suitable for construction in the near future.[2] The SRL reactor[3,4] consists of a cylindrical (calandria) tank, 18.5 ft in diameter and 17 ft high, containing a cold D_2O moderator and 244 vertical pressure tubes containing 41.7 tons of natural uranium fuel. The reactor was designed to deliver 302 Mw(e) net at a thermal rating of 1269 Mw. The fuel elements are cooled by circulating pressurized heavy water, which enters the reactor at 223°C and leaves at 280°C.

In the ORNL concept of the reference plant, steam is generated in a U-tube stainless steel heat exchanger at 287 psig and is admitted to a turbogenerator of either the noncondensing or partial-extraction type. Low-pressure exhaust or extracted steam at about 10 psig passes into a brine heater. The heated brine is pumped into a flask evaporator, where fresh water is prepared. The reference reactor used in our study differs from the SRL reactor in that light water is used to cool the reactor-core pressure tubes and it is much larger (see Appendix A for design data on this reactor).

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[2]R. P. Hammond et al., Preliminary Background Studies of the Prospects for Economical Desalination of Sea Water Using Nuclear Energy, ORNL TM-432 (November 1, 1962).

[3]D. F. Babcock et al., Heavy-Water-Moderated Power Reactors — A Status Report, DP-480 (March 1960).

[4]Evaluation and Design — Heavy Water Moderated Power Reactor Plants, Sargent and Lundy report SL-1773 (TID-8530) (April 1960).

The reference station resulting from the ORNL desalination study was one consisting of three separate reactors[2] with a total installed capacity of 25,000 Mw(t). Although the three reactors are designed to share a common containment building and operating crew, they would be operated independently, and any one reactor could be shut down while the other two were operating. The containment building, which is 170 ft high and 940 ft long, has two wings for housing two 190-ft-long turbine generators each, which have a combined output of 4230 Mw. However, the net plant output is 3545 Mw, since the water plant is a substantial power load. The reactor vessels and primary circulating systems are composed of 1389-Mw(t) modules, each module containing 220 pressure tubes. Each reactor, which is rectangular in shape, consists of six modules. The reactors are refueled while in operation.

Our study also includes fabrication costs in fuel element fabrication plants sized for a 3500-Mw(t) and a 100,000-Mw(t) reactor plant.

ASSUMPTIONS IN THE FUEL ELEMENT COST STUDY

The reference fuel element, which is similar to those being developed at SRL and at Hanford Atomic Products,[5] consists of two principal constituents: metal cladding and the contained oxide. This particular design, while requiring additional development and testing, has a good possibility of resulting in a satisfactory fuel element.

For purposes of this study, the fuel element design shown schematically in Fig. 1 was assumed. The two fuel annuli comprising the element are loaded with UO_2 having a density of 90% of theoretical. Each fuel annulus is capped with Zircaloy end caps grooved on the outside to facilitate attachment of the tube to processing apparatus. The

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[5]M. K. Millhollen, Specifications for Vibrationally Compacted UO_2 Nested Tubular Fuel Element (PRTR Mark II-C), HW-70999 (December 1961).

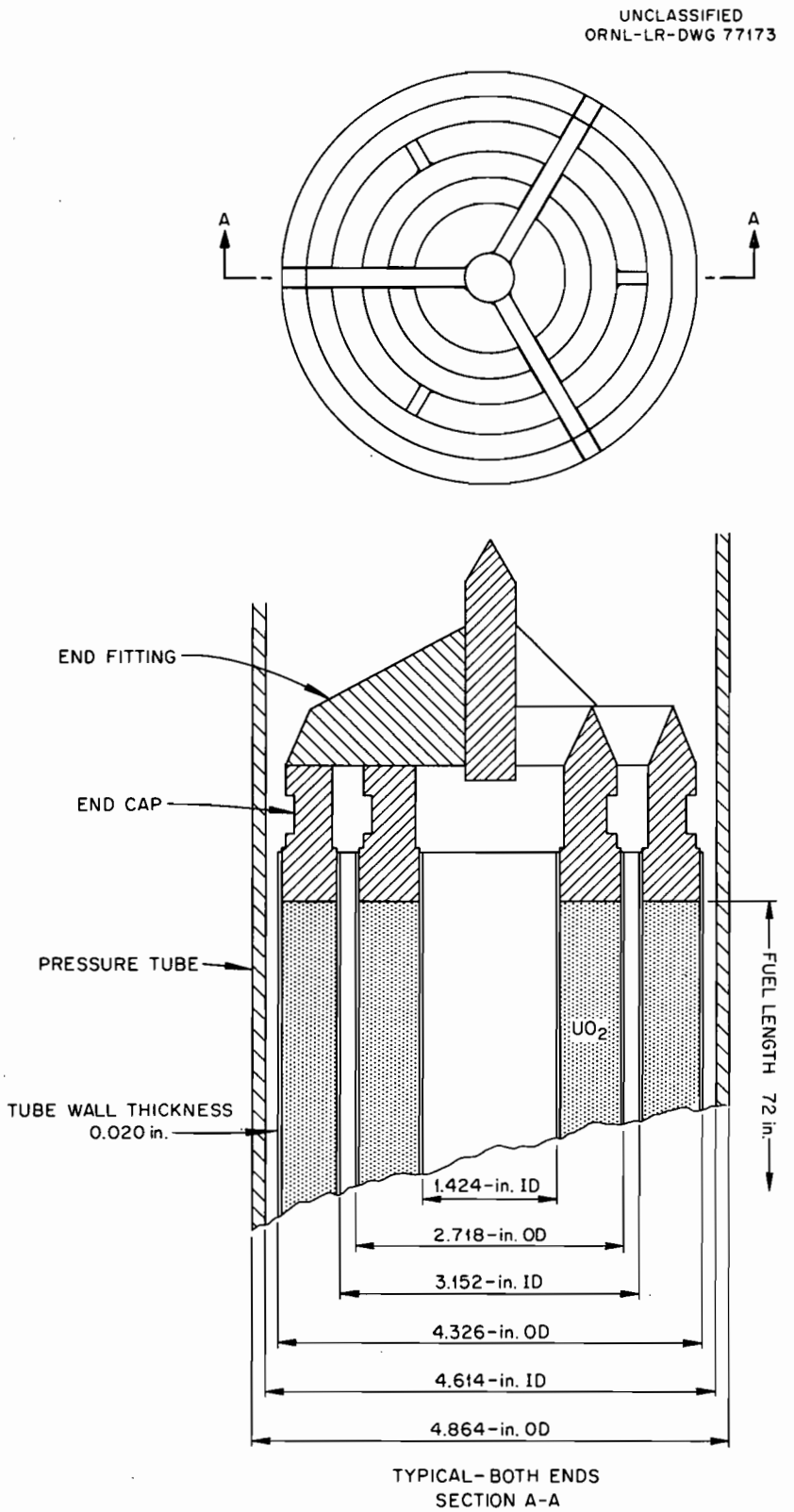

Fig. 1. Reference Fuel Element for Fuel Cost Analysis.

concentric fuel annuli are separated by spider-type end fittings and by spacers at three locations along the fuel element length between the tubes. For each fuel element there are nine such spacers and two end fittings.

On the assumption that the reactors would operate 90% of the time and based on the data in Appendix A, the quantities of fuel and hardware required are those given in Table 1. The following factors were also assumed in the study:

1. The cost of separating hafnium from zirconium would remain at current levels.

2. The production capacity of zirconium sponge plants would far exceed the foreseeable demand even with the requirements of these reactors included.

3. Tubing would be purchased from commercial vendors.

4. Construction of a plant on the same site as the power station for final assembly of fuel elements would be economically and administratively desirable.

5. Vibratory compaction would be the technique used for introducing the oxide into the cladding.

MATERIAL COST

Considerable attention has been given to the cost of Zircaloy-2 hardware. A number of vendors were contacted, and personnel at other sites familiar with the purchase of Zircaloy were consulted. Since the technology for UO_2 is more within current technology than that for thin-wall, large-diameter Zircaloy, the cost of UO_2 was not as extensively explored.

Zircaloy-2

The present production capacity of zirconium sponge plants exceeds 6,000,000 lb/yr. The Atomic Energy Commission has had a contractual agreement with vendors to purchase a specified amount of sponge, which annually amounted to about one half the total production capacity. Since a substantial stockpile of zirconium has developed as a result of

Table 1. Fuel Element Processing Data[a]

	3500-Mw(t) Reactor	25,000-Mw(t) Reactor	100,000-Mw(t) Reactor
Number of fuel elements			
Per loading	2756	19,590	78,360
Per year	1250	8910	35,600
Per working day (250 work-days per year)	5	35.7	142.2
UO_2 [or 0.6% Pu–(99.4% U)O_2]			
Per fuel element, kg			
Inner tube	49	49	49
Outer tube	80	80	80
Per reactor loading, metric ton	355	2540	10,150
Per year (produced), metric ton	161	1150	11,500
Per working day (produced), metric ton	0.645	4.61	18.4
Zircaloy-2 hardware			
Tubing[b] per element, in.	73	73	73
Tubing (each size[b]) per loading, ft	16,750	120,000	479,000
Tubing (each size[b]) per year, ft	7600	54,400	217,500
End caps per annulus			
4.366-in.-OD size	2	2	2
2.758-in.-OD size	2	2	2
End fittings, per element	2	2	2
Spacers, per element	9	9	9

[a]Based on reactor load factor of 90%.

[b]1.424-in. OD × 0.020-in. wall
2.758-in. OD × 0.020-in. wall
3.152-in. OD × 0.020-in. wall
4.366-in. OD × 0.020-in. wall

these contracts, it is unlikely that they will be renewed. All contracts will have terminated during the calendar year 1964, and it is anticipated that the price of zirconium will drop substantially as a result of price-cutting competition. It is estimated further that currently there is a sufficient market for only two companies, and that the market price for zirconium will ultimately stabilize between $4.50 and $6.50 per pound. In this study a median price of $5.50 per pound was chosen.

Large-diameter, thin-wall tubes are traditionally difficult, and therefore expensive, to manufacture. Following consultation with a number of people in the field, it was considered feasible to produce tubing in the four sizes required for the reference fuel element: outside diameters of 1.424, 2.758, 3.152, and 4.366 in., and in each case a 0.020-in. wall.

In addition to the required tubing, the Zircaloy shapes required are square bar for the fuel element spacers, round bar for the end fittings, plate for the end fittings, and pipe for the end caps. The cost of the various Zircaloy shapes will vary as a function of volume, specifications, and inspection required. The prices predicted for the four different sizes of tubing and for the other Zircaloy shapes required for each reactor size are shown in Table 2. The prices for the shapes for the 3500-Mw(t) reactor were predicted at less than the current market prices, since it is believed that large orders of the few sizes required would substantially reduce the current prices.

