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NATIONAL HTGR FUEL RECYCLE DEVELOPMENT PROGRAM PLAN

Prepared by
OAK RIDGE NATIONAL LABORATORY
and
GULF GENERAL ATOMIC

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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This is the Program Plan as of December 1970

AUGUST 1971

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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UNION CARBIDE CORPORATION
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SUMMARY

1. INTRODUCTION

High-Temperature Gas-Cooled Reactors (HTGR) have the potential of lowering power costs and improving fuel utilization if fuel recycle capability is established. The objective of the National HTGR Fuel Recycle Development Program is to develop recycle technology such that commercial plants for reprocessing and refabrication of HTGR fuels can be built and operated economically. To accomplish this objective, it is necessary to perform process and equipment development, involving engineering design and testing. The operations considered take place between the discharge of spent fuel elements from the reactor and the return of refabricated fuel elements to the reactor; these include fuel shipping, handling, storage, fuel purification and recovery, refabrication, and waste management. This report describes a plan for accomplishing the program objective and outlines a systematic, orderly, and timely effort. The work is delineated into four specific task areas, designated as Fuel Reprocessing Development, Fuel Refabrication Development, Recycle Fuel Irradiations, and Commercial Recycle Plant Studies. This program plan represents the status of plan on December 31, 1970 and does not necessarily represent the final position of the USAEC.

2. PROGRAM BUDGET AND SCHEDULE

A graphical schedule summarized in Table 1 traces the program from development work in fiscal year 1970 through demonstrated operation of a recycle-fuel pilot plant and conceptual design of a commercial plant in 1980. A total of $48,987,000 in operating expense is associated with the program plan through 1980; the capital costs associated with equipment and facility modifications required for pilot plant operations total $7,831,000. The program costs as a function of task area and year are summarized in Table 2, and Table 3 summarizes capital costs associated with fuel reprocessing and refabrication development.

3. TECHNICAL AND ECONOMIC BACKGROUND

The HTGR fuel cycle begins with a fuel containing thorium and ^{235}U. The thorium is converted into ^{233}U, and when fuel cycle equilibrium is reached about half the fissile material needed for reactor refueling is provided by the ^{233}U. The fuel is in the form of microspherical particles (coated kernels of oxide or carbide with fissile kernels having TRISO coatings and fertile kernels having BISO coatings), bonded together in fuel sticks and inserted into large hexagonal

Table 1. Summary of HTGR Fuel Recycle Development Program Schedule

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
REPROCESSING DEVELOPMENT											
Process Development and Head-End Pilot Plant Design	—	—	—	—	—						
Head-End Pilot Plant Equipment Fabrication and Installation, and Cold Operational Testing				—	—	—	—				
Head-End Pilot Plant Hot Demonstration							—	—	—	—	—
Acid Thorex Pilot Plant Design				—	—						
Acid Thorex Pilot Plant Equipment Fabrication and Installation, and Cold Operational Testing					—	—	—				
Acid Thorex Pilot Plant Hot Demonstration							—	—	—	—	—
REFABRICATION DEVELOPMENT											
Process Development and Refabrication Pilot Plant Design	—	—	—	—	—						
Refabrication Pilot Plant Equipment Fabrication and Installation, and Cold Operational Testing					—	—	—				
Refabrication Pilot Plant Hot Demonstration							—	—	—	—	—
RECYCLE FUEL IRRADIATIONS											
Capsule Irradiation Tests and Peach Bottom Irradiation Tests	—	—	—	—	—						
Proof Tests in FSVR				—	—	—	—	—	—	—	
Refabricated Fuel Irradiation Tests in FSVR							—	—	—	—	—
COMMERCIAL RECYCLE PLANT											
Engineering and Economic Studies		—	—	—	—	—	—	—	—		
Commercial Plant Conceptual Design		—	—				—	—	—	—	—

Table 2. Summary of Costs of HTGR Fuel Recycle Development Program

Task Title	Cost, $1,000, for Each Fiscal Year													Total Manpower and Material
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	After	
Fuel Reprocessing Development	249	685	1,112	1,640	1,841	2,771	2,140	1,280	1,280	1,244	1,100			15,342
Fuel Refabrication Development	680	1,390	2,633	3,008	4,565	3,786	3,096	2,424	2,666	2,180	2,000			28,428
Recycle Fuel Irradiations	120	160	410	305	165	150	152	85	110	100	15	256	51	2,079
Commercial Recycle Plant Studies		94	310	342	396	276	320	524	600	226	50			3,138
Total Operating Budget	1,049	2,329	4,465	5,295	6,967	6,983	5,708	4,313	4,656	3,750	3,165	256	51	48,987
Total Capital Budget														7,831
Total AEC Budget														56,818

Table 3. Summary of Capital Expenditures for Fuel Reprocessing and Refabrication Development

Task Area	Costs ($'s in Thousands)
Fuel Reprocessing Development	
Head-End Pilot Plant	5,700
Acid Thorex Pilot Plant	1,150
Fuel Fabrication Development	981[a]
TOTAL	7,831

[a]The equipment costs for refabrication demonstration were included in the original Thorium-Uranium Fuel Cycle Development Facility, and this amount represents the remainder of those funds.

graphite blocks to form fuel elements. These elements, approximately 31 in. long by 14 in. across the flats, are stacked in the reactor with no added supporting structure. After a four-year exposure, the spent fuel elements are removed from the reactor and reprocessed for fuel recovery and fission product removal. During reprocessing, the elements are mechanically reduced to release the fuel particles. The particles are burned to eliminate their outer carbon coatings and then screened to separate the particles that originally contained ^{235}U from those containing thorium or other materials. This separation step limits the buildup of ^{236}U in subsequent reactor cycles if the spent ^{235}U particles are removed in the reprocessing step. Particle classification accomplishes this separation because particles containing ^{235}U have a silicon carbide coating, which remains intact during burning and gives these particles a larger size than the oxide ash from the thorium BISO-coated particles.

The spent fuel is dissolved and treated by solvent extraction to remove fission products and to separate the ^{233}U from the thorium. The ^{233}U is fabricated into coated particles. The particles are fabricated into fuel sticks and then into fuel elements, which are returned to the reactor.

The recycle fuel must be handled in heavily shielded facilities because of high concentration of ^{232}U, which has daughter products that emit high-energy gamma radiation. Thus, about one-half the fuel elements will be fabricated in a shielded recycle facility; the other fuel elements containing ^{235}U may be fabricated in nonshielded facilities. In addition, only fuel particles containing ^{233}U will be made in the recycle facility; the thorium-containing fertile particles used in the recycle elements will be made in another facility.

Estimates of start-up schedules for commercial 1000-MW(e) HTGR's lead to the conclusion that commercial fuel recycle facilities are needed in 1984; the present program plan is consistent with that need.

4. TASK 100 – FUEL REPROCESSING DEVELOPMENT

The fuel reprocessing development task has three major subtasks: Head-End Reprocessing Development (Subtask 110), Head-End Pilot Plant Demonstration (Subtask 120), and Acid Thorex Pilot Plant Demonstration (Subtask 130). Each is scheduled to give an orderly development that fits the overall schedule of the program, and each is subdivided further into specialized subtasks. The plan presents the need, existing technology, and plan of accomplishment for each subtask.

Subtask 110 is divided into burner feed preparation, in which the graphite fuel elements are treated to minimize the burning needed to remove carbon from the fuel; burner technology, in which carbon is burned from fuel and some fuel is converted to oxides; burner ash handling, in which ^{235}U and ^{233}U are separated by utilizing size differences, if possible, taking advantage of unburned SiC coatings; treatment of classified burner ash, in which SiC-coated particles are further treated as needed to prepare for further processing; alternate methods for maintaining separation of ^{233}U and ^{235}U; scrap recycle; off-gas handling and decontamination; and waste treatment and disposal.

Subtask 120 utilizes the information generated in Subtask 110 and demonstrates that the processes and equipment are satisfactory for preparing irradiated fuel elements for solvent extraction. Since all the spent fuel from the reactor passes through head-end processing, the head-end pilot plant throughput dominates the scale of the fuel recycle plant. Based on experience in the chemical process industry, pilot plants generally need to have throughput rates about 10% or more of a future commercial facility to provide meaningful scale-up data on processes and equipment. Further, to develop the best processes and equipment, pilot plants are usually operated for several years, and hardly ever less than six months. Using these guidelines, the Head-End Pilot Plant was scaled for a throughput rate of about ten Fort St. Vrain Reactor (FSVR) fuel elements per day and considered to operate for a time equivalent to six months at the design throughput rate. Since the pilot plant may not operate always as planned, the program considers that an equivalent six-month run may occur over several years.

