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FUEL CYCLE COSTS FOR A PLUTONIUM RECYCLE SYSTEM

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CHEMICAL TECHNOLOGY DIVISION

METALS AND CERAMICS DIVISION

OAK RIDGE GASEOUS DIFFUSION PLANT

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ABSTRACT

The costs of the chemical and metallurgical steps in the fuel cycle for large desalination reactors are estimated. Both capital and operating costs are presented at varying plant capacities for a Zircaloy-clad fuel element containing depleted uranium and recycled plutonium as the oxides: UO_2--0.5% PuO_2. The chemical steps are reported at throughputs of 1, 10, and 30 short tons of uranium per day; and the metallurgical or fabrication step at throughputs of 1, 3, 5, and 10 tons per day, as specified by the Office of Science and Technology.

The total estimated cost of all the chemical and metallurgical steps drops from $51.17 to $14.68 per kilogram of uranium as the cycle throughput is increased from 1 to 10 tons of uranium per day. All steps decrease in cost as plant capacity is increased, with the most impressive decrease in the irradiated assembly processing step, which decreases from $26.19 to $4.10 to $2.07 per kilogram of uranium as throughput is changed from 1 to 10 to 30 tons of uranium per day.

The contained data in conjunction with previous studies of a natural uranium fuel cycle and results of a current reactor optimization study will yield complete fuel cycle costs and plutonium value in recycle.

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1. SUMMARY

As part of a continuing study of fuel cycle cost for large desalination[1] reactors, the costs of the chemical and metallurgical steps in a recycle plutonium system are estimated. Earlier studies[2] estimated the cost for the natural uranium cycle both with and without processing of the irradiated fuel assemblies.

The fuel assembly, except for the chemical composition of the core, was a duplicate of the assembly considered earlier,[1] which is shown on Fig. 1. The core is composed of depleted uranium and recycled plutonium as a mixture of UO_2--0.5% PuO_2 (solid solution).

Both the capital and operating costs are estimated and reported by process step. The chemical steps are reported at throughputs of 1, 10, and 30 short tons of uranium per day. The metallurgical or fuel assembly fabrication step is reported at throughputs of 1, 3, 5, and 10 tons per day. The throughputs studied were specified by the Office of Science and Technology (OST). The total estimated costs are summarized in Table 1.

Table 1. Total Costs Estimated for Steps in a Plutonium Recycle System

Process Step	Costs ($/kg U) at a Throughput of:		
	1 ton U/day	10 tons U/day	30 tons U/day
UF_6 to U_3O_8	0.78	0.25	0.16
U_3O_8 to UO_3	2.08	0.54	0.38
UO_3 + Pu $(NO_3)_3$ to UO_2-PuO_2	3.77	1.19	0.77
Assembly fabrication	18.35	8.60	-
Irradiated assembly processing	26.19	4.10	2.07

The cost penalty in the fabrication step for the presence of recycle plutonium vs natural uranium is 4.65 and 1.55 $/kg of uranium at 1 and 10 tons of uranium per day, respectively. At 10 tons of uranium per day, all the chemical processing steps for the recycle case cost $1.36/kg of uranium more than for the natural uranium case. However, these cost penalties are counterbalanced by the difference between the costs of ore concentrate and the cost of optimized diffusion plant tails.

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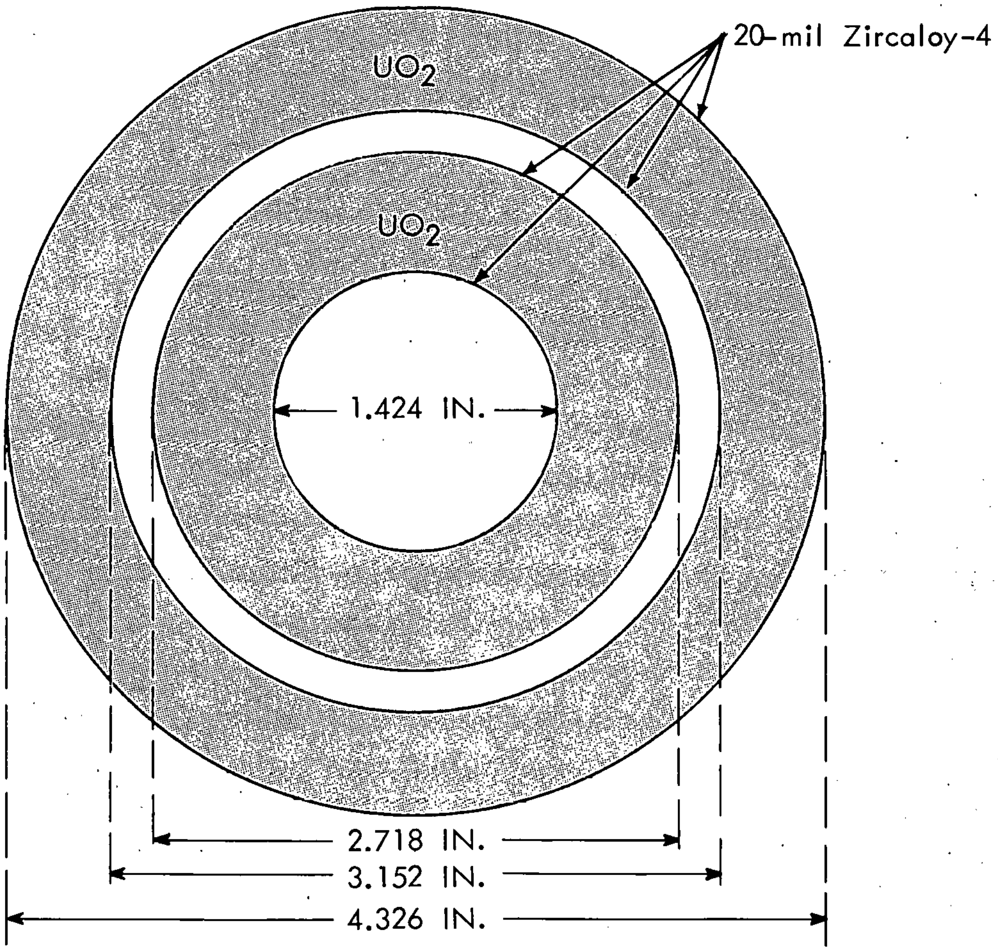

Length = 72 In.

Loading = 18.92 kg U per ft of length, 114 kg U per element

U/Zr = ratio = about 10

Fig. 1. Reference Fuel Assembly Design.

2. INTRODUCTION

Recent studies indicated that large nuclear reactors with good neutron economy may produce heat at a cost low enough to make the production of fresh water from sea water by distillation attractive for most uses. Increase in the size of the various units in a reactor-distillation-fuel-cycle complex was a major factor in the favorable economics.

The first complex studied was based on a reactor moderated by heavy water, cooled by light water, and fueled with natural uranium. The fuel assembly is shown in Fig. 1. The fuel cycle portion of this complex exhibited reduced costs for all the required steps as the production requirement was increased. The reduction in the cost for recovering the plutonium from the irradiated fuel, shown in Table 2, was particularly impressive. In this first study, 4 g of plutonium per kilogram of uranium were produced in the fuel during the irradiation period. At $6.70/g, the value of these 4 g of plutonium approached the estimated total fuel cycle cost of $31.86 and $27.11/kg of uranium (including 10% contingency and $5 per per cent of U_3O_8) at throughputs of 10 and 30 tons of uranium per day, respectively.

Table 2. Processing Costs for the Natural Uranium Case

Plant Throughput (tons U/day)	$/kg U			
	Amortization	Operating	Plutonium Loss	Total
1	13.01	12.26	0.07[a]	25.34
10	1.88	1.98	0.07	3.93
30	0.76	1.18	0.07	2.01

[a] 1/4% loss, with plutonium valued at $6.70 per gram.

The production of the large amounts of plutonium involved in a complex requiring plant throughputs of 10 or more tons of natural uranium per day may adversely affect the value of plutonium. To determine the upper limit for the cost of a natural uranium cycle, a second study was made. In this second study, the irradiated fuel was permanently stored, rather than processed in what is called a "throwaway" cycle. The plutonium generated in the reactor is assumed to have no value. The fuel cycle costs at 10 and 30 tons of natural uranium per day are estimated to be $24.96 and $22.75 per kilogram of uranium, respectively.

To help provide an estimate of the minimum worth of plutonium when large quantities are generated, this third study was made. Once again the fuel is assigned the shape and cladding shown in Fig. 1, but the natural uranium UO_2 is replaced by a mixture of plutonium and depleted uranium oxides: UO_2--0.5% PuO_2. The uranium comes from diffusion plant tails, and the plutonium is recycled from the irradiated fuel processing plant. The recycled plutonium is assumed to contain 30 wt % Pu^{240} and 15 wt % Pu^{242}. The fuel is assumed to contain 5 g of plutonium per kilogram of uranium entering the reactor, and 6 g of plutonium per kilogram of uranium leaving the reactor.

The required fuel cycle for this plutonium recycle case is shown schematically in Fig. 2. Each block on this flowsheet is a process step housed in a single building. The process steps, each estimated and discussed separately below, are:

1. conversion of UF_6 from diffusion plant tails to U_3O_8;
2. purification of the U_3O_8 from step 1 above and conversion to UO_3;
3. preparation of reactor grade UO_2--0.5% PuO_2 from this UO_3 and from the Pu $(NO_3)_3$ recycled from the irradiated fuel processing plant (step 5);
4. fabrication of the fuel assemblies from the mixed oxides and purchased cladding; and
5. chemical processing of the irradiated fuel for the recovery of the plutonium.

