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ESTIMATED LARGE-SCALE PRODUCTION COSTS FOR CLADDING URANIUM METAL FUEL TUBES

R. J. Beaver

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ABSTRACT

Reactor systems considered for economic desalination of sea water appear to be in the range of 3500 to 100,000 Mw (thermal). The magnitude of natural uranium burned per year makes the cost of fuel elements a significant consideration. One of the fuel element designs being proposed consists of two concentric uranium tubes clad with Zircaloy-2.

An economic study was undertaken to compare costs for two schemes of fabricating fuel tubes containing metallic uranium, coextrusion and pressure bonding. Two cladding materials, aluminum and Zircaloy, were considered. In the data presented, the cost of conversion to uranium metal and the costs of fabrication of the uranium metal into tubular stock were ignored.

Fabrication costs for Zircaloy-2-clad tubes ranged between $1.22 and $6.17 per pound of uranium charged to the reactor. The higher costs were associated with 3500-Mw systems, which obviously have the lowest fuel throughput considered. As might be expected, aluminum-clad tubes were cheaper; the cost of the fuel tube per pound of uranium charged to a 100,000-Mw system was approximately $0.74 compared to $1.26 for similarly fabricated Zircaloy-2-clad tubes.

Although coextrusion appeared to be an economical method for cladding uranium tubes with Zircaloy-2, pressure-bonding plants looked attractive, not only because of economics but also because pressure bonding appeared amenable as a technique for cladding Zircaloy-2 as well as aluminum to uranium tubes. Thus, one plant would have the capability of manufacturing both aluminum and Zircaloy-2-clad tubes.

INTRODUCTION

Large reactor systems ranging from 3500 to 100,000 Mw (thermal) are being considered for applications requiring economic desalination of sea water. The reactors are cooled by boiling water in forced circulation and are moderated by a mixture of heavy water and graphite. The average specific power is approximately 12 kw/(kg U) and the heat flux ranges between 200,000 to 300,000 Btu hr^{-1} ft^{-2}. Surface temperature of the cladding is approximately 400°F.

The tentative fuel element conceptual design consists of two tubes, 72 in. long and approximately 3 in. in diameter, one nested in the other and spaced by fins attached to the cladding. The fuel section of each tube is 0.335 in. thick and is protected by 0.020-in.-thick cladding, which is metallurgically bonded to the uranium to promote maximum heat transfer. Total uranium in each fuel element nest is 242 lb.

Large numbers of fuel tubes, ranging from 5000 tubes for a 3500-Mw system to 125,000 tubes for a 100,000-Mw system, are the estimated annual requirements. Thus, the cost of fuel elements represents an appreciable sum of money. A study was therefore undertaken to estimate the future costs of fuel tubes fabricated by a coextrusion method as well as by a pressure-bonding process. Both Zircaloy-2 and aluminum were considered as the cladding material. The estimates were based on plants designed to produce annually 5,000, 37,500, and 125,000 tubes for 3500-, 25,000-, and 100,000-Mw systems, respectively. Estimates were compared on the basis of cost per pound (or kilogram) of uranium charged to the reactor. These estimates are exclusive of the cost of the uranium metal and the cost for fabricating the uranium into working stock.

DESCRIPTION OF THE COMPONENT

The conceptually designed tentative fuel element consists of two clad uranium-metal fuel tubes, one nested within the other, separated by fins attached to the cladding of the tubes. The outer tube is 3.2 in. OD × 2.54 in. ID and the inner tube is 2.18 in. OD × 1.43 in. ID. Each tube is 72 in. long and is clad with 0.020-in.-thick Zircaloy-2 (or possibly aluminum). The exposed ends of the uranium are sealed with end plugs. Each fuel element nest contains 242 lb of natural uranium. A schematic of the tubular nest is illustrated in Fig. 1.

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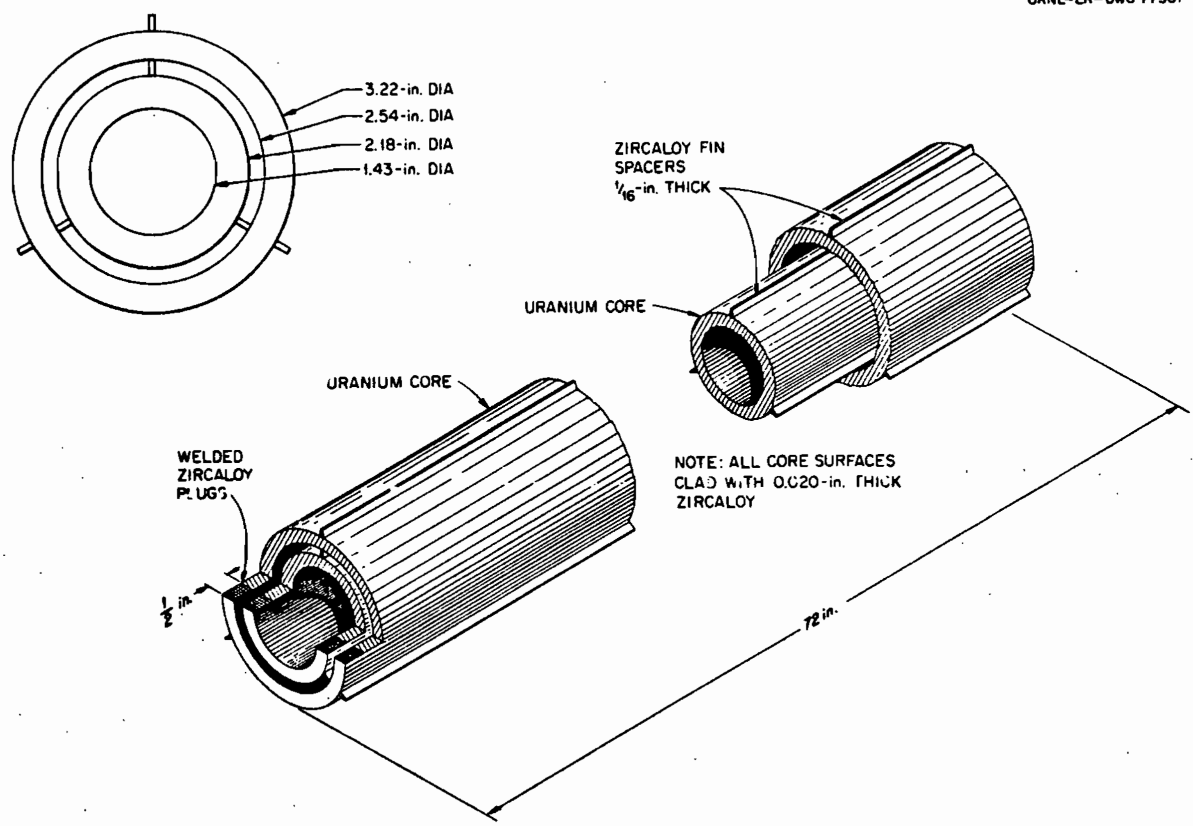

Fig. 1. Schematic Illustration of Fuel Element.