The quantities of Zircaloy required and the total cost of the materials for each reactor are given in Table 3, with, as can be seen, a substantial portion of the cost allotted to pipe for making the end caps. With some refinement of the fuel element design to minimize the quantity of material in the end cap, expenditures for Zircaloy could be reduced considerably.

Table 2. Predicted Prices of Zircaloy Shapes

Zircaloy Shape	Predicted Price (per lb) for		
	3500-Mw(t) Reactor	25,000-Mw(t) Reactor	100,000-Mw(t) Reactor
Tubing (av, all 4 sizes)	$20.00	$17.00	$14.00
Pipe (av, both sizes)	15.73	13.35	11.00
Square bar	12.87	10.93	9.00
Round bar	12.87	10.93	9.00
Plate	12.87	10.93	9.00

Table 3. Summary of Zircaloy Costs

Zircaloy	Annual Cost					
	100,000-Mw(t) Reactor		25,000-Mw(t) Reactor		3500-Mw(t) Reactor	
	Quantity (lb)	Cost	Quantity (lb)	Cost	Quantity (lb)	Cost
Tubing (all sizes)	509,000	$7,126,000	125,250	$2,129,250	17,815	$356,300
Pipe (2.8-in. OD × 1.4-in. ID)	169,000	1,859,000	42,250	564,038	5,915	93,043
Pipe (4.5-in. OD × 3.1-in. ID)	305,000	3,355,000	76,250	1,017,938	10,675	167,918
Square bar	2,630	23,670	658	7,192	92	1,184
Round bar	8,700	78,300	2,175	23,773	305	3,925
Plate	23,700	213,300	5,925	64,760	830	10,682
Total Zircaloy cost		$12,655,270		$3,806,951		$633,052
Two-week inventory		$486,741		$146,421		$24,348

Natural Uranium Dioxide

It was assumed that UO_3 would be supplied to the fuel fabrication plant for conversion to UO_2. Two methods are available for preparing UO_3 in suitable form for vibratory compaction: (1) It may be direct-arc-fused to produce a very dense oxide with a controlled oxygen-to-uranium ratio, at which stage the oxide is ready for crushing and sizing preparatory to vibratory compaction; the cost of this operation on a continuous-production basis is estimated by industry at $0.50 per pound. (2) The UO_2 can be fired at a temperature high enough to produce the density and stoichiometry desired, and the fine particles then sintered at modest temperatures by application of a high-energy impact load such as with a Dynapak press. This technique has been proved by Hanford Atomic Products to be successful on a laboratory scale, but experience in production is limited. The estimated cost savings, however, are sufficiently attractive for Dynapak pressing to be chosen as the reference technique for this study.

METHOD FOR DETERMINING NATURAL URANIUM FUEL FABRICATION COSTS

Manufacturing Process

Manufacture of the fuel element is divided into three areas: the preparation of uranium dioxide for loading into fuel annuli (preassembled concentric tubes), the fabrication of Zircaloy hardware such as end fittings, end caps, and spacers, and the assembly of the fuel element, which includes the operations for filling of the annuli through preparing the fuel element for shipment.

The main fabrication flow diagram for processing the natural uranium fuel elements is shown in Fig. 2. As can be seen, the UO_3 is converted to UO_2 by a hydrogen-reduction step, and then the Dynapaking operation is performed. Although relatively large agglomerates can probably be accommodated by the Dynapaking operation, it was assumed that they would have to be broken down into fine particles and that a commercial micronizer can be used for this purpose. In Dynapaking, the oxide is placed in a stainless steel container, which is subsequently heated and evacuated. After the container is heated to 1100°C, it is

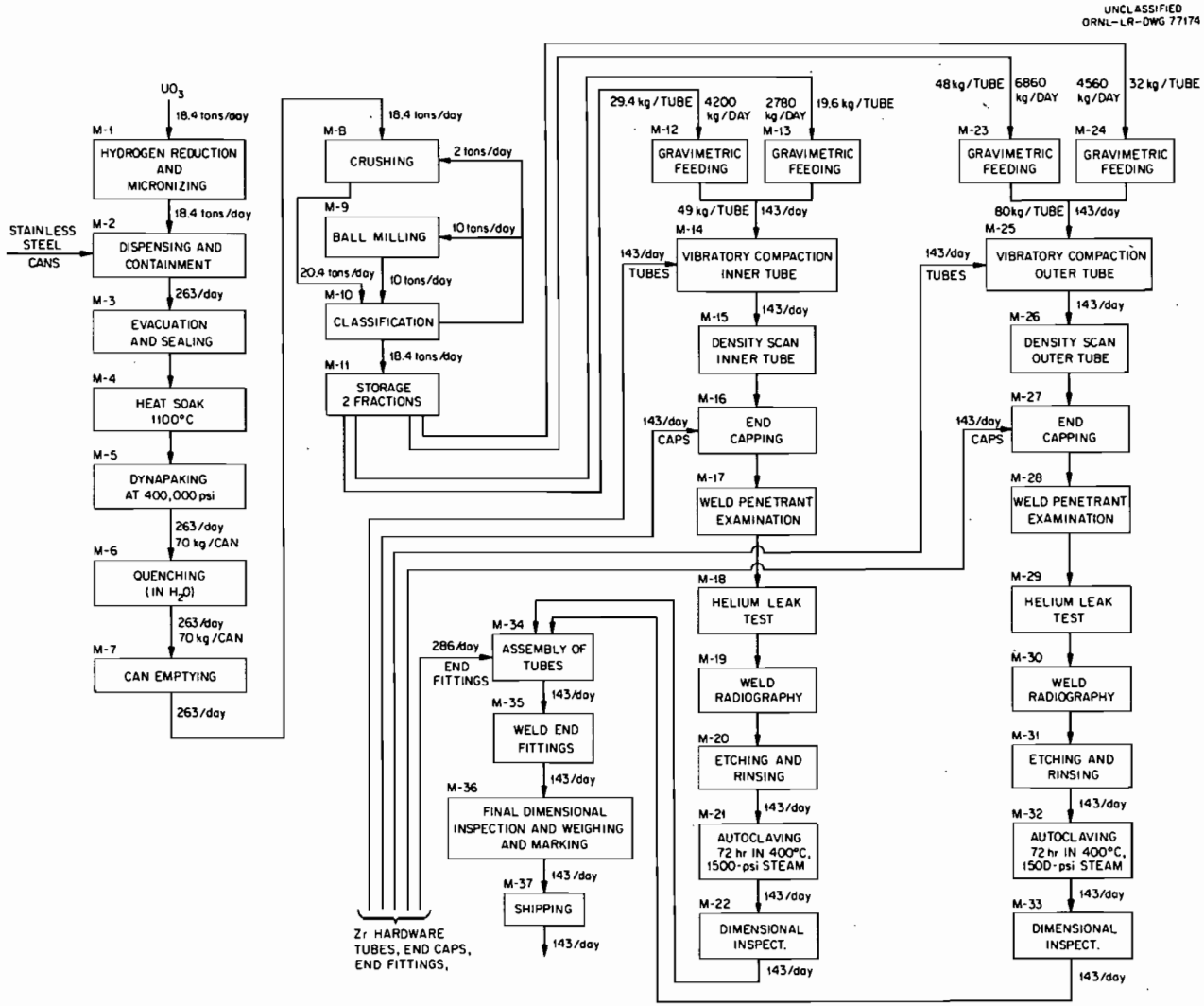

Fig. 2. Main Fabrication Flow Diagram for Concentric-Tube Fuel Element Bearing Natural Uranium. (Refer to Appendix B for description of processes M-1, etc.)

pressed by an impact device at a pressure of 400,000 psi with a carbide die. The resulting oxide, which at this point has a density of approximately 99% of theoretical, is broken up by quenching the can in water to produce thermal shock. The raw material from the Dynapaking operation is then taken from the container and, by means of a crushing, ball-milling, and classifying procedure, sized for use in vibratory compaction.

In the portion of the flowsheet (Fig. 2) depicting the filling and assemblying operation, a production line is shown for both the inner and the outer fuel annulus. In each line the fuel annulus is charged to the vibratory-compaction equipment. The UO_2 is fed into the fuel annulus and vibrated, and then the fuel annulus is scanned for determination of the density of the fuel along its length. The annulus is closed with end caps, which are sealed by welding; the weld is inspected by penetrant examination, helium-leak testing, and radiography. Following acceptance of the weld, the fuel annulus is prepared for assembly with the other fuel annulus by etching, rinsing, and autoclaving to provide a corrosion-resistant surface on the Zircaloy. After both fuel annuli are dimensionally inspected, end fittings are placed onto the assembly and the end caps of the tubes are welded to the fitting blades. As a last step before being shipped, the fuel elements are inspected for conformity to dimensional and weight specifications.

Figure 3 is a flow diagram for manufacture of the Zircaloy tubing, pipe, and bar stock from which the fuel annuli are made. The tubing is ultrasonically inspected to assure its integrity, cut to the required length, machined for receipt of the end caps, and then washed and dried. The end caps are machined from the pipe stock and cleaned. All components for the assembly are etched and rinsed. The inner fuel annulus is created by welding an end cap between the large tube and the small tube. Fuel spacers cut from square Zircaloy bar stock are attached to the outer tube of the inner annulus. The outer annulus is made in the same manner except that no spacers are required.

The end fittings, which are made from Zircaloy plate and bar stock, are processed similarly to the other Zircaloy components. After they are etched, rinsed, assembled, and welded, they may be autoclaved to test their corrosion resistance.