"Ground rules" and estimating methods used in the earlier studies were used. The ground rules were: capital charges at 7.7%/yr, inventory charges at 5.5%/yr, 85% on-stream for each plant in the fuel cycle, and

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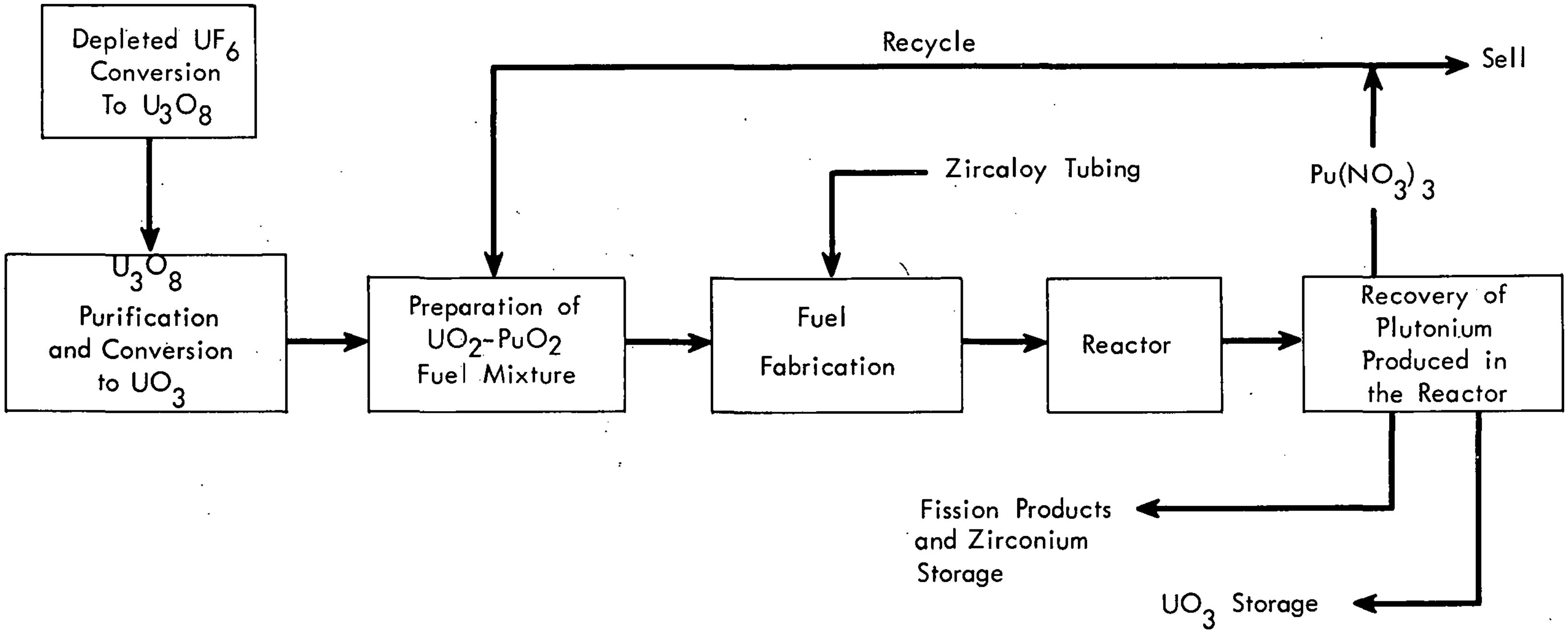

Fig. 2. Schematic Diagram of the UO_2--0.5% PuO_2 Fuel Cycle.

consistent unit material costs. Capital costs were factored from equipment details and process building requirements. Operating costs were determined from labor, materials (including utilities), and overhead.

This study involved several groups of people, including members of the Chemical Technology and Metals and Ceramics Divisions at ORNL and of the Oak Ridge Gaseous Diffusion Plant (ORGDP). In addition, the allowed expenditure of time and money was limited. For this reason, we make no claim for great accuracy of the estimated costs for any one part or even for the whole fuel cycle at one throughput. However, all involved in the study cooperated closely, and all the throughputs received the same attention. Hence, we feel that the decrease in costs with increased throughputs are realistically estimated.

Work is in progress in the Reactor Division to optimize the reactor. Upon completion of the optimization, costs can be calculated for items such as burnup and inventory in order to complete the total fuel cycle and yield values for recycle plutonium at various throughputs.

3. CONVERSION OF UF_6 FROM DIFFUSION PLANT TAILS TO U_3O_8

Capital and the operating costs are estimated[3] for plants to convert UF_6 cascade tails to U_3O_8 at 1, 10, and 30 short tons of uranium per day. A two-step process is used. Uranium hexafluoride is contacted with steam at 500°F in a fluid-bed reactor to form a fine, dense, freeflowing UO_2F_2 powder. The UO_2F_2 is converted to U_3O_8 by pyrohydrolysis in a propane-oxygen flame.

The flowsheet and building layout for the plant capable of handling 30 tons of uranium per day are shown in Figs. 3 and 4, respectively. The capital-cost estimates for the required plants to produce 1, 10, and 30 tons of uranium per day are shown in Table 3. The operating-cost estimate is summarized in Table 4.

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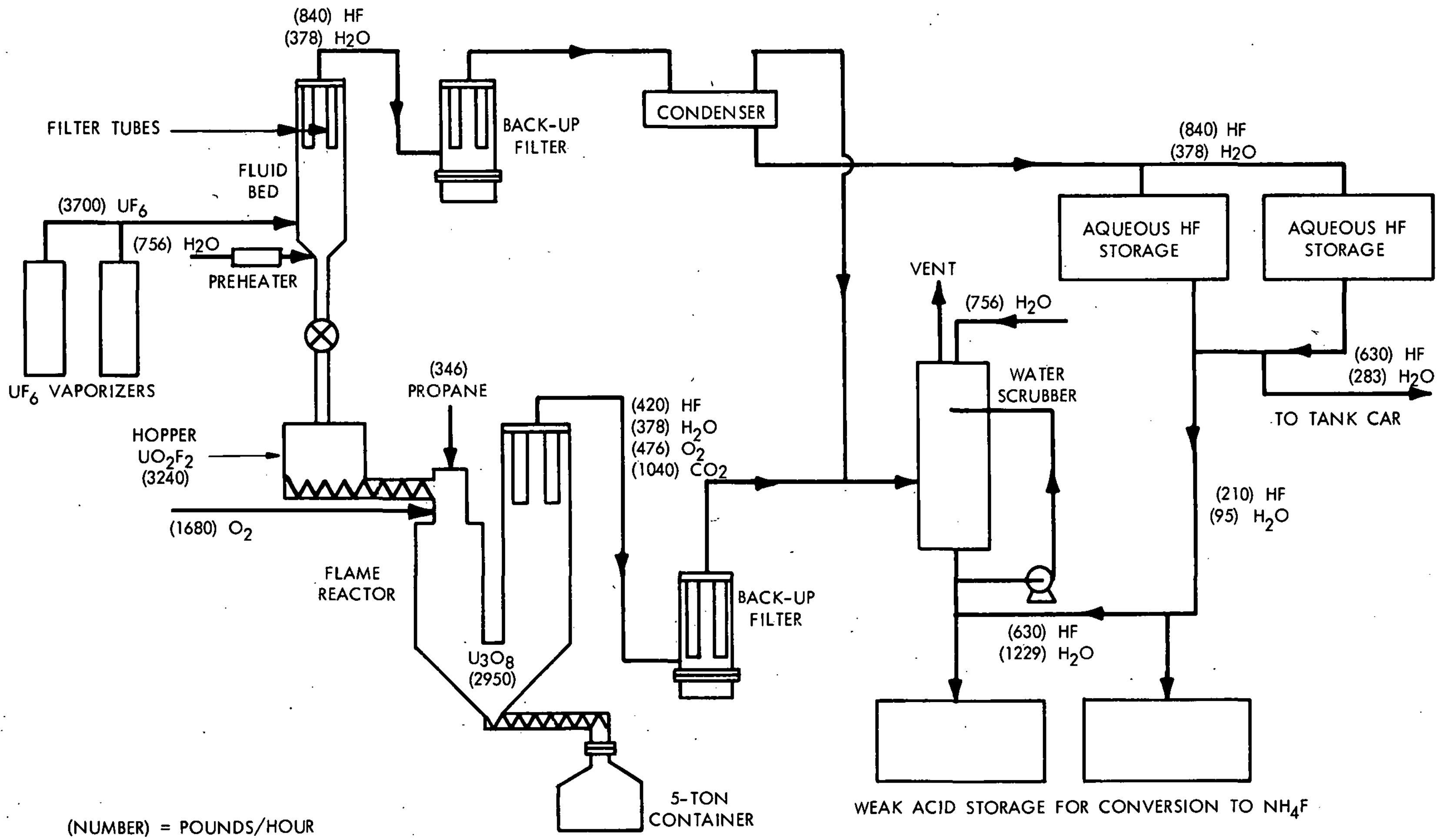

Fig. 3. Conversion of UF_6 to U_3O_8. Schematic flowsheet rate: 30 tons of uranium per day.

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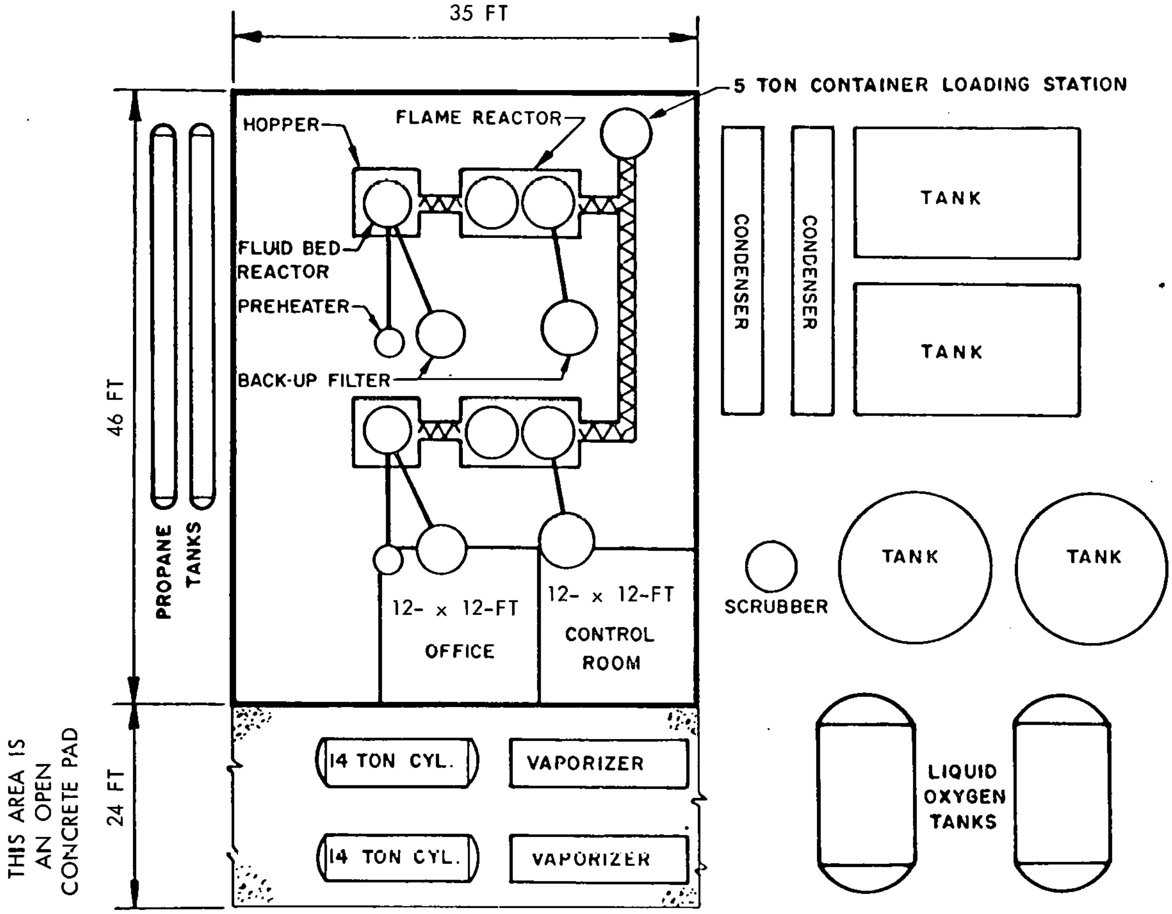

Fig. 4. Building and Layout of Equipment for a UF_6 to UO_3: 30 Tons of Uranium per Day.

