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INFORMAL AEC RESEARCH
AND DEVELOPMENT REPORT

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CENTRAL REPROCESSING PLANT
FOR HTGR FUELS

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INTRODUCTION

The High-Temperature Gas-Cooled Reactor (HTGR) developed by General Atomic utilizes fuel elements consisting of thorium and uranium particles contained in graphite blocks. Fuel cycle economics require that the U-233 formed during reactor operation be recovered and used in the fabrication of new fuel elements. Existing nuclear fuel reprocessing plants and those planned for construction are designed primarily to recover the uranium and plutonium contained in the metallic-sheathed fuel elements from water-cooled reactors. The dissimilarities between HTGR and water reactor fuels result in some differences in reprocessing methods and in reprocessing plant equipment. These differences lie almost exclusively in the area of preparing the fuels for the chemical separation. Unique processes and/or equipment are needed for each fuel type. It is possible to modify a reprocessing plant designed for water-cooled reactor fuels to permit HTGR fuel reprocessing by the addition of the unique facilities needed for HTGR fuels. Studies have been made on adding such facilities to the Nuclear Fuel Services (NFS) plant.^(1, 2) On the basis of cost analyses, however, this approach to reprocessing HTGR fuels cannot be justified.^(2, 3) This results from only a fraction of the NFS plant operating time being available for HTGR fuels. As a consequence the facilities and equipment added for HTGR fuels would have a low utilization factor and a correspondingly high amortization charge. For a reasonable HTGR economy size, it would be necessary to add HTGR fuel reprocessing capability to more than one water-cooled reactor fuel reprocessing plant of the NFS type.

A plant tailored to reprocessing spent HTGR fuels would be expected to yield lower reprocessing charges because only facilities and equipment needed for HTGR fuels would be provided. Accordingly a study was made on a central reprocessing plant specifically for HTGR fuels. This report contains the results of that study. Several variations in the design of HTGR fuel elements are under consideration. In addition, several variations are possible in reprocessing methods, particularly in the fuel preparation (head end) portion. One fuel design and one processing mode are used in this study. Studies on other fuels, reprocessing variations, and plant capacities are planned.

SUMMARY

A conceptual design and reprocessing costs have been developed for a central reprocessing plant to recover the thorium and bred uranium from spent HTGR fuel elements. The plant is sized to serve a 15,000 MW(e) HTGR economy. Flowsheets and material balances were developed for hexagonal block HTGR fuel elements containing pyrolytic carbon coated fertile particles (thorium plus bred uranium as oxides) and silicon carbide coated fissile particles (recycle U-233 plus makeup U-235 as oxides). A plant operating on-line efficiency of 75 percent was assumed. A burn-leach head end process is used to reduce the fuel elements to a solution that serves as feed to a three-cycle solvent extraction process. The plant products are a highly purified uranyl nitrate solution suitable for feed to a refabrication plant and a partially decontaminated thorium nitrate solution which is stored for Th-228 decay. The radioactive waste solutions are solidified and, after an interim storage period, are shipped to a licensed repository for disposal. The fissile particles are isolated and handled in the same manner as the solidified radioactive wastes.

Reprocessing operations and maintenance are carried out remotely. Auxiliary functions such as plant administration, utilities, analytical laboratories, and maintenance shops are incorporated in the plant site.

Based on present-day costs, the capital cost of the plant is estimated to be \$30,803,000. Annual operating costs are estimated at \$4,463,850. For a 15-year plant life, the estimated annual reprocessing charges are \$10,318,000 or \$62 per kilogram of thorium plus uranium in the unirradiated fuels.

Some variations in the makeup of the HTGR fuels can be accommodated through flowsheet modifications. HTGR fuels containing carbide fuel particle kernels or fuels fabricated for a "bred-uranium"* recycle mode can be processed at the same processing rate and, within the limits of accuracy, at the same costs.

Subsequent to this study it appears that the fertile fuel particles may also have a silicon carbide coating. A modification of the reprocessing method described in this study would then be used.

*Defined in HTGR Fuel Variations section.

STUDY ASSUMPTIONS

The flowsheets, material balances, equipment, and plant designs used in this study are based on the following assumptions and criteria:

1. The plant is to be self-sufficient, i.e. all of the ancillary facilities required for sustained operation are to be incorporated into the plant site.
2. Reprocessing capability is to be limited to HTGR fuel elements.
3. A "once-through" two particle, HTGR fuel cycle is used; i.e., the irradiated fissile particles which initially contain the fissile U-233 and U-235 are not reprocessed. The composition of a typical fuel element is shown in Table 1.
4. Where possible, the process steps and plant and equipment designs are to be based on proven technology.
5. The plant is to be capable of reprocessing the HTGR fuel elements from a 15,000 MW(e) HTGR economy.
6. The plant operates at design capacity 274 days per year (75 percent on-line operating efficiency).
7. Plant products are thorium and bred U-233 in the form of nitrate solutions. The bred U-233 is to be shipped as required to an HTGR fuel refabrication plant and is to have a chemical purity adequate for fuel refabrication. Thorium is to be available for fuel refabrication only after 10 to 15 years of decay storage.
8. The reprocessing plant is to be capable of reworking U-233 nitrate solutions from the refabrication plant.
9. The anticipated plant life is 15 years.
10. The plant is located in the United States and meets AEC licensing requirements.

11. Spent HTGR fuels are to be received in large standardized casks (about 40 element capacity) shipped by rail. The elements may be received canned or uncanned.
12. The plant is to be capable of storing fuel elements for 90 days of operation at the design processing rate.
13. Process equipment in radioactive service with less than a 15-year service life expectancy is to be remotely replaceable.
14. High-level radioactive wastes are to be solidified and shipped to repositories for ultimate disposal.
15. Reactor reflector blocks are not shipped to the reprocessing plant for disposal by burning.

On the basis of the above, the reprocessing plant is designed to process the fuel component quantities listed in Table 2.

TABLE 1
FUEL ELEMENT CHARACTERISTICS

Shape	Hexagonal block	
Width (in.)	14.17 across flats	
Length (in.)	31.22	
Weight at discharge (kg/element)		
Graphite fuel block		97.46
Carbon binder		4.94
Fertile particle components		
Thorium	10.48	
Uranium (primarily U-233)	0.30	
Fission products	0.41	
Oxygen (oxides)	1.55	
Pyrolytic carbon and buffer carbon coatings	10.90	
		23.64
Fissile particle components		
Uranium (primarily U-234 and U-236)	0.15	
Fission products	0.42	
Oxygen (oxides)	0.08	
Buffer carbon	0.30	
Silicon carbide	0.36	
Pyrolytic carbon	2.22	
		3.53
		129.57
Particle diameter (microns)		
Fertile particles		
ThO ₂ kernel (core)	350	
With buffer carbon coating	410	
With pyrolytic carbon coating	610	
Fissile particle		
UO ₂ kernel (70% voids)	200	
With buffer carbon coating	260	
With SiC intermediate coating	280	
With pyrolytic carbon coating	400	
Cooling time (days)		
At reactor	90 (minimum)	
At reprocessing plant	120	
At start of reprocessing	210 (minimum)	
Average burnup (MWD/Tonne of actinides)	67,000	
Heat release (BTU/hr/element)		
90 day cooled		1,700
210 day cooled		
Fissile particles	390	
Fertile particles	380	
		770

TABLE 2
FUEL COMPONENT QUANTITIES

Fuel blocks processed ⁽¹⁾			
		14063 per year	
		51.3 per process day	
		38.5 per day (yearly avg.)	
	Kg/fuel block	Kg/year	Kg/process day
Carbon ⁽²⁾	115.52	1,624,500	5928.7
<u>Unirradiated Fuel</u>			
Thorium	11.20	157,500	574.8
Uranium	0.573	8,055	29.4
Total	11.773	165,555	604.2
<u>Irradiated Fuel</u>			
Thorium	10.48	147,450	538.1
Fertile particle U (83% U-233)	0.305	4,290	15.66
Fertile particle fission products	0.410	5,760	21.0
Fissile particle U (primarily U-234 and U-236)	0.150	2,115	7.72
Fissile particle fission products	0.418	5,865	21.4

(1) Based on 3750 fuel elements per 1000 MW(e) reactor and a 4-year fuel life.

(2) Does not include the buffer carbon coating on the fissile particles.

BASIC PROCESS DESCRIPTION

In the flowsheets considered in this study, only the fertile fuel particles are reprocessed to recover the thorium and the bred U-233. The irradiated fissile fuel particles which not only contain relatively little residual U-233 and U-235 but also significant amounts of U-234 and U-236, are isolated, packaged, and stored for eventual disposal or for possible future processing. A burn-leach head end process is used to prepare the fuel components for Acid Thorex solvent extraction recovery. The high-level radioactive wastes are calcined, packaged, and stored for eventual ultimate disposal. Intermediate-level wastes are incorporated into an asphalt matrix and stored.

Burn-leach. The burn-leach head end process for graphite fuels was developed at both Brookhaven⁽⁴⁾ and Oak Ridge^(5, 6) National Laboratories. Application of this process to the reprocessing of the study fuel requires a number of process steps.

1. The fuel blocks are crushed to a size suitable for burner operation.
2. The crushed fuel is burned with oxygen in a fluidized bed reactor (burner) containing an inert bed of fused aluminum oxide (alumina) particles. Burning oxidizes the graphite fuel blocks and pyrolytic carbon fuel particle coatings to carbon dioxide exposing the fertile particle kernels. The silicon carbide coatings on the fissile particles are unaffected.⁽⁷⁾
3. Leaching the burner product (ash) with nitric acid containing a trace of fluoride dissolves the fertile particle components. The silicon carbide coated fissile particles are not dissolved.⁽¹³⁾
4. After rinsing, the leacher solids (fissile particles and alumina) are dried.

5. The dried leacher solids are screened to separate the fissile particles from the alumina.
6. The screened alumina is recycled to the burner.
7. Undersize alumina particles and the fissile particles are transferred to high-level waste processing.
8. Evaporation and steam sparging removes excess nitric acid from the leacher solution.
9. The denitrated leacher solution is routed to solvent extraction processing.

Block diagrams and material balances for the above process steps are shown in Figure 1.

Solvent Extraction. A conventional Acid Thorex solvent extraction flow-sheet^(8, 9, 10) is used to separate and decontaminate the fertile-particle thorium and uranium.

1. The leacher solution is contacted with a solvent containing 30 volume percent tributyl phosphate (TBP) in a normal paraffin hydrocarbon diluent (NPH) to extract the thorium and uranium. The aqueous waste which contains greater than 99 percent of the solvent extraction feed fission products is routed to high-level waste processing.
2. A dilute nitric acid solution strips the thorium and uranium from the 30 percent TBP solvent. The resultant aqueous solution containing the thorium and uranium is concentrated by evaporation.
3. Separation of the thorium and uranium is achieved by contacting the partially decontaminated thorium-uranium solution with 5 percent TBP in an NPH diluent which extracts only the uranium.
4. The uranium-free thorium solution is concentrated by evaporation and routed to storage tanks for decay of the Th-228 isotope.
5. The uranium is stripped from the 5 percent TBP solvent with a dilute nitric acid solution, concentrated by evaporation and routed to holdup tanks.

6. On demand of the fuel refabrication plant, the uranium is purified by extracting with 5 percent TBP in NPH diluent followed by stripping with a dilute nitric acid solution. This uranium purification system is also used to rework uranium recycle material from the refabrication plant. After concentration by evaporation, the purified uranium is shipped to the refabrication plant as a uranyl nitrate solution.
7. The solvent from the strip columns is washed to remove solvent degradation products and residual fission products. The solvent wash waste is routed to intermediate-level waste treatment.

Block flow diagrams and material balances for the solvent extraction processing are shown in Figures 2 and 3.

Waste Treatment. Various process steps are required for the disposal of the radioactive wastes.

1. The fissile particles and undersize alumina particles are sealed in high integrity containers which are transferred to a water-filled basin for interim storage.
2. The high-level radioactive waste solution is concentrated by evaporation and the evaporator overheads are routed to intermediate level waste treatment.
3. Calcination⁽¹¹⁾ converts the concentrated high-level waste to a solid. The calcined waste is sealed in high-integrity containers which are placed in a water-filled basin for interim storage.
4. The intermediate-level waste is concentrated by evaporation and the evaporator overheads are routed to a fractionator for nitric acid recovery.
5. After neutralization with caustic, the concentrated intermediate level wastes are incorporated into an asphalt matrix by combining with emulsified asphalt and dewatering in an evaporator. The asphalt-waste mixture is pumped to a storage tank.
6. After 15 years of storage, the containers of fissile particles and calcined waste are shipped to a salt mine repository for ultimate disposal.⁽¹¹⁾

The waste processing flowsheet and material balances are shown in Figure 4.

EQUIPMENT DESCRIPTION

Fuel Element Receiving and Storage

In considering the method of fuel receiving and storage, it is assumed the spent HTGR fuel elements may arrive uncanned. As a consequence, dry fuel element receiving and storage is used rather than the underwater receiving and storage methods common to metallic-sheathed elements. The arrangement of HTGR fuel reprocessing plant receiving and storage areas is shown in Figures 5 and 6.

The fuel receiving facility is designed to accommodate shipping casks mounted on railroad cars. After the railroad car with its cask in the unloading position is spotted in the unloading area, a shielding collar is lowered onto the cask by a power-operated screw jack. The load-in hatches of the shielded receiving area are opened and the shipping cask shield plug is removed. The HTGR fuel elements are then transferred by the receiving area crane from the shipping cask to the fuel storage area. If uncanned, a grapppler attached to the crane is used to transfer the elements into prepositioned cans in the storage area. Each 20-foot-long by 18-inch-diameter stainless steel can holds 7 hex block fuel elements. The storage area crane is used to place a lid on the filled storage can and to position the can in the storage rack. Reuseable storage cans are used to simplify fuel handling and to permit air cooling and ventilation of the storage area. If the fuel elements are shipped canned, the shipping can, the storage vault, and can handling equipment are to be made compatible so as to permit direct placement of the cans into storage. In this case, empty cans would replace those removed from the shipping cask, and be reused for other fuel shipments.

The receiving area crane is remotely controlled. Receiving operations are observed through a viewing window and by a closed circuit television system. A pair of manipulators is used to aid in the receiving operation and to perform some maintenance functions. Since the receiving area is normally used only for transferring radioactive material between the storage area and a railroad shipping cask, personnel can enter the receiving area when receiving is not in progress to perform the maintenance items that cannot be carried out with the manipulators.

The fuel storage area provides surge storage between fuel receiving and processing and also provides for part of the decay cooling time required between reactor discharge and the start of reprocessing. A 210-day (minimum) cooling time is used to allow for the decay of Pa-233 to U-233. This cooling time also allows fission product I-131 to decay to insignificant levels (about 25 half lives). The fuel storage area (Figure 5 and 6) contains 70 can storage rows accessible from a central transfer aisle. Each row holds 10 cans. With an allocation of two rows for handling purposes, 680 cans or 4760 fuel elements can be held in storage. This is adequate for about 90 days of sustained operation at the design rate of 51.3 fuel elements per day. A once-through ventilation system removes the fission product decay heat from the stored fuel. A fully loaded storage area containing elements ranging in cooling time from 90 to 210 days requires about 45,000 cfm of air to preclude excessive heating.

Operations within the storage area are performed by a remotely operated overhead bridge crane. A closed-circuit television system with crane-mounted cameras is used for operational control. The lights are also crane mounted. The crane bridge drive is located external to the storage area and is connected to the bridge by a shaft extending through the shield wall and a chain and sprocket mechanism. Special connections accessible from the crane maintenance area are used for lubrication of

the bridge drive mechanism. The bridge crane dolly is moved into the crane maintenance area when the crane is not in use or when maintenance is required on the crane, lights or television cameras.

A transfer dolly located in the transfer trench is used for transporting the fuel storage cans between the storage area and the crusher cell. The drive motor for the transfer dolly is located in the crusher cell operating gallery and is linked to the dolly in a manner similar to the fuel storage area bridge crane. A door over the crusher cell end of the trench is used for ventilation control. This door is operated by a rack and pinion mechanism with a hydraulic drive actuator in the operating gallery. Radiation monitors in the trench are used to detect the passage of fuel elements having cooling times significantly less than the specified 210 days.

Fuel Element Crushing

Prior to burning, the hex block fuel elements are reduced to a size compatible with burner feeding and efficient burner operation. Two roll-type crushers, one serving each burner, break the fuel blocks into about 1-inch pieces which are fed to the burner through an air-lock feeder. A crusher automatically shuts down when a collimated radiation detector indicates that a charge of crushed fuel has accumulated in the air lock. The pneumatically operated air lock valves are manually controlled by a process operator. Charges of crushed fuel are added to a burner at 30-minute to 1-hour intervals. At the design processing rate, each crusher handles 1 fuel block every 56 minutes. The crusher cell is at a higher elevation than the burners so that the crushed fuel may be fed to the burner by gravity.

Dusting within the crusher cell is minimized by enclosing each crusher in a purge box. Cell air drawn into a purge box passes through a sintered metal filter unit and is combined with the building ventilation

exhaust air for final filtration. The fines are blown off the filters by an automatic pulse blowback system and are combined with the crusher product.

