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A CONCEPTUAL STUDY OF
A FLUORIDE VOLATILITY PLANT FOR
REPROCESSING LIGHT WATER REACTOR FUELS

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE GASEOUS DIFFUSION PLANT

operated for the **ATOMIC ENERGY COMMISSION** under U. S. GOVERNMENT Contract W-7405 eng 26

OAK RIDGE GASEOUS DIFFUSION PLANT
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Oak Ridge, Tennessee 37830

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A CONCEPTUAL STUDY OF A FLUORIDE VOLATILITY PLANT
FOR REPROCESSING LIGHT WATER REACTOR FUELS

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A B S T R A C T

This report presents an engineering evaluation of a fluoride volatility process for recovery of uranium and plutonium from spent low-enrichment nuclear power reactor fuels. The study was initiated in 1966 at the request of the U. S. Atomic Energy Commission, Division of Reactor Development and Technology, with two primary goals in mind. First, it was important to obtain guidance on the question of volatility process economics as applied to power reactor fuels; and second, an independent assessment of the technological feasibility of the process extrapolated to plant scale was considered desirable. The plant throughput was assumed to be 300 tonnes of uranium per year, which is the expected processing load required for newly constructed and planned nuclear power reactors for the early part of the 1970s.

The study procedure involved the following steps: (1) review and evaluation of experimental data provided by Argonne National Laboratory, Brookhaven National Laboratory, Oak Ridge Gaseous Diffusion Plant, and Oak Ridge National Laboratory; (2) establishment of processing rates and preparation of process flow sheets; (3) conceptual design of the process equipment items, and piping and instrumentation schemes; (4) conceptual design of the process buildings; (5) evaluation of the safety aspects, including analysis of criticality problems, shielding requirements, chemical hazards, and disposal of gaseous, liquid, and solid wastes; (6) sizing of the auxiliary facilities; and (7) preparation of a detailed cost estimate.

The flow sheet includes hydrogen chloride decladding, followed by oxidation of the exposed uranium dioxide, uranium fluorination using bromine pentafluoride, and plutonium fluorination using elemental fluorine. These operations are all conducted on a single multipurpose fluid-bed reactor, and two head-end processing lines are provided. Reagent streams are recycled.

The facility requirements involve a 46,500 sq ft process building, containing process cells with a total area of 2,650 sq ft; an 8,770 sq ft fuel receipt building; a gas filtration system including a 400-foot tall stack; a 23,000 sq ft utility, maintenance, and fluorine plant building; an 8,000 sq ft warehouse; miscellaneous structures for sanitary water service; sewage disposal, security operations; waste storage areas; and a number of general outside improvements.

The estimated capital cost for the conceptual plant is about 26 million dollars without contingency and 33 million dollars with a 25% contingency. With a depreciation charge of 15% per year, the unit capital charge becomes \$16.34 per kg of uranium. The operating cost is estimated to be \$10.98 per kg of uranium; therefore, the total unit processing cost is \$27.32 per kg of uranium.

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A CONCEPTUAL STUDY OF A FLUORIDE VOLATILITY PLANT
FOR REPROCESSING LIGHT WATER REACTOR FUELS

This report presents an engineering evaluation of a fluoride volatility process for recovery of uranium and plutonium from spent low-enrichment nuclear power reactor fuels. The study was initiated in 1966 at the request of the U. S. Atomic Energy Commission, Division of Reactor Development and Technology, with two primary goals in mind. First, it was important to obtain guidance on the question of volatility process economics as applied to power reactor fuels; and second, an independent assessment of the technological feasibility of the process extrapolated to plant scale was desired.

At the outset of the study, the plant throughput was assumed to be 300 tonnes of uranium per year, which was the expected processing load required for newly constructed and planned nuclear power reactors for the early part of the 1970s. The plant was to have a 300-day-per-year on-stream time with the remainder of the year allocated for downtime and major maintenance. Turnaround time, i.e., time needed to clean out the equipment between campaigns, was included in the 300 days of on-stream time.

Specifically, the study procedure involved the following steps: (1) review and evaluation of experimental data provided by Argonne National Laboratory, Brookhaven National Laboratory, Oak Ridge Gaseous Diffusion Plant, and Oak Ridge National Laboratory; (2) establishment of line processing rates and preparation of process flow sheets; (3) conceptual design of the process equipment items and piping and instrumentation schemes; (4) conceptual design of the process buildings; (5) evaluation of the safety aspects, including analysis of criticality problems, shielding requirements, chemical hazards, and disposal of gaseous, liquid, and solid wastes; (6) sizing of the auxiliary facilities; and (7) preparation of a detailed cost estimate.

The information is arranged with a factual summary of the results given first followed by the main body of the report. Attention is called to the Process Critique section of the report, where a critical analysis of process advantages and disadvantages is given as seen by the study group.

The cooperation and support of many persons at the national laboratories and of AEC personnel are highly appreciated; individual contributors are recognized in the acknowledgement section.

SUMMARY

A fluoride volatility plant for reprocessing zircaloy-clad uranium dioxide power reactor fuels at a nominal rate of 1 tonne of uranium per day has been evaluated. The corresponding plutonium processing rate is 9.7 kg per day. Material balance flow sheets were compiled based on a reference flow sheet derived from the experimental work performed at the Argonne National Laboratory; concurrently, process equipment items were sized, and the number of head-end reactors required was established. Conceptual drawings were made for the important process equipment items. Cell and building layouts were prepared, as were conceptual fuel receipt and waste storage area designs. Finally, general plot plans were made to show approximate locations of auxiliary facilities and yard requirements. These drawings appear in the appendix to this report. Cost breakdowns were prepared from the drawings and from auxiliary lists in as much detail as was feasible considering the depth of the study.

It should be stressed that the study is conceptual in nature, and that sufficient manpower and funding were not expended to prepare the equipment designs, process and building layouts, or auxiliary facilities in sufficient detail to achieve high precision in the cost estimate. The study results are, however, felt to be adequate to answer the basic economic questions concerning the competitiveness of the process with the established aqueous routes. Furthermore, it should be kept in mind that the process technology, including scale-up from the relatively small test equipment and evaluation of problems for larger scale operation with irradiated fuels, was not completely developed. In most cases, data were available only from small-scale experiments involving nonirradiated uranium dioxide.

The main reactor used in the process is a two-diameter fluid-bed unit, with 18- and 26-inch-diameter sections. The vessel is 30 feet high, excluding a slide valve, an expansion joint, and the plug penetration section. Fuel assemblies are charged into the upper 26-inch-diameter section, which is 22 feet long, in bundles containing about 1,500 kg of uranium dioxide. Hydrochlorination of the zircaloy cladding is performed at 400°C in a fluidized bed of inert alumina, with the assemblies completely submerged. Volatile chlorides of zirconium and tin leave the reactor, while the uranium dioxide, which is not attacked by the hydrogen chloride, falls to the lower section of the reactor.

The uranium dioxide is then oxidized to U_3O_8 before the uranium is selectively fluorinated with bromine pentafluoride. Oxidation is performed at 450°C, while the interhalogen fluorination is carried out at 300°C. The plutonium, which has been converted to plutonium tetrafluoride during the bromine pentafluoride fluorination step, is then volatilized with elemental fluorine at temperatures ranging from 300 to 550°C. The final bed material is conveyed pneumatically to annular waste storage bins.

A typical charge to the reactor, based on the dimensions of current fuel elements, would consist of either three 8-1/2-inch by 8-1/2-inch by 144-inch-long assemblies or seven 5-1/2-inch by 5-1/2-inch by 144-inch-long units; i.e., about 1300 kg of uranium. The time required for a complete batch cycle is about 60 hours. Two head-end reactors are thus provided to meet the scheduled throughput of 1 tonne of uranium per day. Process gas recycle equipment is designed to handle the off-gas load of only one of these reactors at a time, since operations in the two units can be phased so that simultaneous demands for the same reagents are avoided.

The zirconium and tin chlorides volatilized from the bed, the excess hydrogen chloride, and the hydrogen produced in the decladding reaction are first passed through a fluid-bed cooler-filter unit and a backup filter before being fed to a fluid-bed pyrohydrolysis reactor for conversion of the zirconium and tin compounds to solid waste with concomitant regeneration of the hydrogen chloride. The excess steam leaving the pyrohydrolyzer is condensed, along with part of the hydrogen chloride. This aqueous acid is vaporized and used again as pyrohydrolyzer feed gas. The remaining hydrogen chloride, except for a small amount lost with the hydrogen vent stream, is recirculated to the halogenator.

In the uranium dioxide oxidation step, dry air is used as the oxidant on a once-through basis. The off-gases are vented through a scrubber which also serves as the bromine pentafluoride fluorination vent gas scrubber.

Off-gases from the reactor during the bromine pentafluoride fluorination are directed to a bromine pentafluoride regenerator and then to a cold trapping system which collects the uranium hexafluoride as a solid and condenses most of the bromine pentafluoride as a liquid. The bromine pentafluoride liquid formed drains from the trap continuously and is subsequently vaporized and recycled to the halogenator. A portion of the process gases is vented immediately after the cold traps. After the bromine pentafluoride treatment has been completed, the trapped uranium hexafluoride is drained from the cold trapping system and distilled. Two batch distillation columns are used in series to remove low and high boiling fission products, as well as bromine pentafluoride and any bromine trifluoride which may have formed. The uranium hexafluoride product is withdrawn as a vapor off the top of the second column and is directed to the product collection point. Sorption traps containing sodium fluoride and magnesium fluoride, placed at strategic locations in the process, serve as the principal mode of selectively removing volatile fission product fluorides.

The plutonium recovery has been considered to the point where the plutonium has been fluorinated from the bed and collected in a cold trap. Plutonium technology for purification beyond this point by volatility methods was not available; however, an allowance for the cost of this processing step has been included in the cost estimate.

The Process Critique section of the report treats areas of potential process difficulty. Included in the analysis are comments about such items as bed caking, filtration, corrosion rates, solids transfer, solids sampling, and alternative hardware arrangements. At this writing, it is problematical as to how many of these potential difficulties are, in fact, real, since the relatively early stage of development in some areas precludes accurate prediction.

The estimated capital cost for a 1 tonne of uranium per day fluoride volatility reprocessing facility is about 26 million dollars without contingency and 33 million dollars with a 25% contingency. With a depreciation charge of 15% per year, the unit capital charge becomes \$16.34 per kg of uranium. The operating cost is estimated to be \$10.98 per kg of uranium; therefore, the total unit processing cost is \$27.32 per kg. of uranium. All costs are expressed in terms of 1967 dollars.

The conceptual plant is located on a 200-acre site. Staff requirements were estimated to be 119 people. The facility requirements involve (a) a process building with a total floor area of 46,500 square feet and a volume of 1,030,000 cubic feet, including a process cell area of 2,650 square feet with a volume of 76,000 cubic feet; (b) a fuel receipt building 8,770 square feet in area and 339,000 cubic feet in volume; (c) a cell and process gas filtration system and a 400-foot tall stack for disposal of cell ventilation air and process off-gases; (d) a utility, maintenance, and fluorine plant building having an area of 23,000 square feet; (e) an 8,000-square-foot warehouse; (f) miscellaneous structures for the water pumping, water filtration and treatment, sewage disposal, and security operations; (g) waste storage areas; and (h) a number of the usual general outside improvements associated with a chemical processing plant.

BASES FOR STUDY

Fuel Charge and Design Throughput

The throughput requirements for the conceptual plant were set at 1 tonne of uranium per day. This rate is sufficient, for example, to process about two complete reactor cores per year for stations having electrical power outputs of 1,000 Mw. Since most current and near-future reactors are scheduled to refuel between one-fifth and one-third of their cores per year, the 1-tonne-of-uranium-per-day fuel reprocessing plant could thus meet the fuel processing requirements of from six to ten light-water power reactor sites.

For this study, the standard fuel charge is defined as the base amount of irradiated fuel to be charged to the main reactor for one batch run. The size of the standard fuel charge assumed for this study, along with the initial uranium-235 enrichment, burnup, specific power, and cooling time, is shown in table I. These numbers were arrived at after consideration of the typical Westinghouse, General Electric, and Combustion Engineering fuel assemblies described in table II. Three modules of the Westinghouse or Combustion Engineering size or seven of the General Electric size would be charged at one time for batch processing to reach the desired throughput rate.

TABLE I

INITIAL COMPOSITION AND IRRADIATION CONDITIONS
ASSUMED FOR STANDARD FUEL CHARGE*

Initial** Weight of Uranium Dioxide, kg	1,500
Initial** Weight of Zircaloy Cladding, kg	423
Total Charge, kg	1,923
Initial** Uranium-235 Enrichment, %	2.75
Burnup, Mwd/tonne	25,000
Specific Power, Mw/tonne	25
Cooling Time, days	120

* The standard fuel charge is defined as the base amount of irradiated fuel to be charged to the main process reactor for one run.

** The "initial" weights and enrichments are those in power reactor fuel before irradiation.

TABLE II

TYPICAL FUEL ASSEMBLY AND FUEL ROD DIMENSIONS
FOR CURRENT AND NEAR-FUTURE POWER REACTORS

	Westinghouse*	General Electric†	Combustion Engineering§
<u>Fuel Assemblies</u>			
Rod Pattern	15 × 15	7 × 7	15 × 15
Number of Fuel Rods	204	49	217
Number of Other Rods	21	none	8
Rod Pitch, inch	0.563	0.738	0.553
Nominal Distance Between Adjacent Rods, inch	0.141	0.176	0.140
Cross Section, inch	8.43 × 8.43	5.438 × 5.438	8.16 × 8.16
Probable Cut Length, inch	150	162	142
Shroud	Canless	Removable	Canless
<u>Intermediate Grids</u>			
Type	Eggcrate	Crosswire	Eggcrate
Overall Dimensions, inch	8.45 × 8.45 × 2	5.45 × 5.45 × 2	8.18 × 8.18 × 2
Thickness of Each Strip, inch	0.015	0.015	0.015
<u>Fuel Rods</u>			
Outside Diameter, inch	0.422	0.562	0.413
Clad Thickness, inch	0.0243	0.032	0.024
Diametrical Gap, inch	0.0065	0.010	0.006
Fuel Length, inch	144	144	132
Gas Plenum Length, inch	6	16	6-3/4
Rod Length, inch	150	160	140

* Preliminary Safety Analysis Report, Florida Power and Light Company, Turkey Point Nuclear Generating Units No. 3 and No. 4, Docket No. 50-250 and -251, March, 1966.

† Preliminary Safety Analysis Report, TVA, Brown's Ferry Nuclear Power Station, Docket 50-259 and -260, July, 1966.

§ Preliminary Description and Safety Analysis Report, Consumers Power Company, Palisades Plant, Docket No. 50-255, June, 1966.

Flow Sheet Choice

The general volatility approach taken entails four principal chemical reactions and, on the basis of ANL work, was selected by the Volatility Process Advisory Committee* (VPAC) as the reference fluoride volatility flow sheet. First, the fuel element clad material, an alloy of zirconium and tin, is removed by reaction with anhydrous hydrogen chloride to form the volatile zirconium tetrachloride and stannous chloride. Second, the uranium dioxide ceramic fuel, which is not attacked by the acid gas, is contacted by oxygen and converted from a dense, hard oxide pellet or pellet fragments to a light, fluffy, finely divided U_3O_8 powder. In the third step, the uranium is separated and recovered by fluorinating the U_3O_8 powder with gaseous bromine pentafluoride. The uranium is volatilized as the hexafluoride, which is collected and held for further purification. The plutonium and most of the fission products are converted to nonvolatile fluorides and remain in the reactor. The fourth step is the plutonium volatilization operation. Here, the plutonium tetrafluoride formed during the bromine pentafluoride treatment is fluorinated to volatile plutonium hexafluoride by prolonged contact with concentrated elemental fluorine. The volatilized plutonium hexafluoride is collected and processed further to obtain a pure plutonium product.

Alternate chemical methods can be pointed out for most of the processing modes. For example, it is possible to destroy the zircaloy cladding by reaction with a gaseous hydrogen fluoride-oxygen mixture to form a scaly product composed of nonvolatile compounds of zirconium⁽⁶⁾. This method is undesirable, because the reacted material partially retains its geometric form and hinders the physical expansion of the uranium dioxide as it reacts with the oxygen and hydrogen fluoride mixture to form uranyl fluoride. The expansion of the uranyl fluoride is restricted by the reacted clad material and may ultimately result in bed caking or plugging.

Also, mechanical decladding, i.e., chopping or shearing the fuel modules into small pieces followed by roasting to disintegrate the fuel pellets, might be used instead of the chemical method. Since further development work was required to determine the practicality of this method, the chemical method had the benefit of providing alternative technology.

Processing alternatives are also available for the uranium and plutonium volatilization and separation steps which differ according to the fluorinating agent used. The selective fluorination of the uranium with bromine pentafluoride (or bromine trifluoride), followed by a plutonium fluorination with elemental fluorine, was selected for the conceptual plant. Another possibility, however, is the fluorination of the uranium and plutonium simultaneously with elemental fluorine, followed by separation

* The Volatility Process Advisory Committee, consisting of representatives of ANL, ORNL, ORGDP, and the AEC, was established to guide and coordinate the volatility programs of the various sites.

of the uranium from the plutonium using distillation, thermal decomposition, or sorption on sodium fluoride. Chlorine trifluoride is also a possible fluorinating agent⁽³¹⁾; however, there may be handling problems with this chemical. Also, chlorine trifluoride tends to volatilize some plutonium⁽³²⁾, probably because of the fluorine present with the chlorine trifluoride at equilibrium, and as a result, a plutonium-uranium separation step would be required as with the fluorine-only fluorination scheme.

Several of these processing options, and other related information, are discussed more thoroughly in an addendum to this report to be published in the future.

As mentioned, bromine pentafluoride (or bromine trifluoride)-fluorine fluorination was selected over the single-step elemental fluorine route. The main advantage is that an extremely clean-cut bulk separation of the uranium from the plutonium is achieved, and simplifications in the product handling system are, in theory, possible. Additionally, lower fluorination temperatures are possible, since the rate of fluorination of the U_3O_8 with bromine pentafluoride or bromine trifluoride is apparently faster than with fluorine, and the heat released per mole of uranium hexafluoride formed in the head-end fluid-bed reactor is lower.

Of the two uranium fluorinating agents, bromine trifluoride and bromine pentafluoride, bromine pentafluoride appears to be the better choice, since it can be more easily regenerated quantitatively. Also, in a subsequent distillation step for product purification, the separation of residual bromine trifluoride from uranium hexafluoride would be more difficult than a residual bromine pentafluoride-uranium hexafluoride separation.

After fluorinating the uranium with bromine pentafluoride, the off-gases leave the main fluid-bed reactor and filter unit and pass into a bromine pentafluoride regenerator. Partial separation of the bromine pentafluoride and uranium hexafluoride from the noncondensables then takes place by desublimation and condensation. The separation is carried out in a cold trap, where the uranium hexafluoride is trapped as a solid. The bulk of the bromine pentafluoride condenses, drains off as a liquid, and is revaporized for recycle back to the main fluid-bed reactor. A multistage liquid condensing operation⁽³⁴⁾ could have been used in place of the cold trapping operation, but the cold trapping route is the preferred choice because the loads for the distillation columns are expected to be smaller.

Another method of recovering the uranium hexafluoride from the process gases is sodium fluoride sorption of the uranium hexafluoride. Here, the process gas stream containing uranium hexafluoride contacts sodium fluoride in a stirred fluid-bed sorption unit, and the uranium hexafluoride is removed by formation of a complex with the sodium fluoride. The uranium hexafluoride is then thermally desorbed, and the regenerated

sodium fluoride is returned to the stirred fluid bed. Since the sorption operation may require frequent mechanical maintenance, its use in a remotely maintained cell does not appear advisable. Also, since some bromine trifluoride will undoubtedly be present in the bromine pentafluoride regenerator product gas, the true effectiveness of the uranium hexafluoride sorption separation step may be hindered by concurrent sorption of bromine trifluoride along with the uranium hexafluoride on the sodium fluoride⁽⁹⁾.

Process Design Philosophy

The number of processing lines required to handle the desired throughput was based on performing the four principal chemical steps noted above in each head-end fluid-bed reactor. Another possible method would be to use two reactors in series, whereby the hydrochlorination and oxidation steps could be performed in the first reactor, and the interhalogen and fluorine fluorination steps could be carried out in a second reactor. Equipment for transfer of the beds between reactors would be necessary but might be avoided if the U_3O_8 produced during the oxidation could be selectively elutriated to the fluorination reactor. Still a third alternative could employ three reactors in series, with the third reactor handling the plutonium fluorination step separately. At the time the study was initiated, the development of the latter two alternatives was not sufficiently advanced to warrant consideration in the study, and therefore, the rather straightforward single vessel process mode was used as the study basis. With further process developments, revision of the present study might prove desirable in the future. For this reason, these alternatives will be pursued in more detail in the addendum.

Two 26-inch-diameter reactors are required to handle the desired throughput with the single vessel multiprocess scheme. This size reactor can presumably accommodate a satisfactorily large fuel quantity without encountering the nuclear safety or heat transfer problems that might result if larger diameter reactors were used. Hydrogen chloride, bromine pentafluoride, and fluorine recycle systems are shared in handling the off-gases from the two head-end reactors.

The fuel modules were assumed to be clad with zircaloy-2, and it was also assumed that any other materials used in the construction of the fuel assemblies would eventually be consumed during the course of several process cycles; therefore, no bed dumping step for the specific purpose of removing extraneous materials, such as springs and clips, was included in the processing cycle.

A satisfactory plutonium purification scheme was not available at the time this study was made, and consequently, there could be no detailed cost estimate for this portion of the process. The scheme presented in

this report carries the processing to the point where the plutonium is fluorinated from the bed and collected as solid plutonium hexafluoride in a cold trap, with cost allowances added for the subsequent purification operations.

Waste storage provisions were based on what were judged to be the best available methods at the time of consideration of this phase of the flow sheets. Accordingly, the fluid-bed solid wastes are stored in bins similar to those used in the waste calciner facility at the Idaho Chemical Processing Plant⁽¹⁷⁾. Waste storage economies arising from the application of new technology, requirements for permanent waste disposal in some other manner and surveillance, and larger plant loadings are important factors which will influence waste disposal costs and should be considered in any future review of the operating costs estimated for this study.

Safety requirements were also considered in the process design, particularly those concerned with criticality restrictions, chemical problems, and off-gas venting. The important assumption relative to criticality was that no water will be present in process cells where either uranium or plutonium is handled. Shielding and personnel contamination control were taken into account in the building layout. Conformity to applicable AEC and Federal standards is, of course, mandatory. These phases of the study are discussed in the Safety and General Facilities chapters of the report.

With respect to accountability, it was felt that the initial solution type sampling, comparable to aqueous plant practice, was not possible; however, reliable sampling after several processing steps should be sufficient to establish material balances to customer satisfaction. This assumption is particularly important, since exact determination of the uranium and plutonium input to the fluid bed can be performed only with considerable difficulty. For example, the first time at which the input might be sampled is after the oxidation step, at which point part of the uranium and plutonium will be in the filter unit and the rest will be distributed somewhat heterogeneously in the fluid bed itself. Some bed sampling will be required, however, for nuclear safety controls, but this sampling will not be so frequent as that which would be required if input values for accountability were required for each batch. Accurate measurement of the uranium and plutonium content of the product and waste streams should give a reliable check on material received.

A basic requirement for this study was that the facility be independent and self-sustaining. Auxiliary facilities, such as administration, utilities, warehouse, maintenance, laboratory, and others which would be required to support an operating plant, were provided and considered in sufficient detail to obtain a reasonable basis for costing. The independent facility requirement was only carried to the point of providing an operational plant; the physical plant and staffing, therefore, would not accommodate pilot plant or laboratory process development, fabrication of large equipment items, or extensive construction programs.

The plant site itself was taken to be favorable with respect to meteorology, geology, and general terrain and to be located in a sufficiently isolated area so that undue difficulty with disposal of gaseous and liquid wastes would not occur. Furthermore, convenient access to electrical power, river water, rail and land transportation, and a qualified construction and operating labor supply was assumed. There was no justification for selecting any one particular region of the country, so the necessary decisions for cost analyses were generally based on assumption of conditions applicable in the southeastern portion of the United States.

Maintenance and Decontamination

Remote maintenance was selected for the radioactive processing areas of the plant. The choice was motivated by the high radiation level in the head-end areas; the difficulties associated with decontaminating the interiors and exteriors of the equipment items and with preventing the spread of radioactive dusts throughout the processing area; the probable need for relatively frequent change-out of some radioactive equipment items (such as process filters and sorption traps); and the chance that access to the interior of some of the equipment would be required to remove lumps, cakes, and other nonfluidizable solids. Access to the decontamination, crane maintenance, and railroad areas is possible after appropriate decontamination and isolation of the area have been performed.

A maximum processing cell height of 37.5 feet is required to accommodate the main fluid-bed reactor. Two manipulators are used to perform maintenance. One, mounted on a self-propelled cart, travels on narrow-gauge rails over the length of the processing cells, while the other is mounted on the main processing cell crane bridge which is located in the crane bay above the cells. Both the upper part of the deep cells and the entire depth of the shallow cells can be reached by the latter manipulator. With the two manipulators, all disconnects can be reached and "operated" remotely. After disconnection from associated piping, instruments, and electrical connections, the large equipment in the deep cell area can be removed from the processing cell by lowering it onto a long four-wheeled cart similar to a railroad flatcar which travels on the same tracks as the lower manipulator. The equipment is then rolled ~~through the process cells and through a heavy shielding door into the~~ decontamination area at the far end of the processing canyon. Facilities for exterior decontamination are provided here. After treatment, the equipment is enclosed in a shielded coffin and transported by rail to the burial ground for disposal. All equipment in the deep cell area is capable of being removed and disposed of in this manner.

Complete decontamination of the equipment will not be attempted prior to disposal. In the reactors, the major part of the contained radioactivity can be removed prior to disconnection. This is accomplished by emptying the fluid beds through the normal waste lines at the reactor bottom and then flushing with clean alumina one or more times. If necessary, the

interior of the reactor could be further cleaned by use of the process cell vacuum cleaning system together with the manipulators. All loose contamination is expected to be removed by this combination of methods. Any radioactive cakes, lumps, metallic shards, or ceramic shapes left in the reactor after removal of the main bed, may be dumped out the bottom into a container after removing the bottom flange. The material would be removed from the cell to the waste disposal area in a shielded carrier.

All viewing in the central and east bank of cells is via closed-circuit television; the cameras are equipped with either turret or zoom lenses and mounted with remote aiming adjustments on the manipulators. Two cameras are used to afford some measure of binocular vision to the operator. A fixed TV camera is mounted in two corners of each cell to give an overall view of the processing area. These cameras are plugged in, and may be easily removed and replaced by the overhead crane-mounted manipulator when found defective. All piping connections in the cell between pieces of equipment and between utility supplies and the equipment are made with jumpers. Each jumper is supplied with heaters, control and block valves, leak detector lines, and insulation, as required. Thus, the process and utility piping may be disconnected and hung out of the way when a piece of equipment is to be replaced.

Spare manipulators and a spare crane are provided for reserve service or replacement in the event the in-use units break down. A warm maintenance and decontamination facility is provided in the decontamination cell for both dry and wet decontamination of the manipulators, the crane, and small equipment items which may require repair.

Auxiliaries

The conceptual plant assumes the presence of a sufficient supply of water of adequate purity, the ready availability of 3-phase, 13.8 kv electric power, telephone service, and easy access to a heavy-duty public highway and main-line railroad.

Auxiliary services, such as an emergency power supply, heating and air conditioning, electrical substation and distribution system, water purification, storing, pumping and waste water disposal, and chemical storage and warehousing, are assumed to be an integral part of the plant as constructed. Related costs are included in the capital cost estimate.

Additional plant auxiliaries are a fluorine manufacturing and storage facility capable of producing 1,200 pounds of fluorine per day. A liquid nitrogen storage and vaporizing plant, an air compressing and drying plant for both instrument and process use, a 45% potassium hydroxide storage tank, and a roofed hydrogen chloride, hydrogen fluoride, and bromine cylinder storage area are also provided.

Perhaps the most costly plant auxiliary is the radioactive waste storage facility. Underground bins for the solids wastes, equipped with cooling air blowers and filters, and three small underground radioactive aqueous waste storage tanks are required. A holding lagoon or seepage pit for the disposal of low-level waste is also needed.

Guidelines for Cost Estimate

Generally, cost estimates have been prepared from drawings and from auxiliary equipment lists in as much detail as feasible, considering the depth of the design. The ground rules adopted for the capital cost evaluation are as follows:

1. Cost estimates are made in detail corresponding to the details shown by the conceptual designs, except that allowances are made for items or features not shown on drawings or itemized in the written material but known to be required in facilities of the type described. Thus, when applicable, quantity take-offs are made from drawings, and costs are computed from suitable unit quantity prices. On some equipment items, however, prices are applied on a lump-sum basis related to equipment size.
2. Building area allowances with appropriate cost assignment are used.
3. Allowances of 30% of labor and materials for indirect construction costs and 20% of labor and materials for engineering are made.
4. Allowances for spare and miscellaneous equipment, as well as four months' operating cost in lieu of startup costs, are included in the capital costs.
5. A contingency of 25% is allowed on the total cost obtained from the detailed breakdown.
6. Financing charges, cost of land, and cost of extending public and utility facilities to the plant perimeter are not included.

Operating costs have been estimated based on the following ground rules:

1. A plant staff is formulated based on judgement of process requirements assuming 21 shifts per week of operation, i.e., around the clock, and costs are allocated using wage rates judged to be appropriate for the Oak Ridge area.
2. Operating and maintenance materials are costed based on take-off quantities or by suitable allowances where such take-offs are not feasible.

3. Labor burden and an allowance for consultant, home office, and outside contract work are added as overhead.
4. Fuel transportation costs, special insurance, interest charges, allocated costs from Government agencies for contract administration, profit, and local taxes are not included.
5. A contingency of 25% is added based on the sum of the included items.
6. No penalty is assessed for a total known process loss amounting to less than 1% of the throughput, and since the process appears to be capable of operating with at least a 99% yield, there are no cost corrections for losses.
7. Quoted costs are based on 1967 dollars.

PROCESS TECHNOLOGY

General Process Chemistry

The process chemistry for the reference flow sheet used in this study was derived largely from experiments conducted at the Argonne National Laboratory. A summary of the process treatments to be applied to a standard fuel charge is contained in table III, while process chemistry details are discussed under the sections that follow. The material is presented in the order in which processing is conducted.

HYDROCHLORINATION-PYROHYDROLYSIS

The weight of a typical charge to the halogenator reactor is about 1,920 kg, as detailed in table IV. This charge specification is about that which would be obtained from seven irradiated General Electric fuel modules or three irradiated modules of the Westinghouse or Combustion Engineering types. The charging machine is equipped to contain the modules and to form an air- and dust-tight seal between the charging machine module chamber and the reactor charging port. In operation, the modules are lowered through the charging chute into the reactor until they rest on top of the settled bed. The grapple is then disengaged and withdrawn back into the module chamber, and the charging chamber sealing valves are closed and buffered. The bed is then slowly expanded by fluidization with nitrogen, and the modules are allowed to settle into position for the start of the hydrochlorination-pyrohydrolysis step.

In the hydrochlorination-pyrohydrolysis step, the constituents of the zircaloy-2 cladding are volatilized by reaction with anhydrous hydrogen chloride at 400°C as shown in equations (1) and (2):

$$\Delta H = - 113 \text{ kcal/g-mole}$$

$$\Delta H = - 15.5 \text{ kcal/g-mole}$$

At the expected operating conditions, the reaction between zircaloy and hydrogen chloride gas to form volatile zirconium tetrachloride and hydrogen gas proceeds rapidly with the evolution of a large amount of

TABLE III

SUMMARY OF VOLATILITY PROCESS TREATMENTS

Treatment	Remarks
Hydrochlorination-Pyrohydrolysis	The spent modules are reacted with hydrogen chloride in a reactor containing a fluidized bed of alumina. The zircaloy cladding and some fission products are volatilized as the chloride salts, separated by filtration from nonvolatiles entrained with the vapors, and fixed by pyrohydrolysis as nonvolatile oxides in a second fluid-bed reactor.
Oxidation	The ceramic uranium dioxide fuel pellets remaining in the reactor are oxidized to more reactive U_3O_8 powder to enhance the fluorination of the uranium and plutonium in subsequent steps.
Uranium Fluorination and Purification	The U_3O_8 is fluorinated with bromine pentafluoride and volatile uranium hexafluoride is formed. The entire vapor stream passes through a regenerator where the bromine and bromides produced in the reaction are reconverted to bromine pentafluoride. The uranium hexafluoride is then separated from the bromine pentafluoride and purified, while the recovered bromine pentafluoride is recycled. The plutonium dioxide from the fuel pellets is converted to nonvolatile plutonium tetrafluoride during this fluorination.
Plutonium Fluorination and Purification	The plutonium, now present as plutonium tetrafluoride, is fluorinated with elemental fluorine; the volatilized plutonium hexafluoride is collected and purified, while the fluorine is recycled.
Waste Treatment and Disposal	Radioactive solid and liquid process wastes are removed from the process equipment and placed in permanent storage facilities. Gaseous wastes are scrubbed, diluted, and vented.

TABLE IV
CONCEPTUAL PLANT FEED SPECIFICATIONS*

<u>Component</u>	<u>Weight Percent</u>	<u>Mass, kg</u>
Uranium	66.44	1,277.00
Plutonium	0.645	12.40†
Fission Products	1.650	31.70†
Zirconium	21.620	415.00
Tin	0.330	6.34
Oxygen Associated with Fuel	<u>9.250</u>	<u>178.00</u>
	99.935§	1,920.44§

* Single-batch basis.

† There are slight, but not serious, differences between the plutonium and fission product inventories listed here and those listed in table VI. The values presented in this table were arrived at early in the study and served as design guides; the numbers in table VI, on the other hand, were computed later to give a more complete description of the fuel.

§ The remaining 0.065%, or 1.25 kg, consists primarily of the metallic alloying elements other than tin in the zircaloy-2 clad material.

heat*. Close control of the reactor temperature is necessary to attain a high reaction rate with low reactor corrosion.

A fluid-bed reactor, employing inert alumina grain as the heat transfer medium, was selected on the basis that it would afford the desired close control of reactor conditions. Using such a fluid-bed medium, Brookhaven National Laboratory⁽³⁰⁾ gathered rate data which indicate that reaction rates of over 3,000 mg/sq cm-hr can be obtained at a reaction bed temperature of 450°C.

Low-carbon nickel was chosen as the most suitable general material of construction for the corrosive processing environments. ANL corrosion information indicates that a maximum reactor wall temperature of less than 400°C should be used to minimize attack on the nickel construction material. Reaction rates at this temperature, as determined by BNL, are approximately one-third the rates obtained with similar gas concentrations at 450°C.

Experiments at ANL⁽⁵⁾ with simulated zircaloy-clad uranium dioxide fuel bundles indicate that the hydrogen chloride utilization is greater than 60% during the early portion of the hydrochlorination. The progress of the decladding reaction was continuously monitored by hydrogen analyses of the off-gas stream and by gamma-ray photography of the tube bundle. The fuel bundle reacted gradually from the bottom to the top, and the assembly gradually immersed itself deeper into the fluid bed as the reaction progressed. The overall hydrogen chloride utilization was 17%, but more efficient utilization would be expected in the processing of the long power reactor fuel elements.

An overall reaction time of about 10 hours for hydrochlorination is indicated for the plant reactor, including a small time allowance for penetration of the protective oxide coating that will form on the module surfaces during use. Typical ANL conditions used were 400°C bed temperature and 40 to 85% hydrogen chloride inlet concentration. Based, then, on the above information and on the pressure conditions imposed by the conceptual design, the reactor design operating conditions chosen for this study are (a) bed temperature, 400°C; (b) inlet absolute pressure, 2 atmospheres; (c) superficial gas velocity, 0.75 ft/sec; and (c) inlet hydrogen chloride concentration, 60%.

The upper section of the halogenator where the hydrochlorination occurs has a 25-inch inside diameter (26-inch outside diameter) and is 22 feet high. The diameter of the vessel is sufficiently large to contain the fuel modules and a rack to hold the modules, while permitting free circulation of the surrounding fluidized solids. The bed height, 12 feet,

* As is apparent from equation (1) and from the fuel composition, the reaction of the tin with hydrogen chloride contributes very little either to the heat release or to reagent consumption.

was chosen to assure complete blanketing of the module with the heat transfer medium. As a result, the possibility of an uncontrolled reaction in an uncovered section of the module, with resultant metal melting and fluid-bed caking, is avoided*. A 6-foot-high disengaging section is provided above the fluid bed to minimize carryover from the fluid bed to the filter.