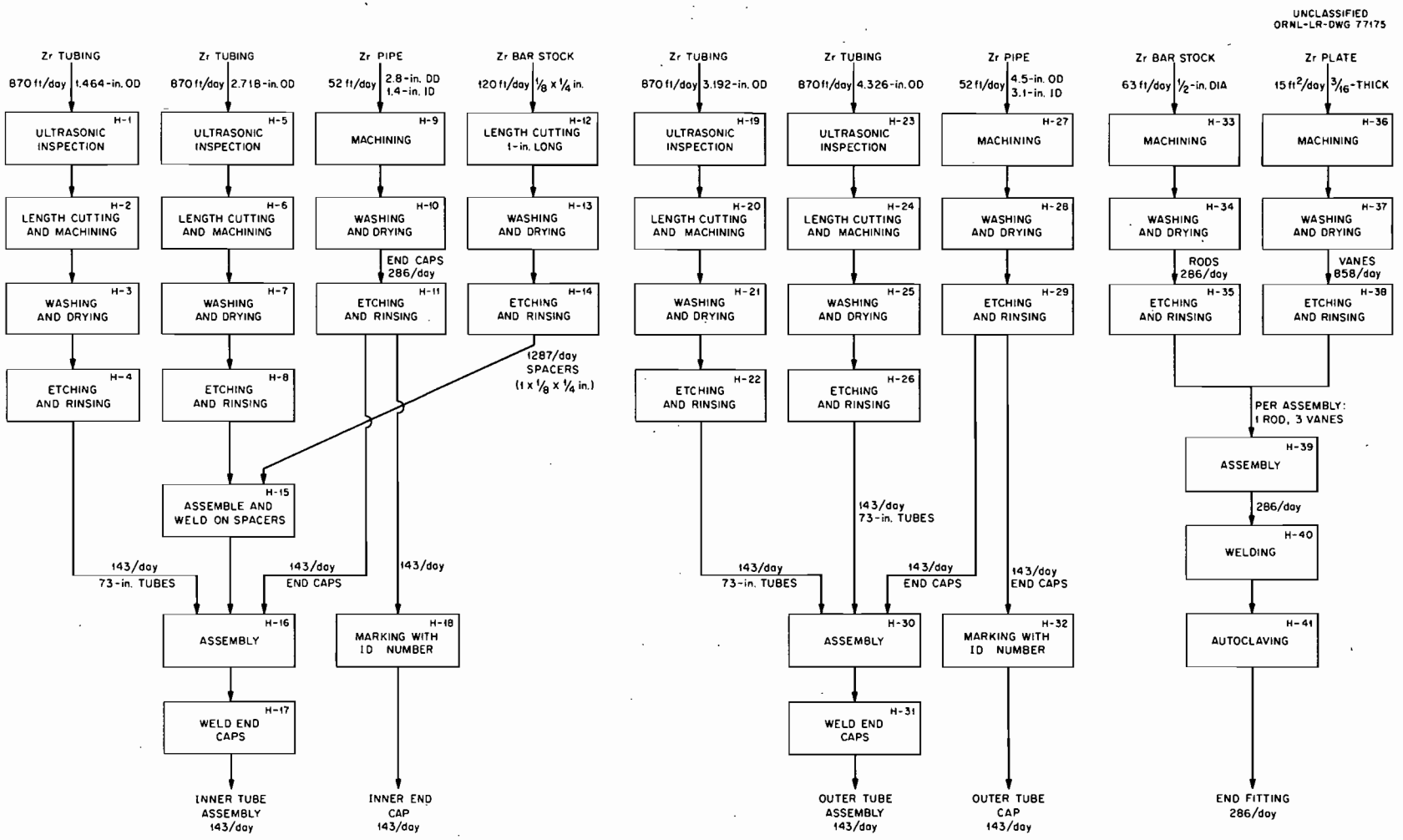

Fig. 3. Zircaloy Hardware Fabrication Diagram for Concentric-Tube Fuel Element.

Processing Data

To process the fuel for the three sizes of reactor systems, three sizes of plants were conceived for the assembly of fuel elements. For the fabrication plants providing fuel for the 100,000- and 25,000-Mw(t) reactor systems, a high degree of automation was planned in order to minimize operating costs. The plant for the 3500-Mw(t) reactor utilizes more direct labor. The two larger plants would operate three shifts per day for a 250-workday year, but the 3500-Mw(t) plant would operate only one shift per day for a 250-workday year.

Processing data based on the flowsheets shown in Figs. 2 and 3 were generated for the three fuel plants; they are given in Appendix B. The tabulation describes the processing steps, the equipment required for each step, and data relating to equipment capacity, load factor, and operating time and to the manpower required. Except for the operating manhours required, the data were compiled for the largest size fabrication plant. These requirements for the 100,000- and the 25,000-Mw(t) plants are for automatic or simiautomatic type of operation, whereas those for the 3500-Mw(t) plant are for operations and equipment requiring a substantial amount of manual work.

Cost Estimate

Costs of the three plants based on available cost factors[6] modified to compensate for the particular conditions of this study and based on the processing data in Appendix B are summarized in Table 4.

The labor costs for the plants are summarized in Table 5 and are based on published data.[7] The manpower requirements and operating costs were derived from the processing data in Appendix B for operational labor and from the proposed organization chart shown in Fig. 4 for

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[6]L. Isakoff, Economic Potential for D_2O Power Reactors, DP-570 (February 1961).

[7]Guide to Nuclear Power Cost Evaluation, Production Costs, Kaiser Engineers, TID-7025, vol 5 (March 15, 1962).

Table 4. Cost Estimate for Fuel Element Plants (Using Natural UO_2)

	100,000-Mw(t) Reactor	25,000-Mw(t) Reactor	3500-Mw(t) Reactor
UO_2-preparation equipment (process steps M-1–M-7[a])	$ 580,000	$ 390,000	$ 147,000
UO_2-sizing equipment (M-8–M-11)	180,000	120,000	39,000
Fuel-loading equipment (M-12–M-15 and M-23–M-26)	420,000	280,000	65,000
End-capping and inspection equipment (M-16–M-19 and M-27–M-30)	470,000	310,000	66,000
Fuel-annulus finishing equipment (M-20–M-22 and M-31–M-33)	520,000	220,000	63,000
Fuel-assembly and finishing equipment (M-34–M-37)	320,000	320,000	41,000
Tube inspection equipment	120,000	120,000	30,000
Machine shop equipment	1,460,000	660,000	107,000
Hardware finishing equipment (welding, etching, etc.)	320,000	200,000	25,000
Hardware welding and assembly equipment	700,000	500,000	31,000
Instrumentation	1,000,000	700,000	60,000
Laboratory equipment	1,000,000	700,000	150,000
Office and data-processing equipment	1,000,000	1,000,000	
Equipment			
Delivered (E)	$ 8,090,000	$ 5,520,000	$ 824,000
Installed (1.4 × E)	$11,330,000	$ 7,730,000	$1,150,000
Plant cost (P) – equipment and building (2.35 × E)	$19,000,000	$12,970,000	$1,940,000
Engineering (0.4 × P)	7,600,000	5,190,000	780,000
Contingency (0.3 × P)	5,700,000	3,890,000	580,000
Preoperation charge (0.25 × P)	4,750,000	3,240,000	490,000
Total plant investment	$37,050,000	$25,290,000	$3,790,000

[a]See Appendix B for all process steps.

Table 5. Summary of Labor Costs for Fuel Element Plants

Category	Wage or Salary Rate	100,000-Mw(t) Reactor Number Required	100,000-Mw(t) Reactor Annual Cost	25,000-Mw(t) Reactor Number Required	25,000-Mw(t) Reactor Annual Cost	3500-Mw(t) Reactor Number Required	3500-Mw(t) Reactor Annual Cost
Plant manager	$25,000	1	$ 25,000	1	$ 25,000	1	$ 20,000
Assistant plant manager	20,000	1	20,000	1	20,000	2 at $15,000 ea	30,000
Shift supervisor	15,000	4	60,000	4	60,000		
Department managers	15,000	9	135,000	9	135,000		
Shift foremen	11,000	24	264,000	24	264,000	4	44,000
Secretary-typists	2.31 per hr	20	96,000	15	72,000	5	24,000
Section supervisors	12,000	10	120,000	10	120,000		
Buyers	8,000	2	16,000	1	8,000	1	8,000
Clerks	2.50 per hr	18	93,800	9	47,000	2	10,000
Watchmen	2.25 per hr	5	23,400	5	23,400	5	23,400
Janitors	2.25 per hr	5	23,400	4	18,700	2	9,400
Engineers/scientists	10,000	21	210,000	15	150,000	7	70,000
Health physicists	8,400	4	33,600	4	33,600	2	16,800
Technicians	7,500	18	135,000	12	90,000	6	45,000
Crafts-journeymen	3.25 per hr	33	223,080	22	149,080	5	34,000
Helpers	2.65 per hr	15	82,680	10	54,680	2	11,000
		190	$1,560,960	146	$1,270,460	44	$ 345,600
Operators	3.50 per hr	120[a]	874,000	67[a]	486,000	30[a]	218,000
		310	$2,434,960	213	$1,756,460	74	$ 563,600
Fringe benefits (+ 20%)			487,000		351,000		113,000
Maintenance materials and operating supplies (60% of above total)			$2,921,960		$2,007,460		$ 676,600
Total operating and maintenance cost			1,753,000		1,204,000		406,000
			$4,675,000		$3,211,000		$1,083,000

[a]Reflects 20% contingency factor applied to manpower requirements in Appendix B.

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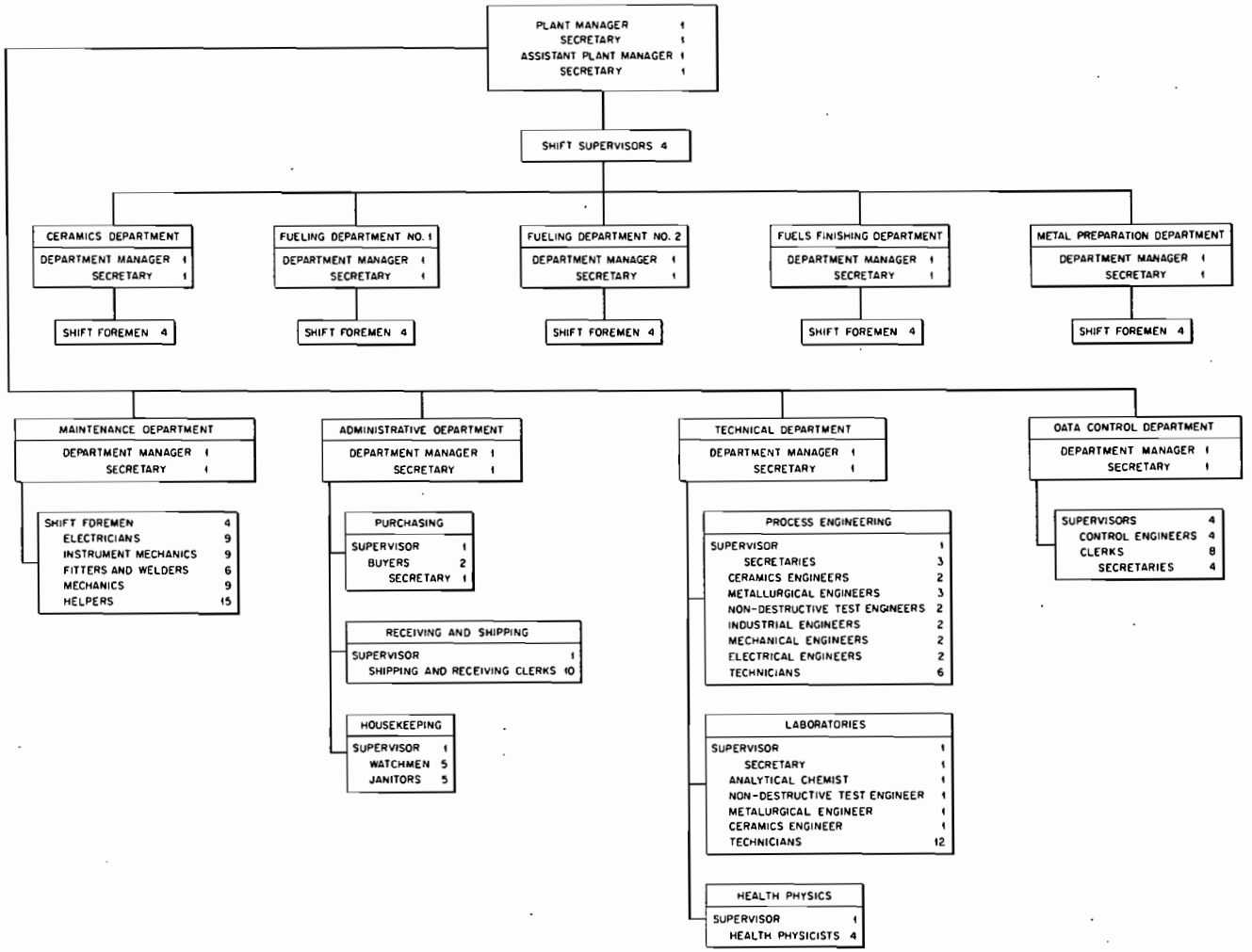

Fig. 4. Organization for 100,000-Mw(t) Natural-Uranium Fuel Fabrication Plant.

management and staff. (The operating labor in Table 5 does not directly correspond to that indicated by Appendix B, because it includes a 20% contingency factor.) The personnel requirements shown in Fig. 4 are for a 100,000-Mw(t) plant, but those for a 25,000-Mw(t) plant would be similar except, of course, less for each function.