Operation of the crusher cell (Figures 5 and 7) is carried out remotely. The crusher cell crane moves a fuel storage can from the transfer trench (Figures 5 and 6) to the tilting fixture. This fixture is a metal frame that can be pivoted about one end between a vertical and a horizontal position by means of a shaft extending through the shield wall to a hydraulically operated rack and pinion mechanism located in the adjacent operating gallery. A cradle receives the storage can and is automatically latched to the fixture frame when the frame is moved from a horizontal orientation. A manipulator operated clamp is actuated to hold the storage can to the cradle. With the tilting fixture and storage can still in a vertical position, the storage can lid is removed by the crane. The can is then tipped to a horizontal orientation and is carried in the cradle by means of the crane to a similar tilting fixture attached to a crusher. A manipulator operated mechanism seals the open end of the storage can to the crusher. The fixture is tilted to a near-vertical position and the fuel blocks fall into the crusher. At the design processing rate almost seven hours are needed to empty a storage can. In-cell electric motors are used to drive the crushers. Operations are observed through viewing windows and by a closed-circuit television with crane-mounted cameras. Lights are wall mounted.

Crusher cell maintenance is carried out remotely. Equipment is held in place by nuts tightened onto studs which are welded to fixed mounting plates. An impact wrench held by the crane or by a manipulator is used to make up or to loosen the nuts. An equipment piece can be replaced by removing the holddown nuts and lifting the piece from its mounting plate with the crane. The piece is moved from the building through the transfer trench, the fuel storage area and the fuel receiving station.

A truck- or train-mounted shielded box spotted below the fuel receiving port is used to transport the equipment piece to a burial ground for disposal or to the air-lock equipment maintenance area for decontamination and repair. The reverse operation is used to install a replacement piece. The remotely operated crane is positioned in the crane maintenance area for storage or for any necessary maintenance on the crane or television cameras. A shielding door between the crusher cell and the crane maintenance area permits contact maintenance of the crane.

Fuel Element Burning

In the burning operation, the graphite fuel blocks, the carbon binder and the pyrolytic carbon fuel particle coatings are oxidized to carbon dioxide by reaction with oxygen. In addition, any carbides in the fertile fuel particles are converted to oxides. Silicon carbide coatings are stable under the conditions of burner operation and only the outer pyrolytic carbon coatings on the fissile particles are removed.⁽⁷⁾ Thus, the fissile particle kernels remain intact along with their buffer carbon and silicon carbide coatings. Since the primary burning reaction is highly exothermic, fuel element burning is carried out within a fluidized bed to provide the heat transfer needed for the necessary temperature control. An inert fluidized bed material with a grain size no smaller than 30 mesh is used to permit subsequent separation of the fissile particles. Fluidized bed burning of graphite fuel elements has been demonstrated on a pilot plant scale^(4, 5, 12) with unirradiated fuel.

Pilot plant experience has shown that burning proceeds at a reasonable rate with bed temperature of 700° to 750°C. Combustion rates of about 15 kg of carbon per hour per square foot of burner bed cross sectional area have been obtained. Fused aluminum oxide (alumina) has proven to be a satisfactory inert fluidized bed material. During burner operation, approximately 90 percent of the oxygen is consumed. Carbon dioxide is the primary component in the burner off-gas with up to 10 percent carbon monoxide and up to 10 percent

oxygen. Noble gas, iodine, and other volatile fission products contained in the irradiated fertile particles also exit in the off-gas. A filter unit containing sintered metal filter elements removes entrained particles from the burner off-gases. Accumulated particulate entrainment is periodically removed from the filter elements by a pulse blowback system and returned to the burner bed. Cooling the off-gas prior to filtration has been shown to improve fission product removal.⁽⁵⁾ Small burners have been successfully operated with beds containing up to 30 percent heavy metal oxides.

In the reprocessing plant, criticality and physical size limitations require two independent burner units. Each burner is capable of processing 50 percent of the daily throughput (51.3 fuel blocks). A sketch of a plant burner is shown in Figure 8. Each burner is a dual diameter unit with a lower 42-inch diameter fluidized bed section and an upper 72-inch diameter deentrainment-cooling section. Type 310 stainless steel is the material of construction. The crushed fuel, added through a side entry line, is supported by an internal grid within the fluidized bed section. Other lines into the fluidized bed are used for adding alumina from a hopper and the fines from the off-gas filter unit. The burner ash, a mixture of alumina and fuel particles, is withdrawn from the bottom of the burner and is pneumatically transported into a burner ash hopper. The process flow-sheet and equipment sizes are based on a burner ash containing 25 weight-percent silicon carbide coated fissile particles plus fertile particle thorium, uranium and fission product oxides. During normal operation, oxygen from a liquid oxygen storage sphere is vaporized, metered, preheated and then introduced into the fluidized bed through a plenum chamber and a distributor plate. The rate of oxygen addition is the primary means of controlling the burning rate.

The heat of combustion is removed by a flow of cooling air. About 12,000 scfm of air flows through a jacket on the burner and through bayonet tubes within the burner. The bayonet tubes also cool the combustion

gases prior to their entry into the off-gas train. Fins on the burner wall and on the upper portion of the bayonet tubes improve heat transfer. Each burner has a closed-loop cooling air system consisting of a compressor, a water-cooled heat exchanger, and a bypass filter. The cooling system is maintained at a pressure of several psig to reduce the size of the air piping and to minimize potential leakage of burner bed material into the cooling air. Normal plant compressed air is used for makeup. A relief system containing an exhaust filter provides protection against overpressurization. Since the cooling air is normally free of radioactive components, the compressors, heat exchangers and filters are located in the operating gallery.

The burner off-gas passes through a number of equipment pieces to reduce the amount of radioactive entrainment. An independent off-gas train serves each burner. A bank of sintered metal filter elements equipped with an integral pulse blowback system removes the bulk of the entrained particles. Because of layout and maintenance considerations, the filter unit is separate from the burner. The burner fines blown off of the filter elements are returned to the burner bed through a dip leg. From the primary filter, the burner off-gas passes through a cooler and then through a silica gel adsorber to remove any fission product ruthenium that may be present as the volatile tetroxide. When necessary, the silica gel bed can be regenerated by washing with water or a dilute nitric acid solution. After ruthenium removal, the burner off-gas passes through a second filter which contains a deep bed of glass fibers. The off-gas is then combined with the building ventilation exhaust air for final filtration by absolute filters prior to atmospheric discharge through the plant stack. An ejector maintains the burner and the off-gas train at a subatmospheric pressure. The fission product noble gases and iodine are not removed. The fission products are kept well within the release limits by building air and atmospheric dilution and by preprocessing decay storage.

Several storage hoppers are associated with each burner. A burner ash hopper provides surge storage between a burner and the leacher. Fuel particles and the attendant alumina are continuously withdrawn from the burner and collected in the burner ash hopper. As required, all or part of the burner ash is transferred to the leacher hopper. The burner ash hoppers are equipped with cooling bayonets to remove the fission product decay heat. Alumina recycled from the leaching and screening steps is accumulated in recycle alumina hoppers for periodic return to the burners. A storage hopper is provided for each burner to receive and store a burner bed load during unscheduled production shutdowns or if burner maintenance is required. Cooling bayonets within the hoppers can be used to remove fission product decay heat. These storage hoppers are connected to their respective recycle alumina hoppers and are also interconnected to permit transfer of material between burners. Makeup alumina is added to a storage hopper from a supply hopper in the operating gallery. An air lock on the addition line provides contamination control. Where gravity flow cannot be used, pneumatic transport methods are used for solids transfer. Cyclone separators on the hopper inlets separate the particles from the pneumatic transport air. The hoppers are vented through a separate pneumatic transport vent system which contains a sintered metal primary filter unit and a secondary glass fiber filter. An ejector maintains the hoppers at a slight vacuum and discharges the filtered transport air into the building ventilation exhaust duct. Particulates accumulated on the primary filter are removed by a pulse blow-back system and are routed to one of the burner ash hoppers.

Both burners are in a common process cell as shown in Figures 5, 7, and 9. The elevation of the burners is below the crushers to allow gravity flow of the crushed fuel into the burners. The cooling air systems for the burners are outside of the process cell shielding wall in the basement of the operating area.

Leaching

The thorium and uranium oxides contained in the fertile particles are put into solution by dissolution with nitric acid. A trace of fluoride is added to catalyze the dissolution.

The principal chemical reactions are:

None of these reactions evolve much heat. In laboratory studies,^(5, 6) boiling 13 M HNO_3 , 0.05 M HF dissolved thorium oxide microspheres contained in an alumina bed in 3 to 6 hours. The burner ash from carbide HTGR fuels was dissolved with boiling 4 M HNO_3 , 0.05 M HF in the same time period. Aluminum nitrate added to the dissolvent to reduce leacher corrosion rates had no adverse effect on dissolution rates.⁽⁶⁾ Cadmium nitrate added for criticality control is not expected to affect dissolution rates. During burner ash leaching some of the alumina also dissolves. In ORNL studies⁽⁶⁾ 0.58 to 2.9 percent of the alumina dissolved during a 5-hour digestion period with boiling 13 M HNO_3 , 0.05 M HF solutions. The fraction dissolved was primarily dependent upon the particular brand of alumina used. Other laboratory studies⁽¹³⁾ have shown that silicon carbide coatings on the fissile particles remain intact during the leaching step. This permits the materials in the fissile and fertile particles to be separated from each other by this leaching step.

The central reprocessing plant leacher is designed for batch operation and is sized to handle the daily output of one burner as a single batch.

Leacher operating time cycles are as follows:

<u>OPERATION</u>	<u>TIME, HOURS</u>
Charge burner ash	0.5
Add leaching acid	0.5
Heat to boiling	0.5
Leach	8.0
Cool solution	1.0
Jet out leacher product solution	0.5
Add rinse solution	0.25
Slurry out alumina and fissile particles	0.5
Jet out rinse solution	<u>0.25</u>
TOTAL	12.0

From the above time cycle, it is seen that the one leacher provided is able to process the output of both burners.

The leacher, shown in Figure 10, is a dual-diameter vessel fabricated from type 309 stainless steel. The lower 30-inch diameter section is sized to contain a charge of burner ash and the upper 48-inch diameter section serves as a solution reservoir. A screen supports the burner ash and provides a small solution space below. Freeboard allowance is 100 percent of the solution plus burner ash volume. An air lift and head pot system is used for recirculation of the leaching acid through the bed of burner ash. The acid solution is elevated from the upper portion of the leacher (solution reservoir) to the head pot from where it flows into a pipe connected to the bottom of the leacher and upward through the bed of burner ash. The solution space below the bed support screen serves as a distributor. A heat exchanger in the recirculation line maintains the leaching acid at the boiling temperature. Coils in the solution

reservoir aid in the initial heatup and postleaching cooldown. The supply systems to the heat exchanger and coils are designed to maintain a positive pressure of steam, water, or air at all times so that any leakage would not contaminate the coil effluent. A second air lift with its suction at the support screen is used for leached burner ash removal. Boron stainless steel grids preclude nuclear criticality within the burner ash bed. Cadmium nitrate added to the leacher solution provides independent criticality protection. An air sparger is included for any necessary mixing. A water-cooled downdraft condenser condenses the overhead vapors which are returned to the leacher. Nitrogen dioxide (NO_2) present in the leacher off-gas is absorbed in the condensing vapors forming nitric acid. Air introduced by the air lift oxidizes nitric oxide (NO) to NO_2 . A steam jet on the recirculation line is used to remove the solutions from the leacher.

Leacher operation begins with the pneumatic transfer of burner ash to the weigh hopper located above the leacher. The weigh hopper, similar in design to the burner ash hopper, is instrumented so the weight of burner ash it contains is recorded. A predetermined weight of burner ash is dropped into the leacher through an addition line containing a remotely operated valve. A normal charge contains 269 kg of thorium, 7.86 kg of fertile particle uranium, 33.6 kg of fissile particles, and 1042 kg of alumina. Leaching acid is then added. If fresh nitric acid is used, a solution containing 13 M HNO_3 , 0.04 M HF , 0.08 M $\text{Al}(\text{NO}_3)_3$, and 0.075 M $\text{Cd}(\text{NO}_3)_2$ is prepared in the chemical makeup area and added batchwise. Sufficient leacher acid, normally 306 gallons, is added to give a terminal thorium concentration of one molar. If fractionator acid (recycle nitric acid) is used, the required volume of nitric acid is metered from the recycle acid tank directly into the leacher. A concentrated solution of the other constituents, prepared in the chemical makeup area, is added separately. The sparger is used to mix the two component streams. During normal steady-state operation, only recycle acid is used. Air-lift recirculation is started and the leacher is brought to its operating

temperatures by supplying steam to the coils. After the boiling point is reached, the steam flow is reduced so as to maintain a 1 to 2 GPM boilup rate. No unusual control problems are encountered since little heat and gaseous reaction products are generated. Recirculation and heating is continued until the fertile particles are dissolved. Since any partially dissolved fertile particles would follow the fissile particles during the subsequent screening step, an eight-hour leaching time is specified to ensure complete dissolution. For flowsheet purposes, it is assumed that about one percent of the alumina dissolves during leaching. After the leaching period, the steam to the coils is shut off and the cooling water turned on to cool the product solution sufficiently to permit jet transfer (50°C). The recirculation air lift is stopped and the solution jetted to the leacher product solution tank.

Rinsing of the residual burner ash is needed to minimize U-233 losses and to prevent fusion of the ash during subsequent drying. Sixty-six gallons of $0.075 \text{ M Cd(NO}_3)_2$ rinse solution, prepared in the chemical makeup area, are added while sparging. Air is supplied to the lower air lift and a slurry composed of the rinse solution and the leached burner ash (alumina and fissile particles) is transferred to the drying hopper. The drying hopper (described below) separates the rinse solution from the burner ash and returns the rinse solution to the leacher. Transfer of the slurry continues until essentially all of the leached ash is removed. The rinse solution is then jetted to the leacher product solution tank and combined with the leacher solution. The leacher is then ready for the next batch of burner ash.

The drying hopper, located above the leacher, serves several functions: (1) it provides the means of separating the leached burner ash from the rinse solution, (2) it serves as a receiver for the leached ash; (3) it provides the means of drying the ash, and (4) it is the feed hopper for the screening step. The hopper shown in Figure 11, has a fine mesh

screen false bottom that retains the alumina and fissile particles but allows the rinse solution to pass through. A valved return line routes the rinse solution back to the leacher. After a batch of leached ash has accumulated, 100 scfm of process air, heated to 400° F by passage through an electrical heater in the operating area, is blown through the bed of alumina and fissile particles for about four hours. The heated air evaporates the residual rinse solution. A water-cooled condenser condenses the water which is routed to the condensate receiver tank. A valved solids line feeds the dried alumina and fissile particles to the mechanical screener.

Screening

A separation of the alumina and the fissile particles in the leached burner ash is warranted by economic considerations. Recovered alumina can be recycled to the burner, thus greatly reducing the amount of fresh alumina required. Also, reducing the volume of the fissile particle waste stream reduces the cost of its required long-term, high-integrity storage.

The leached burner ash components are separated by mechanical screening. The silicon carbide coated fissile particles have a mean diameter of 280 microns. Allowing for a size range of 100 microns, the largest particles would pass through a 42 mesh screen. Since the alumina has a minimum size of 32 mesh, the smallest size ratio between these two components is about 1.5. During processing, the alumina is gradually reduced in size by mechanical attrition and chemical dissolution. Removal of degraded alumina is necessary for the successful operation the fluidized bed burners. Since the specified alumina particle size is larger than the fissile particles, degraded alumina will exit with the fissile particles during the screening step. Thus, screening also provides the means of maintaining the required particle size distribution of the fluidized bed material. For flowsheet purposes, it is assumed that 10 percent of the recycle alumina has degraded and exits with the fissile particles.

The mechanical screener is a totally enclosed, inclined, vibrating screen located below the drying hopper and above the alumina and fissile particle receiver hoppers. Vibration is induced by integral electromagnets. Batch screening operation is used so as to match the operating mode of the leacher. The screening equipment is sized to process 14 tons of leached burner ash per day. At this processing rate, a feed batch (the daily output of one burner) can be screened in two hours.

The two screened product streams are discharged into two individual hoppers. The fissile particle hopper contains boron stainless rods for criticality protection and cooled bayonets to remove the fission product decay heat. Periodically, a batch of fissile particles and degraded alumina is pneumatically transferred to the high-level waste cell for packaging. The alumina is received in a simple hopper and is pneumatically transferred as required to the burner cell for recycle to the burners.

Fissile Particle Packaging

Fissile particle disposal must provide: (1) adequate dissipation of the fission product decay heat, (2) reliable containment of the radionuclides, (3) accountability, and (4) retrievability. To meet the above criteria, the fissile particles are packaged in high-integrity stainless steel containers which are then stored in a water-filled storage basin. Details of the storage basin are discussed elsewhere in this report. The storage containers are made from 8-in diameter, schedule 40, type 304L stainless steel pipe and are 10 feet high. A maximum centerline temperature of 800°C could be attained in an 8-inch container under the following conditions:

1. Storage in 80°F air with forced convection.
2. Fissile particles from reference fuel element.
3. 210-day cooled.
4. Volumetric heat generation rate 1.5 times that from the flowsheet mixture of fissile particles and degraded alumina.

During the normal underwater storage, the maximum centerline temperature would be significantly less than 800°C . The eight-inch-diameter containers are critically safe if no more than eight rows of containers are stored adjacent to each other.

The daily output of fissile particles and degraded alumina is 1.04 ft^3 and 1.65 ft^3 respectively. The bulk volume (35 percent voids) of the combined solids is 4.14 ft^3 per day. Assuming a 6-inch unfilled space in each 10-foot tall container, 1.25 containers are filled daily. With a 10 percent allowance for alumina disposal, a total of 378 fissile particle containers are placed in storage each year.

