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AND DEVELOPMENT REPORT

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DESIGN STUDY AND ECONOMIC EVALUATION
OF
HEAD-END REPROCESSING FACILITY
INTEGRAL WITH AN HTGR POWER PLANT

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I. SUMMARY

SCOPE

Preliminary designs and costs have been developed for nuclear fuel head-end reprocessing facilities integral with a large High-Temperature Gas-Cooled Reactor (HTGR) power plant. Head-end reprocessing is defined as that portion of reprocessing preliminary to solvent extraction or other uranium recovery process. The head-end operation in these studies produces ash of uranium and thorium oxides which are dissolved at a modified existing central reprocessing plant to make a feed solution for the solvent extraction operation. Ash shipping and final uranium and thorium recovery costs have been estimated and added to head-end costs to yield total reprocessing and shipping costs. These costs, based on typical utility company financing with 30-year amortization, are summarized in Tables 1 and 2. It should be recognized that the costs shown in Tables 1 and 2 are influenced by assumptions made at the time the studies began, fuel element design, and by use of facilities that in some cases require extensive modifications to permit reprocessing of HTGR fuel. Studies are underway to evaluate the economies of a reprocessing plant specifically designed to process HTGR fuels from a large HTGR economy. Also, the total costs shown include both shipping and reprocessing components.

Reprocessing of two HTGR fuel element types is considered. Each type consists of loose, carbon-coated fuel particles contained within a graphite body. The graphite bodies are of different shapes; one is a long, slender rod, and the other is a short, hexagonal block. The burning and storage methods of fuel element waste graphite disposal also have been examined.

CONCLUSIONS

From these studies it is concluded that integral reactor head-end reprocessing is practical as a method of reducing the shipping cost portion of fuel cycle costs. Assuming that the cost figures can be linearly extrapolated, reprocessing with an integral head-end becomes cheaper than reprocessing in the modified existing central plant for stations of about 1200-MW(e) capacity when shipping distance is 2800 miles. The economical station size increases to 1500 to 1600 MW(e) for distances of 900 miles one way.

Table 1
SUMMARY OF COSTS FOR HTGR FUEL REPROCESSING AND SHIPPING
(UNBONDED FUEL PARTICLES)
(Basis: 30-Year Amortization of Integral Reactor Head-End Facilities)

Case Element Type Graphite Disposition	Cost (mills/kW-hr)						Shipping Distance (miles)
	IA Rod Storage		IA1 Rod Burn		IB Block Burn		
Reactor Size (MW(e))	660	1000	660	1000	660	1000	
<u>With integral reactor head-end</u>							
Head-end charges							
Annual fixed cost	0.125	0.099	0.088	0.063	0.079	0.056	
Direct operating cost ^a	0.060	0.051	0.091	0.076	0.088	0.073	
Shipping cost ^b							
Rail, cask 1	0.014	0.013	0.015	0.015	0.016	0.015	900
Rail, cask 2	0.006	0.006	0.006	0.006	0.006	0.007	900
Truck, cask 1	0.021	0.022	0.024	0.024	0.026	0.025	900
Rail, cask 1	0.033	0.031	0.035	0.035	0.038	0.037	2800
Rail, cask 2	0.015	0.014	0.015	0.014	0.015	0.015	2800
Ash reprocessing cost ^c	0.116	0.100	0.116	0.100	0.109	0.091	
Total cost							
Rail, cask 1	0.315	0.263	0.310	0.254	0.292	0.235	900
Rail, cask 2	0.307	0.256	0.301	0.245	0.282	0.227	900
Truck, cask 1	0.322	0.272	0.319	0.263	0.302	0.245	900
Rail, cask 1	0.334	0.281	0.330	0.274	0.314	0.257	2800
Rail, cask 2	0.316	0.264	0.310	0.253	0.291	0.235	2800
<u>With central plant head-end</u>							
Shipping cost ^b							
Rail, cask 1			0.070	0.071	0.064	0.064	900
Rail, cask 2			0.031	0.029	0.031	0.030	900
Truck, cask 1			0.117	0.118	0.106	0.106	900
Rail, cask 1			0.169	0.168	0.152	0.152	2800
Rail, cask 2			0.072	0.068	0.072	0.072	2800
Fuel element reprocessing cost ^d			0.189	0.165	0.177	0.149	
Total cost							
Rail, cask 1			0.259	0.236	0.241	0.213	900
Rail, cask 2			0.220	0.194	0.208	0.180	900
Truck, cask 1			0.306	0.283	0.282	0.255	900
Rail, cask 1			0.358	0.333	0.308	0.302	2800
Rail, cask 2			0.261	0.233	0.249	0.221	2800

^aIncludes labor plus chemicals and utilities.

^bSee Appendix F for cask description.

^cAsh processing at existing central reprocessing facility.

^dFuel element processed at existing central reprocessing facility.

Table 2

**SUMMARY OF COSTS FOR HTGR FUEL REPROCESSING AND SHIPPING
(UNBONDED FUEL PARTICLES)**

(Basis: 30-Year Amortization of Integral Reactor Head-End Facilities)

Case Element Type Graphite Disposition	Cost (\$/kg Total Heavy Metals)						Shipping Distance (miles)
	IA Rod Storage		IA1 Rod Burn		IB Block Burn		
Reactor Size (MW(e))	660	1000	660	1000	660	1000	
<u>With integral reactor head-end</u>							
Head-end charges							
Annual fixed cost	98	78	69	49	63	46	
Direct operating cost ^a	47	40	72	60	73	60	
Shipping cost ^b							
Rail, cask 1	11	10	12	12	13	12	900
Rail, cask 2	5	5	5	5	5	6	900
Truck, cask 1	17	17	19	19	21	21	900
Rail, cask 1	26	24	28	27	31	31	2800
Rail, cask 2	12	11	12	11	12	12	2800
Ash reprocessing cost ^c	91	78	91	78	90	75	
Total cost							
Rail, cask 1	247	206	244	199	241	194	900
Rail, cask 2	241	201	237	192	233	188	900
Truck, cask 1	253	213	251	206	249	203	900
Rail, cask 1	262	220	260	214	259	213	2800
Rail, cask 2	248	207	244	198	240	194	2800
<u>With central plant head-end</u>							
Shipping cost ^b							
Rail, cask 1			55	56	53	53	900
Rail, cask 2			24	23	26	25	900
Truck, cask 1			92	92	88	88	900
Rail, cask 1			133	132	126	126	2800
Rail, cask 2			56	53	60	60	2800
Fuel element reprocessing cost ^d			148	129	146	123	
Total cost							
Rail, cask 1			203	185	199	176	900
Rail, cask 2			172	152	172	148	900
Truck, cask 1			240	221	234	211	900
Rail, cask 1			281	261	272	249	2800
Rail, cask 2			204	182	206	183	2800

^a Includes labor plus chemicals and utilities.

^b See Appendix F for cask description.

^c Ash processing at existing central reprocessing facility.

^d Fuel element processed at existing central reprocessing facility.

The combined cost of reprocessing and shipping varies little whether fuel element waste graphite is stored or burned; the differences shown in Tables 1 and 2 are believed to be beyond the precision of the calculations. Variation in shape of the fuel element results in a lower cost for combined reprocessing-shipping of the hexagonal block elements.

The reprocessing costs in Tables 1 and 2* have been developed primarily for comparison of on-reactor site head-end reprocessing with head-end reprocessing in a modified existing multipurpose reprocessing plant.† The costs of modifying this existing plant to make it capable of handling HTGR fuel have been amortized over a small reprocessing load that would be generated during buildup to only a 5000-MW(e) HTGR economy. A single-purpose central reprocessing plant, optimized for HTGR fuel and able to handle a 15,000-MW(e) economy, should give significantly lower reprocessing costs, as indicated in Ref. 1.

II. INTRODUCTION

This report covers fuel reprocessing studies performed by the General Atomic Division of General Dynamics Corporation under U.S. Atomic Energy Commission Contract AT(04-3)-167. The primary objective of this contract is the preliminary design and development of a 1000-MW(e) High-Temperature Gas-Cooled Reactor (HTGR). The studies are intended to evaluate the advantages and disadvantages of head-end reprocessing at the reactor site versus at the central reprocessing plant and to determine the combined reprocessing-shipping costs for each method. The effect of fuel element design on head-end processing at the reactor site is also examined. The advantages and disadvantages of on-site storage of radioactive waste are determined. It is expected that these and future studies can be used as a guide in selecting, developing, optimizing, and locating head-end methods for processing HTGR fuels. The results of the studies are also expected to influence, to some extent, fuel element design and fuel management.

The HTGR is a helium-cooled, graphite-moderated reactor utilizing a U^{235} - U^{233} -Th fuel cycle to produce steam at about 1000°F. A prototype 40-MW(e) HTGR has been constructed for the Philadelphia Electric Company at Peach Bottom, Pennsylvania. A 330-MW(e) HTGR is now being designed for the Public Service Company of Colorado and will be located near Denver, Colorado. The trend of new reactor installations is toward larger power production capacities. For the purposes of study, two reactor sizes have been assumed: 660 MW(e) and 1000 MW(e).

* See also Tables G-1 and G-2 (Appendix G).

† Nuclear Fuels Services (NFS) plant in New York State.

The HTGR fuel element selected for these studies is composed of pyrolytic-carbon-coated thorium and uranium oxide fuel particles and graphite. At the present time there are no reprocessing facilities that can process graphite-type fuel without fairly significant plant modification. The one private reprocessing facility now in operation lacks a means for the separation and disposal of graphite. The addition of graphite head-end facilities to this reprocessing plant would provide the capability for complete reprocessing of HTGR fuels at some added costs over an optimized HTGR reprocessing facility. Another solution would be to install a head-end reprocessing facility integral with the reactor. This solution offers the following advantages:

1. Reduction in spent fuel shipping costs resulting from the reduction in the volume of material to be shipped.
2. Utilization by the graphite-handling head-end of reactor support facilities, for example, ventilation systems, health physics services, and decontamination equipment.
3. The opportunity to develop head-end technology on a small scale before advancing to full-scale reprocessing facilities.
4. The applicability of utility company financing, i. e., 30-year amortization of head-end capital investment.

In these studies, it was assumed that the Th-U²³⁵ particles have no further use in the fuel cycle and that after separation they are stored either at the reactor site or at the central reprocessing plant.

The integral reactor head-end reprocessing concept consists of mechanically and chemically treating, in a plant contiguous to the reactor, spent fuel elements for further reprocessing off-site and storing of the wastes generated by the operation. In addition to possessing the advantages described above, the concept can (1) take advantage of fuel element handling equipment and other reactor facilities which can be used in common; (2) produce a material which can be further reprocessed off-site with minimum modification of off-site reprocessing facilities; and (3) reduce operating expenses by using reactor head-end plant personnel in common, wherever possible.

