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ASSESSMENT OF COATER SIZE FOR THE FUEL REFABRICATION PROTOTYPE PLANT

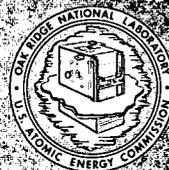
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UC-77 (Gas-Cooled
Reactor Technology)

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METALS AND CERAMICS DIVISION

ASSESSMENT OF COATER SIZE FOR THE FUEL
REFABRICATION PROTOTYPE PLANT

W. J. Lackey, J. D. Jenkins, F. J. Homan,
and R. S. Lowrie

JULY 1974

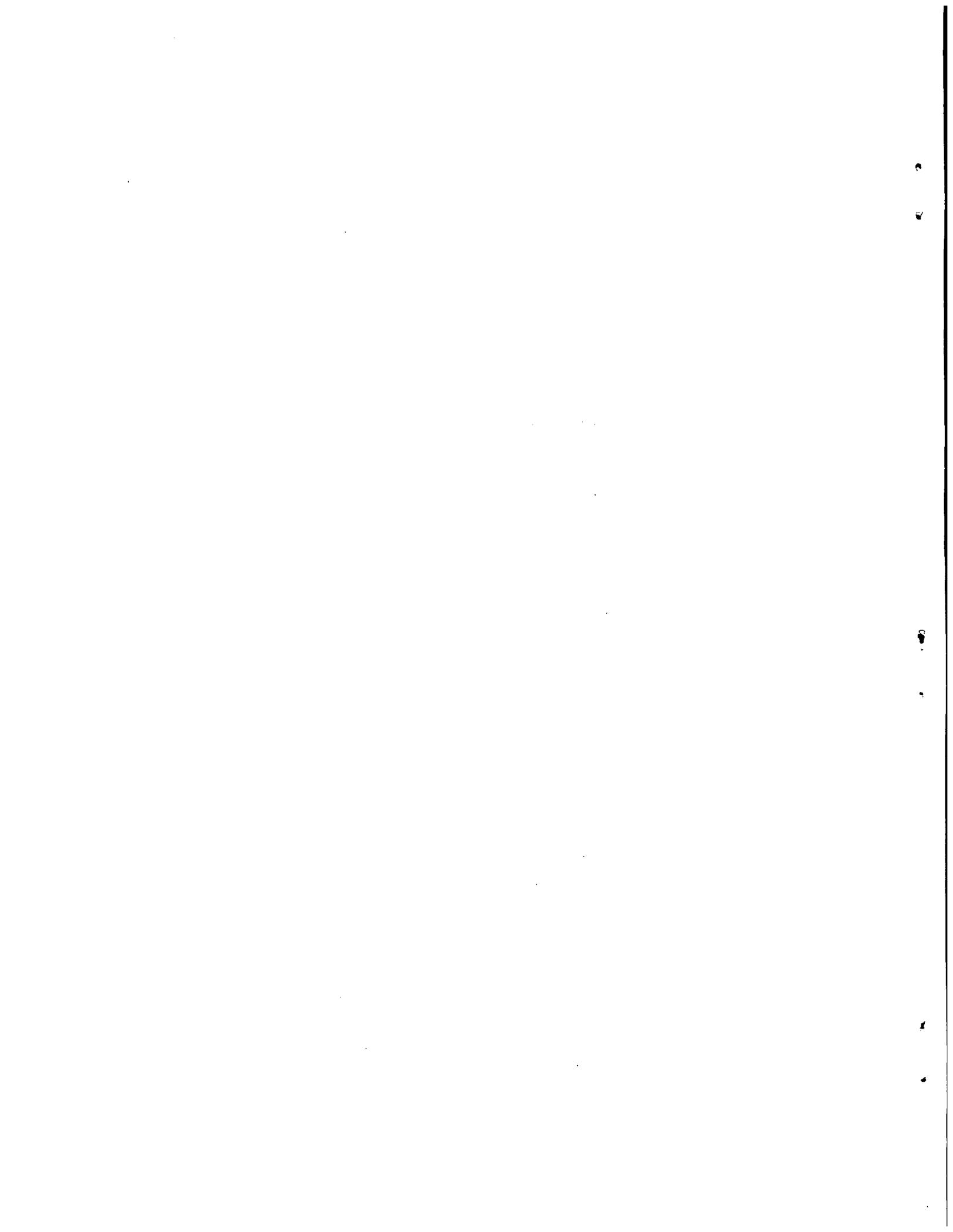
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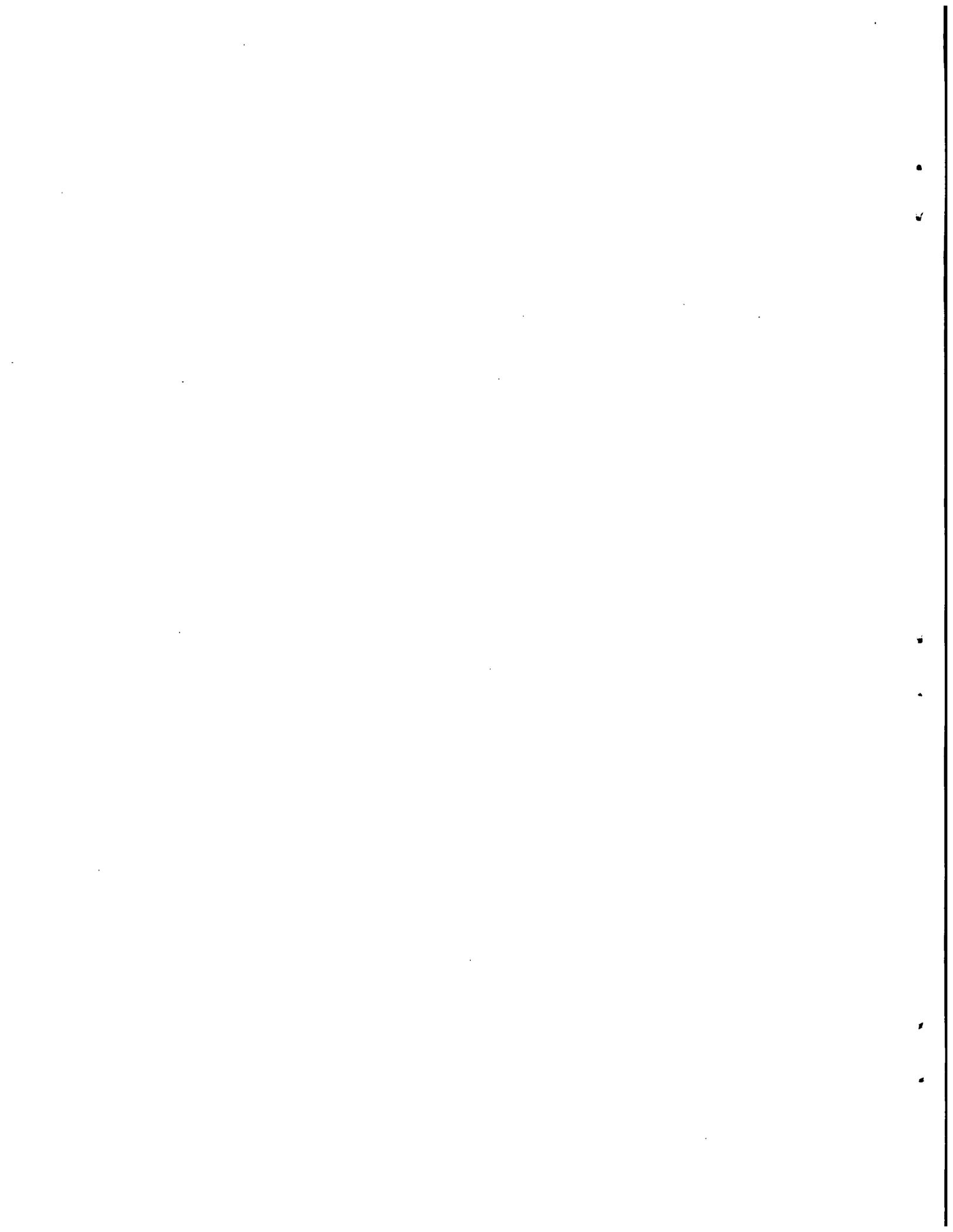