The gaseous zirconium tetrachloride and stannous chloride formed in the hydrochlorination reaction leave the reactor with the excess hydrogen chloride and by-product hydrogen. Vapor pressure data for zirconium tetrachloride and stannous chloride are given in figure 1. At reactor conditions, no significant reaction of the uranium dioxide fuel pellets is expected⁽⁵⁾.

The gaseous products of the hydrochlorination reaction are separated from the entrained solids by double filtration through porous sintered metal tube type filters. The filters are operated at 300 to 350°C to prevent the desublimation of the zirconium tetrachloride and stannous chloride. The filter off-gases are then introduced into a second fluid-bed reactor where the zirconium tetrachloride and stannous chloride are hydrolyzed by contact with steam at 350°C to form solid zirconium oxide, solid hydrated tin oxide, and hydrogen chloride, as shown in equations (3) and (4):

$$\Delta H = - 3 \text{ kcal/g-mole}$$

$$\Delta H = - 51 \text{ kcal/g-mole}$$

In the fluid-bed hydrolysis, fluidized particles of 60-mesh alumina, silica sand, or product zirconium oxide serve as nuclei for the deposition of solid pyrohydrolysis reaction products. The fluidizing gas velocity is 1.2 ft/sec at operating conditions at the reactor outlet. The inlet pressure is about 1.8 atmospheres.

The pyrohydrolysis fluid-bed reactor is batch operated with the product zirconium oxide allowed to accumulate in the bed. The vessel has a 31-inch inside diameter (32-inch outside diameter) and is 17 feet high and, as such, can hold a total zirconium oxide accumulation of about 3,800 pounds while still providing adequate freeboard above the bed. Each standard halogenator charge contributes 1,400 pounds of oxide during decladding, sufficient to raise the bed level approximately 2 feet. Powder drain-off lines are provided on the side of the vessel. The accumulation of oxide from each decladding operation will be transferred

* Recent studies at ANL and ORGDP suggest that it may not be necessary to submerge the fuel modules completely.

VAPOR PRESSURE OF ZrCl_4 AND SnCl_2

Figure 1

to waste storage at the time the fluid-bed halogenators are being recharged with fuel modules.

As far as is known, neither reaction (4) above nor the hydrolysis behavior of other contaminants and fission product chlorides has been studied at the Brookhaven or Argonne Laboratories; however, the tin reaction should be straightforward. A second hydrolysis reaction of zirconium tetrachloride,

$$\Delta H = - 69 \text{ kcal/g-mole}$$

is possible. Use of a large excess of water, i.e., 100% or more, ensures that the reaction proceeds to the dioxide; however, production of some oxychloride is not thought to be detrimental to the operation. Thus, reaction (3) proceeds quantitatively under the reaction conditions used, i.e., 350°C, and a large excess of water vapor. Furthermore, since the heat release of this reaction is essentially nil, 3 kcal/g-mole, only minor cooling is required.

The hydrogen chloride consumed in the deacid reaction is regenerated during hydrolysis. The pyrohydrolyzer off-gas stream is dehydrated by condensation of the unused water vapor at 0°C as approximately 46% hydrochloric acid (see figure 2). The condensed acid, as well as by-product acid from the hydrogen vent gas scrubber (used in lieu of make-up water to minimize aqueous waste volumes and hydrogen chloride losses), are vaporized and recycled to the pyrohydrolyzer. The hydrogen-hydrogen chloride gas mixture leaving the condenser is compressed to 2.0 atmospheres, and approximately 80% of the mixture is recycled directly to the halogenator. The remaining 20% is vented from the recycle system to purge off reaction-generated hydrogen after treatment for removal of residual hydrogen chloride.

This vent gas passes through a second condenser operating at minus 100°C, where most of the hydrogen chloride is removed from the vapor stream by condensation. Figure 3 is a plot of hydrogen chloride vapor pressure versus temperature. The uncondensed hydrogen chloride in the vent gas exiting from the second condenser is scrubbed out with water. ~~The deacidified hydrogen is passed through an absolute filter and vented.~~ The condensed anhydrous hydrogen chloride, together with a small amount of makeup hydrogen chloride added to replace system losses, is vaporized to the pyrohydrolysis gas recycle pumps.

An alternative procedure for handling the vent gas would be to eliminate the minus 100°C condensation and remove all of the hydrogen chloride by scrubbing with water. Since the amount of water needed for this procedure is about six times that required for makeup to the pyrohydrolysis recycle system, the excess acid would have to be neutralized, and the resultant solution would probably be stored as low-level aqueous waste. The added costs for such storage and, as a relatively minor item, for

SOURCE: Van Nuys, C. C., "Enthalpy and Heats of Dilution of the System HCl-H₂O," Trans. American Inst. Chemical Engineers 39: 663-670 (1943).

HCl-WATER PHASE DIAGRAM

Figure 2

VAPOR PRESSURE OF HCl

Figure 3

the additional hydrogen chloride required for makeup were roughly estimated to be such as to justify the minus 100°C condenser system.

OXIDATION

In the oxidation step, the dense uranium dioxide pellets, which have fallen to the lower section of the reactor after being freed from the cladding, are oxidized to U_3O_8 as given in equation (6):

Sintered uranium dioxide has been pulverized at 450°C in experiments at ANL and ORGDP, using oxygen concentrations around 20 volume percent^(8,23). With the expected packed-bed heights of uranium dioxide, movement of the U_3O_8 fines from the packed pellet bed section of the reactor into the fluidized alumina is important to prevent bed caking and plugging. In experiments at ORGDP where the uranium dioxide pellet bed heights were from 1-1/2 to 3 feet; gas velocities on the order of 2.5 to 3.0 ft/sec were required to maintain sufficient elutriation of the U_3O_8 powder from the pellet bed. The reactor design operating conditions for oxidation, therefore, are (1) bed temperature, 450°C; (2) inlet absolute pressure, 2 atmospheres; (3) superficial gas velocity, 3 ft/sec; and (4) inlet gas, dry air. At the design velocity and with minimal pre-heat of the inlet gas, minor cooling is required to remove the heat of reaction liberated in the presence of the fission product radioactivity heat. Any U_3O_8 which is elutriated from the fluid bed is filtered out of the off-gases before the process gas is scrubbed and vented to the atmosphere.

URANIUM FLUORINATION AND PURIFICATION

After complete oxidation of the uranium dioxide, the U_3O_8 is fluorinated with bromine pentafluoride under fluidized conditions. The reaction proceeds as shown in equation (7).

Fluorination of U_3O_8 with bromine pentafluoride has been performed at ANL using alumina as the fluid-bed diluent. The reaction has been described fairly successfully using a diminishing sphere model for the reaction kinetics^(25,7). The integrated rate expression for the model is given in equation (7a).

$$(1 - F)^{1/3} = 1 - kt \quad (7a)$$

where F = fraction of solid reacted,

k = reaction rate constant, $(\text{min})^{-1}$, and

t = reaction time, minutes.

The rate constant has been found to be a function of the temperature and bromine pentafluoride partial pressure (7b):

$$\log k = 0.90 \log P - \frac{2,000}{T} - 0.220 \quad (7b)$$

where P = partial pressure of bromine pentafluoride, mm Hg, and

T = temperature, °K.

The fluorination temperature required to obtain a significant removal rate of the uranium from the fluid-bed reactor is about 200°C. ANL has performed most interhalogen fluorination experiments at about 300°C, where the production rate of uranium hexafluoride is on the order of three times that at 200°C^(26,28). The temperature level at which the fluorination should be conducted is a compromise between a rapid rate on the one hand and the detrimental effects of temperature on the subsequent plutonium recovery on the other. Fluorination temperatures above 350°C cause excessive retention of the plutonium by the bed material⁽²⁷⁾. The plutonium retention is thought to be caused by complexing of the plutonium with fission product fluorides at the higher temperatures or possibly by some high temperature plutonium tetrafluoride diffusion into the alumina bed particles.

From the above information and the pressure conditions imposed by the conceptual design, the reactor design operating conditions chosen for the interhalogen fluorination step are (1) bed temperature, 300°C, (2) inlet absolute pressure, 2 atmospheres; (3) superficial gas velocity, 1 ft/sec; and (4) inlet bromine pentafluoride concentration, 20 volume percent. At the expected operating conditions, the reaction between U_3O_8 and bromine pentafluoride gas to form volatile uranium hexafluoride, bromine, and oxygen gas proceeds rapidly with the liberation of a large quantity of heat. An important consideration here is that caution must be used in the early stages of the fluorination, since a large excess of U_3O_8 will be present in the bed and, at high concentrations of bromine pentafluoride, temperature excursions may be encountered.

The gaseous uranium hexafluoride, bromine pentafluoride, bromine, and oxygen leave the reactor and pass to the filter unit. This unit is maintained at 150°C to prevent the condensation of uranium hexafluoride, bromine pentafluoride and bromine. Vapor pressure data for these condensables and for bromine trifluoride are given in figure 4. The filter off-gases, which are at a pressure of about 1.0 to 1.5 atmospheres, are compressed before being sent to the bromine pentafluoride regenerator.

VAPOR PRESSURES OF UF_6 , BrF_5 , BrF_3 , Br_2

Figure 4

The bromine formed as a by-product in the uranium fluorination, is reacted with fluorine to regenerate bromine pentafluoride:

$\Delta H = -102.5$ kcal/g-mole bromine pentafluoride

The reaction is expected to be rapid above 200°C(20), and therefore, is allowed to proceed unhindered and nearly adiabatically. This method of reacting the bromine and fluorine affords a simple design for the regenerator, a plug flow reactor made from a 10-3/4-inch-diameter pipe 25 feet long. The actual kinetics of the reactions are not known; however, a flame type reaction is expected. The equilibria involved are shown in equations (9) and (10):

Figure 5 presents the equilibrium conversions for the regenerator as a function of temperature. The equilibrium conversion of the bromine is dependent on the starting gas mixture and pressure. The bases for the figure are 2 atmospheres pressure and an initial gas composition of 9.6% uranium hexafluoride, 5.4% bromine, 27.0% fluorine, and 57.7% inerts, typical of concentrations expected in the early portion of the uranium fluorination. Thermal equilibrium calculations for the system indicate that the temperature of the reaction zone will reach about 1000°C; however, the actual temperature will, of course, vary, depending on the amount of preheat used and the initial composition of the gas mixture. Note that temperatures below 400°C are required to give greater than 99% equilibrium conversion of the bromine to bromine pentafluoride. For example, at 600°C, only 69.2% of the bromine is converted to bromine pentafluoride, while 30.8% is converted to bromine trifluoride.

After the process gas leaves the regenerator, it is cooled to 100°C in the precooler before being passed on to the uranium hexafluoride cold trapping system. This system consists of four 16-inch-outside-diameter by 25-foot-long cold traps operated in parallel. The gas is cooled to minus 40°C, at which point the uranium hexafluoride desublimates and deposits on the walls of the traps, while the condensed bromine pentafluoride with some of the uranium hexafluoride dissolved in it drains as a liquid from the traps into an accumulator. The solid-liquid equilibrium phase diagram for bromine pentafluoride and uranium hexafluoride is given in figure 6.

The solid uranium hexafluoride is expected to entrain about 20 mole percent bromine pentafluoride, whereas the bromine pentafluoride liquid leaving the cold trap has about 7.5 mole percent uranium hexafluoride dissolved in it. From the accumulator, the bromine pentafluoride passes to a vaporizer from which it is taken off overhead for recycle back to

EQUILIBRIUM CONVERSION AS A FUNCTION OF TEMPERATURE

Figure 5

SOLID-LIQUID EQUILIBRIUM FOR
THE UF_6 - BrF_5 SYSTEM

Figure 6

the main fluid-bed reactor. The noncondensable stream leaving the cold trap is split in half, with one portion then being combined with the vaporized bromine pentafluoride for recycle. The second portion is vented through another cold trap where most of the bromine pentafluoride not condensed in the uranium hexafluoride cold trapping system is removed and sent to the bromine pentafluoride accumulator. The latter cold trap, the vent cold trap, operates at minus 80°C, which is well below the freezing point of bromine pentafluoride (minus 60°C), and over 90% of the bromine pentafluoride in the vent gas is removed before final process scrubbing. A caustic scrub follows the vent cold trap and is used to remove oxidizing and acid-forming gases from the vent stream.

After completion of the uranium hexafluoride fluorination, the uranium hexafluoride cold traps are heated and drained to the distillation system feed tank. Two still columns are used to separate the uranium hexafluoride from fission products, bromine pentafluoride, and any bromine trifluoride formed in the regenerator or produced from corrosion of the vessels by bromine pentafluoride. The liquid-vapor diagram for the uranium hexafluoride-bromine pentafluoride system⁽¹⁸⁾ is shown in figure 7. Vapor-liquid equilibrium data for the system bromine trifluoride-uranium hexafluoride are not directly available; however, uranium hexafluoride activity coefficients derived from the solid-liquid equilibrium relationships⁽¹⁴⁾, have been combined with total vapor pressure data taken in the range 0 to 30 mole percent uranium hexafluoride⁽¹⁹⁾ to compute the liquid-vapor equilibrium shown in figure 8. Both still columns are operated batchwise, since this requires fewer stages and therefore permits shorter columns. The two distillation columns appear necessary to ensure the required separation of bromine trifluoride and high boiling fission products from the uranium.

Distillation is initiated by charging the reboiler of the first column from the feed tank and operating the column at total reflux. When steady state is reached in the still, bromine pentafluoride is removed from the top of the first column and returned to the bromine pentafluoride recycle portion of the process. The bromine pentafluoride take-off overhead continues until the column is essentially free of bromine pentafluoride. The uranium hexafluoride, free of bromine pentafluoride, is then transferred from the reboiler of the first column to the reboiler of the second column. At this time, a new charge is fed to the first reboiler, and the bromine pentafluoride-uranium hexafluoride distillation is repeated. Similarly, the second still column is operated at total reflux until steady state is reached, at which time the product uranium hexafluoride is withdrawn as a vapor from the top of the column. After completion of the distillation, another transfer from the first reboiler is made, and the procedure is repeated for the second still.

After several batches have been distilled, the second reboiler will have accumulated high boiling fission products and bromine trifluoride. When the concentrations of these components have reached the point where they begin to hinder effective distillation, the reboiler is blown down into a reclaimer. The reclaimer unit then vaporizes all of its contents to

LIQUID-VAPOR EQUILIBRIUM FOR
THE UF_6 - BrF_5 SYSTEM

Figure 7

LIQUID-VAPOR EQUILIBRIUM FOR
THE UF_6 - BrF_3 SYSTEM

Figure 8

the bromine pentafluoride regenerator system, and any bromine trifluoride present is converted to bromine pentafluoride. Before going to the regenerator, however, the gases pass through a fission product trap containing sodium fluoride at a temperature of 400°C for removal of volatile fission product compounds. Fission product fluorides, such as ruthenium and niobium, are sorbed by sodium fluoride, probably by the formation, at the temperature of operation, of an essentially nonvolatile complex salt. The exact decontamination factor will have to be determined experimentally, since this sorbent has not been tested with the proposed recycle flow rates and conditions. The gases also pass through a magnesium fluoride trap at a temperature of 250°C for further fission product cleanup.

The uranium hexafluoride product vapor is passed through a sodium fluoride trap and then through a magnesium fluoride trap for removal of trace amounts of neptunium and technetium before being condensed in a uranium hexafluoride product condenser and drained to a product collection cylinder. If decontamination of the uranium is not found satisfactory because of misoperation, additional decontamination can be performed in rework sorption traps. The product collection tanks are designed such that their contents can be vaporized through the rework sorption trap system back to the product collection cylinders.

PLUTONIUM FLUORINATION AND PURIFICATION

During interhalogen fluorination, the plutonium dioxide present in the halogenator is converted to solid plutonium tetrafluoride. In turn, this material is fluorinated for conversion of the plutonium-to-plutonium hexafluoride vapor in relatively pure form. The plutonium fluorination is begun after completing the interhalogen fluorination and the purge that follows. ANL experiments indicate that the satisfactory operating conditions for effective recovery of the plutonium are as follows: (a) starting bed temperature of 300°C, with a gradual increase in temperature to 550°C as the plutonium is volatilized; (b) inlet pressure, 2 atmospheres; (c) superficial gas velocity, 0.5 ft/sec; and (d) inlet fluorine concentration, 75 volume percent. The reaction of plutonium tetrafluoride with elemental fluorine is given by equation (11):

$$\Delta H = 6.1 \text{ kcal/g-mole plutonium}$$

This reaction is dependent on several factors which include temperature, plutonium tetrafluoride surface area, fluorine concentration, and the past history of the alumina bed. Temperature plays a dual role in the plutonium fluorination rate; the rate of fluorination increases with temperature, and the equilibrium between plutonium hexafluoride and plutonium tetrafluoride favors the formation of plutonium hexafluoride at the higher temperatures⁽²⁹⁾. Equilibrium data are given in table V. Temperature also influences the total recovery of the plutonium, since

fluorination at high temperatures during the bromine pentafluoride step and during the early stages of the plutonium volatilization step result in greater retention of the plutonium by the bed materials. The dependence of the reaction on surface area is expected to be similar to that for most solid-gas reactions. Factors related to the past history of the bed which might influence the plutonium fluorination would be the number of reuses of the alumina; exposure of plutonium tetrafluoride in an alumina bed to high temperatures, such as with oxidation; and the bromine pentafluoride fluorination temperature.

TABLE V
EQUILIBRIUM CONSTANTS FOR THE REACTION⁽³⁵⁾

Temperature, °C	$K = [\text{F}_2]/[\text{PuF}_6]^*$
150	2,630
200	2,220
250	659
300	395
350	257
400	178
450	130
500	99

* $\log k = + 1,331/T + 0.275$, with T in °K.

The plutonium hexafluoride formed in the fluid bed is passed to the fluid-bed cooler portion of the filter unit. Here the off-gases are cooled rapidly to 100°C to minimize the thermal decomposition of plutonium hexafluoride to plutonium tetrafluoride. The gases are then filtered and are directed to a plutonium hexafluoride cold trap system, which consists of eight 6-inch-diameter by 6-foot-long units operated in parallel. The gases are cooled to minus 100°C where the plutonium hexafluoride desublimates and deposits on the trap walls. The noncondensing gases, i.e., fluorine, inerts, and some volatile fission product fluorides, leave the cold traps, are compressed, and 5 to 10% of the stream is vented. The

remaining gases are recycled back to the reactor after the addition of the required makeup fluorine. The vent gases pass through a sodium fluoride fission product trap before being sent to a potassium hydroxide scrubber for removal of fluorine. The fluorine-free gases are then sent to the stack after the necessary filtering and dilution. Upon completion of the fluorine fluorination, the plutonium hexafluoride cold trap is heated, and the collected plutonium hexafluoride is vaporized out and sent to the plutonium purification system.

A satisfactory purification scheme was not available at the time this report was prepared. No attempt will be made here to describe any of the schemes which have been considered.

WASTE TREATMENT AND DISPOSAL

There are three general types of wastes generated in the fluid-bed volatility process. These are (1) solid wastes comprised of the alumina from the halogenator, the pyrohydrolyzer, and fluid-bed cooler; the zirconium oxide from the pyrohydrolyzer, and the sorbents from the various fission product traps; (2) liquid wastes generated by the scrubbing and neutralizing systems; and (3) gaseous wastes primarily composed of the noble gas fission products.

The solid wastes contain most of the long-lived fission products, such as strontium and cesium, and are highly radioactive. The estimated heat generation rate for the fresh wastes is about 9,400 Btu/hr-cu ft of solids. For storage, the solids are conveyed pneumatically from their respective reactors to underground storage bins shielded by concrete and an overburden of earth. The bins are cooled by a forced draft of filtered air; the cooling air is monitored for radioactivity to detect possible leaks in the bins, filtered, and discharged through a stack to the atmosphere. At some future date, after the necessity for forced cooling has diminished, these bins would be converted to permanent storage sites by infiltration of their contents with cement, thus encapsulating the remaining radioactive nuclides and eliminating the need for perpetual surveillance.

The liquid wastes have a relatively low level of radioactivity; they contain such fission product elements as iodine, indium, and antimony. These wastes are alkaline in character, since they are neutralized prior to storage. Their radiation level is such that they cannot be released to the environment; hence, they are stored in an underground steel-lined concrete tank. Because of the relatively low quantity of radioactivity involved, they do not require cooling and sufficient tank area is available to conduct the heat generated by radioactive decay into the earth environment. It may be desirable to concentrate these wastes, but the degree of concentration would have to be determined by experiment.

The gaseous wastes, consisting mainly of the noble gases, xenon and krypton, will be disposed of by dilution and venting. Process vent gases are diluted with ventilation gases amounting to approximately

38,000 cfm and will be diluted further by dispersion into the atmosphere after discharge from the stack. A detailed discussion of the fission product venting problem is presented in the section dealing with cell ventilation and off-gas handling in the General Facilities chapter.

Fission Product Fate

Fission product concentrations in the standard fuel charge were calculated using the SFP code⁽²¹⁾. The calculations were made for fuel irradiated to about 25,000 Mwd/tonne burnup at a specific power of approximately 25 Mw/tonne, and then cooled for 120 days. The estimated energy releases, activities, and weights are given in table VI for the uranium, plutonium, transuranics, and fission products in the irradiated fuel. The initial uranium-235 enrichment was 2.75%.

The fission product distribution, as shown in figure A-1*, was arrived at using known or estimated thermodynamic and physical properties of the compounds involved, some available experimental data, and a limited number of calculations. All quantities shown are based on the reprocessing of one standard fuel charge, i.e., 1,500 kg of uranium dioxide and fission products; thus, the distribution represents average data for one run.

A major portion of the fission products is nonvolatile at the operating conditions encountered throughout the process and, thus, will remain with the alumina fluid-bed media. These fission products, which include such elements as rare earths as well as the long-lived radioactive isotopes of strontium, cesium, and other elements, will be transferred with the alumina fluid-bed material to the underground solids storage vaults. The remaining fission products will be distributed throughout the processing system according to (1) their respective volatilities as chlorides, oxides, or fluorides; and (2) their likelihood of being converted to a nonvolatile solid or liquid form by further reaction in the processing equipment or by sorption in one of the fission product traps.

During the hydrochlorination step, it is anticipated that the portion of the noble gases, krypton and xenon, trapped between the fuel pellet and the cladding will be released and vented from the system. The amount released will depend largely on the irradiation history and the physical form of the fuel. This amount may be as high as 27% of the total noble gas present for pellet fuels that have been exposed to high heat fluxes during irradiation⁽²⁴⁾. After dilution by the appropriate amount of air to maximum permissible concentrations, the krypton and xenon are released to the stack. The remaining noble gas, trapped at grain boundaries within the fuel pellet, will not be released until subsequent

* Figure numbers starting with "A" refer to figures compiled in the appendix.

TABLE VI
TYPICAL FUEL PROPERTIES

SFP CODE RESULTS (AFTER 18 TIME STEPS)

INITIAL FUEL COMPOSITION-			
U-235	3.62600E 04	GRAMS	
U-238	1.28586E 06	GRAMS	
EFFECTIVE TEMPERATURE	400.0	CEGREES C	
RESONANCE FLUX	25.00	PER CENT	
EXPOSURE HISTORY			
IRRADIATED FOR	1000.000	C	AT VARIABLE FLUX WITH 14 TIME STEPS
COOLET FOR	30.000	C	
COOLET FOR	30.000	C	
COOLET FOR	30.000	C	
COOLET FOR	30.000	C	
TOTAL CURIES	5.41129E 06		
TOTAL ENERGY RELEASE	7.52129E 04	BTU/HR	
FROM ALPHA	1.04068E 04	BTU/HR	
FROM BETA	2.70581E 04	BTU/HR	
FROM GAMMA	2.78480E 04	BTU/HR	
TOTAL FISSION PRODUCTS	3.12210E 04	GRAMS	
FINAL ENRICHMENT	1.00	PER CENT	
(U-235 DEPLETION)	65.0	PER CENT	
FINAL U-232 CONTENT (AT DISCHARGE)	11.19	PPB (U-235 BASIS)	
FINAL U-236 CONTENT	4.09005E 02	GRAMS	
FINAL U-238 CONTENT	1.25971E 06	GRAMS	
PU ISOTOPIC DISTRIBUTION AT DISCHARGE			
PU-236	67.56	PPB (U-235 BASIS)	
PU-238	0.93	PER CENT	
PU-239	61.40	PER CENT	
PU-240	32.21	PER CENT	
PL-241	13.15	PER CENT	
PU-242	2.30	PER CENT	
ESTIMATED BURNUP AND POWER	24698.8	MWD/T	AND 24.7 MW/T

ELEMENT	ENERGY RELEASE RATES, BTU/HR.				ACTIVITY, CURIES	WEIGHT, GRAMS
	ALPHA	BETA	GAMMA	TOTAL		
TH	0.	0.	0.	0.	0.	0.
PA	0.	0.	0.	0.	0.	0.
U	6.38840E-02	6.04446E-02	1.98445E-02	8.97729E-02	4.31351E 00	1.27654E 01
NP	3.58937E-02	1.84755E-11	1.12168E-03	3.70153E-02	3.69342E-01	5.37876E 02
PU	3.62684E-02	2.63427E 01	4.76596E 00	3.94794E 02	1.89216E 05	1.22231E 04
AM	5.16758E 01	0.	1.71921E 00	5.36950E 01	4.71748E 02	2.43656E 02
CM	9.99108E 03	0.	1.63582E 02	1.01547E 04	8.09958E 04	4.80829E 01
SE	0.	0.	0.	0.	0.	2.79037E 01
BR	0.	0.	0.	0.	0.	1.47693E 01
KR	0.	4.20969E 01	6.66260E-01	4.27651E 01	9.04055E 03	3.23848E 02
RH	0.	2.57645E-08	0.	2.57645E-08	1.41394E-05	3.06792E 02
SK	0.	1.70314E 03	2.73553E-01	1.70341E 03	2.17129E 05	8.13710E 02
Y	0.	3.34967E 03	1.09870E 01	3.36066E 03	2.88021E 05	4.13841E 02
ZR	0.	1.00156E 03	5.64811E 03	6.64966E 03	3.78008E 05	3.29309E 03
NH	0.	7.62073E 02	1.32619E 04	1.40239E 04	6.81482E 05	1.71413E 01
MO	0.	8.21052E-10	7.43594E-10	1.56445E-09	1.14773E-07	3.14988E 02
TC	0.	2.70195E-02	0.	2.70195E-02	1.38055E 01	8.09187E 02
RU	0.	3.65396E 02	1.67552E 03	2.04091E 03	6.08752E 05	2.08447E 03
RH	0.	5.07141E 03	2.19819E 03	1.20696E 04	6.08912E 05	5.31334E 02
PC	0.	2.26293E-05	0.	2.26293E-05	8.38271E-02	9.02213E 02
AG	0.	7.79483E-03	9.26118E-04	8.72095E-03	1.14356E 00	9.02009E 01
CC	0.	1.06283E 00	5.97845E-02	1.12262E 00	9.84281E 01	4.41376E 01
IN	0.	7.02965E-14	2.08826E-15	7.23848E-14	1.68774E-11	3.18597E 00
SN	0.	4.65466E 01	5.20843E-03	4.65518E 01	4.65537E 03	3.24728E 01
SB	0.	1.71345E 01	7.68086E 01	9.59422E 01	8.46097E 03	1.37984E 01
TE	0.	1.16320E 02	8.93820E 01	2.05702E 02	3.74562E 04	5.37901E 02
I	0.	1.17129E-01	2.37462E-01	3.54596E-01	3.02683E 01	3.12401E 02
XE	0.	6.96579E-04	7.26362E-02	7.33329E-02	2.20268E 01	4.87161E 03
CS	0.	4.94959E 02	6.44110E 02	1.13907E 03	1.32612E 05	2.79331E 02
BA	0.	1.28957E 01	1.50110E 03	1.51399E 03	1.13902E 05	1.18499E 03
LA	0.	2.09468E 01	1.36154E 02	1.57101E 02	2.58648E 03	1.19019E 03
CE	0.	1.91960E 03	7.19871E 02	2.63968E 03	9.45103E 05	2.49978E 03
DR	0.	1.69235E 04	1.70760E 03	1.86311E 04	8.46313E 05	1.06351E 03
ND	0.	1.62677E 00	2.05886E 00	3.68565E 00	3.76634E 02	3.30603E 03
PM	0.	3.79316E 02	1.71187E-13	3.79316E 02	2.55477E 02	2.72690E 02
SM	1.20489E-07	8.66557E-02	7.27900E-02	1.59447E-01	1.71202E 02	2.77866E 02
EU	0.	2.06063E 00	2.73074E 00	4.79076E 00	1.77467E 03	4.09652E 01
GC	0.	0.	0.	0.	0.	2.03787E-01

processing, since very little pellet degradation is expected to occur during the hydrochlorination step and since there is negligible fission gas diffusion out of the pellets at temperatures below 800°C⁽³⁾.

A number of other fission products will form volatile chlorides, including selenium, zirconium, niobium, molybdenum, technetium, indium, antimony, tin, and tellurium; however, since as noted above, very little pellet degradation is expected during the hydrogen chloride step, only a small portion of these fission products will be volatilized. Those that volatilize, plus radioactive clad components, will react in the pyrohydrolyzer to form nonvolatile oxides or hydroxides; these compounds will be discarded, along with the zircaloy cladding and alloying wastes.

Some fission product bromine and iodine will perhaps volatilize with the noble gases, but in that case, will probably desublime or condense in the refrigerated hydrogen chloride condenser system that follows the pyrohydrolyzer. The condensed bromine and iodine would then circulate with the aqueous hydrogen chloride until blowdown to the neutralizer, where they will be converted to nonvolatile salts by reaction with caustic. More likely, much of the fission product bromine and iodine will combine with uranium freed by the uranium dioxide stoichiometry shift* during irradiation at high temperatures.

In the oxidation step, a portion of the fission products; selenium, bromine, krypton, molybdenum, technetium, ruthenium, tellurium, iodine, and xenon will be volatilized. All of these, with the exception of krypton, xenon, and trace quantities of ruthenium oxides, will be separated from the inert gases in the off-gas scrubbing system and will accumulate in the potassium hydroxide scrubbing liquid. The noble gases, krypton and xenon, and trace quantities of ruthenium will be vented from the system with excess air and will be diluted by the stack gas⁽¹¹⁾.

Most of the fission product activity volatilization occurs at the interhalogen fluorination step where the remaining selenium, bromine, iodine, molybdenum, and technetium, are converted to fluorides or oxyfluorides and the remaining noble gases, krypton and xenon, are released. In addition, partial volatilization of antimony, neptunium, niobium, ruthenium, and tellurium occurs at this point. As in the previous step, the vent gas stream is routed through a potassium hydroxide scrubber. The noble gases pass through, are diluted by the stack gas, and are vented to the atmosphere. Fission product bromine is converted to bromine pentafluoride in the interhalogen regenerator and remains in the bromine pentafluoride system. A major portion of the other volatilized fission products are dissolved in the liquid bromine pentafluoride in the uranium hexafluoride cold trap, where the temperature will be about minus 40°C. These impurities recycle with the bromine pentafluoride through the reactor, filter-cooler, and regenerator until the bromine pentafluoride is blown down to

* Phase equilibria conditions at high temperatures include the presence of free uranium.

the reclaimer. The fission product impurities will subsequently be removed from the reclaimer through sodium fluoride and magnesium fluoride sorption traps to the bromine pentafluoride regenerators.

A smaller portion of the fission products generated during interhalogen fluorination is transferred to the uranium hexafluoride purification still along with the uranium hexafluoride and the residual bromine pentafluoride that drains from the cold traps with the uranium hexafluoride. All of these fission product fluorides, with the exception of technetium and tellurium, boil at temperatures appreciably higher than uranium hexafluoride and, consequently, concentrate in the reboiler of the second still column, where they remain until discharged to the aforementioned reclaimer.

The boiling points of neptunium and technetium compounds formed are such that they will be present to some extent in the uranium hexafluoride stream leaving the second still; however, both should be collected in the magnesium fluoride polishing trap, resulting in a neptunium-technetium-free uranium hexafluoride stream.

The fate of tellurium is somewhat questionable, since the fluorides are not readily removed by sorption on sodium fluoride or magnesium fluoride or by caustic scrubbing. Small amounts of tellurium are expected to be present in the uranium hexafluoride fed to the distillation system; however, since tellurium hexafluoride is much more volatile than the uranium hexafluoride, it is distilled off with the bromine pentafluoride in the first still column and is returned to the bromine pentafluoride recycle system. The tellurium will accumulate in the bromine pentafluoride hold-up until, ultimately, the vent gases will contain as much tellurium as will be fed to the system. Venting of tellurium-laden gases through activated alumina traps placed downstream of the off-gas scrubber is expected to remove most of this contaminant. The true effectiveness of alumina traps for removing the tellurium has not been conclusively shown⁽³⁷⁾, and trace amounts of tellurium will probably be vented to the stack; however, decontamination to at least the maximum permissible concentrations should be possible.

During the direct fluorination step, small amounts of antimony, neptunium, niobium, tellurium, tin, and zirconium, and somewhat larger amounts of ruthenium will be volatilized from the halogenator⁽¹¹⁾. The fluorides of zirconium and tin are only slightly volatile at process conditions during this step and, thus, will desublime on the alumina in the fluid-bed cooler. The fate of the remaining fission products at this step, however, cannot be firmly established, since a definite decontamination scheme for plutonium has not been chosen. It was assumed that, except for tellurium, sufficient fission product decontamination of the vent gases could be achieved using an additional sorption step with sodium fluoride. As mentioned above, tellurium fluorides are not appreciably sorbed and cannot be removed satisfactorily by scrubbing. Therefore, the vent gases will also be passed through the tellurium (activated alumina) trap. The amount of tellurium volatilized at the fluorine

fluorination step, however, will be small compared to the previous step, and no problem should occur in regard to venting trace quantities.

The fission products, therefore, appear to fall into five general categories. First, there are fission products which do not volatilize upon reaction with hydrogen chloride, oxygen, bromine pentafluoride, or fluorine. Second, there are those which volatilize during hydrochlorination but form hydrolyzable chlorides and are trapped in the pyrohydrolyzer. The fission products from groups 1 and 2 are conveyed pneumatically from their respective reactors and are stored as dry solids in stainless steel bins located in underground vaults equipped with forced-air cooling systems to remove the heat of radioactive decay. Approximately 95% of the heat generated from the total fission product load will be found in these waste streams. Third, there are fission products which are volatilized by reaction with bromine pentafluoride and fluorine, and are sorbed in the fission product traps. These elements form an additional solid waste which may be stored in the same bin and vault system used for the solid wastes from the first group. The fourth group is comprised of fission products which are trapped in either the aqueous hydrogen chloride and bromine pentafluoride or are accumulated in the scrubbing systems. These aqueous wastes are stored in underground tanks similar, except in size, to those employed for the storage of nonheating neutralized aqueous wastes at Savannah River or Hanford. The fifth group consists of the noble gases and other trace contaminants which are discharged from the stack. No special treatment is required for these elements; however, sufficient air flow must be maintained through the stack to dilute them to tolerable concentrations.

Materials of Construction

Selection of proper materials of construction is a major consideration in most chemical processes and particularly so in radiochemical operations. The problems associated with corrosion in this process are mainly connected with the alternating use of hydrogen chloride and fluorinating agents at high temperatures and in the highly radioactive environment of the halogenation reactor. Adequate materials of construction are available for use with either of the gases at the intended operating temperatures.

Nickel is suitable for use in hydrogen chloride at temperatures up to about 400°C; at higher temperatures, corrosion rates are appreciably increased. Since nickel is also resistant to attack by fluorine, it is a logical choice for the reactor construction material; in addition, since temperatures of 550°C will be encountered during the plutonium fluorination step, low carbon nickel must be used. Present information indicates a corrosion rate of about 30 mils/year⁽³³⁾ based on tests performed by cycling the metal alternately in hydrogen chloride and fluorine under envisioned reaction conditions. More information on the effect of long-term cycling between hydrogen-hydrogen chloride-zirconium

tetrachloride atmosphere, the bromine pentafluoride-uranium hexafluoride atmosphere, and the fluorine-plutonium hexafluoride atmosphere is needed with fission products present.

Both Inconel and type 304 stainless steel are suitable materials of construction for the pyrohydrolysis reactor and filter tubes, although the use of either of these alloys presupposes that no condensation occurs, since both alloys are corroded rapidly by aqueous hydrogen chloride. In this report, Inconel was chosen as the material of construction for the pyrohydrolysis reactor and its filter tubes.