Subtask 120 (Head-End Pilot Plant Demonstration) is divided into equipment design, equipment procurement and testing, equipment installation, cold operational testing of the pilot plant, hot operational testing of the pilot plant, treatment and disposal of associated wastes, material handling, and process development support. The principal operations involve sawing and crushing the spent fuel element, separating moderator graphite from the fuel material by screening, followed by burning the fuel in a fluidized bed. The resulting materials are separated by sieving into "burned fissile" and "fertile" particles. At this point, fuels initially having BISO coatings can be leached and prepared for solvent extraction processing. After crushing and burning steps, TRISO-coated fuels are also leached and prepared for solvent extraction processing. The planned location of the Head-End Pilot Plant is the Thorium-Uranium Recycle Facility (TURF), ORNL Building 7930, which is a remotely maintained and operated hot cell facility built especially for demonstration and development of thorium fuel cycle technology.

Subtask 130 demonstrates application of the acid thorex solvent extraction process to the separation and purification of ^{233}U from the thorium and fission products. It is also subdivided into design, procurement and testing of equipment, installation of equipment, cold operational testing, hot demonstration, waste treatment and disposal, material handling, and process development support. The acid thorex pilot plant will be a modification of the preexisting remotely operated but directly maintained Thorex Pilot Plant in ORNL Building 3019. The capacity of the plant is about 6 kg ^{233}U/day, which exceeds the requirements associated with the Head-End Processing Pilot Plant. The principal operations involve separation of the uranium and thorium from the fission products in an extraction column, followed by separation of uranium from the thorium in a partitioning column. The uranium is then separated from the organic solvent in a stripping column and, after evaporation, is transferred to the refabrication pilot plant.

5. TASK 200 — REFABRICATION DEVELOPMENT

The refabrication development task has two major subtasks: Refabrication Process Development (Subtask 210) and Refabrication Pilot Plant Demonstration (Subtask 220). Each is scheduled to fit the overall schedule of the program and is subdivided into specialized subtasks. The plan presents the need, existing technology, and work plan for each subtask.

Subtask 210 is divided into sol preparation, in which the thorium and uranium nitrates from reprocessing are converted to oxide sol by amine extraction in the solex process; microsphere preparation, in which the sol is dehydrated to form small spherical particles of oxide; microsphere coating, in which layers of pyrolytic carbon and possibly SiC are deposited on the fuel particles; particle handling and inspection; fuel stick fabrication in which coated fuel particles are blended in molds, injected with binder, and cured into cylindrical rods; fuel element fabrication, in which the fuel sticks are inserted into graphite blocks; and recycle of off-specification material.

Subtask 220 utilizes the information obtained from Subtask 210, and demonstrates that the processes and equipment are satisfactory for refabrication of fuel elements. As in the other pilot plant subtasks, the work is divided into process and equipment design, procurement and testing of equipment, installation of equipment, cold operational testing of pilot plant, hot demonstration, waste treatment and disposal, materials handling, and process development support. The principal operations involve converting the $^{233}UO_2(NO_3)_2$ (from the Acid Thorex Pilot Plant) into a sol by solvent extraction digestion; using the sol-gel process to convert thoria and urania sols into calcined microspheres; coating the microspheres with various layers of pyrolytic carbon and SiC; blending coated fuel particles; combining fuel particles, graphite filler and binder materials to form fuel sticks, which are then carbonized; and assembling the final fuel element. The scale of operations permits about two recycle elements to be fabricated per day; this throughput is about 5% of that envisioned for a large commercial facility. The planned location of the Fuel Refabrication Pilot Plant is the Thorium-Uranium Recycle Facility (TURF).

6. TASK 300 — RECYCLE FUEL IRRADIATIONS

The irradiation task has four subtasks: Capsule Irradiation Tests (Subtask 301), Peach Bottom Irradiation Tests (Subtask 302), Large-Scale Proof Tests (Subtask 303), and Refabricated Fuel Irradiation Tests (Subtask 304). The scheduling and needs of the irradiation program are followed by presentations of the requirements, technology, and plan of each subtask. Subtask 301 includes small-scale tests in test reactors of developmental fuel particles and fuel sticks. Subtask 302 covers irradiation in the Peach Bottom Reactor of special fuel elements simulating as far as possible the fabrication methods and operating conditions anticipated for HTGR recycle fuel. Both subtasks will provide information on irradiation performance as well as irradiated material for laboratory and engineering tests of reprocessing methods. In Subtask 303 two full-size

HTGR elements, made by recycle fabrication methods but containing ^{235}U rather than ^{233}U, will be tested to verify the capability of the refabrication methods for producing fuel with satisfactory performance. Finally, Subtask 304 will test fuel elements produced in the cold start-up and hot operation of the Refabrication Pilot Plant. Irradiation testing of recycle fuel fabricated during the pilot plant hot demonstration runs provides the final proof and performance tests of the recycle technology developed in this program.

7. TASK 400 — COMMERCIAL RECYCLE PLANT STUDIES

The primary aim of the commercial studies task is to ensure that the technology developed in this program is meaningful to a commercial fuel recycle plant. Thus, an important consideration is feedback to the development tasks of the needs of a commercial plant, and this feedback is the aim of Subtask 410, Engineering and Economic Studies. The subtask is subdivided into process evaluation, which guides the development and evaluates development data for design needs; fuel shipping methods and costs; irradiated fuel storage, which considers the optimum timing, size, and location of storage sites; and waste management and by-product recovery. The engineering studies should be completed in 1978. Subtask 420 concerns the conceptual design of a commercial recycle plant, and translates the results of the development program into a meaningful document for future use. The conceptual design activities include plant layouts, equipment and systems designs, and the preparation of a conceptual design report.

1. INTRODUCTION

The High-Temperature Gas-Cooled Reactor (HTGR) system using the Th-^{233}U fuel cycle has the potential of both lowering power production costs and improving the utilization of our thorium and uranium resources. Studies of HTGR fuel cycle economics have shown that ^{233}U has a relatively high value in HTGR's. As a result, it is economically important to develop HTGR fuel recycle technology. This report summarizes a plan for developing that technology in a logical and economical manner, and is based on information developed in USAEC-sponsored programs at Gulf General Atomic (GGA) and Oak Ridge National Laboratory (ORNL).

The recycle development program is to be carried out largely at ORNL, making use of available facilities such as TURF (Thorium Uranium Recycle Facility) and the Thorex Pilot Plant. The recycle pilot plant demonstration also considers use of these facilities, and constitutes part of the development and proof testing of processes and equipment. However, the Idaho processing plant is also available to the USAEC for carrying out the head-end processing part of the recycle demonstration. Thus, while this report considers the entire fuel recycle demonstration to be carried out at ORNL, permitting the program plan to be outlined in a specific and thorough manner, it does not necessarily represent the position of the USAEC concerning the location of the head-end processing pilot plant.

1.1 OBJECTIVE

The primary objective of this program is the development of fuel recycle technology that is required to establish and support commercial HTGR fuel recycle operations. The intermediate objectives of the program are the development of reprocessing and refabrication processes, equipment, practices, and procedures and demonstration of pilot-scale reprocessing and refabrication operations. A conceptual design of a large-scale recycle plant will be produced during the development program, to be followed by design and construction of a commercial plant by private industry. This program is intended to integrate the efforts of both the AEC and private industry in meeting the objectives.

This program plan outlines the development and demonstration work, provides a schedule for an orderly and efficient approach to commercially acceptable fuel recycle procedures, and establishes the associated priorities, timing, and budget estimates. The program plan does not necessarily represent the final position of the USAEC.

1.2 SCOPE

The scope of the National HTGR Fuel Recycle Development Program includes spent fuel reprocessing, recycle fuel fabrication, storage and shipping where concerned with recycle fuel, waste management, recycle fuels irradiation, conceptual design of a commercial recycle plant, and liaison with private interests in the design and construction of a commercial recycle plant. This program is intended to develop recycle technology for a reference fuel element containing fuel sticks of coated ceramic fuel particles. Alternative fuels will be investigated only to the extent of determining their relative merits. Nonrecycle fuel design or fabrication technology will not be developed in this program. The technology of nonrecycle fuels will be adapted to recycle fuels wherever possible.

The National HTGR Fuel Recycle Development Program Plan is directed toward:

1. summarizing as of December 1970 the development work and the work schedule required to develop a commercial fuel recycle industry for the HTGR in a well ordered, economic manner, and
2. supplying budget estimates and documenting justifications for the development work.