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ASSESSMENT OF COATER SIZE FOR THE FUEL
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ABSTRACT

An assessment of the economic and technical advantages and disadvantages associated with use of 9-in.-diam coaters in a remote HTGR refabrication plant rather than use of 5-in.-diam coaters was conducted. The larger coater is clearly favored from the economic standpoint. Criticality considerations dictate that 9-in.-diam coaters must never be flooded with hydrogenous materials and thus the furnace coolant and soot scrubbing media cannot be water or any other hydrogenous material. Suitable alternate materials that are not good moderators appear to be available. Development of a 9-in.-diam coater to the state of development currently existing for the 5-in.-diam prototype remote coater would require about one million dollars and 2 1/2 to 3 years. We recommend that 5-in.-diam coaters be used in the TURF prototype plant, but also recommend immediate parallel development of the 9-in.-diam coater.

INTRODUCTION

Current plans call for the use of two 5-in.-diam coaters in the fuel refabrication prototype plant to be located in the Thorium Uranium Recycle Facility (TURF). The coater size of 5 in. in diameter was selected several years ago. The purpose of this report is to reassess coater size in the light of current technology. It will be shown that the cost of coating decreases with increasing coater size for coaters having a diameter of up to 9 in. and thus, if practical, larger coaters are desired. Larger coaters of 9.5 in. diameter have been used to coat fertile material, but only coaters 5 in. or less in diameter have been used for fissile material. As implied above, criticality considerations are paramount in determining the practicality of larger coaters for fissile materials. The coaters considered here are for coating fissile material in either commercial or prototype refabrication plants.

COATING COSTS VERSUS COATER SIZE

Although one intuitively feels that the cost of coating should decrease with increasing coater size, a quantitative economic evaluation seemed worthwhile. Also, it was of interest to calculate the benefit-to-cost ratio associated with developing a 9-in.-diam remote coater compared to use of 5-in.-diam coaters. These economic questions were answered using as a basis the cost and operating data listed in Table 1. Coaters varying in diameter from 1 to 11 in. were considered. As will be shown later, 9- and 11-in.-diam coaters must be of the nonhydrogenous type. The additional cost associated with this requirement, although only a small fraction of the coater cost, was included for the 9 and 11 in. coaters. The values in Table 1 were based on an assumed fabrication plant having an output of 150 kg of heavy metal per day (45,000 kg/year) in the form of TRISO-II coated $(4\text{Th},\text{U})\text{O}_2$ particles. A plant with this output would serve about 30 reactors if the fissile particles had a thorium-to-uranium ratio of 4:1. If the kernels were of the undiluted resin type having a uranium density of 3.2 g/cm^3 then a plant with the same number of coaters would have an output of about 270 kg of uranium per day. Thus, for the resin particle case the assumed plant would serve about 54 reactors. The refabrication plant was assumed to come on line in 1985 and operate for 20 years. The direct construction cost was assumed to be \$1300 per ft^2 of hot cell area. A fixed charge rate of 30% per year, a discount rate of 10%, and an annual rate of inflation of 5% were assumed. All cost values were present worthed to January 1975. The cost of developing a 9-in.-diam remote coating furnace was conservatively taken to be one million dollars annually for a period of three years beginning in 1975.