Condensers, lines, and holding drums are required in the hydrogen chloride recycle system for concentrations ranging from 46% hydrogen chloride to essentially anhydrous hydrogen chloride liquid. Hastelloy-B, impervious graphite, or glass-lined steel are among the available materials used successfully with all concentrations of the aqueous acid. There is some question as to the suitability of impervious graphite or glass-lined equipment in radiochemical plants, since extensive damage might occur even during remote routine maintenance operations, such as gasket replacement. Moreover, even though the radiation level in this equipment should be relatively low, there may be some damage to the resin impregnant usually employed in impervious graphite. Taking everything into consideration, Hastelloy-B is probably the most suitable material of construction for the aqueous acid-containing equipment. The degree and effect of fluoride contamination of the liquid hydrogen chloride streams require investigation.

Either nickel or Monel is quite suitable for exposure to fluorine or uranium hexafluoride at temperatures up to 550°C, copper can be used at lower temperatures, and Teflon or filled Teflon is an adequate material for gasketing in regions of relatively low radioactivity for temperatures up to about 200°C. When bromine pentafluoride is present with the uranium hexafluoride, nickel or Monel is the recommended material of construction, with nickel preferred over Monel. Nickel appears to be the most satisfactory material of construction for handling plutonium hexafluoride in the fluorine recycle equipment.

PROCESS DESCRIPTION

The Process Description section of this report is concerned primarily with the physical operation of the plant. The Process Flow and Control, Process Cell Layout and Maintenance, Sampling and Accountability, and Chemical Storage and Makeup, are discussed individually.

The Process Flow and Control section describes the interrelationships among the various process equipment items, i.e., how they are interconnected physically and how the flows, temperatures, concentration of reagents, etc., are monitored and regulated. The overall plant process is subdivided into five processing systems:

1. Main Reactor System.
2. The Pyrohydrolyzer and Hydrogen Chloride Recycle System.
3. Bromine Pentafluoride Recycle and Uranium Hexafluoride Purification System.
4. Fluorine Recycle and Plutonium Hexafluoride Recovery System.
5. Off-Gas Handling and Scrubber System.

In the Process Cell Layout and Maintenance section, the guidelines which governed the layout of process equipment in the processing areas are discussed. The Sampling and Accountability portion presents a discussion of the uranium and plutonium accountability procedures and how they might be implemented.

The chemical makeup requirements and the various operations involved in the preparation of process solutions and special sorbents are itemized in the Chemical Storage and Makeup section.

The operating cycle is discussed first to give a general idea of how the different systems are interrelated. It must be kept firmly in mind that the time allowances for the various operations are estimates based on limited processing experience with nonirradiated materials at ANL and ORGDP. Also, there are areas of extrapolation not yet covered in the experimental programs.

As noted previously, the processing rate in the conceptual plant is a nominal 1 tonne of uranium per day with a 300-day per year on-stream time. The time required to process the 1,277 kg charge of uranium in a single reactor through one complete cycle is predicted conservatively to be 55 hours as shown in table VII. Use of predicted minimum times for each of the processing steps would lead to a shorter overall cycle time. For example, the hydrochlorination portion of the cycle might require 8 hours instead of 10, the oxidation step 10 hours instead of 14, and the plutonium fluorination step 11 or 12 hours instead of 15. In

short, the processing time estimated for a complete cycle would be 9 or 10 hours less if a less conservative viewpoint had been taken.

TABLE VII
SCHEDULE FOR A REACTOR OPERATING CYCLE

Operation	Time, hours
Charging	1.0
Heatup	2.0
Hydrochlorination	10.0
Purge	1.0
Oxidation	14.0
Bromine Pentafluoride Fluorination	8.0
Purge	1.0
Flush and Recharge Fluid-Bed Cooler	2.0
Fluorine Fluorination	15.0
Purge	<u>1.0</u>
Total Time Required to Process One Charge	55.0
Miscellaneous and Downtime	<u>6.0</u>
Total Time for a Reactor Operating Cycle	61.0

In the absence of more definitive experimental data, the conservative approach has been taken. Two reactor lines must be installed to meet the plant production requirement. Based on the nominal plant processing rate and two reactor lines in operation, the actual available time for each cycle is 61 hours, or 6 hours over that required for processing. This extra time is available for miscellaneous operations and downtime between cycles.

The three recycle systems for hydrogen chloride, bromine pentafluoride, and fluorine, are capable of handling the off-gases from one of the

reactors at a time. With proper scheduling, both reactors could be operated without simultaneously requiring the same reagent.

Process Flow and Control

MAIN REACTOR SYSTEM

Process Flow

The main reactor system flow sheet is shown in figure A-2. This system consists of two halogenators, two fluid-bed cooler and filter units, two backup filters, and a solids collection and sampling system. The charge is contacted on a batchwise basis, with hydrogen chloride, oxygen, bromine pentafluoride and fluorine in four separate steps in the halogenators, while the remaining system equipment is used to filter the reaction off-gases and obtain a sample of the halogenator beds.

Each halogenator, AIV-101, is a two-zone fluid-bed reactor, the bottom zone being 18 inches in outside diameter by 7 feet high and the top zone being 26 inches in outside diameter by 22 feet high, excluding the superstructure which contains a slide valve, expansion joint, and an extended piece protruding through and above the cell plug. The transition piece between the two zones is conical and contains a grid of bars perpendicular to the reactor axis which supports the fuel element charge during the decladding step. Both the upper and lower zones of the reactor are forced draft cooled to remove the reaction heat. The available heat transfer area is increased by external fins welded to the reactor shell. Electrical furnaces supply the heat required to raise the reactor to operating temperature.

The processing procedure described in this section should suffice to present the general approach in the process head end; however, changes in procedure and processing conditions are sure to follow once the plant has been in operation for a time. Each reactor is operated in the same manner, but identical process steps are not conducted concurrently. In this way, a recycle system carries the load of only one reactor at a time.

Incoming fuel element assemblies will be stored under water in the fuel storage pool in borated steel baskets. Three Westinghouse or Combustion Engineering type modules or seven General Electric type modules will be charged at one time. For charging, the modules will be strapped together in a skeleton rack which will also provide space for interstitial flow between modules so that good gas distribution can be achieved during processing. Once the elements have been placed in the racks and strapped together, they can be picked up vertically by a grapple and raised into a fuel charger by a winch which is mounted inside the charger itself. The racks will be consumed, along with the zirconium clad material during hydrochlorination.

The fuel charger is mounted on a carriage which operates on overhead tracks so that the unit can be positioned over either reactor. The charger is a sealed unit with a leak-tight disconnect which mates with the fuel entry port flange on the top of the halogenator. A slide valve, located close to the bottom of the charger, can be used to seal the unit during movement between process areas.

A bellows is provided between the slide valve and the bottom flange of the charger. This bellows, together with a piston assembly mounted on the main body of the charger, permits the application of force on the charge flange when it is connected to the halogenator fuel entry flange. A self-contained winch and grapple within the charger are operated remotely from outside the crane bay shielding. A strain gauge load cell is provided to indicate the weight supported by the winch cable and to verify that the cable is not hung up or bound. A cable travel indicator gives the position of the grapple.

The fuel is added to the halogenator on top of the diluent alumina bed when static. The charging operation proceeds as follows: The modules are removed from the underwater storage and dried in the fuel drying and handling cell. The ends of the elements are cut off, and the appropriate number of assemblies are strapped in a skeleton rack. The fuel drying and handling cell is opened to the crane bay, and the charger is positioned over the opening. The grapple is lowered and engages the rack which is positioned below the opening. A cell manipulator is used to help secure the charger grapple to the charging rack. The rack, with its fuel elements, is then lifted into the charger, and the bottom slide valve on the charger is closed. The blind flange over the fuel entry port on a halogenator is then removed, and the charging assembly is moved to a position over the port. During the time that the halogenator fuel entry port is open, a vacuum purge is maintained in the reactor. The charger carriage is equipped for two-directional movement in a horizontal plane and, assisted by guides, is programmed for precise alignment of the mating flanges. After final alignment, the charger is sealed to the fuel entry port by the piston-bellows assembly on the bottom.

After sealing and with the slide valve to the halogenator-reactor remaining closed, the charger slide valve is opened, and the charger and fuel entry port are leak tested and buffered with nitrogen. The slide valve on the reactor is then opened, and the winch cable with the attached modules and rack are lowered into the reactor. The grapple is disengaged, leaving the fuel element resting on top of the static alumina bed. After retrieving the grapple and closing the reactor slide valve, the charger is purged, evacuated, buffered with nitrogen, and disconnected. The charger is then returned to the fuel drying and handling cell ready for a repeat operation; the blind flange is replaced over the fuel entry port to the reactor; and the seal is leak tested. The bed in the reactor is fluidized so that the modules sink to the fuel charge support plate in preparation for the start of the hydrochlorination cycle.

Before the hydrochlorination cycle is begun, the reactor furnaces are turned on to heat the reactor, while nitrogen gas is recirculated to maintain fluidization and effect rapid heating of the bed material. When a fluid-bed temperature of 400°C is reached, the hydrochlorination step is begun.

During the hydrochlorination step, anhydrous hydrogen chloride, diluted with recycle by-product hydrogen, flows into the halogenator at the bottom of the reactor, which is filled with 5/8-inch-diameter alumina balls. The gas then escapes into a distribution cone welded to the bottom zone of the reactor. The bottom of the cone is suspended below the gas inlet and thereby forms an annular pocket with the reactor wall. The pocket serves as a vapor seal and prevents backflow of alumina into the gas inlet line. As the gas mixture passes upward through the reactor, it contacts the zircaloy cladding of the fuel elements, forming gaseous zirconium tetrachloride, stannous chloride, and hydrogen. Granular alumina, which fills the portion of the reactor surrounding the fuel modules, as well as the interstices in the modules, is agitated turbulently by the gas and conducts the heat of reaction to the reactor wall by successive contact with the modules and the wall. The gas becomes depleted in hydrogen chloride and enriched in zirconium tetrachloride, stannous chloride, and hydrogen as it passes up through the bed. As the cladding is volatilized from the fuel element, the released uranium dioxide, having a greater density than the alumina bed, falls down into the lower zone of the reactor and remains there until the oxidation step.

The gas leaves the reactor through the gas outlet nozzle and flows through an arching connecting line to a self-contained fluid-bed cooler and filter unit, AIV-601 and AIV-201. During the hydrochlorination step, slight cooling is done, and the gas is maintained at 350°C as it flows through the fluid-bed cooling section of the unit. Primary filtration of the gases is performed in the filter section of the unit. The fluid-bed cooler and filter is 17 feet high overall by 32 inches outside diameter, with a conical reducer at the lower end. The fluid-bed portion is 5 feet high, including the bottom conical section. The vessel is equipped with twenty-four 3-inch-diameter by 4 feet long sintered nickel filter tubes and an automatic blowback system. The filter tubes are attached to a tube sheet, which is supported at the flanged joint at the top of the vessel. A flanged head on the unit allows for filter replacement in case of extreme plugging or failure of an individual tube.

After primary filtration, the gas then flows to a backup filter, AIV-202, an 18-inch-diameter by 6-foot-high cartridge type unit containing fourteen sintered nickel filter tubes. This secondary filter system is located immediately before the process gas inlet to the pyrohydrolyzer and removes alumina particles, corrosion products, and other particulates which originate in the interconnecting piping. From here, the gas flows into the hydrogen chloride recycle system where the hydrogen chloride is recovered and fed back to the reactor.

After the hydrochlorination has been completed, the halogenator, the fluid-bed cooler and filter, and the backup filter, are purged with nitrogen for 1 hour. The purge gases are vented through the scrubber system normally used for the hydrogen vent. During the purging operation, the reactor furnace is on and the fluid bed is heated to 450°C.

When the reactor has reached a temperature of 450°C and the hydrogen concentration in the purge off-gases is sufficiently low, the oxidation step is started. Dry air from the plant air supply system is used as the oxidant and flows through the 18-inch-diameter section at a superficial velocity on the order of 2.5 to 3.0 ft/sec. The uranium dioxide, which gravitates after decladding to form a bed at the bottom zone of the reactor, reacts from the top of the pellet accumulation, and the U_3O_8 fines formed are swept into the fluidized alumina bed above. Zonal heaters, located around the lower portion of the halogenator, maintain the top 6 to 12 inches of the packed bed of uranium dioxide at 450 to 500°C with the lower portion of the bed held at less than 300°C. The alumina and U_3O_8 present in the upper portions of the reactor are maintained at 450°C.

The halogenator off-gases are directed to the fluid-bed cooler and filter. Any elutriated U_3O_8 fines or alumina in the gas is de-entrained and filtered out in this unit. Also, the gas is cooled to 100°C and then vented through the backup filter to an off-gas scrubber. The scrubber is described below under Off-Gas Handling and Scrubbing System.

When the oxidation step is completed, the reactor is cooled to 300°C, and without purging, the off-gases from the backup filter are directed to the bromine pentafluoride recycle system. Then, bromine pentafluoride is added to the halogenator feed. After an initial period of rather low bromine pentafluoride concentration, the concentration is increased to 20 volume percent. The gas follows the same flow path as before, except that the filtered off-gases are passed to the bromine pentafluoride recycle system. The fluid-bed cooler cools the reactor off-gases to 200°C.

If uranium-bearing materials are elutriated to the fluid-bed cooler and filter they will probably fluorinate to uranium hexafluoride during interhalogen fluorination. If, in plant practice, interhalogen fluorination cannot take place in the fluid-bed cooler and filter, the bed will have to be returned to the halogenator for additional bromine pentafluoride treatment.

After the interhalogen fluorination is completed, the bromine pentafluoride addition to the reactor is discontinued, and a nitrogen purge is initiated. The purge gas, after passing through the backup filter, is directed to the bromine pentafluoride vent gas scrubber. The reactor temperature is maintained at 300°C during the purge.

During interhalogen fluorination, some plutonium may be carried over to the fluid-bed cooler and filter. After interhalogen fluorination is complete, this material must be returned to the halogenator for fluorine

treatment. The fluid-bed cooler and filter cannot be operated at the high temperature necessary for the fluorine reaction. Therefore, after the fluid-bed cooler and filter have been flushed, the system has been purged, and the cooler bed has been transferred to the main reactor, a new bed charge is made up with plutonium-depleted alumina from material in the solids hold tank, AIV-401. Then, fluorine is fed to the reactor to begin the plutonium fluorination. The gas flow is kept low enough at this point to prevent elutriating the solid plutonium tetrafluoride from the halogenator; however, the velocity must be high enough to give good fluidization and solids mixing. The proper gas velocity will have to be established by experience. As the gas enters the fluid-bed cooling portion of the primary filter, it is rapidly cooled to 100°C to keep the plutonium hexafluoride from thermally decomposing to nonvolatile plutonium tetrafluoride. The gases are then filtered and directed to the plutonium hexafluoride cold traps. The fluorine passes through the trap, is compressed, and is returned to the halogenator. The fluorine concentration is maintained at about 75 to 90 volume percent by venting some of the recycle gases and then adding makeup fluorine having a concentration greater than 95% fluorine.

The fluid beds would then be analyzed for uranium and plutonium to assure reaction completion. Nonvolatile fission products accumulate in the alumina. A fraction of the halogenator bed is routed through the solids collection and sampling facility, and the samples obtained are analyzed chemically. In addition, the solids hold tank in the collection and sampling facility can provide temporary storage for the radioactive alumina, which may either be returned for reprocessing and reuse, or transferred to permanent waste storage if the alumina is too loaded with decaying nuclides and the analyses show the uranium and plutonium concentrations are sufficiently low. The solids collection and sampling system consists of a filter, AIV-203, two samplers, and a solids hold tank, AIV-401. Solids are fed pneumatically to the filter unit, which is 16 inches in outside diameter by 9 feet high and contains ten 3-inch-diameter by 4-foot-long sintered stainless steel filter tubes. The solids fall to the bottom of the filter unit and flow by gravity to the first sampler, which takes a continuous 5% cut. The rejects then flow to the solids intermediate hold tank. The sample stream flows to a second sampler, similar to the first, where a second 5% cut is taken as the sample intended for analysis. The remainder of the first cut is directed to the solids intermediate hold tank. This hold tank is 54 inches in diameter by about 12 feet high overall and contains an internal assembly consisting of fourteen 10-inch-diameter by 6-foot-long cylinders held between two conical shaped tube sheets. In use the solids fill the cylinders and forced air cooling through the spacing between the cylinders facilitates the removal of the heat generated in the solids. The transporting air, after filtration, is directed to a process off-gas scrubber.

Process Control

The fuel charging machine is designed to be operated from outside the crane bay shielding. It is therefore equipped with hydraulic and electrically operated controls and readout devices to permit remote manipulation of the necessary mechanisms for (a) raising and lowering, (b) charger positioning, and (c) position reading. The load on the winch mechanism and the length of cable played out from the cable spool can be determined with sufficient accuracy to ascertain when the fuel elements have bottomed on the reactor bed. The combination of the two readings is required as a check to prevent premature release of the grapple if the elements were to bind when only partly lowered into the halogenator. Remote reading temperature and pressure instrumentation is also required to assure proper functioning of the charger in the event of long-term sealed storage of a fuel element. Overload safety switches and limit switches are provided to avert damage to the charger from operator error.

Control of the main reactor system is set up in the following manner. The flow of gas to each halogenator reactor is maintained at the desired level for hydrochlorination, oxidation, interhalogen fluorination, and fluorine fluorination steps by automatic control valves and suitable flow instrumentation in each reactor gas inlet line. The control of the content of the different reactants in each step is discussed later under the Process Control section of each of the recycle systems.

The reaction temperature is controlled through automatic instrumentation regulating the flow of cooling air and/or the furnace heat input. If the system is operated smoothly, automatic control of the cooling air will maintain the reactor at a constant temperature. In the event of an upset or if the reactor temperature starts to be out of control because of a reaction excursion, the following sequence of events is programmed to occur: First, full flow of cooling air will be applied, and furnace heaters will cut off; second, at a preset wall temperature slightly above the control point, the flow of reaction reagent from the recycle system will be stopped. The concentration of the reacting reagent in the process gas flow will therefore drop rapidly, decreasing the reaction rate and thus allowing the temperature to drop as the reagent in the system is consumed. In the event the temperature still remains high for some reason, an emergency nitrogen purge can be introduced manually to quench the reaction further.

Excess gas is vented from the different recycle systems automatically by pressure control valves in the vent lines. These valves will be open on a pressure increase and close on a pressure decrease, thus maintaining a constant system pressure.

Wall temperatures of electrically heated equipment, such as the primary and backup filters, and of electrically traced piping are maintained utilizing conventional temperature measurement and temperature control instrumentation.

Controls for the solids collection and sampling system are also required. Wall temperatures within the solids hold tank will be controlled automatically by cooling air flow. Since no reactions will be occurring in this equipment, no further provisions are felt to be necessary.

PYROHYDROLYZER AND HYDROGEN CHLORIDE RECYCLE SYSTEM

Process Flow

The flow sheet for the pyrohydrolyzer and hydrogen fluoride recycle system is shown in figure A-3. The equipment consists of a pyrohydrolyzer and its filter; a backup filter; aqueous and anhydrous hydrogen chloride subsystems, each with a condenser, hold tank, and boiler; a vent scrubber system; and a hydrogen chloride recycle gas compressor.

The zirconium tetrachloride-stannous chloride-hydrogen-hydrogen chloride gas mixture leaving the main reactor system is fed to the pyrohydrolyzer during the dechlorination step. The off-gases pass through the main reactor backup filter and enter the bottom of the pyrohydrolysis reactor which contains a fluidized bed of inert solids, such as alumina or zirconium dioxide. The pyrohydrolyzer, AIV-102, is a cylindrical fluid-bed reactor, 18 feet high, including the pyrohydrolyzer filter. The reactor is 32 inches in outside diameter and has an active bed height of 60 inches. The process gas enters through a ball check valve at the apex of a conical gas distributor. A water vapor-hydrogen chloride mixture from the aqueous hydrogen chloride reboiler, AIV-603, is injected into the fluid bed 1 foot above the gas distributor through three parallel, multiple port, gas inlet pipes. The process gas and the water vapor react in the bed of fluidized solids to form zirconium oxide and hydrogen chloride gas. The zirconia, as well as the oxides of tin and some fission products, forms on the bed solids and is allowed to accumulate in the reactor until the hydrochlorination of the reactor charge has been completed. Since the evolution of heat in the pyrohydrolysis is small, only minor reactor cooling, other than by natural convection and radiation, is necessary. Heat is supplied automatically by the reactor furnace as required to hold the bed temperature at the desired level. After the hydrochlorination has been completed, the excess oxide is drained off, sampled, and transferred pneumatically to high level solids waste storage bins. The off-gas from the reaction zone, with the metallic chlorides removed, passes upward through the disengaging section and is filtered free of solids in the sintered Inconel filter assembly, AIV-204, located above the reactor. This filter is built as an integral part of the pyrohydrolyzer and contains forty 3-inch-diameter by 48-inch-long sintered Inconel tubes. Solids accumulating on the filter are discharged periodically back into the reactor by a programmed, momentary reversal of the gas flow. The solids-free gas mixture leaves the pyrohydrolysis reactor filter and passes through a backup sintered Inconel filter assembly, AIV-205, which is similar in design to the primary filter, AIV-201, with the exception that blowback is manual rather than automatic. The backup filter prevents the passage of radioactive solids into the

condenser system in the event of rupture of one or more tubes in the primary pyrohydrolysis filter. The gas from the backup filter flows into the first of two condensers.

In the first condenser, AIV-602, a 6-inch-diameter by 15-foot-long shell and tube heat exchanger with 80 square feet of condensing surface, the gas is cooled from the pyrohydrolysis reactor temperature of about 350 to 0°C. As the gas cools, most of the contained water vapor, along with part of the hydrogen chloride, condenses to a 46 weight percent hydrogen chloride-54% water solution. The solution drains to the aqueous hydrogen chloride reservoir, a 100-gallon capacity surge tank, AIV-402, and the uncondensed gas continues to the hydrogen chloride recycle compressor.

The hydrochloric acid solution that accumulates in the reservoir is pumped to a boiler, AIV-603, where it is evaporated and recycled to the pyrohydrolyzer. The boiler is a shell and tube heat exchanger operated as a flash evaporator and is 6 inches in diameter by 8 feet tall, with 28 square feet of heat transfer surface.

The hydrogen chloride recycle compressor, AIV-501, is a peripheral type machine with two stages similar to the compressor shown in figure 9. About 80% of the compressed gas flow is recycled directly to the halogenator; the remaining 20% flows to the anhydrous hydrogen chloride condenser, AIV-604, a shell and tube heat exchanger 6 inches in diameter containing 21 square feet of heat transfer area. Here the gas is cooled to minus 100°C and about 83% of the contained hydrogen chloride is condensed as anhydrous liquid, while the uncondensed gases flow to the chloride vent scrubber system. The condensed hydrogen chloride drains to a 60-gallon reservoir, AIV-403, and then to a boiler, AIV-605. Makeup anhydrous hydrogen chloride liquid is added to the boiler to replace small quantities of gas lost to the vent, and the liquid hydrogen chloride is then vaporized for recycle to the pyrohydrolyzer, thus completing the circuit.

The waste hydrogen and accompanying hydrogen chloride are vented through the chloride vent scrubber, AIV-301, a 6-inch-diameter by 10-foot-high packed tower, where the hydrogen chloride is dissolved in water. The amount of water fed to the scrubber is equivalent to the quantity consumed in the pyrohydrolysis reaction. The resultant acid is collected and pumped through the cooler, AIV-606, to the aqueous hydrogen chloride reservoir to supply the makeup water for the pyrohydrolysis reaction.

The hydrogen, now essentially free of acid, is vented through the cell off-gas heater and absolute filters, where it is diluted with air to a nonexplosive concentration and vented to the atmosphere through the stack.

Process Control

Control of the hydrochlorination-decladding process is achieved in the following manner. The flow of recycle gas to each halogenation reactor is maintained at the desired level by an automatic control valve and

TWO STAGE PERIPHERAL COMPRESSOR

Figure 9

suitable flow instrumentation in each reactor gas inlet line. The composition of the feed gas, over the course of a run, will probably range from 40 to 80% hydrogen chloride in nitrogen. The anhydrous hydrogen chloride content of the gas feed is maintained at the desired level by monitoring the halogenator off-gas hydrogen concentration with an analyzer whose output signal controls the flow of reagent gas from the anhydrous hydrogen chloride reboiler. For example, an increase in hydrogen concentration will call for an increase in the hydrogen chloride flow. A level control valve is used to regulate the liquid hydrogen chloride flow from the anhydrous hydrogen chloride reservoir. As the demand for hydrogen chloride decreases, the gaseous hydrogen chloride control valve closes. The reboiler would be protected with high pressure relief or alarm instrumentation.

Excess hydrogen is vented from the recycle system automatically by a pressure control valve in the vent line. This valve will open on a pressure increase and close on a pressure decrease, thus maintaining a constant system pressure.

Wall temperatures of electrically heated equipment, such as the pyrohydrolyzer and pyrohydrolyzer filters, and of electrically traced piping are maintained utilizing conventional temperature measurement and control instrumentation.

The gas flow to the pyrohydrolyzer from the reactor is determined by the control of reactor gas inlet flow; hence, no independent control of the process gas stream flow to the pyrohydrolyzer is used. The water-hydrogen chloride recycle flow, however, must be controlled to maintain an excess of water vapor over that required by the zirconium tetrachloride reaction at all times. To obviate the necessity for precise control of the excess and to deal with normal variations in the zirconium tetrachloride flow, the water rate has been set at a nominal three times the stoichiometric requirement for the reaction.

Provision of adequate excess steam is assured by maintaining a flow of recycle water vapor to the pyrohydrolyzer sufficient to hold a set minimum concentration of water in the outlet gas stream. This water concentration will be measured by a suitable water detection device. The maximum flow is determined by the physical limitations of the equipment involved. If this maximum is reached, it will be necessary to decrease manually the hydrogen chloride concentration in the halogenator feed, and in turn, the amount of zirconium tetrachloride to the pyrohydrolyzer will be decreased.

BROMINE PENTAFLUORIDE RECYCLE AND URANIUM HEXAFLUORIDE PURIFICATION SYSTEM

Process Flow

The flow sheet for the bromine pentafluoride recycle and uranium hexafluoride purification system is shown in figure A-4. The system consists of a compressor, bromine pentafluoride regenerator, gas precooler,

uranium hexafluoride cold trapping system, bromine pentafluoride vaporizer, bromine pentafluoride vent cold trap, uranium hexafluoride distillation system, blowdown reclaiming, uranium hexafluoride product polishing sorbent traps, uranium hexafluoride product condenser, uranium hexafluoride product collection tank, and the necessary intermediate surge tanks.

The purpose of the bromine pentafluoride recycle portion of the system is to regenerate bromine pentafluoride from the uranium fluorination gaseous products, to remove bromine pentafluoride and uranium hexafluoride from the stream, and to recycle the recovered bromine pentafluoride to the halogenator. Venting is performed to remove the inleakage of inerts, such as the compressor seal purge and filter blowback gases. The gases are automatically vented through a pressure control valve located in the vent line downstream of the vent cold trap.

The purpose of the uranium hexafluoride purification subsystem is to produce a uranium hexafluoride product which is sufficiently purified to meet specifications for uranium hexafluoride delivered to the AEC.

Immediately after passing through a halogenator backup filter, the off-gases produced during the uranium fluorination operation are compressed in a two-stage peripheral compressor equipped with a variable speed drive, AIV-504. The gas then flows into the bromine pentafluoride regenerator, AIV-103, which is fabricated from concentric pipes. Regeneration of the bromine pentafluoride takes place in the center pipe as the off-gases which contain bromine are contacted with fluorine. The gases enter through a concentric nozzle made of 1- and 5-inch-diameter pipe with fluorine passing through the center pipe and the off-gas through the annulus. The reaction is exothermic, and cooling air is passed through the shell side of the vessel to remove the liberated heat. When the bromine pentafluoride is formed, the gas temperature rises nearly adiabatically and is then cooled down to 400°C in the finned section of the regenerator. The lower 12 feet of the regenerator pipe is finned both internally and externally.

Upon leaving the regenerator, the gas is cooled to 100°C in the gas pre-cooler, AIV-607, which is a 10-3/4-inch-diameter unit 20 feet long with internal and external fins for forced air cooling. The process gas then flows to the cold trapping system. Four 16-inch-outside-diameter by 25-foot-long traps, AIV-608A through D, are provided. Here the gas is cooled still further, to minus 40°C, at which point the bulk of the uranium hexafluoride gas desublimates onto the interior walls of the cold traps while the bromine pentafluoride gas condenses as a liquid and drains to an approximately 40-gallon accumulator, AIV-405. The bromine pentafluoride solution then flows to the bromine pentafluoride vaporizer, AIV-609, where it is vaporized and mixed with a portion of the undensified gas stream leaving the uranium hexafluoride cold traps. This gas mixture is then recycled back to the halogenator main fluid-bed reactor. The bromine pentafluoride vaporizer is 16 inches in diameter by 7-1/2 feet long and is electrically heated.

The remaining fraction of the uncondensed gas from uranium hexafluoride cold traps is vented through a bromine pentafluoride vent cold trap, AIV-610, which is 16 inches in diameter by 10 feet long. The gas is cooled to minus 80°C in this unit so that bromine pentafluoride and any contained uranium hexafluoride will desublime. The gas passes through a mist filter at the exit of the trap and is then scrubbed in the same scrubber as used for the oxidation off-gases. A potassium hydroxide solution is used. The scrubbing system is described below under the section entitled Off-Gas Handling and Scrubbing.

After the bromine pentafluoride fluorination step has been completed in the main fluid-bed reactor, the uranium hexafluoride cold traps are heated and drained into the 150-gallon still system feed tank, AIV-407. The distillation is performed batchwise in two still columns and their associated reboilers, condensers, and reflux drums.

Column one, AIV-304, 15 inches in diameter and 40 feet tall, with 58 bubble-cap trays, affords the separation of bromine pentafluoride and low boiling fission products from the uranium hexafluoride. The bromine pentafluoride and low-boiling fission products are distilled overhead. When the desired uranium hexafluoride separation is obtained in the first unit, the contents of the reboiler are charged to the second column, AIV-305. This column, which is 8 inches in diameter by 30 feet long and contains 55 bubble-cap trays, separates the high-boiling fission products and bromine trifluoride from the uranium hexafluoride product. The uranium hexafluoride is removed as vapor from the top and is directed to sodium fluoride and magnesium fluoride polishing traps, AIV-302 and AIV-303, respectively. Each trap is annular in design with a 12-inch outside diameter and a 5-inch inside diameter. The trap length is 5 feet. The traps operate at elevated temperatures, and by selective sorption, fission product impurities are removed from the uranium hexafluoride passing through. The trap contains channels for air cooling and fits into a furnace which is designed to accommodate the annular geometry. After the uranium hexafluoride passes through the sorbent traps, it is condensed in a 10-3/4-inch-diameter by 6-foot-long uranium hexafluoride product condenser, AIV-615, and then drained to the product collection tank, AIV-410. The external surface of the condenser is finned for forced air cooling.

Sludges from both the second still column reboiler and the bromine pentafluoride vaporizer are processed in the blowdown reclaimer, AIV-616. This unit is 14 inches in diameter by 8 feet long and is electrically heated. Bromine pentafluoride, bromine trifluoride, uranium hexafluoride, and fission product fluorides are evaporated from the unit through sodium fluoride and magnesium fluoride sorption traps, AIV-306 and -307, respectively, and fed back to the bromine pentafluoride regenerator. The sorption traps are of the same design as the uranium hexafluoride

polishing traps. When the reclaimer becomes too radioactive, it will be removed from the process cell for burial and then will be replaced.

Process Control

Control of the bromine pentafluoride recycle and uranium hexafluoride purification step is accomplished in the following manner. The flow of recycle gas to each halogenation reactor is maintained at the desired level by an automatic control valve and suitable flow instrumentation in each reactor gas inlet line. The bromine pentafluoride content of the gas feed is regulated by monitoring the inlet bromine pentafluoride concentration with an analyzer, probably a gas chromatograph, whose output signal controls the flow of gas from the bromine pentafluoride vaporizer.

The fluorine flow to the bromine pentafluoride regenerator will be varied inversely with the concentration of fluorine in the regenerator off-gases. Process control is maintained using a fluorine analyzer in the regenerator gas exit line and a flow regulator valve in the fluorine inlet. Detection of fluorine in the outlet stream above a set concentration will call for a decrease in the inlet fluorine flow.

The cooling air flow to the regenerator is normally held at a constant level but will be increased if the wall temperature of the unit exceeds a preset value.

The cold traps are cooled by the vaporization of a suitable refrigerant in external cooling coils. The temperature is controlled by the action of a self-regulating refrigerant expansion valve. On-off control of the refrigerant compressor is accomplished through the usual high and low compressor discharge pressure relays. The trap is supplied with electric heaters for the uranium hexafluoride draining step. The heating is initiated manually after valving out the refrigerant supply. Automatic temperature and pressure instrumentation is provided to prevent overheating and/or overpressuring the traps. The trap pressures and on-stream pressure drops are recorded continuously. The outlet nozzles for draining liquid bromine pentafluoride are electrically heated to prevent plugging by any solids slush, i.e., uranium hexafluoride solids in the bromine pentafluoride.

Flow of liquid bromine pentafluoride from the bromine pentafluoride accumulator to the bromine pentafluoride vaporizer is controlled by regulating the level in the bromine pentafluoride vaporizer. The vaporizer would be protected with high pressure relief or alarm instrumentation.

Conventional control techniques are used for the uranium hexafluoride distillation equipment. In addition, the uranium hexafluoride product take-off stream from the still is monitored with a bromine analyzer to ensure the proper operating conditions for uranium hexafluoride decontamination from this impurity.

The sorption trap temperatures are measured by wall thermocouples and are closely regulated by furnace controls set to maintain automatically the desired trap temperatures. In cases where the fission product heat release may become significant, the sorption trap temperatures can be regulated by automatic air cooling.

FLUORINE RECYCLE AND PLUTONIUM HEXAFLUORIDE RECOVERY SYSTEM

Process Flow

The flow sheet for the fluorine recycle and plutonium hexafluoride recovery is shown in figure A-5. The system consists of a recycle compressor with attendant interstage cooler, a cold trap, a sodium fluoride vent sorption trap, and the necessary equipment to process vent gases. The purpose of this system is to recycle the fluorine and to collect the volatilized plutonium hexafluoride for further plutonium purification.

After a 1-hour purge, following uranium fluorination, valving is adjusted so that gas from the halogenator backup filter flows immediately to the plutonium hexafluoride cold traps, AIV-617A through H, where the gas is cooled to about minus 100°C to desublime the plutonium hexafluoride. Liquid argon is used as an evaporating coolant. The lines to the cold trap are kept short to reduce the amount of surface area contacted by plutonium hexafluoride and thereby to minimize the plutonium hexafluoride decomposition which results from this contact. Once the plutonium hexafluoride has been trapped, the noncondensed portion of the off-gas is compressed in a two-stage peripheral compressor equipped with a variable speed drive, AIV-505, and a fraction of this stream is vented through the sodium fluoride vent sorption trap, AIV-310, and subsequently scrubbed with potassium hydroxide solution. The fluorine off-gas scrubber is described below under Off-Gas Handling and Scrubbing. Makeup fluorine is added to the remaining gas to maintain a fluorine concentration of above 75 volume percent; this stream is then recycled to the halogenator reactor.

Process Control

The flow of fluorine recycle gas to the halogenator is maintained at the desired level by an automatic control valve and suitable flow instrumentation in the inlet line to the reactor. The fluorine concentration in the feed is held at a predetermined level, using a fluorine analyzer whose output controls the flow of makeup fluorine. The reactor furnace is on during the entire plutonium fluorination cycle, since the fluorination of plutonium tetrafluoride is endothermic and must be performed at temperatures above 300°C. A conventional temperature controller is used to maintain the proper reactor temperature.

Control methods for the plutonium hexafluoride cold trap system are essentially identical to those for the uranium hexafluoride cold traps.

The sorption trap temperature is measured with a wall thermocouple and is closely regulated by automatic furnace controls. When the fission product release becomes significant, the trap temperature is regulated by air cooling.

OFF-GAS HANDLING AND SCRUBBING

Process Flow

The off-gas handling and scrubbing systems are shown in figure A-6 for both process and cell off-gases. The off-gas scrubbing and handling system for the declad step was described earlier, since it is an integral part of the hydrogen chloride recycle system. The gases from the system are diluted to below the lower hydrogen explosive limit with the ventilation exhaust stream from the hydrogen chloride recycle cell and are then eventually discharged to the atmosphere through the plant stack.

