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FUEL CYCLE COSTS FOR A PLUTONIUM

RECYCLE SYSTEM

- F. E. Harrington
- E. D. Arnold
- D. C. Brater
- D. A. Douglas
- S. H. Smiley
- W. G. Stockdale
- J. W. Ullmann
- A. L. Lotts

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CHEMICAL TECHNOLOGY DIVISION  
METALS AND CERAMICS DIVISION  
OAK RIDGE GASEOUS DIFFUSION PLANT

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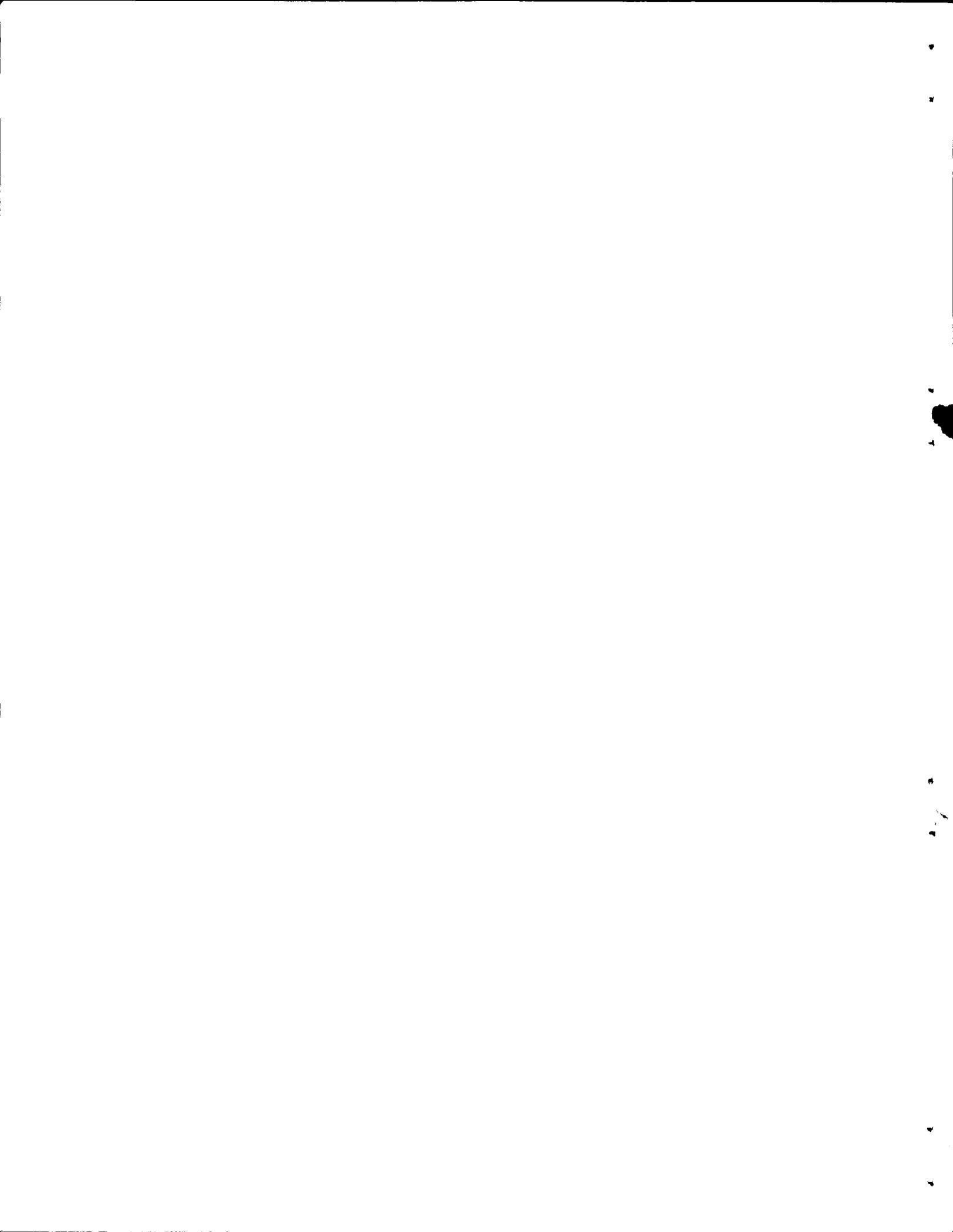
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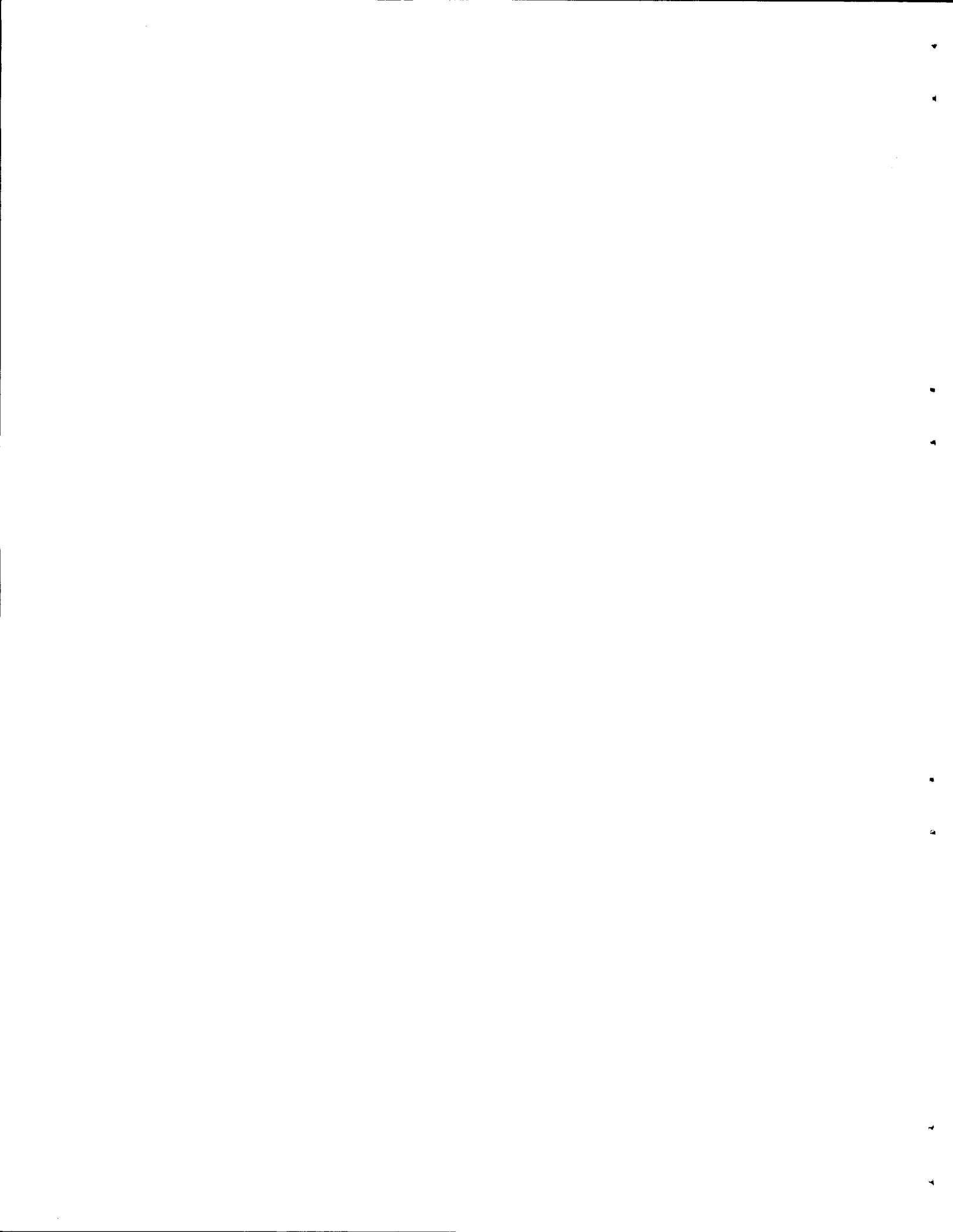


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## FUEL CYCLE COSTS FOR A PLUTONIUM RECYCLE SYSTEM

F. E. Harrington

|               |                 |
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| E. D. Arnold  | S. H. Smiley    |
| D. C. Brater  | W. G. Stockdale |
| D. A. Douglas | J. W. Ullmann   |

A. L. Lotts

## 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:  $\text{UO}_2$ -0.5%  $\text{PuO}_2$ . 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<sup>1</sup> reactors, the costs of the chemical and metallurgical steps in a recycle plutonium system are estimated. Earlier studies<sup>2</sup> 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,<sup>1</sup> which is shown on Fig. 1. The core is composed of depleted uranium and recycled plutonium as a mixture of  $\text{UO}_2$ --0.5%  $\text{PuO}_2$  (solid solution).