The results of the economic analysis are summarized in Table 2. The last entry shows that the coating cost per kilogram of heavy metal decreases on increasing the coater diameter from 1 to 9 in. The higher cost per kilogram for the 11-in. coater compared to the 9-in. coater probably reflects inconsistencies in the capital and operating cost estimates rather than signaling an optimum coater diameter. The apparent large cost advantage resulting from use of a 9-in. rather than a 5-in.

Table 1. Input for Comparing Remote Coating Costs
for Different Size Coaters

	Coater Diameter (in.)			
	1	5	9	11
Coating Furnace and Effluent Treatment Equipment Capital Cost (Thousands of dollars per coater)	100	225	315	380
Direct Hot Cell Construction Cost Based on \$1300 per ft ² (Thousands of dollars per coater)	104	195	234	260
Coater Lifetime (year)	8	8	8	8
Hot Cell Lifetime (year)	20	20	20	20
Charge (kg of heavy metal per coating run)	0.04	1	4	5
Duration of Coating Run Required to Deposit all Layers (hr)	5	5	5	5
Percent of Time Coater is Gainfully Used	75	60	55	50
Number of Coaters	1042	52	14	13
Manpower (hr per day per coater)				
Operators	28	32	64	70
Quality Control	4	5	7	8
Quality Assurance	1	1	1	1
Maintenance	10	16	55	80
Coater Components (dollars per coating run)				
Frit	4	15	25	30
Coating Chambers	1.5	6	20	40
Heating Element	2.5	7	20	40
Coating Gases (dollars per kg heavy metal)				
Acetylene	0.6	0.6	0.6	0.6
Propylene	0.6	0.6	0.6	0.6
Silane	1.6	1.6	1.6	1.6
Argon	2.0	2.0	2.0	2.0
Hydrogen	5.4	5.4	5.4	5.4
Electricity for Coater (dollars per coating run based on \$0.02/kWhr)	1.5	7	19	24

Table 2. Coating Costs in Millions of Dollars as a Function of Coater Size for a 150 kg/day Remote Plant

	Coater Diameter (in.)			
	1	5	9	11
Direct construction	108	10.1	3.3	3.3
Equipment	<u>222</u>	<u>25.0</u>	<u>9.4</u>	<u>10.2</u>
Subtotal A	330	35.1	12.7	13.5
Site improvement (0.5% of Subtotal A)	1.6	0.2	0.1	0.1
Owners' cost (4.7% of direct construction)	50.8	4.7	1.6	1.6
Indirect cost (74.7% of direct construction)	80.7	7.5	2.5	2.5
TOTAL Capital Cost (Subtotal B)	<u>463</u>	<u>47.5</u>	<u>16.9</u>	<u>17.7</u>
Direct manpower cost per year at \$12,000/man-year	67.0	4.2	2.7	3.0
Indirect manpower cost per year (50% of direct)	33.5	2.1	1.3	1.5
Coating gases per year	0.5	0.5	0.5	0.5
Coater components per year	9.0	1.3	0.7	1.0
Furnace power per year	<u>1.7</u>	<u>0.3</u>	<u>0.2</u>	<u>0.2</u>
TOTAL Operating Cost Per Year	112	8.4	5.4	6.2

Calculation of Cost per kg of Heavy Metal

Capital cost component ^a (\$/kg heavy metal)	3087	317	113	118
Operating cost component (\$/kg heavy metal)	<u>2490</u>	<u>187</u>	<u>120</u>	<u>138</u>
TOTAL Cost ^b (\$/kg heavy metal)	5577	504	233	256

^aBased on 30% capital cost (i.e., cost per year equated to 30% of Subtotal B.

^bFor the resin case described on page 2, it follows from the ratio of heavy metal densities that the costs in dollars per kg of uranium are about three times the tabulated values.

coater is thought to be real. The potential savings arising from the use of 9-in. rather than 5-in.-diam coaters is large compared to the estimated cost of developing a 9-in. coater. The present worth benefit and development costs are 93.1 and 2.86 million dollars, respectively, which results in a benefit-to-cost ratio of 33. The benefits would be larger if greater HTGR penetration into the electrical economy were assumed.

CRITICALITY CONSIDERATIONS

An important design criterion for any coating furnace is that it must be subcritical in the worst possible accident configuration. The worst possible accident configuration for a 9-in.-diam coater would probably be achieved if the coating chamber and the containment shell of the furnace were flooded with an hydrogenous moderator while charged with a batch of uncoated particles. Subsequent boiling of the moderator or continued gas flow could levitate the particles in the liquid to achieve an undesirably high hydrogen-to-uranium ratio. In a recent test, a 5-in.-diam Plexiglas conical-type coating chamber was deliberately flooded with water. Unfortunately, with typical flows of air into the coating chamber, both bare and coated ThO_2 particles were dispersed rather uniformly throughout the water to a height of about 1 ft. Similar results were obtained when a porous plate-type coating chamber was flooded. The prototype remote furnace, as currently designed, could be flooded with cooling water or with kerosene from the off-gas scrubber should the latter become plugged with soot.