The National HTGR Fuel Recycle Development Program Plan is composed of four specific areas of activity.

1.2.1 Task 100 – Reprocessing Development

This task is the development of processes and equipment required to remove intact spent fuel particles from the spent fuel elements, to separate the recycle (fertile) fuel particles from the fissile fuel particles, and to recover and decontaminate the ^{233}U from the recycle fuel particles.

1.2.2 Task 200 – Refabrication Development

This task is the development of remotely operable processes and equipment for making fuel particles containing recycled ^{233}U and for assembling these fuel particles into HTGR fuel elements.

1.2.3 Task 300 – Recycle Fuel Irradiations

This task is the proof testing and qualification of fuel particles and fuel elements made with the processes and equipment developed for refabrication and providing sufficient irradiated fuel to test, on a significant scale, the processes and equipment developed for reprocessing.

1.2.4 Task 400 — Commercial Recycle Plant Studies

This task is the study of developments in the reprocessing and refabrication areas and their impact on the timing, operability, maintainability, and economics of the commercial recycle plant, and the use of these studies to assist in guiding development program tasks.

In the execution of this program, available and applicable engineering standards and quality assurance practices for designing, constructing, and operating the pilot-plant equipment will be utilized. Concurrent with process and equipment development, standards and procedures will be developed where they are not available or are inadequate to define the technology required to support commercial fuel recycle.

2. PROGRAM BUDGET AND SCHEDULE

Information on the funding and overall scheduling needed for timely completion of the program is collected in this section.

2.1 TIMING AND SCHEDULE

The timing of the program is controlled by two considerations: the most propitious date to start commercial recycle operations and the best utilization of research and development resources — funds, manpower, and facilities. A study of the economics of HTGR fuel recycle and the development required (see Chapter 3) indicates 1984 as the ideal date for the start of commercial recycle operations. The schedule of the development program that must be followed to achieve this objective is shown in Fig. 2.1. The schedules for the four tasks are broken down further in the chapters on these tasks.

2.2 BUDGET

The total cost of the program to the AEC is somewhat over $50 million, with the bulk of the money being spent at a rate of $5 million to $6 million per year during 1972 through 1978. The total is broken down in Table 2.1, which shows the distribution of operating costs with time and among the principal tasks and subtasks. The capital requirements are for equipping and modifying pilot plant facilities at ORNL and will be needed principally during 1973 through 1975. These expenses are itemized for the three pilot plants in Tables 2.2, 2.3, and 2.4. An expenditure of about $80 million from 1978 to 1983 is expected for the construction of the commercial recycle plant. However, this will be private funds of the commercial reprocessor and hence is not shown in the tables of AEC expenditure, and this task is not included in this program.

2.3 KEY PROGRAM MILESTONES

Key milestones of the program plan are given in Table 2.5. These milestones have been indicated on the program schedule, Fig. 2.1, and also on individual schedules of the tasks given in subsequent chapters of this plan.

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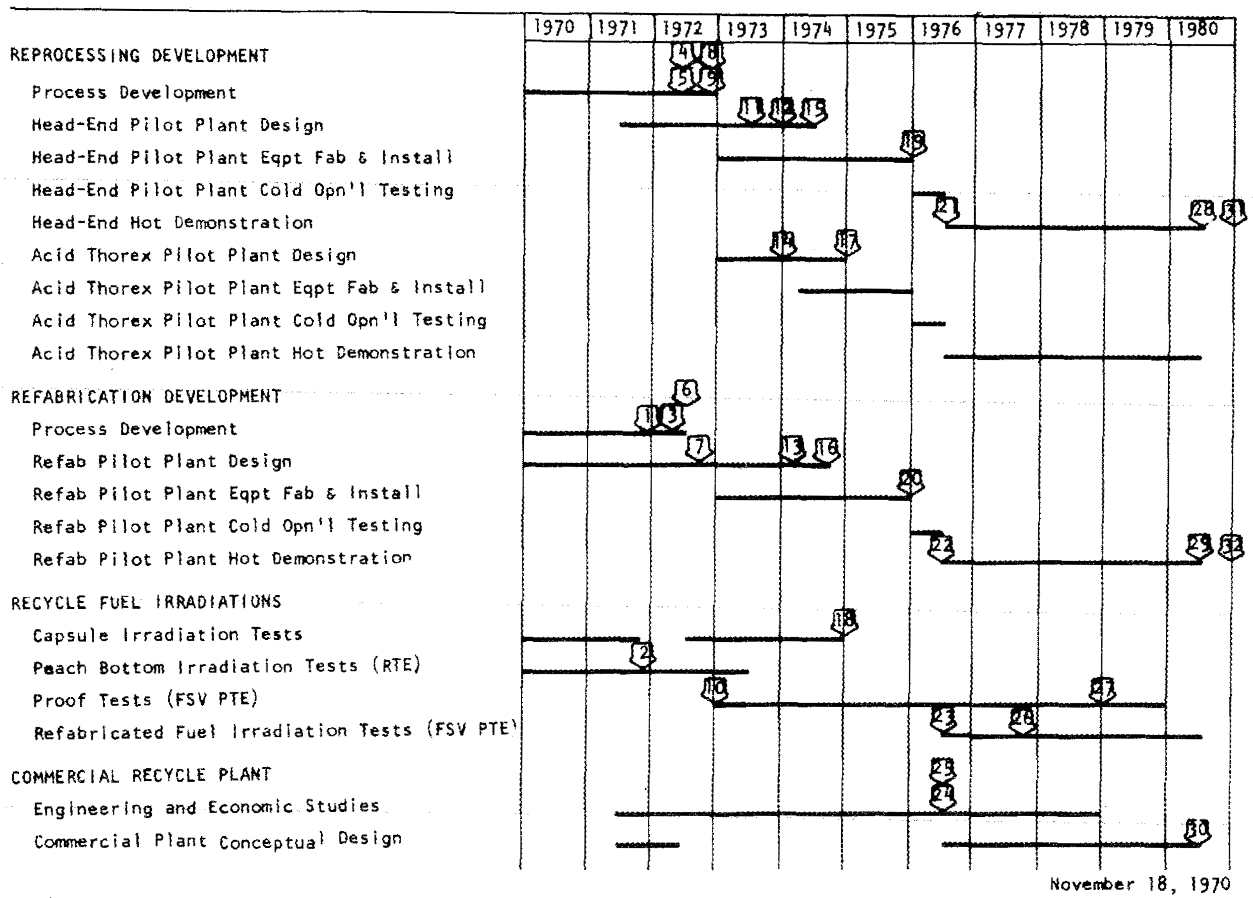

Fig. 2.1. The HTGR Fuel Recycle Development Program Schedule. The numbered arrows refer to the milestones described in Table 2.5 in this chapter.

Table 2.1. Summary of Costs of HTGR Fuel Recycle Development Program

Task	Task Title	Cost, $1,000, for Each Fiscal Year													Total Manpower and Material
		1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	After	
110	Head-end reprocessing development	249	685	1,112	1,104	797	495	100	0	0	0	0	0		4,542
120	Head-end pilot plant demonstration	0	0	0	536	772	1,704	1,368	708	708	672	600	0		7,068
130	Acid Thorex pilot plant demonstration	0	0	0	0	272	572	672	572	572	572	500	0		3,732
210	Refabrication process development	480	590	1,158	1,814	1,383	678	542	0	0	0	0	0		6,645
220	Refabrication pilot plant demonstration	200	800	1,475	1,194	3,182	3,108	2,554	2,424	2,666	2,180	2,000	0		21,783
300	Recycle fuel irradiations	120	160	410	305	165	150	152	85	110	100	15	256	51	2,079
	Irradiation units[a]	0	(200)	(100)	(100)	(50)	0	0	0	0	0	0	0		(450)
400	Commercial recycle plant studies	0	94	310	342	396	276	320	524	600	226	50	0		3,138
Total operating budget		1,049	2,329	4,465	5,295	6,967	6,983	5,708	4,313	4,656	3,750	3,165	256	51	48,987
Total capital budget															7,831
Total AEC budget															56,818

[a]Not included in totals.