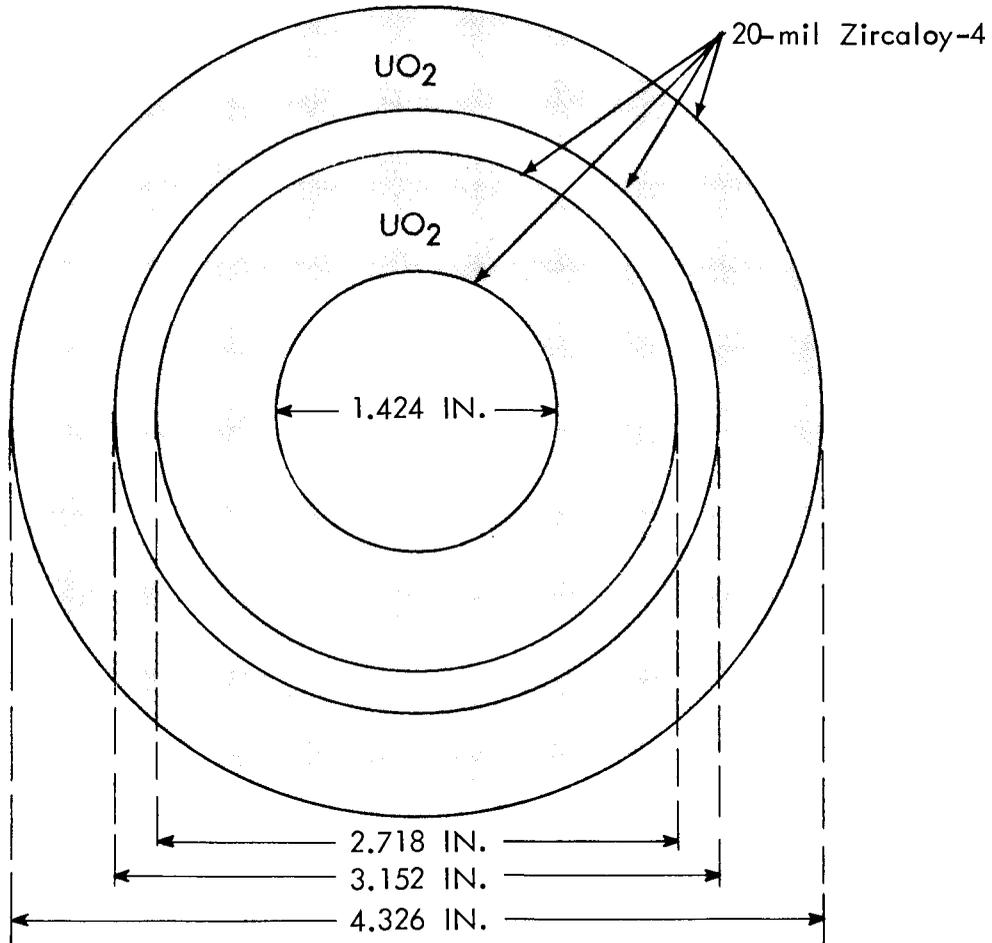
Both the capital and operating costs are estimated and reported by process step. The chemical steps are reported at throughputs of 1, 10, and 30 short tons of uranium per day. The metallurgical or fuel assembly fabrication step is reported at throughputs of 1, 3, 5, and 10 tons per day. The throughputs 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<br>U/day                      | 10 tons<br>U/day | 30 tons<br>U/day |
| $\text{UF}_6$ to $\text{U}_3\text{O}_8$                                    | 0.78                                | 0.25             | 0.16             |
| $\text{U}_3\text{O}_8$ to $\text{UO}_3$                                    | 2.08                                | 0.54             | 0.38             |
| $\text{UO}_3 + \text{Pu}(\text{NO}_3)_3$ to $\text{UO}_2$ - $\text{PuO}_2$ | 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<br>(tons U/day) | \$/kg U      |           |                   |       |
|----------------------------------|--------------|-----------|-------------------|-------|
|                                  | Amortization | Operating | Plutonium<br>Loss | Total |
| 1                                | 13.01        | 12.26     | 0.07 <sup>a</sup> | 25.34 |
| 10                               | 1.88         | 1.98      | 0.07              | 3.93  |
| 30                               | 0.76         | 1.18      | 0.07              | 2.01  |

<sup>a</sup>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

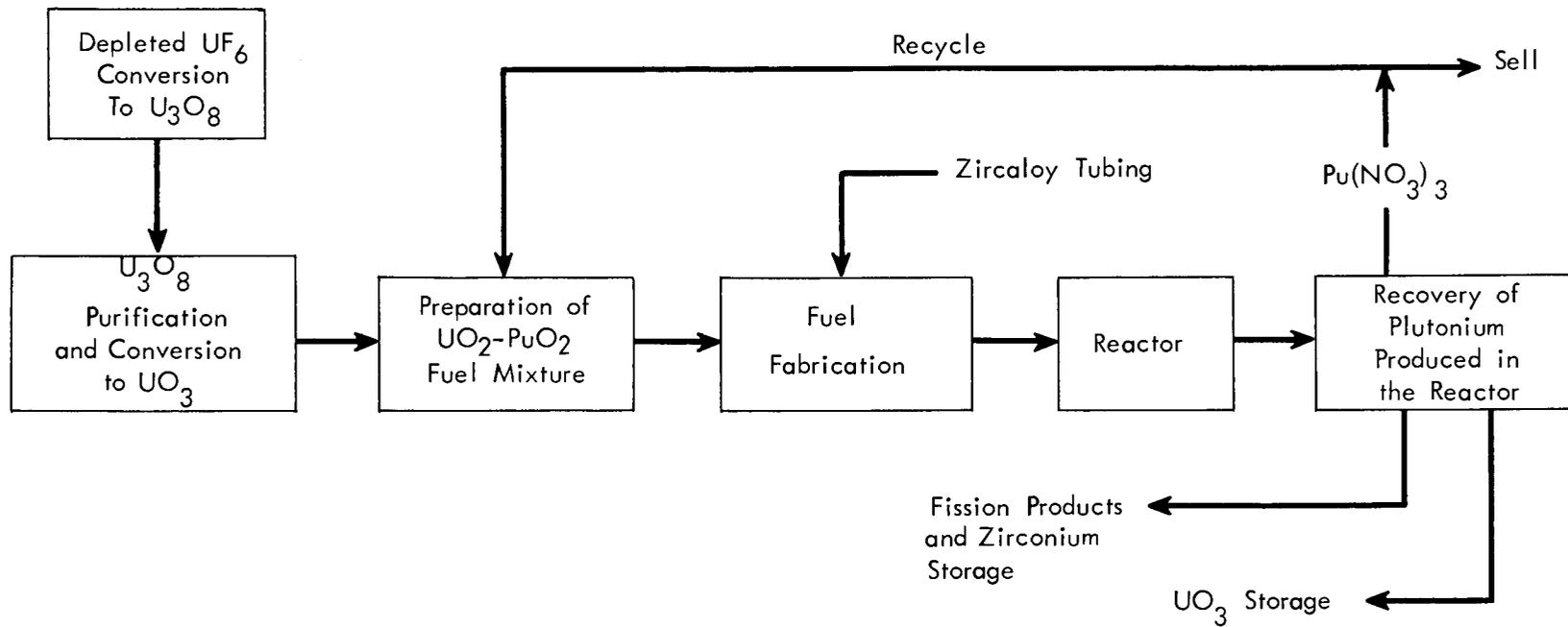


Fig. 2. Schematic Diagram of the  $\text{UO}_2$ --0.5%  $\text{PuO}_2$  Fuel Cycle.