All costs incurred in the fabrication of the reference fuel element containing natural uranium are summarized in Table 6 for the three plants. The total costs, per kilogram of uranium, are $15.55, $9.62, and $5.35 for 3500-, 25,000-, and 100,000-Mw(t) reactor plants, respectively, which correspond to fabrication plant production rates of 0.645, 4.61, and 18.4 metric tons per day. The cost summary is presented graphically in Fig. 5. Attention is called to the fact that these costs do not include expense for fuel material.

DEPLETED-URANIUM–PLUTONIUM FUEL FABRICATION COSTS

Large-scale reactors with the attendant throughput of tonnes of uranium per day will produce substantial amounts of plutonium. A question of some importance is: What will the real market value of this by-product be? One basis by which a very conservative value can be estimated is its calculated worth as an enrichment added to the natural uranium fuel. As part of this analysis, the cost of fabricating elements containing 0.6% plutonium and 99.4% depleted uranium dioxide was estimated.

The natural-uranium fuel cost analysis was used as a basis for estimating many of the steps for this study. One significant change in the process was the decision to substitute the sol-gel technique as a method of obtaining the mixed oxides of uranium and plutonium, which eliminated hydrogen reduction and Dynapak from the flowsheet.

The equipment for processing plutonium must be operated remotely and must be installed in shielded, sealed canyons, in contrast to the contact techniques that can be used in fabricating natural-uranium fuel elements. In the particular case being studied, a cursory study by

Table 6. Summary of Fabrication Costs of Fuel Elements Bearing Natural Uranium for 100,000-, 25,000-, and 3500-Mw(t) Reactors

	Fabrication Costs					
	100,000-Mw(t) Reactor[a]		25,000-Mw(t) Reactor[b]		3500-Mw(t) Reactor[c]	
	Total per Year	Per kg of U	Total per Year	Per kg of U	Total per Year	Per kg of U
Total operating and maintenance	$ 4,675,000	$1.15	$3,211,000	$3.16	$1,083,000	$ 7.57
Services (10% of above)	468,000	0.12	321,000	0.32	108,000	0.76
Indirect plant cost (7.7% of capital)	2,853,000	0.70	1,947,000	1.92	292,000	2.04
Inventory charge (6% of 2-week supply) for Zircaloy-2 material	29,000	0.01	9,000	0.01	2,000	0.01
		$1.98		$5.41		$10.38
Zircaloy-2 hardware	12,655,000	3.12	3,807,000	3.75	633,000	4.43
Rejects (5%)		0.25		0.46		0.74
		$5.35		$9.62		$15.55

[a]4060 tonnes of U per yr; 35,600 elements per yr.

[b]1015 tonnes of U per yr; 8910 elements per yr.

[c]143 tonnes of U per yr; 1250 elements per yr.

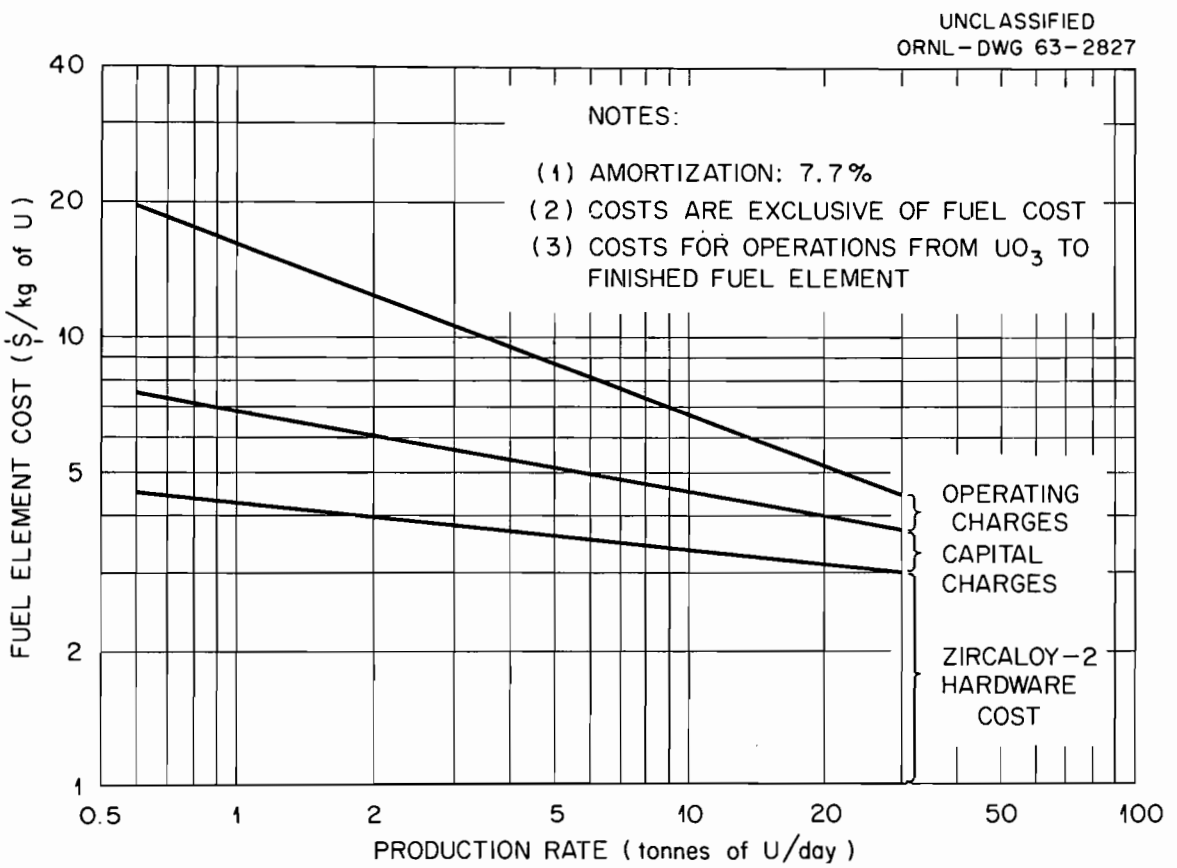

Fig. 5. Effect of Plant Size on the Cost of Fabrication of Zircaloy-Clad, Natural Uranium Oxide, Concentric-Tube Fuel Element.

Arnold[8] indicated that 12 in. of concrete shielding should be used to provide adequate protection from penetrating radiation. Contact methods would be used in maintenance of the equipment only if no more than a short period of time were required; otherwise, the offending equipment would be removed to a maintenance area.

The flowsheet for the fabrication of concentric-tube elements containing PuO_2-UO_2 is given in Fig. 6. The operations with PuO_2-UO_2 as received from the sol-gel calcination step commence with the comminution steps and proceed through the remainder of the process in exactly the same manner as for the natural-uranium case. The requirements for Zircaloy hardware are also identical.

In estimating the cost of the fuel elements bearing PuO_2-UO_2, liberal use of the natural-uranium study was made in obtaining various contributions to the cost. For example, three remotely operated plants were conceived, but they were estimated by using some parts of the plant estimates for the natural-uranium case, as were the manpower-requirement estimates.

The estimates for the three plants are given in Table 7. The organization chart for the 100,000-Mw(t) plant is given in Fig. 7. It was assumed that approximately 40% more operators would be required for these plants than for the natural-uranium plants. However, Table 7 reflects more than the 40% increase, since there are fewer steps in this case. The complete labor summary is given in Table 8.

All costs are summarized in Table 9 and presented graphically in Fig. 8.

In comparing the natural-uranium case with the plutonium-enriched case, it should be recognized that the two studies involve different fuel preparation processes. As a result, a number of fabrication steps were eliminated in the production of the plutonium-bearing elements. Thus the cost data favor the remote fabrication case and show a smaller cost differential than would be estimated for two studies on a comparable basis.

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[8]E. D. Arnold, Chemical Technology Division, personal communication.