Calculations of infinite reflected cylinders of $\text{H}_2\text{O}-\text{ThO}_2-^{233}\text{UO}_2$ (ref. 1) indicate that such mixtures can become critical at diameters of about 6 in. for 4:1 thorium-to-uranium particles and 5 in. for 1:1 thorium-to-uranium particles. Criticality is achieved at readily obtainable hydrogen-to-uranium ratios if particle levitation is allowed.

A series of Monte Carlo calculations have been run to investigate the criticality problems associated with a finite length 9-in.-diam coating furnace. The calculations modeled three possible configurations for a water-cooled furnace with a kerosene off-gas scrubber. These were:

(1) normal operation, (2) the furnace tube and outer containment shell flooded with kerosene and the particles resting on the bottom, and (3) the furnace tube and outer containment shell flooded with kerosene and the particles levitated within the furnace tube to achieve an optimum hydrogen-to-uranium ratio. Fuel kernel compositions of $(4 \text{ Th,U})\text{O}_2$ and $(\text{Th,U})\text{O}_2$ were considered, and the fuel kernel charge was assumed to be either 10 kg or 25 kg. Table 3 presents the details and results of these calculations.

The following conclusions can be drawn.

1. Cooling or off-gas scrubbing with a hydrogenous material cannot be allowed in a 9-in.-diam furnace if the possibility of flooding and particle levitation is present (cases 8, 9, 10, 14, and 15).

2. For a thorium-to-uranium oxide ratio of 1:1, a 10-kg charge of coated particles quiescent on the bottom of a kerosene-flooded furnace is limiting (case 13).

3. In the absence of a hydrogenous moderator, a 9-in. furnace is critically safe for reasonable batch sizes. (Additional calculations recently completed confirm this conclusion.)

4. Note that where flooding is assumed, criticality is more likely for coated particles than for bare particles. The reason for this is that application of the coating in effect disperses the particles and therefore increases the quantity of hydrogenous material in the immediate vicinity of the uranium.

Other criticality calculations that we have performed show that a 9-in. coater for particles having a Th:U ratio as high as 8:1 would have to be of the nonmoderated type. Criticality calculations (ref. 1) also show that a 9-in.-diam furnace is feasible even for UC_2 or carbonized resin derived particles which have Th:U ratios as low as 0:1 provided there are no hydrogenous moderators present. Prior to carbonizing resin particles, the hydrogen-to-uranium ratio is about 10 and thus criticality considerations might limit batch size if carbonization was performed in a 9-in.-diam furnace. Carbonization of resin particles in an auxiliary furnace to about 500°C , which is sufficient to remove most of the hydrogen, would alleviate this problem.

Table 3. Problem Description and Calculated k_{eff}^a for Possible 9-in.-diam coating Furnace Configurations

Case	Th:U	Condition	Charge of Heavy Metal (kg)	Particle Type	Calculated k_{eff}
1	4:1	Normal operation	25	Bare	0.153
2	1:1	Normal operation	10	Bare	0.167
3	1:1	Normal operation	25	Bare	0.335
4	1:1	Normal operation	10	Coated	0.104
5	4:1	Flooded, no levitation	10	Bare	0.580
6	4:1	Flooded, no levitation	10	Coated	0.836
7	4:1	Flooded, levitated H:U = 50	10	Bare	0.868
8	4:1	Flooded, levitated H:U = 100	10	Bare	1.027
9	4:1	Flooded, levitated H:U = 200	10	Bare	1.120
10	4:1	Flooded, levitated H:U = 50	25	Bare	1.087
11	4:1	Flooded, levitated H:U = 50 + ^{234}U	10	Bare	0.851
12	1:1	Flooded, no levitation	10	Bare	0.725
13	1:1	Flooded, no levitation	10	Coated	0.954
14	1:1	Flooded, levitated H:U = 50	10	Bare	1.184
15	1:1	Flooded, levitated H:U = 100	10	Bare	1.283

^aThe effective multiplication constant (k_{eff}) is less than unity for a subcritical system, unity for a just critical system, and greater than unity for a supercritical system.

NONHYDROGENOUS COATER

Since it appears that a 9-in.-diam coater can be safely operated only if there is no chance of water or other hydrogenous moderators entering the coater, we should consider the feasibility of eliminating moderating liquids from the coating system. There are three primary sources of moderating liquid. These are (1) water for cooling the gas injector, electrodes, furnace shell, and other furnace components, (2) kerosene or varsol that might be used to scrub the effluent generated during carbon coating, and (3) an aqueous sodium hydroxide solution used to scrub the HCl and unreacted silane present in the effluent during silicon carbide coating. These sources of moderators are discussed below.

COOLING WATER

With a considerable development effort, it should be feasible to cool the gas injector, electrodes, furnace shell, etc., with one of the freons (carbon-chlorine-fluorine compounds), perchloroethylene, or some other nonhydrogenous coolant and thus eliminate this source of water. The freons are free of hydrogen and thus are not good moderators. The heat capacity of the freons is about 20% that of water which may make it difficult to obtain adequate cooling of the electrodes and gas injector or frit holder. Cooling of the frit holder is thought to be critical because of the undesirable tendency of the coating gas to heat on passing through the frit. Excessive heating causes decomposition of the coating gas and eventual plugging of the frit. Also, modifications to allow accommodation of the relatively high vapor pressure of the freons would be required. Perchloroethylene appears to be a preferable coolant.