Table 2.2. Summary of Capital Expenditure for Reprocessing Development — Head-End Pilot Plant

Item	Approximate Cost
Process Equipment	
Burner feed preparation equipment	$ 300,000
Burner and ash handling equipment	330,000
Classified burner ash treating equipment	175,000
Off-gas handling and decontamination equipment	400,000
Subtotal process equipment	1,205,000
Engineering	600,000
Total process equipment	$1,805,000
Waste Treatment and Disposal	
Solid waste disposal equipment	$ 200,000
Gaseous waste disposal equipment	95,000
Subtotal waste treatment and disposal	295,000
Engineering	150,000
Total waste treatment and disposal	$ 445,000
Material Handling	
Spent fuel receiving and storage area	$2,930,000
Cooling tower	100,000
Subtotal material handling	3,030,000
Engineering	420,000
Total material handling	$3,450,000
Total Head-End Pilot Plant	$5,700,000

Table 2.3. Summary of Capital Expenditures for Reprocessing Development — Acid Thorex Pilot Plant

Item	Approximate Cost
Process Equipment	
Leacher	$ 50,000
Extraction column modifications	60,000
Boron-containing Raschig rings	10,000
Centrifuge for solids removal	50,000
Partitioning column pulser	10,000
Off-gas handling and decontamination equipment	320,000
Subtotal process equipment	500,000
Engineering	250,000
Total process equipment	$ 750,000
Waste Treatment and Disposal	
Solid waste disposal equipment	$ 100,000
Gaseous waste disposal equipment	90,000
Subtotal waste treatment and disposal	190,000
Engineering	90,000
Total waste treatment and disposal	$ 280,000
Material Handling	
Feed-charging mechanism	$ 50,000
^{233}U withdrawal system	30,000
Subtotal material handling	80,000
Engineering	40,000
Total material handling	$ 120,000
Total Acid Thorex Pilot Plant Modifications	$1,150,000

Table 2.4. Summary of Capital Expenditures for Refabrication Development — Refabrication Pilot Plant[a]

Item	Approximate Cost
Sol preparation equipment	$ 110,500
Microsphere preparation equipment	110,000
Microsphere coating equipment	207,000
Fuel stick fabrication equipment	102,000
Fuel element assembly equipment	86,000
Data handling and process control	233,000
Subtotal equipment	848,500
Engineering	20,000
Contingency	113,025
TOTAL	$ 981,525[b]

[a]The equipment costs for refabrication demonstration are included in the original TUFCDF (TURF) construction authorization.

[b]This amount represents the remainder of project funds in AEC Directive No. CL-281.

Table 2.5. HTGR Fuel Recycle Development Program Milestones

Milestone[a]	Task	Event	Date
1	200	Establish fuel stick fabrication technology	January 1972
2	300	Complete hot cell studies with first Peach Bottom test element	January 1972
3	200	Establish microsphere coating technology	March 1972
4	100	Establish method for burner feed preparation	July 1972
5	100	Establish leacher technology	July 1972
6	200	Establish fuel element assembly technology	July 1972
7	200	Issue pilot plant conceptual design report (Refabrication Pilot Plant)	September 1972
8	100	Establish particle separation method	January 1973
9	100	Establish off-gas handling method	January 1973
10	300	Insertion of large-scale proof test elements into FSVR	January 1973
11	100	Complete construction of fuel handling facility	July 1973
12	100	Issue pilot plant conceptual design report (Head-End Pilot Plant)	January 1974
13	200	Issue pilot plant preliminary design report (Refabrication Pilot Plant)	March 1974
14	100	Issue pilot plant conceptual design report (Acid Thorex Pilot Plant)	January 1974
15	100	Issue pilot plant preliminary design report (Head-End Pilot Plant)	July 1974
16	200	Issue pilot plant final design report (Refabrication Pilot Plant)	September 1974
17	100	Issue pilot plant preliminary design report (Acid Thorex Pilot Plant)	January 1975
18	300	Complete capsule irradiation tests	January 1975
19	100	Complete construction of pilot plants (Head-End and Acid Thorex Pilot Plants)	January 1976
20	200	Complete construction of pilot plant (Refabrication Pilot Plant)	January 1976

Table 2.5 (Continued)

Milestone[a]	Task	Event	Date
21	100	Initiate hot demonstration of pilot plants (Head-End and Acid Thorex Pilot Plants)	July 1976
22	200	Initiate hot demonstration of pilot plant (Refabrication Pilot Plant)	July 1976
23	300	Insertion of refabricated test elements into FSVR	July 1976
24	400	Selection of reprocessing process (commercial plant studies)	July 1976
25	400	Selection of refabrication process (commercial plant studies)	July 1976
26	300	Examination of proof test elements	September 1977
27	300	Examination of proof test elements	January 1979
28	100	Complete reprocessing demonstration	July 1980
29	200	Complete refabrication demonstration	July 1980
30	400	Issue commercial recycle plant conceptual design report	July 1980
31	100	Issue reprocessing demonstration final report	January 1981
32	200	Issue refabrication demonstration final report	January 1981

[a]Milestones are indicated by these numbers in Fig. 2.1 and in development schedules in later chapters.

3. TECHNICAL AND ECONOMIC BACKGROUND

To give sound basis for understanding the tasks discussed in the main body of this document, the technology and economics of the fuel recycle are reviewed in this chapter.

3.1 FUEL CYCLE

The HTGR's being developed in the United States will use the Th-^{233}U cycle. The initial core will be fueled with Th-^{235}U (the ^{235}U from 93%-enriched uranium), with increasing amounts of ^{233}U used as it is produced and recovered. Since the conversion ratio of the type HTGR under consideration is about 0.8 with a fuel exposure time of four years, makeup ^{235}U will have to be used throughout the life of the reactor. These conversion ratios are valid only if the spent ^{235}U, which contains ^{236}U, is not recycled with the ^{233}U. Techniques have been proposed to keep the spent ^{235}U separate from the ^{233}U; these will be explained in subsequent sections. The penalty for recycling various amounts of uranium containing the steady-state amount of ^{236}U is described in Appendix A.

3.2 FUEL ELEMENT

The fuel element for the reference HTGR is a hexagonal block of graphite approximately 31 in. long and 14 in. across the flats, as shown in Fig. 3.1. In both the reference 1000-MW(e) HTGR and the Fort St. Vrain HTGR (FSVR) currently being constructed, these fuel elements will be stacked in a close-packed array. No supporting structure or additional moderator material is needed. The typical fuel element contains 102 helium coolant holes and 210 fuel holes. A slightly modified fuel element, shown in Fig. 3.2, contains large holes for the control rods. The FSVR fuel elements are described in Appendix B.

3.3 FUEL

The fuel used in the HTGR is in the form of ceramic kernels (microspheres), coated with pyrolytic carbon and silicon carbide and bonded into sticks that fit into the fuel holes in the graphite blocks.[1] The coatings on the kernels prevent the rapid spread of fission products in the reactor system. An inner layer of low-density pyrolytic carbon is applied to all kernels to provide voids for the fission products and to protect the outer coating from fission recoil damage. The outer layers, which may be either a single layer of high-density pyrolytic carbon or a layer of silicon carbide sandwiched between two layers of