Table 3. Capital Cost Estimate (Dollars) for a Plant to Convert UF_6 to U_3O_8

Item	1 and 10 tons U/day	1 ton U/day,	10 tons U/day,	30 tons U/day	
	No. of Components Required	Cost ($)	Cost ($)	No. of Components Required	Cost ($)
UF_6 vaporizer	2	5,000	65,000	2	65,000
Fluid bed	1	5,000	28,000	2	60,000
Fluid-bed back-up filter	1	1,000	4,500	2	10,000
Condenser	1	-	5,000	2	15,000
Steam preheater	1	500	2,000	2	4,000
UO_2F_2 hopper	1	2,000	4,500	2	10,000
Flame reactor	1	4,000	18,000	2	40,000
Flame reactor cooler and filter	1	4,000	18,000	2	40,000
Flame reactor back-up filter	1	1,000	4,500	2	10,000
U_3O_8 hopper	1	3,000	7,000	2	15,000
Product conveyor	1	2,000	8,000	1	10,000
Water scrubber	1	-	7,000	2	20,000
80% HF tank	1	2,000	10,000	2	20,000
25% HF tank	1	3,000	12,000	2	24,000
Portable U_3O_8 refeed system	1	2,000	5,000	1	5,000
Propane storage tank	1	2,000	10,000	1	20,000
Liquid-oxygen storage tank	1	20,000	65,000	2	130,000
Oxygen vaporizer	1	5,000	10,000	2	20,000
Filter tube	150[a] 18[b]	2,000	13,000	440	40,000
Total Equipment Cost		63,500	296,500		558,000
Installed equipment cost (150%)		95,500	445,000		837,000
Piping (50%)		48,000	223,000		419,000
Instruments (25%)		24,000	89,000		126,000
Electrical (50 kw)		5,000	30,000		50,000
Building cost		15,000	55,000		90,000
Total Physical Cost		187,500	842,000		1,522,000
Engineering and construction supervision (60%)		113,000	505,000		913,000
Contingency (35%)		66,000	295,000		533,000
Start-up cost		20,000	100,000		200,000
Cylinder transport truck and forklift		-	75,000		75,000
Total		386,500	1,817,000		3,243,000

[a]150 for 10 tons U/day.

[b]18 for 1 ton U/day.

Table 4. Operating Cost Estimate for a Plant to Convert UF_6 to U_3O_8

	30 Tons U/day	10 Tons U/day	1 Ton U/day
Operating labor, $/yr	85,000	59,000	33,000
Supervisory labor, $/yr	24,000	16,000	12,000
Maintenance labor, $/yr	134,000	71,000	17,000
Other labor, $/yr	47,000	29,000	12,000
Total labor, $/yr	290,000	175,000	74,000
Overhead, $/yr	363,000	219,000	93,000
Maintenance materials, $/yr	75,000	40,000	10,000
Direct materials, $/yr	390,000	130,000	13,000
Worked materials, $/yr	8,000	3,000	500
Total operating cost, $/yr	1,126,000	567,000	190,500
Unit operating cost, cents/kg of uranium	13.31	20.13	67.54
Amortization, cents/kg of uranium	2.95	4.95	10.56
Total unit cost, cents/kg of uranium	16.26	25.08	78.10

4. PREPARATION OF REACTOR GRADE UO_3

The U_3O_8 produced in the above UF_6-to-U_3O_8 conversion must be purified of fluorine and possible other contaminants, and its physical characteristics must be suitable for conversion to reactor feed material. This is done by solvent extraction. Steam denitration of the extraction product stream yields a product with the desired surface area and density. A schematic flowsheet of the required plant is shown in Fig. 5.

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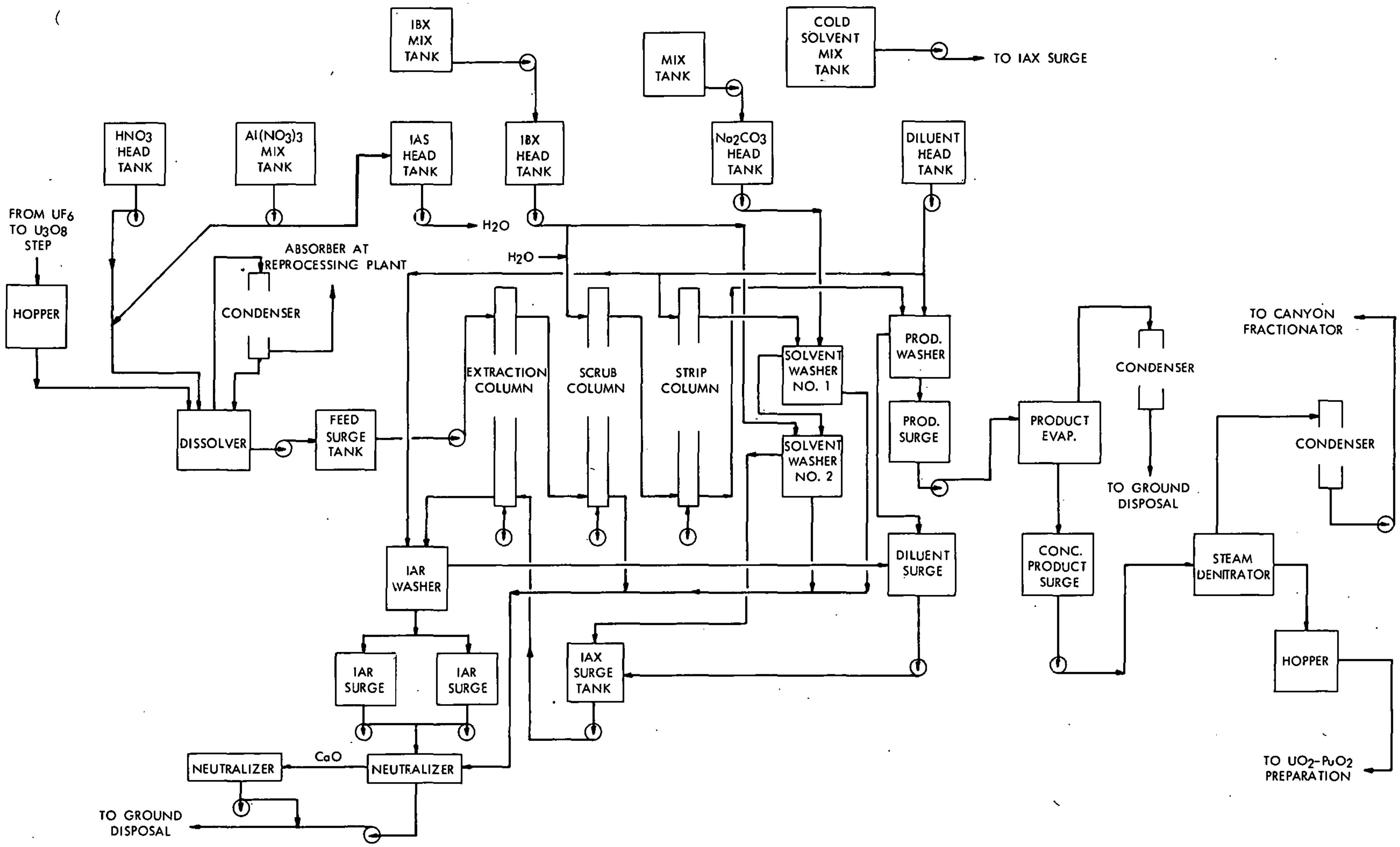

Fig. 5. Preparation of Reactor Grade UO_3 from U_3O_8.

The purification of uranium by solvent extraction is widely used. The U_3O_8 is dissolved in nitric acid, and sufficient aluminum, as aluminum nitrate, is added to complex the fluoride. The uranium is extracted with 30% tributyl phosphate and returned to an aqueous nitrate solution by a water strip. The stripped product is concentrated by evaporation and converted to UO_3 by steam denitration.

Laboratory tests by R. H. Rainey and L. M. Ferris of ORNL show that the U_3O_8 product from ORGDP Pilot Plant runs dissolves readily in nitric acid, and that the resulting solution has satisfactory distribution coefficients at flowsheet conditions. Also, steam denitration has been used in the pilot-plant preparation of ThO_2 for the "sol-gel" process.

Equipment required for the U_3O_8-to-pure-UO_3 is sized for plant throughputs of 1, 10, and 30 tons of uranium per day. This information is incorporated in Table 5, which presents the estimates of the capital costs. The buildings for the process equipment are shown in Figs. 6, 7, and 8. Capital costs estimated for the 1-, 10-, and 30-tons-of-uranium-per-day plants are 56.3, 14.7, and 8.6 cents per kilogram of uranium, respectively.

The estimated unit costs, summarized in Table 6, are 152.2 39.4, and 29.7 cents per kilogram of uranium for the 1-, 10-, and 30-tons-of-uranium-per-day plants, respectively. In the cost estimates, the following assumptions are used:

1. Labor: \$7500/man year; process operators at 10, 15, and 25 men for the 1-, 10-, and 30-tons-per-day plants, respectively; maintenance labor at 6, 8, and 10 men for the 1-, 10-, and 30-ton-per-day plants; and other labor at 25% of the sum of process and maintenance labor.

2. Utilities: 1.3 times the sum of steam and electricity costs; 25.8 lb steam at 20¢/1000 lb required per pound of uranium; 3.9, 2.9, and 2.4 kwhr electricity per pound of uranium at 4 mills/kwhr for the 1-, 10-, and 30-ton-per-day plants.

3. Materials: Maintenance materials at 150% of the cost of maintenance labor; 0.66 lb of 60% HNO_3 per pound of uranium, at 4¢/lb for the acid; one mole of $Al(NO_3)_3$ per mole of fluoride, with

Table 5. Estimates of the Capital Costs for a Plant to Prepare Reactor Grade UO_3