Fissile particle packaging begins with the pneumatic transfer of the fissile particles from the fissile particle hopper to a weigh hopper in the waste packaging cell. A line containing a flexible section and a remotely controlled valve is connected to a storage container located in a filling station. A predetermined weight of fissile particles is dropped into the container. The fill line is disconnected and a plug is screwed into the fill hole on the container. The container is moved to a nearby welding station where the plug is seal-welded in place. After welding, the storage container is placed into a water-filled monitoring tank to check for leakage. A continuous stream of water from the monitoring tank is recirculated through a radiation monitor located in the operating area. An increase in radioactivity would be indicative of a leak. Since the material packaged in the fissile particle containers has been leached and rinsed in the leacher, the quantity of radioisotopes that would dissolve in the monitoring tank water from a leaky container would not cause gross contamination of the water. A container in which a leak was detected would be returned to the welding station where the plug would be removed, replaced, and rewelded. After several days, the fissile particle container is transferred to the water-filled storage basin. The overhead crane is used to supply empty storage containers. A portable rack is filled with a two-weeks supply of containers in the air lock and then moved to the waste processing cell.

Solvent Extraction Feed Preparation

The Acid Thorex flowsheet used for the solvent extraction decontamination and separation of the fertile particle materials requires that the feed solution be acid deficient in order to achieve a high fission product decontamination factor. An acid-deficient solution is one in which the free nitric acid concentration has a negative value. Since the combined leacher product and leacher rinse solution has a high nitric acid content, 6.84 molar, a denitration (nitric acid removal) step is necessary. Thorex pilot plant studies^(9,10) at the Oak Ridge National Laboratory have demonstrated adequate feed solution denitration by evaporation to a high salt concentration in a nitric acid stripper. Steam sparging during denitration was also demonstrated to reduce the required operating temperature which, in turn, reduces the corrosion rates in the stripper equipment. Denitration is achieved by vaporizing the excess nitric acid by the combination of evaporation and steam sparging. Decontamination from fission product ruthenium is particularly troublesome in the solvent extraction processing of thorium fuels. Other Oak Ridges studies⁽⁹⁾ have shown that ruthenium decontamination can be improved by the addition of sodium bisulfite, NaHSO_3 , to the denitrated solvent extraction feed solution.

In the reprocessing plant, the combined leacher product and rinse solutions contained in the leacher product receiver tank are mixed, sampled for accountability, and then transferred to the stripper feed tank. The solution is then air lifted at a controlled rate into the continuously operated stripper. In the stripper the excess nitric acid and water is vaporized leaving a highly concentrated solution containing thorium and uranium nitrates. A continuous steam sparge is used to reduce the operating temperature to about 275°F. The steam and nitric acid vapors pass through a packed deentrainment tower and are condensed in the stripper condenser. The concentrated stripper bottoms continuously overflow into a small water-cooled pot. Sufficient dilution water is metered into the overflow

pot to dilute the bottoms to a thorium concentration of 1.5 molar and the mixture is air lift transferred to the stripper receiver tank. The dilution water contains the sodium bisulfite needed for enhanced ruthenium decontamination. Tankage in the operating area is used for the makeup and addition of this dilute NaHSO_3 solution. Periodically the acid-deficient stripper product is transferred from the stripper receiver tank to the solvent extraction feed tank where the solution is sampled. Any necessary chemical adjustments are made at this point using the utility makeup and utility head tanks in the operating area.

The plant stripper, shown in Figure 12, is a 20-inch diameter pot 40 inches high and surmounted by a 12-inch-diameter by 10-foot-high tower packed with Raschig rings. Vapors from the top of the tower pass directly into the condenser. The condensate is routed to the condensate receiver tank and combined there with the condensate from the leached burner ash drying step. The noncondensable vapors are combined with those from the leacher for passage through a silica gel adsorber and a fiberglass bed filter before being combined with the building exhaust air for final filtration. An ejector located downstream of the fiberglass filter maintains the stripper and leacher at a slightly negative pressure. A steam sparger and a water-cooled overflow pot are incorporated with the stripper in addition to the normal services. Because of the relatively high operating temperature, the stripper coils are designed for 100 psig steam. A positive pressure of steam, water, or air is maintained on the coils at all times to preclude inward leakage of solution and contamination of the coil effluent. The pot, tower, and condenser are fabricated from type 309 stainless steel.

The ratio of U-233 to uranium plus thorium is sufficiently low (2.4 percent) to preclude nuclear criticality problems in the stripper.⁽¹⁴⁾

The head end equipment pieces are listed in Table 3.

TABLE 3
HEAD END EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia. (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp (°C)	Pressure (psig)	Material
1.	Liquid oxygen storage tank	1	40,000 gal.	---	(21.75 ft. dia. sphere)				-200	---	---
2.	Burner gas preheater	2	---	96 KW	(18 in by 6 in.)			8	750	10	Incoloy sheathed elements, 304SS duct
3.	Burner	2	---	(upper section) (lower section)	78 48	18	--	---	750	-1 to 8	310 SS
4.	Burner ash hopper	2	19 ft ³	4.5x10 ⁴ BTU/hr	28	6	--	12 (cooling bayonets)	750	-1	310 SS
5.	Recycle alumina hopper	2	30 ft ³	---	36	5.7	--	---	200	-1	304L SS
6.	Burner storage hopper	2	48 ft ³	4.5x10 ⁴ BTU/hr	44	6.7	--	30 (cooling bayonets)	750	-1	304L SS
7.	Fuel element crusher	2	5 tons/day	---	--	--	--	---	300	---	SS
8.	Crusher vent filter	2	15 scfm	---	16	2.75	--	4 (filter area)	300	-1	304L SS
9.	Burner off-gas primary filter	2	690 acfm	---	32	6.7	--	73 (filter area)	750	-1	310 SS
10.	Burner off-gas secondary filter	2	200 scfm	---	48	4	--	---	200	-1	Fiberglass filter media, 304L SS
11.	Burner off-gas cooler	2	---	2x10 ⁵ BTU/hr	10	--	10	120	500	-1 shell 100 tubes	304L SS
12.	Burner cooling air compressor	2	12,000 scfm	400 HP	--	--	--	---	150	5 inlet 10 outlet	CS
13.	Burner cooling air cooler	2	12,000 scfm	3.7x10 ⁶ BTU/hr	42	--	12	6750 (finned tubes)	250	10	CS

TABLE 3 (continued)
HEAD END EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia. (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure (psig)	Material
14.	Burner cooling air filter	4	1000 scfm	---	(1 ft	sq.)	1.5	---	250	10	CS
15.	Burner off-gas silica gel adsorber	2	200 scfm	---	48	4	--	---	200	-1	304L SS
16.	Leacher weigh hopper	1	19 ft ³	4.5x10 ⁴ BTU/hr	28	6	--	12 (cooling bayonets	200	-1	304L SS
17.	Leacher	1	900 gal.	(upper section) (lower section)	48 30	13	--	210 (coils)	120	-1	309SCb SS
18.	Leacher condenser	1	---	2x10 ⁶ BTU/hr	18	8	--	300	120	-1	309SCb SS
19.	Leacher receiver tank	1	550 gal.	---	38	10	--	50 (coil)	120	-1	309SCb SS
20.	Stripper feed tank	1	550 gal.	---	38	10	--	50 (coil)	120	-1	309SCb SS
21.	Stripper	1	55 gal.	3x10 ⁵ BTU/hr	20 12	3 3 (reboiler) 10 (tower)	--	20 (coil)	135	-1	309SCb SS
22.	Stripper condenser	1	---	5x10 ⁵ BTU/hr	11	--	6	45	135	-1	309SCb SS
23.	Stripper receiver tank	1	550 gal.	---	38	10	--	50 (coil)	120	-1	309SCb SS
24.	Condenser off- gas heater	3	---	2.5x10 ³ BTU/hr	6	--	2	2	150	-1	304L SS
25.	Silica gel adsorber	1	100 scfm	---	34	4	--	---	100	-1	304L SS
26.	Off-gas filter	1	200 scfm	---	48	4	--	---	100	-1	Fiberglass filter media, 304L SS

TABLE 3 (continued)
HEAD END EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia. (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure (psig)	Material
27.	Drying hopper	1	30 ft ³	---	36	0.7	--	---	400	-1 to +1	304L SS
28.	Mechanical screener	1	14 tons/day	---	(2 ft.by 2 ft.)		7	---	100	-1	304L SS
29.	Drying hopper air heater	1	100 scfm	15 KW	(8 in.by 8 in.)		1.5	---	300	20	Incoloy sheathed elements, 304L SS
30.	Drying hopper condenser	1	100 scfm	5x10 ⁴ BTU/hr	8	--	9	44	300	-1	304L SS
31.	Fissile particle hopper	1	4 ft ³	---	14	4.4	--	5 (cooling bayonets)	300	-1	Boron SS
32.	Alumina receiver hopper	1	18 ft ³	---	32	4.7	--	---	200	-1	304L SS

Solvent Extraction Flowsheet

A solvent extraction process is used to separate the fertile particle materials into (1) a U-233 product solution, (2) a thorium solution, and (3) a salt waste that contains the fission products. The inherent differences in the relative solubilities of the fuel element constituents between the aqueous and solvent phases is used to effect the required separations. The flowsheet utilized in the HTGR fuel reprocessing plant is based on the Acid Thorex process developed by the Oak Ridge National Laboratory⁽⁹⁾⁽¹⁰⁾ and includes three solvent extraction cycles. The Acid Thorex process utilizes nitric acid as the salting agent. Pulse column solvent extraction contactors similar to those used in most of the nuclear fuel reprocessing plants are used. Each cycle has an extraction column, a strip column, a solvent treatment system and related auxiliary equipment. The solvent extraction flowsheet and material balance are presented in Figures 2 and 3. The bulk of the fission products are separated from the thorium and uranium in the first cycle. Separation of the thorium and uranium is achieved in the second cycle and the third cycle removes the residual fission products, the U-232 daughters and nonradioactive impurities yielding a highly purified U-233 product. The third cycle solvent extraction equipment is sized to process the fertile particle U-233 from irradiated HTGR fuel elements in one-half the time required in the other processing equipment. Thus, the third cycle need only operate 50 percent of the process days. This permits the third-cycle equipment to be used for repurifying and/or dedaughterizing uranium recycled from the refabrication plant. If the recycle material contains both uranium and thorium, it may be necessary to blend the material with the second-cycle feed or to run the recycle material as a separate batch through the second and third cycles. The repurification flowsheet used would depend on the batch size and on the percentages of thorium present.

In the first cycle extraction column, the thorium and uranium are coextracted from the feed solution by a solvent composed of 30 volume

percent tributyl phosphate (TBP) in an inert diluent. The diluent is a normal paraffin hydrocarbon fraction (NPH) with normal dodecane as the prime constituent. This diluent is used in the AEC reprocessing plants at Hanford and Savannah River and has proved to be satisfactory. The acid-deficient feed solution is periodically transferred from the solvent extraction feed tank to the column feed (HAF) tank from where it is continuously metered into the midpoint of the first extraction (HA) column. Acid deficiency reduces the extractability of some of the fission products. A scrub stream (HAS) metered into the top of the column provides additional decontamination. Low concentrations of phosphoric acid and ferrous sulfamate in the HAS enhance decontamination from protactinium and the fission products. The ferrous ion also reduces the trace quantities of plutonium present to the inextractable +3 valence state so that the plutonium exits with the fission product waste stream. An intermediate scrub stream (HAIS) containing 5M HNO_3 provides some of the required salting strength and the remainder is supplied by a 13M HNO_3 stream (HAA) added near the bottom of the column. The various aqueous streams intermix as they move downward through the column and exit as the waste stream (HAW). The HAW is essentially devoid of thorium and uranium but contains greater than 99.9 percent of the fission products. The solvent stream (HAX) is metered into the bottom of the column from the solvent storage tank, rises countercurrent to the aqueous stream, extracts the uranium and thorium and some of the nitric acid, and overflows as the product stream (HAP). Within certain tolerances, a proper balance of the various streams must be maintained to achieve acceptable decontamination and waste losses. In addition, an excessive thorium concentration in extractants containing more than 10 percent TBP gives rise to the formation of a second solvent phase which renders the pulse columns inoperable. The use of an extractant with a TBP content sufficiently low to preclude second solvent phase formation would require an excessively high extractant flow in the first cycle. The HAW is routed to the waste processing cell for disposal and the HAP cascades into the bottom of the strip (HC) column.

In the HC column, a single aqueous stream (HCX) containing 0.01M HNO_3 is metered into the top, strips the thorium, uranium and nitric acid from the HAF, and exits as the product stream (HCP). The stripped solvent overflows to the HO solvent treatment system for purification. Because of solubility and operability considerations, the volume of the HCP stream is nine times that of the HAF. In order to minimize equipment sizes, the HCP is reduced in volume by evaporation prior to being fed to the second solvent extraction cycle. This evaporation also minimizes the quantity of nitric acid needed. Through evaporation, the thorium concentration is restored to the HAF value of 1.5 molar. Some solvent is entrained with and dissolved in the HCP. If the solvent remains with the HCP during evaporation, it will undergo chemical and thermal degradation and impair the operation and effectiveness of the subsequent solvent extraction cycle. This solvent is removed by steam stripping. The steam used is that generated during evaporation.⁽¹⁵⁾ The solvent exits with the condensed evaporator overheads which also contains traces of fission products and nitric acid. This steam stripping procedure causes refluxing of nitric acid present in the feed and thus reduces the amount of nitric acid that appears in the condensate. Since an acid-deficient feed is not necessary in the second cycle, the nitric acid present in the HCP appears in the second cycle feed (evaporator bottoms) and provides some of the required salting strength.

In the second solvent extraction cycle, the thorium and uranium are separated from each other and the uranium receives additional decontamination. The second cycle extraction (1A) column is continuously fed from the 1A column feed tank which also serves as the receiver tank for the HCP evaporator bottoms. The 1AX (5 volume percent TBP in a NPH diluent) is metered into the bottom of the 1A column from the 1AX solvent tank. Uranium is more readily extracted than thorium by a TBP solvent. By adjusting the relative 1AF and 1AX flow rates, all of the uranium and only a portion of the thorium is extracted. A 2M HNO_3 scrub stream (1AS)

added to the top of the column not only enhances decontamination of the uranium bearing solvent stream (1AU) but also strips any extracted thorium back into the aqueous stream. Thus the 1AU is essentially free of thorium. All of the thorium exits with the aqueous effluent. The 1AU stream cascades into the bottom of the 1C column where the uranium is stripped back into the aqueous stream by the 1CX. The 1C column product (1CU) is steam stripped and reduced in volume by evaporation in a manner similar to the HCP stream. The stripped 1C column solvent effluent is routed to the 1O solvent treatment system for purification.

The thorium contained in irradiated HTGR fuel elements contains Th-228 from the decay of U-232. Some of the Th-228 decay daughters emit highly energetic alpha and gamma radiation. As a result recovered and purified thorium has a significantly higher radiation level than naturally occurring thorium. The cost of natural thorium is sufficiently low that the inherently higher cost of using freshly recovered thorium as feed material to a refabrication plant cannot be justified. After 10 to 15 years of storage, the Th-228 and its daughters decay to levels comparable to natural thorium.⁽¹⁶⁾ Therefore the recovered thorium (1AT) from the 1A column is reduced in volume by evaporation and stored for 10 to 15 years as an acidic nitrate solution. In order to minimize the tankage required for thorium storage, the solution volume is reduced to the limits of thorium solubility. Since the 1AT contains a moderate nitric acid concentration and since nitric acid reduces the solubility of thorium nitrate, the 1AT evaporator is operated so as to evaporate a significant portion of the nitric acid. No steam stripping of the 1AT is used for solvent removal since this operation refluxes the nitric acid. The small amount of solvent present will undergo total chemical and/or radiolytic decomposition during the storage period. A portion of the HCP evaporator condensate is also added to the 1AT evaporator to aid in nitric acid removal. The 1AT overheads are condensed and routed to the intermediate level waste cell for nitric acid recovery and disposal. Denitration of the 1AT by a procedure

used in the head end stripper can not be used for reasons discussed later. The concentrated thorium solution continuously overflows the thorium evaporator to a receiver tank. Periodically the $2.26\text{M Th(NO}_3)_4$, 1M HNO_3 solution is transferred from the receiver tank to the thorium storage facilities.

As discussed previously, the third solvent extraction cycle is designed to purify not only the uranium from reprocessed HTGR fuels but also that recycled from the fuel refabrication plant. The concentrated uranium solution from the 1CU evaporator overflows to a receiver tank and is then transferred to either one of two storage tanks. These storage tanks have sufficient capacity to store the uranium output from 30 days operation. Another storage tank is provided to receive and store the re-cycle material from the refabrication plant. The uranium purification flowsheet is similar to the second solvent extraction cycle with the following exceptions:

1. An acid addition stream is metered into the 2A column feed from the storage tanks. This acid addition provides part of the required salting strength and dilutes the feed for better column operability.
2. Dual scrub streams are used. A top scrub (2AS) of demineralized water minimizes both the nitric acid and ordinary chemical impurity content of the 2A column product (2AU). A 3.8M HNO_3 intermediate scrub (2A1S) furnishes the remainder of the required salting strength and improves decontamination.
3. The 2A column aqueous effluent (2AW) is routed to the intermediate level waste cell for disposal.
4. The concentrated uranium product is routed directly from the 2CU evaporator receiver tank to the uranium loadout area for shipment to the fuel refabrication plant.