STUDY CONSIDERATIONS

Fabrication Processes

Two methods for processing this type of fuel element and obtaining satisfactory bonding between the uranium and the cladding were examined. Considerable development has shown that little difficulty should be experienced in bonding Zircaloy to uranium by the hot extrusion process.[1] Another attractive method is to gas-pressure bond Zircaloy to uranium. Although this technique has not been as extensively developed as

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[1]A. R. Kaufmann et al., "Zirconium Cladding of Uranium and Uranium Alloys by Coextrusion," pp. 157–81 in Fuel Elements Conference, Paris, November 18–23, 1957, TID-7546, Book I (March 1958).

extrusion, results available indicate that it is equally suitable.[2] Pressure bonding appears to be the most economical way to bond aluminum to nickel-plated uranium. In fact, this process was used successfully in preparing a core loading of fuel elements for the Organic-Moderated Reactor Experiment.[3]

The coextrusion process can be designed to produce several completely clad and sealed tubes in one extrusion through the press. The feasibility has been demonstrated[1] by Kaufmann et al. However, at the present time the process does not appear to be as amenable as the alternate in which a 33-ft-long tube is extruded. The long extrusion is subsequently cut into five 6-ft-long tubes, and the exposed edges are plugged. This method also appeared more acceptable to Isakoff in his study of the economics in coextrusion fabrication.[4] This process requires a press of sufficient capacity to extrude a billet 15 to 20 in. in diameter and reducing it in cross-sectional area by a ratio of 30 to 40. Before the ends of the sectioned tubes can be sealed, some uranium must be dissolved out; this can be done with 50% HNO_3. The uranium may then be sealed by welding plugs to the ends of the tubes. The spacer fins can be attached by high-frequency resistance welding. In this study, the billet parts – thick-walled uranium and Zircaloy tubes, Zircaloy end plugs, and steel sheaths, nose cones, and plugs – were considered as items purchased and delivered to the extrusion plant for assembly into billets.

In the pressure-bonding process, the uranium and zirconium tubes and the zirconium plugs were also procured for assembly at the pressure-bonding plant. The pressure-bonding autoclave was of sufficient size to permit bonding of 30 nests at once. The composite parts, sized to the finished product dimensions, are assembled; then the end plugs are welded in vacuum in an electron-beam welder and are gas-pressure bonded in the

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[2]S. J. Paprocki, Battelle Memorial Institute, Columbus, Ohio, personal communication, March 1963.

[3]E. E. Garrett et al., Hot-Pressure Bonding of OMR Tubular Fuel Elements, NAA-SR-5120 (July 30, 1960).

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

autoclave. Finally, the spacer fins are high-frequency resistance welded to the bonded tubes.

In pressure bonding aluminum to uranium, the fabrication practices are quite similar to those for cladding uranium with Zircaloy. The exceptions are that the uranium is electroplated prior to bonding and the extruded aluminum tubes received at the pressure-bonding plant have spacer fins integrally attached.

Materials

Uranium, alloyed with minor additions of elements such as zirconium or molybdenum, was considered as the reference fuel material.

Zircaloy-2, because of its acceptable corrosion resistance, low thermal-neutron absorption cross section, and compatibility with uranium, was selected as the reference cladding material. Aluminum was not selected as the reference cladding because of its marginal corrosion resistance; however, since it is economically attractive, it was examined as an alternate.

Material Cost

Uranium

The cost for the fabricated uranium metal used in preparation of the composite tubes was not assigned a value. (Isakoff[4] estimated the cost of uranium at $1.00/lb.)

Zircaloy-2

The cost of Zircaloy-2 is estimated in Table 1. The cost assignments show that as the annual production requirements increase with system power, the cost per pound decreases.

Table 1. Estimated Cost of Zircaloy-2

System Power (Mw)	Number of Tubes Required Per Year		Cost ($/lb)
	Extrusion	Pressure Bonding	
3,500	1,700	10,000	16.00
25,000	13,000	75,000	13.00
100,000	86,000	250,000	11.00

Tinamel Steel

Present technology in extrusion of Zircaloy-clad uranium indicates that the uranium and zirconium can be protected from oxidation by sheathing with either copper or steel. Tinamel steel was selected in preference to copper for its lower cost. The cost of this sheath for each extrusion billet was estimated at $20.00.

Aluminum

Finned aluminum extruded tubes for pressure bonding were estimated as follows.

Tubes Required Per Year	Cost Per Pound
10,000	$3.00
75,000	2.00
250,000	1.75

METHODS OF ESTIMATING FIXED AND VARIABLE COSTS

The methods used by Isakoff[4] were generally followed, except depreciation was assigned as 15% (instead of 10%) of total plant investment and total plant investment was based on multiplying the cost of equipment (delivered) by 5.6 (instead of 3.2). In this plan, the variable costs consist of the following items:

1. direct labor
2. supervision
3. service – 10% of direct labor plus maintenance

4. maintenance — 5% of total plant investment per year
5. raw materials.

Manpower costs were assigned as follows:

operators	\$ 8,000/man-year
clerical	6,000/man-year
service	4,000/man-year
supervision	15,000/man-year

The fixed costs consist of indirect plant costs, overhead at two-thirds of indirect plant costs, management at one-third of indirect plant cost, and inventory charges at 6%. The annual indirect plant costs consist of (1) depreciation, 15% of total plant investment; (2) taxes, 2% of total plant investment; and (3) insurance, 1% of total plant investment.