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<sup>3</sup> 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.

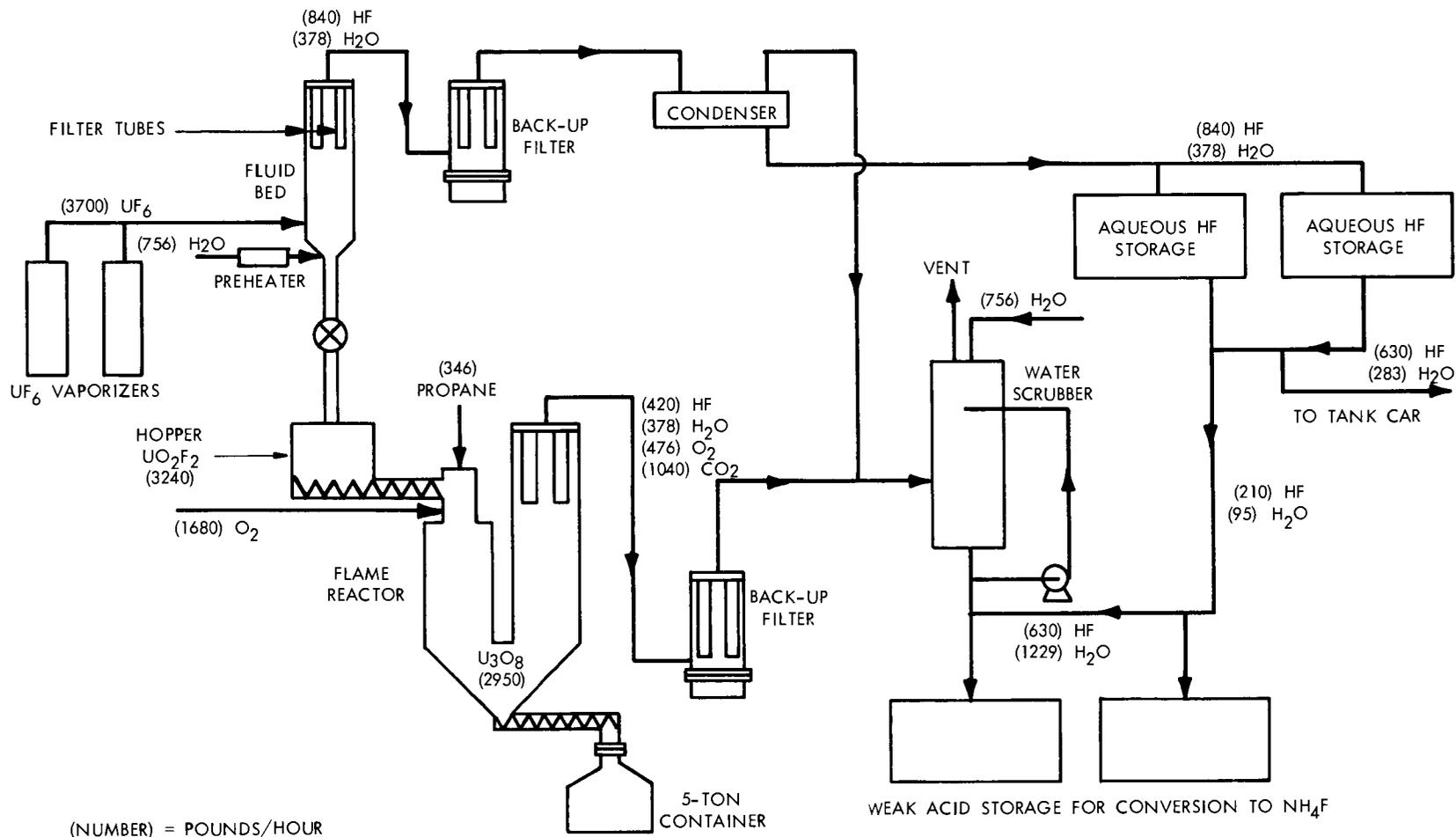


Fig. 3. Conversion of  $UF_6$  to  $U_3O_8$ . Schematic flowsheet rate:  
30 tons of uranium per day.

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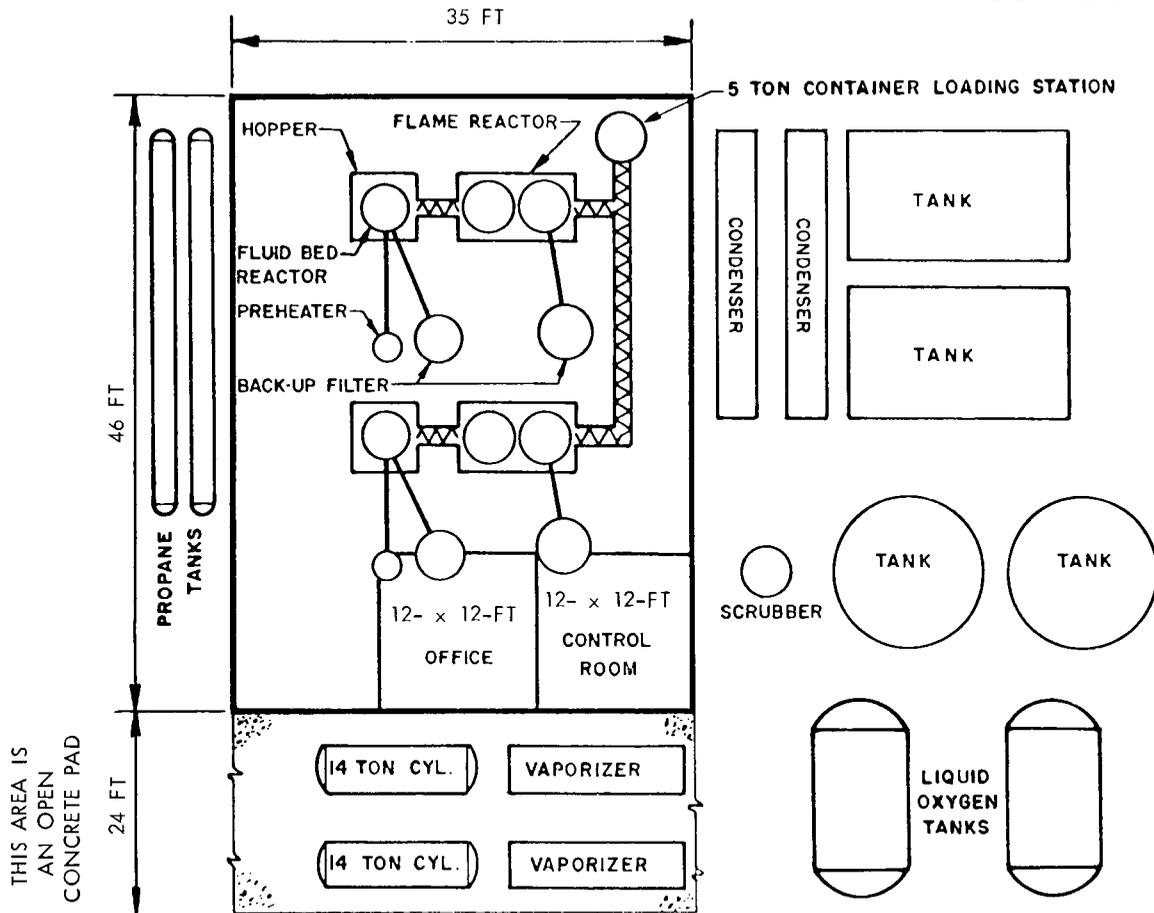


Fig. 4. Building and Layout of Equipment for a  $UF_6$  to  $UO_3$ : 30 Tons of Uranium per Day.

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

| Item  | 1 and 10 tons<br>U/day              | 1 ton<br>U/day, | 10 tons<br>U/day, | 30 tons<br>U/day              |           |
|---|-------------------------------------|-----------------|-------------------|-------------------------------|-----------|
|   | No. of Components<br>Required       | Cost (\$)       | Cost (\$)         | No. of Components<br>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 <sup>a</sup><br>18 <sup>b</sup> | 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<br>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 |

<sup>a</sup>150 for 10 tons U/day.