In common with the reactor, the head-end reprocessing facility uses the following facilities located in or near the reactor building: fuel handling and storage facilities, hot service facility for equipment maintenance, decontamination system, radioactive waste disposal equipment, and reactor plant ventilation system.

III. BASES OF DESIGN STUDY

Several alternative fuel element designs and head-end reprocessing routes are possible candidates for consideration in this and future reprocessing studies. To avoid repetition and unnecessary detailing, the "base case" approach to design is used. In this approach, one fuel element and one reprocessing route have been arbitrarily designated the "base case" (Case 1A). Work on this case has been done in some detail, and other cases are developed by examining the differences from the base case. The process cases examined are as follows:

Case 1A: Integral reactor, head-end reprocessing;
rod-type fuel element; graphite storage.

Case 1A1: Integral reactor, head-end reprocessing;
rod-type fuel element; graphite burning.

Case 1B: Integral reactor, head-end reprocessing; hexagonal
block-type fuel element; graphite burning.

In all cases, fuel particles are assumed to be free and unbonded to the graphite body of the fuel element.

Throughput rates for the head-end facilities have been set at a rate designed to process the annual reactor discharge in 43 weeks or less. This figure is the estimated time during which shared reactor equipment is available for reprocessing use.

Two kinds of fuel elements were used as bases of study: the single-dial, hexagonal spine (rod-type) element and the hexagonal block element.

The first fuel element, shown in Fig. 1, consists of an upper reflector section, fuel-bearing sleeve sections, a center spine, and a bottom reflector section. The fuel element body is composed entirely of graphite, which serves as both structural and moderator material. The element has the external appearance of a solid graphite cylinder, 4.67 inches in diameter by 240 inches long, with a grappling knob at the top for handling. Although different types of fuel loadings have different uranium-thorium and boron contents, in this study it was assumed that the elements have an average identical loading insofar as head-end reprocessing throughput is concerned. The fuel-containing sleeve assembly consists of fueled sections connected by cemented threaded joints. Each sleeve section has holes containing beds of pyrolytic-carbon-coated fuel particles. The spine assembly consists of several sections connected by cemented threaded joints to make the complete spine. The 26-inch-long lower reflector and

Fig. 1--Single dial, hexagonal spine (rod type) fuel element

the 28-inch-long upper reflector are made of a solid piece of graphite. The upper reflector is joined to both the fuel sleeve assembly and the center spine. The fuel bed consists of a homogeneous mixture of two types of particles: the first had a substrate of a mixture of thorium and U^{235} (about 93% enriched) as oxides; the other has a substrate of thorium oxide. The fuel substrates are coated with two layers of carbon: a low-density carbon buffer coating and an external pyrolytic carbon coating. Typical parameters of the particles are:

	<u>Type I</u>	<u>Type II</u>
Th:U ratio	3.5:1	All Th
Substrate diameter (μ)	220	350
Coating thickness (μ)	100	100
Particle diameter (μ)	420	550

The second element, shown in Fig. 2, consists of a hexagonal graphite block 15.61 inches long and 14.17 inches across flats. In this study, it is assumed that each has an identical average fuel loading. The fuel particles, loaded in the holes of the graphite block, are as described for the rod-type element.

Several alternative types of fuel elements, differing primarily in fuel particle composition and treatment (i.e., particles bonded to each other and the graphite body, carbide substrate particles, and particles with silicon carbide or zirconium carbide coatings), are subjects of future studies.

The fuel burnup varies slightly, depending on the reactor and the element. An average burnup of 79,000 MWd/tonne of uranium plus thorium is used as a basis for design for the rod-type element, and 88,000 MWd/tonne is used for the hexagonal block element.

Table 3 summarizes, for the two types of fuel elements studied, the characteristics of importance in fuel reprocessing.

Table 3
FUEL ELEMENT CHARACTERISTICS

	<u>Rod Type</u>	<u>Block Type</u>
Diameter (inches)	4.67	----
Width across flats (inches)	----	14.17
Length (inches)	240.0	15.61
Gross weight (kg)	118.80	62.7
Thorium loading (kg)	7.93	5.54
Uranium loading (kg)	0.67	0.49

Fig. 2--Hexagonal block fuel element

IV. PROCESS DESCRIPTIONS

GENERAL

In the three cases presented (IA, IA1, and IB), many common bases have been established. The process systems are designed for remote maintenance of auxiliary equipment either in place by using manipulators or by removing to the reactor hot service facility. Cooling water, potable water, ventilation systems, electrical services, steam, compressed air, storm and sanitary sewers, and shipping and receiving facilities are shared with the reactor. Although the head-end facilities are integrated with the reactor complex, operations are subservient to the reactor, and reactor operation is completely independent of the reprocessing unit.

The head-end process consists essentially of the grinding, screening, and burning of fuel elements, which have been stored for 120 days or longer to permit decay of Pa^{233} and to lower the general activity to reduce shipping costs. Reprocessing rates have been set on the basis of six rod-type elements or ten hexagonal block elements per operating day (42 to 51 kg of heavy metal per day). When only fuel particles are burned, an 8-hour operating day is used. When structural graphite is also burned, a 24-hour operating day is used.

As part of the head-end process, several equipment items are used in common with the reactor. These items, associated with fuel handling, equipment maintenance, and waste handling, are as follows:

1. Fuel Transfer Machine. This device handles and stores fuel elements and reflector blocks and provides shielding to protect operating personnel. It is transported by crane or rails between the reactor vessel, the reactor fuel storage facility, and the reprocessing cell. The reactor is equipped with a gas purge system to prevent release of activity when the fuel transfer machine is in use.
2. Hot Service Facility. This facility, provided primarily to permit repairs of reactor equipment, is used in similar service for maintenance of reprocessing equipment. The facility consists of a shielded cell, decontamination facilities, ventilation system, and remotely operable tools and manipulators.
3. Shielding Casks. The casks transport the reactor and reprocessing equipment to the hot service facility. The casks are moved with the reactor building crane or on rails.

4. Gaseous Waste Disposal System. The system consists of piping, tanks, valves, filters, radioactivity monitors, and stack. Suspect gas from throughout the reactor and reprocessing facility are routed through this system for monitoring and disposal.

CASE IA: ROD-TYPE FUEL ELEMENT, GRAPHITE STORAGE

In brief, the process consists of transporting the fuel elements to the process cell; sawing the elements into sections; separating the structural graphite, the thorium particles, and the thorium-uranium particles from each other; packaging and storing the crushed graphite and thorium-uranium particles; and burning the thorium particles to remove the graphite coating. The thorium-oxide product is packaged and shipped to an off-site fuel reprocessing plant for recovery of thorium and U^{233} . These operations are described in detail in the following paragraphs. Illustrations and a material balance are presented in Appendix A. Equipment numbers in this section refer to items on the flow diagrams. Some auxiliary items, such as hoists and manipulators, are not shown on the flow diagrams. Fuel particles are identified by their preirradiation composition.

Spent Fuel Storage and Transportation

Spent fuel is discharged from the reactors once each year: 730 fuel elements from a 660-MW(e) unit and 1110 fuel elements from a 1000-MW(e) unit. As part of the reactor operation, the elements are moved in the fuel transfer cask from the reactor to the reactor fuel storage vault. After a decay period of about 120 days, and when no other fuel handling operations are in progress, the spent fuel is transported in the fuel transfer cask to the process cell.

Six elements are loaded from the fuel storage vault into the fuel transfer cask. This load constitutes the daily charge to the head-end reprocessing unit and is processed in an 8-hour period. The fuel transfer cask is moved on rails to a position directly over the charging hole of the process cell and is connected to the cell through the reactor isolation valve (a part of an existing reactor facility).

Process Cell Operation

To charge the sawing unit (S-1801), the indexed feed tube of the unit is rotated to the vertical position and the fuel element is lowered from the cask into the feed tube. The tube, with the fuel element inside, is rotated to the horizontal position. The element is moved forward in the feed tube in measured increments by means of a stud inserted in a longitudinal slot in the feed tube and propelled by a motor-driven lead screw. The element

is moved forward under the saw blade to a position indexed to make a cut in the middle of a fuel-bearing portion of the fuel element. Successive cuts are made as processing progresses. The cut-off segments of the elements (about 31 inches long) are within the shaker portion of the sawing unit. Fuel particles are removed from the graphite portions of the fuel segment by shaking. The shaker is then rotated to discharge the other end of the two-chambered fuel segment. Fuel particles are discharged to a vibrating screen (S-1803), and the graphite sleeve and spine are released from the shaker (by rotation) into the crusher (S-1802). Crushed graphite is also dropped onto the vibrating screen. The vibrating screen separates by size the thorium fuel particles, the thorium-uranium fuel particles, and the crushed graphite, and discharges them into their respective weighing units (S-1806, S-1804, and S-1805). Total weights of components are compared with estimated fuel element total and component weights as an operation check.

Thorium-uranium particles and crushed graphite are packaged separately and placed in long-term storage (described later in this section).

Batch charges of thorium particles (containing U^{233}) are weighed from the thorium particle weighing unit into the thorium particle feed hopper (T-1805).

Once each day, about 142 pounds (1.1 cubic feet) of particles are airveyed from the thorium particle feed hopper (T-1805) into the oxidizer (S-1807). A charge of alundum (about 250 pounds) is introduced into the oxidizer by airveying from the alundum bin (T-1801).

After the oxidizer has been charged, fluidizing air is admitted to the unit. Inlet air and/or oxygen are heated by the gas preheater (E-1801) to bring the oxidizer up to burning temperature. Burning rate is controlled by adjusting the oxygen-to-air ratio of the oxidizer inlet gas. The progress of the burning cycle is monitored by combustion gas analyzers in the off-gas system.

At the end of the oxidizer burning cycle (4 to 6 hours) the thorium-ash alundum is cooled and transported with fluidizing air into the thorium ash bin (T-1802). A sample point is located at the oxidizer outlet to permit analysis of product ash.

Weighed amounts of thorium ash are metered from the thorium ash bin through the thorium ash weighing unit (S-1809) and into a shipping can located on a can positioner (S-1821). When filling is complete, the can positioner is moved horizontally from under the filling tube. The can is then lifted by a bridge-mounted hoist (G-1801) and placed in a six-place, rotating thorium-ash can carousel (S-1812). As each can is filled, it is

moved into the can carousel and a threaded plug closure is installed with manipulators (S-1813 and S-1814). When six shipping cans are filled, the can carousel, with cans in place, is lifted by the hoist and placed in a position directly beneath the cell unloading hatch. Index pins are provided for exact positioning of the carousel. The shipping cans are brushed and vacuumed to remove loose, external contamination and then lifted from the carousel, one at a time, into the fuel element transfer cask, which is in position over the loading hatch. Rotation of the carousel by the manipulators positions each shipping can in alignment with the lifting mechanism of the fuel transfer cask. Shipping cans are unloaded from the fuel element transfer cask into a spent fuel shipping cask for off-site shipment.