Scrubbing Liquid for Effluent Treatment

Because of the limited amount of heat that can be released to the hot cell, it is thought impractical to burn the soot and hydrocarbons present in the effluent during deposition of carbon coatings. Another reason why burning of the effluent is not attractive is that containment of the exhaust would be difficult. Failure to contain radioactive particles and gases as well as the soot emanating from the burner would result in contamination of fuel and other pieces of equipment in the cell. Burner maintenance would also be high and even with a burner, a soot filter is needed for treating the burner effluent. Nearly all of our experience in treating the effluent from carbon coaters has been obtained by using several designs of fiberglass bag-type filters such as the one shown in Fig. 1. Such filters perform very well insofar as collection of the soot is concerned. However, hydrocarbon vapors pass through the warm filter, subsequently cool, and deposit downstream as naphthalene crystals and liquid hydrocarbons. These deposits are very undesirable in that they quickly plug the High Efficiency Particulate Absolute (HEPA) filters. Because of this, we have designed and are currently fabricating the scrubber shown in Fig. 2. This scrubber will replace the soot filter

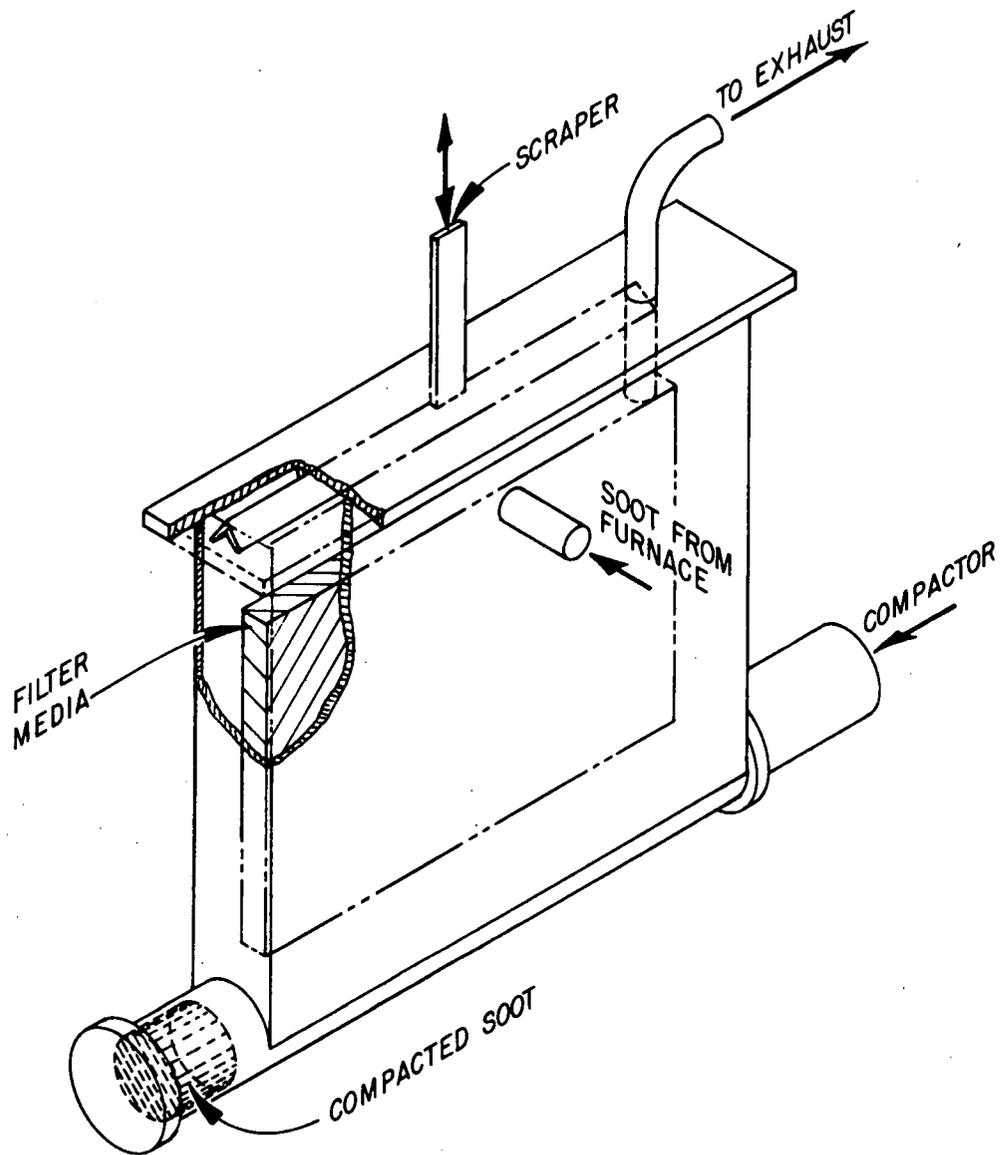


Fig. 1. Scrapper-Type Fiberglass Bag Soot Filter.