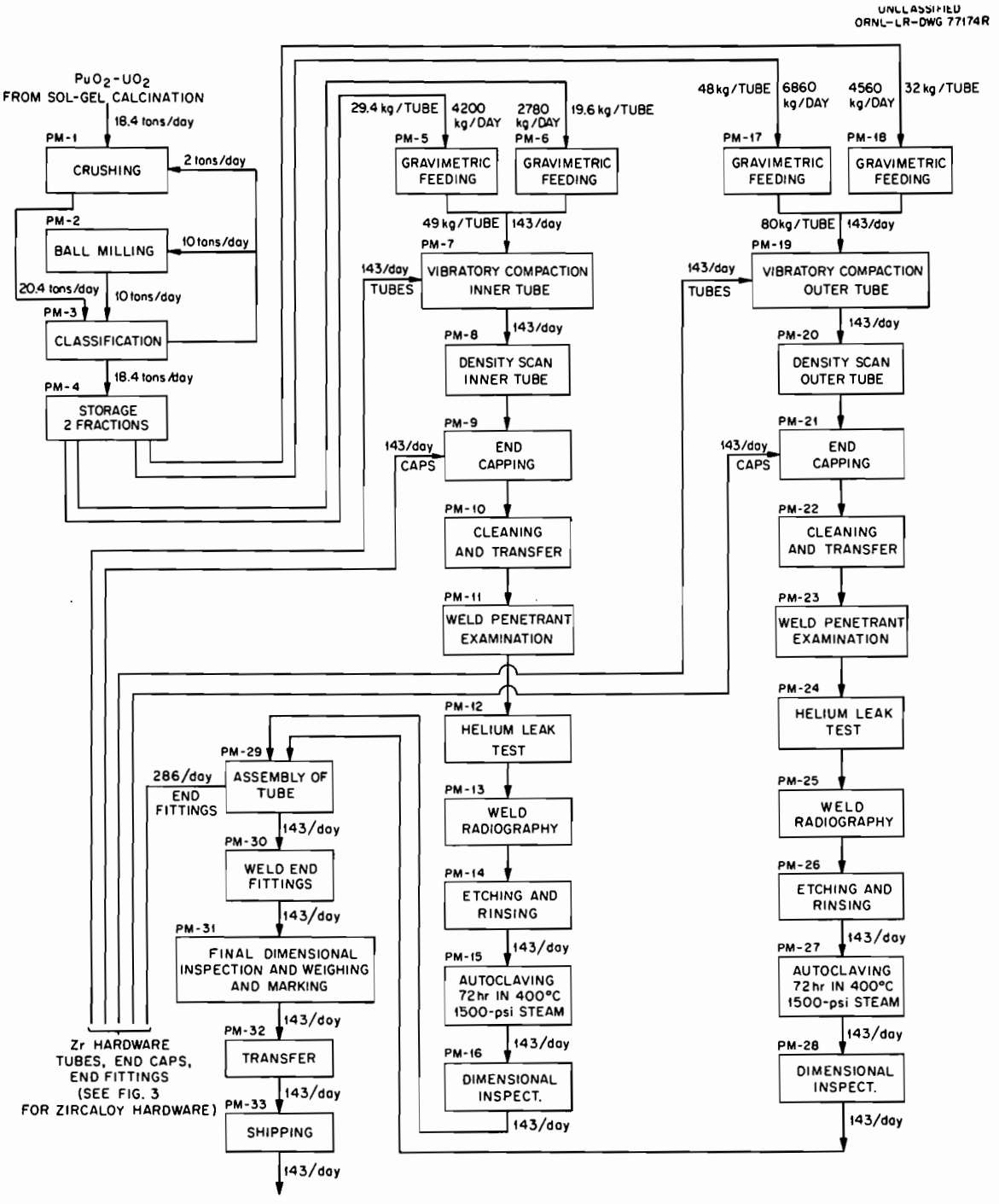

Fig. 6. Fabrication Flow Diagram for Concentric-Tube Element Bearing PuO_2-UO_2. (The processes M-1, M-2, etc., described in Appendix B would, in general, apply to this case.)

Table 7. Cost Estimate for Fuel Element Plants for the PuO_2–Depleted-UO_2 Case

	Costs		
	100,000-Mw(t) Reactor	25,000-Mw(t) Reactor	3500-Mw(t) Reactor
UO_2-sizing equipment (process steps PM-1–PM-4)[a]	$ 300,000	$ 210,000	$ 90,000
Fuel-loading equipment (PM-5–PM-8 and PM-17–PM-20)	630,000	420,000	100,000
End-capping and inspection equipment (PM-9–PM-13 and PM-21–PM-25)	705,000	465,000	100,000
Fuel-annulus finishing equipment (PM-14–PM-16 and PM-26–PM-28)	780,000	330,000	95,000
Fuel-assembly and finishing equipment (PM-29–PM-33)	480,000	480,000	60,000
Tube inspection equipment	120,000	120,000	30,000
Machine shop equipment	1,460,000	660,000	107,000
Hardware-finishing equipment (welding, etching, etc.)	320,000	200,000	25,000
Hardware welding and assembly equipment	700,000	500,000	31,000
Instrumentation	1,500,000	1,050,000	180,000
Laboratory equipment	1,000,000	700,000	150,000
Office and data-processing equipment	1,000,000	1,000,000	
Equipment delivered (E)	$ 8,995,000	$ 6,135,000	$ 968,000
Shielded cells ($500 per ft^2)			
9900 ft^2	$ 4,950,000		
7500 ft^2		$ 3,750,000	

Table 7 (continued)

	Costs		
	100,000-Mw(t) Reactor	25,000-Mw(t) Reactor	3500-Mw(t) Reactor
Main process building ($30 per ft^2)			
138,000 ft^2	$ 4,140,000		
97,600 ft^2		$ 2,928,000	
Hardware fabrication building (calculated from natural-uranium case)	2,460,000	1,410,000	
Building construction	11,550,000	8,088,000	
Equipment installed (1.4 × E)	12,600,000	8,590,000	$1,350,000
Plant cost (P) — equipment and building	24,150,000	16,678,000	2,620,000 (2.7 × E)
Engineering (0.5 × P)	12,075,000	8,339,000	1,310,000
Contingency (0.3 × P)	7,240,000	5,000,000	786,000
Preoperation charge (0.25 × P)	6,030,000	4,170,000	655,000
Total plant investment	$49,495,000	$34,187,000	$5,371,000

[a]See Appendix B for description of "m" processes, which, in general, would apply to this case.

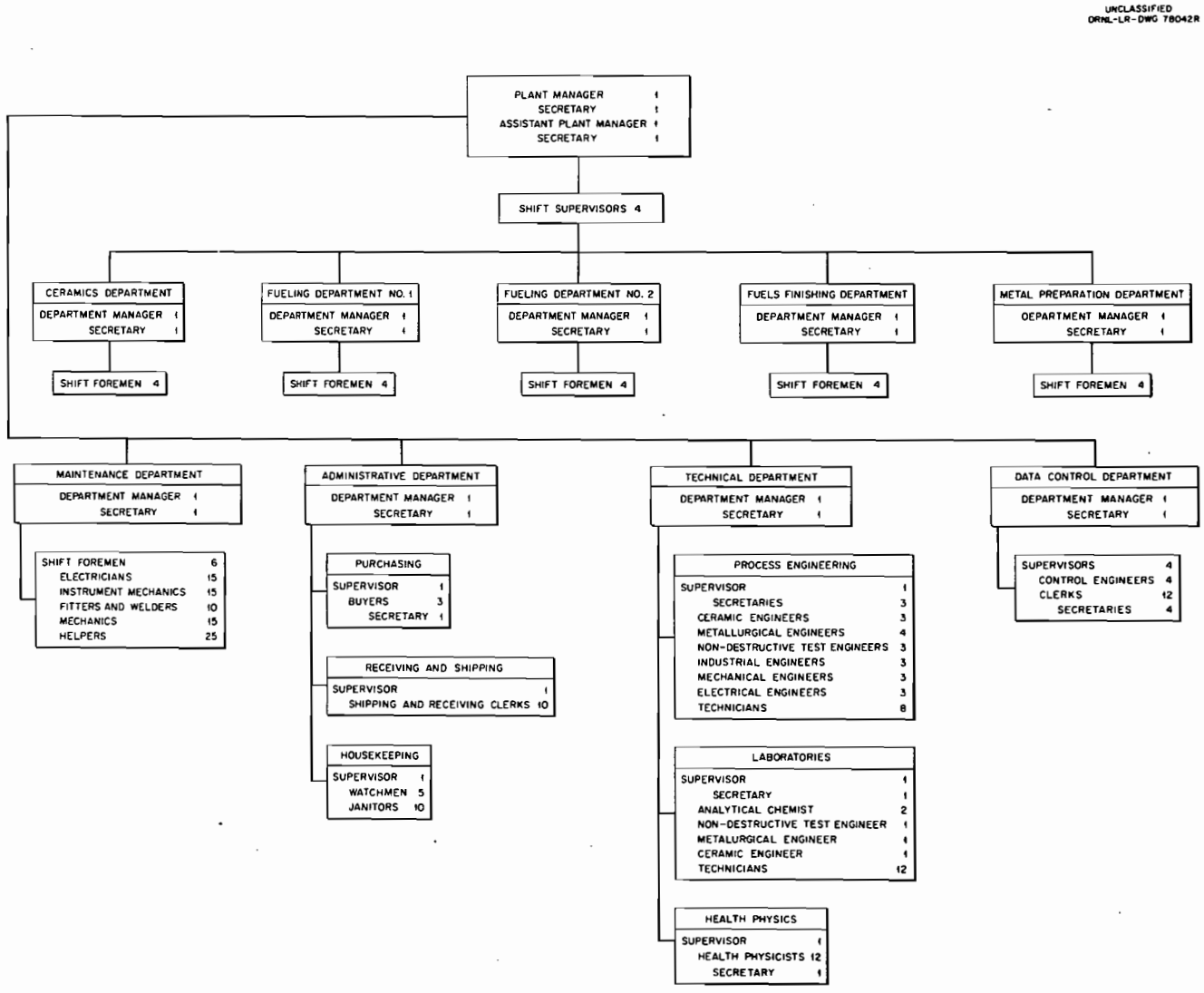

Fig. 7. Organization for 100,000-Mw(t) Depleted-Uranium-Plutonium Fuel Fabrication Plant.

Table 8. Summary of Labor Costs for PuO_2–Depleted-UO_2 Fuel Element Plants

Category	Wage or Salary Rate	Labor Costs: 100,000-Mw(t) Reactor Number Required	100,000-Mw(t) Reactor Annual Cost	25,000-Mw(t) Reactor Number Required	25,000-Mw(t) Reactor Annual Cost	3500-Mw(t) Reactor Number Required	3500-Mw(t) Reactor Annual Cost
Plant manager	$25,000	1	$ 25,000	1	$ 25,000	1	$ 20,000
Assistant manager	20,000	1	20,000	1	20,000	2	30,000
Shift supervisor	15,000	4	60,000	4	60,000		
Department manager	15,000	9	135,000	9	135,000		
Shift foremen	11,000	26	286,000	26	286,000	4	44,000
Secretary-typists	2.31 per hr	21	100,800	16	76,800	5	24,000
Section supervisors	12,000	10	120,000	10	120,000		
Buyers	8,000	3	24,000	2	16,000	1	8,000
Clerks	2.50 per hr	22	114,600	11	57,300	2	10,000
Watchmen	2.25 per hr	5	23,400	5	23,400	5	23,400
Janitors	2.25 per hr	10	46,800	8	37,400	4	18,800
Engineers/scientists	10,000	28	280,000	20	200,000	9	90,000
Health physicists	8,000	12	100,800	12	100,800	6	50,400
Technicians	7,500	20	150,000	13	97,500	7	52,500
Crafts-journeymen	3.25 per hr	55	371,800	36	243,400	8	54,000
Helpers	2.65 per hr	25	137,800	17	93,700	3	16,500
		252	$1,996,000	191	$1,592,300	57	$ 441,600
Operators	3.50 per hr	170[a]	1,238,100	105[a]	764,700	42[a]	305,900
		422	$3,234,100	296	$2,357,000	99	$ 747,500
Fringe benefits (+ 20%)			646,800		471,400		149,500
			$3,880,900		$2,828,400		$ 897,000
Maintenance materials and operating supplies (60% of above total)			2,328,500		1,697,000		538,200
Total operating and maintenance			$6,209,400		$4,525,400		$1,435,200

[a]Reflects a 20% contingency factor applied to manpower requirements in Appendix B.