The process off-gases from the oxidation and bromine pentafluoride fluorination steps are combined after leaving their respective systems and are processed in the same scrubber; the plutonium fluorination off-gas is handled in a separate, but similar, scrubbing system. The process equipment for both the oxygen-bromine pentafluoride and the fluorine scrubbing systems consists of aqueous potassium hydroxide gas scrubbers, 12 inches in diameter with a 10-foot-high packed section, demisters, gas preheaters, and two banks of HEPA filters arranged in series. The scrubbers convert the fluorine and bromine pentafluoride in the process off-gases to neutral salts, potassium fluoride and potassium bromine, to prevent the oxidizing gases from contacting the filter media. The filters are constructed of glass and asbestos fibers. Both materials are susceptible to attack by acidic, oxidizing fluoride gases; hence, the removal of bromine pentafluoride and fluorine is necessary prior to filtration. In addition, the potassium hydroxide in the scrubbers will remove such volatile fission products as iodine, bromine, selenium, molybdenum, technetium, and ruthenium from the process off-gas and will prevent their release to the atmosphere. Some volatilized fission products, such as ruthenium tetroxide and tellurium hexafluoride, are only partly trapped by the scrubbing solution. The volatile ruthenium tetroxide possibly may be converted by the scrubbing to ruthenium dioxide, a nonvolatile oxide which would be removed as a particulate by the HEPA filters. On the other hand, solid sorbent traps containing activated alumina are available to remove the last of the tellurium hexafluoride from the scrubber off-gas streams.

Process Control

The scrubber liquid flows are controlled automatically to give the required liquid flow by use of a flow orifice-differential pressure cell-control valve combination located on the discharge side of the recirculating pumps. In-line water-cooled heat exchangers are located upstream of the pumps to remove excess reaction heat from the scrubber solutions. A self-operating temperature control valve regulates the flow of cooling

water through a heat exchanger, thus maintaining reasonably constant scrubber solution temperatures. A 200-gallon tank is used to hold the solution for each scrubber. The volume and density of the tank contents are monitored remotely, and solution samples are analyzed periodically to determine when makeup solution should be added or when the tank contents should be discharged.

Process Cell Layouts and Maintenance

All fuel element recovery work is undertaken in a canyon located in the process building. The canyon is subdivided into cells, each of which is designed for a specific processing system. The equipment layout plan and section drawings, figures A-7, A-8, and A-9, show the locations and relative sizes of the process cells and the equipment items. The relationship is given in the building floor plan and sections in figures A-10 and A-11. Arrangement of the cells and the equipment within the cells was arrived at from considerations of process piping, expected activity levels, containment, ease of operation, and ease of maintenance, as well as the general desirability of grouping equipment according to the chemicals present and the chemical operations being performed. The cell areas and elevations were, of course, dictated by the number and sizes of the equipment items to be used.

Even though the actual amount of contamination and radiation within the individual cells was not known, the expected relative radiation levels of the cells were deduced based on the equipment in use, and the expected fission product distribution. The cells, listed in order of decreasing radiation level, are:

1. Head-end cell
2. Fuel drying and handling cell
3. Bromine pentafluoride recycle and uranium hexafluoride purification cell
4. Fluorine recycle and plutonium hexafluoride collection cell
5. Plutonium purification and packaging cell
6. Sampling cubicles
7. Scrubber cell
8. Hydrogen chloride recycle cell
9. Recirculating cooling air cell
10. Uranium hexafluoride product cell

All of the cells are to be maintained remotely by a crane, which operates overhead in the center of the canyon, and associated manipulators. If future data show the radiation levels to be low enough in the last four cells listed above, direct or semidirect maintenance may be used, provided easy area and equipment decontaminations are possible.

For the deep central cells, i.e., the head-end cell, the bromine pentafluoride recycle and uranium hexafluoride purification cell, and the scrubber cell, the track-mounted remotely operated manipulator located at the floor level supplements the overhead crane and manipulator. A manipulator at the lower level of the deeper cells was desirable, since maintenance and repair operations at this elevation would be very difficult, if not impossible, to perform with the overhead crane and its manipulator. The lower manipulator traverses the full length of the deepest cells on a track-guided, self-propelled cart. Both the crane and the cart-mounted manipulator are equipped with closed-circuit television for viewing. Auxiliary wall-mounted television cameras are also provided in each cell for overall cell viewing. Spare crane and cart-mounted manipulators are also provided for emergency use.

The cells are arranged so that the higher activity areas are located approximately in the center of the canyon. Although the cells on the southern bank of the canyon are also "hot", their placement on the outside wall affords the advantage of using master-slave type manipulators in the cells. In these particular cells, it is very desirable to be able to work with equipment more directly and to use hand tools and to handle loose equipment effectively. Shielded viewing windows are also provided to improve ease of operation.

The head-end cell was centrally located relative to the different recycle cells to minimize the piping required from the main reactor to the three recycle systems. Short connecting lines from the reactor to the hydrogen chloride and fluorine recycle systems were deemed particularly important, since small pressure drops were desired in the hydrogen chloride recycle system, and since as small a process contacted area as possible was needed in the fluorine recycle lines to minimize plutonium hexafluoride decomposition. The head-end cell contains the halogenators, the filter coolers, the backup filters, the solids hold tank and its filter, the pyrohydrolyzer, and the pyrohydrolyzer primary filter and backup filter.

Adjacent to the head-end cell on the east side is the bromine pentafluoride recycle and uranium hexafluoride purification cell, which contains the bromine pentafluoride regenerator, the gas precooler, uranium hexafluoride-bromine pentafluoride cold traps, bromine pentafluoride recycle equipment, the blowdown reclaimers, the fission product accumulator, the uranium hexafluoride distillation equipment, and the uranium product polishing traps. Next to this cell is the scrubber cell which contains process gas and cell ventilation gas caustic scrubbers.

The decontamination area, equipped with a decontamination enclosure for externally cleaning contaminated equipment, is located at the east end of the canyon away from the high radiation level equipment. To permit limited access to this area for routine operations, shielding and ventilation barriers are interposed between the area and the high radiation level cells. The decontamination area is also serviced by the overhead maintenance crane and manipulator, and room is provided for a wet decontamination facility and a warm shop for the direct maintenance of small nonexpendable equipment. A storage and maintenance area is also provided for the overhead crane and manipulator.

The plutonium hexafluoride collection cell is adjacent to, and west of, the head-end cell. The plutonium hexafluoride cold traps, the fluorine recycle compressor, and the plutonium hexafluoride process vent sodium fluoride trap are located in this cell. As in the other process cells, this cell is serviced by the overhead crane and manipulator; however, the cart-mounted manipulator is not needed, since the cell depth is only 18 feet compared with 37.5 feet for the other in-line cells.

The plutonium purification cell, the fuel drying and handling cell, and two sampling cubicles are located on the south side of the main processing canyon. As noted above, these cells are equipped with master-slave manipulators and shielding windows to facilitate remote operation and maintenance. The overhead crane and manipulators have access to the interior of the cells for removal and replacement of large equipment items, and in addition, a small conveyor system is provided for the movement of waste materials, shipping containers, samples, and the like. Since the plutonium product cell equipment requirements cannot be established because of flow sheet uncertainties, the cell size has tentatively been set at 180 square feet, with three windows and three manipulator stations.

The fuel drying and handling cell is equipped with remotely operated saws for removing fuel module end pieces and a jig which is used to group the required number of modules into a reactor charge. These modules can be stored at this point until ready for transfer to the halogenator.

The two sample cubicles contain the necessary equipment for withdrawing samples from the main processing equipment and preparing them for analysis. One of these stations is used exclusively for solids; there alumina and other granular samples may be subdivided prior to transfer to the laboratory analytical cells, and if necessary, ground to a size suitable for analysis. The second cubicle is used for volatile salts, e.g., uranium hexafluoride and bromine pentafluoride, and for miscellaneous samples, such as liquids from the scrubbers. The transfer to the laboratory analytical cells is by shielded conveying system.

The three process cells in the north side of the canyon are, from west to east, the hydrogen chloride recycle cell, the recirculating cooling air cell, and the uranium hexafluoride product collection cell. All of the equipment required to recover and recycle the hydrogen chloride,

except for the pyrohydrolyzer and its associated filters, are contained in the first of these cells. Equipment for recirculating the cooling air and for removing heat from the air are located in the second cell. This equipment consists of two finned radiator type heat exchangers and two blowers. The recirculated air is directed through ducts to and from the fluid-bed reactors, bromine pentafluoride regenerator, precooler, and miscellaneous condensers and sorbent traps. The eastern-most cell contains the uranium hexafluoride product condensers, collection tanks, and two sorption traps to perform reworking of the product. Provision can be made in this cell for the recovery of neptunium from the sorbent traps and, perhaps, from the plutonium purification waste.

Sampling and Accountability

A basic requirement of a power reactor fuel reprocessing plant from the material management point of view is that purification and recovery of the uranium and plutonium be accomplished with low losses. In addition, it is necessary that the power plant and the reprocessing facility concur on the amount of valuable material in a spent fuel shipment in order to determine how much recovered uranium and plutonium should be returned. The mechanism set up for satisfying both these requirements is the accountability procedure. All parties involved should be in agreement on these procedures, including the supervisory government agencies.

Volatility processing would be conducted on a campaign basis, i.e., with a set number of batches of like fuel from the same shipper processed before a shutdown for cleanout or a change in the type of feed. Material management goals should be readily achieved with this type of production operation. Unfortunately, there appears to be no direct means of accurately determining the uranium and plutonium contents of received irradiated fuel. The usual procedure, followed in aqueous plants, is to analyze for uranium and plutonium inputs at the first opportunity. This ordinarily occurs when the uranium and plutonium are distributed uniformly in a medium whose weight, volume, and composition can be assessed accurately. There are no accountability precedents specific to a nuclear fuel reprocessing plant using a fluoride volatility process, but at least some portions of an accountability scheme for a volatility process can be formulated by reference to aqueous plant practice. The quantity of uranium and plutonium in the product and waste streams must also be adjudged; the resulting total, when compared with the quantity fed, provides a measure of unaccountable losses.

There should be two accountability categories, measured loss and process yield. The measured loss simply consists of the summation of the uranium and plutonium discharged in all exit streams, except product, divided by the measured input amount of uranium and plutonium. The process yield consists of the measured product amount of uranium and plutonium divided by the measured input amounts.

There appears to be little conceptual difficulty in considering what is meant by measurement of uranium and plutonium contained in the waste streams or in the product, although there can be considerable discussion as to what accuracy, sampling, frequency, etc, are required. There is, however, a problem connected with the measured input amount. In clad fuel rods salvage work, the input amount of valuable fissile materials cannot be established by sample measurement prior to processing, since representative sampling is essentially impossible. In an aqueous reprocessing plant, incoming solid salvage is dissolved in acid and the solutions are transferred to tanks for sampling and volume measurement prior to recovery operations. The measured input quantity is determined by adding the amount of uranium contained in the tanks to the quantity in the residues generated prior to transfer to the sample tanks. The quantity of uranium in such residues is hopefully quite small.

To develop an analogous procedure for a volatility process requires selection of that process stream in the volatility plant which is comparable strategically to the dissolver product solution in an aqueous process. One might argue that the fluid bed itself could be sampled after oxidation and before volatilization of the uranium; however, getting representative samples from the bed by simply drawing material off through a pipe at one or even several points appears questionable. What would probably be required is an in-line sampler through which all bed material is passed.

A satisfactory accountability procedure for the single-vessel flow sheet may be possible without involving troublesome weighing, bed sampling, and analyses of the fluid beds to get measured plant inputs. Samples from the fluid bed after oxidation could be taken to determine the ratio of plutonium to uranium in the irradiated fuel for later use. The uranium input could be established from analyses and weighings of the uranium hexafluoride and bromine pentafluoride liquids collected in the bromine pentafluoride recycle equipment after the interhalogen fluorination is completed, since at this point, the liquids containing the volatilized uranium could be readily sampled. The uranium remaining with the bromine pentafluoride between interhalogen fluorinations should be small and can be estimated fairly accurately; therefore, accountability errors which might result from uncertainties in this uranium holdup should be small as long as uranium analyses are performed after each bromine pentafluoride fluorination. Once the uranium input has been established, the plutonium input can be computed using the plutonium-to-uranium ratio observed for the bed after the oxidation step. In addition, a reasonably accurate secondary check on the uranium and plutonium content of the fuel can be gotten by calculations based on records of the irradiation history of the fuel assemblies.

Product measurements can be made very accurately. The product uranium hexafluoride will be quite pure, and any correction for purity will be small and accurate. Weighing may be accomplished to one part per thousand with check weights used to improve accuracy, and sampling may readily be performed on the decontaminated material.

Although the final product form of the plutonium has not been chosen, as yet, it may also be measured very accurately in a manner similar to that used for uranium. Its purity, hopefully, will also be high, and sampling and weighing may be done with precision.

Getting accurate waste stream measurements will present somewhat greater problems due to sampling difficulties and the presence of dilute materials, including varying amounts of radioactivity. Nevertheless, precision of measurement need not be very high, since the total uranium and plutonium content in these streams will be relatively small. For example, consider the uranium in the waste alumina. Tests at ANL indicate that the percentage of the uranium input which winds up here may be less than 0.02% of the uranium charge for a single batch. The concentration of uranium in the alumina is, then, about 100 ppm.

Even though the absolute amount of plutonium is only about one-hundredth of the amount of uranium in each processing batch, the quantities of plutonium and uranium remaining with the alumina are about the same after completion of one treatment cycle. For the first cycle, the amount of plutonium retained by alumina is about 2% of that charged. The amount, however, increases only slowly with subsequent cycles so that, after three batches have been processed, in excess of 99% of the cumulative amount of plutonium charged has been volatilized. Actually, the alumina may possibly be used for up to five batches, depending upon the buildup of fission product activity in the solid wastes.

To measure the quantity of uranium and plutonium lost in the alumina waste, it will first be necessary to determine the weight of the alumina to be discarded. A precision of about 5% should be attainable. The precision of determination of the weight per batch should be considerably better than that for determination of the uranium or plutonium content. Accordingly,

$$\sigma_q^2 = \sum_i W_i^2 \sigma_x^2$$

where σ_x^2 = variance of measurement of weight fraction uranium in a batch of waste,

σ_q^2 = variance of measurement of quantity of uranium in a batch of waste, and

W_i = weight of i^{th} batch of waste.

Also, for a campaign involving a lot containing n batches,

$$\sigma_Q^2 = \sum_{i=1}^n W_i^2 \sigma_x^2$$

where σ_Q^2 = variance of measurement of amount of uranium waste for a lot of n batches.

Finally, for equal sized batches,

$$\frac{\text{Error Range for a Lot of } n \text{ Batches}}{\text{Error Range for a Batch}} = \frac{1}{\sqrt{n}}$$

$$\text{Where Error Range per batch at 95\% confidence level} = \frac{2\sigma_Q}{Q} = \pm \frac{2\sigma_x}{x}$$

$$\text{Error Range per lot at 95\% confidence level} = \frac{2\sigma_Q}{Q} = \pm \frac{2\sigma_x}{\sqrt{nx}}$$

As an example, suppose there are twenty-five batches in a lot and it is desired to know the quantity of uranium in the waste stream within 0.05% of process input at the 95% confidence level. Since only 0.02% of the input uranium leaves with the waste stream, it is only necessary to determine the value within 250% of itself. Accordingly,

$$\frac{2\sigma_Q}{Q} = 2.5 \text{ and } \frac{2\sigma_x}{\sqrt{nx}} = 2.5$$

$$\text{Thus } \frac{\sigma_x}{x} = \frac{5}{2} (2.5) = 6.25$$

For $x = 100$ ppm,

$$\sigma_x = 625 \text{ ppm,}$$

and the analysis of the waste stream need be precise only to $\pm 1,250$ ppm.

Similarly for plutonium, where 1% of the input is lost to the waste stream, it is sufficient to know the plutonium content of the waste stream to a precision of 25 ppm.

In this discussion, sampling and analytical errors have been lumped together. It is intended that a stream sampler be used in the conceptual plant, i.e., all of the solid stream passed through a sampling stream which takes a 100% cut for a fraction of the time; hence, the sampling precision will probably be better than the analytical precision. On the other hand, if a dip or spot sample is taken from a settled or fluidized bed, not only is the probability of large random errors increased, but also bias due to nonhomogeneity of the bed may be encountered. The latter procedure would obviously be easier to use, but it is doubtful that it will be found acceptable.

Gas waste streams will be analyzed for uranium using an on-stream unit backed up by spot sampling. Liquid wastes will be sampled after mixing by sparging.

If large accountability discrepancies are found, the process could be shut down at any time and cleaned out. In such a case, all inventory would be processed down to some readily sampled process point. Neutron counting and extended fluorination of the system would be undertaken to uncover and remove all residual valuable material from the system. There is little possibility of significant undetected accumulation if such precautions are employed. As operating experience is gained, the need for such mid-campaign checks should decrease. Final cleanout of the system at the conclusion of a campaign, accompanied by analyses and weighing of all waste and product streams, should provide an accurate check of the quantity of material processed.

In summary, the possibility of obtaining satisfactory accountability for the volatility process described in this report appears good; however, many of the techniques employed will be different from those used for aqueous processing.

Chemical Storage and Makeup

Special facilities are provided for the storage of the nonradioactive process chemicals that are used throughout the plant. Dry chemicals will be stored in the warehouse or in the chemical makeup area adjacent to the processing canyon in the main building. Chemical solutions received in bulk, such as potassium hydroxide, will be stored out-of-doors in suitable tanks in the storage area adjacent to the warehouse and pumped to the operating areas. Refer to figure A-12, the plant plot plan, and to figure A-10 for the locations of these areas. Provisions are made in the chemical makeup area for transferring alumina to the fluid-bed reactors, preparation of sorbent-grade sodium fluoride from sodium bifluoride, feeding of makeup anhydrous hydrogen chloride to the process, and preparation of scrubber solution and other process chemicals. The following chemicals are required:

<u>Chemical</u>	<u>Container Size</u>	<u>Storage Capacity</u>
Al_2O_3 Grain, 60-Mesh	100-pound bag	300 bags
HCl, Anhydrous	60-pound cylinder	200 cylinders
KOH, 45% Solution	6,000-gallon tank car	15,000 gallons
$\text{NaF} \cdot \text{HF}$, 1/8-Inch Pellets	100-pound drum	75 drums
HF, Anhydrous	6,000-gallon tank car	25,000 gallons
LiF	5-pound bottle	10 bottles
$\text{KF} \cdot \text{HF}$	500-pound drum	10 drums
MgF_2	100-pound drum	10 drums

Equipment Function and Description

Design bases and brief descriptions are given in this section for the major pieces of equipment used in the plant. Equipment numbers are given to facilitate location of each item on the flow sheet for the system.

MAIN REACTOR SYSTEM

1. Main Fluid-Bed Reactor, AIV-101 (see figure A-13)

a. Purpose

To contain a fluid bed of alumina in which spent irradiated fuel elements are submerged for volatility processing to recover valuable fissionable materials and to provide adequate heat transfer surface for control of the highly exothermic hydrochlorination, oxidation, and fluorination reactions involved.

b. Design Bases

(1) Hydrochlorination Step

Operating Wall Temperature, °C	400
Operating Inlet Pressure, atmospheres	2.5
Superficial Velocity, ft/sec	1.0
Inlet Hydrogen Chloride Concentration, volume percent	60
Design Cooling Fluxes (inside wall), Btu/hr-sq ft	
Maximum	13,000
Average	8,000
Design Cooling Duty (maximum), Btu/hr	800,000
Coolant Air Supply (maximum), scfm	4,000

(2) Oxidation Step

Operating Bed Temperature, °C	450 to 500
Operating Inlet Pressure, atmospheres	2.0
Superficial Velocity in Lower Section, ft/sec	2.5 to 3.0
Inlet Oxygen Concentration, volume percent	20

Design Cooling Duty, Btu/hr	
Bottom Section	none
Top Section (radioactive heat release)	300,000

Coolant Air Supply (to top section), scfm	1,500
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(3) Bromine Pentafluoride Fluorination

Operating Bed Temperature, °C	300
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Operating Inlet Pressure, atmospheres	2.0
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Superficial Velocity, ft/sec	1.0
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Inlet Bromine Pentafluoride Concentration, volume percent	20
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Design Cooling Duty (maximum), Btu/hr	720,000
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Coolant Air Supply (maximum), scfm	4,000
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(4) Fluorine Fluorination

Operating Bed Temperature, °C	300 to 550
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Operating Inlet Pressure, atmospheres	2.0
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Superficial Velocity, ft/sec	0.50
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Inlet Fluorine Concentration, volume percent	75 to 90
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(5) Dimensions

Bottom Section (pellet bed zone) - 18 inches outside diameter by 7 feet high

Top Section - 26 inches outside diameter by 22 feet high.
The overall height is 32 feet.

(6) Material of Construction

Nickel (low carbon)

(7) Number Required

Two

The reactor is composed of two cylindrical sections joined by a conical transition piece. The top cylindrical portion is large enough to accommodate seven 5.5-inch by 5.5-inch by 12-foot-long fuel elements (General Electric) or three 8.5-inch by 8.5-inch by

12-foot-long fuel elements (Westinghouse or Combustion Engineering). During operation, the reactor will contain approximately 2,000 kg of alumina, which will submerge the fuel elements and supply sufficient bed height to give ample effective heat transfer area. A grid plate supports the fuel elements during decladding and allows the uranium dioxide to fall to the bottom portion of the reactor. Fluidizing gases enter at the bottom of the 18-inch-diameter section through a conical gas distributor section which contains 5/8-inch-diameter balls. Additional gas inlets are provided in the top section. The reactor is cooled by forced air within a 2-inch annulus surrounding both top and bottom sections. Fins on the outside of the reactor provide needed heat transfer area and are enclosed in a sheet metal jacket. Heat is supplied to the reactor by radiation from the outer wall of the annular cooling air passage. The heat is transferred by conduction and radiation from a remotely replaceable electric furnace. The furnace elements are constructed so that controlled-zone heating can be applied in the bottom section. Heat is applied uniformly to the upper section rather than zone controlled.

2. Fluid-Bed Cooler and Filter, AIV-601 and AIV-201 (For Typical Sintered Metal Filter, See Figure A-14)

a. Purpose

The cooler portion provides a fluid-bed heat transfer media for cooling the reactor off-gases and also removes elutriated U_3O_8 particles for reflux to the reactor. The filter portion of the unit removes particulates entrained from the fluid-bed cooler.

b. Design Bases

(1) Hydrochlorination Step

Operating Temperature, °C	350
Operating Inlet Pressure, atmospheres	1.7
Superficial Velocity, ft/sec	0.7
Design Cooling Duty, Btu/hr	100,000
Cooling Air Supply (maximum), scfm	1,000

(2) Oxidation Step

Operating Temperature, °C	200
Operating Inlet Pressure, atmospheres	1.3
Superficial Velocity, ft/sec	1.0 to 1.5

Design Cooling Duty, Btu/hr	250,000
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Cooling Air Supply (maximum), scfm	2,000
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(3) Bromine Pentafluoride Fluorination

Operating Temperature, °C	200
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Operating Inlet Pressure, atmospheres	1.5
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Superficial Velocity, ft/sec	0.6
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Design Cooling Duty, Btu/hr	100,000
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(4) Fluorine Fluorination

Operating Temperature, °C	100
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Operating Inlet Pressure, atmospheres	1.5
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Superficial Velocity, ft/sec	0.3
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Design Cooling Duty, Btu/hr	250,000
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(5) Dimensions

Shell - 32 inches in outside diameter by 17 feet tall, overall. Along the cooler bed section, the outer diameter is 36 inches, thus giving a 2-inch annulus along the outer periphery for cooling air.

Filter Tubes - Twenty-four 3-inch-diameter by 4-foot-long tubes. Filter flow - 4 scfm/sq ft

(6) Material of Construction

Shell - nickel

Filter Tubes - sintered nickel

(7) Number Required

Two

Off-gases from main reactor enter the vessel at the bottom of an inverted conical distributing section. The wider mouth of this cone is welded to the 32-inch outside diameter of the vessel. Alumina, in a fluidized state, fills the vessel to 2 feet above the top of the cone. The charge is approximately 750 kg of alumina. There is about 4 feet of freeboard between the top of the fluid bed and the bottom of the filter tubes. The filter tubes are arranged

on a 5-inch triangular pitch so that sets of 5 or 7 tubes can be blown back automatically in sequence.

3. Backup Filter, AIV-202 (See Figure A-14)

a. Purpose

To provide filtration of the main filter off-gases should the main filter fail.

b. Design Bases

(1) Operating Conditions

Temperature, °C 100 to 350

Pressure, atmospheres 1.5

Filter Flow, scfm/sq ft 4

(2) Dimensions

Shell - 18 inches in outside diameter by 6 feet tall

Filter Tubes - Fourteen 3-inch-diameter by 4 feet long

(3) Material of Construction

Shell - nickel

Filter Tubes - sintered nickel

(4) Number Required

Two

The load on this filter should be low; and therefore, blowback is manual rather than automatic. The entire filter assembly is to be replaced as a unit if a filter plugs or fails.

4. Solids Hold Tank Filter, AIV-203 (See Figure A-14)

a. Purpose

To remove solids from the carrier gas after pneumatic transfer from the reactor to a solids sampling station.

b. Design Bases

(1) Operating Conditions

Temperature, °C 100 to 300

Pressure, atmospheres	1.1
Filter Flow, scfm/sq ft	10

(2) Dimensions

Shell - 16 inches in outside diameter by 9 feet tall

Filter Tubes - Ten 3-inch-diameter by 4-foot-long

(3) Material of Construction

Shell - stainless steel

Filter Tubes - sintered stainless steel

(4) Number Required

One

Solids and gases enter the filter shell tangentially; whereupon, most of the solids fall to the bottom conical section of the filter. Manual blowback is provided. The filtered solids then flow through one sampler where a 5% cut is taken. The 5% cut then flows through another sampler where a second 5% is taken. The rejects from both samplers are fed to the solids sample tank, AIV-401.

5. Solids Hold Tank, AIV-401 (See Figure A-15)a. Purpose

To provide holdup for bed diluent containing radioactive wastes before transfer to bin storage.

b. Design Bases(1) Operating Conditions

Bed Temperature (maximum), °C	1,300
Pressure, atmospheres	1 to 2
Design Cooling Duty, Btu/hr	400,000
Cooling Air Supply (maximum), scfm	2,000

(2) Dimensions

Shell - 54 inches in outside diameter by about 12 feet in overall height. The waste would be held in fourteen 10-inch schedule-40 pipe sections 6 feet long located internally on a triangular pitch with a 11-3/4 inch center-to-center spacing.

(3) Material of Construction

Shell - steel

Tubes - stainless steel

(4) Number Required

One

The solids enter through a 2-inch-diameter pipe welded to an inverted conical distributor at the top of the vessel. The pipe sections are welded to a conical tube sheet at the top and bottom of the shell. Solids fill the outer pipes first and overflow into the center. The tank capacity is about 3,000 kg of alumina. Discharge of solids is accomplished by pneumatic transfer from the bottom cone of the vessel.

Cooling air enters a conical cooling jacket on the bottom cone through two 5-inch-diameter pipes. The air flows up the conical jacket and into the space between the pipe sections through holes located on the periphery of the shell. Baffles are provided for uniform air distribution over the full length of each pipe. The cooling air leaves the shell through a 6-inch pipe located near the top of the shell.

6. Gas Preheaters, AIV-618A & Ba. Purpose

To heat inlet gases to the halogenator.

A preheater for the inlet gases to the halogenator may or may not be needed. Inclusion of the preheaters was made to ensure flexibility of halogenator operation and of processing procedure.

HYDROGEN CHLORIDE RECYCLE SYSTEM1. Pyrohydrolyzer, AIV-102a. Purpose

To convert the volatile zirconium tetrachloride to nonvolatile zirconium oxide for ease of permanent storage.

b. Design Bases(1) Operating Conditions

Temperature, °C	350 to 400
Pressure, atmospheres	1.84
Fluidizing Velocity, ft/sec	
Inlet (maximum)	0.8
Outlet	1.2
Cooling Load (maximum), Btu/hr	50,000

(2) Dimensions

32 inches inside diameter by 18 feet, excluding filter section

(3) Material of Construction

Inconel

(4) Number Required

One

The zirconium tetrachloride gas stream enters the reactor through a ball check valve at the bottom of an inverted conical gas distribution section. Water vapor enters through three parallel pipes, each pipe having six gas injection ports pointing downward. The pipes are located 1 foot above the ball check valve. Product powder is usually drained off through a 2-inch-diameter pipe which is located on the side of the vessel at the level of original fluidized bed. The powder is transferred pneumatically to the solids sample system and to waste storage. In addition, the bed may be completely drained through similar powder outlet lines in the conical gas distributor section on the bottom of the vessel. Heat is supplied by remotely replaceable electric furnaces. Cooling for temperature control is provided by forced air within a 1-inch annulus surrounding the bed section only. The pyrohydrolyzer filter, AIV-204, is constructed integrally with the fluid-bed de-entrainment section.

2. Pyrohydrolyzer Filter, AIV-204 (See Figure A-14)a. Purpose

To remove zirconium oxide fines from the hydrolysis reactor off-gases.

b. Design Basis(1) Operating Conditions

Temperature, °C	300
-----------------	-----

Pressure, atmospheres	1.29
-----------------------	------

Filter Flow, scfm/sq ft	2
-------------------------	---

(2) Dimensions

32 inches outside diameter by 5 feet high; filter area, 100 square feet

(3) Material of Construction

Shell - Inconel

Filter Tubes - sintered Inconel

(4) Number Required

One

The filter is designed as an integral part of the pyrohydrolysis reactor; all powder blown off the tubes falls directly into the fluid bed. Two banks of nine tubes each and two banks of eleven tubes each are employed. Automatic sequential blowback of each bank of tubes is employed.

3. Pyrohydrolyzer Backup Filter, AIV-205 (See Figure A-14)a. Purpose

To prevent spread of radioactive contamination and plugging of process lines in the event the pyrohydrolysis primary filter (AIV-204) should rupture.

b. Design Basis(1) Operating Conditions

Temperature, °C	250
-----------------	-----

Pressure, atmospheres	1.15
-----------------------	------

Filter Flow, scfm/sq ft	4
-------------------------	---

(2) Dimensions

18 inches inside diameter by 6 feet high; filter area,
60 square feet

(3) Material of Construction

Shell - Inconel

Tubes - sintered Inconel

(4) Number Required

One

The filter is equipped for manual blowback.

4. Chloride Scrubber, AIV-301a. Purpose

To remove hydrogen chloride from hydrogen vent gas.

b. Design Basis(1) Operating Conditions

Temperature, °C 25

Pressure, atmospheres 2.45

(2) Dimensions

6 inches inside diameter by 10 feet high

(3) Material of Construction

Chemical Stoneware

(4) Number Required

One

The unit is packed with ceramic saddles and is operated using recycled hydrochloric acid.

5. Aqueous Hydrogen Chloride Reservoir, AIV-402a. Purpose

To provide surge capacity for aqueous hydrogen chloride recycle flow.

b. Design Basis(1) Operating Conditions

Temperature, °C	0
-----------------	---

Pressure, atmospheres	1.15
-----------------------	------

(2) Capacity

100 gallons

(3) Dimensions

2 feet in diameter by 5 feet long

(4) Material of Construction

Hastelloy B

(5) Number Required

One

This tank is provided with tubing wrapped on the outside for cooling with minus 15°C brine and is insulated. This is required to prevent revaporization of the condensed aqueous hydrogen chloride.

6. Anhydrous Hydrogen Chloride Reservoir, AIV-403a. Purpose

To provide surge capacity for anhydrous hydrogen chloride.

b. Design Bases(1) Operating Conditions

Temperature, °C	minus 100
-----------------	-----------

Pressure, atmospheres	2.72
-----------------------	------

(2) Capacity

60 gallons

(3) Dimensions

2 feet in diameter by 5 feet long

(4) Material of Construction

Nickel

(5) Number Required

One

External refrigeration coils are provided, and the unit is insulated. This is required to prevent revaporization of the condensed anhydrous hydrogen chloride.

7. Chloride Scrubber Hold Tank, AIV-404a. Purpose

To contain aqueous hydrogen chloride for recycle to the chloride vent scrubber.

b. Design Basis(1) Operating Conditions

Temperature, °C	25
-----------------	----

Pressure, atmospheres	2.45
-----------------------	------

(2) Capacity

90 gallons

(3) Dimensions

2 feet 6 inches in diameter by 3 feet long

(4) Material of Construction

Hastelloy B

(5) Number Required

One

This unit is welded to the bottom of the chloride scrubber.

8. Hydrogen Chloride Recycle Gas Compressor Unit, AIV-501 (See Figure 9)a. Purpose

To supply hydrogen chloride to the main fluid-bed reactors (halogenators), AIV-101.

b. Design Bases(1) Operating Conditions

Temperature, °C	120
Discharge Pressure, atmospheres	2.86
Suction Pressure, atmospheres	1.09
Flow, scfm	120

(2) Material of Construction

Pumping Head - nickel

Remainder - steel

(3) Number Required

Two

This pump is a two-stage variable-speed peripheral compressor with a filter and an interstage cooler. The compressor will operate at about 11,000 rpm and will require a buffered seal.

9. Aqueous Hydrogen Chloride Pump, AIV-502a. Purpose

To supply pressurized aqueous hydrogen chloride to the aqueous hydrogen chloride reboiler.

b. Design Bases(1) Operating Conditions

Temperature, °C	0
Discharge Pressure, psig	32
Suction Pressure	Flooded
Flow, gpm	0.4

(2) Material of Construction

Hastelloy B

(3) Number Required

One

The pump is a remote head diaphragm type unit used to eliminate shaft seal leakage difficulties.

10. Scrubber Solution Pump, AIV-503

a. Purpose

To recycle aqueous hydrogen chloride through chloride vent scrubber system.

b. Design Bases

(1) Operating Conditions

Temperature, °C	25
Discharge Pressure, psig	30
Flow, gpm	1.5

(2) Material of Construction

Durichlor

(3) Number Required

One

A canned rotor type pump is used to minimize difficulties with the shaft seal.

11. Aqueous Hydrogen Chloride Condenser, AIV-602

a. Purpose

To cool hydrogen chloride recycle from 350 to 0°C and to condense essentially all the water vapor present in this stream.

b. Design Bases

Type - Vertical tube and shell heat exchanger

(1) Operating Conditions

Cooling Duty, Btu/hr	383,000
Shell Side, Chilled Brine	
Inlet Temperature, °C	minus 15
Outlet Temperature, °C	5

Tube Side, Hydrogen Chloride-Hydrogen-Water Mixture	
Pressure, atmospheres	1.15
Inlet Temperature, °C	350
Outlet Temperature, °C	0
Flow, lb/hr	655

(2) Dimensions

Fifty-five 1/2-inch-diameter tubes in a 6-inch-diameter external shell 15 feet long; tube side area, 80 square feet.

(3) Material of Construction

Hastelloy B

(4) Number Required

One

The exchanger consists of an external shell and an integral insert which fits into the shell. The insert is a welded assembly containing a tube bundle which is mounted between tube sheets and sealed in a jacket. Piping, welded to the flanged head of the shell, conveys refrigerant between the jacketed side of the tubes and the outside of the shell. Process gases to be cooled enter through the shell wall and flow through the tubes before leaving through the shell wall. Close spacing between the jacket and the external shell of the exchanger limits short circuiting of the gas. The refrigerant jacket and tube assembly may be removed for replacement by unbolting the head from the shell.

12. Aqueous Hydrogen Chloride Boiler, AIV-603a. Purpose

To supply water vapor to the pyrohydrolyzer.

b. Design Bases(1) Operating Conditions

Heat Duty, Btu/hr	372,000
Shell Side, Condensing Steam	
Temperature, °C	150
Tube Side, Boiling Hydrogen Chloride-Water	
Temperature, °C	110

(2) Dimensions

6 inches in diameter by 8 feet tall; heat transfer area,
28 square feet

(3) Material of Construction

Hastelloy B

(4) Number Required

One

The boiler is a vertical shell and tube heat exchanger with boiling liquid in the tubes and condensing steam in the shell. In essence, it is similar in design to an inverted cooler-condenser (AIV-602). The tube bundle is removed downward.

13. Anhydrous Hydrogen Chloride Condenser, AIV-604a. Purpose

To remove anhydrous hydrogen chloride from the hydrogen-hydrogen chloride vent gases.

b. Design Bases(1) Operating Conditions

Heat Duty, Btu/hr	39,500
-------------------	--------

Shell Side, Evaporating Ethane	
Temperature, °C	minus 110
Pressure, psia	4.2

Tube Side, Hydrogen Chloride plus Hydrogen	
Pressure, atmospheres	2.72
Inlet Temperature, °C	0
Outlet Temperature, °C	minus 100

(2) Dimensions

6 inches in diameter by 8 feet tall; heat transfer area,
21 square feet

(3) Material of Construction

nickel

(4) Number Required

One

The design of this unit is similar to that of AIV-602.

