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PRELIMINARY DESIGN FOR A HEAD-END REPROCESSING
FACILITY INTEGRAL WITH AN HTGR POWER PLANT

by

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April 29, 1966

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PRELIMINARY DESIGN FOR A HEAD-END REPROCESSING
FACILITY INTEGRAL WITH AN HTGR POWER PLANT^{*}

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K. G. Steyer and H. E. Stelling

This is a preprint of a paper to be presented at the
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SUMMARY

Preliminary designs for head-end reprocessing facilities integral with an HTGR power plant have been prepared for the following:

1. Two widely differing fuel element configurations: long slender rods and short thick blocks.

2. Two types of fuel element graphite treatment: storage and burning.

In all cases, a thorium-uranium oxide ash is produced which is suitable for further reprocessing in existing off-site reprocessing facilities (modified slightly for ash handling and thorium recovery and storage). The designs make maximum use of reactor auxiliary equipment, services, and personnel by sharing fuel handling equipment, hot service facilities for equipment maintenance, the decontamination system, the radioactive waste disposal system, and the reactor plant ventilation system and stack.

The head-end reprocessing facilities are designed for remote maintenance with major equipment repairs made in the reactor hot service facility.

The shape of the fuel element has been found to have only a slight effect on the process and equipment. (The study is based on fuel particles not bonded to each other or to the fuel element graphite.)

Costs are being developed for spent fuel shipping, ash shipping, and on-site and off-site fuel reprocessing so that cost comparisons can be made for various fuel cycle alternatives.

INTRODUCTION

This report covers fuel cycle studies performed by General Atomic Division of General Dynamics Corporation under U. S. Atomic Energy Commission Contract AT(04-3)-167. The primary object of this contract

is preliminary design and development of a 1000 MW(e) High-temperature Gas-cooled Reactor (HTGR).

The HTGR, based on the U^{235} - Th^{232} - U^{233} fuel cycle, is characterized by extremely high fuel burnup: 80,000 MWd/tonne or higher. Consequently, the frequency of fuel reprocessing and recycling is low. The HTGR fuel element consists essentially of the fuel and the carbon moderator. Some advantage might be derived by preparing the fuel elements at the reactor site for further reprocessing in existing facilities. For example, separation of fissile and fertile materials and disposal of graphite on-site would reduce shipping costs by reducing the volume of material to be shipped.

The purpose of the reprocessing studies described here is to evaluate the advantages, the disadvantages, and the costs of head-end reprocessing units which are integral with the reactor and make maximum use of reactor facilities. These continuing studies are an important part of the fuel cycle considerations for advanced HTGR power plants.

INTEGRAL REACTOR HEAD-END REPROCESSING

Integral reactor head-end reprocessing consists of (1) mechanically and chemically treating, in a plant contiguous to the reactor, spent fuel elements for further reprocessing off-site, and (2) storage of the wastes generated by the operation. The concept was developed for the following reasons:

1. To take advantage of fuel element handling equipment and other reactor facilities which can be used in common.
2. To reduce the volume of spent nuclear material shipped off-site.
3. To produce a material which can be further reprocessed with minimum modification of existing off-site reprocessing facilities.
4. To reduce operating expenses by using reactor and head-end plant personnel in common wherever possible.

BASIS OF DESIGN STUDY

The studies discussed here are based on either a 660 MW(e) or a 1000 MW(e) reactor. The facilities used in common by the reactor and head-end reprocessing unit consists of the following items located in or near the reactor building:

1. Fuel handling and storage facilities
2. Hot service facilities for equipment maintenance
3. Decontamination system
4. Radioactive waste disposal equipment
5. Reactor plant ventilation system and stack

Several alternative fuel element designs and head-end reprocessing schemes were studied. From these, a fuel element design and head-end reprocessing scheme were selected and preliminary designs were made for all major process equipment, the process cell or building, and major cell accessories such as cranes and the ventilation system. Capital and operating costs are being developed for a base case. Similar costs for alternative elements and processes can be obtained by determining detailed costs for only those items which differ in the alternative and the base case.

The head-end reprocessing unit is designed for remote maintenance. Maintenance of process equipment and auxiliary services is performed either with the equipment in place, using manipulators, or after the equipment is transferred to the hot service facility for maintenance.

Cooling water, potable water, the stack, electrical services, steam, compressed air, storm and sanitary sewers, change rooms, and shipping and receiving facilities are shared with the reactor. Management, health physics, clerical, general office, and miscellaneous service personnel required for reactor operations can also be used for the reprocessing unit. Production, maintenance, laboratory, and engineering personnel, primarily attached to the head-end reprocessing unit, may assist in reactor operations such as fuel unloading and loading.