Table 9. Summary of Fabrication Costs of Fuel Elements Bearing PuO_2–Depleted UO_2 for 100,000-, 25,000-, and 3500-Mw(t) Reactor Plants

	Fabrication Costs					
	100,000-Mw(t) Reactor[a]		25,000-Mw(t) Reactor[b]		3500-Mw(t) Reactor[c]	
	Total per Year	Per kg of U + Pu	Total per Year	Per kg of U + Pu	Total per Year	Per kg of U + Pu
Total operating and maintenance	$ 6,209,400	$1.53	$4,525,400	$ 4.46	$1,435,200	$10.03
Services (10% of above)	620,940	0.15	452,540	0.45	143,520	1.00
Indirect plant cost (7.7% of capital)	3,810,000	0.94	2,630,000	2.59	414,000	2.90
Inventory charge (6% of 2-week supply) for Zircaloy-2	29,000	0.01	9,000	0.01	2,000	0.01
		$2.63		$ 7.50		$13.93
Zircaloy-2	12,655,000	3.12	3,807,000	3.75	633,000	4.43
		$5.75		$11.25		$18.36
Rejects (8%)		0.45		0.90		1.47
		$6.30		$12.15		$19.83

[a]4060 tonnes of U + Pu per yr; 35,600 elements per yr.

[b]1015 tonnes of U + Pu per yr; 8910 elements per yr.

[c]143 tonnes of U + Pu per yr; 1250 elements per yr.

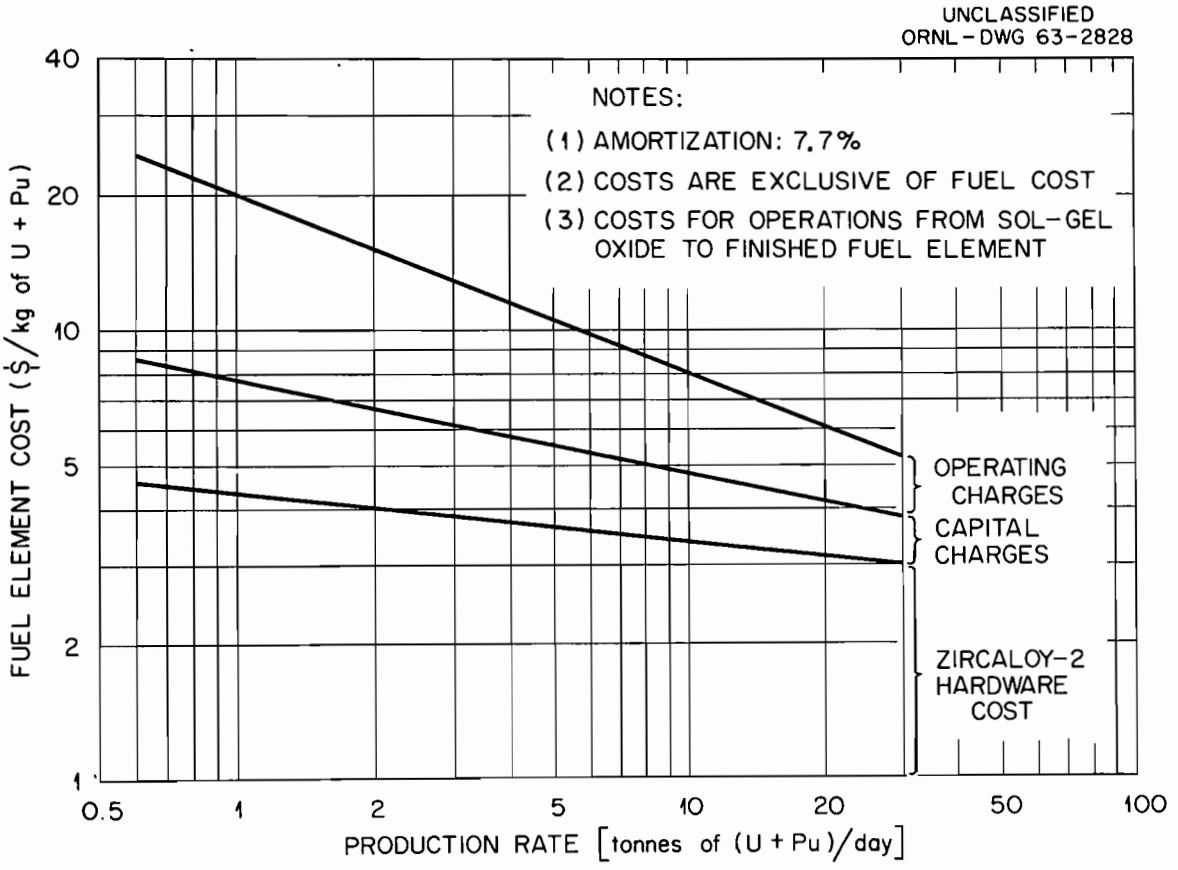

Fig. 8. Effect of Plant Size on the Cost of Fabricating Zircaloy-Clad Plutonium-Depleted-Uranium Concentric-Tube Fuel Elements.

SUMMARY AND CONCLUSIONS

The fabrication costs, per kilogram of uranium, of natural-UO_2, Zircaloy-clad, concentric-tube fuel elements for the 100,000-, 25,000-, and 3500-Mw(t) reactors which correspond to production rates of 0.645, 4.61, and 18.4 metric tons per working day were estimated at \$5.35, \$9.62, and \$15.55, respectively. The same fuel element bearing 99.4% depleted UO_2 spiked with 0.6% PuO_2 was estimated to cost, per kilogram of uranium plus plutonium, \$6.30, \$12.15, and \$19.83, respectively, for the three reactor systems. In the natural-uranium case all costs from UO_3 to finished fuel elements, but excluding the UO_3 and uranium expense, are included. In the plutonium-depleted uranium all costs from sol-gel-prepared oxide to finished elements, but excluding expenses for oxide, plutonium, and uranium, are included.

It is to be noted that the difference between the costs for fabricating plutonium-containing fuel elements and those for natural-uranium fuel elements is greater than would appear from a casual inspection of the results of this study. The two flowsheets are different: the process assumed for the plutonium-depleted-uranium case requires 10% less steps than the process assumed for natural uranium.

In an analysis of this magnitude, conducted within a short period of time, some of the data and judgments are obviously more reliable than others. Therefore the following factors may influence a long-range analysis of the study:

1. The cost of zirconium sponge seems to be a conservative value; it may be less than was predicted.

2. The cost of fabricated Zircaloy tubing may be optimistic. If more inspection is found to be needed and the tolerance requirements change, as much as \$3.00 could be added to the price quoted.

3. The costs for end fittings and end caps are significant variables. Those used in this study are considered to be very conservative since these items are massive in the assumed fuel element concept.

4. The cost of fabrication involved a rapid estimate of construction, equipment, and manpower requirements, obviously creating many opportunities for error, particularly since no plants of this type exist

on any scale at the present time. Until a detailed engineering study is conducted, these costs must remain very uncertain. However, it is believed that they are conservative.

5. The staff proposed for each plant is generous compared with many present fuel fabrication plants. However, it is thought to be realistic when compared with current practice in other major industrial fields.

6. The satisfactory performance of a fuel element of this design is still only theoretical. The attractive costs per kilogram of uranium are achieved in part by minimizing the pounds of Zircaloy required. It should be noted that no elements as large as the reference design have ever been fabricated or tested under irradiation. Success has not been 100% in the testing of much smaller elements of this configuration.

ACKNOWLEDGMENTS

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APPENDIX A

DATA FOR REFERENCE PROCESS HEAT REACTORS

General

Reactor type	Pressure tube, boiling water
Fuel	Vibratory-packed natural UO_2 (or 6 g of Pu per kg of depleted U as oxide)
Moderator	Mixture of 80 vol % D_2O–20 vol % dumped graphite
Reflector	2 ft of graphite bottom and sides; 2 ft of 80 vol % D_2O–20 vol % graphite top
Coolant	Boiling H_2O in forced circulation
Owner	State of California
Location	Southern California coast
Reactor total thermal power	3665 Mw, 26,200 Mw, 104,700 Mw
Reactor thermal power, fuel only	3500 Mw, 25,000 Mw, 100,000 Mw
Amount of reactor power in moderator	4.5%
Load factor	90%

Materials Properties

H_2O in D_2O moderator	0.4 mole %
Density of graphite	1.6 g/cc
Density of UO_2	9.81 g/cc (90% theoretical)
Calandria tube material	Aluminum 6061, T6
Pressure tube material	Zircaloy
Gas between tubes	CO_2
Calandria tank material	Steel (aluminum alternate)

Appendix A (continued)

Reactor Dimensions

Reactor shape	Rectangular parallelopipêd with corners taken off		
Lattice dimensions	Square array on 9-in. pitch		
Core size	3500 Mw(t)	25,000 Mw(t)	100,000 Mw(t)
Number of rows	27	39	39
Number of columns	27	102	402
Number of tubes off corners	40	60	72
Total number of tubes	689	3918	15,672
Core height, ft	20.25	29.25	29.25
Core width, ft	20.25	78.5	301.5
Core length (length of tube), ft	24	30	30
Number of fuel elements	2756	19,590	78,360
Calandria vessel			
Height, ft	27.25	36.25	36.25
Width, ft	25.25	83.5	306.5
Length, ft	29	35	35

Detail Lattice Dimensions

Calandria tube	
Inside diameter	5.114 in.
Outside diameter	5.214 in.
Wall	0.050 in.
Pressure tube	
Inside diameter	4.614 in.
Outside diameter	4.864 in.
Wall	0.125 in.