Each solvent extraction cycle has its own solvent treatment system which removes solvent impurities formed by radiolytic and chemical degradation experienced during passage through the pulse columns. Removal

of these degradation products is necessary for the proper chemical and mechanical operation of the solvent extraction system. Dibutyl phosphate (DBP), one of the degradation products of TBP, combines with thorium to form a slimy precipitate. All three solvent-treatment systems have identical basic flowsheets although the equipment sizes differ because of variations in throughput requirements. The solvent effluent from the strip column is routed to a tank solvent washer where the solvent is contacted with a dilute solution of sodium carbonate. The solvent continuously overflows the tank washer into an attached reservoir from where it is metered into the bottom of a pulse column (HO1, 1O1, or 2O1). A sodium carbonate stream introduced into the top of the column countercurrently scrubs the solvent. These scrub solutions are prepared in operating area makeup tanks and are metered to the columns from head tanks. A column scrub effluent serves as the scrub feed to the related tank washer. Spent sodium carbonate solution is continuously withdrawn from the washer and routed to the solvent wash waste tank. The partially treated solvent cascades from the pulse column to a packed column (HO2, 1O2, or 2O2) where it is countercurrently contacted with a dilute nitric acid scrub stream. The solvent effluent from this final treatment column overflows to the solvent storage tank for return to the extraction column (HA, 1A, or 2A). The acid effluent flows into the solvent wash waste tank where it is neutralized by the sodium carbonate. Periodically the wash waste is transferred through a decanter to the intermediate-level waste cell for disposal. The decanter separates any entrained solvent and returns it to the tank solvent washer. When necessary, fresh makeup solvent may be added to one of the systems via its tank solvent washer.

Solvent Extraction Equipment

Pulse columns are used for the extraction, strip, and one of the solvent treatment contactors for the three solvent extraction cycles. The HA column which is typical of the pulse columns used in the HTGR fuel

reprocessing plant is shown in Figure 13. In pulse columns, contacting of the solvent and aqueous phases is achieved by using an externally imposed pulsing action on the column contents to force the phases through horizontal sieve plates. This action causes the intimate mixing of the two phases needed for effective extraction. A typical sieve plate has 1/8-inch diameter holes on 1/4-inch centers with the holes indented to form a nozzle.⁽¹⁵⁾ The pulsing action moves the column contents through an amplitude of 0.5 to 1 inch at a frequency of 50 to 120 cycles per minute. In any particular column, the pulsing conditions can be varied to give the optimum efficiency at the operating throughput rate.

The extraction and strip columns are conservatively designed to operate at a throughput rate of 800 gallons per hour per square foot, sum of both phases. In the solvent treatment columns the design throughput rate is 500 gallons per hour per square foot. Table 4 summarizes the column diameters and heights. The column heights are based on the number of stages required and typical stage heights obtained in column operation.^(9, 15) Column diameters are sufficiently small to preclude criticality problems at the U-233 concentrations obtainable within the columns.

Disengaging sections at both ends of the columns are sized to give a 10-minute (minimum) holdup time for the effluent stream. For criticality purposes, annular disengaging sections⁽¹⁷⁾ with concrete cores are used on the extraction and strip columns. The interface between the two solvent extraction phases can be maintained in either the top or bottom disengaging section. During column operation, a layer of solids (crud) accumulates at the interface and builds up to an equilibrium value. This interface crud contains undesirable impurities and a high concentration of fission products. Because the interface crud exits with the nearest effluent stream, the interface is maintained in the disengaging section opposite the primary product effluent. Top interface positions are used in the strip columns and those in the extraction and solvent treatment columns are at the bottom.

TABLE 4
SOLVENT EXTRACTION COLUMNS

Column	Dia. (in.)	Height (ft)	
		Plate Section	Overall
HA	7.0	27.7	32.7
HC	8.3	21.0	26.5
1A and 2A	3.0	28.0	32.1
1C and 2C	3.0	22.0	26.1
HO1	8.0	20.0	22.5
HO2	8.0	8.0	10.5
1O1 and 2O1	4.0	20.0	22.5
2O1 and 2O2	4.0	8.0	10.5

The required pulsing action is produced by an air pulse generator schematically shown in Figure 14. This air pulser system is similar to that in use at Hanford.⁽¹⁸⁾ A three-way solenoid valve alternately charges and vents air to and from a pulse leg connected to the pulse column below the plate section. The varying air pressure causes a pulsing action in the pulse leg which transmits the motion to the column contents. A variable-speed motor connected to the cam that operates the solenoid valve switch permits changing the pulse frequency. The pulse amplitude may be varied by changing the air pressure.

The HO2, 1O2, and 2O2 solvent treatment columns contain Raschig ring packing in place of sieve plates and are not pulsed. All of the columns are fabricated from type 304L stainless steel. The columns are vented to the vessel vent header.

The columns are instrumented to maintain proper flow control of the various streams and to detect abnormal conditions. Standard flow control

systems are used for all of the influent streams. The scrub and strip streams which contain only nitric acid use in-line blending of concentrated nitric acid and water proportionately metered from pipe headers. Scrub streams containing dissolved salts are metered from the head tank. Flow rates of the aqueous effluent streams are controlled so as to maintain a fixed column interface position. An indication of column performance is obtained by sensing and recording static pressures of the operating columns. In-line monitors on the column waste streams detect and warn of excessive waste losses. Additional in-line monitors on the 1CU and 2CU streams give alarm if the U-233 concentrations are outside prescribed operating limits.

Several evaporators are associated with the solvent extraction operation, namely those for the HCP, 1AT, 1CU, and 2CU streams. These evaporators are shown in Figures 15, 16, and 17. Factors considered in the design of the evaporators include:

1. Nuclear criticality.
2. Decontamination of the overheads.
3. Removal of the solvent contained in the evaporator feed stream.
4. Explosive reactions between solvent and evaporator bottoms.
5. Consequences of a reboiler leak.

Nuclear criticality considerations are important only in the 1CU and 2CU evaporators (U-233 only). In the HCP evaporator, the thorium dilutes the fissile U-233 sufficiently to preclude nuclear criticality.⁽¹⁴⁾ Fissile uranium is normally not present in the 1AT evaporator. The 1CU and 2CU evaporators which normally contain U-233 at high concentrations are designed to be critically safe by virtue of their geometry.

All of the evaporators have deentrainment towers packed with Raschig rings to minimize the carryover of the concentrated bottoms with the

overheads. Chevron-type grids below the packing also effect some de-entrainment. In the HCP, 1CU, and 2CU evaporators, the feed stream is introduced through a distributor within the packed tower and flows counter-current to the steam from the boiling bottoms. This contacting with steam removes entrained solvent from the feed.

Under certain conditions, degraded solvent can react explosively with evaporator bottoms.⁽¹⁵⁾ The conditions are: (1) a high nitrate concentration, (2) the presence of degraded solvent, and (3) a solution temperature greater than 275°F. Operational errors and/or process upsets can lead to the presence of high nitrate concentrations and degraded solvent. The operating temperature, however, can be limited by design. Maximum steam pressure to the evaporators is set at 30 psig (275°F). Dual temperature instruments warn of excessively high temperatures and open a dilution water addition valve if a preset solution temperature (270°F) is exceeded. This temperature limitation precludes removal of the excess nitric acid in the 1AT stream by a denitration step similar to that used in the head end.

To minimize the potential for contamination of the reboiler steam condensate, a positive pressure of steam or air is maintained on the reboiler at all times so that any leakage is into the evaporator. The HCP, 1CU, and 2CU evaporators have separate thermosyphon reboilers. This type of reboiler has a high heat transfer coefficient and is readily applicable to evaporators requiring safe geometry designs for nuclear criticality. The thorium evaporator has a simple pot-type reboiler with a steam coil. Since the thorium is normally evaporated to a high concentration, a relatively high solution holdup is needed to prevent serious overconcentration during process fluctuations. The evaporator product solutions continuously overflow directly to a receiver tank or into overflow pots equipped with transfer air lifts. Type 304L stainless steel is the material of construction for the evaporators and auxiliaries. The steam coil in the thorium evaporator is made from titanium.

Noncondensable off-gases from the evaporator condensers are vented to a common vent header. An ejector on the evaporator vent header maintains the evaporator systems at a slight vacuum. The off-gases are discharged to the building ventilation exhaust system after passing through a heater, to evaporate residual liquid entrainment, and a deep bed glass fiber filter, to remove solids.

The tank solvent washer for the treatment of the solvent effluent from the HC column is shown in Figure 18. A turbomixer, similar in design to those used in AEC reprocessing plants ^(18,19), is used for mechanical contacting of the solvent and the sodium carbonate solution present in the washer. Basically, the turbomixer is a double suction pump that draws the aqueous sodium carbonate from below and the solvent from above, mixes them with a flat-blade impeller, and discharges the mixture to the tank where the two phases disengage. Clear solvent overflows into the integral reservoir for subsequent transfer to the HO1 column. The tank solvent washers in the other two solvent-treatment systems are smaller but similar in design and operation.

A listing of the solvent extracting process equipment is contained in Table 5.

High-Level Waste Processing

The bulk of the fission products initially contained in the irradiated fertile particles exits the solvent extraction operation as a highly radioactive aqueous solution. This solution also contains nitric acid and various inert salts. The safe operation of the reprocessing plant requires that these fission products be confined indefinitely. With high-level wastes, the heat released by fission-product decay greatly complicates confinement. In recent years, intensive efforts have been undertaken at AEC facilities to develop and prove adequate and economically feasible disposal techniques for highly radioactive wastes. ^(11,20) The primary objective of these efforts is to immobilize the waste by conversion to a stable solid,

TABLE 5
SOLVENT EXTRACTION EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure, (psig)	Material
1.	Feed tanks	5	550 gal.	---	38	10	--	50 (coil)	120	-1	304L SS
2.	HA column	1	---	---	7	32.7	--	---	75	-1	304L SS
3.	HC column	1	---	---	8.5	26.5	--	---	75	-1	304L SS
4.	HCP evaporator	1	50 gal.	1.7×10^6 BTU/hr	--	20	--	126(reboiler)	135	-1 35 reboiler	304L SS
5.	HCP evaporator condenser	1	---	1.7×10^6 BTU/hr	12	8	--	100	100	-1	304L SS
6.	1A and 2A columns	2	---	---	3.5	32.1	--	---	75	-1	304L SS
7.	1C and 2C columns	2	---	---	3.5	26.1	--	---	75	-1	304L SS
8.	1AT evaporator	1	---	2.3×10^5 BTU/hr	36 14	4 10	(reboiler) (tower)	76(reboiler)	135	-1 35 reboiler	304L SS Ti reboiler tubes
9.	1AT evaporator condenser	1	---	2.3×10^5 BTU/hr	8	5	--	15	100	-1	304L SS
10.	1CU and 2 CU evaporator	2	7 gal.	1.6×10^5 BTU/hr	5	21.5	--	12(reboiler)	135	-1 35 reboiler	304L SS
11.	1CU and 2CU evaporator condenser	2	---	1.6×10^5 BTU/hr	5	--	6	10	100	-1	304L SS
12.	1CU and 2CU product receiver tanks	2	21 gal.	---	5	11.5	--	9 (coil)	100	-1	304L SS
13.	Uranium storage tanks	3	310 gal.	---	75	11	--	40 (coil)	100	-1	304L SS
14.	HCW solvent wash tank	1	260 gal.	---	33	4.5	--	25 (coil)	50	-1	304L SS

TABLE 5 (continued)
SOLVENT EXTRACTION EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia. (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure (psig)	Material
15.	HO1 column	1	---	---	8	22.5	--	---	50	-1	304L SS
16.	HO2 column	1	---	---	8	10.1	--	---	50	-1	304L SS
17.	HO solvent wash waste tank	1	100 gal.	---	25	4	--	25 (coil)	100	-1	304L SS
18.	HO decanter	1	20 gal.	---	10	5	--	--	50	-1	304L SS
19.	1O and 2O solvent wash tank	2	60 gal.	---	22	3.3	--	20 (coil)	50	-1	304L SS
20.	1O1 and 2O1 column	2	---	---	4	22.5	--	---	50	-1	304L SS
21.	1O2 and 2O2 column	2	---	---	4	10.1	--	---	50	-1	304L SS
22.	1O and 2O solvent wash waste tank	2	50 gal.	---	20	3	--	20 (coil)	100	-1	304L SS
23.	1O and 2O decanter	2	5 gal.	---	5	5	--	---	50	-1	304L SS
24.	1O and 2O solvent storage tank	2	300 gal.	---	28	10	--	20 (coil)	50	-1	304L SS

package the solids and store them indefinitely in a manner that precludes release of hazardous radioisotopes to the environment. The disposition of the radioactive wastes arising from HTGR fuel reprocessing is in line with this approach. The high-level waste solution from irradiated HTGR fuels is converted to a granular solid by calcination in a fluidized bed calciner. This solidification technique is currently in use at the Idaho Chemical Processing Plant. (11, 20, 21, 22)

Basically, the waste disposal flowsheet consists of evaporation to reduce the waste volume, conversion to a solid in a fluidized bed calciner, packaging in high-integrity stainless steel containers and interim storage in a water-filled basin. Ultimate storage techniques for the containers of solidified wastes are still under study at AEC facilities.⁽¹¹⁾ For purposes of this study, shipment to a salt mine repository after an interim storage period is assumed.

The HAW is routed from the HA column to a high-level waste accumulator tank. From here, the HAW is metered to a packed scrubber tower where it flows countercurrent to the off-gases from the fluidized bed calciner. The scrubber serves several purposes: (1) it cools the calciner off-gas, (2) the oxides of nitrogen in the calciner off-gas are absorbed in the HAW and converted to nitric acid, (3) volatile ruthenium tetroxide in the off-gas is reduced by the entrained solvent in the HAW to nonvolatile ruthenium dioxide and recycled, and (4) the entrained solvent is removed by steam stripping. The scrubber aqueous effluent flows directly into the evaporator solution reservoir and the scrubbed calciner off-gases are combined with the evaporator overheads for deentrainment by passage through the packed evaporator tower.

During evaporation, the concentrated high-level waste is limited to a total nitrate concentration of eight molar. At higher nitrate molarities, significant quantities of ruthenium are converted to the volatile tetroxide which complicates off-gas cleanup. All of the nitric acid in the HAW is

volatilized; part in the evaporator and the remainder in the calciner. The acid is recovered in the high-level waste evaporator condensate as a $2M\ HNO_3$ solution. Although the nitric acid vapors pass through a de-entrainment tower, the fission-product content of the condensate is too high to permit it to be fed to the nitric acid recovery fractionator. The high-level waste evaporator condensate is combined with the intermediate-level waste for redistillation. Noncondensable calciner and evaporator off-gases pass through a silica gel adsorber to remove traces of ruthenium tetroxide and then through a filter packed with glass fibers for particulate removal. An ejector after the filter maintains the system under a slight vacuum and discharges the gases into the building ventilation exhaust duct for final filtration with the building air.

Proper operation of the calciner requires a chemical adjustment of the calciner feed (concentrated HAW). The presence of calcium is needed to complex the fluoride in the HAW in order to minimize calciner corrosion.⁽²³⁾ During calcination, aluminum nitrate, the prime nonvolatile constituent in the HAW, is converted to alumina. The presence of boric acid is needed so that the desirable amorphous form of alumina is produced rather than the undesirable alpha form.⁽²¹⁾ A chemical addition stream containing calcium as the nitrate and boron as sodium tetraborate (borax) is metered into the high-level waste evaporator. The makeup tank and the head tank for this chemical addition stream are located in the operating area.

The high-level waste evaporator and the calciner off-gas scrubber are shown in Figure 19. The scrubber is a 9-foot-high by 14-inch-diameter tower packed with Raschig rings. HAW is introduced through a distributor near the scrubber top. A spray ring located above the HAW distributor is used for any necessary internal decontamination of the tower. The evaporator has a thermosyphon type reboiler connected to an 18-inch-diameter solution reservoir. For the reasons discussed earlier, the reboiler steam

pressure is limited to 30 psig and the reboiler is pressurized whenever radioactive solutions are in the evaporator. The 10-foot-high by 22-inch-diameter Raschig-ring-packed tower surmounting the solution reservoir removes much of the entrainment in the evaporator and calciner off-gases. A wire mesh pad above the packing provides additional deentrainment. When needed the deentrainment pad and the tower packing may be flushed with water from a spray ring at the top of the tower. The evaporator system is made from type 304L stainless steel with the exception of the reboiler tubes, which are titanium.

During normal operation, the concentrated HAW continuously overflows the evaporator into a receiver tank. After a process shutdown, the evaporator contents may be transferred to the receiver tank by a steam jet. Periodically, the concentrated waste is air lifted from the receiver tank to the calciner feed tank.

The high-level waste is fed into the fluidized bed calciner through a two-fluid atomizing nozzle. Air is used as the atomizing gas. With the exception of calciner startup, the calcined waste is the fluidized bed media. For startup, alumina is added to form the initial bed. During operation, bed particle growth by waste deposition is offset by particle attrition and by bed withdrawal so that a steady-state particle distribution develops in a relatively short time. External electric heater elements maintain a calciner operating temperature of 600°C . The fluidizing gas is steam superheated to 600°C by electric heater elements in the steam supply line. At the bottom of the fluidized bed, the fluidizing gas velocity is 1.1 feet per second. Steam is used as the fluidizing gas because it is condensable and the volume of gas requiring treatment beyond the evaporator condenser is significantly reduced.

The nitric acid and water contained in the calciner feed evaporate and, at the calciner operating temperature, the nitrate salts decompose into gaseous oxides of nitrogen and solid oxides. Fluorine is retained in the

calcine as the stable calcium fluoride. Likewise, both sulfate and phosphate are retained as stable salts. Prior to passing into the scrubber for contacting with the HAW steam, the bulk of particulate entrainment in the calciner off-gas is removed by sintered metal filters. A pulse blowback system periodically blows the solids off the sintered metal filters and returns them to the calciner. Superheated steam is used as the blowback gas which, like the fluidizing gas, is subsequently condensed. In the scrubber, the oxides of nitrogen resulting from the decomposition of the nitrate salts are absorbed in the HAW, forming nitric acid. The air introduced as the atomizing gas with the calciner feed provides the oxygen required for the conversion of NO to NO₂.