Results of the analyses were given in dollars per pound or kilogram of uranium charged to the reactors.

CALCULATION OF COST

For Zircaloy-clad uranium tubes fabricated by the extrusion process, the relationships shown below were used to calculate the total cost.

1. Cost of uranium fabrication (C_U) per pound of uranium charged to the reactor:

$$C_U = \frac{(\pi/4)(b^2 - c^2)(12E)(\rho_U)(f_U)}{(\pi/4)(b^2 - c^2)(E - 3)(12)(\rho_U)(A)} = \frac{(U_f)(E)}{(E - 3)(A)} .$$

2. Cost of Zircaloy tubes (C_{Zr_t}) per pound of uranium charged to reactor:

$$C_{Zr_t} = (\pi/4)(a^2 - b^2 + c^2 - d^2)(12E)(\rho_{Zr})(f_{Zr})/Z .$$

3. Cost of Zircaloy end plugs (C_{Zr_e}) per pound of uranium charged to reactor:

$$C_{Zr_e} = (\pi/4)(b^2 - c^2)(5L)(\rho_{Zr})(f_{Zr})/Z .$$

4. Cost of Zircaloy fin ($C_{Zr_{fin}}$) per pound of uranium charged to reactor:

$$C_{Zr_{fin}} = (3)(w)(t)(l)(\rho_{Zr})(f_{Zr})/Z \quad .$$

5. Fixed and variable costs (C_{fv}) per pound of uranium charged to reactor:

$$C_{fv} = (F + V)/Z \quad .$$

6. Total cost (C_t) per pound of uranium charged to reactor:

$$C_t = C_U + C_{Zr_t} + C_{Zr_e} + C_{Zr_{fin}} + C_{fv} \quad .$$

Nomenclature

a = outer diameter of composite tube, inches

b = outer diameter of fuel core, inches

c = inner diameter of fuel core, inches

d = inner diameter of composite tube, inches

l = length of individual fuel element tube, feet

w = width of Zircaloy fin, inches

t = thickness of Zircaloy fin, inches

ρ_U = density of uranium (0.69 lb/in.^{3})

ρ_{Zr} = density of Zircaloy (0.23 lb/in.^{3})

f_U = raw material and basic fabrication cost of uranium, dollars (not estimated)

f_{Zr} = raw material and basic fabrication cost of Zircaloy, dollars

E = extrusion ratio based on length in feet, where $E > 30$

A = product yield

L = length of Zircaloy plug, inches

Z = $(\pi/4)(b^2 - c^2)(E - 3)(12)(\rho_U)(A)$, pounds

V = variable plant costs, dollars

F = fixed plant costs, dollars

In this processing scheme, the billet components — Zircaloy tubes, end plugs, and fins; uranium billets; and steel sheaths and end plugs — are delivered to the extrusion plant for assembly and extrusion into the composite tubes.

For pressure-bonded tubes the cost calculation in terms of dollars per pound of uranium charged to the reactor consisted of the raw material and fabrication costs of the Zircaloy (or aluminum) tubes, end plugs, and fins and the fixed and variable costs associated with producing the finished pressure-bonded fuel tube. A rejection rate of 15% of the pressure-bonded product was factored into the final cost.

RESULTS

Production of Zircaloy-Clad Tubes by the Coextrusion Process

The flow of this process is outlined in Table 2. Equipment costs include automation visualized to meet the requirements for 25,000- and 100,000-Mw reactor systems. Such automation was not integrated into the plant designed to supply a 3500-Mw system because of the low production rate.

The equipment and annual material costs are listed in Table 3. The major cost items are the extrusion press, the equipment for welding the spacer fins, and the hoist and conveying equipment. The cost of the extrusion press is the same for a plant supplying only 5000 tubes per year as it is for a plant supplying 125,000 tubes per year because the size of the billet to be extruded requires the same high-capacity press. The cost of this equipment has a drastic effect in increasing the cost of the finished product when only an annual supply of 5000 tubes is required. Conversely, the fact that only one extrusion press is required on a 3-shift basis to manufacture 125,000 tubes annually has a significant effect in reducing the cost of the extruded tube.

The manpower requirements are listed in Table 4 and are based on the results of the time and motion estimates included in Appendix A.

Table 2. Flow Diagram of Extrusion Process for Fabricating Zircaloy-Clad-Uranium Tubes

1. Receiving of All Billet Components
2. Inspection of All Components
3. Welding of Tinamel Sheath
    a. Nose cone to sheath
    b. Evacuation stem to end plug
4. Vapor Degreasing
    a. Zircaloy and uranium components
5. Acid Pickling
    a. Uranium in 50% HNO_3
    b. Zircaloy in 48% HNO_3–2% HF
6. Acid Rinsing
    a. Zircaloy in 15% HNO_3–15% $Al(NO_3)_3$
7. Water Rinsing
    a. Zircaloy
    b. Uranium
8. Air Drying
    a. Zircaloy
    b. Uranium
9. Assembly of Billet Parts
10. Welding Tinamel Rear Plug to Billet
11. Leak Detection of Billets
12. Evacuation and Sealing of Billets
13. Preheating of Billets
14. Extrusion of Billets
15. Slitting of Extruded Tubes
    a. 72-in.-long segments
    b. Croppings
16. Acid Pickling
    a. Removal of Tinamel in 50% HNO_3
17. Water Rinsing of Composite Tubes
18. Air Drying of Composite Tubes
19. Go No-Go Dimensional Inspection of Composite Tubes
20. Zyglo Inspection for Surface Defects
21. Chemical Machining of Uranium Ends of Composite Tubes in 50% HNO_3
22. Water Rinsing of Composite Tubes
23. Air Drying of Composite Tubes
24. Welding of End Plugs to Composite Tubes
25. Ultrasonic Inspection for Nonbonds in Composite Tubes
26. Zyglo Inspection of End Closures of Composite Tubes
27. Welding of Fins to Composite Tubes
28. Autoclave Testing for Corrosion Resistance
29. Crating and Shipping

Table 3. Equipment and Materials Costs for Cladding Uranium Tubes with Zircaloy by Coextrusion