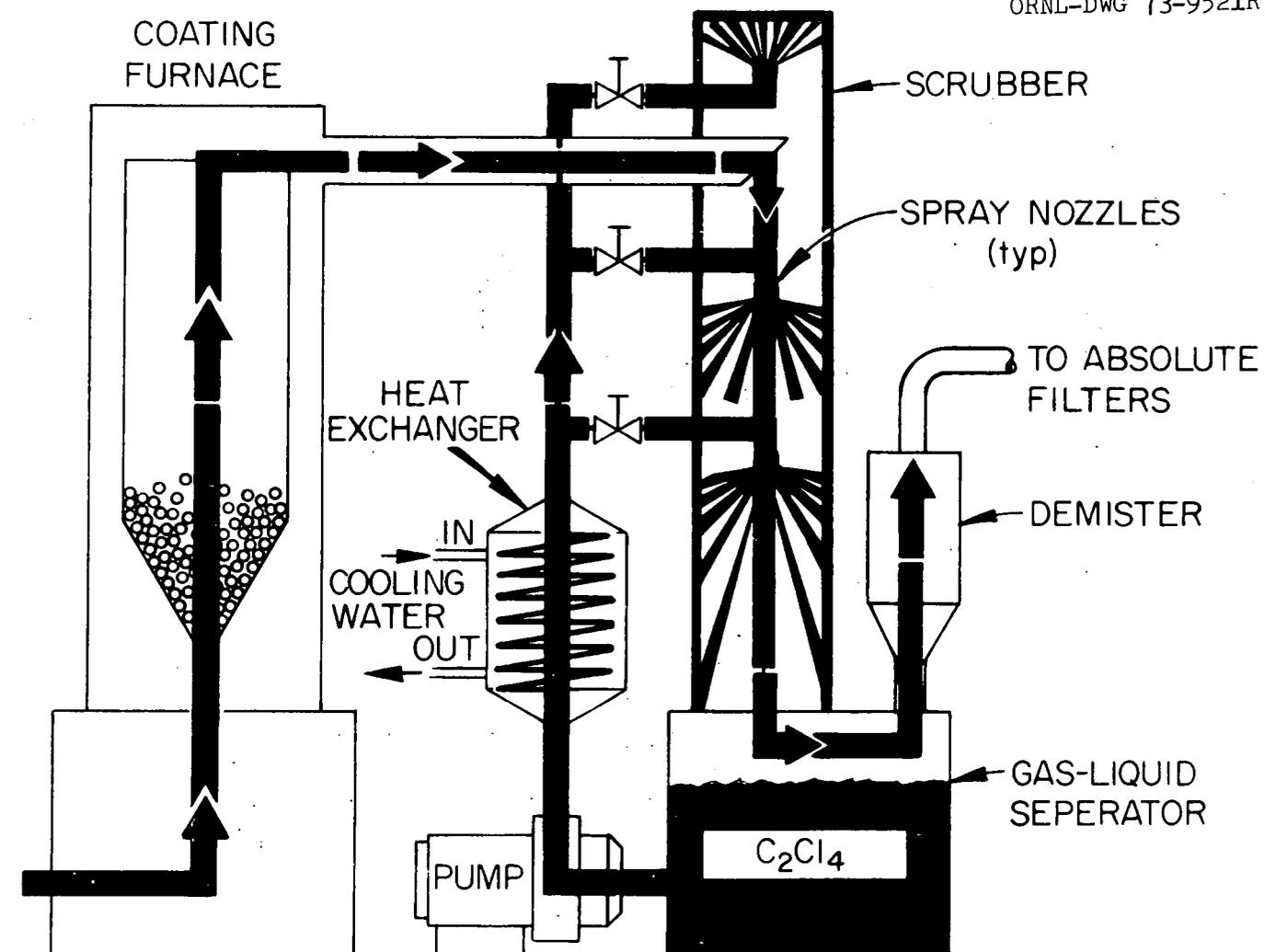


Fig. 2. Perchloroethylene Scrubber for Removing Soot and Hydrocarbons Present in the Effluent during Carbon Coating.

and hopefully will trap the soot and dissolve the hydrocarbons in the organic scrubbing liquid. It is plugging of this scrubbing column that could conceivably result in flooding the coater with the scrubbing liquid.

Originally, kerosene or varsol were considered for use as the scrubbing liquid. However, because kerosene and varsol are good moderators, they are undesirable for use with a 9-in. coater. Because of the presence of the soot, we do not feel that a trap located between the furnace and the scrubber would be a sufficiently reliable means of preventing the scrubbing liquid from entering the furnace. The freons are noted for their degreasing power and were also considered for use as the scrubbing liquid. Ability to dissolve organics is desired because of the presence of liquid hydrocarbons mentioned above. However, the high vapor pressure of the freons essentially rules out their use for this application. An additional problem with the freons is the possibility of contamination of the coated particles with fluorine and chlorine as a result of freon backstreaming into the furnace.

Fortunately, perchloroethylene (C_2Cl_4) appears well suited for use as the scrubbing liquid. It is nonhydrogenous and an excellent degreaser. It also has the additional advantage, when compared to kerosene, of not being flammable. Also, its vapor pressures appear suitably low since its boiling point is $120^\circ C$. The vapor pressure at $25^\circ C$ is 25 mm Hg. Thus, perchloroethylene would probably be a good liquid for use in scrubbing the effluent present during carbon coating.*

Of course, it would be possible to eliminate the scrubber from the coating system by using one of the bag-type filters. If this approach were taken, the hydrocarbon vapors that pass through the bag could be removed by a cold trap. The requirements for design and maintenance of such a trap are currently unknown.

*Note added during proof: The perchloroethylene scrubber has been used about a dozen times to deposit both buffer and isotropic carbon coatings as well as to carbonize resin particles. The performance of the scrubber was excellent.

Sodium Hydroxide Solution for Effluent Treatment

The appreciable quantity of HCl vapor and the smaller quantity of unreacted silane that are present in the effluent during deposition of silicon carbide coatings cannot be released to the atmosphere. The HCl and silane have been successfully removed by scrubbing with an aqueous solution of sodium hydroxide using the equipment shown schematically in Fig. 3. Since the effluent is mostly gaseous, the sodium hydroxide scrubber does not have to be located as near the coating furnace as does the scrubber used for the carbon coating effluent, but the sodium hydroxide scrubber is coupled directly to the furnace via the exhaust line. It is likely, however, that a liquid trap or check valve or other device could be built into this line that would be sufficiently foolproof to permit operation with no risk of getting the solution into the furnace. One complicating factor to such an approach is that the exhaust gas, even in the case of silicon carbide coating, contains a fine particulate material that could conceivably fill or plug the liquid trap or make a check valve inoperative. Perhaps the effluent gas could be passed through the perchloroethylene scrubber to remove particulates and then routed to the sodium hydroxide scrubber via a line that includes a trap.