In-cell storage space is provided for the empty cans that are to be filled with the thorium ash and thorium uranium particles. The empty cans are loaded into the process cell via the empty can conveyer (S-1823). A pair of lead gate valves (S-1827) closes the cell opening. The cans are fitted with lifting knobs to permit remote handling with a storage can grapppler (S-1825) suspended on the hoist cable.

Removal of equipment less than 2 feet in diameter from the process cell is accomplished by remotely disconnecting the equipment with a process cell monorail hoist (G-1801) and a process cell monorail hoist transfer bridge (G-1802), positioning it in an equipment removal parking stand (S-1815), and lifting it through a cell hatch into the reactor equipment transfer cask. Larger items are lowered through a floor hatch into the reactor circulator removal cask. Decontamination and maintenance are performed in the reactor service facility. Hoist and bridge maintenance are performed in a shielded bay adjacent to the process cell.

Operations inside the process cell are observed (1) through a lead glass window, (2) by a portable television camera (to be moved about by the hoist), and (3) by a television camera mounted on the hoist.

Drainage of the process cell is provided through the process cell sump to monitored reactor liquid waste tanks.

Off-Gas Cleanup

Oxidizer off-gas contains CO₂, CO, O₂, N₂, volatile fission products, and particulate matter. Off-gas leaves the oxidizer and passes through the gas cooler (E-1806), where the gas is cooled to 750°F to protect the sintered metal filter in the cyclone separator (S-1808). Most of the particulate matter is removed by the separator and the sintered metal filter. Provision for back-blowing the filters permits periodic cleaning of accumulated particulate. Particulate is returned to the oxidizer via a dip leg extending into the bed. Off-gas from the cyclone separator is further cooled

by a gas cooler (E-1802). Air is the cooling medium for the gas coolers (E-1802 and E-1806) and the oxidizer. The closed circuit of cooling air is, in turn, cooled by water in the air cooler (E-1803). Cooling air is recirculated by the air circulators (C-1802 and C-1802S). Off-gas from the cyclone passes through the silica gel adsorber (A-1801) to remove ruthenium and cesium, is drawn through the absolute filters (F-1802 and F-1802S), and is discharged to the stack via exhaust fans (C-1802 and C-1802S). Cell ventilating air is admitted to the cell through an absolute filter (F-1801). Exhaust fans (C-1801 and C-1801S) discharge the air to the reactor ventilation system and stack. Particulate and gas radiation detectors monitor the gas and air discharged.

Thorium-Uranium Particle Storage

At the reactor site, packaged thorium-uranium particles are stored in a vault adjacent to the process cell. Space is provided to store particles produced during the 30 years of anticipated reactor life. The vault is equipped with an array of vertical metal tubes designed to maintain particle storage cans in a critically safe configuration and to provide a path for cooling air. Additional vault equipment includes a monorail hoist system, television cameras, ventilation filters, and blowers. A maintenance bay is provided for servicing the hoist and the hoist transfer dolly.

Thorium-uranium particles are weighed into storage cans from the thorium-uranium particle weighing unit (S-1804). The can is moved from under the filling spout by the can positioner (S-1822), and a threaded-plug closure is installed with manipulators. The can is lifted with the storage can grappeler (S-1825) and the process cell monorail hoist and transfer bridge (G-1801 and G-1802) and placed in the thorium-uranium transfer chute (S-1816). The chute provides a passageway from the process cell into the thorium-uranium storage vault. In the vault, the storage can is lifted with a storage can grappeler, the thorium-uranium storage monorail hoist, and the transfer dolly (S-1825, G-1805, and G-1806) and placed in a selected storage tube. The operation is monitored with television cameras. To allow for possible future processing of thorium-uranium particles, and to provide temporary storage for thorium ash, the storage cans can be retrieved from the vault and returned to the process cell via the thorium ash return chute (S-1826).

Vault ventilation air is provided through the thorium-uranium storage roughing filter (F-1811) and is channeled into a lower plenum, up through the storage tubes into the upper plenum, and to three thorium-uranium storage absolute filters (F-1807, F-1808, and F-1809) and three thorium-uranium storage ventilation blowers (C-1805, C-1806, and C-1807). Initially, only one filter and one blower are required for cooling. As vault loading and heat loading increase, two filters and two blowers are required.

The remaining unit is a spare, and a spare ventilation cell is provided. The face of each absolute filter is monitored with a local radiation monitoring unit; filters are changed at predetermined radiation levels or at high pressure drop. Air is discharged to the reactor stack.

Vault drainage is provided to a monitored liquid waste tank in the reactor facility.

Graphite Storage

Graphite from the crusher and screen is discharged from the graphite weighing unit into 55-gallon storage drums located on the drum positioner (S-1820). When a drum is filled, the drum positioner is moved from under the weighing unit to permit lifting with the graphite storage drum tongs (S-1824) and the cell hoist and dolly. The closures are then installed with manipulators, and the drum surface is brushed and vacuumed to remove loose contamination. One week's production may be temporarily stored in the process cell.

To move graphite drums from the process cell to the graphite storage vault, a floor plug is removed and the drums are lifted from the storage position and lowered onto the graphite drum transfer car (S-1819). Three drums are loaded on the car and the car is pulled by a car puller (S-1828) along rails through a tunnel connecting the bottom of the process cell to the entry chamber of the graphite storage vault. In the entry chamber, the graphite drums are lifted from the transfer car with the graphite storage drum tongs and the graphite storage monorail hoist and transfer dolly (G-1803 and G-1804). The vault entry chamber is viewed by television camera to facilitate drum handling. The vault entry chamber serves also as an entry for empty drums and as a hoist and dolly service area. The area may be isolated from the storage vault by a sliding lead door.

In-cell storage space is provided for the empty drums, which enter the system via a loading room at grade level. The drums are lowered by the graphite drum conveyer (S-1818) and moved under the hoist by the graphite conveyer (horizontal) (S-1817). The drums are lifted by the hoist onto the transfer car, are transported back through the tunnel, and are lifted into the process cell by the in-cell hoist.

The vault is below grade and is equipped with ventilating equipment, television cameras, a lead glass window, and a monorail hoist system for handling the drums. The vault holds the graphite produced during five years of reactor operation and is designed for the addition of five-year storage volume increments. Drum handling operations are observed and controlled from a viewing gallery located adjacent to the vault, the entry chamber, and the ventilation equipment room.

Vault ventilation is provided through an above-grade inlet, a graphite storage ventilation roughing filter (F-1804), graphite storage ventilation absolute filters (F-1804 and F-1806), and two exhaust blowers (C-1804 and C-1804S). During normal operation, both filter units and one exhaust blower are used. Filters are changed as indicated by pressure drop or surface radiation. Air is discharged to the reactor stack. Vault drainage is provided by graphite storage sump pumps (P-1801 and P-1801S) located in the entry chamber. Water is discharged to a monitored reactor liquid waste tank.

Fresh air is supplied to the graphite storage vault viewing gallery by an above-grade suction pipe to two blowers (C-1809 and C-1809S), which keep the gallery pressurized to 2 inches of H₂O. The air is exhausted above grade.

CASE IA1: ROD-TYPE FUEL ELEMENT, GRAPHITE BURNING

Case IA1 is the same as Case IA except that fuel element structural graphite is burned rather than stored. Thus, graphite storage facilities are not required. The additional burning load of this graphite is accommodated by operating portions of the system for 24 hours per day and by increasing the size of some equipment items. The feed rate remains at six elements per day. These operations are illustrated and a material balance is given in Appendix B.

CASE IB: HEXAGONAL BLOCK-TYPE FUEL ELEMENT, GRAPHITE BURNING

Case IB is the same as Case IA1 except that the hexagonal block-type fuel element is processed. The feed rate to the process cell is 10 fuel blocks per day, which is approximately equal in graphite quantity to the 6 rod-type elements used in Cases IA and IA1. These operations are illustrated and a material balance is given in Appendix C.

V. REPROCESSING PLANT DESIGN PARAMETERS

CRITICALITY, DECAY HEAT REMOVAL, AND SHIELDING

Studies were made of the criticality of containers and of arrays of containers for fuel particle storage (Ref. 2). The following fuel particle types were considered:

1. Unirradiated pyrolytic-carbon-coated Th²³²-U²³³ oxide particles with a thorium-to-uranium ratio of 3.5:1 (reactor charge composition).
2. Unirradiated pyrolytic-carbon-coated U²³³ oxide particles.
3. Irradiated (depleted) Th-U²³³ particles.

Values of k_{eff} as a function of storage container radius and of container wall thickness were obtained for bare and reflected cylinders. For water-flooded infinite arrays, k_{eff} was obtained for various distances between container walls. These data determined the dimensions of the storage containers, the container arrays, and the container wall.

Graphite and particle storage bins were designed as slabs, primarily for heat dissipation reasons rather than criticality.

Calculations of k_{eff} showed that a shipping cask holding twenty 4.5-inch-i. d. cans filled with a mixture of alundum and spent Th-U²³³ oxide ash were critically safe even if both cask and cans were accidentally flooded with water.

Heat generation and maximum temperature calculations were made for a variety of storage container configurations. These calculations were used as the basis for the design and selection of the containers for thorium-uranium particles, Th-U²³³ ash, and graphite.

No unusual shielding is required for the processing cell, the storage vaults, or the shipping cask.

EQUIPMENT DESIGN AND MAINTENANCE

Equipment less than 2 feet in diameter is remotely disconnected with an impact wrench and removed from the process cell by the monorail hoist system. The equipment is positioned in a parking stand and lifted through a cell hatch into the reactor auxiliary transfer cask. Decontamination and maintenance are performed in the reactor hot service facility. Hoist and bridge maintenance are performed in a shielded bay adjacent to the process cell.

The 300-series stainless steels are used as construction material for process equipment. Sawing, crushing, and grinding machines are of closed design and are equipped with vents to draw off graphite dust and thus minimize dusting of the process cell with graphite. Equipment is driven by air motors or shielded electrical motors, depending on the size of the equipment being operated.

Material is pneumatically conveyed to the oxidizer. All other flows of graphite, fuel particles, and ash are by gravity. The oxidizer, which is constructed of 310 stainless steel, is the major piece of cell equipment and is designed for removal from the cell via the reactor auxiliary transfer cask. Maintenance of the oxidizer is performed in the reactor hot service facility.