Cost Item	Cost for Three Power Levels		
	3500 Mw[a]	25,000 Mw[b]	100,000 Mw[c]
Equipment			
Conveyors	$	$ 100,000	$ 100,000
Hoist, lift, and monorail	5,000	100,000	100,000
Extrusion equipment	1,000,000	1,000,000	1,000,000
Furnaces	5,500	21,000	21,000
Welding equipment	200,000	400,000	600,000
Inspection equipment	22,000	53,000	138,000
Chemical equipment	12,100	42,500	96,000
Autoclaves	50,000	150,000	300,000
Miscellaneous	7,500	27,000	32,000
Totals (E)	$1,302,100	$ 1,893,500	$ 2,387,000
Materials (annual supply)			
Chemicals and gases	$ 11,100	$ 78,000	$ 195,000
Dies etc.	12,000	90,000	300,000
Steel cans for billets	20,000	150,000	500,000
Totals	$ 43,100	$ 318,000	$ 995,000
Total Plant Investment (5.6E)	$7,291,200	$10,603,600	$13,367,200

[a] 5000 tubes per year.

[b] 37,500 tubes per year.

[c] 125,000 tubes per year.

The manufacturing costs are summarized in Table 5. For an annual production of 5000 tubes, the contribution to the total cost is $5.26/lb. For an annual production of 37,500 tubes, this cost decreases to $1.25. When the annual production rate increases to 125,000 tubes, the cost is reduced to $0.57. This is considered to be a minimum, because the full capacity of such a plant is utilized 24 hr each day of a 250-working-day year.

Table 4. Manpower Costs for Cladding Uranium Tubes with Zircaloy by a Coextrusion Process

Personnel	Annual Rate	3500 Mw		25,000 Mw		100,000 Mw	
		Number Required	Cost per year	Number Required	Cost per year	Number Required	Cost per year
Operators	$ 8,000	25	$200,000	83	$664,000	218	$1,744,000
Clerical	6,000	2	12,000	5	30,000	9	54,000
Service	4,000	2	8,000	4	16,000	9	36,000
Subtotal		29	$220,000	92	$710,000	236	$1,834,000
Supervision	15,000	1	15,000	4	60,000	8	120,000
Total		30	$235,000	96	$770,000	244	$1,954,000

Table 5. Manufacturing Costs for Cladding Uranium Tubes with Zircaloy by a Coextrusion Process

Cost Item	Costs Per Year		
	3500 Mw	25,000 Mw	100,000 Mw
Variable cost			
Direct labor	$ 220,000	$ 710,000	$1,834,000
Supervision	15,000	60,000	120,000
Service (10% of direct labor + 10% of maintenance)	42,800	101,300	221,500
Maintenance (5% of total plant investment)	208,300	303,000	381,000
Miscellaneous supplies (0.5% of total plant investment)	20,800	30,300	38,200
Raw Materials	43,100	318,000	995,000
Total variable	$ 550,000	$1,522,600	$3,589,700
Fixed cost			
Depreciation (15% of total plant investment)	$1,093,650	$1,590,600	$2,005,050
Taxes (2% of total plant investment)	145,800	212,080	267,340
Insurance (1% of total plant investment)	72,900	106,040	133,670
Subtotal (indirect plant cost)	$1,312,350	$1,908,720	$2,406,060
Overhead (2/3 of indirect plant cost)	$ 873,800	$1,273,000	$1,602,400
Management (1/3 of indirect plant cost)	436,900	634,000	801,200
Inventory charges at 6%	6,000	45,000	150,000
Total fixed	$2,629,050	$3,855,720	$4,959,660
Total fixed and variable	$3,179,050	$5,378,320	$8,549,360
Cost per fuel element nest	$1,271.60	$303.00	$136.80
Cost per pound of uranium charged to the reactor	$5.26	$1.25	$0.57

Table 6 compares the total cost per pound (or kilogram) of uranium charged to the reactor. For a plant supplying 5000 tubes annually the sum of the Zircaloy costs and the total fixed and variable costs contribute $6.17 to the cost per pound of uranium charged to a 3500-Mw reactor system. This cost is reduced to $2.12 for a 25,000-Mw system requiring an annual supply of 37,500 tubes and $1.22 for a 100,000-Mw system requiring an annual supply of 125,000 tubes. These costs are exclusive of the cost of the basic uranium stock.

Table 6. Costs per Pound of Uranium Charged to the Reactor for Cladding Uranium Tubes with Zircaloy by a Coextrusion Process

Material	Cost for Each Power Level[a]		
	3500 Mw	25,000 Mw	100,000 Mw
Uranium	X	X	X
Zirconium			
Cladding	$ 0.81	$ 0.77	0.55
End closures	0.08	0.08	0.08
Fins	0.02	0.02	0.02
Total fixed and variable cost	5.26	1.25	0.57
Totals	$ 6.17 + X	$ 2.12 + X	$ 1.22 + X
Cost per kilogram of uranium charged to the reactor	$13.57 + 2.2X	$4.66 + 2.2X	$2.68 + 2.2X

[a]Cost per pound of uranium charged to the reactor.

Production of Zircaloy-Clad Tubes by the Pressure-Bonding Process

The flow of this process is outlined in Table 7. As for the extrusion process, as much automation as possible was allowed for plants producing 37,500 and 125,000 tubes annually. For plants producing 5000 tubes annually such automation was not integrated because of the low production rate.

Table 7. Flow Outline of Process for Pressure Bonding Zircaloy to Uranium

1. Inspection of Components at Vendor Sites
2. Receiving Tubular Components and End Plugs
3. Degreasing
   a. Uranium
   b. Zircaloy
4. Acid Cleaning
   a. Uranium in 50% HNO_3
   b. Zircaloy in 48% HNO_3–2% HF
5. Water Rinsing of Uranium and Zircaloy
6. Air Drying of Uranium and Zircaloy
7. Assembly of Composite Tube
8. Electron Beam Welding of Top and Bottom End Plugs
9. Leak Detection of Sealed Composite Tube
10. Welding of Fins to Composite Tube
11. Assembling of Tubes into Loading Fixture
12. Pressure Bonding
13. Leak Detection of Pressure-Bonded Composite Tube
14. Go No-Go Dimensional Inspection of Composite Tube
15. Autoclave Testing of Corrosion Resistance
16. Crating and Shipping

The manpower requirements are summarized in Table 8, and are based on the time and motion study included in Appendix B. The equipment, materials, and total plant investment costs are itemized in Table 9. The equipment costs for plants supplying the 3500- and 25,000-Mw systems are significantly less than for the coextrusion process. For a plant supplying a 100,000-Mw system, the equipment costs are similar. The main reason for the differences is the high cost of the extrusion press compared to the less expensive pressure-bonding equipment.