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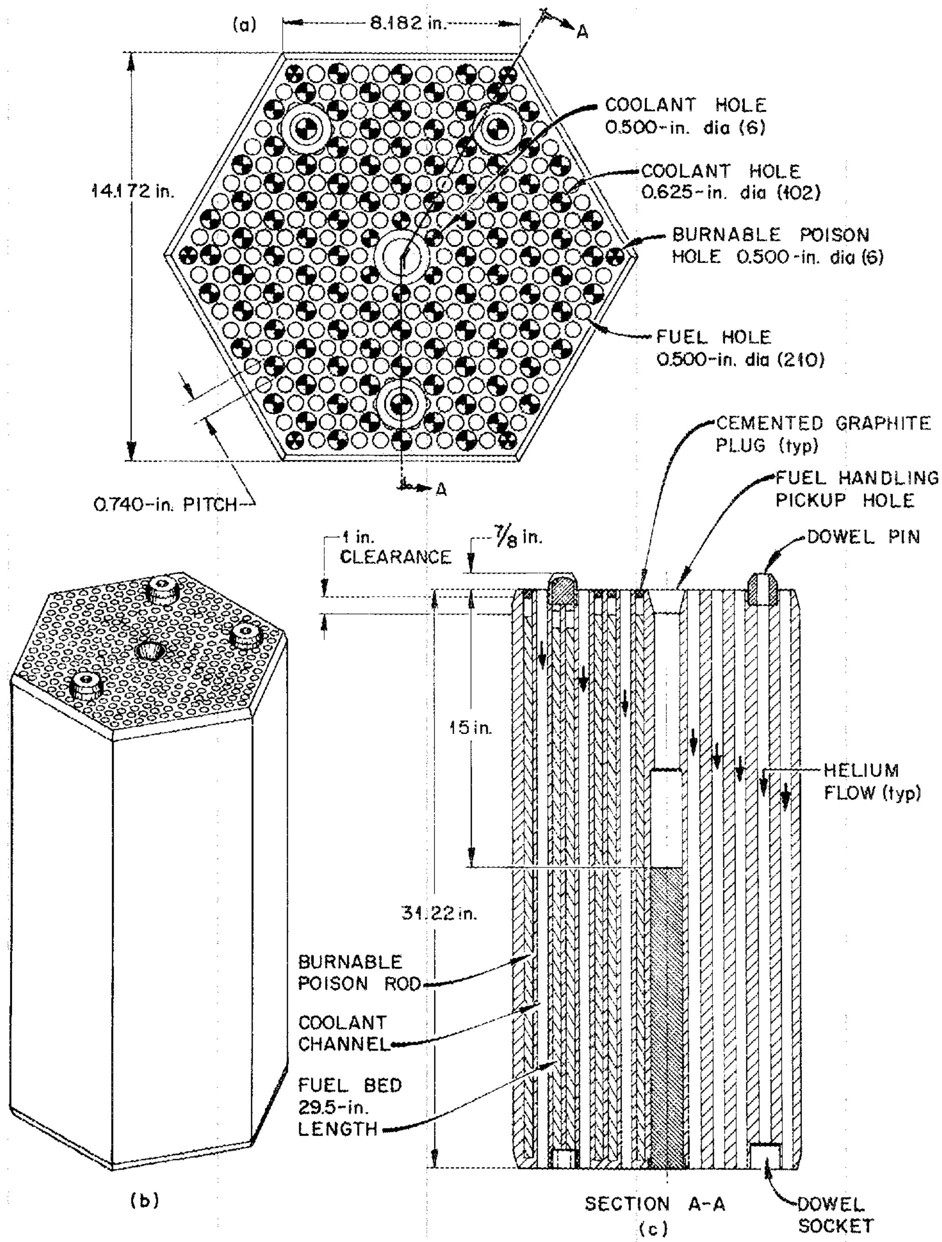

Fig. 3.1. Typical 1000-MW(e) HTGR Fuel Element.

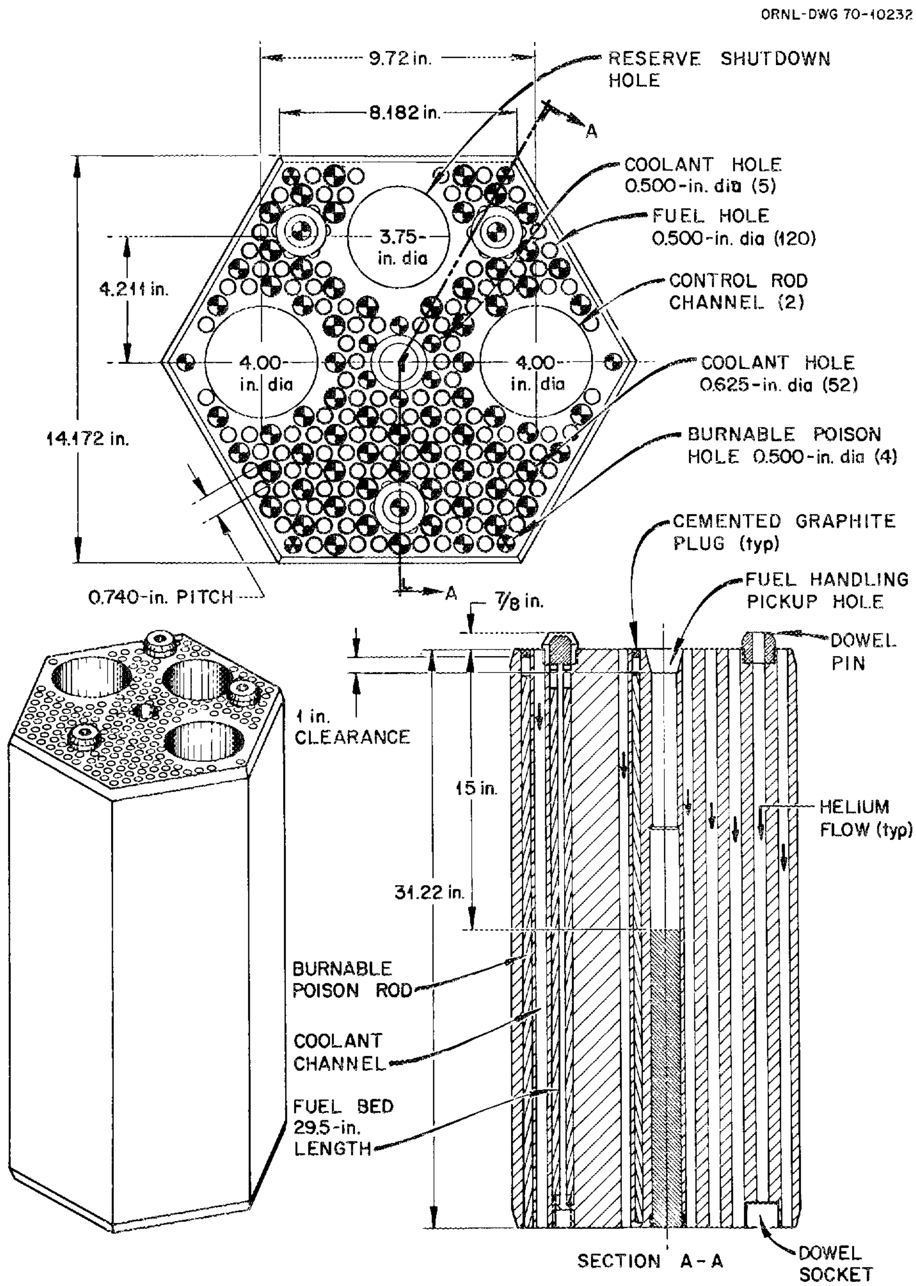

Fig. 3.2. Typical 1000-MW(e) Modified Fuel Element with Control Rod Passage.

high-density pyrolytic carbon, act as a pressure vessel to contain the fission products. The principal reason for the silicon carbide coating in the 1000-MW(e) reactor is to keep the particle intact during early stages of reprocessing so it can be classified by size from other particles, although the silicon carbide is also a more effective diffusion barrier to some fission products.

Four types of particles are used to allow for maintaining separation of spent ^{235}U (containing ^{236}U) from ^{233}U and to minimize the fabrication costs. The latter is possible because particles containing only thorium or ^{235}U can be fabricated at considerably lower cost in a separate facility from the ^{233}U particles since shielding is not necessary. The four particle types are one fertile particle and three fissile particles: a fissile particle containing ^{235}U with a pyrolytic carbon coating, called the BISO fissile particle; a fissile particle containing ^{235}U coated with both pyrolytic carbon and silicon carbide, called the TRISO fissile particle; and a fissile particle containing ^{233}U with a pyrolytic carbon coating, called the recycle particle. Only one type of fissile particle is used in any one fuel element. Fissile particles are mixed with fertile particles before the fuel stick is formed.

Two types of elements are used at one time in the core: element A and element B. Every element contains the ThC_2 fertile particle. The TRISO fissile particle is contained in element B. This particle contains ^{235}U and can be separated from the other particles by size classification because of the SiC coating. Initially, until ^{233}U is available, element A contains the BISO fissile particle. Although this particle cannot be size classified from the fertile particle, most of these elements will be removed before full burnup is achieved (four years for the reference fuel design). Thus significant quantities of ^{235}U will remain, and it is economically warranted to reprocess these elements without separation of the particles. The penalty associated with neutron absorptions in ^{236}U bred from ^{235}U becomes large only when this nuclide builds up to large concentrations due to its continued production from ^{235}U makeup fuel. In later core loadings, the same element B as in the initial fueling is used, and the recycle particle is used in element A. Since this particle contains only ^{233}U and thorium no separation of particles is required.

The coated particles are described in Table 3.1. Carbide kernels were chosen for the initial loadings and for the fertile particles because the manufacturing capability to produce these particles in large quantities already exists.

Table 3.1. HTGR Reference Fuel Particle Descriptions[a]

Property	Particles Common to Both Initial and Recycle Fuel		BISO[c] Fissile Particle for Initial Fuel	Recycle Particle
	Fertile Particle	TRISO[b] Fissile Particle		
Particle number	1	3	2	4
Kernel composition	ThC_2	$^{235}UC_2$	$^{235}UC_2$	$(Th,^{233}U)O_2$
Kernel diameter, μm	400	100	100	350
Coating thickness, μm				
Buffer carbon	50	50	50	80
Inner dense carbon		20		
Silicon carbide		20		
Outer carbon	70	30	70	120
Total particle diameter, μm	640	340	340	750
Ratio of coating thickness to kernel diameter	0.30	1.2	1.20	0.57

[a]Particles will be bonded into fuel sticks for insertion into hexagonal graphite block fuel elements. Sticks containing about 15% B_4C in a graphite matrix will be used in the corner holes of the fuel elements as a burnable poison.