VI. WASTE MANAGEMENT

Wastes produced from head-end reprocessing consist of structural graphite, thorium-uranium fuel particles, and burner off-gas. In addition, some aqueous wastes are produced during head-end equipment decontamination operations. In subsequent uranium recovery and decontamination operations, aqueous fission product wastes, aqueous thorium solutions, solid aluminum wastes, and gaseous wastes are generated.

To examine methods of structural graphite disposal, data for two head-end reprocessing routes were developed. In the first (Case IA), graphite is reduced in size (crushed), separated from the fuel particles, packaged, and placed in cooled underground vaults for long-term storage. This method has the advantage of requiring smaller oxidizer and off-gas facilities because only the graphite coating from the fuel particles is burned. The disadvantage is, of course, that large graphite storage vaults are required. In the drawings (Appendix A), only the first increment of storage is shown. During the life of the reactor, an additional vault will be required every 5 years for a 660-MW(e) reactor and every 3.3 years for a 1000-MW(e) reactor.

In the second route (Case IA1), graphite is burned in the oxidizer and no graphite waste storage vaults are required. To accommodate the greatly increased burning load, it is necessary to significantly enlarge the oxidizer and the off-gas cleanup system and to operate the facility on a 24-hour day rather than the 8-hour day used for Case IA. In comparing costs for the two process routes, no significant difference is found for the 660-MW(e) reactor; for the 1000-MW(e) reactor, costs for graphite burning are slightly lower. It is recommended, therefore, that for head-end facilities located either at the reactor site or at a central reprocessing plant, the graphite be disposed of by burning.

The HTGR fuels considered here contain two particle types: the fuel charged as thorium oxide and that charged as a mixture of thorium and uranium oxides. In these studies, the thorium particles are processed to recover bred U^{233} . Because of the U^{236} content, the uranium in the thorium-uranium particles is not recovered; therefore, long-term storage

of these particles is employed. (Storage facilities are described in other sections of this report.) It has been assumed that facilities of the same type will be provided at the integral reactor head-end and the central reprocessing facility.

The head-end oxidizer emits combustion gases contaminated with radioactive particulate matter and gases. Except for Kr^{85} , C^{14} , and tritium, the combustion gases are decontaminated by the off-gas cleanup train and directed to the reactor ventilation system, where they are diluted with reactor system ventilating air and discharged to the reactor stack. Calculations indicate that the discharge gas at the reactor site is below permissible concentrations. (3)

Liquid wastes produced at the integral reactor head-end facility are those generated during equipment decontamination prior to maintenance operations. These wastes are combined with similar reactor system wastes for treatment and disposal, using reactor facilities. The thorium and uranium recovery operation at the central reprocessing plant generates the usual highly radioactive wastes, which are treated, concentrated, and placed in long-term storage. In addition, interim decay storage of thorium solutions is employed. A storage period of 10 to 20 years allows time for the decay of Th^{228} and Th^{234} . At the end of this period, thorium solutions are cool enough for reuse, and the stainless steel storage tanks can be used again for subsequent thorium decay storage.

Spent alundum from the burn-leach operation is packaged in barrels and buried as low-activity waste.

VII. COST DEVELOPMENT

HEAD-END CAPITAL AND OPERATING COSTS

Head-end capital and operating costs were developed as detailed in Appendix D. Head-end capital costs were obtained by applying the indirect or overhead cost factors shown in Table D-1 to building and equipment direct costs. The indirect costs are based on studies for an on-site fluoride volatility plant, (4) a reprocessing plant at the Dresden Reactor, (5) and the Idaho Chemical Processing Plant (ICPP) waste calciner. (6)

Startup costs (Table D-2) are assumed to be one-half the annual operating labor, materials, supplies, and utilities expenditures.

Total capital costs and startup costs are combined and capitalized by applying the annual fixed charge percentage developed in Table D-3. To illustrate the effects of different modes of financing, fixed charge

percentages for the process cell and equipment and the thorium storage cell have been calculated with a 30-year amortization period (Table D-4) and, alternatively, with a 10-year amortization period (Table D-5). Thirty-year amortization is generally conventional for utility companies; the shorter period is more typical of chemical and petroleum companies. Therefore, annual fixed charges based on the longer period of amortization have been used for a head-end unit built integral with a power station.

In Case IA, which has facilities for storing graphite waste, waste storage vaults are built in increments sized to hold a five-year waste accumulation from a 660-MW(e) reactor (or a 3.3 year accumulation from a 1000-MW(e) reactor). These units, therefore, are amortized over these shorter periods of time. In the development of costs, no charge has been made for long-term surveillance of stored graphite or thorium-uranium particles for the period starting immediately after the end of reactor life; it is assumed that such charges are included with similar charges required for the reactor.

Operating manpower requirements are developed in Table D-6. Plant operation and maintenance are estimated to take less than the full year, with reprocessing labor available for reactor loading and fresh fuel handling. An interchange of labor between reactor and reprocessing unit is assumed; no charge is made for reactor use of reprocessing personnel. Overhead costs are assumed to be 75% of direct labor costs: 25% for employee benefits and 50% for plant overhead.

Tables D-7 and D-8 present usage and costs for materials, supplies, and utilities. Quantities are based on the material balances, and costs are based on estimates from current periodicals.

CENTRAL FACILITY REPROCESSING COSTS

Central facility reprocessing costs were developed as detailed in Appendix E and are summarized in Table E-1. Fuel reprocessing costs are based on work done jointly by Nuclear Fuel Services (NFS) and General Atomic to estimate the cost of HTGR fuel reprocessing and represent the cost for a small HTGR economy. Capital cost estimates (Table E-2, Mode I) have been adjusted (Mode IV) to include the added cost of separation (Mode II) of the two types of particles and storage of thorium-uranium particles (Mode III).

The NFS-General Atomic cost study was based on an assumption that HTGR fuel elements from only 5000 MW(e) of HTGRs would be processed through this modified facility between 1972 and 1980. With a larger throughput during this period the reprocessing costs would be expected to

decrease significantly, but time did not permit an evaluation of this parameter during the short course of the study. Thus, the cost of facilities added to the NFS plant was amortized over 375 operating and 125 turnaround days (or 187, 500 kg of heavy metals). The cost of reprocessing HTGR fuel elements and thorium particle ash is thus higher than can be expected of large HTGR economies. An evaluation of advanced converters⁽¹⁾ presents a reprocessing cost of \$87.40 per kg of heavy metals when the uranium particles are stored instead of reprocessed. This cost is based on a 15,000-MW(e) reactor economy with the capital cost of the reprocessing plant amortized over approximately 10 years at 22% fixed charges (about 2,000,000 kg of heavy metal). It is believed that a single-purpose central plant optimized for HTGR fuel reprocessing will result in even lower costs per kg of heavy metal.

Daily operating costs are adjusted to the Mode IV capability by applying the ratio of capital costs (shown in Table E-2) as a multiplier to certain operating items, and by incorporating new depreciation and interest charges into the daily operating cost, as developed in Table E-3.

Central facility ash reprocessing costs are developed from data published in the NFS hearings before the Joint Committee on Atomic Energy (Ref. 7), but with investment requirements increased by an assumed \$1,000,000 for recovery and storage facilities to handle ash. The published NFS daily processing charge for ThU₂-UO₂ fuels is adjusted, as shown in Table E-4, to include the additional cost of facilities required for ash reprocessing.

NFS reprocessing charges are based on the capability of processing 500 kg/day of heavy metals. The process days, shown in Table E-5, include turnaround days as specified by NFS.

SHIPPING COSTS

Shipping costs were developed as detailed in Appendix F. The calculation⁽⁸⁾ assumes one-way shipping distances of 900 and 2800 miles. Reflectors are shipped in the same manner as the fuel elements. For determining rail shipping rates, a shipment value of less than \$0.40/lb has been used. Resultant rates are \$1.62/cwt for the 900-mile distance and \$4.17/cwt for the 2800-mile distance.

To obtain the charge for casks and equipment for both rail and truck shipments, it is assumed that the number of HTGRs is sufficient to make cask sharing possible. Because of the cask sharing, no more than 80% cask utilization can be achieved.

VIII. CONCLUSIONS

The conclusions are based on the reprocessing of fuel elements containing loose, unbonded pyrolytic-carbon-coated fuel particles. Integral reactor head-end reprocessing has been examined for two power station sizes, 660 MW(e) and 1000 MW(e). Assuming the cost figures developed for these cases can be linearly extrapolated, reprocessing with an integral reactor head-end becomes cheaper than reprocessing in the modified existing central plant for stations with 1200- to 1600-MW(e) capacity, depending on the shipping distance. Cost for the small capacity station is based on a shipping distance of 2800 miles, and for the higher, a shipping distance of 900 miles. This conclusion is based on data in Tables 1 and 2, for which 30-year amortization of reactor head-end investment costs is assumed. Data for a 10-year amortization period are presented in Appendix G.

Use of the large (120-ton) cask shipped by rail was determined to be advantageous for either distance. Use of smaller shipping casks favors integral reactor head-end plants at even lower power station capacities than indicated above.

Fuel element shape was found to have an effect on reprocessing costs. Costs for reprocessing hexagonal block-type elements are generally lower than those for the rod-type element. This is due primarily to the lighter loading of heavy metals (higher fuel burnup) in the hexagonal block than in the rod element. The reprocessing-shipping costs for the hexagonal block element reprocessed completely at a central plant were found to be from 0.012 to 0.050 mills/kW-hr less than those for the rod element. When an integral reactor head-end operation is employed, the reprocessing-shipping costs for hexagonal block elements are from 0.016 to 0.019 mills/kW-hr less for rod type elements.

As discussed in Section VII, the cost of HTGR fuel reprocessing shows the normal effect of small throughput to a reprocessing plant. This cost is also influenced by utilizing an existing multipurpose central reprocessing plant modified to accept HTGR fuels. These modifications, primarily the addition of head-end facilities, add to the cost disproportionately if the modifications are amortized over a small reprocessing load (low throughput). During this initial period, reactor located head-ends are most competitive with central plant head-ends. For large reactors and shipping distances, the greater cost of reactor located head-ends can be offset by the savings of shipping fuel particle ash rather than the whole fuel element as when the central plant head-end is used.