The manufacturing costs are summarized in Table 10. Because of the fuller utilization of a plant producing 37,500 tubes annually, a

Table 8. Manpower Costs for Cladding Uranium Tubes with Zircaloy by a Pressure-Bonding Process

Personnel	Annual Rate	3500 Mw		25,000 Mw		100,000 Mw	
		Number Required	Cost per year	Number Required	Cost per year	Number Required	Cost per year
Operators	$ 8,000	28	$224,000	127	$1,016,000	318	$2,544,000
Clerical	6,000	2	12,000	8	48,000	18	108,000
Service	4,000	2	8,000	7	28,000	5	20,000
Subtotal		32	$244,000	142	$1,092,000	341	$2,672,000
Supervision	15,000	1	15,000	4	60,000	10	150,000
Totals		33	$259,000	146	$1,152,000	351	$2,822,000

Table 9. Equipment and Material Costs for Cladding Uranium Tubes with Zircaloy by a Pressure-Bonding Process

Cost Item	Cost		
	3500 Mw	25,000 Mw	100,000 Mw
Conveyors	$	$ 40,000	$ 120,000
Hoist, lift and monorail	30,000	260,000	620,000
Welding equipment	225,000	250,000	750,000
Inspection equipment	52,000	58,000	174,000
Pressure-bonding equipment	80,000	120,000	360,000
Chemical and miscellaneous	15,500	28,000	52,000
Total Equipment (E)	$402,500	$756,000	$2,076,000
Materials (annual supply) chemical and gases	$ 25,000	$150,000	$ 450,000
Total plant investment (5.6E)	$2,254,000	$4,233,600	$11,625,600

significant cost decrease from $1.99 to $0.73 per pound of uranium charged to the reactor occurs when the production rate increases from 5000 tubes per year. Increasing the plant size to produce 125,000 tubes annually only decreases the corresponding cost to $0.63. As might be expected, the fixed plus variable costs are more favorable for pressure-bonding plants than for extrusion plants supplying 5000 to 37,500 tubes annually. This conclusion is evident in the comparison of Table 10 with Table 5. For larger plants producing 125,000 tubes annually, total fixed plus variable costs favor the extrusion process.

As listed in Table 11, the total cost per pound of uranium charged to the reactor (excluding the cost of the uranium) decreases from $2.86 for tubes for a 3500-Mw reactor system to $1.45 for a 25,000-Mw system. For a 100,000-Mw system, the cost is reduced to $1.26 per pound of uranium charged to the reactor. Comparing Table 11 with Table 6 shows that the pressure-bonding process costs less for the 3500-Mw and 25,000-Mw systems. Tubes for the 100,000-Mw reactor are slightly less expensive by the extrusion process because of the full utilization of the capacity of the extrusion press.

Table 10. Manufacturing Costs for Cladding Uranium Tubes with Zircaloy by a Pressure-Bonding Process

Cost Item	Costs Per Year		
	3500 Mw	25,000 Mw	100,000 Mw
Variable cost			
Direct labor	$ 244,000	$1,092,000	$3,672,000
Supervision	15,000	60,000	150,000
Service (10% of direct labor + 10% of maintenance)	30,800	121,200	400,300
Maintenance (5% of total plant investment)	64,400	120,640	331,840
Miscellaneous supplies (0.5% of total plant investment)	6,400	12,060	33,180
Raw materials	25,000	150,000	450,000
Total variable	$ 385,600	$1,555,900	$5,037,320
Fixed cost			
Depreciation (15% of total plant investment)	$ 338,100	$ 635,100	$1,744,900
Taxes (2% of total plant investment)	45,080	84,720	267,340
Insurance (1% of total plant investment)	22,540	42,360	133,670
Subtotal (indirect plant cost)	$ 405,720	$ 762,180	$2,145,910
Overhead (2/3 of indirect plant cost)	$ 270,210	$ 507,620	$1,429,240
Management (1/3 of indirect plant cost)	135,100	253,810	714,620
Inventory charges at 6%	6,000	45,000	150,000
Total fixed	$ 817,030	$1,568,610	$4,439,770
Total fixed and variable	$1,202,630	$3,124,510	$9,477,090
Cost per fuel element nest	$481.20	$176.05	$151.63
Cost per pound of uranium charged to the reactor	$1.99	$0.73	$0.63

Table 11. Cost per Pound of Uranium Charged to the Reactor for Cladding Uranium Tubes with Zircaloy by a Pressure-Bonding Process

Material	Cost for Each Power Level[a]		
	3500 Mw	25,000 Mw	100,000 Mw
Uranium	X	X	X
Zirconium			
Cladding	$ 0.77	$ 0.62	$ 0.53
End closures	0.08	0.08	0.08
Fins	0.02	0.02	0.02
Total fixed and variable cost	1.99	0.73	0.63
Totals	$ 2.86 + X	$ 1.45 + X	$ 1.26 + X
Cost per kilogram of uranium charged to the reactor	$6.29 + 2.2X	$3.19 + 2.2X	$2.77 + 2.2X

[a]Cost per pound of uranium charged to the reactor.

Aluminum Cladding by Pressure Bonding

The process for cladding aluminum to uranium is essentially the same as for bonding Zircaloy to uranium. A major difference in addition to changes in bonding temperatures and pressures is that prior to bonding the uranium is electroplated with nickel.

The equipment, total plant investment, manpower, and total fixed and variable costs include integration of an electroplating facility. As listed in Tables 12, 13, and 14, total costs are not significantly higher than those listed for the Zircaloy pressure-bonding plant.