An alternative to the use of a sodium hydroxide scrubber is removal of the HCl by reaction with a dry solid such as CaO in a packed tower. Channeling of the gas in dry towers is a common problem, but by using several towers, this shortcoming could probably be endured. Disposal of the used particulate material after it has become slightly radioactively contaminated might be a problem. Also, we do not know if the unreacted silane will be decomposed and neutralized by this dry tower type treatment.

DISCUSSION

From the long-term economic viewpoint, use of 9-in.-diam coaters is clearly preferable to the use of smaller coaters even when estimated development costs are considered. Consequently, the reference fissile coater for commercial refabrication plants, and for that matter, fresh fuel plants should be 9 in. in diameter since no overriding technical problems are envisioned for the long run.

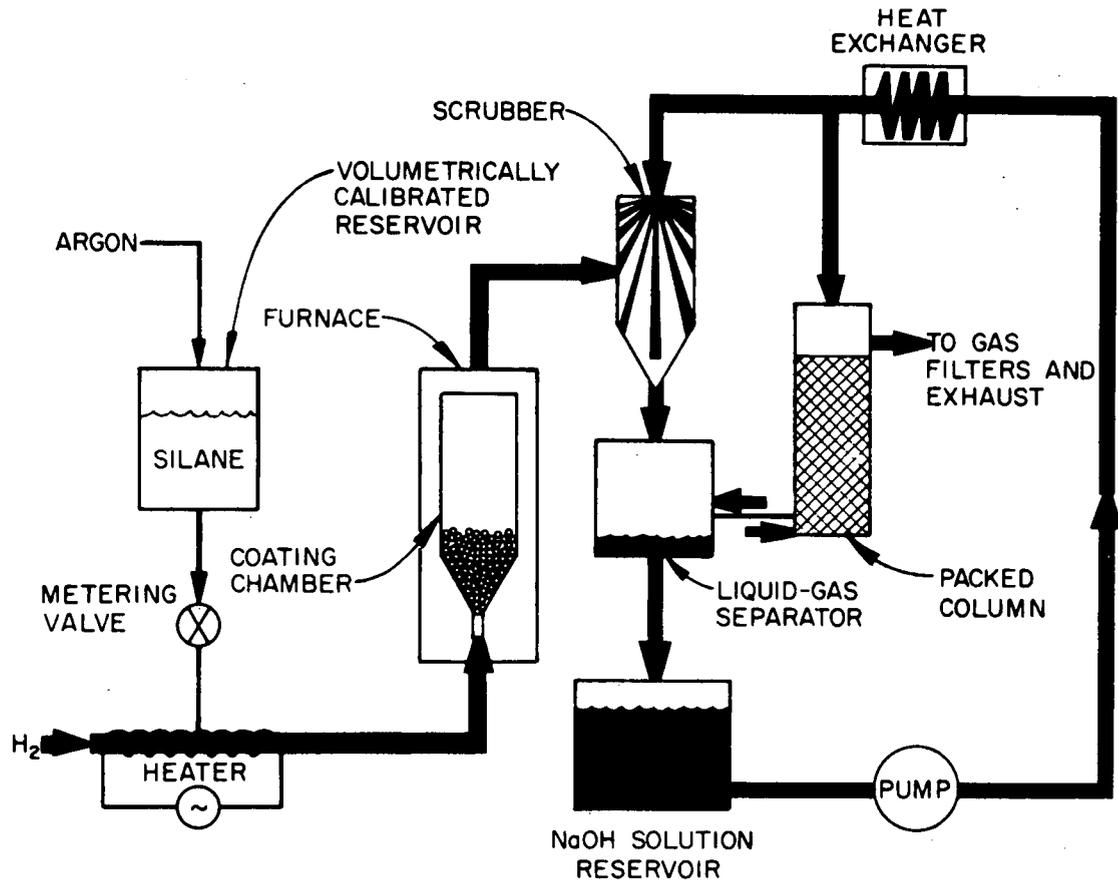


Fig. 3. Schematic of Coating Furnace and Effluent Treatment Equipment for Deposition of Silicon Carbide.

For the short term (i.e., for TURF) whether or not to use 9-in.-diam coaters is a trade-off of the additional equipment and process development effort required for a 9-in.-diam coater vs the gain from having the larger coater in the prototype plant demonstration. In addition to scheduling, the factors one must consider in making this trade-off are summarized in Table 4. The additional time and cost required to develop a 9-in.-diam coater to a state of development comparable to that currently existing for the prototype remote 5-in.-diam coater are estimated in Fig. 4 and Table 5. Note that the elapsed time is 34 months and the estimated cost is 1.05 million dollars. (The cost and time required for additional irradiation testing to develop a 9-in. coater was not included.) To meet the schedule in Fig. 4, development of the 9-in. coater would have

Table 4. Comparison of 5- and 9-in.-diam Remote Coaters
for Coating Fissile Particles

Item	Diameter (in.)	
	5	9
Development Cost	+	-
Long-Term Coating Economics	-	+
State of Equipment Development		
Gas Injector	±	±
Gas Distributor	+	-
Electrodes	+	-
Furnace Coolant	+	-
Effluent Treatment	+	-
Particle Unloader	±	±
General Hardware	+	-
State of Process Development		
Buffer Coating	+	-
LTI Coating	+	-
SiC Coating	+	-
Product Inspection	-	+
Expected Product Quality	+	-
Plant Licensing (Criticality)	+	-
Product Licensing	+	-
Ease of Equipment Development	+	-
Ease of Process Development	+	-

CODE: + or - represents advantage or disadvantage,
respectively.