Item No.	Description	1 ton/day Size	1 ton/day Purchased Cost	10 tons/day Size	10 tons/day Purchased Cost	30 tons/day Size	30 tons/day Purchased Cost
1	HNO_3 head tank, main floor	400 gal, 3-1/2 ft diam x 5-1/2 in. high, SS	$ 3,500	4000 gal, 8 ft diam x 10-1/2 ft high, SS	$ 9,000	8000 gal, 10 ft diam x 13-1/2 ft high, SS	$ 12,000
2	$Al(NO_3)_3$ mix tank, main floor	Same as above, + agitator and hopper	5,000	Same as above, + agitator and hopper	11,700	Same as above, + agitator and hopper	15,500
3	IAS head tank	400 gal, 3-1/2 ft diam (see 1) x 5-1/2 in. high, SS	3,500	400 gal (see 1), 8 ft diam x 10-1/2 ft high, SS	9,000	800 gal, (see 1), 10 ft diam x 13-1/2 ft high, SS	12,000
4	IBX mix tank	50 gal, 1-1/2 in. diam x 4 ft high, SS	1,500	500 gal, 3-1/2 ft diam x 7 ft high	3,800	1000 gal, 5 ft diam x 7 ft high	5,000
5	IBX head tank	Same as 4	1,500	Same as 4	3,800	Same as 4	5,000
6	Na_2CO_3 mix tank, main floor	400 gal, 3-1/2 ft diam x 5-1/2 ft high, + agitator and hopper; see 2	5,000	4000 gal, 8 ft diam x 10-1/2 ft high, + agitator and hopper; see 2	11,700	8000 gal, 10 ft diam x 13-1/2 ft high, + agitator and hopper; see 2	15,500
7	Na_2CO_3 head tank	400 gal, 3-1/2 ft diam x 5-1/2 ft high; see 1	3,500	4000 gal, 8 ft diam x 10-1/2 ft high; see 1	9,000	8000 gal, 10 ft diam x 13-1/2 ft high; see 1	12,000
8	Diluent head tank	50 gal, 1-1/2 ft diam x 4 ft high	1,500	150 gal, 2-1/2 ft diam x 4 ft high	2,400	400 gal, 3-2/3 ft diam x 5 ft high	3,500
9	Cold solvent mix tank	80 gal, 2 ft diam x 3-1/2 ft high	1,900	250 gal, 3 ft diam x 5 ft high	2,800	250 gal, 3 ft diam x 5 ft high	2,800
10	Dissolver, main floor	1200 gal, 4-2/3 ft diam x 9-1/3 ft high, 40 ft^2 coil; agitated	8,300	12,000 gal, 10 ft diam x 20 ft high, 400 ft^2 coil; agitated	28,500	2-12,000 gal, 2-400 ft^2 coil; 2-agitated	57,000
10A	Hopper - feed to dissolver		500		1,000		2,000
11	Dissolver condenser	40 ft^2, 6-5/8 in. diam x 9 ft long	1,600	400 ft^2, 14 in. diam x 14 ft long	4,400	2-400 ft^2	8,800
12	Feed surge tank	1200 gal, 4-2/3 ft diam x 9-1/3 ft; 40 ft^2 coil	5,600	12,000 gal, 10 ft diam x 20 ft high; 400 ft^2 coil	15,000	2-12,000 gal	30,000
13	IAR surge tank	2-400 gal; see 1	7,000	2-4000 gal; see 1	18,000	2-8,000 gal; see 1	24,000
14	Neutralizers; located on main floor. Requires either a platform or feed from 2nd floor	2-600 gal, 6 ft diam x 6-1/2 ft high, agitated; hopper for addition of line	11,000	2-6000 gal, 10 ft diam x 10-1/2 ft high, agitated; hopper for addition of line	25,900	2-12,000 gal, 12 ft diam x 14 ft high, agitated; hopper for addition of line	39,500
15	Product evaporator, main floor	2-3/4 ft diam x 8 ft high, 200 ft^2 heating surface	56,000	8-1/2 ft diam x 12 ft high, 2000 ft^2 heating surface	184,000	14-1/2 ft diam x 18 ft high, 6000 ft^2 heating surface	336,000
16	Product surge tank, main floor	100 gal, 2-1/2 ft diam x 5 ft high	2,100	1000 gal, 5 ft diam x 7 ft high	5,000	3000 gal, 7-1/2 ft diam x 9 ft high	6,900
17	Concentrated product surge tank	100 gal, 2-1/4 ft diam x 5 ft high	2,100	1000 gal, 5 ft diam x 7 ft high	5,000	3000 gal, 7-1/2 ft diam x 9 ft high	6,900
18	Evaporator condenser	100 ft^2, 10-3/4 in. diam x 10 ft long	2,000	1000 ft^2, 20 in. diam x 18 ft long	9,000	3000 ft^2, 33 in. diam x 20 ft long	21,000
19	Steam denitrator: rotating drum 6 RPM; batch loaded and discharged steam purged during denitration electric furnace heated; vac system + lights; vac system materials transfer	3 ft diam x 9 ft long, 80 kw heat, peripheral area = 85 ft^2 at $300/$ft^2$ factor, 6-over direct rotary vac system	27,000	6 ft diam x 24 ft long, 800 kw heat, peripheral area = 452 ft^2 at $200/$ft^2$, vac system	110,400	3-6 ft diam x 24 ft long, 800 kw heat each, peripheral area = 452 ft^2, vac system	331,200
20	Denitration condenser	150 ft^2, 10-3/4 in. diam x 12 ft long	2,300	1500 ft^2, 24 in. diam x 18 ft long	12,000	4500 ft^2, 42 in. diam x 20 ft long	27,000
21A	Extraction columns pulse plate section 25 ft high, 1/8 in. holes, 23% free area, 2 in. spacing, 151 plates, main floor	6 in. diam pulsed section, 12 in. diam ends, overall length 32 ft; $30/in. diam plate	27,200	20 in. diam pulsed section, 3 ft diam ends, overall length 34 ft	90,600	36 in. diam pulsed section 5 ft diam ends, overall length 36 ft	163,000
21B	Scrub column, main floor	Same as 21A	27,200	Same as 21A	90,600	Same as 21A	163,000
21C	Strip column, main floor	Same as 21A	27,200	Same as 21A	90,600	Same as 21A	163,000
22	Pulse pumps, main floor	3-2 HP	7,500	3-50 HP special	45,000	3-75 HP special	60,000

Table 5. Continued

Item No.	Description	1 ton/day Size	1 ton/day Purchased Cost	10 tons/day Size	10 tons/day Purchased Cost	30 tons/day Size	30 tons/day Purchased Cost
23	Solvent washer, main floor	2-200 gal, 2-3/4 ft diam x 4-1/2 ft high; each with Turbomixer, 8 hp	$ 8,400	2-2000 gal, 6-1/2 ft diam x 8 ft high; each with Turbomixer, 20 hp	$ 16,400	2-6000 gal, 10 ft diam x 10 ft high; each with Turbomixer, 2-25 hp	$ 28,800
24	IAX solvent surge, main floor	800 gal, 4-1/2 ft diam x 6-3/4 ft high	4,500	8000 gal, 4-1/2 ft diam x x 11 ft high	12,000	16,000 gal, 13 ft diam x 16 ft high	17,000
25	IAR washer, main floor	50 gal, 1-3/4 ft diam x 2-3/4 ft high with Turbomixer, 5 hp	2,700	500 gal, 4-3/4 ft diam x 6 ft high with Turbomixer, 10 hp	5,500	1500 gal, 6 ft diam x 7 ft high, with Turbomixer, 18 hp	8,200
26	Product washer, main floor	100 gal, 2-1/2 ft diam x 5 ft high, with Turbomixer, 7 hp	3,500	1000 gal, 5 ft diam x 7 ft ft high, with Turbomixer, 14 hp	6,800	3000 gal, 7-1/2 ft diam x 9-1/4 ft high, with Turbomixer, 25 hp	12,400
27	Dilute surges, main floor	50 gal, 1-1/2 ft diam x 4 ft high	1,500	150 gal, 2-1/2 ft diam x 4 ft high	2,400	400 gal, 3-2/3 ft diam x 5 ft high	3,500
28	Metering pumps, misc. sizes	12 units	12,000	12 units	18,000	12 units	24,000
29	Centrifugal pumps, misc. sizes	13 units, ave 5 hp	9,100	13 units, ave 25 hp	16,900	13 units, ave 30 hp	22,100
30	Bin to hold material from steam denitrator		1,200		5,000	3 required	15,000
31	Solids pneumatic conveying system		10,000		20,000	3 required	60,000
32 33	Hoppers, movable to bring U_3O_8 to facility-inc truck Hoppers, movable to move UO_3 to next facility-inc truck	6-1 ton	11,800	12-5 ton	22,000	35-5 ton	45,000
34	Seepage pits size	1/2 acre	2,500	5 acres	25,000	15 acres	75,000
35	Pipe, valves, fittings, process		213,780		630,400		1,176,900
36	Instruments		36,000		105,000		196,000
37	Included in building cost: service lines						
38	Insulation		10,000		25,000		50,000
39	Process electrical		10,000		25,000		50,000
40	HNO_3 and solvent storage tank		15,000		25,000		30,000
	Building process area	29 ft x 77 ft = 2233 ft^2		134 ft x 42 ft = 5628 ft^2		152 ft x 66 ft = 10,032 ft^2	
	Process volume	50 x 2233 = 111,650 ft^3		52 x 5628 = 292,656 ft^3		54 x 10,032 = 541,728 ft^3	
	Building cost: normal services		402,000		878,000		1,300,000
	15-ton crane		20,000		25,000		30,000
	Subtotal No. 1		$1,028,580		$2,661,600		$4,644,500
	Installation labor		60,340		175,500		327,900
	Subtotal No. 2		$1,088,920		$2,837,100		$4,972,400
	Yard improvements 15% Subtotal No. 2		163,300		425,600		745,900
	Subtotal No. 3		$1,252,200		$3,262,700		$5,718,300
	Construction overhead 30% Subtotal No. 3		375,600		978,800		1,715,500
	Subtotal No. 4		$1,627,800		$4,241,500		$7,433,800
	AE 15% Subtotal No. 4		244,200		636,200		1,115,100
	Subtotal No. 5		$1,872,000		$4,877,700		$8,548,900
	Contingency 10% Subtotal No. 5		187,000		487,700		855,000
	TOTAL		$2,059,000		$5,365,000		$9,404,000
	Cents/kg of uranium		56.3		14.7		8.6

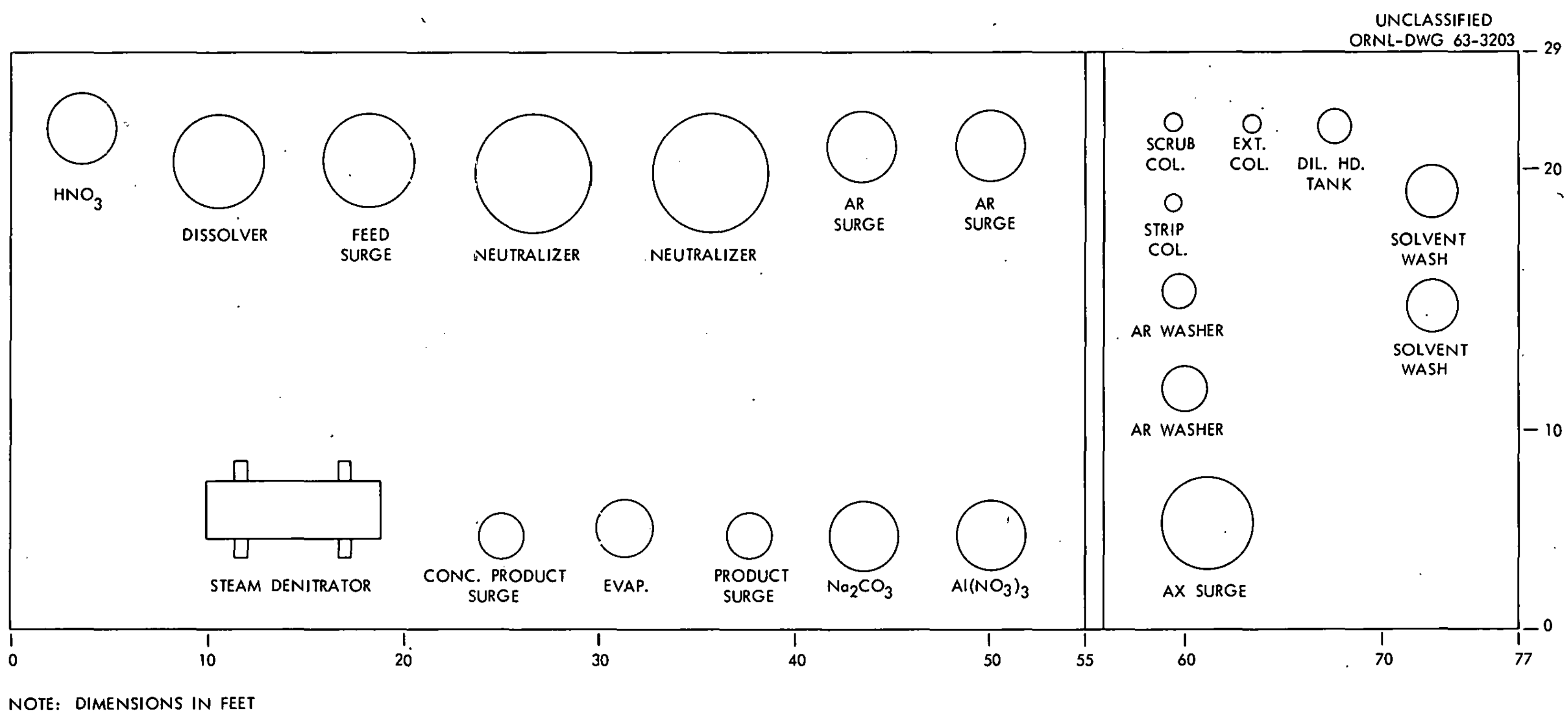

Fig. 6. Plant Layout for Conversion of U_3O_8 to UO_3 at 1 Ton of Uranium per Day.