Data presented in Table 15 show the same trend of decreasing total cost per pound of uranium charged to the reactors as cited previously for Zircaloy-clad elements. The product from plants producing tubes for a 3500-Mw reactor system is more than twice as expensive as from those producing tubes for a 25,000-Mw system, that is, $2.32 vs $0.90 per pound of uranium charged to the reactors, exclusive of the cost of the uranium tube. As the production requirements increase to 125,000 tubes annually for the 100,000-Mw system, a reduction to $0.74 occurs.

Table 12. Equipment and Materials Costs for Cladding Uranium Tubes with Aluminum by a Pressure-Bonding Process

Cost Item	Cost		
	3500 Mw	25,000 Mw	100,000 Mw
Conveyors	$	$ 40,000	$ 120,000
Hoist, lift, and monorail	50,000	300,000	700,000
Welding equipment	225,000	250,000	750,000
Inspection equipment	52,000	58,000	174,000
Pressure-bonding equipment	80,000	120,000	360,000
Chemical and miscellaneous	27,500	60,000	134,000
Total Equipment (E)	$434,500	$828,000	$2,238,000
Materials (annual supply chemicals and gases)	$ 40,000	$200,000	$ 550,000
Total Plant Investment (5.6E)	$2,433,200	$4,636,800	$12,532,800

Because of the differential in the costs of aluminum and Zircaloy, the cost for aluminum-clad elements is in every case significantly less than that for the Zircaloy-clad uranium. For example, a plant producing tubes for a 25,000-Mw system produces aluminum-clad tubes for $0.90 per pound of uranium charged to the reactors (exclusive of the cost of the uranium tube) whereas the cost for Zircaloy-clad tubes is $1.45 per pound of uranium charged to the reactors.

It should be pointed out that a 0.335-in.-thick uranium-metal annulus for the fuel element was chosen for comparison with a similar element in which the fuel annulus is packed with UO_2. From the standpoint of obtaining maximum exposure to thermal neutrons, an element of this thickness may not be optimum. Isakoff[6] suggests that a fuel thickness much less might be more appropriate in the interest of maximizing irradiation exposure and claims this should reduce the annual fuel element costs. He reasons that the volume increase of uranium caused by long exposure to thermal neutrons is probably determined by the irradiation exposure, the external restraints on the uranium metal due to the cladding and coolant pressure, and the temperature of the uranium.

[6] L. Isakoff, personal communication, Dec. 13, 1962.

Table 13. Manpower Costs for Cladding Uranium Tubes with Aluminum by a Pressure-Bonding Process

Personnel	Annual Rate	3500 Mw		25,000 Mw		100,000 Mw	
		Number Required	Cost per year	Number Required	Cost per year	Number Required	Cost per year
Operators	$ 8,000	32	$256,000	139	$1,112,000	354	$2,832,000
Clerical	6,000	2	12,000	8	48,000	18	108,000
Service	4,000	2	8,000	7	28,000	5	20,000
Subtotal		36	$276,000	154	$1,188,000	377	$3,960,000
Supervision	15,000	1	15,000	4	60,000	10	150,000
Totals		37	$291,000	158	$1,248,000	387	$4,110,000

Table 14. Manufacturing Costs for Cladding Uranium Tubes with Aluminum by a Pressure-Bonding Process

Cost Item	Costs Per Year		
	3500 Mw	25,000 Mw	100,000 Mw
Variable cost			
Direct labor	$ 276,000	$1,188,000	$ 3,960,000
Supervision	15,000	60,000	150,000
Service (10% of direct labor + 10% of maintenance)	34,550	132,000	431,800
Maintenance (5% of total plant investment)	69,500	132,000	358,000
Miscellaneous supplies (0.5% of total plant investment)	6,950	13,000	35,200
Raw materials	40,000	200,000	550,000
Total variable	$ 442,000	$1,725,000	$ 5,485,000
Fixed cost			
Depreciation (15% of total plant cost)	364,950	695,550	1,879,500
Taxes (2% of total plant cost)	48,660	92,740	250,660
Insurance (1% of total plant cost)	24,330	46,370	125,330
Subtotal (indirect plant cost)	$ 437,940	$ 834,660	$ 2,255,490
Overhead (2/3 of indirect plant cost)	$ 291,640	$ 555,910	$ 1,501,830
Management (1/3 of indirect plant cost)	145,820	277,850	750,910
Inventory charges at 6%	6,000	45,000	150,000
Total fixed	$ 881,400	$1,713,420	$ 4,658,230
Total fixed and variable	$1,323,400	$3,438,420	$10,143,230
Cost per fuel element nest	$529.20	$193.69	$162.24
Cost per pound of uranium charged to the reactor	$2.19	$0.80	$0.67

Table 15. Total Cost per Pound of Uranium Charged to the Reactor for Cladding Uranium Tubes with Aluminum by a Pressure-Bonding Process

Material	Cost for Each Power Level[a]		
	3500 Mw	25,000 Mw	100,000 Mw
Uranium	X	X	X
Aluminum	\$ 0.13	\$ 0.10	\$ 0.07
Total fixed and variable	2.19	0.80	0.67
Totals	\$ 2.32 + X	\$ 0.90 + X	\$ 0.74 + X
Cost per kilogram of uranium charged to the reactor	\$5.10 + 2.2X	\$1.98 + 2.2X	\$1.62 + 2.2X

[a]Cost per pound of uranium charged to the reactor.

The maximum volume change that a fuel element can safely withstand is dependent on the extent to which the cladding can be stretched without splitting. The relationship that appears to fit this condition is

$$\delta = (2/3)(\Delta V/V)(2t/D) \quad ,$$

where

δ = % cladding strain,

$\Delta V/V$ = % volume change,

t = uranium thickness, and

D = outer diameter of the tube.

It is obvious that for tubes of the same outside diameter the cladding of a thinner fuel annulus will be strained less than the cladding of a thicker annulus for an equivalent exposure. In addition, the uranium-metal temperature of the thinner core will be less, which will also tend to decrease thermal stresses. In comparing an 0.352-in.-thick fuel annulus with an 0.176-in. fuel annulus, Isakoff estimated that the temperature difference would be 53°C (400 vs 347°C) with a relative thermal neutron exposure of possibly as high as 2 and a relative cost advantage of 0.75 in favor of the element with the 0.176-in.-thick fuel annulus.