14. Anhydrous Hydrogen Chloride Boiler, AIV-605

a. Purpose

To recycle gaseous hydrogen chloride to the main fluid-bed reactors (halogenators), AIV-101A and B, from the anhydrous hydrogen chloride reservoir, AIV-403.

b. Design Bases

(1) Operating Conditions

Heat Duty, Btu/hr	32,490
Tube Side, Boiling Hydrogen Chloride (Anhydrous)	
Temperature, °C	minus 62
Pressures, atmospheres	3

(2) Dimensions

12 inches in diameter by 8 feet long; heat transfer area, 12.7 square feet

(3) Material of Construction

Nickel

(4) Number Required

One

This heat exchanger is heated by externally mounted (clam shell electric) heaters. The unit and its heaters are insulated to prevent moisture condensation, and external refrigeration coils are provided for additional temperature control.

15. Chloride Scrubber Recycle Cooler, AIV-606

a. Purpose

To remove the heat of solution (hydrogen chloride in water) from the scrubber recycle stream.

b. Design Bases

Type - Vertical shell and tube

(1) Operating Conditions

Cooling Duty, Btu/hr	15,800
Shell Side - Brine from Aqueous Hydrogen Chloride Condenser, AIV-602	
Inlet Temperature, °C	5
Outlet Temperature, °C	6
Flow, lb/hr	13,800
Tube Side - Scrubber Solution	
Inlet Temperature, °C	25
Outlet Temperature, °C	10
Flow, lb/hr	566 (68 gph)

(2) Dimensions

12 inches in diameter by 10 feet tall; heat transfer area,
30 square feet

(3) Material of Construction

Hastelloy B

(4) Number Required

One

BROMINE PENTAFLUORIDE RECYCLE AND URANIUM HEXAFLUORIDE PURIFICATION1. Bromine Pentafluoride Regenerator, AIV-103 (See Figure A-16)a. Purpose

To convert the bromine evolved in the off-gas from the main reactor back to bromine pentafluoride for reuse.

b. Design Bases(1) Operating Conditions

Wall Temperature, °C	< 550
Pressure, atmospheres	2.4
Design Cooling Fluxes (inside area), Btu/hr-sq ft	2,000
Design Cooling Duty (maximum), Btu/hr	500,000
Cooling Air Supply (maximum), scfm	3,000

(2) Dimensions

Center Pipe (regenerator):

Nonfinned Section - 10-3/4 inches in outside diameter by
13 feet longFinned Section - 10-3/4 inches in outside diameter by
12 feet long

Outer Shell: 16 inches in outside diameter by 28 feet long

(3) Material of Construction

Nickel

(4) Number Required

One

Process gases and fluorine enter the regenerator through concentric nozzles which keep the two gas mixtures separated until contact occurs just beyond the nozzle. Some preheating of the process gases in process piping may be required to assure that an initiating reaction temperature is obtained. Once the process gases and fluorine begin to react, the reaction proceeds essentially adiabatically, and a temperature of about 1000°C is reached. In the nonfinned section at the regenerator inlet, the internal reaction temperature is high but the wall temperatures are relatively low. The gases are cooled sufficiently so that fins may be used at the exit for improved heat transfer. With this design, the temperature of the fins will not exceed 550°C, which is deemed the maximum allowable temperature for this material. Thirty 4-inch-high fins are welded to the inside wall of the regenerator.

Cooling of the regenerator tube is accomplished with forced air. Thirty 2-11/32-inch-high fins are welded to the outside wall at the exit end for a length of 12 feet.

2. Sodium Fluoride Sorber Polishing Trap, AIV-302 (For Typical Sorbent Trap, see Figure A-17)a. Purpose

To remove traces of volatile fission products from the uranium hexafluoride product.

b. Design Bases(1) Operating Conditions

Temperature, °C

400

Pressure, atmospheres 3.0

Gas Contact Time, seconds > 40

Cooling Air Supply (maximum), scfm 100

(2) Capacity

91 kg

(3) Dimensions

12 inches outside diameter by 5 inches inside diameter by
5 feet high

(4) Material of Construction

Nickel

(5) Number Required

Two

These traps are integral cartridge types designed for easy replacement as a unit. For ease in heating and cooling, each trap is constructed in the form of an annular cylinder which fits into a furnace opening with heaters along both the inner and outer walls. The traps can be replaced without disturbing the heaters. Cooling is accomplished using forced air which flows between the furnace liners and the outside walls of the trap. It is expected that the life of these traps will be limited, not by trapping capacity, but by the quantity of radioactivity sorbed. No regeneration cycle is contemplated.

3. Magnesium Fluoride Sorber Polishing Trap, AIV-303 (See Figure A-17)

a. Purpose

To remove final traces of volatile fission products from the uranium hexafluoride product.

b. Design Bases

(1) Operating Conditions

Temperature, °C 100 to 400

Pressure, atmospheres 3.0

Gas Contact Time, seconds 60

(2) Capacity

57 kg

(3) Dimensions12 inches outside diameter by 5 inches inside diameter by
5 feet high(4) Material of Construction

Nickel

(5) Number Required

Two

These traps are identical to the sodium fluoride sorber polishing trap, AIV-302.

4. Uranium Hexafluoride Purification Still Column Number 1, AIV-304
(See Figure A-18)

a. Purpose

To remove bromine pentafluoride from the uranium hexafluoride for return to the bromine pentafluoride recycle system.

b. Design Bases(1) Operating Conditions

Temperature, °C	70 to 90
-----------------	----------

Pressure, atmosphere	ca. 3.0
----------------------	---------

(2) Dimensions

15 inches inside diameter by 40 feet tall

(3) Material of Construction

Nickel

(4) Number Required

One

This column will be operated as a batch column and contains fifty-eight bubble cap trays spaced about 8 inches apart. The reflux ratio will vary from about 12 to 1,000 during a batch run. Trace heaters are provided to maintain an adiabatic operation.

5. Uranium Hexafluoride Purification Still Column Number 2, AIV-305
(See Figure A-18)

a. Purpose

To remove low boiling fission products and bromine trifluoride present in the uranium hexafluoride.

b. Design Bases

(1) Operating Conditions

Temperature, °C 90

Pressure, atmospheres ca. 3.0

(2) Dimensions

8 inches inside diameter by 30 feet tall

(3) Material of Construction

Nickel

(4) Number Required

One

This column will be operated as a batch column and contains fifty-five bubble cap trays spaced about 6 inches apart. Trace heaters are provided to maintain an adiabatic operation.

6. Sodium Fluoride Fission Product Trap, AIV-306 (See Figure A-17)

a. Purpose

To remove fission products which accumulate in the bromine pentafluoride vaporizer and in the reboiler of the second still column.

b. Design Bases

(1) Operating Conditions

Temperature, °C 400

Pressure, atmospheres 2 to 2.5

Gas Contact Time, seconds > 20

Cooling Air Supply (maximum), cfm 100

(2) Capacity

91 kg

(3) Dimensions

12 inches outside diameter by 5 inches inside diameter by
5 feet high

(4) Material of Construction

Nickel

(5) Number Required

One

This unit is similar in design to trap AIV-302.

7. Magnesium Fluoride Fission Product Trap, AIV-307 (See Figure A-17)a. Purpose

To remove fission products which accumulate in the bromine pentafluoride vaporizer and in the reboiler of the second still column.

b. Design Bases(1) Operating Conditions

Temperature, °C	100 to 400
Pressure, atmospheres	2 to 2.5
Gas Contact Time, seconds	> 20
Cooling Air Supply (maximum), cfm	100

(2) Capacity

57 kg

(3) Dimensions

12 inches outside diameter by 5 inches inside diameter by
5 feet high

(4) Number Required

One

This unit is similar in design to trap AIV-302.

8. Sodium Fluoride Sorption Rework Trap, AIV-308 (See Figure A-17)

a. Purpose

To provide additional cleanup by sodium fluoride sorption for the uranium hexafluoride product if product specifications are not obtained in regular operation.

b. Design Bases

(1) Operating Conditions

Temperature, °C 400

Pressure, atmospheres 3.0

Gas Contact Time, seconds 40

(2) Capacity

91 kg

(3) Dimensions

12 inches outside diameter by 5 inches inside diameter by 5 feet high

(4) Material of Construction

Monel

(5) Number Required

One

This trap is similar in design to the sodium fluoride polishing trap, AIV-302, except for the fact that no air cooling is provided.

9. Magnesium Fluoride Sorption Rework Trap, AIV-309 (See Figure A-17)

a. Purpose

To provide additional cleanup by magnesium fluoride sorption for the uranium hexafluoride product if product specifications are not obtained in regular operation.

b. Design Bases(1) Operating Conditions

Temperature, °C	100 to 400
-----------------	------------

Pressure, atmospheres	3.0
-----------------------	-----

Gas Contact Time, seconds	60
---------------------------	----

(2) Capacity

57 kg

(3) Dimensions

12 inches outside diameter by 5 inches inside diameter by
5 feet high

(4) Material of Construction

Monel

(5) Number Required

One

This trap is similar in design to the sodium fluoride polishing trap, AIV-302, except for the fact that no air cooling is provided.

10. Bromine Pentafluoride Accumulator, AIV-405a. Purpose

To provide a surge volume for the bromine pentafluoride vaporizer.

b. Design Bases(1) Operating Conditions

Temperature, °C	minus 50
-----------------	----------

Pressure, atmospheres	2.5
-----------------------	-----

(2) Capacity

Hold Capacity, 300 kg

(3) Dimensions

14 inches in outside diameter by 6 feet long

(4) Material of Construction

Nickel

(5) Number Required

One

External refrigeration coils are provided, and the unit is insulated to prevent revaporization of the condensed bromine pentafluoride.

11. Bromine Pentafluoride Distillate Accumulator, AIV-406a. Purpose

To provide a bromine pentafluoride surge volume between the first uranium hexafluoride purification still column and the bromine pentafluoride recycle system.

b. Design Bases(1) Operating Conditions

Temperature, °C

70

Pressure, atmospheres

ca. 3.0

(2) Capacity

50 gallons

(3) Dimensions

24 inches in diameter by 3 feet long

(4) Material of Construction

Monel

(5) Number Required

One

12. Uranium Hexafluoride Hold Tank, AIV-407a. Purpose

To provide a hold volume for the uranium hexafluoride trapped in the cold traps, and to serve as a feed tank for the distillation column.

b. Design Bases(1) Operating Conditions

Temperature, °C 90

Pressure, atmospheres ca. 3.0

(2) Capacity

150 gallons

(3) Dimensions

24 inches in outside diameter by 8 feet long

(4) Material of Construction

Nickel

(5) Number Required

One

Electrical trace heaters will be provided to heat the tank contents to about 90°C so that the uranium hexafluoride can be pressurized into the still column by its own vapor pressure.

13. Bromine Pentafluoride Reflux Drum, AIV-408a. Purpose

To provide a withdrawal point and surge volume for bromine pentafluoride distillate.

b. Design Bases(1) Operating Conditions

Temperature, °C 70

Pressure, atmospheres 2.5

(2) Capacity

5 gallons

(3) Dimensions

12 inches in diameter by 18 inches long

(4) Material of Construction

Monel

(5) Number Required

One

Sufficient surge volume is provided so that distillate can be removed intermittently while maintaining a constant reflux rate.

14. Uranium Hexafluoride Reflux Drum, AIV-409a. Purpose

To provide surge volume for uranium hexafluoride distillate.

b. Design Bases(1) Operating Conditions

Temperature, °C	90
-----------------	----

Pressure, atmospheres	ca. 3.0
-----------------------	---------

(2) Capacity

5 gallons

(3) Dimensions

12 inches in diameter by 18 inches long

(4) Material of Construction

Monel

(5) Number Required

One

Sufficient surge volume is provided so that distillate can be removed intermittently while maintaining a constant reflux rate.

15. Uranium Hexafluoride Product Collection Tank, AIV-410a. Purpose

To provide a collection point for the product uranium hexafluoride.

b. Design Bases(1) Operating Conditions

Temperature, °C	25 to 90
-----------------	----------

Pressure, atmospheres	3.0
-----------------------	-----

(2) Capacity

220 gallons

(3) Dimensions

30 inches in diameter by 6 feet long

(4) Material of Construction

Monel

(5) Number Required

Two

Each collection tank is provided with electrical heaters to be used if revaporization of product through sorbent traps is required.

16. Bromine Pentafluoride Recycle Gas Compressor, AIV-504 (See Figure 9)a. Purpose

To move the reactor off-gases to the uranium hexafluoride cold traps and the recovered interhalogen gases through the bromine pentafluoride recycle system back to the main fluid-bed reactor.

b. Design Bases(1) Operating Conditions

Suction Pressure, atmosphere	1
------------------------------	---

Discharge Pressure (maximum), atmospheres	2.4
---	-----

Suction Temperature, °C	100.0
-------------------------	-------

Flow, scfm	110
------------	-----

(2) Material of Construction

Pumping Head - nickel

Remainder - steel

(3) Number Required

One

This pump will be a two-stage variable-speed peripheral compressor with a filter and an interstage cooler. The compressor will operate at about 11,000 rpm and will require a buffered seal. Air will be used as the cooling medium.

17. Gas Precooler, AIV-607a. Purpose

To cool the regenerator off-gases so that the heat load on the uranium hexafluoride cold trapping refrigeration system may be minimized.

b. Design Bases(1) Operating Conditions

Temperature, °C	
Shell Side: Inlet	70
Outlet	90
Inside: Inlet	400
Outlet	100
Pressure, atmospheres	2.0 to 2.5
Design Cooling Flux, Btu/hr-sq ft	1,000
Design Cooling Duty (maximum), Btu/hr	150,000
Coolant Air Supply (maximum), scfm	2,000

(2) Dimensions

Inner Pipe - 10-3/4 inches in diameter by 20 feet long
 Shell Side - 16 inches in diameter

(3) Material of Construction

Nickel

(4) Number Required

One

The gas precooler is a concentric pipe heat exchanger in which process gas passes through the inner pipe while coolant flows through the shell. The precooler is finned both on the inside and outside

of the regenerator with a total of sixty fins running the length of the cooler. Forced air is used for cooling.

18. Uranium Hexafluoride Cold Trap, AIV-608 (See Figure A-19)

a. Purpose

To condense the uranium hexafluoride and bromine pentafluoride from the process gas and to hold up most of the uranium hexafluoride as a solid while allowing most of the bromine pentafluoride to drain off as a liquid. Subsequently, the solid uranium hexafluoride would be liquefied and drained off for distillation.

b. Design Bases

(1) Operating Conditions

Condensation Step Temperature, °C	
Inlet	100
Outlet (gas)	minus 40
Pressure, atmospheres	2.5
Heat Load, Btu/hr	40,000
Temperature for Uranium Hexafluoride	
Draining, °C	100

(2) Capacity

Hold capacity, 630 kg of uranium hexafluoride

(3) Dimensions

16 inches in diameter by 25 feet long; heat transfer area, 450 square feet

(4) Material of Construction

Nickel

(5) Number Required

Four

This unit is a 16-inch-diameter pipe with internal axial fins. Coolant pipes are welded to the outside of the trap. The gas inlet and outlet connections are located on the same end of the trap to permit allowance for expansion and contraction during the temperature cycle. The bromine pentafluoride liquid drain outlet is also at

the gas inlet end of the trap. The gas outlet is a 5-inch-diameter pipe which extends through the center of the trap to the end opposite the inlet. The solid uranium hexafluoride, which collects on the internal chilled surfaces, is melted by means of external electrical heaters (25 kw per trap) with the traps isolated from the process flow. The liquid is then drained to a hold tank, AIV-407, for subsequent feed to the distillation system.

19. Bromine Pentafluoride Vaporizer, AIV-609

a. Purpose

To vaporize the bromine pentafluoride recovered during cold trapping for recycle back to the main fluid-bed reactor.

b. Design Bases

(1) Operating Conditions

Temperature, °C	65
Pressure, atmospheres	2.0
Design Heat Load, Btu/hr	125,000

(2) Dimensions

14 inches in outside diameter by 7-1/2 feet long

(3) Material of Construction

Nickel

(4) Number Required

One

Electrical heaters are provided which are placed next to the bottom half of the vessel. Approximately 37 kw is required.

20. Bromine Fluoride Vent Gas Cold Trap, AIV-610

a. Purpose

To recover most of the uranium hexafluoride and bromine pentafluoride present in the bromine pentafluoride fluorination vent gases.

b. Design Bases(1) Operating Conditions

Temperatures, °C

Inlet

minus 40

Outlet

minus 80

Pressure, atmospheres

2.5

Heat Load, Btu/hr

3,500

(2) Capacity

Hold Capacity, 60 kg

(3) Dimensions

16 inches in diameter by 10 feet long; heat transfer area,
250 square feet

(4) Material of Construction

Nickel

(5) Number Required

One

The design of this trap is similar to that of the uranium hexafluoride cold trap, AIV-608 (see figure A-19).

21. Still Column 1 Reboiler, AIV-611a. Purpose

To provide boilup for still column 1.

b. Design Basis(1) Operating Conditions

Temperature, °C

90

Pressure, atmospheres

3.0

Heat Load, Btu/hr

155,000

(2) Dimensions

30 inches in diameter by 7 feet long

(3) Material of Construction

Nickel

(4) Number Required

One

This vessel is an integral part of still column 1 and is equipped with electric shell heaters (60 kw). Internal baffling containing a nuclear poison is used to assure nuclear safety.

22. Bromine Pentafluoride Overhead Condenser, AIV-612a. Purpose

To condense the bromine pentafluoride vapor and provide a liquid reflux to still column 1.

b. Design Bases(1) Operating Conditions

Temperature, °C	70
Pressure, atmospheres	2.5
Heat Load, Btu/hr	155,000
Cooling Air Supply, scfm	2,000

(2) Dimensions

10-3/4 inches in diameter by 6 feet long; heat transfer area, 40 square feet

(3) Material of Construction

Monel

(4) Number Required

One

This unit is cooled by forced air in the finned external surfaces of the condenser. The internal surface is also finned to give a 3.0-to-1 finned-to-unfinned surface area ratio.

23. Still Column 2 Reboiler, AIV-613a. Purpose

To provide boilup for still column 2.

b. Design Bases(1) Operating Conditions

Temperature, °C 100

Pressure, atmospheres 3.0

Heat Load, Btu/hr 26,000

(2) Dimensions

30 inches in diameter by 7 feet long

(3) Material of Construction

Nickel

(4) Number Required

One

This vessel is an integral part of still column 2 and is equipped with electric shell heaters (10 kw).

24. Uranium Hexafluoride Overhead Condenser, AIV-614a. Purpose

To condense the uranium hexafluoride overhead vapors from still column 2 and to provide reflux liquid.

b. Design Bases(1) Operating Conditions

Temperature, °C 80

Pressure, atmospheres 2.5

Heat Load, Btu/hr 26,000

Cooling Air Supply, scfm 500

(2) Dimensions

6 inches in diameter by 3 feet long; heat transfer area,
7 square feet

(3) Material of Construction

Nickel

(4) Number Required

One

This unit is cooled by forced air on the finned external surfaces of the condenser. The internal surface is also finned to give a 3.0-to-1 finned-to-base surface area ratio.

25. Uranium Hexafluoride Product Condenser, AIV-615a. Purpose

To condense the product uranium hexafluoride prior to filling cylinders.

b. Design Bases(1) Operating Conditions

Temperature, °C	90
Pressure, atmospheres	3.0
Design Cooling Duty, Btu/hr	7,500
Coolant Air Supply (maximum), scfm	500

(2) Dimensions

Each condenser consists of a 5-foot-long finned tube, 10 inches in diameter, mounted in a 16-inch-diameter shell

(3) Material of Construction

Monel

(4) Number Required

Two

Forced air is used as the coolant. Thirty 2-11/32-inch fins are welded to the outside wall of the condenser tube to enhance heat transfer. No fins are welded to the inside wall of the condenser tube.

26. Blowdown Reclaimer, AIV-616a. Purpose

To reclaim uranium hexafluoride and bromine pentafluoride from reboiler and vaporizer blowdown materials.

b. Design Bases(1) Operating Conditions

Temperature, °C	65 to 70
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Pressure, atmospheres	2.0 to 2.5
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Design Heat Load, Btu/hr	125,000
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(2) Dimensions

14 inches in diameter by 8 feet long

(3) Material of Construction

Monel

(4) Number Required

One

The design of this unit is the same as the bromine pentafluoride vaporizer, AIV-609.

FLUORINE RECYCLE AND PLUTONIUM HEXAFLUORIDE RECOVERY SYSTEMS1. Vent Sodium Fluoride Trap, AIV-310 (See Figure A-17)a. Purpose

To remove traces of plutonium hexafluoride and fission products from the fluorine recycle vent stream.

b. Design Bases(1) Operating Conditions

Temperature, °C	400
-----------------	-----

Pressure, atmospheres	2.0
-----------------------	-----

Gas Contact Time, seconds	> 50
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Cooling Air Supply (maximum), scfm	100
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(2) Capacity

91 kg

(3) Dimensions

12 inches outside diameter by 5 inches inside diameter by
5 feet high

(4) Material of Construction

Nickel

(5) Number Required

One

The design of this unit is the same as that used for the polishing sorber trap, AIV-302.

2. Fluorine Recycle Gas Compressor, AIV-505 (See Figure 9)a. Purpose

To recirculate the recycle fluorine back to the main fluid-bed reactor.

b. Design Bases(1) Operating Conditions

Suction Pressure, atmosphere	1
Discharge Pressure (maximum), atmospheres	2.4
Suction Temperature, °C	minus 100
Flow (gas), scfm	60

(2) Material of Construction

Pumping Head - nickel

Remainder - steel

(3) Number Required

One

This unit has the same general design as the bromine pentafluoride recycle compressor, AIV-504. Air is used in the interstage cooler.

3. Plutonium Hexafluoride Cold Trap, AIV-617 (See Figure A-20)

a. Purpose

To desublime the plutonium hexafluoride from the halogenator off-gas produced during fluorination with elemental fluorine. Subsequently, heat would be applied to empty the trap, and the plutonium hexafluoride would be purified.

b. Design Bases

(1) Operating Conditions

Plutonium Hexafluoride Desublimation Step	
Inlet Temperature, °C	100
Outlet Temperature, °C	minus 100
Temperature for Emptying the Trap, °C	100
Pressure, atmospheres	1.5

(2) Dimensions

6 inches in diameter by 6 feet long

(3) Material of Construction

Nickel

(4) Number Required

Sixteen

Internal finning is provided with the fins 4 feet long. Electrical heaters and coolant tubes are fastened to the outside of the trap shell. A 10-inch-diameter containment shell surrounds each trap and is continuously purged, and the purge gas is monitored for plutonium hexafluoride. Eight primary traps are arranged in a 2 by 4 array with a 20-inch center-to-center separating distance. Eight additional traps in a similar arrangement are provided as spares. Separate cold boxes are employed to house each array and its associated piping. A conceptual layout and piping scheme for a 3 by 4 array involving 4-inch-diameter cold traps is shown in figures A-21 and A-22. Layout dimensions for 4-, 6-, and 8-inch-diameter traps are tabulated in figure A-21.

PROCESS CRITIQUE

Major Technology Problems

The basic technology for the fluid-bed volatility reprocessing of nuclear power reactor fuels has been tested on a small scale at ANL with non-irradiated fuel material. Work was performed on a 2- and 3-inch-diameter reactor scales. Fluid-bed work has also been done at the ORGDP in a two-diameter reactor, 10 inches and 5 inches. Work performed at ORGDP included studies on the oxidation and hydrochlorination steps, as well as testing of typical components, such as compressors, filters, sorbent traps, connectors, and valves. BNL and ORNL have also engaged in fluoride volatility experimentation relative to low enrichment fuels.

It should be mentioned early that one of the main advantages of the volatility process is that relatively few processing steps are involved, and consequently, a small number of equipment items is needed. Accordingly, relatively small cell volumes are required. For example, the area and volume of process cells in the NFS plant are 7,460 square feet and 243,000 cubic feet, whereas only 2,740 square feet and 72,600 cubic feet are estimated for the present design. The NFS plant has about 115 notable equipment items, and the present plant has only about 65 notable items.

It is anticipated that some aspects of volatility processing, particularly those connected with reactor scale-up and the associated mechanical equipment, such as the valves, connectors, pumps, and solids transfer systems required for remote maintenance locations, cannot be evaluated adequately except on a scale approaching the full-plant size. At the time of the preparation of this report, there were many areas for which there was little test data available for design. The assumptions made regarding scale-up of various equipment items, operability, and potential process problems were based on the chemistry of the fluorides of uranium, plutonium, and the contaminants expected to be present, as well as knowledge of fluid-bed performance as applied to fluoride volatility systems. This process critique and, for that matter, the complete evaluation should be viewed with the above-described state of process development in mind and the realization that, while some of the potential problems discussed may be easily solved, other areas of difficulty may have gone unrecognized.

Fluoride volatility faces major technological problems with plutonium recovery and purification. To begin with, the compound of plutonium to be volatilized, plutonium hexafluoride, is chemically unstable at the temperatures that will be encountered in the process. Its decomposition is not rapid enough to undermine the process, but the formation of the decomposition product, plutonium tetrafluoride, in process equipment and lines will make accountability difficult. In addition, a satisfactory volatility method for the decontamination of the collected plutonium hexafluoride has not been established to date. In this regard, the

fission products, ruthenium and niobium, appear to be the most troublesome components. This difficulty should not render the process unfeasible, since aqueous purification using ion exchange, is possible.

The distribution of volatile fission products throughout the processing system may also introduce some difficulties. Calculations of their volatilities and estimation of their mobilities under process conditions give an indication of their distribution. There is no substitute, however, for actual pilot plant experience, since the unknowns in the chemistry of these elements and possible fluctuations in process conditions may result in unexpected and, quite likely, undesirable accumulations of radioactive materials in unplanned-for locations.

Two particularly volatile fission products, selenium and tellurium, are expected to be volatilized as relatively inert, noncondensable fluoride gases in the fluorination steps. Information on methods of removal of these fluorides from the fluorination off-gases is limited. Recent tests with activated alumina indicate that this sorbent can effectively remove tellurium. Low yields and the nuclear inactivity of the selenium permit a relaxation of concern for the fission product fate of this case. Additional work is required to develop a suitable chemical disposal system for these gases, particularly since consideration of ground accumulation rates and the possible proximity of the fuel reprocessing plant to populated areas could result in the need for stringent control.

Sorption is the principle mode of removal of the volatile fission products from the process gases. The major sorbent is sodium fluoride and effective removal of most of the volatile fission products will depend on its performance. Further investigation is required of such items as (a) the effect on sorbent life of the amount of fission products sorbed and of the heat generated by radioactivity; (b) the effect of sorbed impurities on uranium retention; (c) the degree of pellet degradation and/or lumping during reactor operation; and (d) the handling, sampling, and disposal of pellets.

The magnesium fluoride sorbent traps are used mainly for removal of technetium and neptunium. The fraction of the uranium charge which is trapped on magnesium fluoride during the bromine pentafluoride fluorination should be small, since these traps should have a relatively long life. It is interesting to note at this point that there is some interest in the recovery of neptunium and technetium. Neptunium-237 is a potentially valuable by-product for use as an irradiation target for the production of plutonium-238 which is one of the more desirable heat sources in isotopic power generation. Technetium has a promising future as an alloying agent for refractory powders. The estimated amounts of these materials in the fuel to be reprocessed over a year's period are 18.5 and 193 kg, respectively. Unfortunately, only about 70% of the neptunium and about 60% of the technetium charged are expected to be collected in the magnesium fluoride traps, since portions of these fission products are expected to be volatilized in the other process steps and lost if provisions for recovery are not made. For this study, it has been assumed

that none of the neptunium and technetium will be recovered in a salable form; therefore, no credits have been included in the cost estimate.

Major Operating and Design Problems

One of the major process operating difficulties which can occur is caking of the fluid beds. Caking of fluid beds is not unknown, particularly when low melting or easily sinterable elements or salts are present. Fluid-bed caking in fuels reprocessing plants would be particularly objectionable due to the extreme undesirability, if not impossibility, of manually rodding out a highly contaminated reactor. No troubles have been encountered as yet with caking of the alumina bed during the bench-scale hydrochlorination or fluorination of simulated uranium dioxide-zircaloy clad fuels. Nevertheless, it should be realized that a wide variety of fission product elements and their chlorides and fluorides will be present in plant operation during and after the volatilization of the zirconium from the bed. The effects of the retained elements and salts on the caking tendencies of the alumina bed have not yet been defined and should be examined in detail. In particular, caking difficulties might be expected to occur after a bed is allowed to settle in preparation for charging of additional modules.

In this connection, i.e., admission of fuel elements to the halogenator, design of the charging machine and the charging operation leaves considerable room for thought and ingenuity. In particular, positioning of the charge, load sensing, and process sealing arrangements are likely to be troublesome. For the preferred mode of operation, the charger lowers a bundle of elements onto the bed, the grapple is opened, releasing the elements, and is then withdrawn into the charger housing. The reactor is then isolated with buffered valves, and a flow of gas sufficient to expand the bed is supplied in cyclic fashion to allow the elements to sink gradually to the bottom. If this technique fails because the elements tend to cock and to hang up or because they drop too fast, it may be necessary to fluidize the bed while charging and then to lower the elements through the bed to the module support. While the latter approach is sure to result in greater dusting, in either case, sealing of the system from the crane bay or charging area and minimization of contamination spread during charging are bound to be significant problems.

Filter life and performance are also important factors in the operability of this plant, particularly with regard to the halogenator off-gas filters. Plugging of the sintered nickel filter elements in this position has been experienced at ORGDP during the hydrochlorination of zircaloy. The exact cause of plugging has not been determined, yet it is known that zirconium tetrachloride and hydrogen chloride are involved. Porous sintered filters made of stainless steel and Inconel have also plugged. If a suitable sintered metal filter material cannot be found, a separate off-gas filtering unit will be required for the chemical de-clad step. Since only

minor plugging occurs during the oxidation and fluorination steps, sintered nickel filter tubes could be used for filtering the reactor off-gases during these steps. Even during the fluorination steps, filter plugging or degradation may result from too rapid a reaction of the bromine pentafluoride or fluorine with reactive powders which have accumulated on the filter surfaces. Plugging of the filters in either instance would make it difficult to complete the hydrochlorination or fluorination of the reactor charge and would probably shut down the reactor line until the filter assembly could be replaced. Of course, the major problem, i.e., during hydrochlorination, could be circumvented if a successful mechanical decladder could be developed.

Another problem arises from the gradual accumulation in the reactor of nonreactive fuel element hardware, such as Inconel plenum springs and grid plates. The presence of these components in the fuel modules may dictate discharge of the reactor contents more often than would be otherwise necessary. A method of overcoming this may be to use a nonconsumable strainer-type basket which can be removed from the reactor after each complete cycle carrying the extraneous material with it, but contamination problems would be great if this were adopted. Hopefully, future fuel elements will tend toward all zircaloy hardware and thereby eliminate the problem.

Elutriation, particularly during the oxidation step, could cause problems in that fuel material is transferred out of the main fluid-bed reactor to the fluid-bed cooler and must be returned to the reactor bed for subsequent processing. The planned method of returning the elutriated material is by pneumatic transfer. Elutriation during the fluorination steps could also cause problems, since complete fluorination of the uranium and plutonium would be hindered if large fractions of the powders were elutriated to the fluid-bed cooler. Fluorination of the elutriated material might be difficult to accomplish or to control in the fluid-bed cooler; therefore, the powders might have to be returned to the main reactor bed.

Of course, elutriation would be an advantage in a two-vessel scheme where the hydrochlorination and oxidation are performed in the first vessel, while the fluorination steps are performed in the second. Here, the material elutriated during oxidation can be transferred directly to the second vessel for further processing. This possibility will be discussed further in a planned addendum to this report.

Caking problems may also be present in the pyrohydrolysis fluid bed. A number of fission products, as well as the tin in the zircaloy cladding, will volatilize during the hydrochlorination step and be deposited in the pyrohydrolyzer. The effect of these elements on bed fluidity is unknown and should be determined; furthermore, the effect of the presence of quantities of zirconium oxychloride (formed as a result of an insufficient excess of water vapor) on fluid-bed operation and subsequent handling steps should be defined.

The buildup of large amounts of fines and/or oversize particles in the pyrohydrolysis fluid bed will also affect operating conditions with this equipment. An increase in average particle size will increase the required minimum fluidizing velocity, while the generation of excessive quantities of fines will necessitate more frequent and harder blowback of the pyrohydrolysis filters. Both contingencies, carried to extremes, would require dumping and replacement of the bed, possibly at a frequency which is uneconomical because of increased downtime and solid waste storage volume requirements. Pyrohydrolyzer filter life must be evaluated over a fairly wide range of fluid-bed operating conditions.

Jumper design* is another potential problem area. A jumper must be designed to be removable by remote maintenance, and the connections must be leak tight.

With regard to materials of construction, the major area for improvement lies with the halogenator. It would be desirable to have a more chemically resistant material of construction for this reactor than nickel, since the limitation of 400°C for the wall temperature in the decladding step curbs the volatilization rate for the zirconium. Difficulty is also possible with the material of construction employed for the aqueous hydrogen chloride containing equipment in the hydrogen chloride recycle system. Hastelloy B is a suitable material of construction. Unfortunately, there is a possibility that fluoride deposited on the metal surfaces in the halogenator during the fluorination step may volatilize into the pyrohydrolysis unit and its associated aqueous hydrogen chloride equipment during a subsequent hydrochlorination step, thus aggravating the corrosion problem.

Use of a low temperature mechanical refrigeration, i.e., minus 100°C as in the hydrogen chloride recovery system, can introduce operational difficulties which could be complicated by radiation damage to the refrigerant. Alternative processes, such as scrubbing with aqueous hydrogen chloride and distillation of the resulting solution, are potentially feasible for the recovery of the hydrogen chloride; however, additional and more complex equipment would be required.

Special analytical instruments will be needed to monitor gas concentrations at several locations. During hydrochlorination, the recycle gases are analyzed continuously for hydrogen. The concentration of hydrogen can be determined using a thermal conductivity cell, perhaps after removal of hydrogen chloride by trapping and replacement with a constant reference flow of nitrogen. By measurement of the vent flow, sufficiently accurate estimates of the rate of hydrogen generation for monitoring the dissolution cycle should be feasible. The exit gases from the pyrohydrolyzer must be checked for percentage water to assure that a sufficient excess of water is present at all times. A boiling point analyzer

* The term, jumper, of course, refers to a prefabricated section of piping having remote connectors on both ends to connect process equipment to permanently installed nozzles.

or perhaps a liquid density measuring instrument might be used for this purpose. For the oxidation step, an oxygen analyzer could be used to monitor the progress of the oxidation. This has been done successfully at ORGDP during oxidation runs in the semiworks unit. Gas chromatographic techniques are probably the most effective means for resolving the gas compositions for the bromine pentafluoride fluorination step⁽¹⁰⁾; however, development work for an instrument of this type would be required. Fluoride analyzers based on the reaction between sulfur dioxide and fluorine to form sulfuryl fluoride should be satisfactory for the determination of reagent concentrations in the gases fed to the scrubber. Analysis of the product stream can probably be satisfactorily obtained by gas chromatography and/or a spectrochemical method. A neutron counter may be satisfactory to monitor the plutonium hexafluoride generation rate during the plutonium fluorination step.

Because of the activity level of the fuel and the uncertainties as to process difficulties and ease of equipment decontamination, remote maintenance was selected for all the process cells. The plant layout was made on the assumption that placing the hydrogen chloride recycle and uranium and plutonium product recovery cells alongside the reactor cell would result in a more economic arrangement than use of a long canyon.

Thus, for the building scheme shown, it is possible to use the overhead remote handling equipment in the hydrogen chloride recycle and the product recovery cells. There is a possibility that direct maintenance might be permissible in these two cells. Whether the building layout for a future scheme should be changed to allow direct maintenance in these areas is, of course, dependent on knowledge of the activity encountered with each operation and the ease of decontamination of the areas.

The lack of a suitable plutonium recovery and purification flow sheet is the single greatest obstacle to volatility process fruition. Obviously, there are no engineering data for large-scale equipment for this portion of the plant. On the other hand, a wealth of engineering data has come from ORGDP and ANL on other head-end reactor operations. Extensive work on component equipment has defined the design concepts which appear practical for plant compressors, valves, samplers, and connectors; nevertheless, more data are necessary for equipment in a continuous operation and for important process auxiliaries. Complications become evident when one analyzes the rigors associated with reactor operations and the demands on process auxiliaries, as well as problems related to material balance, criticality, etc. Indeed, engineering and design can be extremely difficult and challenging with regard to fuel charging systems; solids loading and discharge valves; conventional and unique in-line instrumentation; and a number of specialties, such as bed samplers and seals for radiochemical service in corrosive atmospheres at elevated (and cycling) temperatures. Finally, the interrelation between all components must be defined, since system integration poses special problems in process operation and control.