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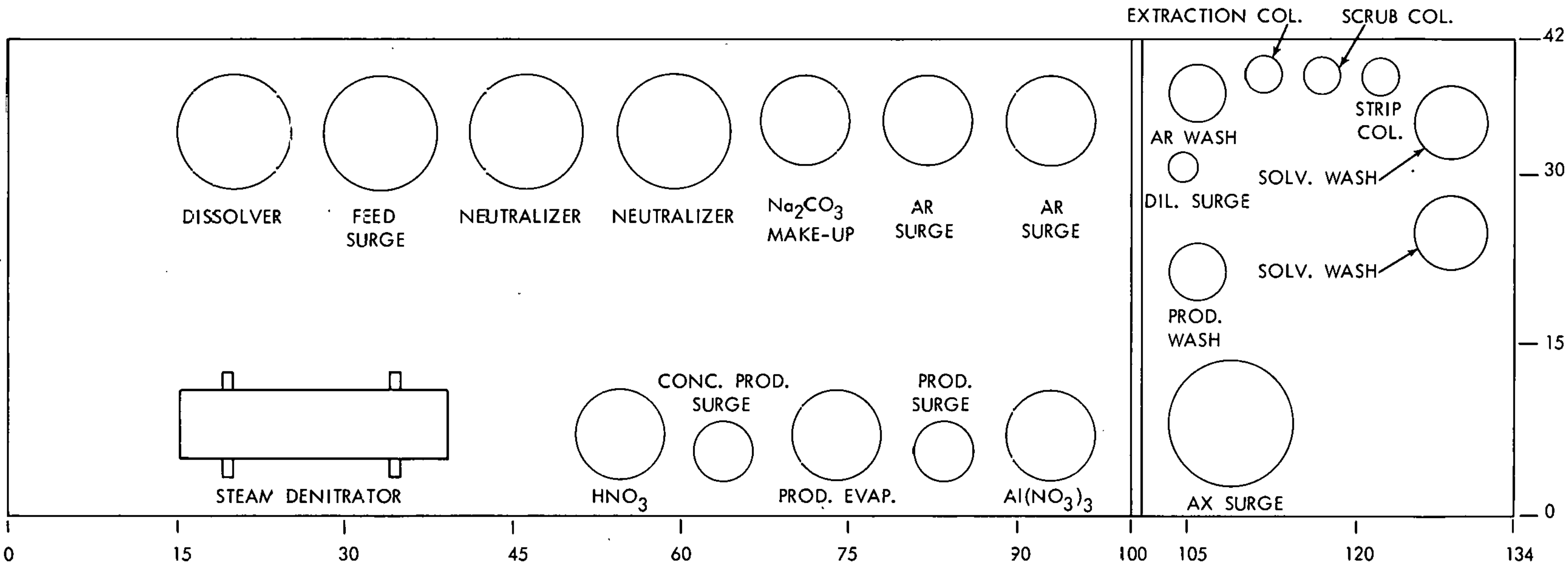

NOTE: DIMENSIONS IN FEET

Fig. 7. Plant Layout for Conversion of U_3O_8 to UO_3 at 10 Tons of Uranium per Day.

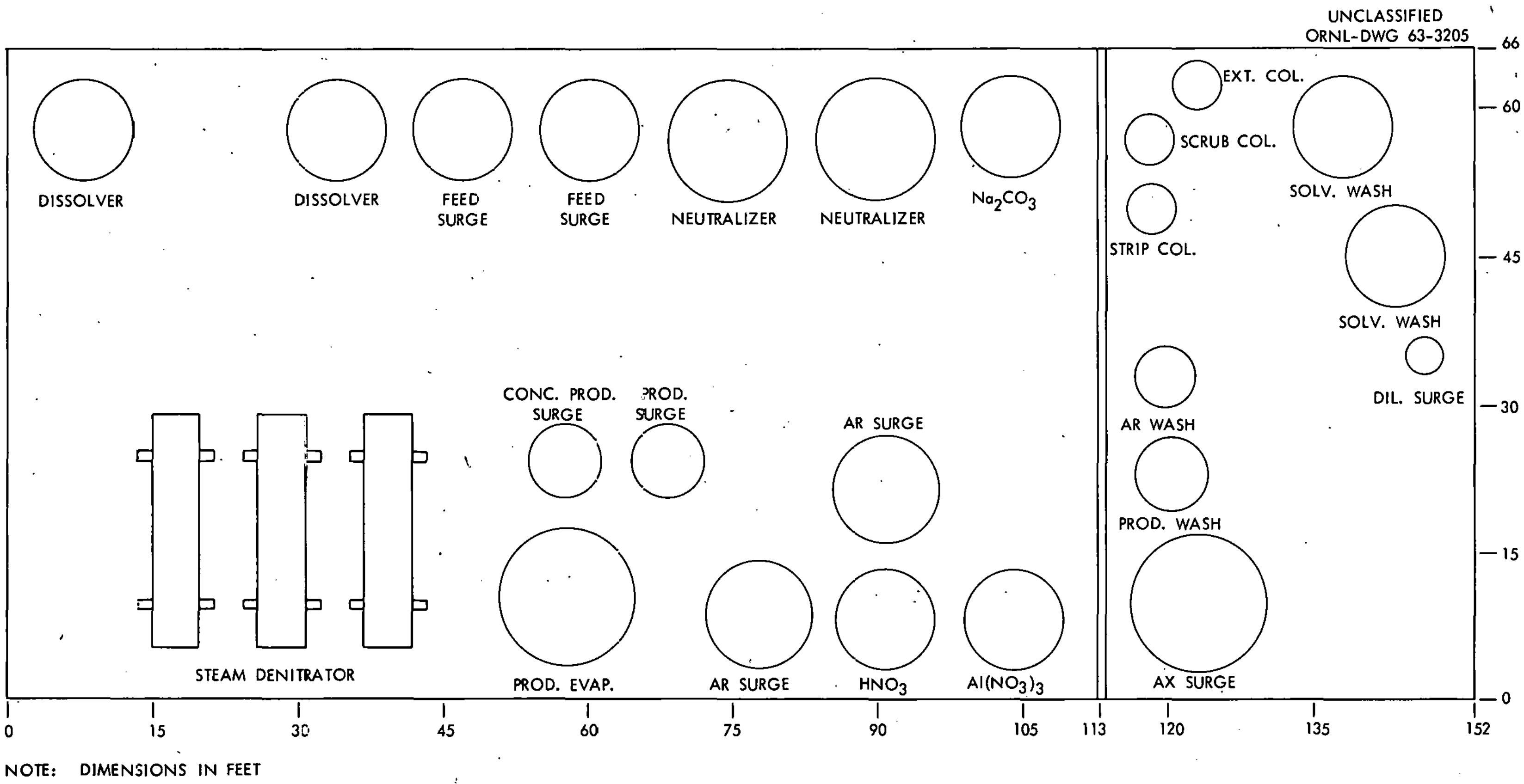

Fig. 8. Plant Layout for Conversion of U_3O_8 to UO_3 at 30 Tons of Uranium per Day.

fluoride equal to 1% of the uranium, at 12¢/lb as solid for the $Al(NO_3)_3$; 0.3% solvent loss to solvent extraction aqueous raffinate, 30% of solvent as tributyl phosphate, at 50¢/lb; 0.75 lb CaO per pound of uranium at 0.7¢/lb for the CaO; and other materials at 1¢ per pound of uranium.

4. Overhead: 100% of total labor.

Table 6. Unit Costs for the Preparation and Conversion U_3O_8 to Pure UO_3

Item	Costs (cents/kg of uranium)		
	1 ton U/day	10 tons U/day	30 tons U/day
Labor	53.0	7.5	4.0
Utilities	5.9	4.8	4.0
Materials	40.3	19.6	17.8
Overhead	53.0	7.5	4.0
Operating total	152.2	39.4	29.8
Amortization	56.3	14.7	8.6
Grand Total	208.5	54.1	38.4

5. PREPARATION OF REACTOR GRADE UO_2-PuO_2

Reactor grade UO_2--0.5% PuO_2 is assumed to be prepared by the "sol-gel"[4] process. This process was developed initially for the preparation of ThO_2--3.4% $U^{233}O_2$ and is now being studied for the preparation of a variety of similar fuels. The mixed thorium-uranium oxide fuels are being prepared in a remotely operated pilot plant at Oak Ridge National Laboratory. The successful preparation of mixed uranium-plutonium oxide fuels has been accomplished in the laboratory.