Appendix A

DRAWINGS AND MATERIAL BALANCE

FOR CASE IA

INDEX

<u>Drawing Title</u>	<u>Drawing No.</u>
Block Flow Diagram Integral Reactor Head-End Reprocessing Case IA (Base)	SK-1(PF)
Process Flow Diagram and Material Balance Integral Reactor Head-End Reprocessing Case IA (Base)	SK-3(PF) (2 sheets)
Process Flow Diagram Integral Reactor Graphite Storage Case IA (Base)	SK-9(PF)
Process Flow Diagram Integral Reactor Th-U Storage Case IA (Base)	SK-10(PF)
Layout Study III Integral Reactor Head-End Reprocessing Case IA (Base)	SK-12(PA) (Plan) SK-13(PA) (Sections)
Layout Study Integral Reactor Graphite Storage Case IA (Base)	SK-11(PA) (Plan) SK-17 (Sections)
Layout Study Integral Reactor Th-U Storage Case IA (Base)	SK-15(PA) (Plans) SK-16(PA) (Sections)
Layout Study III Integral Reactor Head-End Reprocessing Case IA (Base)	SK-18(PP) (Plot Plan)
Integral Reactor Head-End Reprocessing Plant Perspective Case IA (Base)	SK-21(PA)

(6)-ELEMENTS PER STREAM DAY

[illegible]

* @ 60°F, ONE ATMOSPHERE

PRELIMINARY
JUNE 29, 1966

PROCESS FLOW DIAGRAM
INTEGRAL REACTOR
HEAD-END REPROCESSING
CASE 1A (BASE)

GENERAL ATOMIC
DIVISION OF GENERAL DYNAMIC

F.B. 222-100 - San Diego, California 92122		
PROD. NO.	CRIMINAL NUMBER	DATE

317F	SK-3 (PF)	
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C-1804 & C-1804S
VENTILATION
BLOWERS
1500 CFM
3 HP

PRELIMINARY
ISSUE
JULY 15, '65

[illegible]

F-1811
ROUGHING
FILTER
16 FT²

F-1807, F-1808
F-1809 & F-1810
ABSOLUTE
FILTERS
16 FT²

C-1805, C-1806
C-1808
VENTILATION
BLOWERS
10 HP
6" H₂O

PRELIMINARY
ISSUE
JULY 23, 65

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PRELIMINARY
JULY 23, 1965

FOR NOTES & REFERENCES
SEE DWG SK 11 (PA)

DATE	REVISION	BY	CHK	DES	APP	APP	SCALE
							1/4" = 1'-0"

LAYOUT STUDY
INTEGRAL REACTOR
GRAPHITE STORAGE
CASE 1A (BASE)

GENERAL ATOMIC	PROJECT NO.	DRAWING NUMBER	DATE
317F SK 11 (PA)	317F	SK-17(PA)	

317F SK 11 (PA)

GRAPHIC SCALE

[illegible]

SECTION 13-13

SECTION A-A

FOR NOTES & REFERENCE
SEE SK 15 (PA) PLAT VIEWS

PRELIMINARY
JULY 23, 1965

LAYOUT STUDY INTEGRAL REACTOR TH-U STORAGE CASE 1A (BASE) SECTIONS				GENERAL ATOMIC DIVISION OF GENERAL DYNAMICS P.O. BOX 608 SAN DIEGO 1, CALIFORNIA			
DATE	ISSUE DESCRIPTION	DR	CHK	DES	APPD	SCALE	317SK-16 (PA)

317SK 16 (PA)

PRELIMINARY
JULY 28, 1965

							<small>THIS DOCUMENT CONTAINS PROPRIETARY INFORMATION WHICH IS THE PROPERTY OF THE GENERAL ATOMIC DIVISION OF GENERAL DYNAMICS CORPORATION OR THE UNITED STATES GOVERNMENT. POSSESSION OF OR ACCESS TO THIS DOCUMENT WHICH MAY BE GRANTED BY GENERAL ATOMIC TO ANY PERSON OR ORGANIZATION WILL IN NO WAY CONSTITUTE PUBLIC DISCLOSURE OF NOR ACT TO TRANSFER TITLE TO SUCH INFORMATION. THIS DOCUMENT WILL BE RETURNED TO GENERAL ATOMIC UPON REQUEST OR WHEN EVER IT IS NO LONGER REQUIRED FOR THE PURPOSE FOR WHICH IT WAS SUPPLIED. THE INFORMATION CONTAINED HEREIN MAY NOT BE COMMUNICATED TO OTHERS NOR USED IN ANY WAY OTHER THAN AS AUTHORIZED BY GENERAL ATOMIC NOR COPIED IN WHOLE OR IN PART WITHOUT THE EXPRESS WRITTEN CONSENT OF GENERAL ATOMIC.</small>	CASE 1A (BASE)				
								INTEGRAL REACTOR		GENERAL ATOMIC		
								HEAD END		DIVISION OF GENERAL DYNAMICS		
								REPROCESSING PLANT		P.O. BOX 608 SAN DIEGO, CALIFORNIA 92112		
								- PERSPECTIVE -		PROJ NO	DRAWING NUMBER	ISSUE
										317F	SK-21 (PA)	
LTR	DATE	ISSUE DESCRIPTION	DR	CHK	DES	APPD	APPD	SCALE				

Appendix B

DRAWINGS AND MATERIAL BALANCE

FOR CASE 1A1

INDEX

<u>Drawing Title</u>	<u>Drawing No.</u>
Block Flow Diagram	SK-23(PF)
Integral Reactor	
Head-End Reprocessing	
Case IA1	
Process Flow Diagram and Material Balance	SK-22(PF)
Integral Reactor	(2 sheets)
Head-End Reprocessing	
Case IA1	
Integral Reactor	SK-31(PA)
Head-End Reprocessing	
Plant Perspective	
Case IA1	
Layout Study II	SK-28(PA)
Integral Reactor	(Plan)
Head-End Reprocessing	SK-29(PA)
Case IA1	(Sections)
	SK-27(PP)
	(Plot Plan)
Mechanical Details	SK-26(PA)
Integral Reactor	
Fuel and Reprocessing	
Case IA1

(6) ELEMENTS PER STREAM DAY[illegible]

PRELIMINARY
JUNE 29/1966

PROCESS FLOW DIAGRAM
INTEGRAL REACTOR
HEAD END REPROCESSING
CASE 1A1 (BASE)
SHEET 2 OF 2

GENERAL ATOMIC		
DIV. OF GENERAL DYNAMICS		
P.O. BOX 500 SAN JOSE, CALIFORNIA 95128		
NO.	DRAWING NUMBER	ISSUE
F	SK-22 (PF)

PRELIMINARY
DEC. 16, 1963

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									INTEGRAL REACTOR HEAD END REPROCESSING PLANT		GENERAL ATOMIC DIVISION OF GENERAL DYNAMICS P.O. BOX 608 SAN DIEGO, CALIFORNIA 92112	
									- PERSPECTIVE -		PROJ. NO. DRAWING NUMBER ISSUE	
											317F SK-31 (PA)	
DATE	ISSUE DESCRIPTION					DR	CHK	DES	APPD	APPD	SCALE

REFERENCES -

PROCESS FLOW - THOR-URANIUM STORAGE	SK 10
PROCESS FLOW - REPROCESSING	SK 22
PROCESS CELL - PLAN	SK 28
PROCESS CELL - SECTIONS	SK 29
MECHANICAL DETAILS	SK 26
THOR-URANIUM STORAGE - PLAN	SK 15
THOR-URANIUM STORAGE - SECTIONS	SK 16

DATE	REVISION	BY	CHK	DES	APP	APP	SCALE	1/10" = 1'-0"

LAYOUT STUDY II
INTEGRAL REACTOR
HEAD END
REPROCESSING
CASE IA1 - PLOT PLAN

PRELIMINARY
OCTOBER 13, 1965

GENERAL ATOMIC
DIVISION OF GEORGIA INSTITUTE OF TECHNOLOGY
P.O. BOX 1000
ATLANTA, GEORGIA 30302
PROJECT NO. 317F
DRAWING NUMBER SK-27 (PP)

Appendix C

DRAWINGS AND MATERIAL BALANCE

FOR CASE IB

INDEX

<u>Drawing Title</u>	<u>Drawing No.</u>
Block Flow Diagram Integral Reactor Head-End Reprocessing Case IB	SK-30(PF)
Process Flow Diagram and Material Balance Integral Reactor Head-End Reprocessing Case IB	SK-32(PF) (2 sheets)
Integral Reactor Head-End Reprocessing Plant Perspective Case IB	SK-36(PA)
Layout Study I Integral Reactor Head-End Reprocessing Case IB	SK-33(PA) (Plant) SK-34(PA) (Sections)
Layout Study I Integral Reactor Head-End Reprocessing Case IB	SK-35(PP) (Plot Plan)

PRELIMINARY
ISSUE
JAN. 20, 1966

NOTE: FUEL PARTICLE DESIGNATION REFERS TO PRE-IRRADIATION COMPOSITION.

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LTR	DATE	ISSUE DESCRIPTION	DR	CHK.	DES	APPD.	APPD.	SCALE	PROJ. NO.	DRAWING NUMBER	ISSUE	
								NONE	317F	SK-30 (PF)

(10) AVERAGED FUEL BLOCKS PER STREAM DAY

STREAM NUMBER	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
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* @ 60°F. ONE ATMOSPHERE.