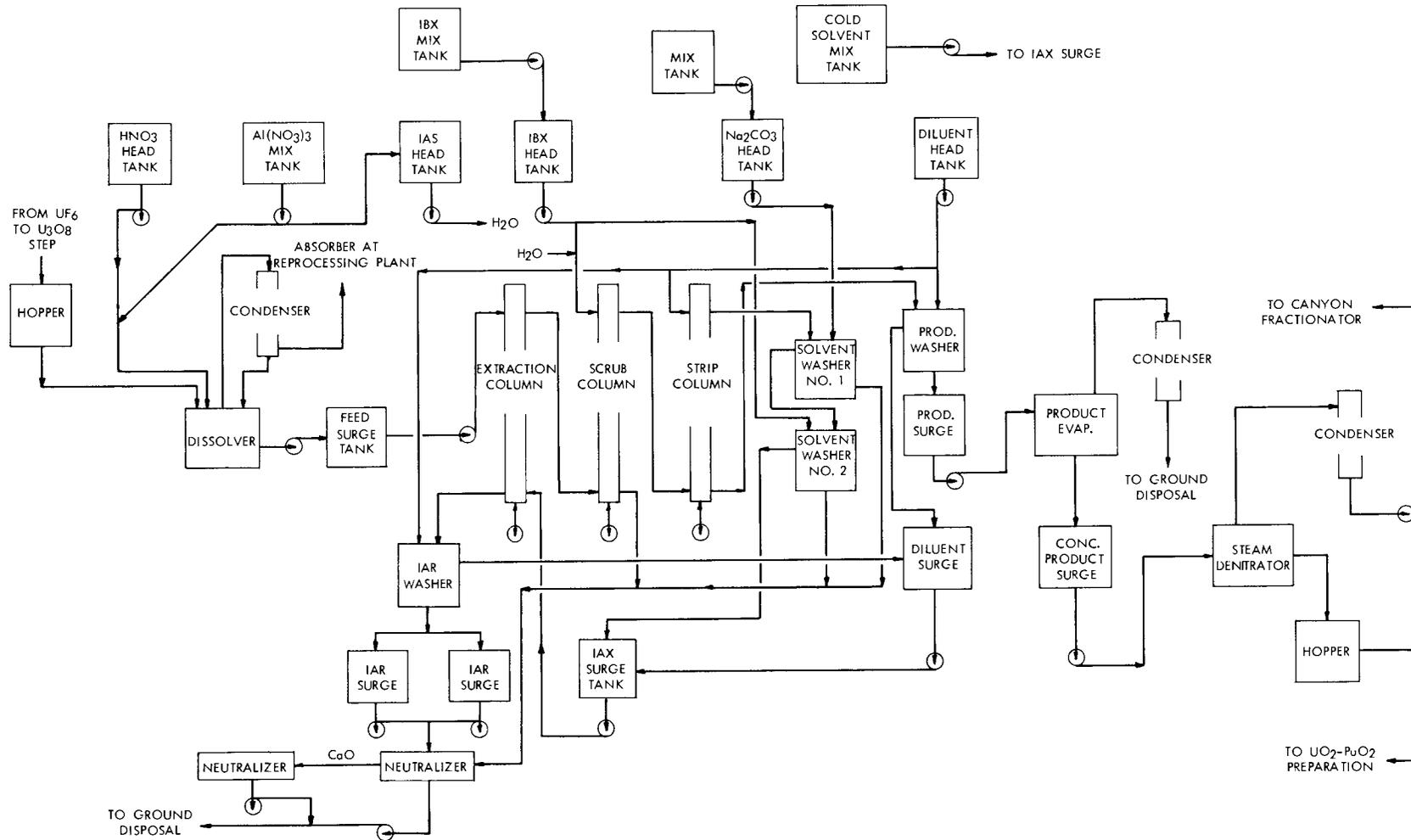
<sup>b</sup>18 for 1 ton U/day.

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

|   | 30 Tons<br>U/day | 10 Tons<br>U/day | 1 Ton<br>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,<br>cents/kg of uranium | 13.31            | 20.13            | 67.54          |
| Amortization,<br>cents/kg of uranium        | 2.95             | 4.95             | 10.56          |
| Total unit cost,<br>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<sub>3</sub> from U<sub>3</sub>O<sub>8</sub>.

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  $\text{UO}_3$ 

| Item No. | Description  | 1 ton/day  |                | 10 tons/day  |                | 30 tons/day  |                |
|----------|--|--|----------------|--|----------------|--|----------------|
|          |  | Size   | Purchased Cost | Size   | Purchased Cost | Size   | Purchased Cost |
| 1        | $\text{HNO}_3$ 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        | $\text{Al}(\text{NO}_3)_3$ 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        | $\text{Na}_2\text{CO}_3$ 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        | $\text{Na}_2\text{CO}_3$ 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 <sup>2</sup> coil; agitated   | 8,300          | 12,000 gal, 10 ft diam x 20 ft high, 400 ft <sup>2</sup> coil; agitated  | 28,500         | 2-12,000 gal, 2-400 ft <sup>2</sup> coil; 2-agitated   | 57,000         |
| 10A      | Hopper - feed to dissolver   |  | 500            |  | 1,000          |  | 2,000          |
| 11       | Dissolver condenser  | 40 ft <sup>2</sup> , 6-5/8 in. diam x 9 ft long  | 1,600          | 400 ft <sup>2</sup> , 14 in. diam x 14 ft long   | 4,400          | 2-400 ft <sup>2</sup>  | 8,800          |
| 12       | Feed surge tank  | 1200 gal, 4-2/3 ft diam x 9-1/3 ft; 40 ft <sup>2</sup> coil  | 5,600          | 12,000 gal, 10 ft diam x 20 ft high; 400 ft <sup>2</sup> 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 <sup>2</sup> heating surface   | 56,000         | 8-1/2 ft diam x 12 ft high, 2000 ft <sup>2</sup> heating surface   | 184,000        | 14-1/2 ft diam x 18 ft high, 6000 ft <sup>2</sup> 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 <sup>2</sup> , 10-3/4 in. diam x 10 ft long   | 2,000          | 1000 ft <sup>2</sup> , 20 in. diam x 18 ft long  | 9,000          | 3000 ft <sup>2</sup> , 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 <sup>2</sup> at \$300/ft <sup>2</sup> factor, 6-over direct rotary vac system | 27,000         | 6 ft diam x 24 ft long, 800 kw heat, peripheral area = 452 ft <sup>2</sup> at \$200/ft <sup>2</sup> , vac system | 110,400        | 3-6 ft diam x 24 ft long, 800 kw heat each, peripheral area = 452 ft <sup>2</sup> , vac system | 331,200        |
| 20       | Denitration condenser  | 150 ft <sup>2</sup> , 10-3/4 in. diam x 12 ft long   | 2,300          | 1500 ft <sup>2</sup> , 24 in. diam x 18 ft long  | 12,000         | 4500 ft <sup>2</sup> , 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 HF   | 7,500          | 3-50 HF special  | 45,000         | 3-75 HF special  | 60,000         |

Table 5. Continued

| Item No. | Description   | 1 ton/day  |                | 10 tons/day  |                | 30 tons/day  |                |
|----------|---|--|----------------|--|----------------|--|----------------|
|          |   | Size   | Purchased Cost | Size   | Purchased Cost | Size   | 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 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 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       | Hoppers, movable to bring U <sub>3</sub> O <sub>8</sub> to facility-inc truck | 6-1 ton  | 11,800         | 12-5 ton   | 22,000         | 35-5 ton   | 45,000         |
| 33       | Hoppers, movable to move UO <sub>3</sub> to next facility-inc truck           |  |                |  |                |  |                |
| 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 <sub>3</sub> and solvent storage tank                                     |  | 15,000         |  | 25,000         |  | 30,000         |
|          | Building process area   | 29 ft x 77 ft = 2233 ft <sup>2</sup>                                 |                | 134 ft x 42 ft = 5628 ft <sup>2</sup>                              |                | 152 ft x 66 ft = 10,032 ft <sup>2</sup>                            |                |
|          | Process volume  | 50 x 2233 = 111,650 ft <sup>3</sup>                                  |                | 52 x 5628 = 292,656 ft <sup>3</sup>                                |                | 54 x 10,032 = 541,728 ft <sup>3</sup>                              |                |
|          | 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            |