The proposed process is shown schematically on Fig. 9. This process is a direct scale-up of successful laboratory tests discussed above, plus

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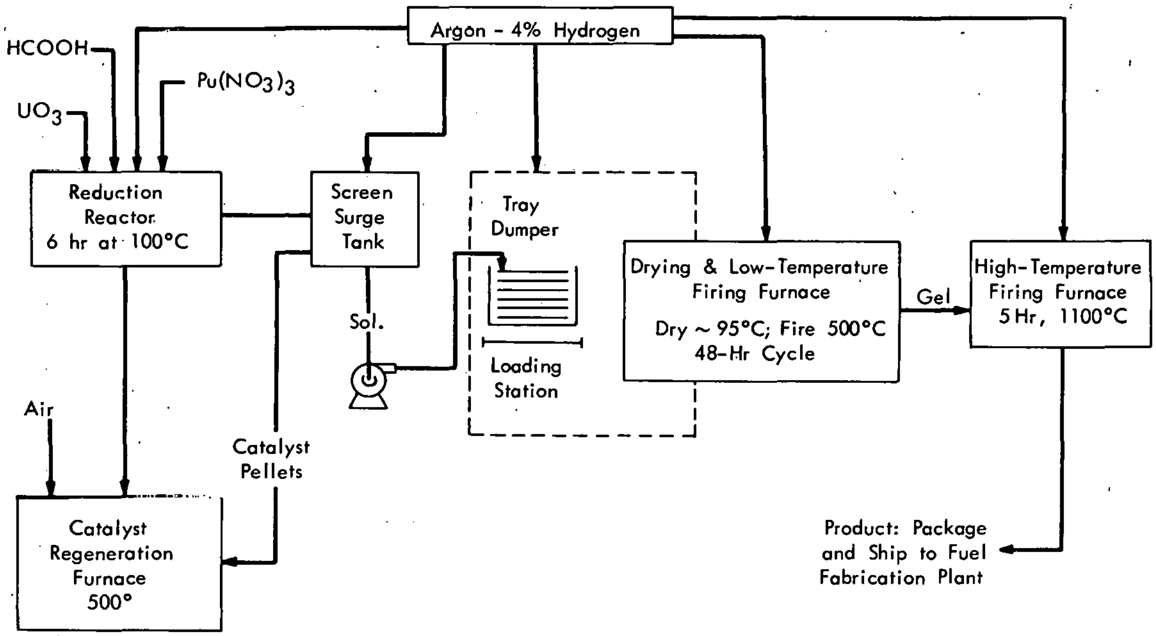

Fig. 9. Block Flowsheet for Preparation of Reactor Grade UO_2--0.5% PuO_2.

pilot plant experience with the preparation of mixed thorium-uranium oxide fuel. A 45% solids sol is prepared from the steam-denitrated UO_3, recycled $Pu(NO_3)_3$, formic acid, and water. The U(VI) in the sol is reduced to U(IV) in 6 hr at 100°C in the presence of a platinum-on-alumina catalyst and hydrogen. The pelleted catalyst is separated from the sol by screening and is regenerated by firing at 500°C in the presence of air. The sol is dried to a gel, fired to 500°C, and cooled. Up to the completion of this low-temperature firing, the uranium is protected at all times by an Ar--4% H_2 blanket gas to prevent reoxidation. The final step is a 5-hr, 110°C firing in the presence of an Ar--4% H_2 blanket to ensure maximum reduction. The high-fired product has the desired density and surface area and is packaged and shipped to the fuel fabrication plant.

The equipment required for the 1-, 10-, and 30-tons-of-uranium-per-day plants is presented with the capital cost estimate in Table 7. This equipment assumes batch operations and the process briefly outlined above. The size of the furnace for the sol drying and low-temperature firing of the gel is the limiting factor in the throughput of a single line of equipment. Several proposals are being considered, and they may result in a less expensive operation from both capital and operating viewpoints. Two of these proposals are: (1) a shaft furnace for high firing and (2) cheaper blanket gases than Ar--4% H_2. The process equipment does not use any advanced concepts but is scaled up directly from the successful laboratory procedures and the batch furnace experience in the mixed thoria-urania pilot plant.

The recycled plutonium contains 30 wt % Pu^{240} and 15 wt % Pu^{242}. The calculated values for the radiation dose rates and shielding requirements are:

1. At a distance of 1 ft from fuel assembly:
   2.3 mrem/hr from neutrons
   2.0 mrem/hr from plutonium x rays and gammas
   0.6 mrem/hr from spontaneous fission gammas
   2.0 mrem/hr from alpha excitation x rays and other sources
   ———
   6.9 mrem/hr, total

Table 7. Costs for the Preparation of Reactor Grade UO_2-PuO_2

Item No.	Description	1 ton/day Size	1 ton/day Installed Cost	10 tons/day Size	10 tons/day Installed Cost	30 tons/day Size	30 tons/day Installed Cost
1	$Pu(NO_3)_3$ surge tanks	250 gal, 304L, 3 ft diam x 5 ft high	$ 3,200	2500 gal, 6-1/2 ft diam x 10 ft high	$ 9,000	2-2500 gal, Pyrex Raschig rings	$ 18,000
2	Pump: canned motor 304L	5 gpm at 10 psig	1,200	50 gpm at 10 psig	2,800	2-50 gpm at 10 psig	5,600
3	Reduction reactor: 304L, SS, agitated Ar--4% H_2 blanket, large bottom outlet, H_2 gas line	700 gal, 5 ft diam x 7.5 ft high; agitator	6,750	7000 gal, 10 ft diam x 12 ft high; agitator	15,400	2-7000 gal; agitator	30,800
4	Screen tank: horizontal with removable 3/16 in. x 3/16 in. opening screen based; large 304L Ar--4% H_2 blanket	3 ft diam x 7 ft long, 370 gal	5,950	6 ft diam x 14 ft long, 2961 gal	11,600	2-6 ft diam x 14 ft long, 2961 gal each	23,200
5	Sol pump: canned motor-water purge	1 gpm at 10 psig, 304L	700	10 gpm at 10 psig, 304L	1,400	2-10 gpm at 10 psig, 304L	2,800
6	Drying carts: to hold 10-5 ft x 6 ft trays holding 3/4 in. to 1 in. sol, 2 positions	4 carts with trays at $\$2/ft^2$	10,400	40 carts with trays, less 50%	100,000	120 carts with trays, less 10%	281,000
7	Cart loading station: hand pipe header with valve rotating rose to load trays	1 unit	2,000	2 units	4,000	6 units	12,000
8	Drying furnace: tunnel type, front and rear opening doors; electrical resistance heating with spares, 500°C max temp; Ar--4% H_2 blanket	Inside dimensions: base, 11-1/2 ft x 7 ft x 8 ft high; 75 kw at 315/kw; 2 required	69,000	Inside dimensions: base, 66-1/2 ft x 7 ft x 8 ft, 375 kw at 285/kw; 4 required	508,500	Inside dimensions: base, 66-1/2 ft x 7 ft x 8 ft; 375 kw at 285/kw; 12 units	1,454,000
9	Cart dumper: device to pick up drum cart on side and vibrate to dump product to a hopper; remote operated	1 unit	12,500	2 units	25,000	6 units	75,000
10	Catalyst furnace: electrical resistance, air atmosphere, 500°C max temp; front remotely operated door; spare heating elements	Inside dimensions: 3 ft x 4 ft x 3 ft; 12 kw at 315	6,500	Inside dimensions: 5 ft x 5 ft x 6 ft; 120 kw	52,300	Inside dimencions: 5 ft x 5 ft x 6 ft; 120 kw; 2 required	105,500
11	High-firing furnace: 1100°C max temp, chrome Al resistors, spare elements; front remotely opening door; ceramic trays, each holds 1 drying cart of material	4 ft x 5 ft x 4 ft, 5 trays, 3 ft x 4 ft; 92 kw at 315	37,500	13 ft x 7 ft x 7 ft, 10 trays 5 ft x 6 ft; 460 kw; 2 required	301,000	13 ft x 7 ft x 7 ft; 10 trays, 5 ft x 6 ft; 460 kw; 6 required	904,000
12	Product packaging	1 unit	7,000	2 units	14,000	3 units	21,000
13	Pnuematic conveying system for solids	3 required	30,000	6 required	60,000	15 required	150,000
14	Vacuum system outlets for cell cleanup, $500/outlet, plus filters, fans, etc.	15 outlets	17,500	60 outlets	45,000	84 outlets	62,000
15	Measuring device or scales to determine load per shelf; see above (13)	Remote, 1 unit	700	2 units	1,400	6 units	4,200
16	Scales for product packaging station	Remote, 1 unit	500	2 units	1,000	3 units	1,500
17	G. M. manipulators, model 300	4 required	168,000	7 required	294,000	11 required	462,000
18	Model-8 manipulators, assume 1 pair per window	9 pair	94,500	15 pair	157,500	24 pair	253,000

Table 7. Continued

Item No.	Description	1 ton/day Size	1 ton/day Installed Cost	10 tons/day Size	10 tons/day Installed Cost	30 tons/day Size	30 tons/day Installed Cost
19	Windows: 1 ft thick at $10,000 each	9	$ 99,000	15	$ 165,000	24	$ 264,000
20	Process piping, valves, fittings, etc.		50,000		100,000		200,000
21	Process instruments	12 major units	36,000	14 major units	42,000	27 major units	81,000
22	Process electrical starters, conduct, wire, transformers, labor, etc.	500 kw	25,000	3800 kw	190,000	10,000 kw	500,000
23	Process insulation: included in equipment costs						
24	Formic acid head tank and feed pump (not SS)	55 gal, 1 gpm Chempump	800	375 gal, 5 gpm Chempump	1,100	1000 gal, 5 gpm Chempump	1,500
25	Process ventilation ducts, fans, filters	10,000 cfm, 10 changes per hr at $10/cfm	100,000	35,500 cfm, 10 changes per hr at $9/cfm	320,000	91,200 cfm, 10 changes per hr at $8/cfm	730,000
	Subtotal No. 1		$ 784,500		$2,420,900		$5,639,100
	Building costs (including plumbing, lighting, heating, ventilation, fire protection, normal building services)		332,000		942,650		1,518,700
	Cost of cell area (excluding windows, manipulators, etc.)		300,000		852,000		1,641,000
	Cost of crane - overhead, 25 ton		30,000		50,000		60,000
	Misc. equipment, such as Argon-H_2 blanket system and forgotten equipment, 10% of Subtotal No. 1		78,200		242,000		563,900
	Subtotal No. 2		$1,524,700		$4,507,550		$9,422,700
	Services and utilities yard		228,700		676,100		1,414,200
	Total materials and labor		1,753,400		5,183,700		10,836,900
	Construction overhead 30% of materials and labor		526,000		1,555,000		3,251,000
	Subtotal No. 3		$2,279,000		$6,738,700		$14,088,000
	Architect engineer, engineering, 15% of Subtotal No. 3		341,900		1,010,800		2,113,200
	TOTAL		$2,621,000		$7,749,500		$16,201,000
	New total with 50% contingency		$3,931,500		$11,624,000		$24,302,000
	Dollars/yr at 7.7%		302,700		895,000		1,871,000
	Cents/kg of uranium		107.4		31.7		22.2

This dose rate would be reduced to 0.5 and 0.25 mrem/hr by 5 and 8 in. of normal concrete, respectively.

2. At a distance of 1 ft from a 10-ft-diam disk: 0.37 and 22 mrem/hr for 50 and 3000 lb of UO_2--0.5% PuO_2 powder, respectively.

3. At the surface of a sphere; 51 and 200 mrem/hr for a 50- and 3000-lb sphere, respectively. These values served as a guide to plant design for both this step and the fuel fabrication.

Views of the structures required to house the plants for the production of 1, 10, and 30 tons of uranium per day are shown on Figs. 10, 11, 12, and 13. Twelve inches of concrete is provided to separate the processing equipment from plant personnel. The equipment is arranged in a canyon, with a separate cell allotted to each major process step. In-cell General Mills manipulators are provided for routine cell operations and maintenance. The processing cells are entered only when absolutely necessary, and then only after a general cleanup.