PRELIMINARY
JUNE 29, 1966

										PROCESS FLOW DIAGRAM INTEGRAL REACTOR HEAD END REPROCESSING CASE 1B (BASE) SHEET 2 OF 2										GENERAL ATOMIC DIVISION OF GENERAL DYNAMICS 1000 E. 9TH AVE., PITTSBURGH, PA. 15213									
																				SCALE: NONE									
DATE: _____ ISSUE DESCRIPTION: _____ DR: _____ CML: _____ DES: _____ APPD: _____ APPD: _____										PROJ. NO. 317F DRAWING NUMBER SK-32 (PF)										REVIS: _____

PRELIMINARY

JAN. 10 1966

										<p>THIS DOCUMENT CONTAINS PROPRIETARY INFORMATION WHICH IS THE PROPERTY OF THE GENERAL ATOMIC DIVISION OF GENERAL DYNAMICS CORPORATION OR THE UNITED STATES GOVERNMENT. POSSESSION OF OR ACCESS TO THIS DOCUMENT WHICH MAY BE GRANTED BY FEDERAL ORDER TO ANY PERSON OR ORGANIZATION WILL IN NO WAY CONSTITUTE PUBLIC DISCLOSURE OF INFORMATION FOR WHICH IT WAS SUPPLIED. THE INFORMATION CONTAINED HEREIN MAY NOT BE COPIED, REPRODUCED, OR TRANSMITTED IN ANY FORM OR BY ANY MEANS, WITHOUT THE EXPRESS WRITTEN CONSENT OF GENERAL ATOMIC.</p>		<p>CASE 1B</p>			
										<p>INTEGRAL REACTOR HEAD END REPROCESSING PLANT - PERSPECTIVE -</p>		<p>GENERAL ATOMIC DIVISION OF GENERAL DYNAMICS P.O. BOX 88 - SAN DIEGO, CALIFORNIA 92112</p>			
										<p>REQ. NO.</p>		<p>DRAWING NUMBER</p>		<p>SCALE</p>	
										<p>317F</p>		<p>SK-36 (PA)</p>		<p>SCALE</p>

PLAN

PLAN C-C

NOTES & REFERENCES -
 PROCESS FLOW - THOR.-URANIUM STORAGE SK 32
 THOR.-URANIUM STORAGE - PLAN SK 15
 THOR.-URANIUM STORAGE - SECTIONS SK 16
 PROCESS CELL - PLAN SK 33
 PROCESS CELL - SECTIONS SK 34

PLAN 13-13

SECTION A-A

PRELIMINARY
 JAN 20, 1966

LAYOUT STUDY I INTEGRAL REACTOR HEAD END REPROCESSING CASE 1B PLOT PLAN									
DATE	SCALE	BY	CHECKED	APPROVED	DATE	PROJECT NO.	DESIGNER	REVISOR	DATE
						317F	SK-35 (PP)		

317F SK-35 (PP)

Appendix D

HEAD-END CAPITAL AND OPERATING COSTS

Table D-1
CAPITAL COSTS (IN DOLLARS)

Item	Process Cell			Th-U Storage Cell		Graphite Storage Cell
	Case			MW(e)		
	IA	IA1	IB	660	1000	
Building and equipment cost ^a	990,000	1,173,300	1,004,100	362,800	471,000	451,400
Construction overhead and profit (25%) ^b	<u>248,000</u>	<u>294,000</u>	<u>251,300</u>	<u>90,600</u>	<u>117,000</u>	<u>102,800</u>
Subtotal	1,238,000	1,470,300	1,255,400	453,400	588,000	554,000
Engineering design and fee (15%) ^b	<u>185,800</u>	<u>220,500</u>	<u>188,300</u>	<u>68,000</u>	<u>88,000</u>	<u>83,000</u>
Subtotal	1,423,800	1,690,800	1,443,700	521,400	676,000	637,200
Contingency (25%) ^b	<u>356,000</u>	<u>423,500</u>	<u>361,000</u>	<u>130,200</u>	<u>169,000</u>	<u>159,000</u>
Total capital cost	1,779,800	2,114,300	1,804,000	651,600	845,000	796,200

^aReference 9.

^bIndirect cost percentages are based on estimates for facilities of similar size and function (see Refs. 4, 5, and 6).

Table D-2
STARTUP COSTS (IN DOLLARS) ^a

Item	Case IA		Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Labor	94,800	112,200	140,000	154,300	140,000	154,400
Material and supplies	21,400	31,400	45,100	68,700	43,500	65,700
Utilities	1,000	1,600	2,600	3,900	2,700	4,100
Maintenance materials	<u>30,800</u>	<u>61,600</u>	<u>36,000</u>	<u>36,000</u>	<u>30,000</u>	<u>30,000</u>
Total startup costs	148,000	206,800	223,700	262,900	216,200	254,200

^aOne-half of annual operating costs (see Tables D-6 and D-8).

Table D-3
ANNUAL FIXED CHARGE ON INVESTMENT ^a

Item	Process Cell (%)		Graphite Storage (%)	
			660 MW(e)	1000 MW(e)
Return on money invested	6.75	6.75	6.75	6.75
Depreciation				
30 years	1.11			
10 years		7.32		
5 years			17.50	
3.3 years				27.90
Interim replacement	0.35			
Insurance	0.40	0.40	0.40	0.40
Federal income taxes	3.40	3.40	3.40	3.40
State and local taxes	<u>2.45</u>	<u>2.45</u>	<u>2.45</u>	<u>2.45</u>
Total	14.46	20.32	30.50	40.90

^aReference 10.

Table D-4

CAPITAL COSTS AND ANNUAL FIXED COSTS FOR HEAD-END FACILITIES
(30-Year Amortization)

Item	Case IA		Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Capital costs (dollars) ^a						
Process cell	1,779,800	1,779,800	2,114,300	2,114,300	1,804,000	1,804,000
Th-U storage cell	651,600	845,000	651,600	845,000	651,600	845,000
Graphite storage cell	796,000	796,000	-----	-----	-----	-----
Startup ^b	148,000	206,800	223,700	262,900	216,200	254,200
Annual fixed charge (%) ^c						
Process cell + Th-U storage cell	14.46	14.46	14.46	14.46	14.46	14.46
Graphite storage cell ^d	30.50	40.90	-----	-----	-----	-----
Annual fixed charge (dollars)						
Process cell + Th-U storage cell + startup	373,000	409,000	432,000	466,000	386,000	419,000
Graphite storage cell	<u>242,000</u>	<u>326,000</u>	<u>-----</u>	<u>-----</u>	<u>-----</u>	<u>-----</u>
Total	615,000	735,000	432,000	466,000	386,000	419,000
Mills/kW-hr ^e	0.125	0.099	0.088	0.063	0.079	0.056

^a Table D-1^b Table D-2^c Table D-3^d Graphite storage capacity is 5 years for 660-MW(e) facility; 3.3 years for 1000-MW(e) facility.^e kW hours = 4.91×10^9 kW-hr/yr for 660 MW(e) 7.45×10^9 kW-hr/yr for 1000 MW(e)

85% reactor operating factor used.

Table D-5
CAPITAL COSTS AND ANNUAL FIXED COSTS FOR HEAD-END FACILITIES
(10-Year Amortization)

Item	Case IA		Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Capital costs (dollars) ^a						
Process cell	1,779,800	1,779,800	2,114,300	2,114,300	1,804,000	1,804,000
Th-U storage cell	651,600	845,000	651,600	845,000	651,600	845,000
Graphite storage cell	796,000	796,000	-----	-----	-----	-----
Startup ^b	148,000	206,800	223,700	262,000	216,200	254,200
Annual fixed charge (%) ^c						
Process cell + Th-U storage cell	20.32	20.32	20.32	20.32	20.32	20.32
Graphite storage cell ^d	30.50	40.90	-----	-----	-----	-----
Annual fixed charge (dollars)						
Process cell + Th-U storage cell + startup	523,000	575,000	607,000	655,000	542,000	580,000
Graphite storage cell	<u>242,000</u>	<u>326,000</u>	<u>-----</u>	<u>-----</u>	<u>-----</u>	<u>-----</u>
Total	765,000	901,000	607,000	655,000	542,000	580,000
Mills/kW-hr ^e	0.156	0.121	0.124	0.088	0.110	0.078

^a Table D-1

^b Table D-2

^c Table D-3

^d Graphite storage capacity is 5 years for 660-MW(e) facility; 3.3 years for 1000-MW(e) facility.

^e kW hours = 4.91×10^9 kW-hr/yr for 660 MW(e)

7.45×10^9 kW-hr/yr for 1000 MW(e)

85% reactor operating factor used.

Table D-6

OPERATING MANPOWER USAGE AND COST ^a

	Salary or Wage Rate \$/year	Case IA		Case IA1		Case IB	
		No	Expense \$/year	No.	Expense \$/year	No.	Expense \$/year
<u>660 MW(e) 5 days/week</u>							
Shift supervisor	11,600	2	23,200	3	34,800	3	34,800
Chemical engineer	10,000	1	10,000	1	10,000	1	10,000
Operator	8,200	3	24,600	5	41,000	5	41,000
Operator helper	7,600	3	22,800	5	38,000	5	38,000
Instrument man	8,400	1	8,400	2	16,800	2	16,800
Laboratory technician	6,500	1	6,500	1	6,500	1	6,500
Accountability/clerk	5,500	1	5,500	1	5,500	1	5,500
Mechanic	7,400	1	7,400	1	7,400	1	7,400
Subtotal			108,400		160,000		160,000
Fringe benefits and overhead (75%)			81,300		120,000		120,000
Total			189,700		280,000		280,000
Mills/kW-hr			0.039		0.057		0.057
<u>1000 MW(e) 6 days/week</u>							
Shift supervisor	11,600	3	34,800	3	34,800	3	34,800
Chemical engineer	10,000	1	10,000	1	10,000	1	10,000
Operator	8,200	4	32,800	7	57,400	7	57,400
Operator helper	7,600	3	22,800	5	38,000	5	38,000
Instrument man	8,400	1	8,400	2	16,800	2	16,800
Laboratory technician	6,500	1	6,500	1	6,500	1	6,500
Accountability/clerk	5,500	1	5,500	1	5,500	1	5,500
Mechanic	7,400	1	7,400	1	7,400	1	7,400
Subtotal			128,200		176,400		176,400
Fringe benefits and overhead (75%)			96,200		132,300		132,300
Total			224,400		308,700		308,700
Mills/kW-hr			0.030		0.042		0.042

^a Manpower shared with reactor is not shown.

Table D-7

MATERIAL, SUPPLIES, AND UTILITIES USAGE

	Case IA (8 hours/day)					Case IAl (24 hours/day)				Case IB (24 hours/day)			
	Units	Units per Hour	Units per Day	Units per Year		Units per Hour	Units per Day	Units per Year		Units per Hour	Units per Day	Units per Year	
				660 MW(e)	1000 MW(e)			660 MW(e)	1000 MW(e)			660 MW(e)	1000 MW(e)
Operating days				122	185			132	200			143	216
<u>Material and supplies</u>													
Oxygen	SCF	144	864	105,100	159,800	1730	41,520	5,468,000	8,304,000	1550	37,200	5,312,000	8,035,000
Air	SCF	804	4824	587,100	892,400	1525	36,600	4,820,000	7,320,000	1690	40,460	5,792,000	8,791,000
Alundum	lb		246	29,940	45,510		1232/wk	32,030	48,770		1240/wk	35,960	53,570
Cans													
Th-U particles	Can		1.2	146	222		1.2	146	222		1.2	118	179
Th ash	Can		3.6	438	666		3.6	474	720		3.6	514	778
Drums			3.2	421	592	----	----	-----	-----	----	----	-----	-----
Days													
Burning of particles only				121.7	185.0			121.7	185.0			98.4	149.0
Burning of particles only + reflectors				131.7	200.0			131.7	200.0			142.8	216.0
<u>Utilities</u>													
Cooling water	1000 gal	1.1	27.4	3,330	5,062	7.4	179	23,516	35,712	6.2	150	21,386	32,348
Electricity													
Equipment	kW-hr	81	2904	353,400	537,200	136	4,224	556,300	844,800	150	4,560	651,200	985,000
Lights	kW-hr	40											