A portion of the calcined waste is periodically withdrawn from the calciner and discharged into high-integrity containers for disposal.

The calciner, shown in Figure 20, is a dual diameter vessel with an 11-inch diameter fluidized bed section and a 25-inch diameter disengaging section. The sintered metal filters are located in the upper portion of the disengaging section. Fluidizing steam is introduced through a gas distributor below the fluidized bed and the concentrated waste solution feed nozzle is near the top of the bed. A 30-kilowatt resistance heater wrapped around the outside of the fluidized bed section supplies the required thermal energy. An air distributor placed at the bottom of the heater provides a secondary means of removing the fission product decay heat should the operation of the calciner be interrupted unexpectedly. Normally, the fluidizing gas would remove the decay heat in the absence of an aqueous feed stream.

With few exceptions, the packaging and storage operations and equipment are similar to those used for the fissile particles. The 10-foot-high storage containers are made from 6-inch, schedule 40, type 304L stainless steel pipe. The calcine is thermally stable⁽²⁴⁾ at the maximum centerline temperature of 560°C attainable with this diameter container.

A screw conveyor periodically transports the calcine from the bottom of the calciner to a prepositioned storage container. The volume of calcine transported is measured by two independent means; the number of revolutions of the screw conveyor and a vertically adjustable collimated radiation detector external to the storage container. A filled calcined waste storage container is sealed, monitored, and transferred to the storage basin in a manner identical to the fissile particle containers.

The 102-kilogram daily output of calcined waste (bulk density of about 1 kg/l).⁽²²⁾ requires 1.8 storage containers. Including a 10 percent allowance for startup, shutdown, and decontamination wastes, 542 calcined waste storage containers are filled annually.

Intermediate-Level Waste Processing

Intermediate-level wastes have radioisotope concentrations sufficiently low to preclude significant thermal problems from fission product decay but high enough to require long-term confinement. In reprocessing HTGR fuels, intermediate-level wastes arise from the following sources:

1. Head end stripper condensate .
2. Drying hopper condensate .
3. Solvent wash wastes from the three solvent treatment systems.
4. Condensates from the HCP and thorium evaporators.
5. Aqueous waste from the 2A column (2AW).
6. Condensate from the high-level waste evaporator.
7. Condensate from intermediate-level waste solidification.

Other intermediate-level wastes can be produced by the elution of the low-level waste treatment ion exchange columns and by periodic decontamination of process equipment.

Safety considerations indicate the desirability of storing intermediate-level waste as an immobile solid. Solidification of such wastes and incorporation into asphalt by batch processes is utilized at some European nuclear facilities.^(20, 25) Continuous processing methods are under active investigation at the Oak Ridge National Laboratory.^(26, 29) Asphalt greatly reduces the leaching rate of the radioisotopes should water contact the stored waste. This approach is used to immobilize the intermediate-level waste from HTGR fuel reprocessing.

In summary, intermediate-level waste processing consists of reducing the waste volume by evaporation, neutralizing the concentrated waste with caustic, mixing with asphalt, and heating to remove the residual water. The waste-bearing asphalt is piped to a storage tank where it cools and solidifies. Evaporator overheads are condensed and then fed to a nitric acid fractionator to recover the nitric acid for reuse in the process. The condensed fractionator overheads are collected, monitored, and released to the environment. When necessary, these overheads are routed through the low-level waste treatment facility to reduce the radioisotope content to government standards for environmental discharge.

In operation, the various intermediate-level waste streams are routed to an accumulator tank. From here, the composite waste (1.3M HNO_3 , 0.018M NaNO_3) is metered into an evaporator which reduces the waste volume by a factor of about 50. During evaporation, more than 90 percent of the nitric acid present in the intermediate-level waste is vaporized. The nitric acid and water vapors pass through a packed de-entrainment tower before being condensed. The condensate flows through a decanter and into the nitric acid fractionator feed tank. Solvent that follows the overheads is separated by the decanter and discharged to the neutralizer tank. Noncondensable vapors from the evaporator condenser are combined with those from the silica gel adsorber in the high-level waste evaporator off-gas train.

The intermediate-level waste evaporator, shown in Figure 21, is similar in design to the high-level waste evaporator but has a larger capacity. Because of the larger evaporation requirements, the diameters of the reboiler and deentrainment tower are greater. Like the other evaporators, the reboiler steam pressure is limited to 30 psig.

The evaporator bottoms (6M HNO_3 , 1M NaNO_3) continuously overflow into a receiver tank. From the receiver tank, the concentrated waste is transferred to a neutralizer tank where it is mixed with a 50 percent caustic solution (19M NaOH) added from an operating gallery head tank. Ten percent excess caustic is used to ensure complete neutralization. The now-alkaline waste is air lifted at a controlled rate from the neutralizer, in-line blended with asphalt, and fed to a wiped-film evaporator (asphalt blender). An emulsified asphalt⁽²⁷⁾ containing 63 weight percent asphalt, 35 weight percent water and 2 weight percent emulsifying agent is added from an operating gallery head tank. This asphalt is the type normally used in the surface treatment of roads. In the asphalt blender, the water in the waste and in the asphalt is removed by vaporization, subsequently condensed in a water-cooled condenser, and recycled to the intermediate-level waste evaporator. Noncondensable off-gases pass through a filter, an ejector which maintains the asphalt blender system under a slight vacuum, and are combined with the building ventilation exhaust air for final filtration. The residual intermediate-level waste solids (NaNO_3 , NaOH , and fission products), incorporated into an asphalt matrix, exit the asphalt blender at 320°F as a viscous but pumpable liquid. This mixture is pumped through heated lines to an underground storage tank. Although satisfactory mixtures containing 60 weight percent solids have been prepared,⁽²⁷⁾ the reprocessing plant flowsheet is conservatively designed to produce a mixture containing 50 weight percent solids. The annual volume of asphaltic waste (specific gravity = $1.5^{(26)}$) is 4680 ft^3 . This includes a 20 percent allowance for startup, shutdown, and decontamination wastes.

The asphalt blender (Figure 22) is a steam-jacketed, wiped-film evaporator. The wiper blades are 12 inches in diameter, three-feet long, and are driven at 300 RPM by an electric motor that has an integral speed reducer. Because of the relatively high temperature requirements, the jacket is designed for 120 psig steam. The unit is fabricated from type 304L stainless steel.

The overhead condensate from the intermediate-level waste evaporator contains an economically recoverable concentration of nitric acid (1.2 molar). Also, the residual fission product concentration is too high to permit direct release to the environment. To recover the acid and to obtain additional decontamination, the condensate is processed through a nitric acid fractionator.

The fractionator, shown in Figure 23, consists of a tower packed with Raschig rings, a thermosyphon reboiler, a solution reservoir, a condenser, and a reflux metering system. Condensed evaporator overheads are metered from the nitric acid fractionator feed tank to a distribution plate at the midpoint of the fractionator tower. A portion of the condensed fractionator overheads are returned to a distributor plate at the top of the column. These aqueous streams absorb essentially all of the nitric acid contained in the vapor from the reboiler. The tower height⁽¹¹⁾ and operating conditions are designed to give a concentrated fractionator bottoms containing 60 percent nitric acid and a condensed overhead containing only a trace of acid. Solvent entrained with the fractionator feed will also be present in the overheads. The concentrated acid is routed to the recycle acid tank for reuse in the head end leacher. The amount recovered is essentially the amount required for leacher operation. Most of the residual fission products in the fractionator feed are contained in the recycle acid. The fractionator overheads are routed to a collection tank in the low-level waste treatment facility. An ejector maintains the fractionator system under a slight vacuum. Titanium is the

material of construction for the fractionator tower, solution reservoir, and reboiler. The condenser is made from type 304L stainless steel.

Equipment pieces used in the high- and intermediate-level waste processing are listed in Table 6.

Radioactive Service Tanks

A number of feed, storage, and receiver tanks are used in the head-end, solvent extraction, and waste processing remote operations. These radioactive service tanks are listed in Table 7. The process requirements for many of the tanks are sufficiently similar that some degree of design standardization is possible. Space requirements, nuclear criticality, and special process needs impose limits on the degree of standardization obtainable. With the exception of the U-233 receiver and storage tanks, the waste container monitoring tank and the solvent washers, the tanks are simple, vertical, cylindrical vessels. The high concentrations of U-233 in the product streams from the 1CU and 2CU evaporators require the associated tankage to have critically favorable designs (Figure 24 and 25). A rectangular tank for waste container monitoring is used to minimize the cell spare requirements. The integral reservoirs on the solvent wash tanks (Figure 18) result in nonsymmetrical vessels.

All of the tanks are equipped with coils for heating and cooling, samplers, instrumentation to measure solution specific gravity, height and temperature, a means of agitation, and a means of solution transfer. The tank coil influent is designed and instrumented so as to maintain a positive pressure of steam, water, or air at all times to preclude contamination of the coil effluent should a coil leak develop. The possibility of a coil leak is minimized by using heavy-wall pipe and by using coil supports that eliminate coil abrasion caused by thermal cycling. All of the tanks with the exception of the solvent wash tanks are agitated by submerged air lift circulators. This type of agitation has no moving parts that require maintenance. Air introduced in this manner also serves to

TABLE 6
WASTE PROCESSING EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia. (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure (psig)	Material
1.	Waste accumulator tank	3	1350 gal.	---	58	10	---	100(coil)	100	-1	304L SS
2.	HLW evaporator	1	80 gal.	6.7x10 ⁵ BTU/hr	18	19.3	---	130(reboiler)	135	-1 35 (re-boiler)	304L SS Ti reboiler tubes
3.	HLW evaporator condenser	1	---	8.7x10 ⁵ BTU/hr	15	7	---	160	120	-1	304L SS
4.	Calciner off gas scrubber	1	---	---	14	9	---	---	500	-1	304L SS
5.	Concentrated waste tank	3	50 gal.	---	16	5	---	40(coil)	100	-1	304L SS
6.	HLW calciner	---	---	30 KW	11 (calciner) 25 (tower)	15.1	---	---	500	-1	310 SS
7.	Calciner fluidizing steam heater	1	---	10 KW	(10 in. by 10 in.)	---	1.5	---	600	100	Incoloy sheathed heaters, 310 SS
8.	Filter blowback steam heater	1	---	1 KW	4	---	1.5	---	600	100	Incoloy sheathed heaters, 310 SS
9.	ILW evaporator	1	---	3.4x10 ⁶ BTU/hr	24(reboiler) 36(tower)	21.5	---	500(reboiler)	135	-1 35 (re-boiler)	304L SS Ti reboiler tubes
10.	ILW evaporator condenser	1	---	3.4x10 ⁶ BTU/hr	20	9	---	400	110	-1	304L SS
11.	ILW neutralizer tank	1	350 gal.	---	42	5	---	100(coil)	100	-1	304L SS
12.	Asphalt blender	1	---	2.5x10 ⁵ BTU/hr	15	5.5	---	9(jacket)	180	-1 100 (jacket)	304L SS
13.	Asphalt blender condenser	1	---	2.5x10 ⁵ BTU/hr	10	5	---	40	100	-1	304L SS
14.	ILW condensate decanter	1	130 gal.	---	36	2.5	---	---	50	-1	304L SS
15.	Nitric acid fractionator	1	100 gal.	5.1x10 ⁶ BTU/hr	22(reboiler) 43(tower)	28.75	---	435(reboiler)	145	-1 45 (re-boiler)	titanium
16.	Fractionator condenser	1	---	5.1x10 ⁶ BTU/hr	25	---	6	455	100	-1	304L SS
17.	Recycle acid tank	1	1600 gal.	---	72	8	---	50(coil)	100	-1	304L SS
18.	HLW off-gas filter	1	100scfm	---	30	4	---	---	100	-1	Fiberglass filter media, 304L SS
19.	Silica gel adsorber	1	100scfm	---	34	4	---	---	100	-1	304L SS

TABLE 6 (continued)
WASTE PROCESSING EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia. (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure (psig)	Material
20.	Fissile particle weigh hopper	1	4 ft. ³	---	14	4.4	---	5(cooling bayonets)	300	-1	Boron SS
21.	Waste container welding station	2	---	---	---	---	---	---	---	---	SS
22.	Waste container monitoring tank	1	520 ft. ³	---	(4 ft. by 11 ft.)	12	---	---	50	---	304L SS
23.	Waste storage basin heat exchanges	6	(air cooled induced draft)	3x10 ⁶ BTU/hr	(20 ft. by 8 ft.)	6	---	1200(finned tubes)	---	50	C.S., Aluminum
24.	LLW collection tank	2	5000 gal.	---	120	10	---	---	50	-0.1	304L SS
25.	Stripper feed preheater	1	---	3.3x10 ⁵ BTU/hr	10	3.5	---	7	135	50	304L SS
26.	Stripper	1	180 gal.	1.5x10 ⁵ BTU/hr	40 6	3 10	(reboiler) (tower)	6(reboiler)	135	-1 35(re-boiler)	304L SS
27.	Stripper cooler (primary)	1	---	1.3x10 ⁵ BTU/hr	8	---	3	12	100	10	304L SS
28.	Stripper cooler (secondary)	1	---	1.5x10 ⁵ BTU/hr	6	6.5	---	19	75	100	304L SS
29.	Stripper condenser	1	---	1.5x10 ⁵ BTU/hr	6	---	3	3	100	-1	304L SS
30.	Stripper decanter	1	15 gal.	---	12	2.5	---	---	75	-1	304L SS
31.	Elutant tank	1	1500 gal.	---	72	7	---	20(coil)	75	-0.1	304L SS
32.	Ion exchange column	2	150 gal.	---	30	5	---	---	50	25	304L SS
33.	Effluent tank	2	2500 gal.	---	78	10	---	---	50	-0.1	304L SS
34.	Asphalt blender off-gas filter	1	50 scfm	---	24	4	---	---	50	-1	304L SS glass fiber filter media

TABLE 7
RADIOACTIVE SERVICE TANKS

Service		Size	
Leacher receiver		A	
Stripper feed		A	
Stripper condensate receiver		A	
Stripper receiver		A	
Solvent extraction feed		A	
HA column feed		A	
HAX feed		A	
HCP evaporator receiver		A	
HO solvent washer		260 gal. 33 in by 4.5 ft	
HO solvent wash waste		100 gal. 25 in by 4 ft	
1AX feed		F	
1AT evaporator receiver		A	
1CU evaporator receiver		E	
1CU product storage (2 tanks)		D	
1CW solvent washer		H	
1O solvent wash waste		G	
Uranium rework		D	
2AX feed		F	
2CU evaporator receiver		E	
2O solvent washer		H	
2O solvent wash waste		G	
High-level waste accumulator		C	
High-level waste evaporator receiver		B	
Calciner Feed		B	
Waste container monitoring		520 ft ³ , 4 ft by 11 ft by 12 ft	
Intermediate-level waste accumulator		C	
Intermediate-level waste evaporator receiver		B	
Intermediate-level waste neutralizer		C	
Nitric acid fractionator feed		C	
Recycle acid		1600 gal. 72 in by 8 ft	
A	550 gal. 38 in by 10 ft	E	21 gal. 5 in by 11.5 ft
B	50 gal. 16 in by 5 ft	F	300 gal. 28 in by 10 ft
C	1350 gal. 58 in by 10 ft	G	50 gal. 20 in by 3 ft
D	310 gal. 75 in by 11 ft	H	60 gal. 22 in by 3.3 ft

maintain the hydrogen formed by solution radiolysis below its lower explosive limit. As described earlier, turbomixers are used in the solvent washers. These mechanically driven mixers are designed to be remotely replaceable. Solutions are transferred by steam jets or by air lifts depending on the head requirements. Two-stage air lifts⁽¹⁵⁾ are used for solutions that require metering at controlled rates.

All of the radioactive service tanks are vented to a vessel vent header. An ejector discharging into the building ventilation exhaust system maintains the header and the tanks at a slight vacuum. A deep-bed fiberglass filter on the ejector inlet removes particulate entrainment. Before entering the filter, the vent gases pass through a heater to evaporate liquid entrainment and prevent liquid accumulation in the filter. The solvent extraction columns are also vented to the vessel vent header.

Off-Gas and Ventilation Air Treatment

Various gaseous waste streams containing radioactive contaminants arise during the reprocessing of HTGR fuels. These gas streams require treatment to remove the radioactive contaminants to levels that permit safe environmental release. The contaminants can be solid particles, liquid mists, and gaseous fission products. Liquid and solid particulates may contain any of the radioisotopes present but the gaseous radioactive fission products of concern are limited to Xe, Kr, I, Ru, and tritium. In addition, the burner off-gas contains $C^{14}O_2$. Removal of particulate contaminants is essentially independent of the chemistry of the radioisotopes and can be done effectively by mechanical means such as filtration and impingement. Gaseous radioisotopes, however, require chemical means to effect their removal.

In reprocessing 210-day-cooled HTGR fuel elements, ruthenium is the only volatile fission product requiring removal from the process off-gases. The noble gases and tritium fission products remaining in the

fuel elements received at the plant can be safely dispersed through the plant stack as can the C-14.⁽¹⁾ During fuel element storage, the I-131 decays to levels sufficiently low that it too can be dispersed safely. However, proper administrative controls are required to preclude processing of fuels cooled less than about 210 days. A radiation detector in the transfer trench between the fuel storage area and the crusher cell would warn of the passage of fuel elements with higher-than-normal radiation level characteristic of short-cooled fuels. Although elemental ruthenium is not volatile, several chemical forms are. In the reprocessing plant, volatile ruthenium tetroxide is formed in several of the processing steps. Ruthenium tetroxide can be removed by adsorption on silica gel, scrubbing with caustic, or reduction to nonvolatile ruthenium dioxide.^(15, 30) Both silica gel adsorption and reduction to particulate RuO₂ are used in HTGR fuel reprocessing. The application of these methods are contained in the process description.