± signifies that no significant difference is
expected.

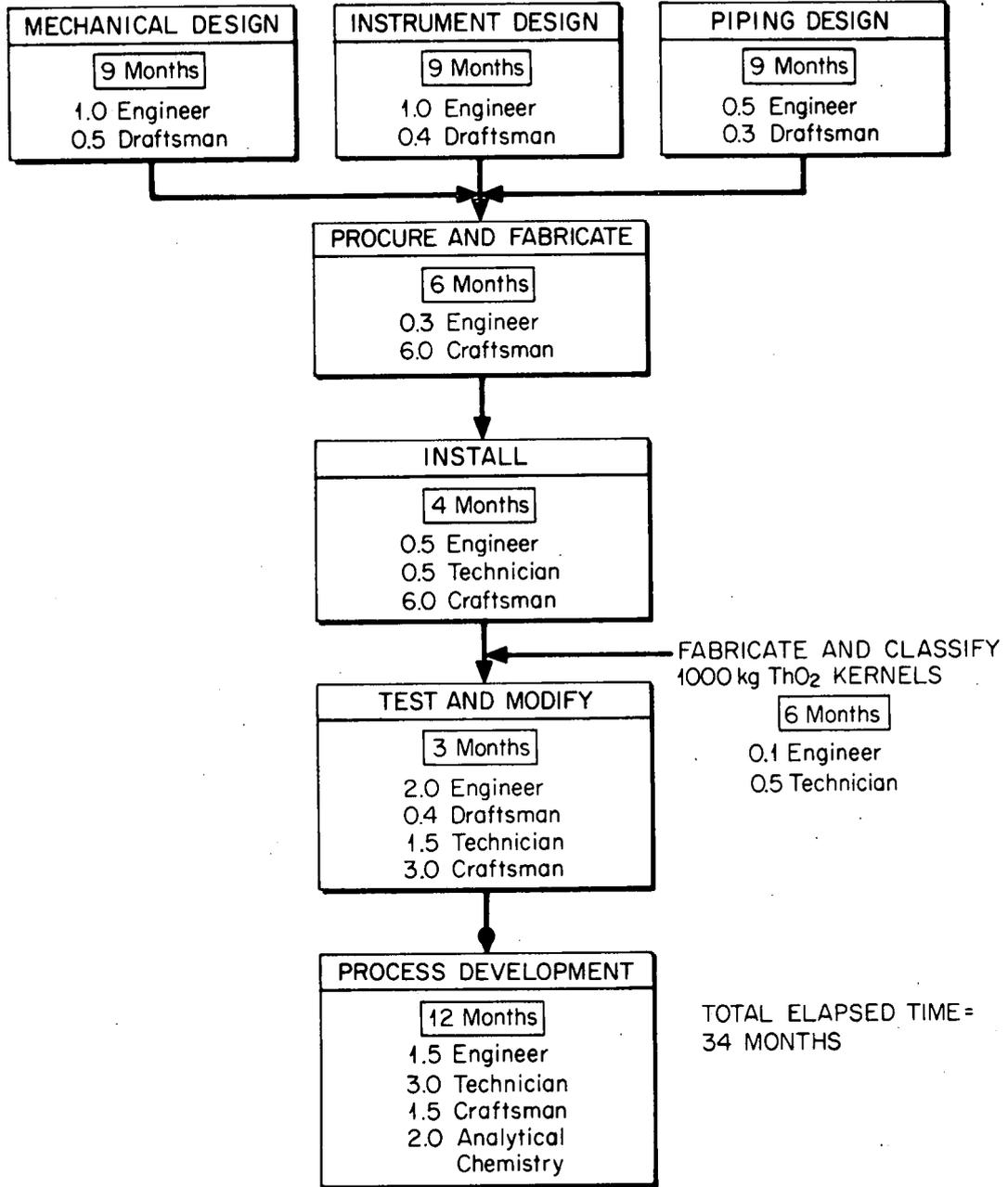


Fig. 4. Time Estimates to Develop a 9-in.-diam Remote Coater to the State of Development Currently Existing for a 5-in.-diam Coater.

Table 5. Cost Estimate to Develop a 9-in.-diam Coater
to the State of Development Currently Existing
for a 5-in.-diam Coater

Item	Many years	Cost (Thousands \$)
Manpower		
Engineer	4.8	240
Draftsman	1.0	25
Technical	3.8	150
Craftsman	7.3	185
Analytical Chemistry	2.0	80
Procurement		170
Coating Chambers, Frits, Heaters		25
20% Contingency		175
TOTAL		1050

to be given high priority and all of the assumed manpower would have to be made available. Even with virtually unlimited manpower and funding, this schedule could not be accelerated by more than six months. The 1.05 million dollars is in addition to the currently anticipated level of funding for the development program. The current funding would be required even if the additional 1.05 million dollars for the 9-in. coater were approved. The current funding would be used to continue development of equipment for effluent treatment, temperature monitoring and control, and numerous other equipment items as well as be used for continuing process development.

We recommend that 5-in.-diam coaters be used in the TURF prototype plant, but also recommend parallel development of the 9-in.-diam coater. Great emphasis should be placed on immediately beginning development of the larger coater because of the large benefit-to-cost ratio and also because of the large absolute cost savings.

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