Summary of Calculations

In summary, estimates of the fabrication costs of uranium-metal tubes clad with Zircaloy or aluminum for annual productions of 5000, 37,500, and 125,000 tubes are listed in Table 16. The costs are shown per pound of uranium charged to the reactor and are exclusive of the cost of the raw material and fabrication costs of the uranium stock.

Table 16. Cost per Pound of Uranium Charged to the Reactor (Exclusive of Uranium Costs)

Cladding	3500-Mw System (5000 tubes/year)		25,000-Mw System (37,500 tubes/year)		100,000-Mw System (125,000 tubes/year)	
	Extruded	Pressure-Bonded	Extruded	Pressure-Bonded	Extruded	Pressure-Bonded
Zircaloy	$6.17	$2.86	$2.12	$1.45	$1.22	$1.26
Aluminum		2.32		0.90		0.74

Because of the uncertainties in these estimates, no preference can be made between extrusion cladding and pressure bonding of Zircaloy-clad uranium, except for the 3500-Mw system which requires an annual supply of only 5000 tubes. In this instance, the cost differential is sufficient to warrant the selection of pressure bonding.

Because of the lower basic cost of aluminum tubes compared to Zircaloy tubes, the cost of aluminum-clad uranium tubes is significantly less than that of Zircaloy-clad tubes. This difference appears sufficient to warrant continued development of aluminum alloys as cladding for fuel elements cooled by pressurized water. Such consideration also justifies possible selection of pressure bonding as the method for cladding uranium with Zircaloy in preference to the extrusion process. Obviously, a plant producing Zircaloy-clad tubes by pressure bonding would require little change to fabricate aluminum-clad elements if they were subsequently requested.

CONCLUSIONS

1. In a plant producing an annual supply of 5000 Zircaloy-clad uranium-metal tubes for a 3500-Mw reactor system, a pressure-bonding process should produce tubes more economically than the extrusion process. Exclusive of the cost of the uranium-metal tube, cladding by pressure-bonding costs $2.86 per pound of uranium charged to the reactor compared with $6.17 for the coextrusion.

2. In a plant producing an annual supply of 37,500 Zircaloy-clad uranium tubes for a 25,000-Mw system, the pressure-bonding process appears cheaper than extrusion cladding: $1.45 vs $2.12 per pound of uranium charged to the reactor.

3. In a plant producing an annual supply of 125,000 Zircaloy-clad uranium tubes for a 100,000-Mw system, the extrusion process appears to be slightly more economical than pressure bonding: $1.22 vs $1.26 per pound of uranium charged to the reactor. This difference is too small to be significant.

4. In plants producing aluminum-clad tubes by the pressure-bonding process, the cost per pound of uranium charged to the reactor (exclusive of the uranium-metal tube cost) is $2.32, $0.90, and $0.74 for the annual requirements of 3500-, 25,000-, and 100,000-Mw systems, respectively. These costs are significantly less than the cost of the Zircaloy-clad tubes, mainly because of the lower cost of aluminum.

5. Zircaloy-clad uranium tubes, especially those for 25,000- and 100,000-Mw systems, can be fabricated economically by either an extrusion process or by pressure bonding. Aluminum-clad tubes, which have long-range possibilities for significant cost decreases, can best be fabricated by pressure bonding. Careful consideration should, therefore, be given to producing Zircaloy-clad uranium tubes by the pressure-bonding process in preference to coextrusion, because in the future such plants may be converted to fabricating aluminum-clad uranium tubes without drastic changes.

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APPENDIX A

Process Description and Manpower Requirements for Cladding Uranium with Zircaloy by a Coextrusion Process

APPENDIX A

Extrusion Cladding of Uranium with Zircaloy-2 — Manpower Requirements

Task	3500 Mw (4 billets/day)		25,000 Mw (30 billets/day)		100,000 Mw (100 billets/day)	
	Number of Shifts	Man Days	Number of Shifts	Man Days	Number of Shifts	Man Days
Receive and inspect billet components (Zircaloy, uranium and steel)	1	1	1	2	3	9
Clean all components (degrease, acid pickle, water rinse, air dry)	1	1	1	1	2	4
Assemble and leak detect billets						
Weld steel nose plug to can			1	2	1	2
Weld steel evacuation tube to rear plug	1	2	1	2	1	2
Assemble			1	2	1	2
Weld rear plug to can			1	2	1	2
Leak detect			1	2	1	2
Evacuate and seal billets						
Evacuate at 200°C to $<5\mu$	1	1	1	2	1	2
Forge stem closed			1	2	1	2
Weld stem			1	1	1	2
Preheat billets at 600°C for 4 hr	1	1	1	1	3	6
Extrude billets	1	1	1	4	3	12

APPENDIX A (continued)

Task	3500 Mw (4 billets/day)		25,000 Mw (30 billets/day)		100,000 Mw (100 billets/day)	
	Number of Shifts	Man Days	Number of Shifts	Man Days	Number of Shifts	Man Days
Slit tubes to length and separate croppings	1	1	1	3	2	4
Remove steel jackets by pickling	1	1	3	5	3	9
Inspect surface and dimensions						
Go No-Go gages	1	2	1	3	2	4
Zyglo inspection	2	4	3	14	3	30
Prepare tube ends						
Chemically mill uranium ends	1	2	2	8	3	15
Rinse in H_2O and air dry						
Assemble and weld end closures	1	1	3	3	3	12
Inspect tubes						
Ultrasonic for bonds	1	3	3	9	3	30
Zyglo for end closures	1	3	3	6	3	15
Attach Zircaloy fins	1	3	3	9	3	21
Autoclave tubes	1	1	3	9	3	27
Crate and ship	1	1	1	3	2	4

APPENDIX B

Process Description and Manpower Requirements for Pressure-Bonding Zircaloy to Uranium Tubes

APPENDIX B1

Process Description and Manpower Requirements for Pressure-Bonding Zircaloy to Uranium