The estimated unit costs for the 1-, 10-, and 30-ton-of-uranium-per-day plants are 377, 119, and 77 cents per kilogram of uranium.

The estimated operating costs for plants with the same production capacities are summarized in Table 8. Argon--4% hydrogen gas requirements at 3 cents/ft^3 are allowed at four volume changes a day for the reduction vessel, drying furnace, and high-firing furnance; and two volume changes a day for the filter vessel, tray loading area, and the air lock. Utilities are allowed at twice the electrical load with electricity at 4 mills/kwhr. Labor requirements at $7500 per man-year are estimated at:

1. Direct operations: 20, 45, and 70 men for the plants producing 1, 10, and 30 tons of uranium per day.

2. Maintenance: 8, 18, and 28 men for the three plant sizes.

3. Other labor: 25% of sum of direct operations and labor.

Maintenance materials are assumed to be equal in cost to maintenance labor. Chemicals, principally four moles of formic acid per mole uranium, are estimated to cost 2 cents per pound of uranium. Overhead is allowed at 100% of the total labor cost.

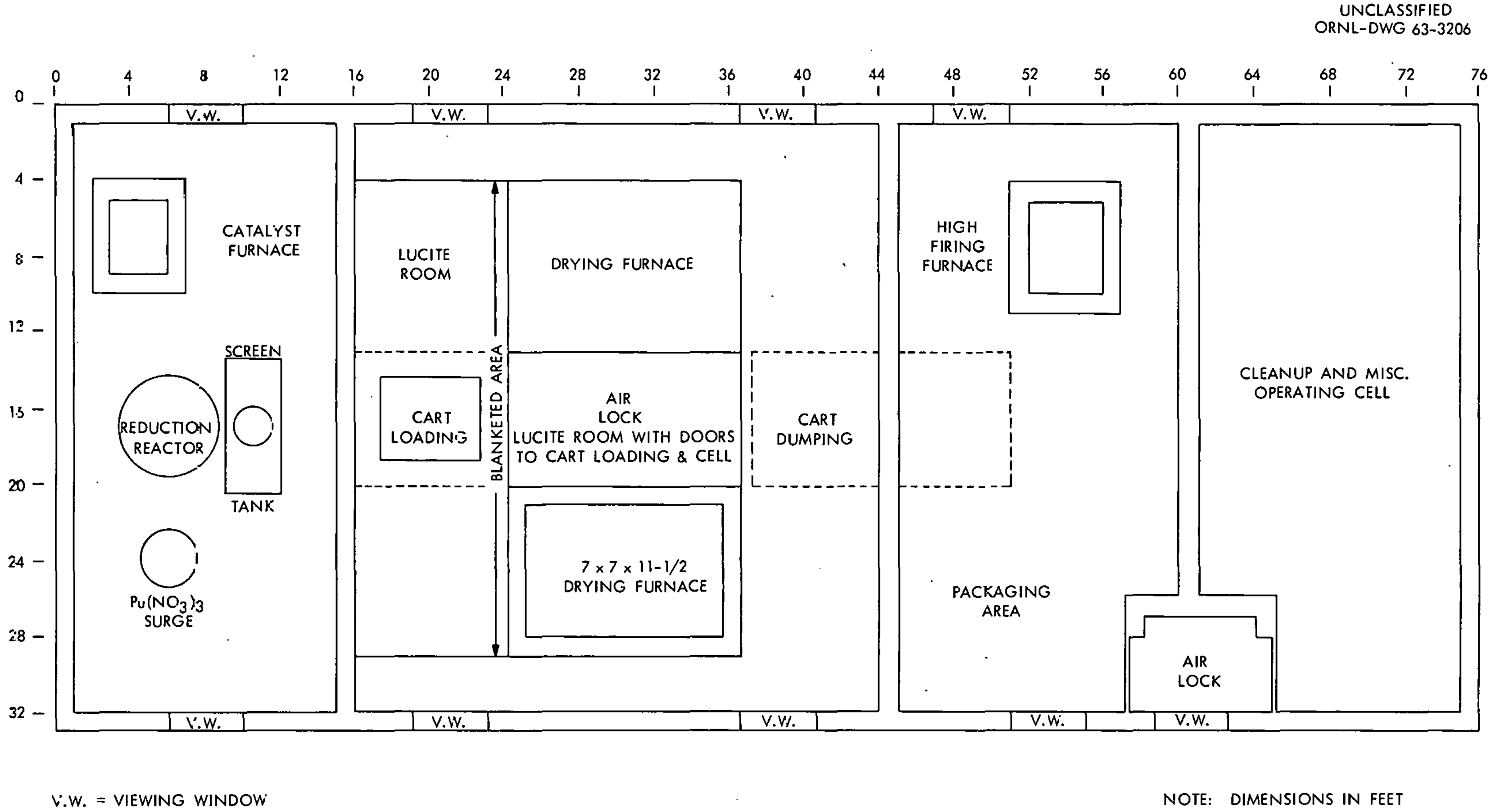

Fig. 10. Cell Equipment Layout for Preparation of 1 Ton per Day of Reactor Grade UO_2-PuO_2.

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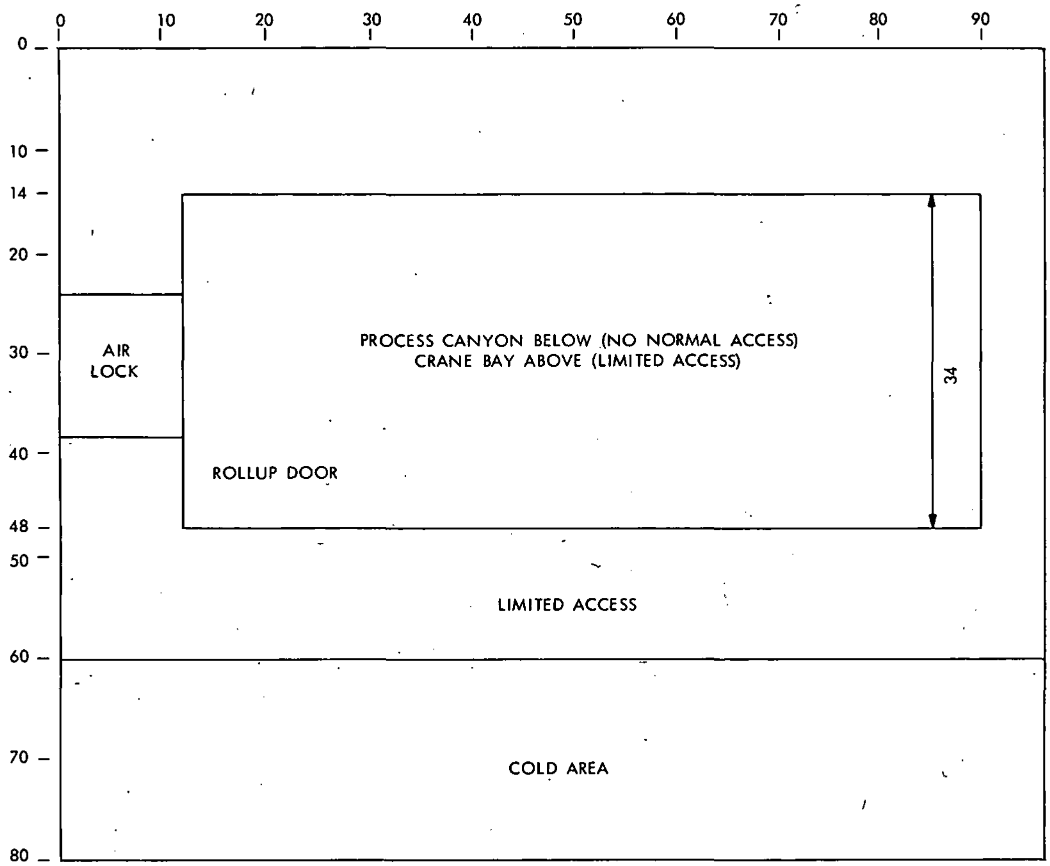
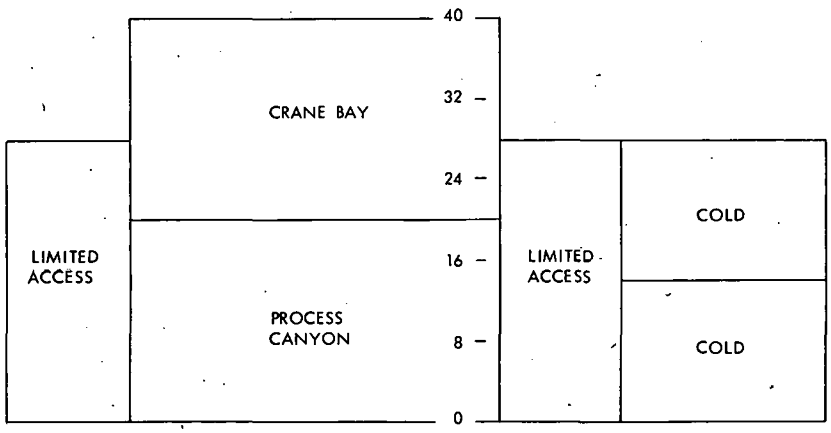


NOTE: DIMENSIONS IN FEET



NOTE: DIMENSIONS IN FEET

Fig. 11. Plan and Section of Plant Required for Preparation of 1 Ton per Day of Reactor Grade UO_2-PuO_2.