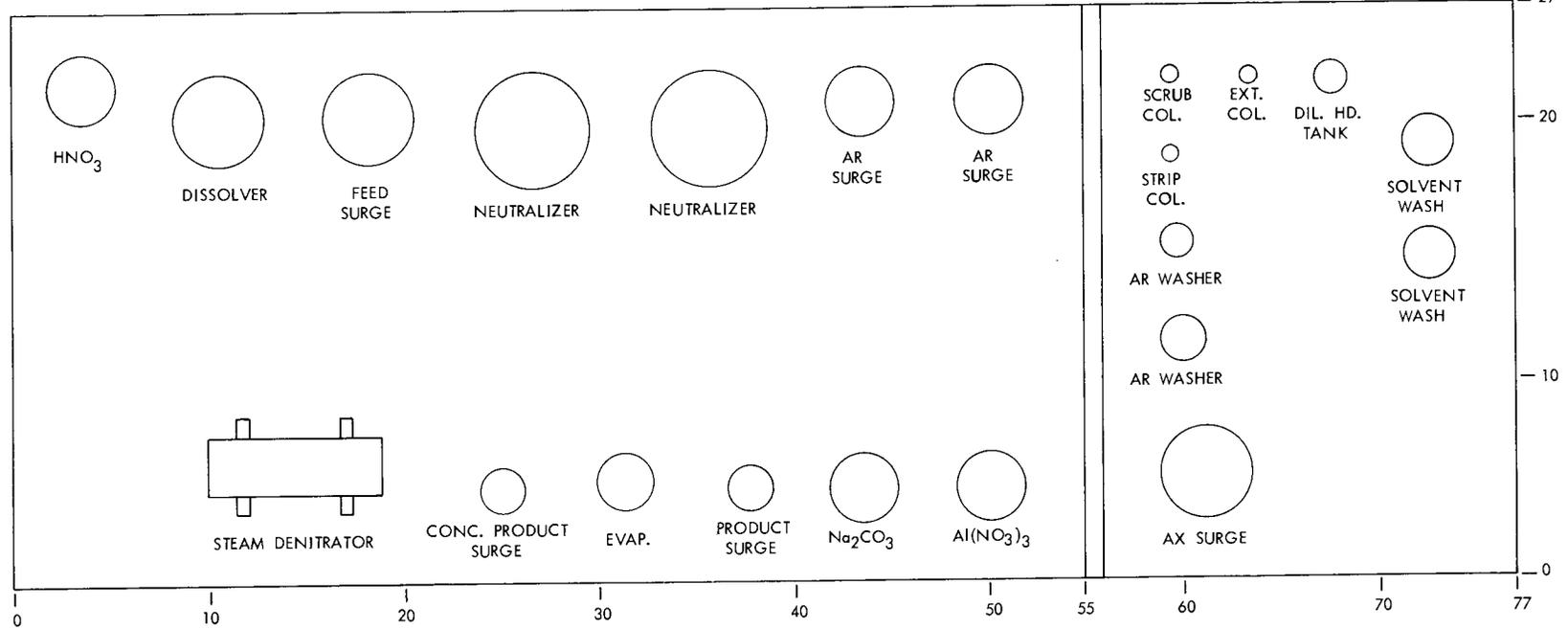
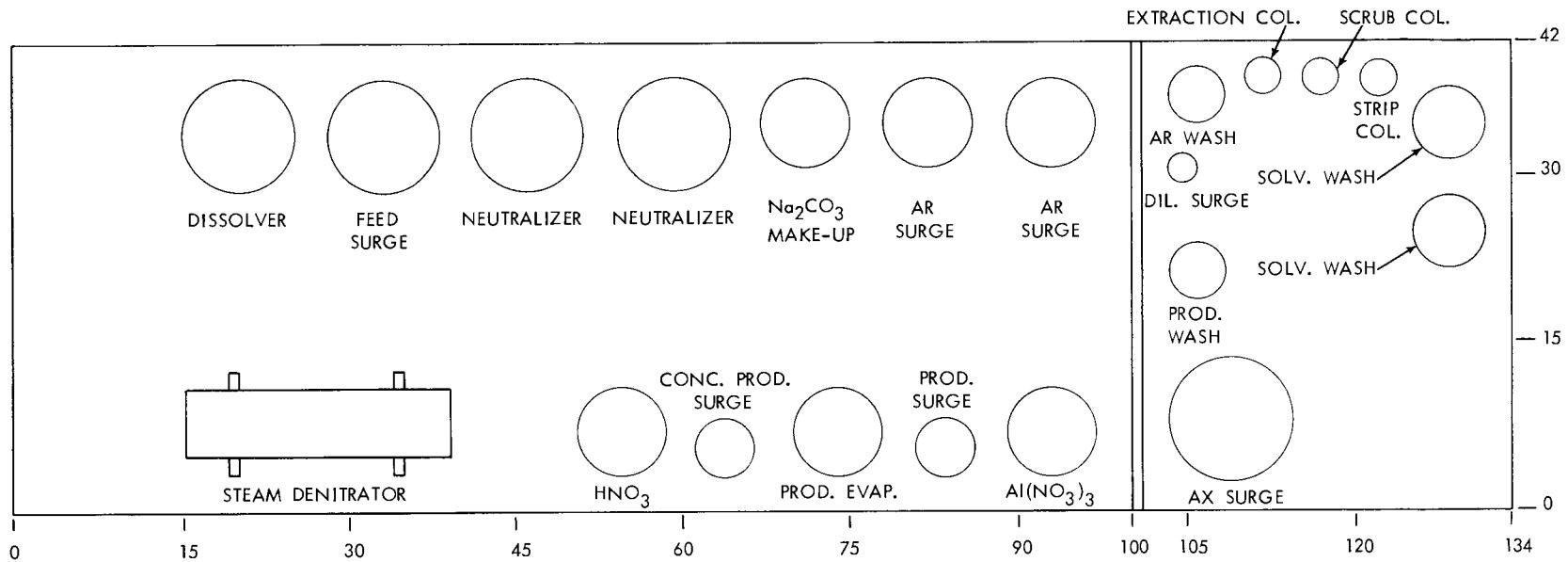
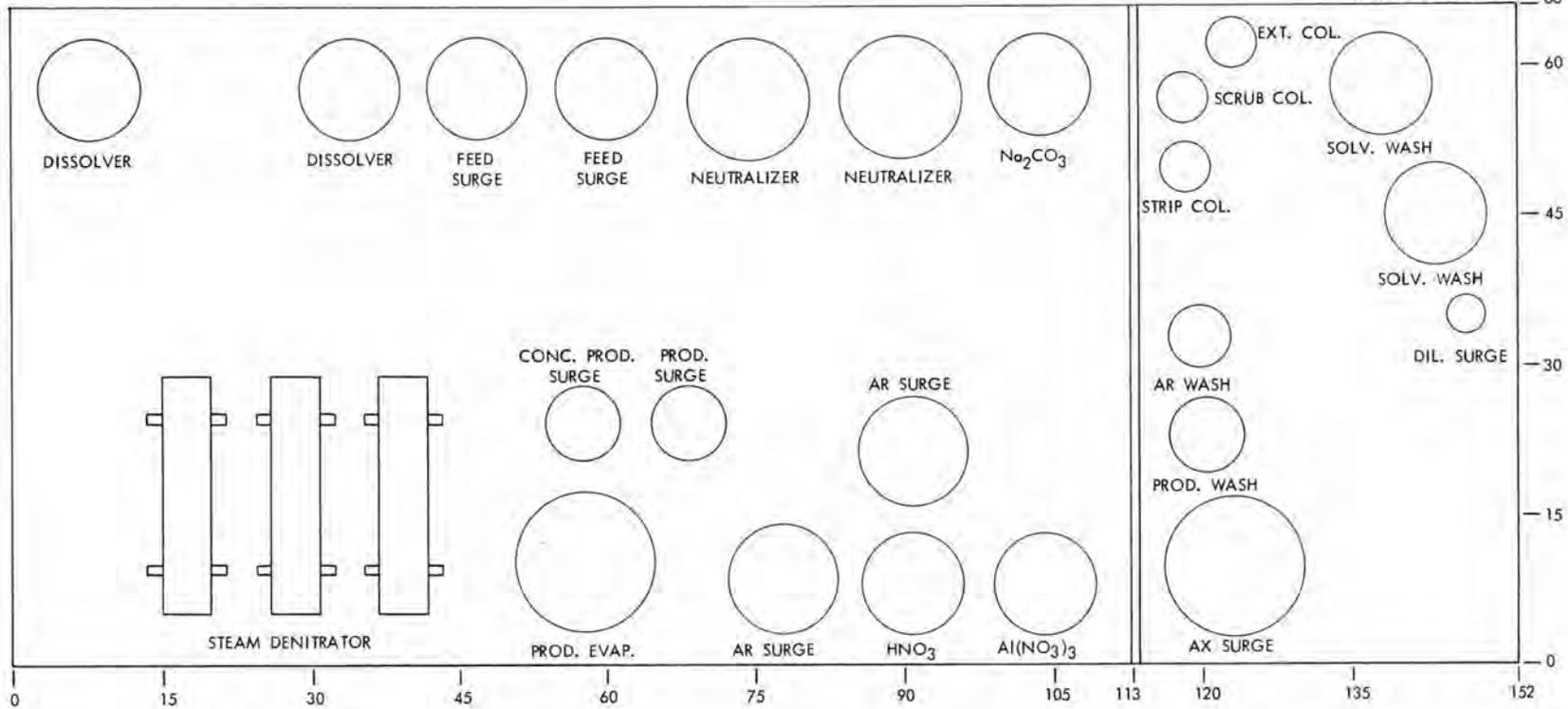