General Problems

It is planned that pneumatic transfer will be used to empty solids from fluid beds and possibly from the backup filters and sorbent traps. Sampling and at least semiquantitative analyses of solids are required before the material is conveyed to waste storage. For satisfactory performance of the plant waste transfer systems, it will be necessary to establish (a) reliability of the solids entrainer design, (b) durability and reliability of isolation valve systems, (c) the degree of separation of fine and coarse materials at the collection point, (d) required conveying velocities, and (e) the likelihood of sticking or plugging in the conveying pipe. Conveying of solids could, of course, be quite different if any lumps or cakes are in the conveyed powder or if the lines tend to plug for any reason.

A major advantage of the volatility process over an aqueous process lies in the smaller volume of waste generated. The fluid-bed volatility waste volumes, as estimated in this study, are from about 0.11 to 0.13 gallon of high level solid waste per kilogram of uranium. This may be compared with aqueous process waste volumes from about 0.34 to 0.63 gallon of high level aqueous slurry per kilogram of uranium. Since there are many unresolved ground rules and questions concerning the final disposition of volatility process wastes, the cost of disposing of the solid waste is uncertain. Before a true comparison of effects of waste volume on waste storage can be made, the most economic and satisfactory permanent waste storage methods for both the aqueous and volatility processes must be established.

In the volatility process, the absence of chemical elements which have good neutron moderating characteristics will probably permit larger quantities of fissile materials to be present in process equipment than are possible in aqueous reprocessing. Although the process and equipment have been reviewed from a criticality standpoint, additional study is undoubtedly needed in this area before a plant could be approved. Because of the large size proposed for some of the process equipment, such as the halogenators and the fluid-bed coolers, cooling with dry air has been employed extensively. Wet decontamination of the larger pieces of equipment could present substantial problems. Poisoning of the decontamination solutions would certainly be necessary; however, because in-cell maintenance would be remote, decontamination need not be so extensive as would otherwise be required.

Mass control appears to be the only mode of criticality prevention if practical equipment sizes are to be used for the halogenator and filters; however, geometry control is used for most of the remaining equipment items. Plutonium is the crucial fissile element, since uranium enrichments of less than about 5% uranium-235 present no criticality problems in dry systems. Accurate accountability of the plutonium inventory in individual pieces of equipment containing heterogeneous mixtures of solids is difficult, and thereby, the criticality control problem is aggravated. The amount of plutonium allowed in the process equipment will depend not

only on the plutonium density but also on the accuracy of the accountability procedure used. The plutonium criticality problem becomes more acute for higher throughput plants, since the same plutonium mass limit will be imposed on the process but greater plutonium inventories will be present in the equipment. If other criticality control methods, such as neutron poisoning, can be used effectively, the plutonium criticality problem may be alleviated.

GENERAL FACILITIES

Site Arrangement

One of the ground rules for this study was that the conceptual plant should be an independent facility. It was consequently necessary to size auxiliary areas and buildings, as well as the main processing building, to permit the estimation of capital costs for the facility.

The general site arrangement is outlined in the plant plot plan, figure A-12. This drawing shows site improvements, including the relative positions of the following auxiliaries: (1) the waste storage areas and burial grounds; (2) the off-gas filters and stacks; (3) the utility building; (4) the warehouse; and (5) miscellaneous items, such as the water supply station, the sewage disposal plant, and the main guard station.

The plant location itself was taken to be favorable with respect to meteorology, geology, and general terrain. In addition, the plant was assumed to have easy access to utilities and transportation facilities, but to be located in a sufficiently isolated position so that undue difficulty with disposal of gaseous and liquid wastes would not accrue. The following simplifying assumptions were made: (1) a river with sufficient water flow is located on the site, (2) 13.8 kv electric service and public telephone service are available, (3) railroad service can be obtained, (4) the terrain is essentially level with 8 feet of earth overburden on limestone to a depth of 30 feet, and (5) the nearest public highway is about 2 miles from the plant gate.

Fuel Receipt, Storage, and Handling

The fuel receiving and storage facility is located in the main process building and consists of four general areas, as shown in figures A-10 and A-11. These areas are serviced by a 100-ton bridge crane.

The first area, the receiving station, is an open area near the end of of the fuel storage pool and contains a railroad spur and truck entry. This area is equipped with steam and detergent wash nozzles and clean water rinsing nozzles for the removal of external dirt and any external radioactivity present as a result of a shipping cask leak. To contain the contamination washed from the cask, the wash water is held in a sump prior to transfer to the aqueous waste treatment area for disposal. After washdown, the clean fuel cask is transferred to the cask unloading pool.

The cask unloading pool is approximately 25 feet square and 62 feet deep. In this pool, the cask lid is removed, and the fuel modules are extracted from the cask and are placed in storage baskets for transfer to the storage pool. A minimum shielding thickness of 11 feet of water is

maintained above the fuel elements during all transfer operations. Fuel elements are transferred from the cask to the storage baskets using a 5-ton hoist, equipped with grapples, which travels on the same bridge as the 100-ton cask unloading crane. Viewing devices are installed in this area to allow inspection of the fuel elements. Ruptured fuel elements are sealed in special containers to prevent contamination of the storage pool water, and these containers, when used, are leak tested before storing with nonleaking elements.

The fuel elements in their storage baskets, are then transferred to storage racks in the third area, the fuel storage pool, using a 20-ton traveling bridge crane. The storage pool is 28.5 feet deep with about 2,400 square feet of storage area. Entry to the storage pool from the cask unloading pool is through a gasketed removable gate, which is used to separate the two areas and to confine contamination to the cask unloading pool in the event a ruptured fuel element is received.

The unloaded cask is transferred to the fourth area, the cask decontamination pit and storage area, for removal of internal radioactivity, if present, and for inspection prior to return or storage. Any necessary maintenance on the cask is carried out after decontamination and while in storage.

When ready to be processed, the fuel elements, in their storage baskets, are removed from the storage racks and transferred to the fuel drying and handling cell using an underwater conveyor. In the fuel drying and handling cell, the fuel elements are dried by circulating air, and after drying, the metal end pieces are removed by sawing. The number of elements required for a reactor charge is then loaded into a consumable skeleton rack and held in position, using aluminum or zirconium metal straps. After a lifting bail is installed, the reactor charge is ready for transfer to the fuel charger.

Process Building

The process building contains, in addition to the process and the fuel handling cells, areas designated for administration and maintenance, a laboratory, a control room, decontamination and hot shop, change rooms, a chemical makeup facility, air conditioning and ventilation facilities, electrical load centers, crane bay, and various access corridors.

Table VIII presents floor area and cubage statistics. The building floor plan and elevation are shown in figures A-10 and A-11, respectively. Ordinarily, a considerable number of trial building layouts is required before an acceptable plan on which to base the actual construction design is achieved. It is not asserted that the plans presented in this section have reached such a degree of sophistication, although a significant amount of thought and engineering effort has gone into this phase of the evaluation. Although the layout problems are not completely solved, the drawings give a substantial idea of how the process building might look.

TABLE VIII
FLOOR AREAS AND CUBAGES FOR PROCESS BUILDING

Item	Area, sq ft	Volume, cu ft
Administration Area	4,270	51,300
Air Conditioning and Ventilation	2,110	27,300
Change and Rest Rooms	3,150	38,100
Chemical Makeup and Storage	2,790	39,100
Control Room	1,430	25,700
Corridors	1,750	22,100
Crane Bay	4,250	127,500
Crane Maintenance and Storage	630	17,200
Decontamination and Warm Shop	1,930	92,100
Electrical	1,250	15,000
Equipment Aisles	2,030	28,400
Fuel Receipt and Storage	8,770	339,200
Instrument Racks	1,430	15,700
Laboratory	5,070	72,900
Maintenance	1,910	26,700
Process Cells	2,650	76,300
Product Handling and Packaging	<u>1,060</u>	<u>14,800</u>
TOTAL	46,480	1,029,400

ADMINISTRATION

The administration area has been included as an integral part of the process building and is allotted 4,270 square feet of area. In addition to offices for supervisory and clerical personnel, space is included for a dispensary, a lunch room, and guard and fire headquarters.

PROCESS CELLS - LAYOUT AND MAINTENANCE

The process building floor plans and sections give the sizes and locations of the process cells relative to other process building areas. All the process cells, the fuel entry cell, and the sampling cells are arranged so that a single maintenance crane, equipped with manipulators and a hoist, can service them. A second maintenance crane is installed as a spare. Each crane is provided with manipulator equipment. As mentioned previously, a track-mounted manipulator is provided in the deep central cells. Viewing in the process cells is by television; however, viewing windows are provided for the fuel drying and handling cell, the plutonium hexafluoride purification cell, and the sampling cells.

An intercell conveyor system connects the plutonium hexafluoride purification, fuel drying and handling, and sample cells to the decontamination area and laboratory. This system enables plutonium product, small equipment, waste fuel element hardware, or samples to be removed from their respective cells for shipment, disposal, or analysis, as required.

The estimated concrete thickness required for shielding is 66 inches for the equipment located in the head-end cell and the fuel drying and handling cell. These areas require more shielding than any other in the plant. In this design, 72 inches of concrete has been provided between personnel areas and both the head-end cell and the cell for fuel drying and handling.

If defective equipment in the head end, bromine pentafluoride recycle and uranium hexafluoride purification, or the scrubber cells is to be removed, the vessel will be emptied and flushed for rough decontamination before being disconnected and taken to the decontamination area by the track-mounted manipulator. Equipment in all other cells can be removed by the overhead crane through cell hatches located in the crane bay floor. The outside of the equipment to be buried is cleaned in the decontamination cell by a dry process, such as sand blasting, before being placed in a cask and being removed from the canyon. A railroad spur is provided in the decontamination area of the canyon for removal of shielded uncontaminated equipment for burial. Aqueous decontamination facilities are also available in the decontamination cell for small items, such as valves, pump heads, and instruments.

Cell areas and volumes are listed in table XI. Process equipment containing liquid bromine pentafluoride, aqueous and anhydrous hydrogen chloride, aqueous scrubber solutions, and plutonium have been placed in

separate cells to isolate liquid bromine pentafluoride, to restrict water from the vicinity of large quantities of fissile uranium and plutonium and to provide secondary containment of the alpha emitting plutonium. Partitioning of the process area also facilitates control of cell ventilation.

TABLE IX
PROCESS CELL AREAS AND VOLUMES

Item	Area, sq ft	Volume, cu ft
Head End	396	15,840
Hydrogen Chloride Recycle	320	5,760
Bromine Pentafluoride Recycle and Uranium Hexafluoride Collection	495	21,610
Fluorine Recycle and Plutonium Hexafluoride Collection	281	5,050
Uranium Hexafluoride Product Handling	176	3,170
Plutonium Hexafluoride Purification and Product Handling	180	3,240
Fuel Drying and Handling	204	3,670
Scrubber	305	12,670
Sampling Cubicles	160	2,880
Recirculating Cooling Air	132	2,380
TOTAL	2,649	76,270

CONTROL ROOM

A single control room is provided in the process building so that the process monitoring functions can be centralized. Process instrumentation readings are displayed on a graphic panelboard; remote valving, temperatures, and flows are controlled from this location. The central control room is thus the heart of the process operation. Corrective action for all process upsets and emergencies is taken from the control room, since it is the center of communication by radio or telephone to all other

locations in the plant. Also, maintenance television viewing equipment and a data logger will be installed here. The control room occupies 1,430 square feet of building area and has a volume of 25,700 cubic feet.

DECONTAMINATION AND MAINTENANCE

Both cold and warm maintenance areas and a decontamination site are included in the process building. In the latter area, sufficient additional decontamination of small equipment items, such as valves, connectors, and pumps, is undertaken so that this equipment can be repaired in the adjacent warm shop. The decontamination and warm shop areas occupy 1,930 square feet and 92,100 cubic feet, and are located convenient to the crane maintenance area.

Crane maintenance is performed above the decontamination and warm shop. This area is separated from the crane bay by a steel door. Heavy shielding is provided in the plugs of the process cells to prevent direct radiation exposure on workers while crane repairs are performed. Crane maintenance space allocated is 630 square feet.

A field maintenance shop, totaling 1,910 square feet and 26,700 cubic feet, is employed for local, relatively minor repairs to equipment from the cold portions of the plant. In addition to field maintenance, testing and calibration are performed on the various instruments used in the plant. A larger, more complete, maintenance area is provided in a nearby utilities building, where fabrication of replacement parts is accomplished, and more extensive repairs are made. A standard assortment of maintenance equipment would be installed in the shops. Repair of large, heavily contaminated equipment, such as the fluid-bed reactors, is considered uneconomical, and accordingly, no provision has been made for this type of work.

EQUIPMENT AISLES

Equipment aisles are located on the northern and western sides of the canyon. Refrigeration units for the different condensers and cold traps are located in these aisles. Four refrigeration systems are provided covering a temperature range from minus 15°C to minus 180°C. The systems are shown in figure A-23, which also gives the tonnage of each system and illustrates the equipment items requiring substantial refrigeration. In addition to the refrigeration units, miscellaneous auxiliary equipment is located in the equipment aisles. Also, sufficient floor space is available for spare equipment storage. There is approximately 2,030 square feet of floor space in this area.

CHEMICAL MAKEUP

The chemical makeup area is used mainly for supplying caustic to scrubbers; however, provisions are also made for preparing solutions for the warm shop decontamination tanks. The area and cubage allocated for chemical makeup and storage are 2,790 square feet and 39,100 cubic feet.

LABORATORY

The laboratory contains four analytical cells, each equipped with manipulators, related tools, and with three feet of shielding. Two sample cells, containing transfer devices, are provided in an adjacent sample corridor. Direct access through double doors to the outside is provided to simplify the transfer of large laboratory equipment.

The laboratory is equipped with such standard items as hoods and work benches for general analytical work and with specialized tools for such jobs as emission spectrometry, assay determination, and counting. A limited amount of metallurgical examination equipment may also be included. Some desk space is available in the laboratory. The laboratory floor area is 5,070 square feet and its volume is 72,900 cubic feet.

CHANGE AND REST ROOMS

A central change room and miscellaneous smaller clothing exchanges are located throughout the building, as required, for male personnel. Rest rooms for both sexes are located adjacent to the control room in the administration area. Change and rest rooms occupy a total of 3,150 square feet and 38,100 cubic feet.

VENTILATION

Space is included in the building for the ventilation and air conditioning equipment. The administration area, laboratory, and control room are air conditioned. Area air pressures are controlled so that the ventilation flows from the radioactively colder areas to progressively higher level process cells. The floor area and volume allotted for the ventilation equipment are 2,110 square feet and 27,300 cubic feet, respectively.

MISCELLANEOUS

The process building is provided with two electric power substations adjacent to the building. At these points, the 3-phase, 13.8 kv inlet power is reduced to 480 volts, 3-phase. Building distribution lines connect to the supply through the switchgear in the building electrical center and the load is further subdivided to the individual circuits in the electrical control center. An auxiliary power generator is provided to supply emergency ventilation and lighting requirements.

A recirculating cooling air system is provided for removal of heat from numerous equipment items. This system consists of a blower and a radiator type gas cooler along with ducts for directing air to and from the equipment items. A flow diagram for the cooling air, giving flow requirements and the equipment involved, is presented in figure A-23. A spare blower and heat exchanger system are provided.

Off-Gas Handling

The cell ventilation off-gas is filtered through both roughing and absolute filters prior to discharging to the stack. Process waste gases are also routed to the stack after being scrubbed and filtered. An emergency auxiliary blower system is provided, and the stack is equipped with a radiation monitoring system. Details of the ventilation routes are shown graphically in figure A-6.

Smoke detectors are employed in all off-gas ducts to detect releases of uranium hexafluoride or other smoke-forming compounds. Since excessive amounts of bromine pentafluoride and fluorine could cause rapid filter deterioration, the cell exhaust ventilation would automatically be directed to two-cell off-gas scrubbers in series if these chemicals are detected.

The height and flow requirements for the stack were based on the attainment of satisfactory atmospheric dilution factors*. The following assumptions were made:

1. Wind velocity is 3 miles per hour.
2. Vent quantities could be averaged over 24-hour periods, although the actual rate of venting at any particular time would be dependent on the portion of the processing cycle being performed in the process equipment.
3. Radiation control guide values were based on MPC values for a 168-hour-per-week industrial exposure.

The first assumption is conservative in that wind velocities at the top of the stack will usually be higher than 3 miles per hour in most locations. The second assumption is not conservative, since peak venting rates might be several times the average. The third assumption is conservative as far as plant personnel exposure is concerned; however, this is not so for the general public, since radiation control guide values

* Atmospheric dilution factor is defined as the downwind ground concentration divided by the unit emission rate. The maximum average value is that which will occur over periods on the order of 1 hour at the "optimum" distance downwind from the stack⁽²⁾.

for this portion of the population should probably be set at about 10% of the MPC values⁽¹²⁾.

It was also assumed in establishing required dilution factors that the wind is unidirectional. Whether any credit can be taken for dispersal of the vented material over the points of the compass is, of course, dependent on the site meteorological conditions.

The conceptual design of the stacking system for the volatility plants represents satisfaction of minimal requirements. Proper evaluation of both the air contamination and fallout problems requires establishment of meteorological and other local conditions, as well as the maximum hourly discharge rates.

Assuming tellurium removal during scrubbing and in activated alumina traps, the concentration of krypton-85 in the process vent gas determines the size of the stack. Tellurium has been a troublesome fission product in stack gases from volatility processes in the past; however, removal of most of this element by scrubbing and sorption on activated alumina prior to venting appears feasible now and thereby probably eliminates the tellurium stacking problem. The atmospheric dilution factor for disposal of the krypton is approximately 5.6×10^{-5} . A 400-foot stack with a minimum flow of 60,000 cfm and a velocity of 3,000 feet per minute was selected. The calculated atmospheric dilution factor for this stack is 6.2×10^{-6} , which is better than required. It is quite possible that regulations in effect at many plant locations would necessitate provision of a krypton detention system so that venting could be stopped under adverse atmospheric conditions, such as inversion, without shutting down the operation. Such a system might involve selective sorption in a liquid, such as chilled refrigerant-12, or charcoal. There was no provision made for this type of facility in the conceptual plant.

Waste Storage Requirements

A summary of the size of major solid and liquid waste streams generated during plant operation is given in table X. A discussion of the waste streams and the storage of solid and liquid wastes from the process viewpoint was presented in the section dealing with general process chemistry in the Process Technology chapter. The process liquid wastes are of a low activity level and contain almost none of the troublesome materials, except for iodine and perhaps some tellurium. This situation, coupled with the small volume involved, makes the handling of the aqueous wastes a relatively minor radiological problem. Furthermore, the disposal method chosen for these wastes, namely, tank storage, has been proved satisfactory in operating experiences at Savannah River and at Hanford.

TABLE X
GENERATION RATES OF MAJOR WASTE STREAMS

	Solid Waste		Liquid Waste	
	cu ft/kg U	cu ft/5 yr	gal/kg U	gal/5 yr
Bed Material	0.016	24,000	-	-
Scrubber Solutions	-	-	0.0133	20,000
Allowance for Laboratory, Decontamination, and Miscellaneous Wastes	<u>0.001</u>	<u>2,000</u>	<u>0.0013</u>	<u>2,000</u>
TOTAL	0.017	26,000	0.0146	22,000

Compared with the volume of high level liquid waste generated in aqueous processing, the volume of high level solid waste produced in this plant is quite low. The solids storage scheme proposed here involves the use of underground annular storage bins similar to those shown in figure A-24. This concept is based on the disposal techniques demonstrated at the waste calciner facility at the Idaho Chemical Processing Plant. Accordingly, the total high level waste storage cost, considering both operations and initial investment, is lower for the volatility plant than that for the aqueous plant, even though the cost per unit volume of high level waste is substantially higher. These costs are discussed in more detail in the chapters that follow.

The many unresolved ground rules and questions concerning the final disposition of volatility process wastes must eventually be settled. For one thing, it must be decided whether the solid must be held in a non-leachable matrix. Fission product and contaminant fluoride dusts are only deposited on or comingled with the fused alumina; therefore the radioactivity could potentially be leached or sluiced from the alumina, particularly if ground water were to enter a vault during storage.

The proposed scheme for permanent waste storage is to allow several years decay, after which the volumetric heat release rate would be reduced to a level such that the bin vaults could then be filled with cement for permanent storage. At this point, the bins would require only limited surveillance, since the heat rate is sufficiently low to allow dissipation to the ground⁽³⁶⁾. If future experiences indicate that bin type storage is unsatisfactory for permanent waste disposal, repackaging or relocation of the bin contents could be made. Since retrieval of solids from the bins for storage in small containers may be difficult, as well as expensive, interim storage of solids in water-filled canals with subsequent shipping to a salt mine for permanent disposal may be more economical⁽⁴⁾.

For the purposes of the present study, bin type storage appeared satisfactory and feasible for long-term disposal. If the wastes are retained in the bins, some forced air convection through the cooling passages would be required for a short period of time, after which natural convection would sufficiently remove the fission product heat. Cost for perpetual care using bin type storage has been included in the cost estimate as an operating cost.

The process also generates some sorbent trap wastes. The sorbent traps in the fluorination recycle systems may pick up sufficient activity so that burial of the contents would be undesirable, and the material would be transferred to bin storage. Of course, the process would generate miscellaneous solid wastes, such as clean-up materials and the hardware cut from the as-received fuel before chemical processing. The metal sawdust from the cutting operation is burned, and the ash, along with the other wastes, will be drummed and interred in the burial ground.

The plot plan, figure A-12, shows the locations of the aqueous waste tank farm, the burial ground, and solids waste storage building relative to the other plant areas. The aqueous wastes are stored in three 60,000-gallon capacity stainless steel tanks, of which one is a spare. The necessary instrumentation and auxiliary equipment items are provided here.

Auxiliary Buildings

MAINTENANCE AND UTILITY

This building houses the steam, dry air, and fluorine plants, a maintenance area, and an additional dry chemical storage area. The required building area is about 23,000 square feet. The required chemical storage tanks are located adjacent to the utility building.

Steam Plant

The steam plant consists of two, packaged, 300 hp, boiler systems. One is sufficient for normal operations, including heating. The second is provided as a spare. Fuel oil storage tanks are located nearby. Operation of the steam plant is centered in the utility building.

Dry Air Plant

The air plant consists of two, packaged, 1,100 scfm, compressor-dryer systems. Again, one is sufficient for normal operations, and the second is a spare.

Fluorine Plant

The fluorine plant is equipped for production, purification, compression, and storage of fluorine and for electrolyte makeup and fluorine cell maintenance. The process requires 1,200 pounds of fluorine per day.

Maintenance

About 7,500 square feet of maintenance area is provided in the utilities building for fabrication of replacement parts and repairs to equipment from the cold portions of the plant.

Miscellaneous Chemical and Utility Supply

The center of operations for the liquid and gaseous chemical supplies for the plant is the utility building. Permanent storage tanks are located adjacent to the building, and gas supply manifolds and vaporization stations are located inside or on roofed pads immediately adjacent to the building. Items stored at this point include 70,000 gallons of fuel oil, 25,000 gallons of liquid hydrogen fluoride, 15,000 gallons of potassium hydroxide (greater than 15%), and liquid nitrogen equivalent to 200,000 scf.

WAREHOUSE

The warehouse building includes storage space for equipment and spare parts, laboratory supplies, and materials other than chemicals. The size of the warehouse is 8,000 square feet.

MISCELLANEOUS

Other areas include the water pumping station, water filtration and treatment, sewage disposal, and main gate guard station. Also included in plant facilities are the plant roads, parking lots, rail spurs, and security fencing.

The water pumping and filtration stations were sized on the basis of a plant load of 200,000 gallons per day. A 100,000-gallon capacity water storage tank is provided for fire protection and emergency use.

SAFETY

Criticality Control

Dimensional, mass, and administrative control have been used in the conceptual plant design to ensure nuclear safety. Dimensionally safe equipment is employed where the use of such equipment does not interfere with the operability of the systems, and mass control, along with the judicious application of administrative control, is used for equipment with larger than the minimum critical nuclear dimensions. Administrative control for safety is a proven concept, with a precedent in normal manufacturing plants, as well as in existing nuclear fuel handling facilities.

The process building is planned so that, if a nuclear incident does occur, all of the radioactive material in the process or associated with the incident will be contained within the processing cells and the associated ventilation equipment. Furthermore, the walls of the cell area are of sufficient thickness that serious injury or radiation exposure to personnel is unlikely even in the event of a criticality incident.

Criticality calculations⁽³⁴⁾ were made to explore in detail the design problems associated with various plant equipment items. The generally conservative assumption that equipment was fully water reflected* was employed for all calculations except in the case of the plutonium hexafluoride cold traps. Remotely possible hazards were studied. In addition, it was assumed that all plutonium was present as plutonium-239.

Vessel interaction was not considered in detail in the study, except for the plutonium hexafluoride cold traps where a procedure outlined by the Nuclear Safety Guide⁽²²⁾ was applied. The vessel spacing required for piping should impose sufficient limits on interaction in most circumstances. Additionally, mass limitations were applied to the processing system such that, if all of the charge were in a single vessel, criticality would not result.

One halogenation reactor charge will consist of 1,500 kg of fuel, containing approximately 12 kg of plutonium and 1,300 kg of uranium. The uranium-235 assay is not expected to exceed 5%, even for fuels that have not been irradiated. Thus, to be conservative, the criticality calculations for the uranium systems were made assuming 5% enrichment.

* Actually, materials such as alumina, magnesium, and nickel, can be more effective reflectors than water if their thickness is great enough. An alumina reflector was assumed for some plutonium systems due to the small amount of plutonium and large amount of alumina present.

Calculations have shown that the infinite neutron multiplication factors for homogeneous mixtures of uranium dioxide and alumina do not exceed unity for uranium-235 assays up to 5%, provided no water is present in the mixture. Therefore, it can be assumed that these mixtures are safe from a nuclear standpoint for the geometries encountered in the plant. On the other hand, the infinite multiplication factors for homogeneous mixtures of uranium dioxide and water do exceed unity, and therefore, these systems can maintain a nuclear chain reaction under certain conditions. For example, the minimum critical radius of an infinitely long cylinder of uranium dioxide and water is approximately 5.05 inches, assuming the uranium dioxide density is 10.9 g/cc, the uranium-235 assay is 5%, and the cylinder is reflected with 12 inches of water. Corresponding calculations for spheres at the same uranium dioxide density, assay, and reflection indicate that the minimum critical mass of uranium is approximately 37 kg at a sphere radius of approximately 11 inches.

The calculated critical dimensions for plutonium dioxide systems are highly dependent on the plutonium dioxide density. For uranium dioxide pellet fuels, it is expected that the plutonium will be fairly uniformly dispersed within the pellets. Since the amount of plutonium processed per charge constitutes only a small fraction of the total charge (approximately 1%), its density will be relatively low as long as it is contained in the pellet matrix. Even after the pellets are pulverized at the oxidation step, it is likely that the plutonium will remain dispersed in the uranium oxide-alumina mixture and, thus, will be present at low densities*. To be conservative, criticality calculations were made assuming that the plutonium would segregate and that all plutonium was present as plutonium-239. In addition, it was assumed that the plutonium was surrounded by a 12-inch alumina reflector†. The calculated critical dimensions for plutonium dioxide systems are shown in table XI for various plutonium dioxide densities. Although several densities are shown, it is anticipated that the maximum attainable in situ would be analogous to that of powdered uranium oxides, i.e., about 3.2 grams total uranium per cubic centimeter. Of course, uranium dioxide fuel pellets are intentionally fabricated to higher densities; however, as indicated previously, plutonium will be dispersed in the pellets and, thus, should be at a much lower density than the uranium pellets.

* The chance of plutonium segregation would be greatest after the uranium is removed by selective fluorination at the bromine pentafluoride step.

† Alumina is a better reflector than water at large reflector thicknesses. Due to the small amount of plutonium concerned, a 12-inch reflector of alumina is conceivable.

TABLE XI

CRITICAL DIMENSION OF PLUTONIUM DIOXIDE SYSTEMS*

Plutonium Dioxide Density, g/cc	Critical Radius of Infinite Cylinders, inches	Critical Mass of Spheres, kg plutonium
4.5	2.64	33.02
4.0	2.87	37.75
3.5	3.17	43.90
3.0	3.55	52.08
2.5	4.06	63.65

* All plutonium was assumed to be plutonium-239 with a 12-inch reflector of alumina at a density of 2.5 g/cc.

The uranium and plutonium criticality calculations for the main fluid-bed reactor were based on the oxide salt. The reactor processes several fuel assemblies simultaneously; to meet throughput requirements economically, this requires that the reactor be much larger than the minimum critical dimensions for uranium dioxide-water systems or for plutonium dioxide systems. A geometrically safe diameter is consequently impractical for this vessel, and a mass limit must be used for criticality control. In addition, the minimum critical mass for uranium dioxide-water systems is much smaller than the desired uranium dioxide charge of approximately 1,500 kg. Therefore, water is excluded from the cells containing uranium or plutonium, and the principal cooling medium is dry air. As indicated previously, homogeneous uranium dioxide-alumina systems are inherently safe provided no water is present, since the infinite multiplication factors are below 1.0 at the uranium-235 assays anticipated. Thus, only plutonium mass control is necessary to maintain nuclearly safe operations in the larger equipment items. Based on the conservative assumptions that all plutonium is plutonium-239, that plutonium dioxide segregates into spheres reflected with 12 inches of alumina, and that the plutonium dioxide is present at a density of 4 g/cc, the computed critical mass of plutonium is about 40 kg, a factor of three greater than the amount of plutonium contained in one charge.

The analysis of the pyrohydrolysis fluid-bed reactor follows the same logic as for the main fluid-bed reactor if the absence of water moderation is assured. The accumulation of liquid water in the bed is prevented

by maintaining the temperature of the reactor well above the 109°C condensation point of the hydrogen chloride-water azeotrope. Additionally, it is extremely unlikely that any uranium or plutonium will reach the pyrohydrolysis reactor, since backup banks of tubular sintered metal filter elements are provided to remove from the gas stream any particles carried out of the primary fluid-bed reactor.

Furthermore, buffered, double-valve arrangements* are employed to isolate the hydrochlorination gas recycle system from the fluorination gas recycle system, thus preventing the transfer of volatile uranium or plutonium to the pyrohydrolysis reactor during the fluorination steps.

If uranium or plutonium does get to the pyrohydrolysis fluid bed, it will be as a vapor which will be hydrolyzed by the water vapor in the same manner as the other metal chlorides and will be removed from the gas stream by entrapment in the bed or on the overhead filters. Thus, it is virtually impossible for fissile material to get to the hydrogen chloride recycle or ventilation systems. Accordingly, these systems are not discussed here, although the point should be made that the equipment items are relatively small, and changes in geometry or the introduction of fixed poisons would be relatively straightforward if further study shows the need.

At the uranium fluorination step with bromine pentafluoride, the processing equipment on-line will include uranium hexafluoride cold traps and purification stills; bromine pentafluoride accumulators, vaporizer, and regenerator; and sodium fluoride and activated alumina sorbent traps. No plutonium will be volatilized at this step; thus, the nuclear safety analysis of this system is concerned only with uranium hexafluoride and the hydrogen fluoride which may be present as an impurity in the fluorine used to regenerate the bromine pentafluoride. While not expected to accumulate in large concentrations, hydrogen fluoride can pose a problem due to the neutron moderating capabilities of hydrogen. The presence of bromine pentafluoride, bromine trifluoride, and bromine, along with the fission products, was not considered. This results in a conservative situation, since all of these compounds are poorer moderators than hydrogen fluorine and have relatively large absorption cross sections.

Criticality calculations were made for the sodium fluoride sorber traps assuming the formation of a uranium hexafluoride-sodium fluoride complex ($\text{UF}_6 \cdot 2\text{NaF}$) and a hydrogen fluoride-sodium fluoride complex ($\text{HF} \cdot \text{NaF}$). Although it is expected that hydrogen fluoride will be present only in small quantities, a wide range of concentrations was reviewed in order

* This type of isolation is considered to be, at worst, a double contingency system, since (1) both valves must leak, (2) the buffer pressure must drop below the process pressure, and (3) the instrumentation which functions to shut down the operation automatically must fail before a violation of the containment can occur.

to cover the optimum hydrogen-to-uranium moderating ratios. Calculations based on a uranium density in its complex of 2.5 g/cc*, a hydrogen density in its complex of 0.035 g/cc*, a uranium-235 enrichment of 5%, and a 12-inch water reflector, indicate that the minimum radius for an infinitely long cylinder having an effective neutron multiplication factor of 0.9 is approximately 11.6 inches. The minimum radius occurs at a $\text{UF}_6 \cdot 2\text{NaF}$ concentration of about 40 volume percent in a homogeneous mixture with sodium bifluoride. The minimum critical radius ($k_{\text{eff}} = 1.0$) is approximately 15.5 inches and occurs at a $\text{UF}_6 \cdot 2\text{NaF}$ concentration of about 35 volume percent. Based on these calculations, the sodium fluoride sorber traps are geometrically safe for uranium, since the largest trap employed is annular with a 12-inch outside diameter and a 5-inch inside diameter.

In the criticality analysis for the remaining equipment items on line during the bromine pentafluoride step, the presence of hydrogen fluoride is assumed, and the neutron absorbing effects of bromine, bromine trifluoride, and bromine pentafluoride are neglected. Of course, some vessels, such as the stills, would be expected to contain almost no hydrogen fluoride. In addition, the uranium density in some vessels will be less than in others. To be conservative, all vessels were restricted to the analysis of the case where the theoretical uranium hexafluoride density is achieved and the hydrogen-to-uranium moderating ratio is optimum.

Calculations indicated that, for effective neutron multiplication factors of 0.9 and 1.0, the minimum radii are about 7.93 and 10.1 inches, respectively, for infinite cylinders containing uranium hexafluoride-hydrogen fluoride mixtures. The uranium hexafluoride and hydrogen fluoride densities were assumed to be 5.0 and 1.0 g/cc, respectively, and a 12-inch water reflector was assumed. Based on these calculations and in light of the conservative nature of the assumptions employed, diameters up to about 18 inches should be safe for most of the equipment under consideration, i.e., bromine pentafluoride regenerator, holdup tanks and vaporizer, uranium hexafluoride stills, and cold traps. It may be necessary to introduce fixed neutron absorbers in the reboilers of the uranium hexafluoride stills to allow larger diameters. The use of neutron absorbers has precedence in existing fissile material handling equipment and is considered routine in many installations.

Calculations for the plutonium hexafluoride cold traps were made by taking advantage of the neutron absorbing effect of the trap walls and of the insulating material surrounding the traps. The insulating material was assumed to be a Fiberglas reinforced basic phenolic foam⁽¹³⁾ which contains a significant amount of boron, a good neutron absorber. Preliminary calculations for infinite cylinders of plutonium hexafluoride-hydrogen fluoride mixtures indicated that the minimum critical radius

* The uranium and hydrogen densities in the complexes are consistent with the experimentally determined densities of $\text{UF}_6 \cdot 2\text{NaF}$ and $\text{HF} \cdot \text{NaF}$ of 4.13 and 2.16 g/cc, respectively.

occurred at a plutonium hexafluoride concentration of 100%; i.e., for no hydrogen fluoride present. Therefore, calculations were made for pure plutonium hexafluoride. Calculations indicate that the effective neutron multiplication factor is about 0.87 for infinitely long 8-inch schedule-40 nickel pipes filled with plutonium hexafluoride at a density of 5 g/cc when reflected by the pipe wall, 3.9 inches of reinforced phenolic foam, and 12 inches of water. The effective multiplication factor for an unreflected cylinder of the same dimensions is about 0.73. Six-inch diameter cold traps were used in this study; however, based on the above calculations, the use of 8-inch-diameter plutonium hexafluoride cold traps reflected with the phenolic foam could have been safely employed.

Effective neutron multiplication factors were calculated for the sorber traps in which plutonium could be present. The plutonium was assumed to complex with sodium fluoride sorbent to form $\text{PuF}_4 \cdot \text{NaF}$ and to result in a plutonium density of 4.3 g/cc in this compound. The sorber traps are annular, 12 inches in outside diameter by 5 inches in inside diameter. The results of these calculations indicated that the effective neutron multiplication factors for the traps are greater than 1.0. Thus, if the assumptions under which these calculations were performed are valid, it will be necessary to use neutron absorbers and/or to change the geometry to ensure nuclear safety in this vessel. Although no further calculations were made, it appears reasonable to assume that a safe sorber design can be achieved since geometry changes would be straightforward and, as noted previously, the use of neutron absorbers should present no problem.