Off-gases from processes involving liquids may contain liquid entrainment. In streams containing small amounts of such entrainment, heating is used to evaporate the liquid and leave a very small amount of solid contaminant. Off-gases that contain large amounts of liquid entrainment such as those from evaporators are passed through packed towers where the liquid mists impinge on the packing surfaces, coalesce, and flow back to the process.

Filtration is used to remove solid entrainment. In treating the reprocessing plant gas stream, the three types of filters listed below are used.

<u>Filter Type</u>	<u>Efficiency</u>	<u>Solids Loading Capacity</u>
Sintered metal with pulse blowback ⁽¹¹⁾	Low	High
Glass fiber bed ^(31, 32)	Moderate	Moderate
Absolute ⁽¹⁵⁾	High	Low

All the above filter types can be designed to have acceptably low pressure drops. Many of the gas streams have relatively high concentrations of particulates and require more than one stage of filtration. Sintered metal and/or glass fiber filters are used to remove the bulk of the particulates before final passage through a high-efficiency absolute filter. Particulate loading on sintered metal filters is removed at frequent intervals by integral pulse blowback systems and returned to the process. Failure of sintered metal filters is more likely to occur from corrosion than from plugging. Filters containing a deep bed of glass fibers are capable of retaining large amounts of solid particles.⁽³¹⁾ This type of filter has demonstrated effective service for several years before increased pressure drop necessitates replacement.⁽¹⁸⁾ The individual process off-gas streams, after passing through sintered metal and/or glass fiber filters are combined with the building ventilation exhaust air for final filtration. The various equipment items for off-gas treatment are contained in Tables 3, 5, 6, and 8.

The reprocessing building, including the process cells and fuel storage area, is ventilated to provide a means of controlling the spread of airborne contamination, to provide normal ventilation for occupied areas, and to control temperatures in the radioactive areas. An air flow pattern from the occupied areas through the radioactive zones to the ventilation filters and the plant stack is used to control contamination spread. Supply fans, pressure differentials between areas, and exhaust blowers on the stack inlet are used to sustain the proper air flow pattern during all phases of normal operation. The normal exhaust air volume is about 75,000 cfm. The exhaust blowers alone can maintain the required air flow pattern but at a reduced air volume if some operations such as fuel receiving and reprocessing cell maintenance are curtailed.

The air supply system, located in the operating area, contains two parallel supply units. Each unit is composed of standard filters, heaters,

TABLE 8

MISCELLANEOUS PROCESS EQUIPMENT

No.	Item	No. Req.	Capacity	Duty	Dia (in.)	Height (ft)	Length (ft)	Area (ft ²)	Temp. (°C)	Pressure (psig)	Material
1	Vessel and evaporator vent heater	2	-----	1x10 ⁴ BTU/hr	6	-----	5	22	100	-1	304L SS
2	Vessel and evaporator vent filter	2	250 scfm	-----	48	4	-----	-----	100	-1	Fiberglass filter media, 304L SS
3	Solids transport vent filter (primary)	1	125 scfm	-----	25	5	-----	27 (filter area)	100	-1	304L SS
4	Solids transport vent filter (secondary)	1	125 scfm	-----	36	4	-----	-----	100	-1	Fiberglass filter media, 304L SS
5	Process water cooling tower	1	1500 GPM	2.6x10 ⁷ BTU/hr	(30 ft by 30 ft by 30 ft)		-----	-----	---	---	-----
6	U product vacuum transfer tank	1	8 liters	-----	3.5 I. D.	4.4	-----	-----	50	-12	304L SS
7	Vacuum transfer trap tank	1	10 liters	-----	3.5 I. D.	5.5	-----	-----	50	-12	304L SS
8	U product load-out head tank	1	8 liters	-----	3.5 I. D.	4.4	-----	-----	50	-12	glass
9	U product shipping container	290	8 liters	-----	3.5 I. D.	4.4	-----	-----	25	---	polyethylene

washers and supply fans. Conventional ducting is used to distribute the air throughout the reprocessing building. The ventilation air along with the process off-gas streams discussed above are exhausted through underground ducts to the exhaust air filter unit. This unit is an underground structure containing banks of absolute filters. A damper arrangement permits isolation of individual banks so that the absolute filters can be changed when the accumulation of particulates causes excessive pressure drops. Filtered air is drawn from the filter structure by exhaust blowers and discharged to the atmosphere through the 250-foot-high plant stack. Three exhaust blowers are used, each rated at 50 percent of the design ventilation air volume. Two blowers driven by electrical power supplied to the plant are normally used. The third blower is driven by plant-supplied emergency power and is normally on standby status. With this arrangement, at least partial air flow is available even if normal power sources fail. The stack air is continuously monitored to provide a record of the amount of radioisotopes released and to warn of excessively high release rates.

Equipment Arrangement and Maintenance

Factors that must be considered in arranging equipment within the reprocessing plant include (1) movement of material, (2) process operation and control, (3) shielding, and (4) maintenance. The reprocessing building and equipment layouts are shown in Figures 5, 6, 7, and 9. An in-line arrangement is indicated for the reprocessing building, considering accesses for equipment, solid and liquid transfer, crane coverage, and overall plant arrangement. Equipment pieces are grouped primarily by process steps into process cells and secondarily by shielding requirements. Process operations involving material with a high fission product content (burning, leaching, HA column and high-level waste packaging) are at one end of the building and the remainder of the operations are at the other end. This arrangement permits a change in the thickness

of the concrete shielding wall and a widening of the plant interior in the areas where the generally larger aqueous processing equipment is located. Each process cell has space allocated for the possible future addition of other equipment needed for byproduct recovery or for process changes. Failed equipment may be temporarily stored in these areas to await a more convenient time for final disposition or to allow additional fission product decay. The high-level waste processing area is at one end of the building for easy access to the high-level waste storage basin.

Some equipment pieces are remotely replaceable and others are not. Equipment pieces subjected to abrasion or to a highly corrosive environment and pieces containing mechanisms are designed to be replaceable using remote maintenance techniques. In addition, process equipment pieces that may require changing because of process modifications are also remotely replaceable. Since process solution tanks are not exposed to excessively corrosive conditions and can be designed for long-term service, they can be replaced only by direct contact maintenance. All tank piping connections are welded. Most of the remotely replaceable equipment pieces are contained in racks hung from the shielding wall. A shielded cubical recessed in the concrete shielding wall is located at each rack position. The cubical is accessible from the operating gallery through a sliding shield door. A heavy steel plate at the rear of the cubical provides the necessary shielding from the reprocessing cell when the sliding shield door is open. Service, instrument, and process piping from the equipment pieces terminate at plugs attached to the equipment rack. The plugs penetrate the steel shielding plate through mating holes. Service and instrument piping from nonradioactive areas and process piping from other cubicles end at pipe stubs within a cubicle. Piping tie-ins are made through jumpers connecting the plug terminals with those in the cubicle. The process piping between cubicles is contained in the concrete wall for shielding purposes. This piping concept for remotely

maintainable equipment, illustrated in Figure 6, is similar to that in use at Battelle Memorial Institute, Pacific Northwest Laboratory.^(11, 33)

Some of the replaceable process equipment pieces such as burners and the various filters have gas streams requiring relatively large diameter piping. This piping, which is too large to be accommodated in a cubicle, is connected within the process cells by remote pipe and flange connectors. An impact wrench held by a crane hook is used to tighten or loosen the connectors. These remote in-cell piping connectors are similar to those used in AEC reprocessing plants.⁽¹⁵⁾ In-cell connected remote equipment, unlike that piped through cubicles, need not be located adjacent to an operating gallery. Some equipment pieces, notably the burners, are piped by a combination of cubicle and in-cell connections.

The process cells are serviced by a remotely controlled overhead bridge crane. Although replacing equipment is an important and vital function of the crane, it is used primarily for operations associated with high-level waste processing. The crane moves empty waste storage containers, placed in a transport-storage rack, from the air lock to the high-level waste processing cell and also transports the waste containers between process steps. Consoles located in the various operating areas are used to control the crane. A closed-circuit television system with crane-mounted cameras provides observation of crane movements. Lights are also crane mounted. Operations in the high-level waste cell are supplemented by master-slave manipulators with the operations observed through viewing windows. This area also has wall-hung light fixtures that are remotely replaceable by the crane.

Equipment is moved in or out of the shielded processing cells through an air lock at one end of the building. Hinged shielding doors allow access to the cells and to an adjoining maintenance area. The air lock is also equipped with decontamination facilities for reducing the

radioactivity levels of failed equipment prior to repair. The reprocessing area crane can be moved into the air lock for storage when not in use or for maintenance of the crane and its auxiliaries. The maintenance area has a separate overhead bridge crane and in addition has a ramp and roll door to allow the entrance of a truck.

To replace an item of process equipment, the equipment piece and connecting process lines are first drained and flushed. For cubical connected equipment, a temporary contamination control housing ("green house") is placed in the operating area around the cubical, the cubical is opened and the pipe jumpers connected to the equipment piece are removed. For in-cell connected equipment, the overhead bridge crane disconnects the piping. The crane then moves the equipment piece to the air lock. If an equipment piece is to be disposed of, a shielded burial box can be positioned in the air lock to receive the equipment piece. After the burial box has been closed, it can be moved onto a truck in the maintenance area for transport to a burial ground or to the plant rail siding for transfer to a railroad flat car.

The equipment pieces are arranged within the cell so that any item can be moved over and past all equipment pieces between it and the air lock. This criterion established the height of the reprocessing cell. Several partial walls of concrete divide the reprocessing area into cells. These walls provide some shielding of process solutions and equipment from radioactive sources in the cells. In addition, the walls limit the spread of contamination should a process solution leak develop. Each cell has a 3-inch-deep critically safe sump that runs the length of the cell. The sumps have liquid-level measuring instrumentation, samplers and a transfer jet for emptying the sump to a process tank. The final disposition of the sump contents depends on its chemical content. The interiors of the reprocessing cells are covered with an acid resistant coating up to the top of the equipment.

Adjoining one side of the reprocessing area is a four-level operating area as shown in Figures 5, 26, and 27. All but the basement level are the full length of the reprocessing area. The upper level contains piping headers, flow control systems for the addition of nonradioactive chemicals to the process, instrument transmitters and converters, chemical addition tanks, and exhaust filters serving the analytical laboratory hoods. The second level has some analytical laboratories and a gallery that contains the cubicals serving the replaceable equipment pieces and the process samples. Also on the second level but isolated from the analytical laboratories and the gallery is the equipment room for the electrical switchgear and for the ventilation air supply. The control room is on the ground floor level along with chemical makeup tanks, most of the analytical laboratories, and the uranium product loadout areas. The basement level spans only the burner cell and contains the cooling air equipment for the burners.

Access to the reprocessing building wall opposite the main operating galleries is required only in the area of the high-level waste processing cell. Some of the high-level waste processing requires the use of manipulators. Operation of these manipulators is from a gallery between the crusher cell and the high-level waste storage area. The remotely replaceable welding equipment is connected through cubicals opening to this gallery. Viewing windows in the shielding wall permit observation of the waste packaging operations.

Uranium Product Loadout

Facilities for loading the U-233 product solution into shipping containers are located outside of the shielding wall in a separate room adjacent to the analytical laboratories (Figure 5). Because of the low levels of radioactivity present in freshly decontaminated U-233 solutions, the loadout operation is conducted manually. For contamination control,

the equipment is contained in glove boxes. Maintenance is also done manually.

To minimize leakage, all solution transfers within the loadout area are made by gravity or by vacuum. For vacuum transfers, an ejector creates a vacuum on the receiver tank drawing the solution into the tank. A critically safe trap tank between the ejector and the receiver tank serves to catch any solution should the receiver tank overflow. The trap may be drained back to the 2CU product receiver tank in the uranium purification cell. The ejector discharges to the evaporator vent header.

In operation, a batch of uranium product solution (2M U) is vacuum transferred from the 2CU product tank to a 3.5-inch diameter by 4.4-foot-high stainless steel transfer tank in the uranium loadout station. Because of the differences in elevation, the solution is air lifted from the 2CU tank to a head pot containing the in-cell terminal of the vacuum transfer line. When a batch (normally 7 liters) has accumulated, the flow is stopped by venting the trap tank and shutting off the ejector. A solution sample is taken for analysis, the valving changed and the solution vacuum transferred to the loadout head tank. The head tank, which has the same dimensions as the transfer tank, is made of carefully calibrated glass. After the batch volume has been recorded, the solution is drained into a preweighed polyethylene shipping container positioned in the filling station. The full 3.5-inch ID by 4.4-foot-high container is disconnected, capped, and removed for reweighing. The plastic container is then placed into a stainless steel protective container, which is surrounded by a steel framework (birdcage). These birdcages assure that the shipping containers are spaced sufficiently far apart to preclude nuclear criticality by interaction. The filled containers are now ready for loading onto a truck for shipment to the refabrication plant. Under design processing conditions, the daily output of the uranium purification cycle is 67.1 liters or 9.6 containers. A 30-day supply of shipping containers (290) is provided.

The uranium loadout equipment items are contained in Table 8.

Nonradioactive Service Tanks

A large number of tanks are required for the receiving, storage, makeup, and feeding the various nonradioactive chemicals used in the different process steps. Table 9 contains a list of these tanks along with their auxiliary equipment. The various aqueous makeup and head tanks mentioned in description of the process steps are located in the operating area--the makeup tanks on the ground floor and the head tanks on the upper level. Utility makeup and head tanks are also provided primarily for the makeup and addition of decontamination solutions. The chemicals are added to the makeup tanks from supply headers for liquids and through covered hatches for solids. Chemical composition is established by the volume of liquids and the weight of solids added.

Storage tanks for nitric acid, caustic, and demineralized water are located on concrete pads outside of the main reprocessing building. Caustic and nitric acid are received by tank trucks, which are emptied directly into the storage tanks. The demineralizer in the utilities building supplies the demineralized water storage tank. As needed, caustic is pumped to the caustic head tank in the reprocessing building and to the caustic makeup tank in the low-level waste treatment facility. Nitric acid and demineralized water are pumped continuously into supply headers serving the reprocessing building and the low-level waste treatment facility.

Storage and makeup tankage for the reprocessing plant solvent is contained in a small structure detached from the reprocessing building. There are two storage tanks, one for the diluent and one for the TBP and separate makeup tanks for the 5 percent and 30 percent TBP systems. Separate makeup tanks are used to simplify makeup scheduling and to minimize the possibility of in-plant mixing of the two solvent systems.

TABLE 9
CHEMICAL TANKS IN NONRADIOACTIVE SERVICE

No	Tank Function	Capacity (gal)	Dia (in)	Height (in)	Auxiliaries ⁽¹⁾	Material
1	Demineralized water storage	5000	100	150	P, C, I	C S
2	Nitric acid storage	5000	100	150	P	304L SS
3	Caustic storage	2000	74	111	P, C, I	C S
4	Diluent storage	1000	58	87	P	304L SS
5	TBP storage	250	36	60	P	304L SS
6	30% TBP makeup	500	50	60	P, A	304L SS
7	5% TBP makeup	500	50	60	P, A	304L SS
8	Asphalt storage	1000	58	87	P, C, I	C S
9	Aluminum nitrate solution head tank	100	23	60	-----	304L SS
10	Hydrofluoric acid head tank	50	16	60	-----	Polyethylene
11	Phosphoric acid head tank	50	16	60	-----	316 SS
12	Caustic head tank	250	36	60	P	C S
13	Utility head tank	250	36	60	-----	304L SS
14	Leacher acid makeup	500	50	60	A	316 SS
15	Leacher rinse makeup	100	23	60	A, S	316 SS
16	HAS makeup	500	50	60	A, S, P	304L SS
17	Solvent acid wash makeup	500	50	60	A, P	304L SS
18	Solvent carbonate wash makeup	500	50	60	A, P, S, C	304L SS
19	Solvent wash utility makeup	310	39	60	A, P, S, C	304L SS
20	Utility makeup	250	36	60	A, P, S, C	304L SS
21	Stripper dilution makeup	250	36	60	A, P, S	304L SS
22	HLW evaporator chem. add makeup	50	16	60	A, P, S, C	304L SS
23	Stripper dilution run	250	36	60	-----	304L SS
24	HAS run	500	50	60	-----	304L SS
25	HOS run	310	39	60	-----	304L SS
26	HOB run	310	39	60	-----	304L SS
27	IOS run	50	16	60	-----	304L SS
28	IOB run	50	16	60	-----	304L SS
29	2OS run	50	16	60	-----	304L SS
30	2OB run	50	16	60	-----	304L SS
31	HLW evaporator chem. add run	50	16	60	-----	304L SS
32	Caustic run	50	16	60	-----	C. S.
33	Asphalt run	150	28	60	C, I	C. S.
34	Nitric acid	500	50	60	-----	304L SS
35	Makeup alumina hopper	250	36	60	S	C. S.
36	LLW caustic makeup	250	40	48	P, A, C	304L SS
37	LLW nitric acid makeup	250	40	48	P, A	304L SS

(1) P=pump, C=heating coil, I=insulated tank, A=agitator S=solids addition port

Cross mixing of the solvents would have a serious effect on the operability of the solvent extraction system. Normal paraffin hydrocarbon diluent is received at the plant site in a tank truck and is pumped into the NPH storage tank. The TBP solvent is received in drums, which are emptied into the storage tank as required. As process needs dictate, measured volumes of diluent and TBP are pumped into the appropriate makeup tank, mixed, sampled and pumped into the process. As shown in Figure 28, the emulsified asphalt storage tank is also located in the solvent building. Like the diluent, the emulsified asphalt is received by tank truck.