Table D-8

MATERIALS, SUPPLIES, AND UTILITIES COST

Item	Unit Costs (Dollars)	Cost per Year (Dollars)					
		Case IA (8 hours/day)		Case IA1 (24 hours/day)		Case IB (24 hours/day)	
		660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
<u>Material and supplies</u>							
Oxygen (LOX w/tank)	10.00/MCF	1,051	1,598	54,680	83,040	53,120	80,350
Air	0.03/MCF	18	27	145	220	174	263
Alundum	0.15/lb	4,491	6,827	4,805	7,316	5,394	8,036
Cans							
Th-U particles,		18,700	28,400	18,400	28,400	15,100	22,900
Th ash at \$128 per							
can (used 5 times)	25.60/can	11,213	17,050	12,134	18,432	13,158	19,917
Drums	15.00	6,315	8,800	----	----	----	----
Total		41,788	62,782	90,164	137,408	86,946	131,466
Mills/kW-hr		0.0085	0.0084	0.0184	0.0184	0.0177	0.0177
<u>Utilities</u>							
Cooling water	0.10/1000 gal	333	506	2,352	3,571	2,139	3,235
Electricity	0.005/kW-hr	1,767	2,686	2,782	4,224	3,256	4,925
Total		2,100	3,192	5,134	7,795	5,395	8,160
Mills/kW-hr		0.0004	0.0004	0.0010	0.0011	0.0011	0.0011
<u>Maintenance materials</u>							
<u>Concrete</u>							
Installed cost		(154,600)		(206,600)		(206,600)	
Equipment							
Installed cost		(835,400)		(969,700)		(797,500)	
2% concrete		3,092		4,132		4,132	
7% equipment		58,478		67,879		55,825	
Total		61,570		72,011		59,957	
Mills/kW-hr		0.0125	0.0125	0.0147	0.0147	0.0122	0.0122
Total mills/kW-hr		0.0214	0.0213	0.0341	0.0342	0.0310	0.0310

Appendix E

CENTRAL FACILITY REPROCESSING COSTS

Table E-1

CENTRAL FACILITY REPROCESSING COSTS SUMMARY

	Cases IA, IA1	Case IB
<u>Fuel Elements</u>		
660 MW(e)	$\$57,969/\text{day} \times 16 \text{ days/year}^a = \$928,000/\text{year}$ 0.189 mills/kW-hr	$\$57,969/\text{day} \times 15 \text{ days/year} = \$869,000/\text{year}$ 0.177 mills/kW-hr
1000 MW(e)	$\$58,579/\text{day} \times 21 \text{ days/year} = \$1,230,000/\text{year}$ 0.165 mills/kW-hr	$\$58,579/\text{day} \times 19 \text{ days/year} = \$1,113,000/\text{year}$ 0.149 mills/kW-hr
<u>Ash</u>		
660 MW(e)	$\$35,594/\text{day} \times 16 \text{ days/year} = \$569,000/\text{year}$ 0.116 mills/kW-hr	$\$35,594/\text{day} \times 15 \text{ days/year} = \$534,000/\text{year}$ 0.109 mills/kW-hr
1000 MW(e)	$\$35,594/\text{day} \times 21 \text{ days/year} = \$747,000/\text{year}$ 0.100 mills/kW-hr	$\$35,594/\text{day} \times 19 \text{ days/year} = \$676,000/\text{year}$ 0.091 mills/kW-hr

^aDay = revenue day.

Table E-2

FUEL ELEMENT REPROCESSING CAPITAL COSTS

	Costs (Thousands of Dollars)					
	Mode I U + Th Recovery ^a	Mode II U + Th Recovery + Particle Separation	Mode III Th-U Particle Storage ^b		Mode IV (II + III) U + Th Particle Storage	
			660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Capital Costs						
Contractor costs						
Equipment	1338	1338				
Instruments	116	116				
Electrical	123	123				
Structures	1572	1572				
Labor and other fields	1298	1298				
Home office	1654	1654				
Particle separation ^c		500				
Plant operator cost	<u>829</u>	<u>829</u>				
Total	6930	7430	652	845	8082	8275
Capital ratio	1.00	1.07			1.17	1.19

^a20 rods/day. (11)^bSee Appendix D.^cCost is assumed.

Table E-3

FUEL ELEMENT REPROCESSING DAILY OPERATING COSTS

	Costs (Dollars)			
	U + Th Recovery	Average Capital Ratio	U + Th Recovery, U + Th Particle Storage	
			660 MW(e)	1000 MW(e)
Operating labor and supervision	2996	1.18	3535	3535
Maintenance labor and supervision	786	1.07	841	841
Analytical labor and supervision	1374	1.07	1472	1472
Utilities				
Electricity	1074	1.18	1267	1267
Water	217		217	217
Steam	657		657	657
Indirect and other supplies	1000		1000	1000
Process chemicals	2004		2004	2004
Maintenance parts and supplies	2000		2000	2000
Overhead				
Plant	2420		2420	2420
Corporate	600		600	600
ARDA facilities rental	1789		1789	1789
Depreciation (original facility)	3758		3758	3758
Interest (original facility)	1890		1890	1890
Preoperational (original facility)	756		756	756
Depreciation (new facility) ^a	13860		16150	16550
Interest (new facility) ^b	4282		4980	5110
Preoperational (new facility)	500		500	500
Waste storage, standard	944		944	944
Waste storage, special ^c	2400		2400	2400
Waste surveillance, standard	749		749	749
Waste surveillance, special ^c	1200		1200	1200
Contingency reserve and profit ^b	<u>6311</u>		<u>6840</u>	<u>6920</u>
Dollars/day	53,567		57,969	58,579

^a Total capital cost amortized over 500 "Revenue Units."^b 31% of capital cost amortized over 500 "Revenue Units."^c Stainless steel storage tanks for thorium nitrate solution.

Table E-4
ASH REPROCESSING

	<u>Dollars</u>
NFS daily charge, $\text{UO}_2\text{-ThO}_2$ ^a	\$28,544
Depreciation	2,000
Interest ^b	620
Special waste storage ^c	2,400
Special waste surveillance ^c	1,200
Contingency reserve and profit ^d	<u>830</u>
Total	\$35,594

^aReference 7.

^bAssumed cost of additions required for special handling of HTGR ash is \$1,000,000.

Investment is depreciated over 500 "revenue units:

$$\frac{\$1,000,000}{500 \text{ revenue units}} = \$2,000/\text{revenue units}$$

Interest at 31% of investment is proportioned over 500

"Revenue Units": $\frac{0.31 \times \$1,000,000}{500 \text{ revenue units}} = \$620/\text{revenue unit}$

^cStainless steel storage tanks for thorium nitrate solutions.

^d13.4% of the additions (depreciation, interest, special waste surveillance and storage).

Table E-5
PROCESS DAYS REQUIRED

Cases IA and IA1

660 MW(e)	<u>Days</u>
4074 kg heavy metal/year $\div$ 500 kg heavy metal processed/day =	8
Turnaround time	<u>8</u>
	16
1000 MW(e)	
6170 kg heavy metal/year $\div$ 500 kg heavy metal processed/day =	13
Turnaround time	<u>8</u>
	21

Case IB

660 MW(e)	
3520 kg heavy metal/year $\div$ 500 kg heavy metal processed/day =	7
Turnaround time	<u>8</u>
	15
1000 MW(e)	
5340 kg heavy metal/year $\div$ 500 kg heavy metal processed/day =	11
Turnaround time	<u>8</u>
	19

Appendix F

SHIPPING COSTS

Table F-1

ANNUAL DISCHARGE OF PRODUCT ASH AND SHIPPING COSTS^a
 (Trip Distance = 900 Miles One Way)

	Case IA		Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Cans of ash	438	666	474	720	514	778
Rail, cask 1						
Shipments	11	16	12	18	13	19
Cask assemblies required	0.396	0.600	0.440	0.667	0.440	0.667
Shipment costs	59,700	86,700	65,100	97,600	70,500	103,000
Equipment costs	<u>7,200</u>	<u>10,900</u>	<u>8,000</u>	<u>12,100</u>	<u>8,000</u>	<u>12,100</u>
Total cost (\$)	66,900	97,600	73,100	109,700	78,500	115,100
Mills/kW-hr	0.014	0.013	0.015	0.015	0.016	0.015
\$/kg total heavy metals	11	10	12	12	13	12
Rail, cask 2						
Shipments	3	4	3	4	3	5
Cask assemblies required	0.088	0.133	0.088	0.133	0.088	0.133
Shipment costs	26,600	35,400	21,600	35,400	26,600	44,300
Equipment costs	<u>4,800</u>	<u>7,400</u>	<u>4,800</u>	<u>7,400</u>	<u>4,800</u>	<u>7,400</u>
Total cost (\$)	31,400	42,800	31,400	42,800	31,400	51,700
Mills/kW-hr	0.006	0.006	0.006	0.006	0.006	0.007
\$/kg total heavy metals	5	5	5	5	5	6
Truck, cask 1						
Shipments	21	32	23	35	25	37
Cask assemblies required	0.792	1.200	0.826	1.266	0.826	1.266
Shipment costs	101,300	154,400	111,000	168,800	120,600	178,500
Equipment costs	<u>5,700</u>	<u>8,600</u>	<u>5,900</u>	<u>9,100</u>	<u>5,900</u>	<u>9,100</u>
Total cost (\$)	107,000	163,000	116,900	177,900	126,500	187,600
Mills/kW-hr	0.021	0.022	0.024	0.024	0.026	0.025
\$/kg total heavy metals	17	17	19	19	21	21

^aReference 8.

Basis: Rail, cask 1

38-ton cask, 2 casks/RR car, 21 ash cans/cask; total round trip shipment cost is \$5,430/trip; cask-RR car annual cost is \$18,150/unit.

Rail, cask 2

120-ton cask, 1 cask/RR car, 180 ash cans/cask; total round trip shipment cost is \$8,855/trip; cask-RR car annual cost is \$55,500.

Truck, cask 1

38-ton cask, 1 cask/truck, 21 ash cans/cask; total round trip shipment cost is \$4,824/trip; truck-cask annual cost is \$7,175/unit.