[b]TRISO designates three types of coatings of the kernel: buffer, silicon carbide, and dense pyrolytic carbon.

[c]BISO designates two types of coatings of the kernel: buffer and dense pyrolytic carbon.

3.4 REACTORS

At present the only operating HTGR in the United States is the Peach Bottom Nuclear Generating Station located near Delta, Pennsylvania.[2] This reactor uses a hot-pressed fuel compact rather than the bonded fuel particles of future HTGR's. However, fuel elements similar to those for future HTGR's have been inserted in the Peach Bottom Reactor. These fuel elements will provide a test of the reference fuel and several advanced fuels and will provide a reasonably large quantity of irradiated material for reprocessing development.

The Fort St. Vrain Reactor[3] is scheduled to be in operation in 1971. This reactor is a 330-MW(e) HTGR being built for the Public Service Company of Colorado. This reactor is a prototype of the 1000-MW(e) HTGR's, with many features of the two reactor types similar. Of importance to this program is that the basic fuel and fuel element type (coated particles bonded together into fuel sticks and inserted into large graphite blocks) are identical.

3.5 FUEL RECYCLE OPERATIONS

Fuel recycle[4] for HTGR's is diagrammed in Fig. 3.3. At fuel cycle equilibrium, spent fuel in the form of elements A and B is removed from the reactor and after short-term storage sent to be reprocessed. The reprocessing operations include head-end and solvent extraction reprocessing. In head-end reprocessing the particles are removed from the elements, classified into particle types, and prepared for solvent extraction.

In solvent extraction reprocessing, the fuel is treated by the Acid Thorex Process to remove fission products and separate the uranium from the thorium. The thorium will be stored for 15 years to allow its activity to decay to a level approximately that of unirradiated thorium. The uranium contains large quantities of ^{232}U. Because of the short half-life of ^{232}U (74 years) and the high-energy gamma activity of its decay products, heavily shielded facilities will be needed not only for the reprocessing facility but for the refabrication facility as well.

The purified ^{233}U is transferred from the reprocessing facility to the refabrication facility, where it is fabricated into oxide kernels by the sol-gel technique for producing microspheres. In this process, thorium is added to the fuel.* The oxide microspheres are coated with pyrolytic carbon and, after mixing with the coated ThC_2 particles (produced in another facility), bonded into fuel sticks. The fuel sticks are loaded into fuel elements, and these are canned and shipped to the reactor. Since the HTGR conversion ratio is less than 1, fresh fuel is also supplied to the reactor in the form of type B elements fabricated in unshielded facilities.

All of the processing facilities — fresh fuel fabrication, fuel reprocessing, and refabrication — would be designed to handle a number of large HTGR's to take advantage of the effect of scale on costs.

3.6 SPENT FUEL LOADS

The quantity of spent fuel available for reprocessing is not easy to predict since the schedule of HTGR construction is not well established. However, sufficient information is available to determine a range of possible fuel

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*The addition of thorium is currently specified because the technology of fabricating this mixed oxide particle is further advanced.

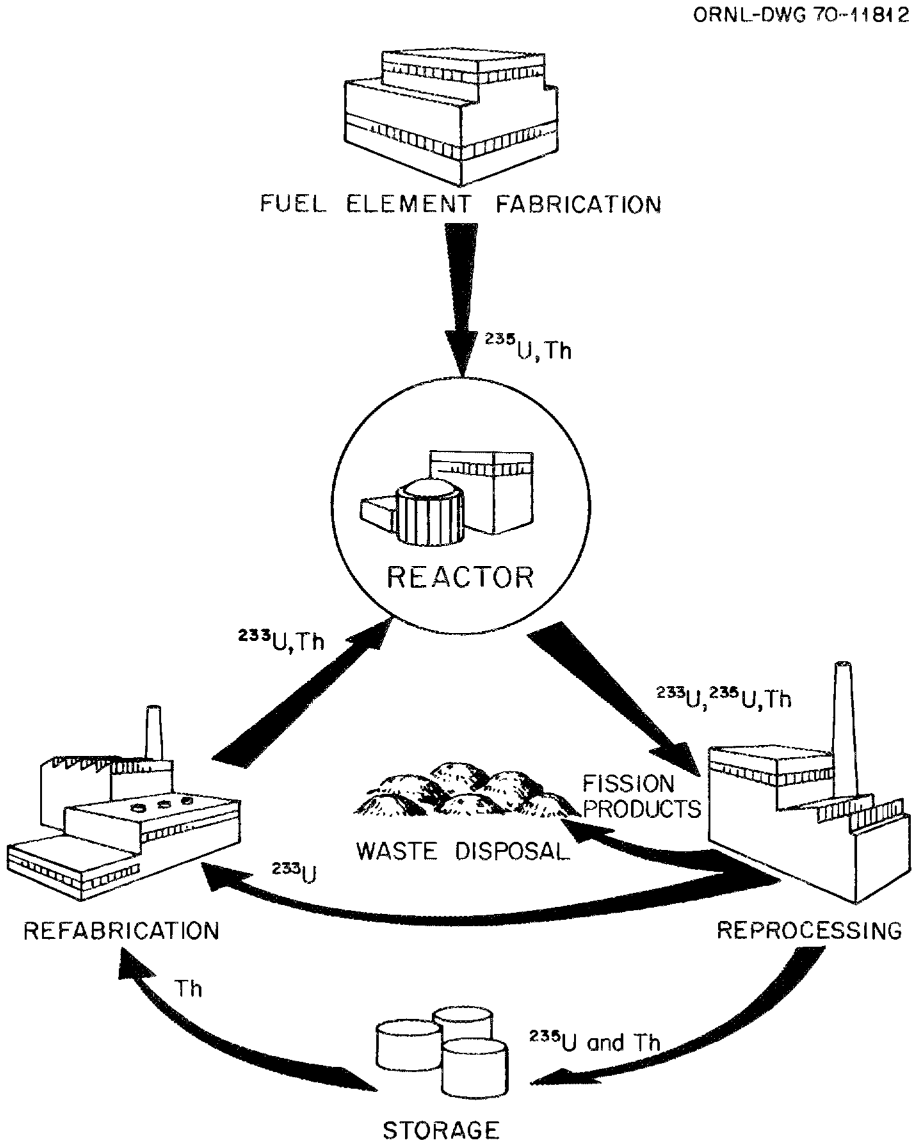

Fig. 3.3. HTGR Fuel Recycle.

quantities, shown in Table 3.2. Considering the spent fuel availability in 1984, the projected startup date for commercial HTGR fuel recycle operations, the quantity of available fuel from several sources can be predicted. The FSVR will have discharged approximately 30 metric tons of metal (U + Th + fission products) in spent fuel elements. It is estimated that the first 1000-MW(e) reactor will go into commercial operation in 1977. Accepting this assumption, and further assuming that the schedule of reactors constructed is as postulated in the conservative growth rate depicted in case 1 of Table 3.2, about 330 metric tons of metal will be available for reprocessing in 1984, with 115 metric tons of the available metal being discharged from all U.S. HTGR's (FSVR included) in that year. This 330 metric tons includes roughly 11 metric tons of fissile material (^{233}U + ^{235}U).

Table 3.2. Some Predicted 1000-MW(e) Reactor Installation Schedules

Case	Number of HTGR's to be Installed Each Year												
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	Total
1	1	1	2	3	4	4	5	6	6	0	0	0	32
2	2	2	3	5	7	8	7	5	0	0	0	0	39
3	1	3	4	6	10	18	19	20	11	6	4	3	105

The cost benefit analysis of the U.S. Breeder Reactor Program calculates[5] that 136 HTGR's can be economically built between 1980 and 1989. In the linear analysis used in the study, the construction in early years of the reactor growth was limited to four reactors per year for the first two years, eight per year in the next two years, 16 per year in the next two years, and whatever is most advantageous after that. The conservatism of the 1980 introduction date is balanced by the large initial growth, possibly requiring more than one reactor fabricator. Hence, the output in 1984 calculated from that growth rate would not be unrealistic. Again, including FSVR output in the estimates, 240 metric tons of metal would be available in 1984, including 125 metric tons produced in that year alone.