Fig. 6. Plant Layout for Conversion of  $U_3O_8$  to  $UO_3$  at 1 Ton of Uranium per Day.



NOTE: DIMENSIONS IN FEET

Fig. 7. Plant Layout for Conversion of U<sub>3</sub>O<sub>8</sub> to UO<sub>3</sub> at 10 Tons of Uranium per Day.



NOTE: DIMENSIONS IN FEET

Fig. 8. Plant Layout for Conversion of  $\text{U}_3\text{O}_8$  to  $\text{UO}_3$  at 30 Tons of Uranium per Day.

fluoride equal to 1% of the uranium, at 12¢/lb as solid for the  $\text{Al}(\text{NO}_3)_3$ ; 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  $\text{U}_3\text{O}_8$  to Pure  $\text{UO}_3$

| Item            | Costs (cents/kg of uranium) |                  |                  |
|-----------------|-----------------------------|------------------|------------------|
|                 | 1 ton<br>U/day              | 10 tons<br>U/day | 30 tons<br>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 $\text{UO}_2$ - $\text{PuO}_2$

Reactor grade  $\text{UO}_2$ -0.5%  $\text{PuO}_2$  is assumed to be prepared by the "sol-gel"<sup>4</sup> process. This process was developed initially for the preparation of  $\text{ThO}_2$ -3.4%  $\text{U}^{233}\text{O}_2$  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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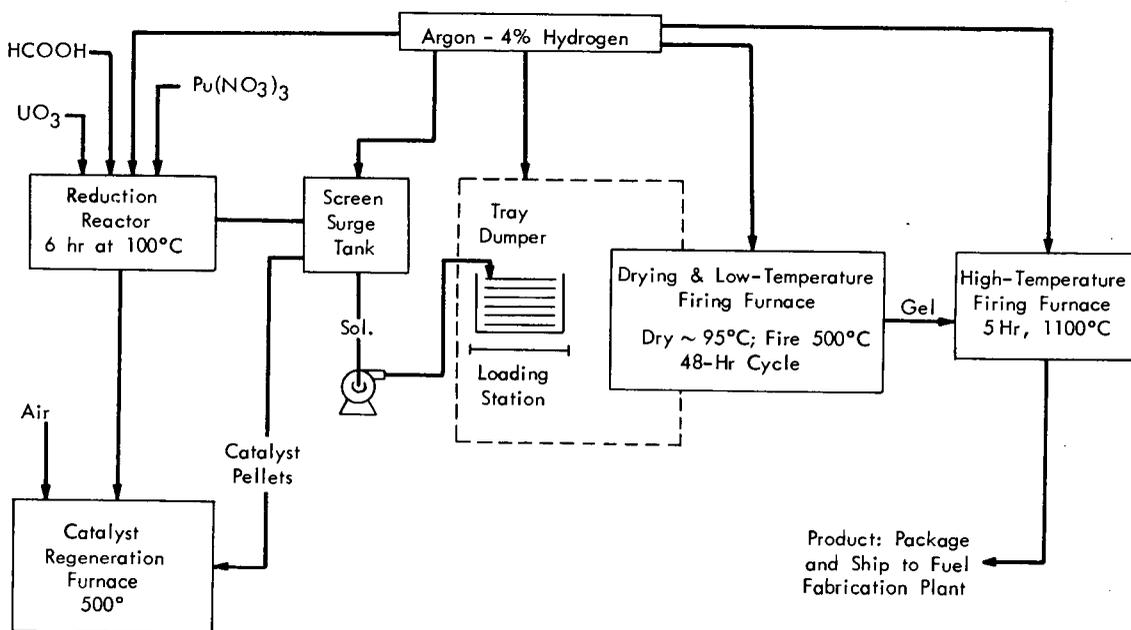


Fig. 9. Block Flowsheet for Preparation of Reactor Grade  $\text{UO}_2$ --0.5%  $\text{PuO}_2$ .

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  $100^\circ C$  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  $500^\circ C$  in the presence of air. The sol is dried to a gel, fired to  $500^\circ C$ , 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,  $110^\circ C$  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  |                | 10 tons/day  |                | 30 tons/day  |                |
|----------|---|--|----------------|--|----------------|--|----------------|
|          |   | Size   | Installed Cost | Size   | Installed Cost | Size   | 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 <sup>2</sup>  | 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 dimensions: 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       | Pneumatic 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                                 |                | 10 tons/day                              |                | 30 tons/day                              |                |
|----------|--|---|----------------|--|----------------|--|----------------|
|          |  | Size                                      | Installed Cost | Size                                     | Installed Cost | Size                                     | 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 <sub>2</sub> 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.