Appendix A (continued)

Lattice area	
UO_2	11.104 in.^{2}
Zr	2.592
Al	0.811
H_2O	4.884
D_2O	47.72
C	11.93
CO_2	1.96
	81.001 in.^{2}

Fuel Elements

Form	2 concentric tubes of UO_2
Cladding	0.020 in. Zircaloy
Inner fuel tube	
Inside diameter	1.424 in.
Outside diameter	2.718 in.
Length	72 in. nominal
Outer fuel tube	
Inside diameter	3.152 in.
Outside diameter	4.326 in.
Length	72 in. nominal
Fuel loading	
Inner tube	7.19 kg of U per ft
Outer tube	11.73 kg of U per ft
Specific power	11.72 kw per kg of U average in reactor
Duty load, each tube	
Maximum	$\int K d\theta = 40$ w/cm
Average	$\int K d\theta = 30$ w/cm

Appendix A (continued)

Heat flux	
Average	216,000 $Btu \cdot hr^{-1} \cdot ft^{-2}$
Maximum	248,000 $Btu \cdot hr^{-1} \cdot ft^{-2}$
Outer tube	
Average	263,000 $Btu \cdot hr^{-1} \cdot ft^{-2}$
Maximum	303,000 $Btu \cdot hr^{-1} \cdot ft^{-2}$
Burnout heat flux at 12.5% quality	754,000 $Btu \cdot hr^{-1} \cdot ft^{-2}$
Coolant channels	
No. 1	
Outside diameter	1.384 in.
Nominal flow area	1.504 $in.^2$
No. 2	
Inside diameter	2.758 in.
Outside diameter	3.112 in.
Nominal flow area	1.632 $in.^2$
No. 3	
Inside diameter	4.366 in.
Outside diameter	4.614 in.
Nominal flow area	1.748 $in.^2$
Fuel burnup (av)	8500 Mwd per metric ton of U
Maximum fuel temperature	2000° C

Reactor Cooling Systems

Inlet to pressure tube	
24-ft tube	398°F, 420 psia
30-ft tube	398°F, 470 psia
Pressure tube discharge at 12.5% quality	423°F, 320 psia
Return stream from evaporator	212°F, 14.7 psia

Appendix A (continued)

Average mass flow rate of coolant	
In 24-ft pressure tube	1.374×10^5 lb/hr (av)
In 30-ft pressure tube	1.718×10^5 lb/hr (av)
In 3500-Mw(t) reactor	942×10^5 lb/hr
In 25,000-Mw(t) reactor	6731×10^5 lb/hr
In 100,000-Mw(t) reactor	$26,952 \times 10^5$ lb/hr
Moderator inlet, outlet temperature	130°F, 190°F
Moderator nominal pressure	Atmospheric
Moderator flow rate	
In 3500-Mw(t) reactor	$\sim 100 \times 10^5$ lb/hr
In 25,000-Mw(t) reactor	$\sim 714 \times 10^5$ lb/hr
In 100,000-Mw(t) reactor	$\sim 2850 \times 10^5$ lb/hr
Moderator cooling system	Single-pass tubular heat exchanger

Miscellaneous Parameters

Type of refueling	On-stream, bidirectional
Reactivity shim control	Moderator level
Reactivity spatial fine control	Poison cables or wires
Scram control	Moderator dump
Radial max/av power density	1.15
Method of control, radial distribution	Rate of fueling
Axial max/av power density	1.15
Method of control, axial distribution	D_2O/C in moderator
Flow meters	Each tube steam and water

APPENDIX B. FUEL ELEMENT PROCESSING DATA[a]

Processing Equipment				100,000-Mw(t) Plant					Operating Manhours Required for		
Step No.	Operation	Equipment	Purpose	Required Production Rate or Capacity	Maximum Equipment Production Rate or Capacity	Equipment Load Factor	Equipment Operating Time (hr)	Manpower Load Factor	100,000-Mw(t) Plant	25,000-Mw(t) Plant	3500-Mw(t) Plant
M-1[b]	Hydrogen reduction and micronizing	Feed storage hopper M-1-1	Stores feed material	18.4 tonnes	50 tonnes	0.37	24	0.2	4.8	2.4	
		Continuous hydrogen reduction furnace M-1-2	Reduces UO_3 to UO_2	876 kg/hr	1500 kg/hr	0.58	21	0.2	4.2	4.2	
		Gas micronizer M-1-3	Assures fine UO_2 particle size (automatic)	876 kg/hr	1500 kg/hr	0.58	21	0.1	2.1	2.1	8
M-2	Dispensing and containment	Feed storage hopper M-2-1	Stores input for dispenser	18.4 tonnes	50 tonnes	0.37	24	0.05	1.2	1.2	
		Volumetric dispenser M-2-2	Automatically dispenses UO_2 to cans	12.6 batches/hr	60/hr	0.21	21	0.2	4.2	4.2	
		Can feeder M-2-3	Automatically conveys cans to dispenser from storage room	12.6/hr	60/hr	0.21	21	0.1	2.1	2.1	8
M-3	Evacuation and sealing	Can conveyer M-3-1	Automatically conveys loaded cans to can sealer	12.6/hr	60/hr	0.21	21	0.1	2.1	2.1	
		Evacuation and sealing machine M-3-2	Automatically evacuates and seals cans by welding, preheating cans to 400°C	12.6/hr	30/hr	0.42	21	0.2	4.2	4.2	4
M-4	Heat soaking	Can conveyer M-4-1	Automatically conveys cans to furnace	12.6/hr	60/hr	0.21	21	0.1	2.1	2.1	
		Continuous furnace M-4-2	Heats cans and UO_2 to uniform 1100°C	12.6/hr	24/hr	0.52	21	0.1	2.1	2.1	2
M-5	Dynapaking	Dynapak feeder M-5-1	Automatically feeds heated cans to Dynapak	12.6/hr	30/hr	0.42	21	0.01	0.2	0.2	
		Dynapak machine M-5-2	Automatically compacts UO_2 in cans at 400,000 psi	12.6/hr	30/hr	0.42	21	0.4	8.4	6.4	
		Automatic ejector M-5-3	Ejects cans from Dynapak to quench tank	12.6/hr	30/hr	0.42	21	0.01	0.2	0.2	4
M-6	Quenching	Quench tank M-6-1	Automatically dumps cans into tank containing H_2O for thermal shocking	12.6/hr	30/hr	0.42	21	0.1	2.1	2.1	
		Conveyer-dryer M-6-2	Automatically conveys cans from quench tank to can opener and air dries them in route	12.6/hr	30/hr	0.42	21	0.01	0.2	0.2	2
M-7	Can emptying	Can opener and dumper M-7-1	Automatically cuts open cans and dumps UO_2 into storage hopper	12.6/hr	60/hr	0.21	21	0.2	4.2	2.1	
		Storage hopper M-7-2	Stores feed to crusher	18.4 tonnes	50 tonnes	0.37	21	0.1	2.1	2.1	4

[a]For one-day operation.
[b]See Fig. 2 for flow diagram.

APPENDIX B (continued)

Processing Equipment				100,000-Mw(t) Plant					Operating Manhours Required for		
Step No	Operation	Equipment	Purpose	Required Production Rate or Capacity	Maximum Equipment Production Rate or Capacity	Equipment Load Factor	Equipment Operating Time (hr)	Manpower Load Factor	100,000-Mw(t) Plant	25,000-Mw(t) Plant	3500-Mw(t) Plant
M-8	Crushing	Conveyer-feeder M-8-1	Automatically feeds UO_2 to crusher	1 tonne/hr	2 tonne/hr	0.50	21	0.1	2.1	2.1	
		Jaw crusher M-8-2	Crushes coarse material	1 tonne/hr	2 tonne/hr	0.50	21	0.1	2.1	2.1	4
M-9	Ball milling	Storage hopper M-9-1	Stores feed to ball mill	10 tonnes	30 tonnes	0.33	24	0.01	0.2	0.2	
		Continuous ball mill M-9-2	Ball milling UO_2 for fine material	476 kg/hr	4000 kg/4-hr cycle	0.50	21	0.2	4.2	4.2	4
M-10	Classifying	Continuous classifiers:									
		M-10-1	Classifies material from crusher	1020 kg/hr	2000 kg/hr	0.51	21	0.1	2.1	2.1	
		M-10-2	Classifies material from ball mill	476 kg/hr	2000 kg/hr	0.24	21	0.1	2.1	2.1	
		Storage hopper bank (2 recycle fractions) M-10-3	Stores UO_2 to be recycled	12 tonnes	30 tonnes	0.40	21	0.01	0.2	0.2	
		Conveyer M-10-4	Conveys UO_2 from recycle hoppers to crusher	95 kg/hr	190 kg/hr	0.50	21	0.1	2.1	2.1	
		Conveyer M-10-5	Conveys UO_2 from recycle hoppers to ball mill	476 kg/hr	1000 kg/hr	0.48	21	0.1	2.1	2.1	16
M-11	Storing	Storage hopper bank (working fractions) M-11-1	Stores two working fractions of UO_2	18.4 tonnes	50 tonnes	0.37	21	0.01	0.2	0.2	
		Conveyers:	Each conveys one fraction of material to gravimetric feeder indicated:								
		M-11-2	To feeder M-12-1	200 kg/hr	500 kg/hr	0.4	21	0.1	2.1	2.1	
		M-11-3	To feeder M-13-1	132 kg/hr	500 kg/hr	0.27	21	0.1	2.1	2.1	
		M-11-4	To feeder M-23-1	327 kg/hr	500 kg/hr	0.65	21	0.1	2.1	2.1	
		M-11-5	To feeder M-24-1	217 kg/hr	500 kg/hr	0.43	21	0.1	2.1	2.1	
M-12, M-13, M-23, and M-24	Gravimetric feeding	Gravimetric feeders M-12-1, M-13-1, M-23-1, and M-24-1[c]	Each feeds one fraction of material to tube assembly	6.8 loads/hr[c]	30/hr[c]	0.23[c]	21[c]	0.2[c]	4.2[c]	2.1[c]	2
M-14 and M-25	Vibratory compaction	Electrodynamic shakers M-14-1, M-14-2 and M-25-1, M-25-2[c]	Automatically vibrate inner and outer tubes, respectively	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]	0.5[c]	10.5[c]	5.25[c]	
		Tube feeders M-14-3 and M-25-3[c]	Feed tubes	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.2[c]	4.2[c]	2.7[c]	8
M-15 and M-26	Density scanning	Gamma absorptiometers M-15-1 and M-26-1[c]	Automatically scan for density of inner and outer tubes, respectively; tied in with vibratory compactor	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]	0.1[c]	2.1[c]	2.1[c]	4

[c]Where equipment pieces are listed together, the operating data are the same for all units but are given here for only one unit.