In normal operation, more than 99% of the uranium and plutonium will be cold trapped, and venting of these elements should be negligible. In addition, any fissile material which passes through the cold traps or the purification systems will be caught, before discharge to the atmosphere, in the vent cold trap in the case of the uranium hexafluoride vent stream and in a vent sodium fluoride trap in the case of the plutonium hexafluoride vent stream. Thus, a double malfunction is required before fissile material can pass out of the reprocessing system to the off-gas scrubber. If it is considered possible for appreciable quantities of uranium or plutonium to reach the off-gas scrubbers, the scrubber solutions could be poisoned.

System emptying and/or cleanouts will periodically be required for the main reactor and associated filters, and possibly for other equipment for accountability and nuclear safety purposes. The nuclear safety philosophy would be to maintain a running balance of the estimated plutonium input, the plutonium product stream, and the known losses. A system cleanout would be required when the amount of plutonium unaccounted for reaches some mass limit which is less than the minimum critical mass. The mass limit will be established upon consideration of the expected input error and the accuracy of the accountability method used. For example, suppose that the maximum in-process inventory for the plant is 20 kg; then, a reasonable material balance deficiency to allow would appear to be about 10 kg, assuming the total 30 kg, representing in-process inventory and material balance deficiency, is considered to be safe under a 40 kg of

plutonium minimum critical mass value. With a processing rate of 9.7 kg of plutonium per day, an overestimation of input of 5%, and an unaccounted for loss of 1%, a 10 kg plutonium deficiency would occur after 17 days of operation. Accountability or other operational requirements may necessitate more frequent cleanout.

Radiation

The protection of plant personnel from all types of penetrating radiation in the plant is achieved through (1) proper design, not only of the process equipment but also of the processing cells, the process building, and the ventilation system; (2) high quality workmanship and enforcement of high construction standards; (3) careful choice and effective training of operating personnel; and (4) constant attention to good housekeeping, particularly in regard to monitoring the operating area for contamination and radiation buildup.

Shielding thicknesses were based on radiation levels of 1 millirem per hour in normal access areas and 10 millirems per hour in limited access areas. Plant personnel are protected by 6 feet of concrete from the high radiation cells of the reprocessing area. In no case did the shielding calculations indicate that thicknesses in excess of 5.5 feet are necessary. Thus, the use of 6 feet provides a safety factor of 1/2 foot. Concrete thicknesses are reduced for the lower radiation areas of the canyon; however, a minimum shielding thickness of 2-1/2 feet is maintained around all process equipment to minimize personnel exposure in the event of a breakthrough of radioactive material or a nuclear excursion. Protection of personnel from direct radiation in the fuel storage area is obtained by 11 feet of water shielding above the fuel elements.

Induced draft ventilation is provided in the process building so that the air flow is from the areas of least contamination through the operating areas and then through the cells. Quick-acting dampers are installed in all ducts to prevent backflow of air from the cells into the adjacent areas in the event of overpressuring of the cells by a nuclear or chemical incident. The cell ambient pressure is maintained below atmospheric pressure at all times. Emergency blowers are available to increase cell ventilation flow in the event of a release and to assure sufficient ventilation for the cells under emergency circumstances.

Temporary loss of power to the ventilation system is guarded against by the use of a double ended electrical substation. An auxiliary diesel electrical generator is provided to power the ventilation system blowers and other emergency equipment in the event of a total electrical failure.

Air radiation monitors are provided to sound an alarm if excessive radioactivity is detected in any of the plant areas outside of the cells, as well as in the ventilation flow from the cells. Process off-gases are scrubbed and filtered to minimize emission of radioactive contaminants

to the atmosphere. Off-gas handling and stack sizing has been discussed further in the chapter on general facilities.

Clothing change areas and air locks are provided so that protective clothing worn for working on or around contaminated equipment may be removed prior to entering clean areas. Dosimeters, film badges, and hand and foot counters are also provided.

The radiation levels of all plant effluents are monitored continuously so that the accidental discharge of excessive amounts of radioactive materials into public water supplies and the atmosphere can be detected. Countermeasures can then be taken quickly. Monitoring of ground water in the vicinity of seepage pits and aqueous storage tanks is done routinely by samples taken from strategically located wells.

Chemical

The major chemical hazards in a radiochemical plant, i.e., the uncontrolled or runaway reaction and the release of toxic or injurious chemicals, are identical to those in a cold chemical plant; however, due to the high radiation levels existing in the equipment, the consequences of an explosion, fire, or release in a sensitive area of the plant could be more severe. The chemical release type of accident is susceptible to the same control measures employed for the release of radioisotopes; i.e., adequate ventilation, scrubbing, filtering, dilution, and ultimate release of the ventilation gases to the atmosphere through a properly designed stack.

The chances of an explosion are fairly small; however, possible causes of such an occurrence include the ignition of mixtures of hydrogen or hydrogen chloride with oxygen, interhalogens, or fluorine. An additional possible cause is the reaction of liquid bromine pentafluoride that has leaked or spilled from a process vessel with such materials as insulation, electrical wiring, paint, etc.

Alarms are provided to detect leaks of combustible gases, and continuous cell ventilation prevents dangerous accumulations. Dilution of the process off-gases to below flammability limits will prevent explosion from these sources. Due to the high vapor pressure of liquid bromine pentafluoride at the probable cell temperatures encountered in the plant, leaks of this type will be readily detected by the gas alarms, and steps will be taken to shut off all process flows to minimize the amount spilled. In addition, the use of curbing and the proper positioning of absorber filled trays below processing vessels and lines in which liquid bromine pentafluoride is handled will localize spills and will do much to minimize a potentially major incident. Generally speaking, when compared with nonradioactive chemical processing plant equipment, the sizes of equipment in this plant are relatively small; thus, the likelihood of severe explosive forces being generated is low.

To the usual dangers of an uncontrolled chemical reaction, such as an explosion, is added the dissemination of fission product radiation throughout the cell area. If the explosion is severe enough to destroy equipment and to disrupt ventilation ducts, returning the plant to normal operation will require long, costly, and laborous decontamination and clean-up, even before equipment replacement can begin. The concomitant loss of valuable uranium and the possible contamination of areas outside the plant perimeter must also be considered. The latter situation could also result in the need for long and costly decontamination operations.

Among those measures taken to guard against such eventualities, perhaps the most important are (a) the proper training of operators, (b) the development and use of adequate operating procedures, and (c) the building of safeguards into the plant equipment. The first two items are, properly, the responsibility of the plant operator and its management. The last item is the responsibility of the design engineer. For example, the design of a nuclear fuels reprocessing plant must exhibit a high degree of engineering integrity. The equipment, tanks, piping, etc, must conform to the applicable engineering codes for the foreseeable process conditions and eventualities. Provision must be made for the proper purging of equipment and piping for assurance that incompatible chemicals are not allowed to mix. Sufficient instrumentation must be provided, not only for complete control of processing conditions, but also to give warning of equipment malfunction. Emergency cut-off valves, both remote and manual, must be located in areas readily accessible to operating personnel, both for normal operation and during emergencies. Ventilation control by compartmentalization of the processing cells and by proper location of inlet and outlet ducts to prevent spread of radioactive dusts and noxious fumes from contaminated areas into clean or less contaminated areas is essential. Although not essential, the proper placement of curbing and drip pans, as mentioned previously, will greatly reduce the reactive surface area for spills of liquid bromine pentafluoride and, thus, should be incorporated into the plant design.

The conceptual nature of this study precluded a complete safety analysis of all aspects of plant operation; however, certain safety provisions are noteworthy. For example, the leakage of fluorine into the fluid bed during the hydrochlorination cycle could have unpleasant consequences because of the presence of hydrogen. To prevent this type of accident, the systems are interlocked so that both fluorine and hydrogen chloride cannot be admitted simultaneously. Similar precautions have been taken to prevent bromine pentafluoride, hydrogen chloride, and oxygen from mixing. Additionally, double valves with nitrogen buffers are installed at all key points in the system to prevent leakage of one gas into the other. Temperature and pressure monitors and alarms are also provided in the process to warn of incipient malfunction in time for effective counter-measures to be taken.

Process off-gases are passed through a caustic solution prior to discharge to the stack to remove fluorine, bromine pentafluoride, hydrogen chloride, etc, and some fission products. Thus, corrosive gases are not vented to the atmosphere. Normally, cell off-gases pass through absolute filters

before discharge, but not through the scrubbing system; however, in the event of an accidental release within a cell, the cell off-gases are automatically diverted to scrubbers to remove any corrosive gases that might damage the filters. Thus, both process and cell off-gases released to the atmosphere will not contain corrosive gases, although considerable amounts could be released without exceeding maximum permissible concentrations.

The potentially hazardous nonradioactive chemicals consumed or generated in the reprocessing plant are listed, together with their specific hazards and threshold limit values, in table XII.

As handling procedures and MPC values are generally available in Manufacturing Chemists Association literature, details of handling procedures are not discussed further.

An additional hazard arises from the fact that, prior to the hydrochlorination cycle, fuel element end hardware will be removed by cutting or shearing. The metal sawdust so obtained constitutes a severe fire hazard if not handled properly^(15,38,1). Since the metal contains induced radioactivity from being irradiated in the reactor, precautions must also be taken against radiation during handling and storing. The massive chunks of metal can be safely disposed of by drumming and burying in the burial ground. The chips or sawdust must be collected and stored in vented drums under water until disposed of. Ultimate disposal of this material is carried out by burning wet in a suitably contained incinerator⁽³⁸⁾. The resulting zirconium oxide can then be safely encapsulated and buried.

General

Safety evaluations required for radiochemical processing plants necessitate consideration of usual industrial hazards in addition to the previously discussed items involving criticality, radiation, or specific process chemical problems. The mechanical, electrical, and nonradioactive chemical handling hazards of the more usual type found in the chemical industry must, of course, be considered in any chemical plant.

Other general aspects of safety include emergency and fire fighting training and medical surveillance of personnel. Fire and emergency vehicles are provided for the plant. The guard force is required also to perform fire fighting and emergency duty with supplemental assistance from specially trained personnel from the maintenance and operating crews. Emergency first aid can be performed by these people; however, serious injuries would be treated at the nearest hospital or by calling a doctor to the plant. Routine medical examinations would be performed by a doctor on a contract basis in facilities supplied at the plant.

TABLE XII

HAZARDOUS CHEMICALS CONSUMED OR GENERATED IN THE FLUORIDE VOLATILITY PROCESS
FOR REPROCESSING SPENT POWER REACTOR FUELS

Chemical	Form	Hazard	Threshold Limit*, ppm
Hydrogen Chloride	Liquid and Gas	Toxic Gas, Corrosive	5
Fluorine	Gas	Toxic Gas, Strong Oxidizing Agent	1
Bromine Pentafluoride	Liquid and Gas	Toxic, Fire Hazard, Corrosive, Oxidizing Agent	1
Bromine Trifluoride	Liquid and Gas	Toxic, Fire Hazard, Corrosive, Oxidizing Agent	1
Bromine	Liquid and Gas	Toxic, Fire Hazard, Corrosive, Oxidizing Agent	1
Chlorine	Gas	Toxic, Corrosive	1
Hydrogen Fluoride	Liquid and Gas	Toxic Gas, Corrosive	3
Hydrogen	Gas	Flammable	-

* The threshold limit value is defined as allowable time weighted average concentration for a normal work day.

PLANT STAFF

The staff requirement for this reprocessing plant is estimated at 119 employees. The plant staff may be categorized in three major groups; i.e., hourly employees; nonexempt salaried personnel, such as technicians and office clerks; and exempt salaried personnel, such as management and technical people. There are 70 hourly employees, 26 nonexempt salaried employees, and 23 monthly employees. A detailed listing showing the personnel distribution is given in table XIII.

Plant staff requirements, particularly for a process which has never been operated on a production scale, cannot be established conclusively and are certainly a matter of opinion, being influenced by company policy, union requirements, labor skill, and customer demands in such areas as accountability and even cost accounting. Staff requirements were estimated based on past experience with cold volatility plants with allowance for radiochemical complications. Personnel allocation took cognizance of requirements for operation as an independent facility.

TABLE XIII
PLANT PERSONNEL

	<u>Number Required</u>
<u>Shift, Exempt Salaried</u>	
Shift Foreman	4
Shift Chemist	4
<u>Shift, Nonexempt Salaried</u>	
Technician	12
<u>Shift, Hourly</u>	
Operator	20
Maintenance	12
Guard-Fireman	10
<u>Day, Exempt Salaried</u>	
Plant Superintendent	1
Chief Engineer	1
Chemical Process Engineer	2
Utility Engineer	1
Mechanical Engineer	1
Chief Chemist	1
Health Physicist	1
Office Manager	1
Bookkeeping, Payroll	1
Purchasing, Stores	1
Accountability	1
Maintenance Supervisor	1
Assistant Maintenance Supervisor	1
Guard and Fire Captain	1
<u>Day, Nonexempt Salaried</u>	
Dispensary Technician	2
Secretary	3
Clerk-Typist	3
Clerk	4
Draftsman	2
<u>Day, Hourly</u>	
Operator	5
Instrument Mechanic	3
Machinist - Sheet Metal	2
Maintenance Mechanic*	5
Welder	3
Rigger	2
Janitor - Laborer	4
Laundry	2
Electrician	2
TOTAL	119

* Can perform pipefitting, millwright, sheet metal, insulation, structural, painting, and rigging work.

COST

Capital Cost Evaluation

The estimated capital costs are summarized in table XIV. The buildings and structures were estimated to cost about 4.9 million dollars, the equipment about 9.9 million dollars, the utilities about 1.1 million dollars, and the land improvements, exclusive of buildings, about 0.3 million dollars. The total basic construction is therefore 16.3 million dollars before engineering and indirect charges are included. The total construction cost, including these items, is 24.4 million dollars. When a contingency is added and allowances are made for spare equipment, miscellaneous other equipage, and startup, the total estimated capital cost of the plant is \$33,000,000.

Where drawings were available, costs were obtained by making take-offs of quantities of materials required and multiplying these by suitable unit costs for material and labor. Where drawings were not available or did not provide adequate detail, assumptions deemed adequate were made for cost allowance. The process and fuel receipt building estimate is based largely on take-offs. The warehouse and utility buildings were costed on a dollars per square foot basis. The required amounts of process equipment, including ancilliary mechanical, instrument, and electrical items, were estimated on a quantity basis generally. The cost of process vessels was estimated from conceptual drawings or from known costs of similar equipment. Drawings were prepared for the larger cost items.

The estimates are, of course, not so accurate as those that could be made from a complete design package for the facility. There may have been a tendency toward oversimplification of some of the construction problems because of the lack of detailed design. For this reason, a contingency of 25% is applied to the total construction cost. It is felt that this allowance is appropriate and that it should not be disregarded; however, it must be emphasized that this contingency does not cover major process changes which might become necessary should further development information be obtained.

There are several factors to be considered in relation to the quoted capital costs:

1. As just stated, process changes which may well occur could affect costs considerably, since the process has not as yet been fully developed.
2. Local construction cost scales and local problems can cause substantial variations in capital requirements; thus, choice of site can have a significant effect on construction costs.

TABLE XIV

ESTIMATED CAPITAL COSTS FOR
INTERHALOGEN VOLATILITY POWER REACTOR
FUEL REPROCESSING PLANT

Basic Construction Costs	Estimated Capital Cost, \$
A. <u>Improvements to Land</u>	
General Grading, Roads, Parking Lot, Railroads, Fence, Walks, Burial Ground, Delaying Basin	332,000
Total Land Improvements	332,000
B. <u>Building and Structure</u>	
Process Building (Administration, Laboratory, and Cells)	3,434,000
Fuel Receipt and Storage	836,000
Utilities, Maintenance, and Chemical Supplies	365,000
Warehouse	256,000
Other	25,000
Total Buildings and Structures	4,916,000
C. <u>Utilities</u>	
Sewers and Sewage Disposal	126,000
Steam, Air, and Water	658,000
Electrical Substations	353,000
Total Utilities	1,137,000
D. <u>Equipment</u>	
Process	
Head End Cell	1,488,000
Hydrogen Chloride Recycle Cell	941,000
Bromine Pentafluoride Recycle and Uranium Hexafluoride Collection Cell	2,174,000
Fluorine Recycle and Plutonium Hexafluoride Collection Cell	451,000
Uranium Hexafluoride Product Handling Cell	386,000
Plutonium Hexafluoride Purification and Product Handling Cell	846,000
Scrubbing Cell	568,000
Fuel Drying and Handling Cell	413,000
Chemical Storage and Supply	938,000
Maintenance	95,000
Laboratory	192,000
Off-Gas Filtration, Stack, and Waste Lines	990,000
Fuel Receipt and Storage	443,000
Total Equipment	9,894,000
Total Basic Construction Cost	16,279,000
Indirect Construction Costs	4,884,000
Design and Engineering Costs	3,256,000
Total Construction Costs	24,419,000
Miscellaneous Equipage	300,000
Contingency	6,180,000
Spare Equipment	1,000,000
Startup Cost	1,109,000
Total Estimated Capital Costs (Rounded)	33,000,000

3. Differences in organization and design philosophy can cause substantial variation in design and thus in capital cost.
4. Escalation of prices to some future plant construction date would, in all probability, result in increases in capital costs.
5. Capital cost includes neither operating capital nor cost of land, which will vary with locality and actual site chosen.
6. Financing charges and the cost of extending public and utility facilities to the plant perimeter are not included.
7. Costs for construction of the solids and aqueous waste storage facilities were not included as a capital item but rather as an operating charge. The cost of the bins was included as an operating cost, since incremental construction of the storage vaults and bins will be used.

The capital cost estimates, as qualified above, are nevertheless felt to be as accurate as warranted by the state of process development and to give a realistic appraisal of the costs involved in such a facility.

The format used for calculation and presentation of capital costs is conventional; however, some discussion may be helpful. The basic costs, i.e., construction labor and materials, are divided under four main headings: Improvements to Land, Buildings and Structures, Utilities, and Equipment.

Only one item appears in the Improvements to Land category. This covers general grading, roads, parking lots, plant railroad, fence, walks, delaying basin, and burial ground.

Under the second subheading, Buildings and Structures, there are five items: (a) Process; (b) Fuel Receipt; (c) Utilities, Maintenance, and Chemical Supplies; (d) Warehouse; and (e) Other. The costs given here are the total labor and material required for construction of building and installation of building service equipment and utility lines. Costs of cranes, manipulators, and viewing windows are included in the cost of the particular building in which they are installed. The item under (e) Other, includes guard stations and miscellaneous sheds.

Under the third subheading, Utilities, there are three items: (a) Sewers and Sewage Disposal; (b) Steam, Air, and Water; and (c) Electrical Substations and Outside Lines. Each item includes equipment and outside distribution lines but no distribution lines inside other buildings, since these have already been included in those building costs. The package steam and air plants are housed in the utilities building.

Under the subheading, Equipment, there are six items: (a) Process; (b) Chemical Storage and Supply; (c) Maintenance; (d) Laboratory; (e) Off-Gas Filtration, Stack, and Waste Lines; and (f) Fuel Receipt and Storage. The process equipment cost is shown separately for each of the process cells and includes the purchase price and installation charges for labor

and materials. Cost for the equipment in the recirculating cooling air cell is included as part of Process Building cost above. Process vessels, pumps, machinery, piping, instrumentation, insulation, and electrical furnaces and motors are included in the equipment category. Chemical Storage and Supply covers storage tanks for purchased chemicals, such as hydrogen chloride and potassium hydroxide; makeup area equipment, and fluorine plant equipment, including piping, electrical, and instrumentation. Maintenance equipment includes such items as lathes, drill presses, saws, sheet metal equipment, welding and milling machines, and miscellaneous hand tools. The laboratory equipment includes hoods, tables, spectrographs, spectrometers, counting apparatus, and miscellaneous conventional laboratory items. Not included are analytical cell structures, windows, or manipulators, since the costs of these are reflected in the process building costs.

The item, Off-Gas Filtration, Stack, and Waste Lines, includes lines and ducts required to take liquid and gaseous wastes to the point of disposal or storage, as well as the cell off-gas filters and auxiliary fans. Fuel receipt equipment includes that required for recirculation, filtration, cooling, and clarification of canal water, complete with piping, instrumentation, and electrical.

The subheading costs above, i.e., Total Land Improvements, Total Buildings, Total Utilities, and Total Equipment, are added to give the Total Basic Construction Cost. This total represents the cost of direct labor and construction. Indirect Construction Costs and Design and Engineering Costs at 30 and 20% of Total Basic Construction Cost, respectively, are then added on to give the Total Construction Cost.

Items covering contingencies, miscellaneous equipage, spare equipment, and startup, are then added to the Total Construction Cost to obtain the Total Estimated Capital Cost. Miscellaneous equipage includes mobile equipment, such as trucks, bulldozers, fork lifts, cars, and a small yard diesel engine; it also covers office furniture and equipment. The contingency was taken as 25% of the Total Construction Cost, plus miscellaneous equipage. Spare Equipment covers spare process vessels, pumps, instruments, valves, piping, and furnaces. Startup cost is an allowance to cover the cost of plant shakedown and trouble shooting necessary before full production can be attained. In this case, it was taken as equal to one-third the yearly operating cost after contingency.

The final total, Total Estimated Capital Cost, represents the investment capital required for the project. It does not include operating capital or the costs of land or funding.

Operating and Unit Cost Evaluation

The estimated operating costs, including amortization of capital costs, are given in table XV. Operating cost per kilogram of fissile material, not including depreciation, is \$10.98. The unit depreciation costs were determined by dividing 15% of the total capital cost by the 3×10^5 kg of fissile material to be processed by the plant over a year's period. The unit depreciation cost is \$16.34 per kg of fissile material. Depreciation is over one-half the total unit cost of \$27.32 per kg, and the use of a lower depreciation rate than 15% would result in further unit cost decreases. The 15% depreciation rate takes both depreciation and profit into account.

Certain items are not included in the operating cost and should be mentioned. These items are fuel transportation costs, special insurance, interest charges, charges for uranium losses less than 1%, and local taxes.

The Total Operating Basic Cost, as given in table XV, is comprised of the sum of two item groups, one consisting of labor costs and the other of materials costs. In the labor group, there are three items: Direct Labor, Maintenance Labor, and Administrative and Technical. Direct Labor covers the operators and maintenance labor. No supervision is included in either item. The item, Administrative and Technical, includes all weekly and monthly salaried personnel. The Labor Costs were calculated based on the plant staff, as described in the previous chapter, and assumed rates generally consistent with Oak Ridge costs. No allowances were made for bonus items, such as hazards pay or portal-to-portal pay; however, shift premiums are included.

Under Materials, the items are direct materials, maintenance materials, equipment replacement, utility materials, and other materials. Direct materials cover process chemicals, such as hydrogen chloride, hydrogen fluoride, alumina, etc. Maintenance materials, not including major equipment replacement, are allowed for at 80% of maintenance labor. Equipment replacement was obtained by assessing the frequency of failure of the larger equipment items and taking proportionate costs from the equipment list. Utility materials include the costs of power, fuel oil, and water and sewage treatment supplies. Other materials cover miscellaneous supplies.

The Total Basic Operating Cost is obtained by totaling total labor and materials. The Total Operating Cost is determined by adding labor burden and other overhead to the Total Basic Operating Cost. Labor Burden was taken at 25% to include cost of payroll taxes, company plans, holiday pay, and overtime necessitated by sickness and vacations. In reference to the last item, the operating staff is such that vacations could probably be handled by putting day personnel on shift; however, realistically, there will be times when this is not feasible and overtime is required. Accordingly, the 25% factor is used instead of perhaps 20%. Other Overhead to include miscellaneous items, such as cost of medical services not provided

TABLE XV
OPERATING COST

	Estimated Operating and Unit Cost*, \$
Direct Labor	245,000
Maintenance Labor	250,000
Administrative and Technical	<u>464,000</u>
Total Labor	959,000
Direct Materials	255,000
Maintenance Materials	200,000
Equipment Replacement	180,000
Utility Materials	147,000
Other Materials	<u>40,000</u>
Total Materials	822,000
Waste Storage	<u>497,000</u>
Total Basic Operating Costs	2,278,000
Labor Burden	240,000
Other Overhead	<u>144,000</u>
Total Operating Cost	2,662,000
Contingency	<u>665,000</u>
Total Estimated Operating Cost	3,327,000
Unit Operating Cost	10.98
Unit Depreciation Cost	<u>16.34</u>
Total Unit Cost	27.32

* Operating costs are in dollars per year, based on 300 days per year operation. Unit costs are in dollars per kilogram of fissile material.

for in the plant staff, travel, cost of personnel on loan from the parent organization, etc, was taken at 15% of Total Labor.

A contingency of 25% of the Total Operating Cost was added to the Total Estimated Operating Cost because the basic assumptions as to size of staff and chemical utilization were unsupported by actual plant operating experience.

The Unit Operating Cost is determined by dividing the Total Estimated Operating Cost by the scheduled yearly processing load, 3×10^5 kg of uranium plus the plutonium load. The Unit Depreciation Cost is figured by dividing 15% of the Total Estimated Capital Cost by a year's processing load. The Total Unit Cost is the sum of the two.

CONCLUSIONS AND RECOMMENDATIONS

While making this study, several assumptions and judgements were made, some of which might well be considered arbitrary; consequently, the plant as designed may be considered to be lacking in some respects. It is felt, however, that the design is satisfactory for its intended purpose to evaluate the economic competitiveness of a fluoride volatility reprocessing plant with an aqueous reprocessing plant. The estimated capital cost of \$33 million for a 300-tonne per year volatility plant compares well with the expected cost of an aqueous plant of similar capacity. From the standpoint of budgeting for actual plant construction costs, accuracy can be drastically affected by decisions regarding location, incorporation of "extras", maintenance and operating modes, escalation factors, choice of contractor, and other items.

Experience appears to show that detailed plant design and small design improvements resulting from a firming up of the technology are likely to increase rather than decrease costs. It is felt that the volatility plant is more vulnerable to this type of cost increase than the aqueous system, and it would not be surprising to see a significant increase in the capital cost of a fully developed volatility process. A 25% contingency was added to the capital cost of the plant design for these reasons.

As hoped for, the evaluation has helped to point up areas of technology that must be developed further before the process can logically be considered ready for even preliminary plant design. This has been true, not only with respect to gaps in technology, but also from the standpoint of process economics. For example, size and duplication requirements for the main process reactors, process filters, other feed handling equipment, compressors, sorbers, etc, made it apparent that alternative approaches in problem areas should be considered.

The conceptual plant design is derived from data supplied by ANL, BNL, ORGDP, and ORNL. The available information, for the most part, was obtained with laboratory-scale equipment, and extensive extrapolation was required to adapt the data to plant size. Thus, numerous decisions were required in scaling the process to the desired throughput. Clarification of the study position should be helped by the discussion which follows.

The first, and perhaps the most important, general decision involved fixing processing rates and operating schedules. The rate chosen, 300 tonnes of uranium per year, was based on a projected reprocessing load of that amount for spent nuclear power reactor fuels for the early period of the 1970s. The load would be handled on a 300 operating day per year basis. A 21-shift per week operation and a 90% on-stream average availability were used to fix hourly processing rates. The on-stream average rate used for equipment sizing is thus approximately 1 tonne of uranium per day, which is sufficient to process the spent fuel from about six power reactor sites, each having a 1,000 Mw electrical output. Slack time was allowed in the plant reactor processing cycle for minor maintenance problems, for

system cleanouts required by accountability, criticality, and for turn-around between processing periods for different fuel types.

A second important general decision was to process whole modules instead of pulled tubes. Thus, the expense of tube pulling was eliminated. Since the batch charge selected to obtain the desired processing rate requires more than one element, dismemberment is not needed in any case.

The fluid-bed volatility process scheme involves several areas where design options are possible. For example, the process, as presented, utilizes a recycle system for the hydrogen chloride reactant. Although a once-through system is possible, the use of hydrogen chloride recycle is preferred because:

- a. The storage problem associated with the quantity of aqueous hydrogen chloride obtained as waste from the once-through process is significant. Without recycle, all hydrogen chloride fed to the process is regenerated as an aqueous solution requiring neutralization and possibly interim storage for an indeterminate period of time because of contained radionuclides. The quantity of activity involved is not known; experimental information relating to this problem is needed.
- b. The chemical cost is reduced, since by recycling the hydrogen chloride recovered by the hydrolysis of the zirconium tetrachloride, the basic reagent used in decladding is water, with only a small amount of hydrogen chloride required to make up losses.
- c. Control over the zirconium-hydrogen chloride reaction is most easily obtained by dilution of the hydrogen chloride with a gas inert to zirconium. In the case of the recycle system, the hydrogen reaction product is used as a diluent. Without recycle, nitrogen or some other inert gas would be required to dilute the hydrogen chloride, thus adding to the chemical cost of the operation.

Recycle systems were also postulated for the bromine pentafluoride and fluorine fluorination systems for similar reasons, i.e., no large reagent waste storage requirements, reagent economy, and small inert diluent gas volumes necessary.

Another major design decision for the process was to use bromine pentafluoride as a selective fluorinating agent for the uranium. Accordingly, the bulk of the uranium is volatilized during the bromine pentafluoride fluorination step without a volatile plutonium compound being formed, thereby enhancing the purity of the collected uranium. In the alternative all-fluorine fluorination process, there would have undoubtedly been some cross contamination in the uranium and the plutonium product streams. Also, the bromine pentafluoride fluorination will hopefully remove the majority of the volatile fission product fluorides before the plutonium is fluorinated, thus improving the decontamination of the plutonium. Unfortunately, significant amounts of ruthenium and niobium probably will remain with the plutonium and create a decontamination problem, since a satisfactory cleanup scheme for these elements has not yet been developed.

The present conceptual study was designed to answer two questions:

1. Is the volatility approach technologically sound as a production operation for recovery of uranium and plutonium from spent low enrichment power reactor fuels?
2. Can a reprocessing plant using volatility methods compete economically with one employing the latest aqueous technology?

From the evaluation of the best available information, the indication is that, in a broad sense, the answer to both of these questions is yes; however, it is clear that, with certain problem areas cleared up through additional engineering and research, there would be firmer grounds for such a decision.

There remains a gap between the available technical knowledge and the information required to design and construct a successful plant. Comprehensive discussions of the state of development of the process is included in the Process Critique section of the report.

In view of the expected spent fuels reprocessing load after 1975, it appears desirable to design future reprocessing plants having throughputs of 2, 3, or even 5 tonnes of uranium per day. Even though the plant described in this study has a design throughput of only 1 tonne of uranium per day, the capacity of the plant can be doubled without major increases in the plant support facilities. Using the batch-type process assumed in the present study, the best approach to increasing the plant capacity is probably to add additional halogenators and increase the capacity of the uranium hexafluoride distillation system. Of course, the fluorine plant capacity would have to be doubled also. This method of increasing plant throughput decreases the idle time for the different recycle systems required for the present design. The alterations and additions would largely involve the head-end cell and the bromine pentafluoride recycle and uranium hexafluoride purification cell. Sparing of the fuel charger and a line of reactor equipment might be expedient, since only a modest allowance for downtime was made in the operating cycle of the conceptual study. No additional fuel storage space would be contemplated, since space for a 6-month backlog is already provided in the present design based on 300 tonnes of uranium per year and is probably sufficient to assure meeting production commitments. Overall, probably a 40% increase in the capital investment should cover modifications.

The techniques assumed for the study are based on batch processing; however, it may be possible to process the spent fuel on a semicontinuous or possibly a fully continuous basis. From an economic standpoint, it would be advantageous to make the process more continuous, since this usually leads to a more compact plant and less expensive operation. One possible semicontinuous process which is being reviewed involves a rotary kiln fed by a shear. The uranium dioxide is oxidized to U_3O_8 in the kiln and is subsequently shaken loose from the zircaloy cladding. The U_3O_8 powder is physically separated from the cladding hulls, and fed somewhat continuously

to a fluid-bed reactor where the uranium is fluorinated with bromine pentafluoride. The plutonium is then fluorinated with elemental fluorine in a second fluid bed which is fed via a continuous overflow from the uranium fluorinating reactor. Other equipment like the bromine pentafluoride regenerator, condensers, cold traps, distillation columns, sorption traps, etc, are used to recover the bromine pentafluoride and fluorine for recycle. The uranium and plutonium compounds remaining after removal of the bromine pentafluoride and fluorine, respectively, are purified, packaged, and shipped. This volatility process is virtually unproved on an operational feasibility basis but should be considered as a potential route.

There are a few areas in the process technology that need further development work, such as plutonium purification, uranium hexafluoride distillation, uranium hexafluoride cold trapping, and filtration. Probably the area which needs the most development is the plutonium purification scheme. Hopefully, this step can be performed without the use of hydrogenous materials, and thereby larger inventories of fissile materials may be permitted in the processing vessels than is the case in aqueous plants. Several schemes have been suggested. One scheme involves the thermal decomposition of the plutonium hexafluoride to plutonium tetrafluoride. An alternate method is the sorption of the plutonium hexafluoride on sodium fluoride followed by dissolution of the sodium fluoride in bromine pentafluoride, bromine trifluoride, or hydrogen fluoride, leaving the plutonium as plutonium tetrafluoride. Unfortunately, neither of these techniques gives satisfactory ruthenium and niobium decontamination. This problem has been circumvented in the plant cost estimate by allowing sufficient capital for an aqueous plutonium purification step which may or may not be more costly than a suitable nonaqueous scheme.

As for the uranium hexafluoride distillation technology, some batch distillations of uranium hexafluoride and bromine pentafluoride mixtures have been performed; however, the scale and manner in which the still column was operated have only limited application to the large system required in the reprocessing plant. A batch distillation system was assumed for the present design, but for increased uranium throughputs, a continuous distillation system would probably be preferred.

Some technology is also lacking for the uranium hexafluoride cold trap. Present design procedures are applicable to traps where only one phase is formed; namely, a solid phase. Solid uranium hexafluoride and liquid bromine pentafluoride will be formed in the reprocessing plant cold trapping system. The potential problem here would be the formation of slush with subsequent bridging and plugging inside the trap, thereby requiring early draining. Before such a trapping system could be put into a reprocessing plant, it would have to be tested and a dependable design procedure established.

A problem which had gone unrecognized in the early stages of the development work on the volatility process is the filtration of the halogenator off-gases. In filter tests at ORGDP, filter tubes of sintered nickel and pressed nickel fiber served satisfactorily in sequential exposures to hydrogen chloride, oxygen, and fluorine gases; however, excessive plugging

occurred when the hydrogen chloride gas mixture was allowed to contact zircaloy and produce zirconium tetrachloride and hydrogen in the off-gases. The rate at which the filter medium plugged would require too frequent a filter replacement for a reprocessing plant committed to a substantial uranium throughput.

Choice of suitable permanent waste management program is clearly one of the more important decisions made for this study. Various sections of the following text describe both the philosophy and details of the waste storage systems assumed for the evaluation. Although it is felt that the method of waste disposal is adequate within the scope of the study, it is true that, considering the waste storage phase alone, considerable economic change can result if different rules are adopted; therefore, alternate cases were considered. Before proceeding with a discussion of the alternatives and the estimated related cost differences, storage methods used in the study are reviewed.

The process wastes consist almost entirely of solids discharged from the fluid beds and sorption traps. This material is stored in air-cooled bins as is done at the Demonstration Waste Calciner Facility (DWCF) at Idaho. Field experience with bin storage has been accumulated during the processing of high activity level wastes in the calciner. This experience includes both pneumatic transfer of solids from the fluid-bed calciner to the bins and operation of the storage bins themselves. The storage method has been judged as proven, and is therefore suited as a prime technique in this study. It is considered reasonable that the life of the bins is long enough to allow decay of the activity in-place with minimum loss of activity to the ground.

The process also requires small aqueous storage tanks to contain scrubber solutions, laboratory wastes, and miscellaneous contaminated liquids. These wastes are of relatively low level and are eventually disposed of by solidification by evaporation, encapsulation, and burial of the residue.

The waste storage capital cost was estimated to be \$1.88 per kg of uranium. Operating cost, which is presumed to involve principally labor, is included in the costs to maintain plant operating force.

If permanent storage in the bins is not satisfactory because of possible eventual leaching by ground water, it may be possible to store the waste for an interim period in the bins before shipping them in stainless steel cylinders to a salt mine for storage in a nonleachable matrix. In this procedure, only the high activity halogenator fluid-bed wastes are stored in the bins and then are removed, mixed with current hydrolyzer fluid-bed wastes, put in cylinders, and shipped to a salt mine. The economic optimum interim storage period was found to be about 6 years.