Task	25,000 Mw Daily Production = 150 Tubes (125 nests)		100,000 Mw Daily Production = 500 Tubes (250 nests)	
	Number of Shifts	Man Days	Number of Shifts	Man Days
Inspection	2	3	3	10
Receiving uranium				
Uncrate and place vertical on racks using crane, 20 tubes per rack. Transfer rack to vapor degreaser by crane.	2	3	3	9
Degreasing uranium				
Place vertical in degreaser and degrease in trichloroethylene vapor.	2	2	3	6
Acid cleaning uranium				
Remove from vapor degreaser and place rack of 20 vertical in 50% HNO_3 pickling solution.	2	2	3	6
First water rinse, uranium				
Remove from pickling tank and place rack of 20 vertical in turbulent H_2O.	2	2	3	6

APPENDIX B1 (continued)

Task	25,000 Mw Daily Production = 150 Tubes (125 nests)		100,000 Mw Daily Production = 500 Tubes (250 nests)	
	Number of Shifts	Man Days	Number of Shifts	Man Days
Second water rinse, uranium				
Remove from first rinse tank and place in second rinse tank.	2	2	3	6
Receiving Zircaloy				
Uncrate and place vertical on racks using crane, 20 tubes per rack. Transfer rack to vapor degreaser by crane.	2	2	3	9
Degreasing Zircaloy				
Place vertical in degreaser and degrease in trichloroethylene vapor.	2	2	3	6
Acid cleaning Zircaloy				
Pickle in 48% HNO_3–2% HF.	2	2	3	6
First water rinse, Zircaloy				
Remove from pickling tank and place rack of 20 vertical in turbulent H_2O.	2	2	3	6
Second water rinse, Zircaloy				
Remove from first rinse tank and place in second rinse tank.	2	2	3	6

APPENDIX B1 (continued)

Task	25,000 Mw Daily Production = 150 Tubes (125 nests)		100,000 Mw Daily Production = 500 Tubes (250 nests)	
	Number of Shifts	Man Days	Number of Shifts	Man Days
Assembly of composite tube				
Crane places uranium vertically on conveyor. Place inner and outer Zircaloy tubes over the uranium along with top end cap.	3	9	3	27
Electron-beam weld of top end cap				
Move assembly vertically into electron-beam welder and weld top cap automatically.	3	3	3	12
Electron-beam weld of bottom end cap				
Reverse assembly, move vertically into electron-beam welder, automatically weld bottom end cap, sealing assembly in vacuum.	3	8	3	27
Pressurizing with helium for leak detection				
Move composite tubes by crane vertically into helium purge tank	3	9	3	27
Leak detecting in water				
Remove from pit and transfer vertically into water tank equipped with viewing ports.	3	9	3	12

APPENDIX B1 (continued)

Task	25,000 Mw Daily Production = 150 Tubes (125 nests)		100,000 Mw Daily Production = 500 Tubes (250 nests)	
	Number of Shifts	Man Days	Number of Shifts	Man Days
Welding fins to tube				
Transfer tubes for high-frequency welding of fins to composite assembly.	3	9	3	27
Assembly of tubes into loading fixture				
Move outer tubes into loading fixture and assemble nests by placing inner tube into outer tube and aluminum sleeve over the assemblage.	3	9	3	27
Pressure bonding				
Transfer nests to pressure-bonding autoclaves	3	9	3	18
Pressurizing with helium for leak detection				
Remove from autoclave and place in helium purge pit.	3	9	3	27
Leak detection in water				
Transfer from helium purge tank to water tank equipped with viewing ports. Remove aluminum sleeve.	3	9	3	12

APPENDIX B1 (continued)

Task	25,000 Mw Daily Production = 150 Tubes (125 nests)		100,000 Mw Daily Production = 500 Tubes (250 nests)	
	Number of Shifts	Man Days	Number of Shifts	Man Days
Inspection				
Transfer by crane and place vertically on conveyor. Test outer and inner diameters of nest with go no-go gages.	3	9	3	12
Autoclave testing				
Test in pressurized-water autoclaves	3	6	3	27
Crating and shipping				
Crate on racks and transfer to storage.	3	6	3	12

APPENDIX B2

Process Description and Manpower Requirements for Pressure-Bonding Zircaloy to Uranium

Task	3500 Mw 5000 tubes/year, 20 tubes/day, 10 nests/day Number of Men
Inspection	1
Receiving uranium	
Uncrate, lift with hoist, and transfer to pickling bath.	1
Degreasing uranium	
Place horizontal in vapor degreaser using above hoist.	1
Acid cleaning, uranium	
Remove from vapor degreaser and place horizontal in pickling tank of 50% HNO_3.	1
First water rinse, uranium	
Rinse in turbulent water.	1
Second water rinse, uranium	
Rinse in turbulent water.	1
Receiving Zircaloy	
Uncrate, lift with hoist, and transfer to pickling bath.	1
Degreasing Zircaloy	
Place horizontal in vapor degreaser using above hoist.	1
Acid cleaning, Zircaloy	
Pickle in 48% HNO_3–2% HF.	1
First water rinse, Zircaloy	
Rinse in turbulent water.	1
Second water rinse, Zircaloy	
Rinse in turbulent water.	1

APPENDIX B2 (continued)

Task	3500 Mw 5000 tubes/year, 20 tubes/day, 10 nests/day Number of Men
Assembly of composite tube	
Place uranium tube vertical, slip Zircaloy tubes and top cap on. Transfer by hoist to electron-beam welder.	3
Electron-beam welding of top end cap	1
Electron-beam welding of bottom end cap	
Reverse assembly and weld.	1
Pressurizing with helium for leak detection	
Place in tank and purge with helium.	2
Leak detection in water	
Place horizontally in tank of water and examine for leaks.	2
Assembling tubes into loading fixture	
Move outer tubes into loading fixture and assemble into nests by placing inner tubes into outer tubes and aluminum sleeve over the assemblage.	2
Pressure bonding	
Transfer nests to pressure-bonding autoclave.	2
Pressurizing with helium for leak detection	
Remove from autoclave and place in helium purge tank.	2
Leak detection in water	
Remove aluminum sleeves and place in water tank for detection of leaks.	2
Inspection	
Test diameters with go no-go gages.	2

APPENDIX B2 (continued)

Task	3500 Mw 5000 tubes/year, 20 tubes/day, 10 nests/day
	Number of Men
Autoclave testing	
Test in pressurized water.	2
Crating and shipping	
Crate in racks and transfer to storage.	2

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