Using 1977 as the date of introduction of the first large HTGR and a more optimistic growth rate in the early years, as shown in case 2 of Table 3.2, the fuel availability is almost double that calculated from the first growth case.

Thus, present expectations of HTGR growth indicate that a substantial quantity of spent fuel containing significant fissionable material will be ready for reprocessing in 1984 when the first commercial plant becomes operational.

3.7 ECONOMIC CONSIDERATIONS

The value of an HTGR fuel recycle program can be gaged with accuracy since HTGR's can be operated without recycle, and therefore the difference in power cost of recycle and nonrecycle operation can be calculated. GGA has calculated[6] that operation of HTGR's without benefit of recycle increases fuel cycle costs 0.2 to 0.3 mill/kWh. The important aspect in determining the value of recycle is that this 0.2 to 0.3 mill/kWh increase results in a 5.3 to 8.0% increase in power cost. To put the potential cost savings of fuel recycle into perspective, the real savings accrued to the economy by the year 2000 is $1.048 billion, assuming construction of reactors as outlined in case 1 of Table 3.2 (a total of 32 reactors built by 1985) and using 0.25 mill/kWh as the power cost savings of recycle operations. Discounted to 1970 at an annual rate of 7%, this savings amounts to $262 million. Compared with the $56.8 million expenditure outlined in this program, which discounts on the same basis to $40.7 million, this savings translates to a cost benefit factor of about 6.

In addition to decreasing the cost of electric power, recycle of HTGR fuel will save a considerable portion of the uranium reserves. The nonrecycle mode of HTGR operation uses about twice as much ^{235}U. By the year 2000, the HTGR system described by case 1 without recycle would use 30,000 metric tons U_3O_8 more than the system using recycle.

3.8 TIMING

An overall study in the economics of an HTGR economy was performed to provide an understanding of the economic problems involved in the timing of the HTGR Fuel Recycle Development Program.[7] The results of this study are shown in Fig. 3.4 and are based upon the reactor schedules shown in Table 3.2. The ordinate in Fig. 3.4 is the difference in total fueling expenditures (discounted at 7% to 1977) between the optimum recycle introduction date and any other introduction date for the three different reactor installation schedules.

The unit cost of fuel recycle has been shown consistently[8–10] to decrease markedly as the throughput of the spent fuel processing and recycle fuel fabrication facilities increases. Therefore, it does not appear to be economically sound to build a succession of small recycle facilities as the fuel recycle

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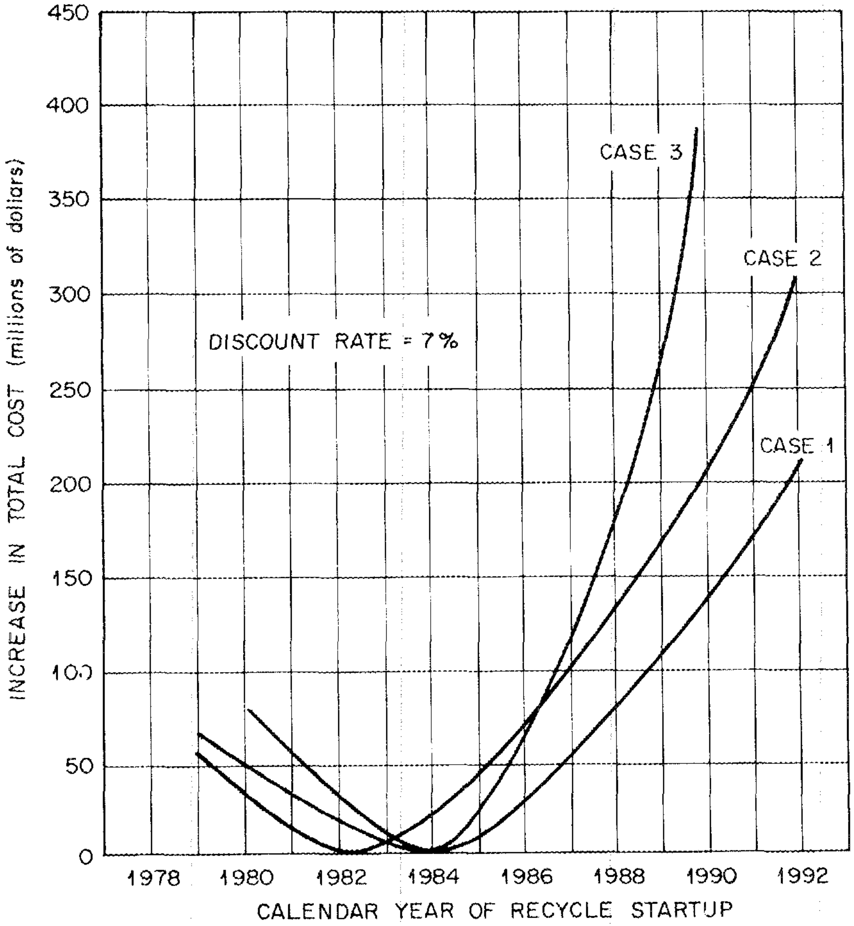

Fig. 3.4. Increase in Total Fuel Cycle Expenditures (Discounted to 1977) as a Function of Time of Recycle Startup. The three cases are schedules of reactor installation given in Table 3.2.

load increases. Rather, spent fuel should be stored and the construction of recycle facilities be delayed until the sum of the stored fuel and the current reprocessing requirements has built up to an economically adequate size. Based on these considerations, the optimum date for start of recycle operations was found to be about seven years after the startup of the first 1000-MW(e) HTGR, or 1984 if the first such reactor begins operation in 1977. In all cases, the economic penalty for being a year early in startup is about half that of being a year late. These results persist throughout all of the growth patterns that were considered. The study also considered discount rates of 0 and 14% as well as the standard 7%; again, the optimum recycle startup date of 1984 persisted, indicating a close balance between the cost of the additional ^{235}U that must be purchased before starting recycle and the cost of having a large recycle facility before there is enough fuel to justify it.

One can determine the schedule of the recycle development program by deducting from the optimum date for introducing commercial fuel recycle the sum of the minimum times required for design and construction of the commercial plant, for design, construction, and demonstration of operation of the pilot plants, and for process and equipment development. A schedule determined in this way is shown in Fig. 2.1, page 5. It is very tight and indicates that the recycle program plan must be implemented at the funding levels shown in Table 2.1, page 6, as soon as possible if the greatest economic benefits are to be realized. This schedule is based on receiving irradiated fuel from the FSVR in sufficient quantity to perform the hot demonstration development work beginning in 1976.

3.9 EXISTING TECHNOLOGY

Only a limited amount of technology is presently available for reprocessing of graphite matrix fuels. Commercial facilities such as the Nuclear Fuel Services, Inc., a subsidiary of Getty Oil Company, Midwest Fuel Recovery Plant, which is being built by General Electric Company, and the Nuclear Fuel Plant to be built by Allied-Gulf Nuclear Service are primarily concerned with the processing of metal-clad UO_2 fuels. Also, the government-owned plants at Hanford and Savannah River are not presently concerned with reprocessing graphite matrix fuels. Some work has been done at the Idaho Chemical Processing Plant (ICPP) on graphite matrix fuel that does not require maintaining separation of ^{233}U from ^{235}U. The information developed at ICPP will be used by the recycle development program wherever applicable. Reprocessing of irradiated thorium metal was demonstrated in the Thorex Pilot Plant at ORNL in 1956. This pilot plant is essentially intact and will be converted to the Acid Thorex Pilot Plant as a part of the recycle development program. Thorium oxide fuel rods have been reprocessed on a production scale at the Hanford and Savannah River plants to recover ^{233}U, with relatively little ^{232}U, for experimental purposes. Metal-clad $(Th,^{233}U)O_2$ was remotely fabricated at ORNL in the Kilorod[11] facility and semiremotely refabricated at the Lynchburg facility of the Babcock & Wilcox Company.[12] Little of this experience on metal-clad fuel elements is applicable to this program. About 32 kg of $(Th,^{233}U)O_2$ microspheres was made and coated at ORNL for use in High-Temperature Lattice Test Reactor physics experiments,[13] and particles of $(Th,U)O_2$, ThO_2, and UO_2 were prepared, coated, and made into fuel sticks for use in the Recycle Test Elements (RTE's) for irradiation in the Peach Bottom Reactor.

3.10 FACILITIES NEEDED

To implement this development program plan, facilities are required for head-end reprocessing demonstration, solvent extraction reprocessing demonstrations, fuel refabrication demonstration, proof test irradiations, and the laboratory development work preceding these demonstration activities. This laboratory development work includes both process development and engineering-scale equipment development. Laboratory development work will be done in available chemical and engineering laboratories and hot-cell facilities at ORNL and GGA.