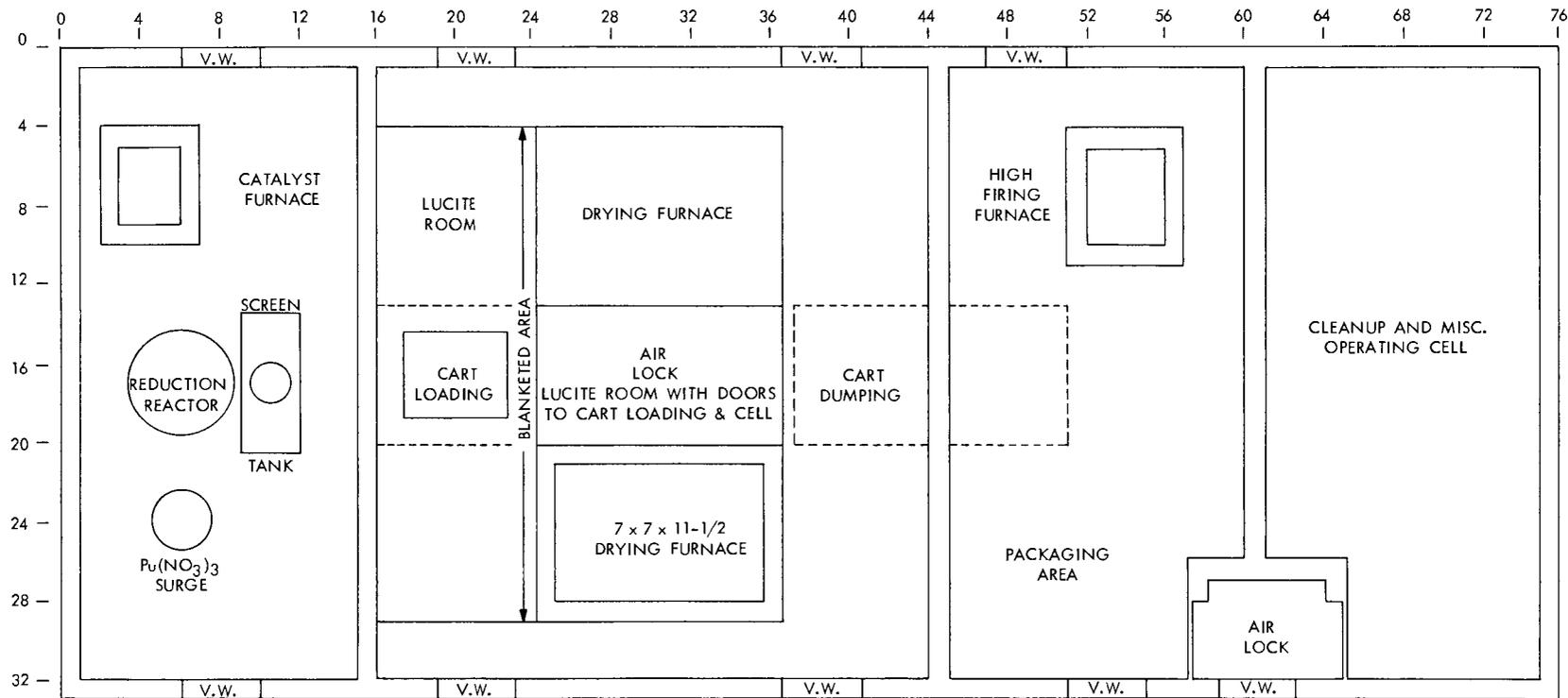
Views of the structures required to house the plants for the production of 1, 10, and 30 tons of uranium per day are shown on Figs. 10, 11, 12, and 13. Twelve inches of concrete is provided to separate the processing equipment from plant personnel. The equipment is arranged in a canyon, with a separate 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<sup>3</sup> are allowed at four volume changes a day for the reduction vessel, drying furnace, and high-firing furnace; 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.

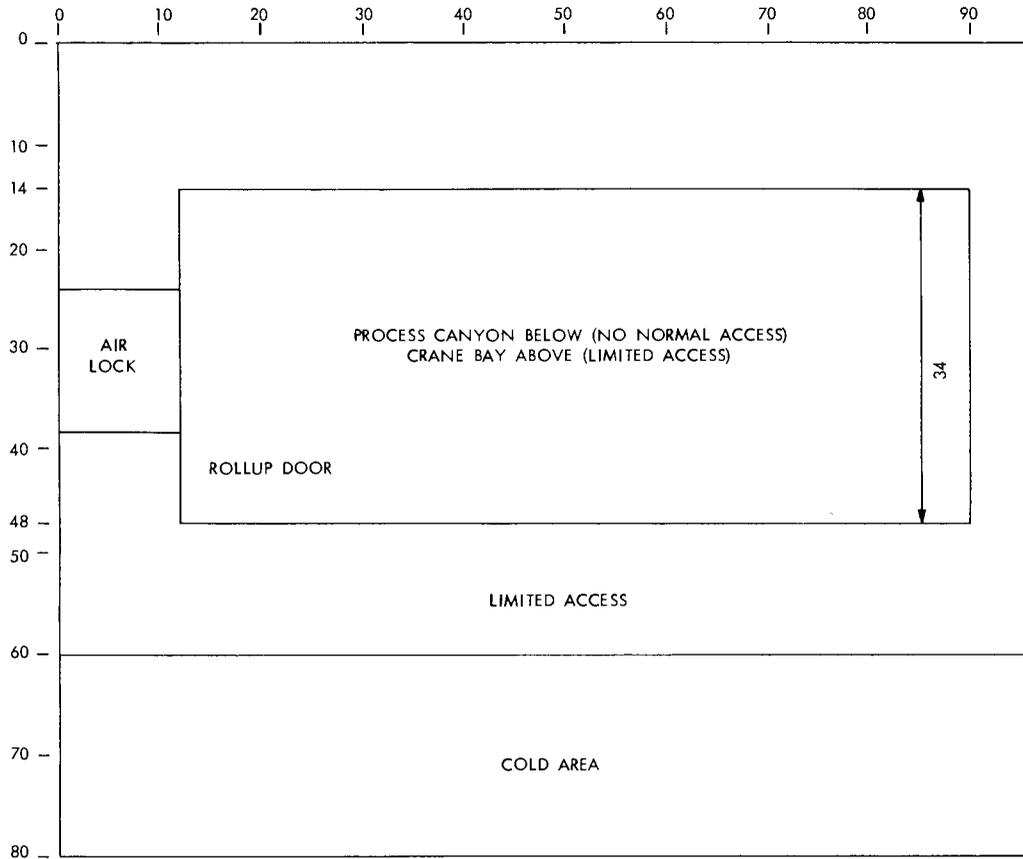
Maintenance materials are assumed to be equal in cost to maintenance labor. Chemicals, principally four moles of formic acid per mole uranium, are estimated to cost 2 cents per pound of uranium. Overhead is allowed at 100% of the total labor cost.



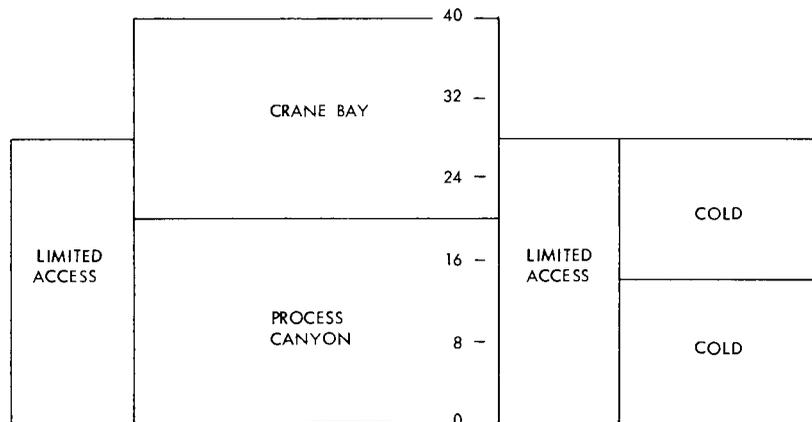
V.W. = VIEWING WINDOW

NOTE: DIMENSIONS IN FEET

Fig. 10. Cell Equipment Layout for Preparation of 1 Ton per Day of Reactor Grade UO<sub>2</sub>-PuO<sub>2</sub>.