There is a reservation associated with the interim solids storage alternative, since it may not be feasible to retrieve waste solids from the bins of the present design. Without information as to the bed caking properties for interim storage of the particular solids involved, it does not seem feasible to design a technically and economically acceptable

solids removal system with any confidence. In view of the problem, a second interim storage alternative was considered. Here the solids from the halogenator bed are put into cylinders and stored in water-filled canals for an optimum interim period of about 15 years, at which time the cylinders are removed from the canal and shipped to a salt mine for permanent disposal. Fluid-bed wastes from the hydrolyzer are shipped immediately to a salt mine without any interim storage.

The waste storage costs as reflected in the two interim storage schemes are \$3.28 per kg of uranium for the first alternative and \$4.38 per kg of uranium for the second alternative. As seen from the three waste costs quoted, it is apparent that the waste disposal scheme with permanent storage in bins is considerably more attractive economically.

To summarize, waste storage costs are an important part of the economic evaluation of any radiochemical processing plant; however, before firm conclusions can be made, it is necessary to have well-established ground rules. Further, there is sufficient room for disagreement even on the selection of ground rules, which are seen to be dependent on the particular site selected; therefore, a firm economic guide cannot be established at this point. Nevertheless, in light of the other areas of uncertainty in this study, the absence of such exactness does not detract significantly from the overall conclusions.

The conceptual plant presumes the use of equipment larger than the minimal critical nuclear dimensions for at least part of the processing equipment. Both uranium and plutonium are present in sufficient amounts and enrichment to result in relatively small critical nuclear dimensions for aqueous systems. Critical conditions with uranium are circumvented, however, by eliminating water from those processing cells where uranium is present. Unfortunately, even in the absence of water, the critical sizes of plutonium cylinders are relatively small at the densities deemed possible in the reactor. Nuclear safety is assured, however, by (a) imposition of administrative controls, including the setting of limits on the plutonium batch size; (b) careful consideration of resultant concentrations of plutonium; (c) the use of nuclear poisons where applicable; (d) the isolation of the uranium hexafluoride and plutonium hexafluoride systems from those using homogeneous materials by double valving and buffering; and (e) the provision of radiation monitors. Dimensionally safe equipment* is employed where the use of such equipment does not interfere with the operability of the systems. Administrative control for safety is a tried and proven concept, having a precedent in normal manufacturing plants, as well as in nuclear fuels reprocessing facilities at Hanford and the Idaho National Reactor Test Stations.

* Conservative assumptions were made on uranium, plutonium, and moderator densities and on the composition of the reflector to determine geometrical limits for the dry systems.

Tentative approvals of the conceptual designs used in the study from the criticality control viewpoint have been obtained from authorities on the subject after informal discussions on the several flow sheets and the individual equipment items. Additionally, in some cases, calculations were made to explore in detail problems connected with various equipment items. Although these calculations generally supported the conclusion that the plant could be operated safely from a nuclear safety standpoint, design changes might be made at a later date to improve the safety factors. Certainly, as part of the responsibility of an eventual operator and architect-engineer, a more detailed evaluation of the various designs from the criticality viewpoint would be performed before the subject could be placed before a hazards review committee for approval.

In view of the results described in more detail in the criticality control section under the chapter on safety, it appears that plutonium criticality is controlling in the plant, and a plutonium mass limit needs to be established. The nuclear safety philosophy would be (a) to maintain a running balance between estimated plutonium input and the sum of the plutonium in the product stream and the plutonium losses, and (b) to require system cleanout when the amount of unaccounted for plutonium reaches some value less than the lowest critical mass for the single piece of equipment in the processing train for which accurate estimates of holdup are not available. As noted previously, with a processing rate of 9.7 kg of plutonium per day, an underestimation of input of 5%, and an unaccounted for loss of 1%, a 10 kg plutonium deficiency would occur after 17 days of operation. A single charge of alumina to the fluid bed will be used with from 3 to 5 charges of fuel to the reactors. Based on a cycle time of 61 hours, the reactors will be emptied for waste disposal every 8 to 13 days. So it appears that accountability and operational requirements will probably necessitate more frequent cleanouts than would criticality control.

It should be noted that vessel interaction has not been considered in detail in this study. Such calculations are not felt necessary with the restriction on the total plutonium mass in the whole system. In any event, the vessel spacing required for piping imposes considerable limitation on interaction.

In summation, it is felt that, despite the relatively large vessels used, the process is safe from a criticality standpoint. In all probability, on the average, plutonium input may be assessed to within a few percent; therefore, cleanouts for accountability and waste disposal would be more frequent than for criticality reasons. If the plutonium input cannot be determined with this precision, it is possible to increase system mass limits by several techniques. The assumptions relating to possible plutonium density and shape of accumulations may be changed after a review of process considerations. Also, external fixed neutron absorbers can be used to decrease reflector effectiveness. Since the halogenator and its associated equipment are the major units which are not geometrically safe, independent treatment of the plutonium balance for each reactor would effectively allow the use of the same material balance discrepancy for a single reactor as was previously used for the whole plant.

A basic requirement of a reprocessing plant is that the purification and recovery be accomplished with low uranium and plutonium losses. It is also necessary to reach an agreement among the concerned parties as to how much uranium and plutonium have been received and, therefore, how much should be returned. The accountability procedure needed to satisfy the above criteria must be agreed upon by all the parties involved, including the supervisory government agencies. Accountability precedents do not exist directly for a nuclear fuel reprocessing plant using a fluid-bed volatility process; and therefore, the procedure formulated for this process has come about by an analogy to an aqueous reprocessing plant.

A conceptual study such as the present one, particularly when based on incomplete experimental results, does not provide enough detail for all accountability problems to be recognized. Of course, accountability requirements influence both the capital and operating costs. It should be mentioned that accountability for such dry processes, as in the feed plants where uranium oxide is converted to uranium tetrafluoride and uranium hexafluoride, and in dry chemistry applications involving conversion of uranium hexafluoride to uranium tetrafluoride, process losses are at a very low level. Obtaining accurate analysis of product and waste streams is not too difficult.

The fluid-bed process presents somewhat different and, in some ways, more difficult accountability problems. Obtaining a representative sample from the fluid-bed system after chemical disintegration of the fuel modules is thought to be a very difficult job. The uranium and plutonium are present in the form of particulates and are probably nonuniformly distributed through the bed. However, it is felt that sufficient data can be obtained for the uranium input from a measurement of the uranium collected after the bromine pentafluoride fluorination. The plutonium input may be established from plutonium-to-uranium ratios obtained from fluid-bed samples taken after oxidation. There are some reservations about the applicability of the plutonium-to-uranium ratio so obtained. Since the plutonium dioxide particles may well be much smaller than the U_3O_8 particles, the plutonium may possibly be elutriated out of the reactor system during the oxidation step.

Fortunately, suitable continuous techniques can be provided for sampling the solid wastes from the system. Sampling problems will be lessened in the solid waste streams, since the waste should be more homogeneous than the solids from the reactor bed and yet less accuracy, percentage-wise, will be required. Off-gases and scrubber solutions may be readily sampled and analyzed, and the amount of product uranium and plutonium can, of course, be determined quite accurately.

Since batch traps are used in the uranium purification and the plutonium fluorination recycle vent, these solids must be analyzed before discard. Normally, all these materials would be very low in uranium or plutonium content, but by mischance, it is possible to have fairly sizable quantities present. It is reasonable to assume that adequate sampling will be obtained.

In summary, there will be no problems with the development of a suitable accountability procedure for the volatility scheme, since it appears that it would be difficult to determine the exact quantities of uranium and plutonium fed into the halogenator. Furthermore, sampling of solids may be troublesome, since the alumina bed and probably the high level sorbent traps must be dumped to waste frequently to remove fission products. Nevertheless, the process is expected to operate within the 1% loss figure assumed for the study.

The fluid-bed reactor is subject to attack by the sequential exposure to anhydrous hydrogen chloride, oxygen, bromine pentafluoride, and fluorine at temperatures ranging from 300°C during the bromine pentafluoride fluorination step to 550°C during the fluorine fluorination step. The operating temperature of the reactor during hydrochlorination is 400°C, and it has been found that temperatures in excess of 450°C result in significantly accelerated corrosion of nickel by hydrogen chloride. This is caused primarily by the volatilizing of the protective nickel chloride film present on the walls at the lower temperatures. In addition to chemical corrosion, conditions suitable for erosive attack may result from the turbulent agitation of the abrasive alumina fluid bed.

Corrosion in the hydrogen chloride recovery equipment is well defined, since these problems have been encountered in commercial processes, and data are available on the resistance of different materials to anhydrous and aqueous hydrogen chloride. Hastelloy-B appears to be one of the more suitable materials.

As for the bromine pentafluoride and fluorine recycle equipment, Monel and nickel should be satisfactory.

The choice of a maintenance mode for radiochemical processing operations must be based on factors such as the radiation level; the ease of decontamination; the ease of repair or replacement of individual items; the frequency of occurrence of maintenance requirements; the amount of sparring provided; the manpower available for maintenance, with allowable exposure to activity being a factor; and the number of processing days allowed per year. Since radiation levels are not uniform throughout the plant, the same maintenance methods need not necessarily be used in all sections of a plant; indeed, the maintenance mode may differ for the same equipment according to the particular problem or problems involved.

For the following discussions, three different maintenance modes are defined:

1. Remote maintenance involves the repair or replacement of possibly heavily contaminated equipment using mechanically operated manipulators and cranes in such a manner that the maintenance operator need not enter the process cells or the crane bay and must not, in any way, be exposed to direct radiation from the equipment in question or neighboring equipment.

2. Semidirect maintenance involves the repair or replacement of equipment by operation of the required maintenance tooling from a distance and/or from behind the portable shielding so that the radiation exposure of maintenance personnel is substantially lowered, thus reducing the need for equipment decontamination.
3. Direct maintenance requires the maintenance operators to perform their duties in a way similar to that encountered in a cold plant. Sufficient equipment decontamination is required to lower the radiation level to a point where reasonable working times are possible without exposing maintenance personnel to radiation dosages in excess of pre-established limits. Protective clothing is used to minimize ingestion or skin contamination.

Obviously, if the decision is made to eliminate personnel exposure, decontamination, and equipment sparing, the only choice is remote maintenance, particularly in all high activity level areas. Some of the less desirable attributes of remote maintenance to be considered in making this choice are (a) the use of high cost remote manipulator equipment; (b) the necessity for custom designed equipment, piping, instrumentation, and electrical modules to allow easy replacement of defective parts; (c) the requirement for somewhat greater working space to allow easy access by remotely operated machines; and (d) the unnecessary maintenance difficulty in the relatively cold areas in contrast with relative ease via the other approaches.

For direct maintenance procedures to be effective, it is necessary to be able to decontaminate thoroughly and rapidly. Only then can the cumulative exposure of maintenance personnel be kept within the established limits while maintaining a reasonable working effort. Not only is the working time per individual limited by radiation exposure, but in addition, maintenance efficiency is decreased by (a) the necessity for wearing suitable protective clothing and (b) the need for substitute personnel for workers on the job who have received the maximum allowable radiation exposures. In some cases where complete decontamination is difficult or impossible, the available manpower can be "used up" in short order because of radiation exposure limitations.

Semidirect maintenance is a compromise. Expensive manipulator equipment is eliminated; furthermore, equipment item construction can be somewhat simplified because the workmen will have a "feel" for what they are doing. This familiarization will be better than with the remote maintenance case but obviously not so good as with the direct maintenance. Even though decontamination requirements can be reduced, personnel are still required to wear protective clothing, and radiation exposure may still limit working time.

In view of the above discussion, it was concluded that remote maintenance would best suit the maintenance requirements of the conceptual plant. In this plant, where most of the equipment is operated at relatively high temperatures and pressures above atmospheric, problems with heaters, thermocouples, and mechanical equipment may be relatively routine. Leaks

in the reactor or the associated piping could lead to the spreading of particulate activity creating a difficult, if not impossible, decontamination problem. Hot pilot plant experience with the molten salt process at ORNL has shown that several months of decontamination work may be required before activity levels are low enough that personnel can enter the cell. Although decontamination of production equipment might be expedited, partly because of improved techniques developed from pilot plant experience, considerably more activity could be expected in the plant cell than in a pilot plant cell. Thus, it was judged that routine decontamination of the main reactor cell would be too difficult to allow direct or even semidirect maintenance. Also, in the event of a major incident, e.g., where the fuel element charge was stuck part way down the reactor and could not be dislodged, the use of semidirect maintenance to remove the reactor or to repair the damage would be virtually impossible. Accordingly, the main reactor cell was considered to be maintained remotely. Sufficient remote viewing equipment and manipulators are provided in the cell to allow for routine maintenance and equipment replacement. In the event of equipment replacement, it is assumed that some decontamination would be accomplished by flushing with the process materials, such as fused alumina, and the scrapped item would be removed to the burial ground. For small items, such as valves, pump heads, and instruments, decontamination and warm shop facilities are provided.

Besides the high level head-end cell, the process canyon has low and intermediate level activity areas. In these areas, the major contamination problems stem from the accumulation of particulate and line-deposited activity as a result of volatilization from the high level equipment. Remote maintenance is also assumed for these cells because of the uncertainty in the amount of contamination that will be present, the question of ease of decontamination, and of criticality problems associated with decontamination by standard aqueous methods. However, the potential use of direct or semidirect maintenance in the hydrogen chloride recycle and uranium hexafluoride product cells should be reviewed when data become available relative to the degree of contamination to be expected in these cells.

In conclusion, the authors feel that fluoride volatility is probably a feasible process which could potentially compete economically with aqueous methods for the treatment of spent low enrichment thermal reactor fuels. Unfortunately, the logical process advantages cannot be firmly established because development work is incomplete; furthermore, it appears probable at this time that the economic incentives for the application of volatility techniques rather than aqueous are not great enough to encourage further investment in this technology for LWR fuels.

It must be recognized, however, that, in any event, the primary advantages of a volatility process, such as the relatively compact plants required, the small volumes of high-level waste generated and the less restrictive criticality constraints could be especially significant when applied to the treatment of high burnup fast breeder reactor fuels. Since the timing for FBR fuel cycle development would permit investigation of the areas

left uncovered by the recent volatility development work, it is felt that fluoride volatility processing may have a future for spent FBR fuels.

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APPENDIX

NOTE:
QUANTITIES REFLECT ONCE THROUGH OPERATION

SEQUENTIAL DATA	F I S S I O N																							P R O D U C T S										TOTAL WEIGHT	FUEL ELEMENTS			ACTIVITY
	HP	SG	BR	Kr	Rp	SP	Zr	Mo	Ma	Tc	Ru	BL	Os	Ag	Cd	IN	Sn	Sb	Te	Se	Cs	BA	La	238U	235U	239Pu												
TOTAL BURNUP/1000G BATCH	311.94	20.33	14.99	531.6	313.8	833.8	424.4	336.0	6.87	3201	821.5	2101	535.5	898.9	97.23	43.79	3.175	32.66	13.76	54.3	309.4	4942	2834	1202	1200	7609	32024	37.67	27.52	5.46								
AFTER HCL STEPS																																						
MALGONATE AIV-IOA+GB	311.94	27.76	14.24	281.9	313.8	833.8	424.4	3226	16.20	341	821.5	2101	535.5	898.9	97.23	43.79	3.048	31.35	13.21	52.18	293.9	4201	2834	1202	1200	7609	38054	37.09	26.73	5.40								
HYDROLYZED AIV-IO2		57							67	180	811							127	131	10	10																	
BLVDOWN			75																45	117	15.5																	
C1 SCRUBBER AIV-606																																						
OUT STACK				49.7																		741																
AFTER OXIDATION STEPS																																						
MALGONATE AIV-IOA+GB	311.94	19.16	11.24	182.4	313.8	833.8	424.4	3226	6.20	2977	534.0	2080	535.5	898.9	97.23	43.79	3.048	31.55	13.21	44.0	247.5	2718	2834	1202	1200	7609	38804	37.02	26.72	5.36								
PROCESS SCRUBBER		8.60	3.00							64	246.4	21								81.5	46.4																	
OUT STACK				99.5																		1493																
AFTER BFA STEPS																																						
MALGONATE AIV-IOA+GB	83.06				313.8	833.8	424.4	3226	5.86			333	535.5	898.9	97.23	43.79	3.048	31.55	0.4	5.1																		
ACT. SOLID	1.987	17.24	11.24						2.532	453	1815									514.9	250.47																	
ACTIVATED ALUMINA TRAPS	1.985	TRACE								48										74.4																		
BLOWDOWN RECLAIMER AIV-61	1.985	1.92							0.4	430	53	332							2.0	2.9	6.3	4703																
BFA POC SCRUBBER	TRACE									15										11.6	2.9																	
OUT STACK																				2900.4	23.7	3.8	80															
AFTER LCL STEPS																																						
ION EXCHANGE		TRACE			313.8	833.8	424.4	3226	5.15			TRACE	535.5	898.9	97.23	43.79	3.048	31.55																				
ION EXCHANGE										51		330																										
ION EXCHANGE SYSTEM	63.58																			4.0																		
OUT STACK																				74	4.0																	
																						TRACE																

† THESE ACCUMULATED FISSION PRODUCTS WILL BE BLOWNDOWN TO THE RECLAIMER AT 616 AND SUBSEQUENTLY SCRUBBED IN SCRUB TRAPS AT 306 & 307.

Figure A-1
FISSION PRODUCT FLOW SHEET

BATCH DETAILS	COMPONENTS	HYDROCHLORINATION										PURGE #1										OXIDATION										Ave. FLUORINATION										F ₂ FLUORINATION																			
		25% UTILIZATION OF 20 MWT % O ₂										12% UTILIZATION OF 20 MWT % O ₂										12% UTILIZATION OF 20 MWT % O ₂										25% UTILIZATION OF 20 MWT % O ₂										100% UTILIZATION OF 20 MWT % O ₂										100% UTILIZATION OF 20 MWT % O ₂									
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10																				
URANIUM 1445 gms AS UO ₂ - 1888 gms AS U ₃ O ₈	UO ₂																																																												
PLUTONIUM 14 gms AS PuO ₂ - 10 gms AS Pu ₂ O ₃	PuO ₂																																																												
SILICONUM 155 gms AS Si - 157 gms AS SiO ₂	Si																																																												
ALUMINA 3750 gms AS Al ₂ O ₃ TOTAL INVENTORY	Al ₂ O ₃																																																												
CYCLE TIME (HOURS)																																																													
CHARGE #	1																																																												
HEAT - UP	0.5																																																												
HYDROCHLORINATION 15	15																																																												
PURGE #1	1																																																												
OXIDATION 15	15																																																												
P ₂ FLUORINATION 8	8																																																												
TOTALS AND AVERAGE ON 3750 gms																																																													
SURFACE AREA (m ²)																																																													

Figure A-2
MAIN REACTOR SYSTEM FLOW SHEET

DWG. NO. E-P 33747A3A

Batch Details		Components		Hydrochlorination *																						Purge #1	
Uranium	1443 Eps. as 10% 1000 Eps. 10% Fe	H ₂	(SCFH)	A5	A6	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	A6	A7	A20
Plutonium	14 Eps. as 10% 1000 Eps. 10% Fe	HCl	(Eg/Hr)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
Zirconium	423 Eps. as 10% 1000 Eps. 10% Fe	H ₂ O	(Eg/Hr)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
Aluminum	2700 Eps. as 10% 1000 Eps. 10% Fe	H ₂	(SCFH)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
TOTAL INVENTORY		H ₂	(SCFH)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
TOTAL GAS FLOW (SCFH)		H ₂	(SCFH)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
TOTAL LIQUID FLOW (GPH)		H ₂	(GPH)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
CYCLE TIME (HOURS)		TEMPERATURE (°C)	(°C)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
HEAT-UP		TEMPERATURE (°C)	(°C)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
HYDROCHLORINATION		TEMPERATURE (°C)	(°C)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
PURGE #1		TEMPERATURE (°C)	(°C)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
OXIDATION		TEMPERATURE (°C)	(°C)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2
TOTAL		TEMPERATURE (°C)	(°C)	A5.5	72.7	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2	17.2	8.57	14.2

Flows based on 50% utilization of 60 m% HCl to halogenator

Figure A-3
PYROHYDROLYZER & HCl RECYCLE
SYSTEM FLOW SHEET

DWG. NO. E-P 33747B

[illegible]

Figure A-4
BrF₅ RECYCLE & UF₆ PURIFICATION
SYSTEM FLOW SHEET

DWG. NO. E-P 33747C1

BATCH DETAILS		COMPONENTS	PuF ₆ RECOVERY %				PURGE %				
			A11	A12	D1	D2	D3	D4	A12	D1	D4
URANIUM	1000 Kgs. as UO ₂ - 1800 Kgs. as UF ₆	N ₂	(SCFH)	850	876	876	15	47	1000	1000	1000
PLUTONIUM	14 Kgs. as PuO ₂ - 18.3 Kgs. as PuF ₆	F ₂	(SCFH)	2360	2344	2344	15	139			
BIRCONIUM	423 Kgs. as B ₂ O ₃ - 571 Kgs. as B ₂ O ₃	PuF ₆	(Kgs./Hr)	0.024	0.024	0.024	1.171	0.001			
ALUMINA	2750 Kgs. as Al ₂ O ₃ TOTAL INVENTORY										
CYCLE TIME (HOURS)											
CHARGING	1	PURGE #2	1								
HEAT-UP	15	F ₂ FLUORINATION	15								
HYDROCHLORINATION	12	PURGE #3									
PURGE #1	1	SUB TOTAL	53								
OXIDATION	14	MISC.	8								
B ₂ O ₃ FLUORINATION	8	TOTAL	61								
TOTAL											

* FLOWS BASED ON 1000% EXCESS F₂ @ 75 mole % F₂

Figure A-5
F₂ RECYCLE & PuF₆ RECOVERY
SYSTEM FLOW SHEET

DWG. NO. E-P 33747D

Figure A-6
PROCESS OFF-GAS & CELL
VENTILATION FLOW SHEET

DWG. NO. E-P 33747 AB

SECTION & DETAIL KEY

HEAD END CELL											
ITEM NUMBER	DESCRIPTION	ITEM NUMBER	DESCRIPTION	ITEM NUMBER	DESCRIPTION	ITEM NUMBER	DESCRIPTION	ITEM NUMBER	DESCRIPTION	ITEM NUMBER	DESCRIPTION
608	HEATER	609	HEATER	610	HEATER	611	HEATER	612	HEATER	613	HEATER
614	HEATER	615	HEATER	616	HEATER	617	HEATER	618	HEATER	619	HEATER
620	HEATER	621	HEATER	622	HEATER	623	HEATER	624	HEATER	625	HEATER
626	HEATER	627	HEATER	628	HEATER	629	HEATER	630	HEATER	631	HEATER
632	HEATER	633	HEATER	634	HEATER	635	HEATER	636	HEATER	637	HEATER
638	HEATER	639	HEATER	640	HEATER	641	HEATER	642	HEATER	643	HEATER
644	HEATER	645	HEATER	646	HEATER	647	HEATER	648	HEATER	649	HEATER
650	HEATER	651	HEATER	652	HEATER	653	HEATER	654	HEATER	655	HEATER
656	HEATER	657	HEATER	658	HEATER	659	HEATER	660	HEATER	661	HEATER
662	HEATER	663	HEATER	664	HEATER	665	HEATER	666	HEATER	667	HEATER
668	HEATER	669	HEATER	670	HEATER	671	HEATER	672	HEATER	673	HEATER
674	HEATER	675	HEATER	676	HEATER	677	HEATER	678	HEATER	679	HEATER
680	HEATER	681	HEATER	682	HEATER	683	HEATER	684	HEATER	685	HEATER
686	HEATER	687	HEATER	688	HEATER	689	HEATER	690	HEATER	691	HEATER
692	HEATER	693	HEATER	694	HEATER	695	HEATER	696	HEATER	697	HEATER
698	HEATER	699	HEATER	700	HEATER	701	HEATER	702	HEATER	703	HEATER
704	HEATER	705	HEATER	706	HEATER	707	HEATER	708	HEATER	709	HEATER
710	HEATER	711	HEATER	712	HEATER	713	HEATER	714	HEATER	715	HEATER
716	HEATER	717	HEATER	718	HEATER	719	HEATER	720	HEATER	721	HEATER
722	HEATER	723	HEATER	724	HEATER	725	HEATER	726	HEATER	727	HEATER
728	HEATER	729	HEATER	730	HEATER	731	HEATER	732	HEATER	733	HEATER
734	HEATER	735	HEATER	736	HEATER	737	HEATER	738	HEATER	739	HEATER
740	HEATER	741	HEATER	742	HEATER	743	HEATER	744	HEATER	745	HEATER
746	HEATER	747	HEATER	748	HEATER	749	HEATER	750	HEATER	751	HEATER
752	HEATER	753	HEATER	754	HEATER	755	HEATER	756	HEATER	757	HEATER
758	HEATER	759	HEATER	760	HEATER	761	HEATER	762	HEATER	763	HEATER
764	HEATER	765	HEATER	766	HEATER	767	HEATER	768	HEATER	769	HEATER
770	HEATER	771	HEATER	772	HEATER	773	HEATER	774	HEATER	775	HEATER
776	HEATER	777	HEATER	778	HEATER	779	HEATER	780	HEATER	781	HEATER
782	HEATER	783	HEATER	784	HEATER	785	HEATER	786	HEATER	787	HEATER
788	HEATER	789	HEATER	790	HEATER	791	HEATER	792	HEATER	793	HEATER
794	HEATER	795	HEATER	796	HEATER	797	HEATER	798	HEATER	799	HEATER
800	HEATER	801	HEATER	802	HEATER	803	HEATER	804	HEATER	805	HEATER
806	HEATER	807	HEATER	808	HEATER	809	HEATER	810	HEATER	811	HEATER
812	HEATER	813	HEATER	814	HEATER	815	HEATER	816	HEATER	817	HEATER
818	HEATER	819	HEATER	820	HEATER	821	HEATER	822	HEATER	823	HEATER
824	HEATER	825	HEATER	826	HEATER	827	HEATER	828	HEATER	829	HEATER
830	HEATER	831	HEATER	832	HEATER	833	HEATER	834	HEATER	835	HEATER
836	HEATER	837	HEATER	838	HEATER	839	HEATER	840	HEATER	841	HEATER
842	HEATER	843	HEATER	844	HEATER	845	HEATER	846	HEATER	847	HEATER
848	HEATER	849	HEATER	850	HEATER	851	HEATER	852	HEATER	853	HEATER
854	HEATER	855	HEATER	856	HEATER	857	HEATER	858	HEATER	859	HEATER
860	HEATER	861	HEATER	862	HEATER	863	HEATER	864	HEATER	865	HEATER
866	HEATER	867	HEATER	868	HEATER	869	HEATER	870	HEATER	871	HEATER
872	HEATER	873	HEATER	874	HEATER	875	HEATER	876	HEATER	877	HEATER
878	HEATER	879	HEATER	880	HEATER	881	HEATER	882	HEATER	883	HEATER
884	HEATER	885	HEATER	886	HEATER	887	HEATER	888	HEATER	889	HEATER
890	HEATER	891	HEATER	892	HEATER	893	HEATER	894	HEATER	895	HEATER
896	HEATER	897	HEATER	898	HEATER	899	HEATER	900	HEATER	901	HEATER
902	HEATER	903	HEATER	904	HEATER	905	HEATER	906	HEATER	907	HEATER
908	HEATER	909	HEATER	910	HEATER	911	HEATER	912	HEATER	913	HEATER
914	HEATER	915	HEATER	916	HEATER	917	HEATER	918	HEATER	919	HEATER
920	HEATER	921	HEATER	922	HEATER	923	HEATER	924	HEATER	925	HEATER
926	HEATER	927	HEATER	928	HEATER	929	HEATER	930	HEATER	931	HEATER
932	HEATER	933	HEATER	934	HEATER	935	HEATER	936	HEATER	937	HEATER
938	HEATER	939	HEATER	940	HEATER	941	HEATER	942	HEATER	943	HEATER
944	HEATER	945	HEATER	946	HEATER	947	HEATER	948	HEATER	949	HEATER
950	HEATER	951	HEATER	952	HEATER	953	HEATER	954	HEATER	955	HEATER
956	HEATER	957	HEATER	958	HEATER	959	HEATER	960	HEATER	961	HEATER
962	HEATER	963	HEATER	964	HEATER	965	HEATER	966	HEATER	967	HEATER
968	HEATER	969	HEATER	970	HEATER	971	HEATER	972	HEATER	973	HEATER
974	HEATER	975	HEATER	976	HEATER	977	HEATER	978	HEATER	979	HEATER
980	HEATER	981	HEATER	982	HEATER	983	HEATER	984	HEATER	985	HEATER
986	HEATER	987	HEATER	988	HEATER	989	HEATER	990	HEATER	991	HEATER
992	HEATER	993	HEATER	994	HEATER	995	HEATER	996	HEATER	997	HEATER
998	HEATER	999	HEATER	1000	HEATER						

Figure A-7
PROCESS CANYON EQUIPMENT
LAYOUT PLAN

DWG. NO. E-P 33747W

S E C I I O N 1

Figure A-8

PROCESS CANYON EQUIPMENT
ELEVATION SECTION SHEET NO. 1

DWG. NO. E-P 33747 X

S E C T I O N 2

PIPE TUNNEL

S E C T I O N 3

Figure A-9
PROCESS CANYON EQUIPMENT
ELEVATION SECTIONS SHEET NO. 2

DWG. NO. E-P 33747 Y

SECTION B DETAIL KEY

Figure A-10
PROCESS BUILDING FLOOR PLAN

DWG. NO. E-S 33747 A

SECTION 1/15
SECTION 2/15
SECTION 3/15
SECTION 4/15
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Figure A.11
PROCESS BUILDING SECTIONS

DWG. NO. E-S 33747 B

DESIGN CONDITIONS	REACTOR VESSEL	COOLING JACKET
MAX. OPERATING TEMP.	1100°F	1600°F
MAX. OPERATING PRESS.	25 PSIG	2 PSIG
MAX. HEAT FLUX (COOLING)	13000 Btu/hr-ft ²	
MAX. HEAT FLUX (HEATING)	6.5 Watts/cm ²	
MATERIALS OF CONSTRUCTION	NICKEL 201 (LOW CARBON)	STAIN. STL. 304L
CORROSION ALLOWANCE	1/8"	NONE

* BASED ON REACTOR VESSEL INSIDE AREA.

Figure A-13
 HALOGENATOR, AIV-101

DWG. NO. E-P 33747 K

Figure A-15
SOLIDS HOLD TANK, AIV-401

DWG. NO. E-P 33747 M

PARTS LIST					MATERIAL
PART NO.	QTY. REQD.	NO. REQD.	DESCRIPTION (NAME, SIZE, ETC.)		
1	1	1	10" SCH 40 PIPE, 27' 9 1/2" LG.	10" SCH 40 PIPE	
2	1	1	10" SCH 40 PIPE, 26' 9 1/2" LG.	10" SCH 40 PIPE	
3	1	1	5" SCH 40 PIPE, 1'-10" LG.	5" SCH 40 PIPE	
4	1	1	1" SCH 40 PIPE, 3'-11 1/2" LG.	1" SCH 40 PIPE	
5	1	1	10" PIPE CAP, STD. WT., BUTT WELD	10" PIPE CAP, STD. WT., BUTT WELD	
6	1	1	10" x 5" CONIC. RND., SCH. 40	10" x 5" CONIC. RND., SCH. 40	
7	1	1	5" x 90° ELL., STD. WT.	5" x 90° ELL., STD. WT.	
8	1	1	1" x 90° ELL., STD. WT.	1" x 90° ELL., STD. WT.	
9	2	2	12" x 90° ELL., SCH. 40	12" x 90° ELL., SCH. 40	
10	1	1	5" HALF FLG. AERODIN. CORP. HARBOR	5" HALF FLG. AERODIN. CORP. HARBOR	
11	1	1	10" FLG. RND. HARBOR CORP. HARBOR	10" FLG. RND. HARBOR CORP. HARBOR	
12	1	1	5" HALF FLG. AERODIN. CORP. HARBOR	5" HALF FLG. AERODIN. CORP. HARBOR	
13	1	1	5" x 5" CONIC. RND., STD. WT.	5" x 5" CONIC. RND., STD. WT.	
14	1	1	1/2" THK. R., 16" O.D.	1/2" THK. R., 16" O.D.	
15	3	3	1/2" THK. R., 2" H x 1/2" CO.	1/2" THK. R., 2" H x 1/2" CO.	
16	1	1	1/2" THK. R., 5 1/2" H x 10 1/2" CO.	1/2" THK. R., 5 1/2" H x 10 1/2" CO.	
17	1	1	1/2" THK. R., 2 1/2" H x 6 1/2" CO.	1/2" THK. R., 2 1/2" H x 6 1/2" CO.	
18	1	1	1/2" THK. R., 5 1/2" H x 5" CO.	1/2" THK. R., 5 1/2" H x 5" CO.	
19	1	1	1/2" THK. R., 16" O.D.	1/2" THK. R., 16" O.D.	
20	30	30	1/2" THK. R., 8" H x 12" O.D.	1/2" THK. R., 8" H x 12" O.D.	
21	1	1	1/2" THK. R., 2 1/2" H x 12" O.D.	1/2" THK. R., 2 1/2" H x 12" O.D.	

DESIGN CONDITIONS	REGENERATOR	COOLING AIR
MAX. OPERATING TEMP.	1000° F	350° F
MAX. OPERATING PRESS.	25 PSIG	5 PSIG
MATERIALS OF CONSTRUCTION	Ni 201 (L.C.)	304 S.S.
CORROSION ALLOWANCE	1/8" IN.	NONE

Figure A-16
Bif₅ REGENERATOR, AIV-103

DWG. NO. E-P 33747 N

Figure A-18
UF₆ DISTILLATION EQUIPMENT

DWG. NO. E-P 33747 U

PARTS LIST				
PART NO.	QTY.	DESCRIPTION	DATE, REV.	REVISION
1	2	STD. WT. PIPE CAP		
2	1	1/2" SCH. 40 PIPE - 5'-1 1/2" LONG		
3	1	1/2" TUC. PLATE - 2 1/2" WIDE x 4'-0" LONG		
4	1	1/2" SCH. 40 PIPE - 5'-0" LONG		
5	1	1/2" TUC. PLATE - 5'-0" LONG		
6	1	1/2" TUC. PLATE - 4" WIDE x 10 1/4" LONG		
7	2	1/2" SCH. 40 PIPE - 8 3/4" LONG		
8	1	1/2" SCH. 40 PIPE - 5'-2 1/2" LONG		
9	1	1/2" SCH. 40 PIPE - 10'-10" LONG		
10	1	1/2" TUC. PLATE - 1 1/2" WIDE x 8'-1" LONG		
11	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
12	1	1/2" SCH. 40 PIPE - 5'-11 3/8" LONG		
13	1	1/2" STD. WT. PIPE CAP		
14	1	1/2" TUC. PLATE - 1 1/2" WIDE x 8'-1" LONG		
15	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
16	1	1/2" STD. WT. PIPE CAP		
17	1	1/2" TUC. PLATE - 1 1/2" WIDE x 8'-1" LONG		
18	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
19	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
20	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
21	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
22	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
23	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
24	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
25	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
26	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
27	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		
28	1	1/2" TUC. PLATE - 15 1/2" O.D. x 8'-1" LONG		

Figure A-20
PuF₆ COLD TRAP, AIV-617

NOTE:

ALL VIEWS BASED ON 3 x 4 ARRAY OF 4" DIAMETER TRAPS.

POSSIBLE VARIATIONS IN TRAP DIAMETER AND ARRAY SIZES				
TRAP DIAMETER	ARRAY SIZE	HEIGHT & WEIGHT REPRESENTATIVE DISTANCE	DICTIONAL REPRESENTATIVE DISTANCE	FEET
4"	3 x 4	55 Cm	1.08	
6"	2 x 4	49 Cm	1.60**	
8"	1 x 3	58 Cm	1.04	

* TO LIMIT INTERACTION TO THAT ALLOWED PER FIG 26 IN NUCLEAR SAFETY GUIDE T I O 7016.

** CONCEPTUAL PLANT DESIGN EMPLOYS 2 ARRAYS OF THIS SIZE.

Figure A-21
PuF₆ COLD TRAPPING SYSTEM LAYOUT

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Figure A-23
REFRIGERATION & COOLING AIR
FLOW SHEETS

PLAN
SOLIDS WASTE STORAGE FACILITY

SECTION

PLAN - SOLID STORAGE ASSEMBLIES
AND DISTRIBUTION SYSTEM

Figure A-24
WASTE STORAGE VAULTS AND BINS

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