The head-end reprocessing plant and reactor are integrated; however, head-end reprocessing operations are subservient to the reactor and reactor operation is entirely independent of the head-end unit.

The spent fuel is stored for 150 days to permit protactinium-233 decay.

The head-end process consists essentially of grinding, screening, and burning fuel element components. The design is based as much as possible on existing technology. Reprocessing rates are six rod-type elements per operating day or ten block-type elements per operating day. This is equivalent to 40 to 50 kilograms of heavy metals per day. If only fuel particles are burned, an operating day is 8 hr; the structural graphite is burned over a 24-hr period.

Fuel Element Description

Two kinds of fuel elements were used as a basis for this study: the long thin rod represented by the single dial, hexagonal spine element and the short thick block represented by the hexagonal block element. The elements are described in the HTGR Quarterly Progress Reports for the periods ending February 28, 1965, and August 31, 1965.

The first type of fuel element, shown in Fig. 1, consists of an upper reflector section, fuel-bearing sleeve sections, a center spine, and a lower reflector section. The fuel element body is composed entirely of graphite which serves as both structural and moderator material. The assembled elements have the external appearance of a solid graphite cylinder 4.7 in. in diameter by 20 ft long with a grappling knob at the top. Although there are several fuel loadings which differ in the thorium-uranium content, it was assumed in this study that the elements all have identical loading insofar as head-end reprocessing throughput is concerned. The element fueled sections are connected by cemented threaded joints. Holes in each sleeve section contain beds of pyrocarbon-coated fuel particles. Both the 26-in.-long lower reflector and the 28-in.-long upper reflector are made of a solid piece of graphite. The upper reflector is joined to both the fuel

Fig. 1--Single dial, hexagonal spine fuel element

sleeve assembly and the center spine. The fuel bed consists of a homogeneous mixture of two types of particles: the first (Type I) has a substrate of a mixture of thorium and uranium-235 (about 93% enriched) as oxides; the other particle (Type II) has a substrate of thorium oxide. The fuel substrates are coated with two layers of pyrocarbon: a low density buffer coating and an external high density coating. Typical parameters of the particles are given in Table 1.

Table 1
TYPICAL PARTICLE PARAMETERS

Parameter	Particle	
	Type I	Type II
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 consists of a hexagonal graphite block about 16 in. long and 14 in. across flats. In this study, it is assumed that each element has an identical average fuel loading. The fuel particles, which are loaded in the holes in the graphite block, are the same as those as described for the preceeding element.

The fuel burnup varies slightly depending on the reactor and/or element. An average burnup of 83,000 MWd/tonne of uranium plus thorium is used as a basis for design.

Some of the characteristics of the two types of fuel elements studied are summarized in Table 2.

SHARED EQUIPMENT AND SERVICES

For this study it is assumed that several equipment items and facilities associated with the reactor are also used to service the head-end reprocessing

Table 2

FUEL ELEMENT CHARACTERISTICS

Characteristic	Type of Fuel Element	
	Single Dial, Hexagonal Spine	Hexagonal Block
Diameter, in.	4.7	----
Width across flats, in.	-----	14
Length, in.	240	16
Gross weight, kg	118.8	62.7
Thorium loading, kg	7.93	5.54
Uranium loading, kg	0.67	0.49

unit. These involve fuel handling, equipment maintenance, and waste handling

The fuel transfer machine is designed to handle and temporarily store fuel and reflector blocks and to provide shielding to protect operating personnel. Depending on reactor design, the fuel transfer machine is transported either by crane or on rails from the reactor vessel to the fuel storage facility, the head-end reprocessing unit, or the fuel shipping area. Isolation valves provide gas-tight closure during the fuel transfer operations at each of these areas. A fuel handling purge system, consisting of a vacuum pump, piping, control valves, instrumentation, and control system, is provided to prevent release of activity to the reactor building atmosphere during handling of the spent fuel.

Spent fuel is temporarily stored in a dry uncanned condition under inert gas at atmospheric pressure in the tubular wells of the reactor fuel storage facility, which has a total nominal capacity of one-third of the reactor core.

The reactor incorporates a hot service facility to enable service, repair, and decontamination work to be performed on reactor equipment. This facility, also used for similar work on head-end reprocessing

equipment, is provided with shielding, decontamination facilities, a ventilation and filter system, and various remotely operated tools and manipulators. Auxiliary transfer casks are provided for removal and transfer of reactor equipment. These casks are moved by the building crane and use in conjunction with the isolation valves. Decontamination operations are performed in the hot service facility with a system consisting of solution storage tanks; pumps; solution filters; air, steam, and hot water supplies; and drain headers. Spent solutions are pumped to the radioactive liquid waste disposal system, where wastes are prepared for off-site shipping and disposal.