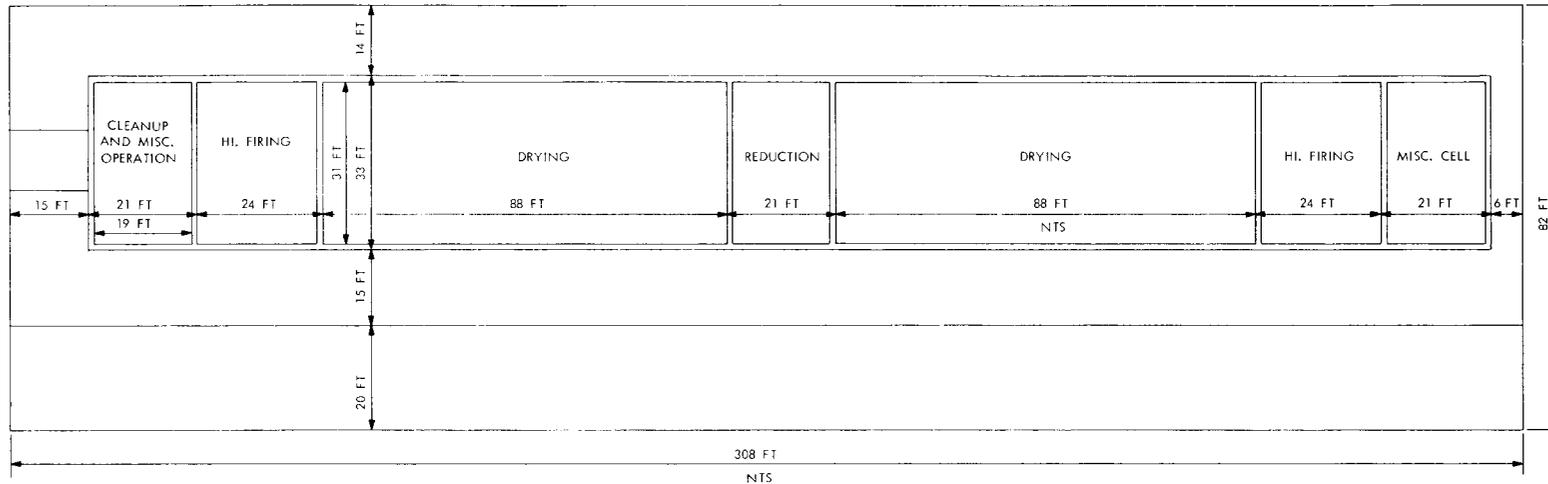


NOTE: DIMENSIONS IN FEET

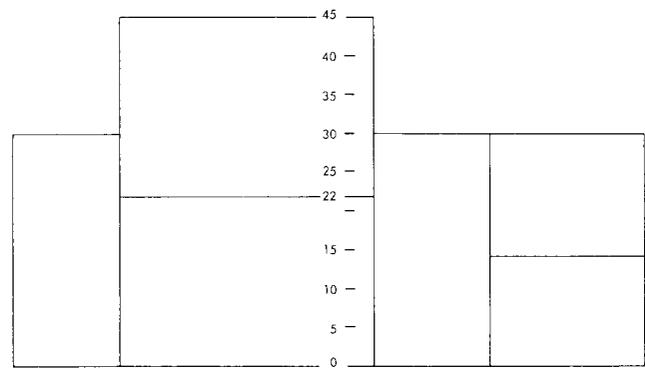


NOTE: DIMENSIONS IN FEET

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



PLAN BUILDING



BUILDING SECTION

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

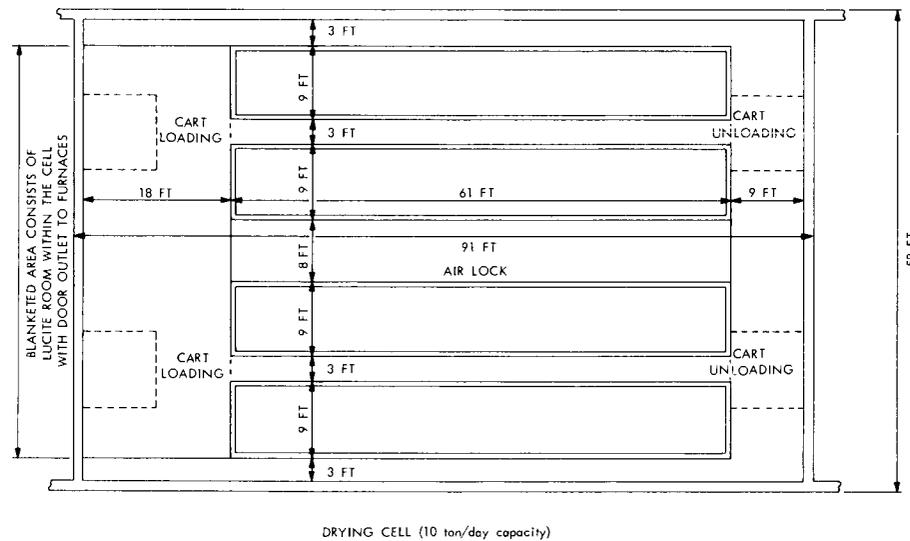
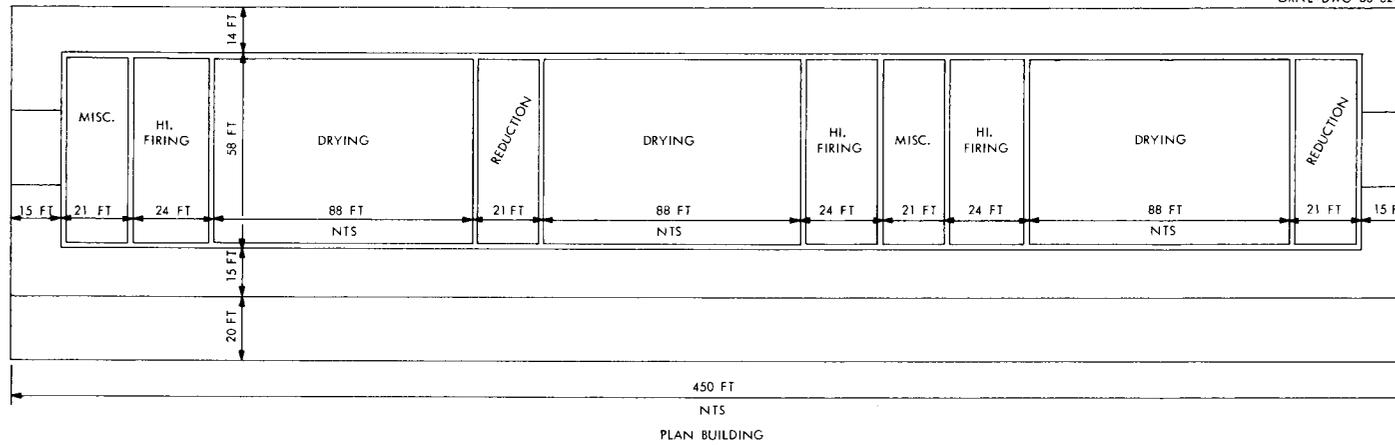


Fig. 13. Plan View of Plant Required for Preparation of 30 Tons per Day of Reactor Grade  $UO_2-PuO_2$ .

## 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<sup>5</sup> 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<br>U/day  | 10 tons<br>U/day | 30 tons<br>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 | <u>270.0</u>    | <u>86.9</u>      | <u>54.8</u>      |
| Amortization         | 107.4           | 31.7             | 22.2             |
| Total                | <u>377.4</u>    | <u>118.6</u>     | <u>77.0</u>      |

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<sup>6</sup> 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  $\text{HNO}_3$  fractionation equipment, to produce  $\text{NH}_4\text{F}$ , 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<br>U/day,<br>or<br>$2.82 \times 10^5$<br>kg/yr | 3 tons<br>U/day,<br>or<br>$8.46 \times 10^5$<br>kg/yr | 5 tons<br>U/day,<br>or<br>$1.41 \times 10^6$<br>kg/yr | 10 tons<br>U/day,<br>or<br>$2.82 \times 10^6$<br>kg/yr |
|--|--|---|---|--|
| UO <sub>2</sub> --0.5% PuO <sub>2</sub> Case |  |   |   |  |
| Capital cost of<br>plant, \$                 | 2.95   | 2.70  | 2.40  | 1.60   |
| Operating cost of<br>plant, \$               | 9.70   | 5.50  | 4.50  | 3.00   |
| Material cost<br>(zirconium), \$             | 4.30   | 3.95  | 3.70  | 3.40   |
| Rejects (8%), \$                             | 1.40   | 1.05  | .80   | .60  |
| Total, \$                                    | <u>18.35</u>   | <u>13.20</u>  | <u>11.40</u>  | <u>8.60</u>  |
| Natural Uranium UO <sub>2</sub> Case         |  |   |   |  |
| Capital cost of<br>plant, \$                 | 2.15   | 2.00  | 1.80  | 1.20   |
| Operating cost of<br>plant, \$               | 6.60   | 3.80  | 3.10  | 2.10   |
| Material cost<br>(zirconium), \$             | 4.30   | 3.95  | 3.70  | 3.40   |
| Rejects (5%), \$                             | .65  | .50   | .45   | .35  |
| Total, \$                                    | <u>13.70</u>   | <u>10.25</u>  | <u>9.05</u>   | <u>7.05</u>  |

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<br>Loss <sup>a</sup> | 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  |

<sup>a</sup>Value of plutonium = \$6.70 g; 1/4% loss.

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