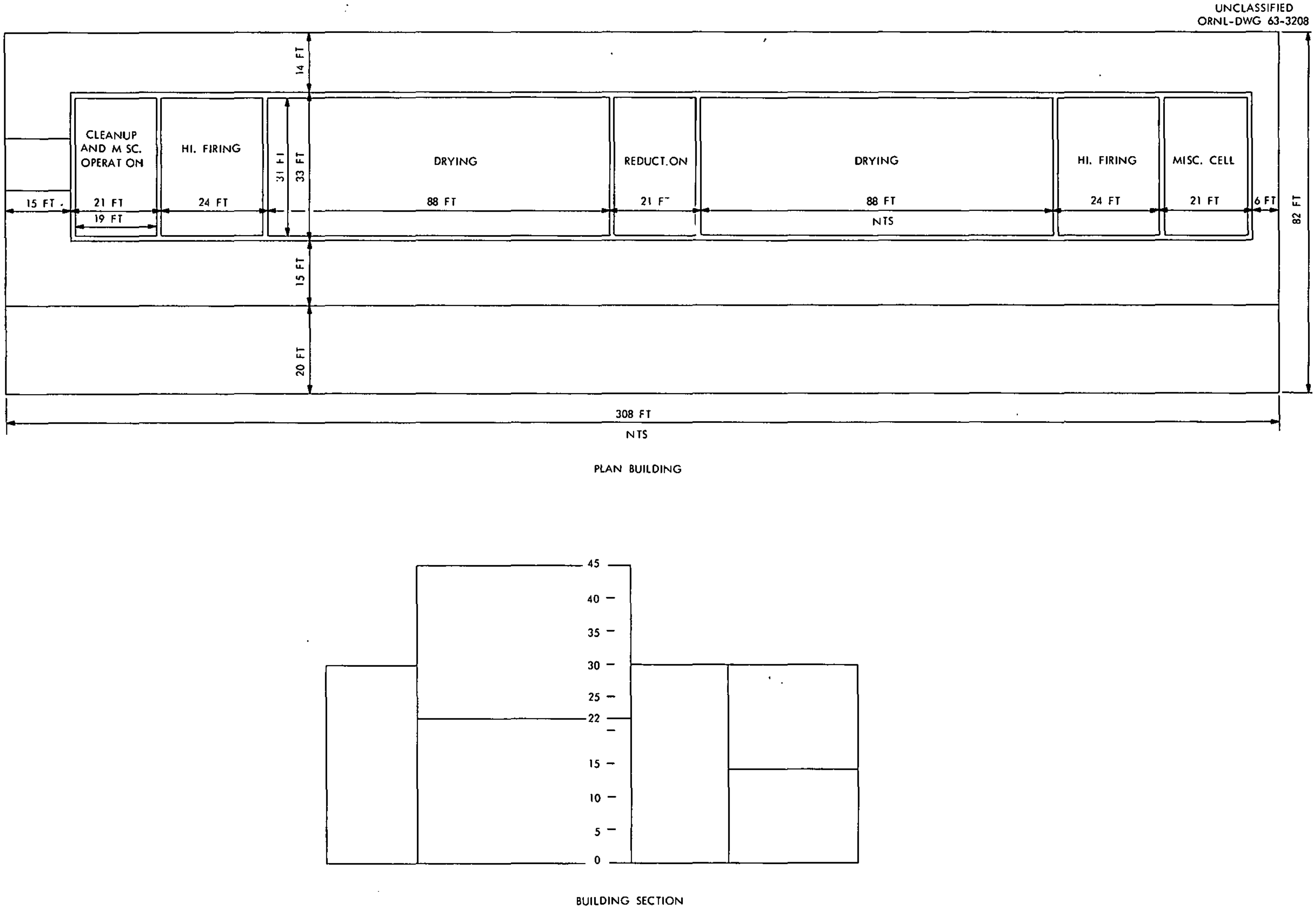


Fig. 12. Plan and Section of Plant Required for Preparation of 10 Tons per Day of Reactor Grade UO_2-PuO_2.

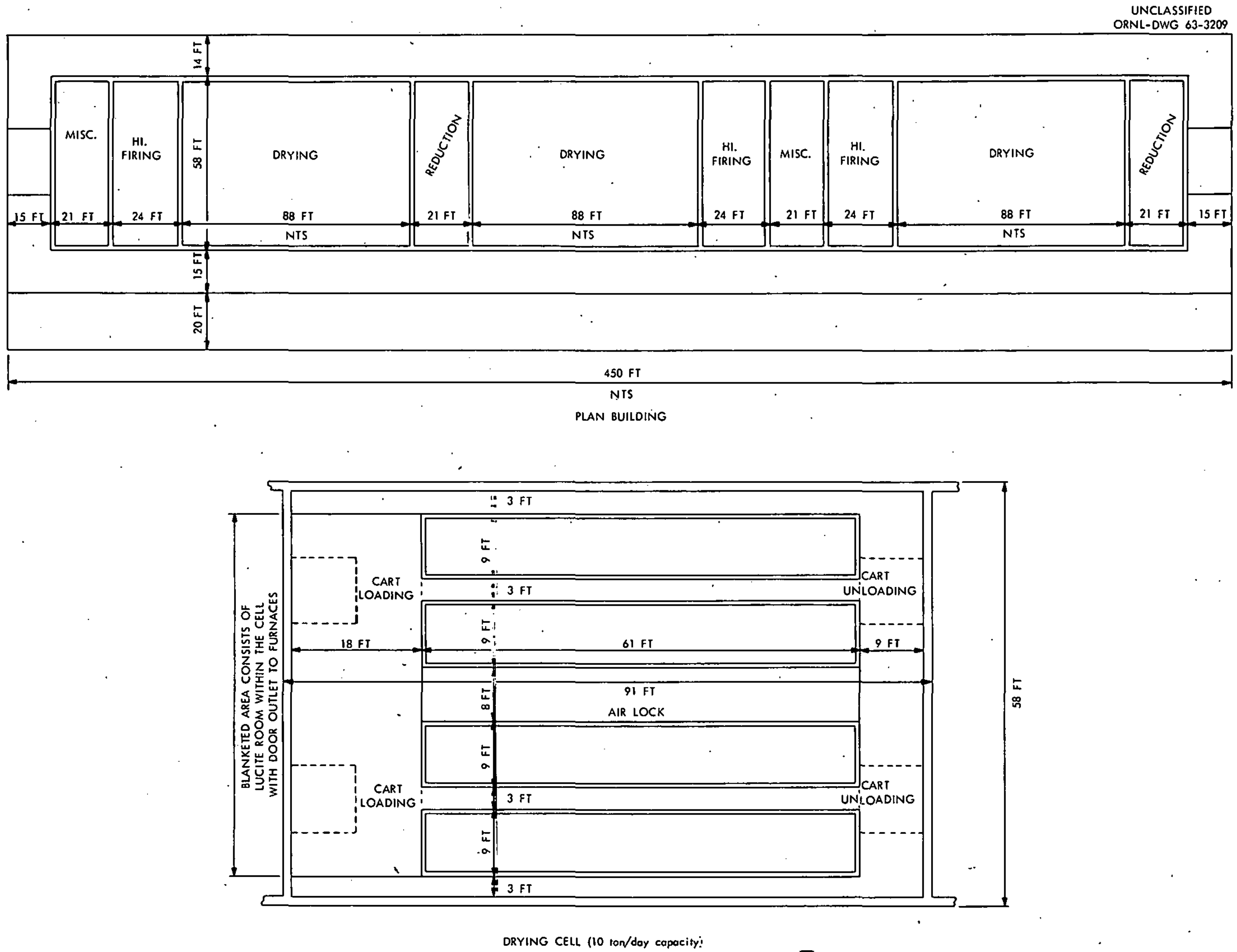


Fig. 13. Plan View of Plant Required for Preparation of 30 Tons per Day of Reactor Grade UO_2-PuO_2.

6. FABRICATION OF FUEL ELEMENTS

The costs are estimated for the fabrication of the fuel elements from the "sol-gel" product. The cost data, summarized below, are reported in a detailed cost analysis[5] now in press.

Table 8. Cost of Preparation of UO_2--0.5% PuO_2 in Cents per Kilogram of Uranium

Item	Production Rate		
	1 ton U/day	10 tons U/day	30 tons U/day
Blanket gas	47.5	28.6	19.4
Utilities	10.6	7.9	7.0
Labor	93.1	20.7	10.8
Materials	25.7	9.0	6.8
Overhead	93.1	20.7	10.8
Total operating cost	270.0	86.9	54.8
Amortization	107.4	31.7	22.2
Total	377.4	118.6	77.0

Based on the dose rate and shielding calculations (Sec 5), preventive maintenance, periodic adjustment of equipment, and minor repairs of equipment are made directly by properly clothed personnel. This serves to keep the equipment and operating costs somewhat lower than would be the case for a completely remote operation.

In the capital cost of the plant, considerable data from the natural uranium UO_2 fuel study are used with little modification. The equipment costs for clean-area operations are unchanged. Remotely operated equipment items are substantially increased. The use of the sol-gel process to produce the mixed oxide eliminates seven steps used in the previous natural uranium fabrication process.

Operating costs are increased over natural uranium, principally for maintenance, process engineering, and health physics.

Material costs, except for an increase from 5 to 8% in reject rate, are unchanged. Zircaloy tubing cost, based on zirconium sponge at \$5.50/lb, ranges from \$20 to \$14/lb.

The capital and operating costs for both the recycle and the natural uranium fuel are reported in Table 9. The cases studied are for production rates of 1, 3, 5, and 10 tons of uranium per day.

7. IRRADIATED FUEL PROCESSING

Processing costs were estimated earlier for natural uranium UO_2 elements. Report DP-566[6] served as a reference for the preparation of both the capital and operating costs. To the base plant reported in DP-566, Case IV, facilities were added for krypton removal, conversion of UNH to UO_3, and a silo storage system for the storage of UO_3.

The capital cost of the base plant at 30 short tons of uranium a day was estimated by continuing the 0.15 exponential relationship of the reported 1- and 10-ton plants. The krypton removal system for the 30 ton plant was estimated to cost $\$5 \times 10^6$, and the costs for the 1- and 10-ton plants were scaled from this estimated using the 0.6 power factor. The cost of the denitration step was estimated at 10 tons per day, and the 1- and 30-ton plants calculated from the 0.6 exponential relationship. The cost of a 20-year silo-storage system, including a pneumatic conveyor system, was estimated at each size.

In the operating-cost estimate, the following unit prices were used: NH_4F, 25¢/lb; electricity, 4 mills/kwhr; steam, 20¢/1000 lb; and water, 20¢/1000 gal. With the exception of the costs above, detail costs were taken directly from report DP-566.

The estimates of this natural uranium fuel cycle are used in estimating the processing costs for the reference plutonium recycle fuel. Both estimates are summarized in Table 10. To the 1-, 10-, and 30-tons-of-uranium-per-day-plant estimates, capital costs are added to process the

50% greater plutonium throughput, to increase the HNO_3 fractionation equipment, to produce NH_4F, and to upgrade equipment items such as the dissolvers, which have reduced criticality safety.

A similar approach is used to estimate the operating costs. Table 10 presents the results of these estimates.

Table 9. Fuel Fabrication Costs: Dollars per Kilogram of Uranium

	1 ton U/day, or 2.82×10^5 kg/yr	3 tons U/day, or 8.46×10^5 kg/yr	5 tons U/day, or 1.41×10^6 kg/yr	10 tons U/day, or 2.82×10^6 kg/yr
	UO_2--0.5% PuO_2 Case			
Capital cost of plant, $	2.95	2.70	2.40	1.60
Operating cost of plant, $	9.70	5.50	4.50	3.00
Material cost (zirconium), $	4.30	3.95	3.70	3.40
Rejects (8%), $	1.40	1.05	.80	.60
Total, $	18.35	13.20	11.40	8.60
	Natural Uranium UO_2 Case			
Capital cost of plant, $	2.15	2.00	1.80	1.20
Operating cost of plant, $	6.60	3.80	3.10	2.10
Material cost (zirconium), $	4.30	3.95	3.70	3.40
Rejects (5%), $	.65	.50	.45	.35
Total, $	13.70	10.25	9.05	7.05

Table 10. Irradiated Fuel Processing Costs for Both the Natural Uranium and 0.5% Recycle Plutonium Fuels

Size of Plant:	Cost (dollars per kilogram of uranium)			
Tons U/day	Amortization	Operating	Plutonium Loss[a]	Total
1 natural uranium	13.01	12.26	0.07	25.34
1 recycle plutonium	13.22	12.97	-	26.19
10 natural uranium	1.88	1.98	0.07	3.93
10 recycle plutonium	1.94	2.16	-	4.10
30 natural uranium	0.76	1.18	0.07	2.01
30 recycle plutonium	0.80	1.27	-	2.07

[a]Value of plutonium = $6.70 g; 1/4% loss.

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