Table F-2

ANNUAL DISCHARGE OF FUEL ELEMENTS AND
SHIPPING COSTS^{a, b}

(Trip Distance = 900 Miles One Way)

	Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Fuel elements	730	1110	984	1490
Reflector elements	60	90	444	675
Total elements	790	1200	1428	2165
Rail, cask 1				
Element shipments	57	86	51	78
Cask assemblies required	2.110	3.200	1.893	2.869
Shipment costs	305,500	467,000	278,000	424,000
Equipment cost	<u>38,300</u>	<u>58,100</u>	<u>34,400</u>	<u>52,100</u>
Total cost (\$)	343,800	525,100	312,400	476,100
Mills/kW-hr	0.070	0.071	0.064	0.064
\$/kg total heavy metals	55	56	53	53
Rail, cask 2				
Element shipments	14	20	14	21
Cask assemblies required	0.484	0.734	0.484	0.734
Shipment costs	124,000	177,000	124,000	186,000
Equipment cost	<u>26,800</u>	<u>40,700</u>	<u>26,800</u>	<u>40,700</u>
Total cost (\$)	150,800	217,700	150,800	226,700
Mills/kW-hr	0.031	0.029	0.031	0.030
\$/kg total heavy metals	24	23	26	25
Truck, cask 1				
Shipments	113	172	102	155
Cask assemblies required	4.180	6.340	3.790	5.740
Shipment costs	545,000	830,000	493,000	747,000
Equipment cost	<u>30,000</u>	<u>45,500</u>	<u>27,200</u>	<u>41,200</u>
Total cost (\$)	575,000	875,500	520,200	788,200
Mills/kW-hr	0.117	0.118	0.106	0.106
\$/kg total heavy metals	92	92	88	88

^aReference 8.Basis: Rail, cask 1

38 ton cask, 2 casks/RR car, 7 rod fuel elements, 14 hexagonal elements/cask; total round trip shipment cost is \$5,430/trip; cask-RR car annual cost is \$18,150/unit.

Rail, cask 2

120 ton cask, 1 cask/RR car, 60 rod fuel elements, 105 hexagonal block elements/cask; total round trip shipment cost is \$8,855/trip; cask-RR car annual cost is \$55,500.

Truck, cask 1

38 ton cask, 1 cask/truck, 7 rod fuel elements or 14 hexagonal block elements/cask; total round trip shipment cost is \$4,824/trip; truck cask annual cost is \$7,175/unit.

^bNot applicable for Case IA.

Table F-3

ANNUAL DISCHARGE OF PRODUCT ASH & SHIPPING COSTS^a
(Trip Distance = 2800 Miles One Way)

	Case IA		Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Cans of ash	438	666	474	720	514	778
Rail, cask 1						
Shipments	11	16	12	18	13	19
Cask assemblies required	0.748	1.132	0.792	1.200	0.836	1.266
Shipment costs	146,100	212,500	159,500	239,000	172,800	252,500
Equipment costs	<u>13,600</u>	<u>20,600</u>	<u>14,400</u>	<u>21,800</u>	<u>15,200</u>	<u>23,000</u>
Total cost (\$)	159,700	233,100	173,900	260,800	188,000	275,500
Mills/kW-hr	0.033	0.031	0.036	0.035	0.038	0.037
\$/kg total heavy metals	26	24	28	27	31	31
Rail, cask 2						
Shipments	3	4	3	4	3	5
Cask assemblies required	0.176	0.267	0.176	0.267	0.176	0.267
Shipment costs	64,500	85,900	64,500	85,900	64,500	85,900
Equipment costs	<u>9,800</u>	<u>14,800</u>	<u>9,800</u>	<u>14,800</u>	<u>9,800</u>	<u>14,800</u>
Total cost (\$)	74,300	100,700	74,300	100,700	74,300	100,700
Mills/kW-hr	0.015	0.014	0.015	0.014	0.015	0.015
\$/kg total heavy metals	12	11	12	11	12	12

^aReference 8.

Basis: Rail, cask 1

38 ton cask, 2 casks/RR car, 21 ash cans/cask; total round trip shipment cost is \$13,290/trip; cask-RR car annual cost is \$18,150/unit.

Rail, cask 2

120 ton cask, 1 cask/RR car, 180 ash cans/cask; total round trip shipment cost is \$21,475/trip; cask-RR car annual cost is \$55,500.

Table F-4

ANNUAL DISCHARGE OF FUEL ELEMENTS AND SHIPPING COSTS^a
(Trip Distance = 2800 Miles One Way)

	Case IA1		Case IB	
	660 MW(e)	1000 MW(e)	660 MW(e)	1000 MW(e)
Fuel element	730	1110	984	1490
Reflector elements	60	90	444	675
Total elements	790	1200	1428	2165
Rail, cask 1				
Element shipments	57	86	51	78
Cask assemblies required	4.040	6.130	3.650	5.530
Shipment cost	757,000	1,142,000	677,000	1,035,000
Equipment cost	<u>73,400</u>	<u>111,200</u>	<u>66,300</u>	<u>100,300</u>
Total cost (\$)	830,400	1,253,200	743,300	1,135,300
Mill/kW-hr	0.169	0.168	0.152	0.152
\$/kg total heavy metals	133	132	126	126
Rail, cask 2				
Element shipments	14	20	14	21
Cask assemblies required	0.924	1.400	0.967	1.467
Shipment cost	301,500	431,000	301,500	451,500
Equipment cost	<u>51,300</u>	<u>77,600</u>	<u>53,700</u>	<u>81,300</u>
Total cost (\$)	352,800	508,600	355,200	532,800
Mills/kW-hr	0.072	0.068	0.072	0.072
\$/kg total heavy metals	56	53	60	60

^aReference 8

Basis: Rail, cask 1

38 ton cask, 2 casks/RR car, 7 rod fuel elements, 14 hexagonal block elements/cask; total round trip shipment cost is \$13,290/trip; cask-RR car annual cost is \$18,150/unit.

Rail, cask 2

120 ton cask, 1 cask/RR car, 60 rod fuel elements, 105 hexagonal block elements/cask; total round trip shipment cost is \$21,475/trip; cask-RR car annual cost is \$55,500.

Appendix G

SUMMARY OF COSTS — 10-YEAR AMORTIZATION

Table G-1

SUMMARY OF COSTS FOR HTGR FUEL REPROCESSING AND SHIPPING
(UNBONDED FUEL PARTICLES)

(Basis: 10-Year Amortization of Integral Reactor Head-End Facilities)

Case Element Type Graphite Disposition	Cost (mills/kW-hr)						Shipping Distance (miles)
	IA Rod Storage		IA1 Rod Burn		IB Block Burn		
Reactor Size (MW(e))	660	1000	660	1000	660	1000	
<u>With integral reactor head-end</u>							
Head-end charges							
Annual fixed cost	0.156	0.121	0.124	0.088	0.110	0.078	
Direct operating cost ^a	0.060	0.051	0.091	0.076	0.088	0.073	
Shipping cost ^b							
Rail, cask 1	0.014	0.013	0.015	0.015	0.016	0.015	900
Rail, cask 2	0.006	0.006	0.006	0.006	0.006	0.007	900
Truck, cask 1	0.021	0.022	0.024	0.024	0.026	0.025	900
Rail, cask 1	0.033	0.031	0.036	0.035	0.038	0.037	2800
Rail, cask 2	0.015	0.014	0.015	0.014	0.015	0.015	2800
Ash reprocessing cost ^c	0.116	0.100	0.116	0.100	0.109	0.091	
Total cost							
Rail, cask 1	0.346	0.285	0.346	0.279	0.323	0.257	900
Rail, cask 2	0.338	0.278	0.337	0.270	0.313	0.249	900
Truck, cask 1	0.353	0.294	0.355	0.288	0.333	0.267	900
Rail, cask 1	0.365	0.303	0.367	0.299	0.345	0.279	2800
Rail, cask 2	0.347	0.286	0.346	0.278	0.322	0.257	2800
<u>With central plant head-end</u>							
Shipping cost ^b							
Rail, cask 1			0.070	0.071	0.064	0.064	900
Rail, cask 2			0.031	0.029	0.031	0.030	900
Truck, cask 1			0.117	0.118	0.106	0.106	900
Rail, cask 1			0.169	0.168	0.152	0.152	2800
Rail, cask 2			0.072	0.068	0.072	0.072	2800
Fuel element reprocessing cost ^d			0.189	0.165	0.177	0.149	
Total cost							
Rail, cask 1			0.259	0.236	0.241	0.213	900
Rail, cask 2			0.220	0.194	0.208	0.179	900
Truck, cask 1			0.306	0.283	0.283	0.255	900
Rail, cask 1			0.358	0.333	0.329	0.301	2800
Rail, cask 2			0.261	0.233	0.249	0.221	2800

^aIncludes labor plus chemicals and utilities.

^bSee Appendix F for cask description.

^cAsh processing at existing central reprocessing facility.

^dFuel element processed at existing central reprocessing facility.

Table G-2

**SUMMARY OF COSTS FOR HTGR FUEL REPROCESSING AND SHIPPING
(UNBONDED FUEL PARTICLES)**

(Basis: 10-Year Amortization of Integral Reactor Head-End Facilities)

Case Element Type Graphite Disposition	Cost (\$/kg Total Heavy Metals)						Shipping Distance (miles)
	IA Rod Storage		IA1 Rod Burn		IB Block Burn		
Reactor Size (MW(e))	660	1000	660	1000	660	1000	
<u>With integral reactor head-end</u>							
Head-end charges							
Annual fixed cost	122	95	97	69	89	65	
Direct operating cost ^a	47	40	72	60	73	60	
Shipping cost ^b							
Rail, cask 1	11	10	12	12	13	12	900
Rail, cask 2	5	5	5	5	5	6	900
Truck, cask 1	17	17	19	19	21	21	900
Rail, cask 1	26	24	28	27	31	31	2800
Rail, cask 2	12	11	12	11	12	12	2800
Ash reprocessing cost ^c	91	78	91	78	90	75	
Total cost							
Rail, cask 1	271	223	272	219	267	213	900
Rail, cask 2	265	218	265	212	259	207	900
Truck, cask 1	277	230	279	226	275	222	900
Rail, cask 1	286	237	288	234	285	232	2800
Rail, cask 2	272	224	272	218	266	213	2800
<u>With central plant head-end</u>							
Shipping cost ^b							
Rail, cask 1			55	56	53	53	900
Rail, cask 2			24	23	26	25	900
Truck, cask 1			92	92	88	88	900
Rail, cask 1			133	132	126	126	2800
Rail, cask 2			56	53	60	60	2800
Fuel element reprocessing cost ^d			148	129	146	123	
Total cost							
Rail, cask 1			203	185	199	176	900
Rail, cask 2			172	152	172	148	900
Truck, cask 1			240	221	234	211	900
Rail, cask 1			281	261	272	249	2800
Rail, cask 2			204	182	206	183	2800

^a Includes labor plus chemicals and utilities.

^b See Appendix F for cask description.

^c Ash processing at existing central reprocessing facility.

^d Fuel element processed at existing central reprocessing facility.

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