APPENDIX B (continued)

Step No.	Processing Equipment: Operating	Processing Equipment: Equipment	Processing Equipment: Purpose	100,000-Mw(t) Plant: Required Production Rate or Capacity	100,000-Mw(t) Plant: Maximum Equipment Production Rate or Capacity	100,000-Mw(t) Plant: Equipment Load Factor	100,000-Mw(t) Plant: Equipment Operating Time (hr)	100,000-Mw(t) Plant: Manpower Load Factor	Operating Manhours Required for: 100,000-Mw(t) Plant	Operating Manhours Required for: 25,000-Mw(t) Plant	Operating Manhours Required for: 3500-Mw(t) Plant
M-16 and M-27	End capping	End capper-welders M-16-1 and M-27-1[c]	Clean tube ends, insert end caps, and weld caps	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]	0.2[c]	4.2[c]	4.2[c]	
		Conveyers M-16-2 and M-27-2[c]	Convey tubes to capper	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.1[c]	2.1[c]	2.1[c]	8
M-17 and M-28	Weld penetrant examination	Conveyer-dippers M-17-1 and M-28-1[c]	Convey tubes from end capper, dip tubes, and stack them for inspection	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]	0.05[c]	1.1[c]	1.1[c]	
		Penetrant chemical tanks M-17-2 and M-28-2[c]	Hold penetrant solutions				21[c]	0.1[c]	2.1[c]	1.1[c]	
		Black light benches M-17-3 and M-28-3[c]	Visual inspection of tubes	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]	0.5[c]	10.5[c]	4.5[c]	2
M-18 and M-29	Helium leak testing	Conveyers M-18-1 and M-29-1[c]	Convey tubes to helium leak tester	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.05[c]	1.1[c]	1.1[c]	
		Leak detectors, automatic M-18-2 and M-29-2[c]	Detect leaks by insertion of weld into test ports (both ends)	13.6 ends/hr[c]	30/hr[c]	0.45[c]	21[c]	0.5[c]	10.5[c]	5.25[c]	5
M-19 and M-30	Weld radiography	Conveyers M-19-1 and M-30-1[c]	Convey tubes to radiograph	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.01[c]	0.2[c]	0.2[c]	
		Radiography outfits M-19-2 and M-30-2[c]	Automatically radiograph welds on both ends	13.6 ends/hr[c]	30/hr[c]	0.45[c]	21[c]	0.5[c]	10.5[c]	5.25[c]	6
M-20 and M-31	Etching and rinsing	Conveyers M-20-1 and M-31-1[c]	Convey tubes from radiograph through etch tanks, rinse tank, dryer and to autoclave	6.8/hr[c]	30/hr[c]	0.45[c]	21[c]	0.1[c]	2.0[c]	2.0[c]	
		Tanks M-20-2 and M-31-2[c]	Acid and rinse baths of tubes	6.8/hr[c]	30/hr[c]	0.45[c]	21[c]	0.1[c]	2.1[c]	2.1[c]	
		Dryers M-20-3 and M-31-3[c]	Air-blast drying of tubes	6.8/hr[c]	30/hr[c]	0.45[c]	21[c]	0.01[c]	0.2[c]	0.2[c]	4
M-21 and M-32	Autoclaving	Autoclaves M-21-1, -2, -3, and -4 and M-32-1, -2, -3, and -4[c]	Treatment of material in 400°C, 1500-psi steam for 72 hr; each autoclave for 1 day's production; one autoclave is off the line for loading	143/3-days[c]	240/3-days[c]	0.20[c]	24[c]	0.22[c]	5.3[c]	2.7[c]	6
M-22 and M-33	Dimensional inspection	Conveyers M-22-1 and M-33-1[c]	Convey tubes to dimensional checking equipment	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.01[c]	0.2[c]	0.2[c]	
		Dimensional inspection equipment M-22-2 and M-33-2[c]	"Go, no-go" inspection and air gaging	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.2[c]	4.2[c]	4.2[c]	10

APPENDIX B (continued)

Processing Equipment				100,000-Mw(t) Plant					Operating Manhours Required for		
Step No.	Operation	Equipment	Purpose	Required Production Rate or Capacity	Maximum Equipment Production Rate or Capacity	Equipment Load Factor	Equipment Operating Time (hr)	Manpower Load Factor	100,000-Mw(t) Plant	25,000-Mw(t) Plant	3500-Mw(t) Plant
M-34	Tube assembling	Conveyers M-34-1 and M-34-2[c]	Convey inner and outer tubes, respectively, to assembly	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.01[c]	0.2[c]	0.2[c]	
		Assembling machine M-34-3	Assembles outer and inner tubes and end fittings	6.8/hr	12/hr	0.57	21	1.0	21.0	7.0	20
M-35	Welding of end fittings	Welding machine M-31-1	Welds both end fittings onto the assembly; associated with assembly step above	6.8 elements/hr	12/hr	0.57	21	0.5	10.5	6.5	10
M-36	Final dimensional inspection, weighing, and marking	Conveyer M-36-1	Conveys elements	6.8/hr	60/hr	0.11	21	0.01	0.2	0.2	
		Dimensional inspection equipment M-36-2	Air-gaging diameter, checking length of fuel element	6.8/hr	60/hr	0.11	21	0.2	4.2	2.1	
		Marking equipment M-36-3	Marks identification number on element	6.8/nr	60/hr	0.11	21	0.2	4.2	2.1	10
M-37	Shipping	Conveyer M-37-1	Conveys elements to shipping station	6.8/hr	60/hr	0.11	21	0.01	0.2	0.2	
		Car loader M-37-2	Loads elements onto special car	6.8/hr	12/hr	0.57	21	0.5	10.5	6.5	4
H-1, H-5, H-19, and H-23[d]	Ultrasonic inspection	Automatic equipment H-1-1, H-5-1, H-19-1, and H-23-1[c]	Automatically inspect tubing	41 ft/hr[c]	70 ft/hr[c]	0.59[c]	21[c]	0.2[c]	4.2[c]	2.7[c]	8
H-2, H-6, H-20, and H-24	Length cutting and machining	Turret lathes H-2-1 and H-20-1[c]	Semiautomatically machine tube ends	6.8/hr[c]	20/hr[c]	0.68[c]	21[c]	0.75[c]	15.8[c]	7.9[c]	4
H-9, H-27, H-33, and H-36	Machining	Turret lathes H-9-1 through H-9-5	Machine end caps	13.6/hr	20/hr	0.68	21	4.0	84.0	34.0	4
		H-27-1 through H-27-6	Machine end caps	13.6/hr	18/hr	0.75	21	4.0	84.0	34.0	
		H-33-1	Cuts ½-in. bar stock and makes end fitting rods	13.6/hr	20/hr	0.68	21	0.5	10.5	3.5	2
		Punch press H-36-1	Punches vanes from 3/16-in. thick stock	41/hr	500/hr	0.08	21	0.05	1.1	1.1	2
H-12	Length cutting	Shear H-12-1 and deburring machine H-12-2	Cuts bar and deburs for spacers	61.2/hr	120/hr	0.51	21	0.5	10.5	3.5	2

[d]See Fig. 3 for flow diagram.

APPENDIX B (continued)

Processing Equipment				100,000-Mw(t) Plant					Operating Manhours Required for		
Step No.	Operation	Equipment	Purpose	Required Production Rate or Capacity	Maximum Equipment Production Rate or Capacity	Equipment Load Factor	Equipment Operating Time (hr)	Manpower Load Factor	100,000-Mw(t) Plant	25,000-Mw(t) Plant	3500-Mw(t) Plant
H-3, H-7, H-10, H-13, H-21, H-25, H-28, H-34, and H-37	Washing and drying	Conveyers H-3-1, H-7-1, H-27-1, and H-25-1[c]	Convey tubes to washer-dryer	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]				
		Washer-dryers H-3-2, H-7-2, H-21-2, and H-25-2[c]	Wash and dry tubes in two-step device	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]				
		Conveyers H-10-1 and H-28-1[c]	Convey end caps to and through washer-dryer	13.6/hr[c]	60/hr[c]	0.23[c]	21[c]	2.0	42.0	28.0	10
		H-13-1	Conveys spacers to and through washer-dryer	61.2/hr	120/hr	0.51	21				
		H-34-1	Conveys rods to and through washer-dryer	13.6/hr	60/hr	0.23	21				
		H-37-1	Conveys vanes to and through washer-dryer	41/hr	120/hr	0.34	21				
		Washer-dryer H-10-2	Washes and dries above items				21				
H-4, H-8, H-11, H-14, H-22, H-26, H-29, H-35, and H-38	Etching and rinsing	Automatic etch-rinse equipment	Loads hardware, etches, rinses, and unloads continuously								
		H-4-1, H-8-1, H-22-1, and H-26-1[c]		6.8 tubes/hr[c]	12/hr[c]	0.57[c]	21[c]				
		H-11-1 and H-29-1[c]		13.6 caps/hr[c]	60/hr[c]	0.23[c]	21[c]	2.0	42.0	28.0	6
		H-14-1		61.2 spacers/hr	120/hr	0.51	21				
		H-35-1		13.6 rods/hr	60/hr	0.23	21				
		H-38-1		41 vanes/hr	120/hr	0.34	21				
H-15	Assembling and welding on spacers	Conveyer H-15-1	Conveys tubes from H-8-1 to H-15-2	6.8/hr	60/hr	0.11	21	0.01	0.2	0.2	
		Automatic assembling and welding equipment H-15-2	Automatically assembles and welds spacers on tubes	6.8/hr	12/hr	0.57	21	0.5	10.5	6.5	10
H-16 and H-30	Assembling	Conveyers H-16-1, H-16-2, H-30-1, and H-30-2[c]	Convey tubes from H-4, H-15, H-22, and H-26, respectively	6.8/hr[c]	60/hr[c]	0.23[c]	21[c]	0.01[c]	0.2[c]	0.2[c]	
		Conveyers H-16-3 and H-30-3[c]	Convey end caps from H-11 and H-29, respectively	6.8/hr[c]	60/hr[c]	0.23[c]	21[c]	0.01[c]	0.2[c]	0.2[c]	
H-17 and H-31	Welding of end caps	Automatic assembling and welding equipment H-17-1 and H-31-1	Automatically assemble tubes and end caps and weld them	6.8/hr[c]	12/hr[c]	0.57[c]	21[c]	0.5[c]	10.5[c]	6.5[c]	4[c]

APPENDIX B (continued)

Processing Equipment				100,000-Mw(t) Plant					Operating Manhours Required for		
Step No.	Operation	Equipment	Purpose	Required Production Rate or Capacity	Maximum Equipment Production Rate or Capacity	Equipment Load Factor	Equipment Operating Time (hr)	Manpower Load Factor	100,000-Mw(t) Plant	25,000-Mw(t) Plant	3500-Mw(t) Plant
H-18 and H-32	Marking with identification	Automatic marking equipment H-18-1 and H-32-1[c]	Automatically load, mark, and box end caps	6.8/hr[c]	60/hr[c]	0.11[c]	21[c]	0.2[c]	4.2[c]	2.1[c]	4
H-39	Assembly	Conveyer H-39-1	Conveys rods	13.6/hr	60/hr	0.23	21	0.01	0.2	0.2	
		Conveyer H-39-2	Conveys vanes	41/hr	120/hr	0.34	21	0.01	0.2	0.2	
H-40	Welding	Automatic welder H-40-1	Automatically assembles and welds the end of fittings	13.6/hr	24/hr	0.57	21	0.5	10.5	6.5	10
H-41	Autoclaving	Conveyer H-41-1	Conveys fittings from H-40 to autoclave	13.6/hr	60/hr	0.23	21	0.01	0.2	0.2	
		Autoclave H-41-2	Autoclaves fittings at 400°C, 1500-psi steam for 72 hr	1144/4-day-cycle	2000/4-day-cycle	0.58	24	0.25	6.0	4.0	6
								Total	688.5	399.1	231

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