Low-Level Waste Treatment

During reprocessing operations, relatively large volumes of aqueous wastes containing low concentrations of fission products are formed. These waste streams are released to the environment for disposal. At times the fission product content of these streams may exceed the release limits established by governmental agencies. Treatment of such wastes is required to reduce the radionuclide content so that environmental release is permissible. Particular radioisotopes of concern are cesium-137, strontium-90, and ruthenium-106. This radionuclide removal is carried out in a low-level waste treatment facility contained in a separate building on the plant site.

The primary source of low-level aqueous waste is the condensed overheads from the 1CU and 2CU evaporators and the nitric acid fractionator. Other possible sources include the effluents from the radioactive service tank coils, evaporator steam condensates and the water in the high-level waste storage basin. Normally these secondary sources are free of contamination. The detection of activity would require immediate corrective action. Equipment for the treatment of low-level wastes is sized for an instantaneous processing rate of 5 gallons per minute. This is 112 percent of the normal flow of the combined fractionator and uranium evaporator overheads.

An ion exchange process is used for fission product removal. This technique has been successfully demonstrated and applied at various AEC sites. (20, 26, 34) Because of the presence of dissolved and entrained solvent in the evaporator and fractionator overheads, the particular flow-sheet employed is one developed for treating condensates from self-boiling high-level aqueous wastes which also contain a similar solvent. (34) Organic matter in the feed stream to an ion exchange column tends to be mechanically removed by the ion exchange bed, causing excessive pressure drops. As a result, a solvent-removal pretreatment step is necessary. In operation, the evaporator and fractionator overheads are alternately accumulated in one of two collection tanks. When a 4,000- to 5,000-gallon batch has been accumulated, it is sampled for fission product analysis. If the laboratory analysis indicates treatment is not necessary, the waste is pumped to a sewer and released to the environment. If treatment is needed, the waste is pumped at a controlled rate to a steam stripper for solvent removal. The stripper feed is heated to the boiling point by steam in a heat exchanger on the feed pump discharge line. Stripper steam is generated by evaporating about 5 percent of the waste. The stripper is a Raschig ring packed tower surmounting a reboiler pot. The waste is fed to the top of the tower. Stripper overheads which contain essentially all of the solvent are condensed and routed through a decanter for separation of the solvent and aqueous phases. The solvent phase has a fission product content too high for release and drains to the elutant collection tank for periodic return to the intermediate-level waste processing cell. The solvent eventually exits with the asphalt waste. The aqueous condensate, which has a very low residual radionuclide content, is combined with the ion exchange effluent. Stripper bottoms are cooled to 100°F by a two-stage water-cooled heat exchanger prior to ion exchange. The first stage of the heat exchanger is on the stripper outlet and cools the bottoms sufficiently to prevent cavitation in the ion exchange feed pump. The second heat exchanger stage is on the pump discharge.

The cooled low-level waste is pumped through two ion exchange columns in series. A strong-acid cation exchange resin bed effectively removes cesium and strontium and effects partial removal of ruthenium. Removal of ruthenium is greatly enhanced by passage through a strong-base anion exchange resin bed. Effluent from the ion exchange columns is alternately collected in one of two collection tanks, sampled, and released to the environment. Periodically the fission products loaded on the ion exchange resins are removed. After the passage of about 2000 bed volumes (30 days of operation) caustic and nitric acid regeneration solutions are pumped through the anion and cation resin beds respectively. The fission product bearing elutant streams are routed to a collection tank and then recycled to the intermediate-level waste processing cell. The regeneration solutions are made up in tankage contained in the low-level waste treatment facility. Low-level wastes requiring treatment but free of solvent may be pumped directly to the ion exchange columns bypassing the steam stripping step. The arrangement of the low-level waste processing equipment is shown in Figure 28 and the sizes of the various equipment pieces are indicated in Table 6. Fission product concentrations in the low-level waste treatment system are sufficiently low that only minimal shielding is required. Contact operation and maintenance are used.

High-Level Waste Storage

The final disposition of highly radioactive wastes resulting from the reprocessing of irradiated fuel elements is a matter of concern to the nuclear industry. Extensive studies are in progress at several AEC and foreign laboratories to develop economical methods for the ultimate disposal of these wastes.⁽¹¹⁾ At the present time, the most promising approach involves conversion of the waste to a solid by calcination, packaging in high integrity containers, interim storage in water-filled basins, and permanent storage in special repositories. For some fuel

types, interim storage as a liquid prior to calcination offers some economic advantage. Although waste calcination development is well advanced, further engineering development is needed on the methods for permanent storage of the solidified waste. Currently, final storage of these wastes in natural salt formations is favored.

In the reprocessing of HTGR fuels, highly radioactive waste solids arise from two sources--the irradiated silicon carbide coated fissile particles and the calcined waste from fertile particle processing. As described previously, these solid wastes are packaged in high integrity, stainless steel containers, 10 feet long and 6 to 8 inches in diameter. Based on current concepts, these containers are suitable for eventual shipment to a salt mine repository for permanent storage.⁽³⁵⁾ In assessing the operating costs of the HTGR fuel reprocessing plant, shipment of these solids to a salt mine repository is assumed. However, economic studies on salt mine disposal^(36, 37) indicate that interim storage of the filled waste containers for several years prior to salt mine disposal results in an overall cost reduction. For cost estimating purposes, a 15-year interim storage period is assumed. The stored fissile particles or the fertile particle wastes may be retrieved at any time during the interim storage period and processed to recover any materials of sufficient value to warrant the processing costs.

An enclosed water-filled basin adjacent to the high-level waste processing cell is used for the interim storage of the packaged waste solids. This structure, shown in Figures 5, 9, and 26, is sized to receive the waste containers from five years of plant operation. Layout of the storage area permits the construction of additional basins as needed. The basin water not only removes the fission product decay heat but also provides the necessary shielding. With a total water depth of 25 feet, about 15 feet of water covers the 10-foot-high containers, allowing direct operation and maintenance within the storage area. Aluminum partitions divide the basin

into a number of bays with each bay accommodating two rows of storage containers. The two waste types are stored in alternate bays and the difference in the container diameter requirements is reflected in the difference in bay widths. Alternating the bays provides the spacing of the fissile particle containers needed for criticality control purposes. The floor area allocated to each fissile particle and calcined waste container is 1.55 sq. ft. and 0.915 sq. ft. respectively.⁽³⁶⁾

In operation, the filled and sealed containers are removed from the monitoring tank in the high-level waste processing cell by the overhead crane and placed into a rack on a swing-arm conveyor. This conveyor swings through a water-filled trench to a central transfer aisle in the storage basin. A bridge crane operating a short distance over the basin water transfers the container from the conveyor to its storage position. The waste containers are hung from support grids in the storage bays by hooks passing through an eye welded to the container lid. Bay widths are adequate to allow passage of a container between the two rows of stored containers. Direct operation and maintenance is used in the storage area. The entire basin is accessible from a walkway around the basin and from a platform on the bridge crane. Limit devices in the crane hoist prevent elevating a container excessively through the shielding water.

Demineralized water is used in the basin to minimize corrosion and to assure water clarity needed for visual operations. The basin water is circulated through a bank of air-cooled heat exchangers to remove the fission product decay heat. The heat exchangers are sized to maintain the water temperature below 105°F at the peak heat generation rate (17 million BTU per hour for a newly filled basin). A portion of the recirculating water is passed through a demineralizer to maintain water purity and clarity. The water is also continuously monitored to detect the presence of fission products indicative of a storage container leak. If leakage is suspected, a portable device consisting of a pump with a telescoping

suction leg and a radiation detector is used to find the faulty container. Water drawn from the vicinity of a suspect container passes through a monitoring cell mounted on the crane. Relatively high fission product content in the water adjacent to a container would indicate a leak. The failed container would be returned to the high-level waste processing cell for rework. The basin water can be processed through the low-level waste treatment facility to remove the fission product contamination. Cesium and to a lesser extent strontium are the only fission products exhibiting high leachability from calcined wastes.⁽³⁸⁾ With the use of the high-integrity stainless steel containers, the probability of a container failure is very small.

At the end of the 15-year interim storage period, the waste containers will be removed from the storage basin and shipped to a salt mine repository for permanent disposal. Shipments will be made by rail with large (about 60-ton) shipping casks. Facilities for loading the casks are not included in the storage basins but will be constructed when needed. These facilities will consist of a railroad spur, a 100-ton crane, a deep water-filled basin, and a transfer aisle equipped with a bridge crane. For loading, the shipping cask is lifted off the railroad car by the 100-ton crane, placed into the deep basin and the cask lid removed. The small bridge crane moves the waste containers from the storage basin, through the transfer aisle and places them into the shipping cask. After the lid has been reinstalled on the filled cask, the cask is removed from the water basin, drained, and returned to the railroad car.

Intermediate-Level Waste Storage

Like high-level waste, the intermediate-level wastes arising from nuclear fuel reprocessing require prolonged confinement to prevent release of radioisotopes to the environment. However, the lower radio-nuclide content and the low fission product decay heat generation rates significantly reduce the storage problems. At the present time, the

intermediate-level wastes resulting from the operation of AEC reprocessing plants at Hanford and Savannah River are evaporated to highly concentrated salt solutions which solidify on cooling.^(11,26) These solidified salts are stored in large, underground tanks. Operational considerations require that the evaporation be done in or near the final storage tank. Wastes stored in this form (salt cakes) are readily soluble in water and continued surveillance is required to assure that ground water or flooding does not release the stored radioisotopes. Recently, AEC laboratories have developed continuous methods for the incorporation of intermediate-level wastes into an asphalt matrix. The leaching rate of fission products contained in asphaltic wastes is greatly reduced⁽²⁷⁾ and the surveillance requirements should be substantially decreased. Also, the asphaltic waste can be pumped reasonable distances through heated pipe lines.

As discussed earlier in this report, the intermediate-level waste arising from the reprocessing of HTGR fuels is incorporated into asphalt with equipment located within the main reprocessing building. This waste stream is then pumped to a storage tank some distance from the building (see Figure 29). The storage tank, shown in Figure 28, is a reinforced concrete underground structure lined with stainless steel. A three-foot earth cover provides the necessary radiation shielding. The tank is sized to hold the intermediate-level waste from 5 years of plant operation. A freeboard allowance of 5 feet is included. The fill line from the reprocessing building and an installed spare line are placed within a concrete encasement which provides a secondary containment. Steam tracing of the fill line maintains the asphaltic waste above its solidification temperature. Once released into the tank, the waste cools and solidifies. To provide a measure of uniformity in waste distribution, nine inlet nozzles are used. Each inlet nozzle can be rotated as needed through a circular pattern 7.4 feet in diameter. The influent waste is routed to one inlet nozzle at a time through a valved piping system. Inlet lines within the tank are heated by electric tapes. The storage tank is vented to the plant stack via

the building ventilation filter. Additional intermediate-level waste storage tanks will be constructed as the need arises.

At the end of the useful life of the reprocessing plant, the asphaltic wastes will be melted, pumped from the tanks to suitable burial containers, and shipped to a licensed burial ground for permanent disposal.

Thorium Storage

As discussed earlier, the partially decontaminated thorium product solution requires storage for a period of 10 to 15 years primarily to allow the thorium-228 isotope to decay to levels consistent with direct refabrication techniques. During the storage period, the residual fission products will also decay to trivial levels.⁽¹⁶⁾ At the design operating rate, the output of acidic thorium nitrate solution is 270 gallons per operating day or 74,000 gallons per year.

Criteria used in the design of the thorium storage tanks are: (1) double containment is required, (2) an individual storage tank is to hold the thorium output from no more than about one year's operation, (3) spare tanks are to be included at a minimum ratio of one spare tank for five working tanks, and (4) shielding from the thorium-228 decay daughters is required. Based on the above and as shown in Figure 28, six stainless steel tanks contained in an underground vault are provided. Each tank has a capacity of 88,000 gallons and can hold one year's output with a 20 percent freeboard allowance. Thus the vault furnishes thorium storage space for five years of operation. As needed, additional vaults will be built.

Concrete support walls divide the vault into six compartments. Openings in the wall allow circulation of air and the flow of liquid to a common sump. The lower portion of the vault is lined with stainless steel. The fill line from the reprocessing building and an installed spare are contained in a concrete encasement. Piping connections to the

individual tanks are made in a diversion box located near the vault. A removable concrete cover block allows access to the box. Should a leak develop in a storage tank, a portable pump can be lowered into the failed tank and/or the vault sump and the solution pumped to the spare tank via the diversion box. The tanks and the vault are vented to the atmosphere through filters.

When the radioisotopes initially present have decayed sufficiently, the thorium nitrate solution is pumped from the tank and shipped off-site for purification and refabrication into fuel elements. The emptied tanks can then be reused.

Utilities

The HGTR fuel reprocessing plant is a self-sufficient facility and the utilities necessary for plant operation are included with the plant. In assessing the utility requirements, it is assumed that a plentiful supply of water is available from a nearby waterway and that an adequate supply of electrical power is available.

Water. Four different water systems are needed: (1) untreated water for coolers and condensers, (2) sanitary water, (3) demineralized water, and (4) fire water. Cooling water represents the largest demand. In order to minimize the fresh water requirements, the cooling water is recycled through a 1500-GPM cooling tower. Pumps in the cooling-tower sump supply headers which distribute the water throughout the plant. Two 300-GPM pumps at an intake structure on the nearby waterway supply the cooling-tower makeup water. Under normal conditions, only one pump is in use. The other pump serves as a standby.

A portion of the water from the supply pumps is treated to meet the sanitary water needs of the plant. Water treatment equipment consisting of a chlorinator and a 1000-gallon accumulator tank is located in the utilities

and shops building. The equipment can supply up to 150 GPM of sanitary water. Hot water is supplied from heaters in the various buildings.

Demineralized water is used for process chemical makeup, for boiler feedwater makeup and in the high-level waste storage basin. These needs are met by diverting a portion of the supply water through a 40-GPM demineralizer unit located in the utilities and shops building. The demineralized water tank discussed previously provides surge storage for the process water. The condensate tanks are used for boiler water surge storage.

Plant fire protection system includes a network of fire hydrants located at strategic positions through the plant. A high tank with a storage capacity of 100,000 gallons serves as a fire water reservoir.

Steam. Plant steam needs, both process and heating, are supplied from two oil-fired boilers located in the utilities and shops building. Each boiler is rated at 20,000 pounds per hour of 200-psig steam. Auxiliaries include a 50,000-gallon underground fuel storage tank and two 10,000-gallon condensate tanks.

Air. The plant compressed air needs are supplied by two 400-horsepower compressors with a combined capacity of 3500 scfm at 100 psig. A portion of the compressed air is passed through a dryer unit rated at 600 scfm to provide the plant instrument air.

Electricity. Electrical power needs are furnished through a 3000-KVA plant substation and distribution panels in the various buildings. In addition to this normal power source, certain critical equipment items are also on an emergency power circuit. A 800-KVA diesel-driven generator can supply emergency power to one of the air compressors, one of the building exhaust blowers, some of the water and process pumps and a portion of the plant lighting. This diesel unit is instrumented to start automatically should the normal power source fail.

Analytical Laboratory

In the reprocessing of HTGR fuels, a knowledge of the chemical composition of the various in-process streams is needed for process control and for accountability. Typical chemical analyses required include total uranium concentration, uranium isotopic composition, thorium concentration, acidity, specific gravity, carbon content, fission product content, impurities in the product solution, organic extractant quality, and concentrations of various metallic ions. Analytical facilities adequately equipped to carry out all of the chemical analyses required for plant operation are incorporated into the plant. The various analytical laboratories and their floor areas are as follows:

<u>Laboratory</u>	<u>Floor Area, Sq. Ft.</u>
1. High level	2,000
2. Alpha	625
3. Emission spectrograph	625
4. Radiochemistry	625
5. Counting room	340
6. Mass spectrometer	625
7. Standards	450
8. Cold chemistry	625
	<u>5,715</u>

The analytical facilities, located in the reprocessing building operating area, occupy a total floor area of 8500 sq. ft. This includes an allowance of 1800 sq. ft. for corridors, offices and other auxiliaries. An additional 1720 sq. ft. of floor space on the upper level is allocated to ventilation filters for the laboratory hoods and glove boxes and to storage space for laboratory supplies.

Major equipment items contained in the various laboratories include:⁽³⁹⁾

1. The high-level laboratory is composed of six interconnected shielded cells 6 feet wide by 5 feet deep by 8 feet high (internal dimensions). Three-foot-thick high-density concrete is used for the front wall, roof, and outside walls of the end cells. The back and cell partitions are two-foot-thick high-density concrete walls. A steel door on the back of each cell opens into a maintenance area. Samples and small equipment items are moved between cells by means of a shielded conveyor. Each cell has a high-density glass viewing window and a pair of master-slave manipulators.
2. The alpha laboratory has two fume hoods and four glove boxes (two shielded and two unshielded). These hoods and glove boxes are vented through absolute filters.
3. The emission spectrograph laboratory contains a high resolution spectrograph with two arc-spark stands and a small darkroom.
4. The radiochemistry laboratory has four fume hoods which are vented through absolute filters.
5. Three instruments are located in the counting room, (a) a 1024-channel analyzer equipped with a lithium-drifted germanium detector; a sodium iodide detector and an alpha pulse height detector; (b) an alpha-beta counter with a sample changer and (c) a single-channel analyzer.
6. The mass spectrometer laboratory has one mass spec unit and space for the future addition of a second unit.
7. The standards and cold chemistry laboratories contain a total of six fume hoods.