Radioactive or potentially radioactive gases produced by head-end reprocessing are treated in the head-end reprocessing area and then sent to the reactor radioactive gas waste system. All potentially radioactive gases entering the reactor gas waste system are collected in an inlet header and directed through a vent gas filter. Filter effluent is continuously monitored for activity. If the activity is less than a preset value, the gases are transferred to the ventilation system exhaust filters for dilution and ultimate disposal via the plant stack. Gases having activities which exceed the preset value are diverted to the gas waste vacuum tank, eventually compressed into a gas waste surge tank, and ultimately disposed of by a controlled bleed-off to the ventilation system exhaust filter and from there to the stack.

PROCESS DESCRIPTION

Head-end processes differ slightly depending on the type of element processed. In general, however, they consist of the following steps:

1. Transport of fuel elements from decay storage to the process cell
2. Crushing or sawing and crushing of the elements
3. Separation of particles from structural graphite.

4. Separation of thorium particles and thorium-uranium particles from each other (particle designation is based on fresh fuel composition)
5. Packaging and storing of the thorium-uranium particles
6. Burning or packaging and storing of the graphite (structural and reflector)
7. Burning of the thorium particles to remove pyrocarbon coating
8. Packaging and shipping of the thorium particle ash to an off-site reprocessing plant for recovery of thorium and uranium-233

Figure 2 is a perspective drawing of the head-end reprocessing unit and waste storage facilities for the process plant incorporating graphite burning.

Typical operations for the rod-type fuel element are described below and outlined in Fig. 3. Some auxiliary items such as the hoist and manipulators are not shown in Fig. 3.

Spent Fuel Storage and Transfer

Spent fuel is discharged from a 660 MW(e) reactor at an average yearly rate of 730 fuel elements. The elements are moved to the reactor fuel storage vault by means of the fuel transfer cask as part of reactor operations. After a fuel decay period of about 150 days, and when no other reactor fuel handling operations are in progress, the fuel transfer cask is used to transport and feed fuel to the process cell.

Fuel elements are moved from the fuel storage vault into the fuel transfer cask. The fuel transfer cask is moved to a position directly over the charging hole of the process cell and is connected to the cell through the reactor isolation valve. Six elements constitute the daily charge to the head-end unit; these six elements are processed in essentially a 24-hr period.

Crushing and Screening

The fuel element is lowered from the fuel transfer cask into a feed device and sawing unit. Fuel element sections are then passed into a

Fig. 2--Integral reactor head-end reprocessing plant

Fig. 3--Block flow diagram, integral reactor head-end reprocessing

crusher where they are broken into relatively large pieces, freeing most of the particles. Structural graphite pieces, which are separated from the particles by screening, are further crushed and delivered to a vibrating screen unit. The particles pass directly to this same screen.

The vibrating screen separates thorium fuel particles, thorium-uranium fuel particles, and the crushed graphite. The thorium-uranium particles are weighed, packaged, and placed in long-term storage for possible future use. These particles can also be processed in the head-end facility. Graphite and thorium particles are collected in a storage hopper from which they are batch weighed and air conveyed to the burner.

Thorium Particle and Graphite Oxidation

Crushed structural graphite and the thorium particles are burned in the same oxidizer over a 5-day period. A charge of alundum (used as a heat transfer medium) is introduced into the oxidizer by airveying at the start of the burning period. Periodically, batch charges of graphite are airveyed from the feed hopper to the oxidizer, during which time the fluidizing gas flow is temporarily stopped.

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

At the end of the oxidizer burning cycle (about 4 days for the graphite and 1 day for the associated particles) the thorium-ash and alundum mixture is cooled and transported with fluidizing air into the thorium ash bin. A sample point is located at the oxidizer outlet to permit monitoring of product mixture.

Weighed amounts of the thorium ash and alundum mixture are metered from the thorium ash bin through a weighing unit and into a shipping can

located on a can positioner. When filling is completed, a plug closure is installed on the can with manipulators, and the can positioner is rotated horizontally under the filling tube. When six shipping cans are filled, the can carrier, with cans in place, is lifted with the hoist and placed in a position directly beneath the cell unloading hatch. Index pins are provided for exact location of the carrier. Shipping cans are brushed and vacuumed to remove loose external contamination and are lifted into the fuel transfer cask positioned over the unloading hatch. Shipping cans are unloaded from the fuel element transfer casks into the spent fuel shipping cask.

Empty cans to be filled with the thorium ash and alundum mixture or thorium-uranium particles are loaded into the process cell via the conveyor. A pair of lead gate valves is used to close the conveyor opening into the cell. In-cell storage space is provided for thirty cans.