Plant Site Arrangement

Although no specific location for the HTGR fuel reprocessing plant has been selected, several site features are assumed. The plant is located within the United States in an area of low population density. The site is reasonably level and the local geology does not impose undue construction or drainage problems. A nearby waterway serves as a source of plant

water and has an outflow for waste water. Ready access to the site by railroad and highway is assumed.

Essentially all of the reprocessing facilities are contained within a 23-acre security area which is enclosed by a chain link fence. This enclosed area is located near the center of a larger area, several hundred acres in extent, owned by the plant operating corporation. The main reprocessing building is located near the midpoint of the security area as shown in Figure 29. Three other major buildings are included on the plant site. These are the administration building, the shops and utilities building, and a warehouse.

The administration building is a conventional single-story office building containing 6000 sq. ft. of floor area. The structure, located at the boundary of the security area, houses the administrative and engineering personnel. Truck and personnel access to the plant is through gates near the administration building. Security guards stationed in a guard house adjacent to the gates limit site access to authorized personnel only. The 8000 sq. ft. shops and utilities building contains the steam boilers, process air compressors, water treatment equipment and their auxiliaries, the maintenance shops, and change and lunch rooms for the plant operating and maintenance personnel. Inventories of the various dry chemicals used for processing and for decontamination are stored in a 4000 sq. ft. warehouse along with spare equipment items.

The parking area for the plant personnel and visitors is near the gate to the security area. Paved roads within the security area allow ready access to the reprocessing building, the warehouse, the shops and utilities buildings, and the chemical receiving tanks. The intermediate-level waste and thorium storage tanks are placed in an area removed from the normal traffic pattern.

COSTS

Operating Cost. In developing the operating costs, it is assumed that the HTGR fuel reprocessing plant operates for 15 years at a 75 percent on-line efficiency using the flowsheet described in this study. Present-day prices are used with no allowance for escalation or interest on operating capital. The operating costs are summarized in Table 10 and detailed in Tables 11 through 16. The plant operating staff of 185 people is based on a self-sufficient company.

TABLE 10
OPERATING COST SUMMARY

	Table With Cost Details	Dollars Per Year
Manpower	11	2,014,000
Chemicals	12	902,150
Utilities	13	206,000
High-level waste disposal	14	972,300
Intermediate-level waste disposal	15	62,500
Solid waste disposal		75,000
Thorium storage	16	231,900
		<hr/> 4,463,850

TABLE 11
MANPOWER REQUIREMENTS

	<u>Number</u>	<u>Salary (\$/year)</u>	<u>Total (\$/year)</u>
Plant Manager	1	20,000	20,000
Assistant Plant Manager	1	17,500	17,500
Production Manager	1	15,000	15,000
Engineering Manager	1	15,000	15,000
Employee Relations Manager	1	12,000	12,000
Personnel Manager	1	12,000	12,000
Laboratory Manager	1	12,000	12,000
Maintenance Manager	1	11,000	11,000
Materials Manager	1	11,000	11,000
Accounting Manager	1	14,000	14,000
Assistant Accounting Manager	1	10,000	10,000
Accountability Manager	1	12,000	12,000
Health Physics Manager	1	11,000	11,000
Shift Supervisors	5	12,000	60,000
Assistant Shift Supervisors	5	10,000	50,000
Engineers	15	11,000	165,000
Power Operators	10	8,000	80,000
Process Operators	50	7,500	375,000
Maintenance Personnel	25	7,800	195,000
Health Physicists	10	7,500	75,000
Chemists	5	10,000	50,000
Laboratory Analysts	21	6,000	126,000
Secretaries	7	5,500	38,500
Clerks	8	5,000	40,000
Guards	7	6,000	42,000
Nurses	2	6,000	12,000
Janitors	2	5,500	11,000
	<u>185</u>		<u>1,492,000</u>
Overheads (35%)			<u>522,000</u>
			<u>2,014,000</u>

TABLE 12
CHEMICAL REQUIREMENTS

<u>Chemical</u>	<u>Annual Consumption</u>	<u>Unit Cost</u>	<u>Annual Cost</u>
Oxygen	1.33×10^8 scf	\$0.005/scf	\$665,000
Alumina	1.38×10^5 lbs	0.70/lb	96,500
HF (100%)	1.23×10^3 lbs	0.32/lb	390
$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	4.95×10^4 lbs	0.04/lb	1,980
$\text{Cd}(\text{NO}_3)_2$	3.32×10^4 lbs	1.50/lbs	49,800
NaHSO_3	5.85×10^3 lbs	0.10/lb	590
H_3PO_4 (100%)	1.15×10^3 lbs	0.15/lb	170
$\text{Fe}(\text{NH}_2\text{SO}_3)_2$	2.78×10^3 lbs	0.31/lb	870
Na_2CO_3	2.27×10^4 lbs	0.025/lb	570
$\text{Na}_2\text{B}_4\text{O}_7$	1.52×10^2 lbs	0.10/lb	20
$\text{Ca}(\text{NO}_3)_2$	1.00×10^4 lbs	0.30/lb	3,000
NaOH (100%)	1.15×10^5 lbs	0.025/lb	2,880
HNO_3 (100%)	5.95×10^5 lbs	0.03/lb	17,900
TBP	1.50×10^4 lbs	0.40/lb	6,000
Diluent	3.90×10^4 lbs	0.10/lb	3,900
Asphalt	3.42×10^5 lbs	0.08/lb	27,400
Cation resin	45 ft ³	25/ft ³	1,130
Anion resin	45 ft ³	90/ft ³	4,050
Miscellaneous			20,000
			<u>\$902,150</u>

TABLE 13

UTILITIES

	Dollars per Year
Electricity ⁽¹⁾	140,000
Fuel Oil ⁽²⁾	<u>66,000</u>
	206,000

Notes:

- (1) Based on an average power load of 1600 KW and \$0.01 per KWh.
- (2) Based on an average steam demand of 15,000 pounds per hour, 80% boiler efficiency and fuel cost of \$0.40 per million BTU's.

TABLE 14
HIGH-LEVEL WASTE DISPOSAL

	Dollars per Year ⁽¹⁾	
	Fissile Particles	Calcined Waste
Containers ⁽²⁾	226, 800	271, 000
Additional storage basins ⁽³⁾	139, 500	139, 500
Shipping ^(4, 5)	55, 900	46, 000
Salt mine disposal ^(5, 6)	35, 900	40, 700
Surveillance ^(5, 7)	8, 500	8, 500
	<u>466, 600</u>	<u>505, 700</u>
TOTAL	\$972, 300	

Notes:

- (1) Assumes none of the waste is processed for byproduct recovery.
- (2) Based on references 11 and 40. Unit costs - fissile particle containers \$600, calcined waste containers \$500.
- (3) Based on a second basin built 5 years after plant startup at a cost of \$1, 962, 000 and a third basin built 10 years after plant startup at a cost of \$2, 232, 000. The third basin includes facilities for loading waste containers into a shipping cask. The costs of the additional basins are normalized over the plant life (15 years) at 6 percent interest, and are split equally between fissile particles and calcined waste.
- (4) Cask costs based on references 35 and 41. Shipping costs based on reference 42 for a 1000-mile distance.
- (5) Expense incurred 15 years after processing. The listed costs are assumed to be invested for 15 years at 6 percent interest to yield actual cost.
- (6) Based on references 35 and 37.
- (7) Assumes 4 process operators required and costs shared equally by the two waste types.

TABLE 15
INTERMEDIATE-LEVEL WASTE DISPOSAL

Cost per tank \$305,500

	<u>Dollars per Year</u>
First tank	0 ⁽¹⁾
Second tank (built 5 years after plant startup)	23,500 ⁽²⁾
Third tank (built 10 years after plant startup)	17,600 ⁽²⁾
Surveillance	2,100 ^(3, 4)
Final disposal	19,300 ^(4, 5)
	<u>62,500</u>

Notes:

- (1) Cost of first tank is included in plant capital cost.
- (2) Cost normalized over plant operating life (15 years) at 6 percent interest.
- (3) For 1/2 man-year annually.
- (4) Expenses incurred 15 years later. The listed costs are assumed to be invested for 15 years at 6 percent interest to yield actual cost.
- (5) Based on \$10 per cubic foot for retrieval, packaging, shipment, and disposal in a licensed burial ground.

TABLE 16
THORIUM STORAGE

Capital cost per storage vault (including indirect costs) \$1,709,000.

	<u>Dollars per Year</u>
First Vault	0 ⁽¹⁾
Second Vault (built 5 years after plant startup)	131,500 ⁽²⁾
Third Vault (built 10 years after plant startup)	98,300 ⁽²⁾
Surveillance	2,100 ⁽³⁾
	<hr/> 231,900

Notes:

- (1) Included in plant capital cost.
- (2) Vault cost normalized over plant operating life (15 years) at 6 percent interest.
- (3) Assumes 1/2 man year annually for 15 years. Listed cost is invested for 15 years at 6 percent interest to yield actual cost.

Capital Cost. The direct constructions costs were estimated by General Atomic Cost Engineering at \$15,622,000 (Table 17). The total capital cost including indirect costs, land, and startup costs is estimated to be \$30,803,000. In deriving the construction cost, the following assumptions were used:

1. Labor costs are the same as those in Denver, Colorado, which are close to the national average.
2. A single general contractor acts as prime contractor responsible for site preparation, procurement, expediting, and testing.
3. Costs are those of September, 1967.
4. There are no costs for unusual travel, subsistence or isolation pay or severe weather conditions.
5. The site is free of obstruction.
6. No rock blasting is necessary.

The capital cost does not include state sales or use taxes, AEC licensing costs, client costs, escalation, interest changes during construction, or research and development.

Reprocessing Charges. The annual reprocessing charges including a contingency reserve fund are estimated to be \$10,318,000 (Table 18). Based on the design annual throughput rate, reprocessing charges per kilogram of thorium and uranium in the unirradiated HTGR fuel is \$62 or 0.098 mills per KWh(e). No credit is taken for the recovered thorium.

TABLE 17
CAPITAL COST

Direct construction cost	\$15, 622, 000
Contractors overhead and profit (25%)	<u>3, 906, 000</u>
	19, 528, 000
Design (15%)	<u>2, 929, 000</u>
	22, 457, 000
Contingency (25%)	<u>5, 614, 000</u>
	28, 071, 000
Land (1000 acres at \$500 per acre)	<u>500, 000</u>
	28, 571, 000
Startup costs (50% of annual operating costs)	<u>2, 232, 000</u>
	30, 803, 000

Annual Fixed Cost

$$\$30, 803, 000 \times 0.1741^* = \$5, 362, 800 \text{ per year}$$

* Based on the following (from reference 41)

Return on investment	6.75%
Depreciation	4.06 (15-year plant life)
Insurance	0.40
Federal taxes	3.40
State and local taxes	2.45
Equipment replacements	<u>0.35</u>
	17.41%

TABLE 18
REPROCESSING CHARGES

	<u>Dollars per Year</u>
Annual Fixed Cost (Table 17)	5,362,800
Operating Cost (Table 10)	<u>4,463,850</u>
	9,826,650
Contingency reserve (5%)	<u>491,300</u>
	10,317,950
Thorium plus uranium = 165,555 kg per year (Table 2)	
Cost per kg = \$62	
Mills per KWh(e) = 0.098	

HTGR FUEL VARIATIONS

The HTGR fuel elements considered in this study are based on a "once-through" fuel cycle; i. e., the fresh fuel has fertile particles containing only thorium and fissile particles containing the fissile uranium (U-233 and U-235). After irradiation, only the fertile particles are processed for recovery of the thorium and bred uranium. The fissile particles are discarded. This study is also based on the oxide form of the thorium and uranium. Some variations in the fuel elements makeup can be accommodated in the reprocessing plant without any equipment changes. Only flowsheet modifications are needed. Two example variations are carbide fuel kernels and fuel elements based on a "bred-uranium" fuel cycle.

Carbide Fuels. HTGR fuel elements with the thorium fuel material in the form of the carbide (versus the oxide) can be reprocessed with only minor changes in the head end flowsheet. During the burning step, the carbide fuel kernel is converted to fine oxide particles. A slight adjustment in the burner oxygen requirements would be needed. The resulting fine thorium oxide particles dissolve more readily than thorium oxide microspheres. This makes it possible to reduce the nitric acid concentration in the leacher acid to about 4 molar without increasing the leacher time cycle.⁽⁶⁾ The lower nitric acid content of the leacher solution simplifies the denitration step and reduces the load both on the intermediate-level waste evaporator and the nitric acid fractionator. In addition, the amount of alumina dissolved is decreased thus reducing the alumina makeup requirements and the quantity of alumina requiring disposal in the

fissile particle and calcined wastes. These flowsheet modifications for carbide fuels should result in a slight decrease in reprocessing costs.

"Bred-Uranium" Cycle Fuel Elements. The process flowsheets used in this study are based on HTGR fuel elements designed for operation with the "once-through" fuel cycle. Here both the recycle U-233 and the makeup U-235 are contained in silicon carbide coated fuel particles and are not recovered. An alternate fuel element is one designed to operate on a bred-uranium fuel cycle. Three particle types are used in the bred-uranium cycle: (a) a thorium particle, (b) a thorium-recycle U-233 particle, and (c) a U-235 particle. Only the U-235 particle has a silicon carbide coating and is discarded. Both the bred U-233 and the unburned recycle U-233 are recovered. In comparison to the once-through cycle, the quantity of fissile uranium (U-233 and U-235) recovered in an equilibrium bred-uranium cycle is increased by 24 percent. Also, the amount of nonfissile uranium (U-234 and U-236) processed is increased with the result that the total amount of uranium processed through solvent extraction is increased by 63 percent. The bred-uranium cycle fuel elements do not have a significant effect on the head end flowsheet but modifications in the solvent extraction flowsheets are necessary. Since the feed solution to the solvent extraction system has a higher uranium content, higher flow rates for the 1A and 2A column extractant streams are needed. The 1CX and 2CX stream flow rates also have to be increased and, as a consequence, the 1CU and 2CU evaporator loads would be higher. These equipment pieces have sufficient excess capacity to accommodate the increased flows. However, because of storage space limitations, the concentrated 1CU would require processing through the uranium purification cycle at more frequent intervals. In addition, the quantity of uranium shipped would increase and more shipping containers would be needed. Although the fissile uranium concentration is higher in the equilibrium bred-uranium cycle, the fissile

uranium to thorium ratio is still sufficiently low that no additional criticality control measures are necessary. ⁽¹⁴⁾

The absence of the recycle U-233 in the silicon carbide coated fissile particles reduces the quantity and volume of these particles. Thus the number of fissile particle containers requiring storage and eventual disposal is decreased. This to some degree offsets the higher reprocessing costs inherent in processing the larger quantity of uranium. Although no detailed analysis has been made, the costs of reprocessing bred-uranium cycle fuel elements are not expected to differ significantly from those for the once-through cycle fuel elements.

DEVELOPMENT NEEDS

Although the reprocessing of irradiated fuels has been conducted in large scale plants for more than 20 years, certain steps in the reprocessing of HTGR fuels require further development before a commercial plant can be designed and constructed. The process steps in need of further development are primarily associated with the head end portion of the flowsheet. To date work on the burn-leach head end process was done on a laboratory and bench scale for the primary purpose of demonstrating the process. The graphite fuels used in the development studies did not contain silicon carbide coated fuel particles and thus differ from the fuels considered in this report. Considerable effort is needed to develop the equipment for fuel element crushing, burning, leaching, and particle separation on a production plant scale for processing HTGR fuels of the type considered in this study. A knowledge of the distribution of fuel particles and alumina during head end processing is also needed so that criticality problems can be assessed. The denitration of the leacher solution by batch operation has been demonstrated in pilot and production plants. However, equipment corrosion has been troublesome. Demonstration of continuous denitration in reliable equipment is needed.

The technology of solvent extraction processing is well advanced and no significant engineering problems remain unsolved. However, the burnup of HTGR fuels is significantly greater than the fuel type processed in production plants. The chemistry and radiation effects from high-burnup fuels should be explored.

Although calcination of the high-level waste in a fluidized bed unit is indicated in this study, other calcination means may be used. Pot, spray,

and phosphate glass waste calcination methods are currently undergoing engineering development and evaluation.⁽¹¹⁾ After these various calcination methods have been sufficiently developed, the most promising method should be studied for application to HTGR fuel reprocessing waste.

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Fig. 3. Uranium final purification block flow diagram

Fig. 4. Waste processing block flow diagram

Fig. 5. Reprocessing building floor plan

Fig. 6. Sections - fuel receiving and storage

Fig. 7. Sections - process cells and operating galleries

Fig. 8. Burner

Fig. 10. Leacher

Fig. 11. Drying hopper

Fig. 12. Stripper

Fig. 13. HA column

Fig. 14. Air pulser system

Fig. 15. HCP evaporator

Fig. 16. 1AT evaporator

Fig. 17. 1CU and 2CU evaporators

Fig. 18. HCW tank solvent washer

Fig. 19. High-level waste evaporator

Fig. 20. High-level waste calciner

Fig. 21. Intermediate-level waste evaporator

Fig. 22. Asphalt blender

Fig. 23. Nitric acid fractionator

Fig. 24. 1CU and 2CU product receiver tank

Fig. 25. 1CU product storage tank and uranium rework tank

Fig. 26. Sections - operating galleries and waste storage basin

Fig. 27. Floor plans - operating galleries

Fig. 28. Miscellaneous tanks and facilities