Observation of operations inside the process cell is accomplished by means of (1) lead glass windows, (2) a portable television camera (moved about by the hoist), and (3) a television camera mounted on the hoist.

Off-Gas Cleanup

Oxidizer off-gas produced by burning graphite with air and/or oxygen contains CO_2 , CO , O_2 , N_2 , volatile fission products, and particulate matter. Off-gas leaves the oxidizer and passes through the gas cooler where the gas is cooled to 750°F to protect the sintered metal filter in the cyclone separator. Most of the particulate matter is removed by the separator and sintered metal filter. Provisions for back-blowing the filters permit periodic cleaning of accumulated particulates. Particulates are returned to the oxidizer via a dip leg extending into the bed. Off-gas from the cyclone separator is further cooled by an additional gas cooler. Air is the cooling medium for the gas coolers and the oxidizer. The closed circuit of cooling air is in turn cooled by water. Off-gas from the cyclone passes through a silica gel adsorber to remove ruthenium and cesium and through absolute filters to remove particulates, and is then discharged to

the reactor stack. Cell ventilating air is admitted to the cell and is discharged through absolute filters. Exhaust fans discharge the air to the reactor stack. Particulate and gas radiation detectors monitor the gas and air.

Thorium-Uranium Particle Storage

Packaged thorium-uranium particles are stored in a vault adjacent to the process cell. For this study sufficient space is provided to store particles produced during the 30 yr of anticipated reactor life. However, the particles can be retrieved for reprocessing if desired. The vault is equipped with an array of vertical metal tubes designed to hold 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, and ventilation filters and blowers.

Thorium-uranium particles are discharged from the process cell into storage cans through a weighing unit. The can is moved from under the filling spout by a can positioner and a threaded-plug closure is installed with manipulators. The can is lifted with a grappler and the monorail hoist and placed in the transfer chute. 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 grappler on the storage monorail hoist and placed in a selected storage tube. The operation is monitored with television cameras. Pending shipment, cans of the thorium ash and aluminum mixture can also be temporarily stored in the particle storage vault.

Vault ventilation air is provided through the roughing filter. The air is channeled into a lower plenum, passes up through the storage tubes into the upper plenum, and then to absolute filters and ventilation blowers. The air is discharged to the reactor stack. Initially only one filter and one blower will be required for cooling. As vault loading and heat loading increases, two filters and two blowers will be required. A third unit is

used as a spare. A spare ventilation cell is provided for possible future ventilation requirements. 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.

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. The following fuel particle types were considered:

1. Unirradiated pyrolytic-carbon-coated $\text{Th}^{232}\text{-U}^{233}$ oxide particles with a thorium-to-uranium ratio of 3.5:1 (reactor charge composition)
2. Unirradiated pyrolytic-carbon-coated U^{233} oxide particles
3. Irradiated (depleted) Th-U^{233} 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 storage containers and container arrays and the container wall thickness.

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

Similar calculations showed that a shipping cask holding twenty-one 4.5-in.-ID cans filled with a mixture of alundum and Th-U^{233} 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 are used as the basis for the design and selection of the containers for thorium-uranium particles, Th-U^{233} ash, and graphite.

No unusual shielding requirements for the processing cell, the storage vaults, or the shipping cask were found.

EQUIPMENT DESIGN

Equipment Maintenance

Equipment less than 2 ft 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.

Process Cell

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

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.

Graphite Storage Vault

For the alternative design case where waste graphite is not burned, a storage vault is provided. Graphite is stored in steel drums. The drums are moved, three at a time, to the storage vault through an underground

tunnel on a remotely operated motorized transfer car. At the graphite vault, the transfer car enters an unloading room or chamber and is remotely unloaded by the storage vault hoist. Drums are carried by the hoist into the vault and stacked for storage. This operation is controlled from the viewing gallery. Operations in both the unloading room and the storage vault may be viewed through lead glass windows or by television. The unloading room may be isolated from the storage vault and used as a hoist maintenance area. Access to the unloading room is provided by a shaft to the surface. Unfilled drums are fed into the system via this shaft.

CONCLUSIONS

Based on existing technology, the on-site head-end reprocessing concept is technically feasible for large HTGRs.

The on-site head-end unit produces material that can be further treated to complete the reprocessing section of the fuel cycle in existing commercial fuel reprocessing facilities.

Differences between rod- and block-type elements, both using pyrolytic-carbon-coated oxide particles, have slight effect on the head-end reprocessing flow scheme or cost.

The volume of material shipped off-site for further reprocessing is substantially reduced.

Fuel accountability determinations may be made at the reactor site to check reprocessing results and charges.

The head-end reprocessing facility can be designed to make effective use of reactor fuel handling equipment.

Further studies are required to evaluate the significance of these conclusions on fuel cycle costs.

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