The head-end reprocessing demonstration and the fuel refabrication demonstration will be performed in pilot plants located in the Thorium-Uranium Recycle Facility (TURF) at ORNL.[14] This facility has shielded chemical and mechanical processing cells, a decontamination cell, an equipment storage cell, a fuel receiving station, a fuel storage basin, and gaseous and liquid waste disposal systems. Since the TURF was designed to handle PWR-type fuel elements, the receiving and storage areas will require some modifications and additions to provide the full requirements of this program.

Solvent extraction reprocessing will be demonstrated in the existing ORNL Building 3019 facility with the Thorex Pilot Plant equipment modified for HTGR fuel.

The irradiations will be done in the Peach Bottom Reactor, the Engineering Test Reactor, and the Fort St. Vrain Reactor.

3.11 ORNL PROGRESS REPORTS

In addition to the topical references cited in this and other parts of this document, two series of progress reports document ORNL research and development work pertinent to HTGR development. These are the series Status and Progress Report for Thorium Fuel Cycle Development and Gas-Cooled Reactor Program Semiannual Progress Report. Recent reports in these series are listed in Table 3.3.

Progress report series by Gulf General Atomic are referenced in Chapter 6, page 99.

Table 3.3. Recent ORNL Progress Reports Containing HTGR Development

Report Number	Period or Period Ending
	Thorium Fuel Cycle Development
ORNL-4629	Jan. 1, 1969–March 31, 1970
ORNL-4429	1967 and 1968
ORNL-4275	Year ending Dec. 31, 1966
ORNL-4001	Year ending Dec. 31, 1965
ORNL-3831	Year ending Dec. 31, 1964
	Gas-Cooled Reactor Program Semiannual
ORNL-4589	March 31, 1970
ORNL-4508	Sept. 30, 1969
ORNL-4424	March 31, 1969
ORNL-4353	Sept. 30, 1968
ORNL-4266	March 31, 1968
ORNL-4200	Sept. 30, 1967
ORNL-4133	March 31, 1967
ORNL-4036	Sept. 30, 1966
ORNL-3951	March 31, 1966
ORNL-3885	Sept. 30, 1965
ORNL-3807	March 31, 1965
ORNL-3731	Sept. 30, 1964

3.12 REFERENCES

1. Gulf General Atomic, HTGR Base Program Quarterly Progress Report for the Period Ending May 31, 1970, GA-10088.

2. Philadelphia Electric Company, Application of Philadelphia Electric Company for Construction Permit and Class 104 License. Part C. Final Hazards Summary Report — Peach Bottom Atomic Power Station. Volume V. Plant Description and Safeguards Analysis (Annexes), NP-9115(Pt.C)(Vol. V) (1963), Annex F.

3. Fort St. Vrain Nuclear Generating Station Final Safety Analysis Report, Public Service Company of Colorado, Denver, Colorado, November 1969.

4. A. L. Lotts and R. G. Wymer, Economics and Technology of HTGR Fuel Recycle, ORNL-TM-2377 (October 1968).

5. Cost Benefit Analysis of the U. S. Breeder Reactor Program, WASH-1126 (April 1969).

6. P. Fischer, S. Jaye, and H. Stewart, Alternate Fuel Cycles for the HTGR, GA-9010 (Oct. 4, 1968).

7. F. J. Furman, R. B. Pratt, and A. L. Lotts, Prediction of the Economically Optimum Time to Initiate Recycle for the High-Temperature Gas-Cooled Reactor Industry Using Computer Program DELAY, ORNL-TM-2704 (December 1969).

8. An Evaluation of Advanced Converter Reactors, WASH-1087 (April 1969).

9. J. J. Shefcik, Cost of Reprocessing HTGR Fuels in Central Plants of Various Capacities, GAMD-8458 (Dec. 29, 1967).

10. A. L. Lotts and D. A. Douglas, Jr., "Refabrication Technology for the Thorium-Uranium-233 Fuel Cycle," pp. 212–245 in Utilization of Thorium in Power Reactors, Report of a Panel Held in Vienna, 14–18 June 1965, International Atomic Energy Agency, Vienna, 1966; also published as ORNL-TM-1141 (June 1965).

11. R. E. Brooksbank, J. P. Nichols, and A. L. Lotts, "The Impact of Kilorod Facility Operational Experience on the Design of Fabrication Plants for ^{233}U-Th Fuels," pp. 321–340 in Thorium Fuel Cycle (Proceedings of Second International Thorium Fuel Cycle Symposium May 3–6, 1966) R. G. Wymer, Coordinator, U.S. Atomic Energy Commission/Division of Technical Information, Oak Ridge, Tennessee, February 1968, CONF-660524.

12. E. C. Moncrief, C. A. Burkart, and D. A. Nitti, "Thorium Fuel Separation Engineering Studies," pp. 509–535 in Thorium Fuel Cycle (Proceedings of Second International Thorium Fuel Cycle Symposium May 3–6, 1966) R. G. Wymer, Coordinator, U.S. Atomic Energy Commission/Division of Technical Information, Oak Ridge, Tennessee, February 1968, CONF-660524.

13. J. R. Parrott, F. L. Daley, F. J. Furman, and J. W. Snider, "Demonstration of $^{233}UO_2$-ThO_2 Microsphere Production by the Sol-Gel Process," Trans. Am. Nucl. Soc. **12**, 27–28 (June 1969).

14. J. W. Anderson, S. E. Bolt, and J. M. Chandler, Safety Analysis for the Thorium-Uranium Recycle Facility, ORNL-4278 (May 1969).

4. TASK 100 – FUEL REPROCESSING DEVELOPMENT

4.1 INTRODUCTION

Fuel reprocessing, one of the key steps in the HTGR fuel cycle, recovers and purifies ^{233}U for fuel refabrication and return to the reactor. Reprocessing development work done thus far has shown that several process alternatives may, with further development, be practical methods of reprocessing.

The goal of this task is to develop and demonstrate fuel reprocessing methods for the reference 1000-MW(e) HTGR fuel and to provide technology for commercial reprocessing plant design, construction, and operation. The separation and recovery of ^{233}U present in the thorium-bearing particles are the primary technical goal of this development task. Although some attention will be given to maintaining the highly burned-up ^{235}U-containing particles as a recoverable process stream, this aspect of the process will be of less importance than ^{233}U recovery. The early availability of fuel from the Fort St. Vrain Reactor (FSVR) makes it essential also to be able to reprocess that fuel in the reprocessing pilot plants to get timely information for the reprocessing technology necessary for commercial plant application. The most significant difference now between the reference 1000-MW(e) HTGR fuel and the FSVR fuel is that current plans call for only the ^{235}U-containing particle to be coated with silicon carbide in the former reactor, whereas all the particles are coated with SiC in the FSVR.

The three major parts of this task are: (1) Head-End Reprocessing Development (Subtask 110), (2) Head-End Pilot Plant Demonstration (Subtask 120), and (3) Acid Thorex Pilot Plant Demonstration (Subtask 130). The pilot plant demonstrations will be complete when the equipment and the operations carried out in the equipment have been proven to be reliable, practical, and capable of economical scale-up in a commercial reprocessing plant. This demonstration will require the reprocessing of unirradiated developmental fuel elements, irradiated materials provided by Task 300, and a number of spent fuel elements from the FSVR. Head-end reprocessing begins with receipt of the fuel elements in a shielded shipping cask and ends with the shipment of the recovered fuel values, as uranyl nitrate, in a shielded shipping carrier. An essential part of the reprocessing scheme is the handling of all waste streams (gaseous, liquid, and solid) in whatever manner is required for their disposal.

Head-End Reprocessing Development (110) will consist of: (1) development of unit processes on a practical engineering scale with unirradiated fuel, (2) tests of unit processes with irradiated fuel samples in small-scale hot-cell equipment, and (3) prototype equipment development, testing, and demonstration with unirradiated fuel. The Head-End Reprocessing Development Subtask will be limited to a study of the reference processes, their problem areas, and a few alternatives to those reference process steps that may prove unsatisfactory during their development.

Specifically, the Head-End Reprocessing Development (110) steps are: (1) Burner Feed Preparation (111), (2) Burner Technology (112), (3) Burner Ash Handling (113), (4) Treatment of Classified Burner Ash (114), (5) Alternate Methods of Maintaining Separation of ^{233}U and ^{235}U (115), (6) Scrap Recycle (116), (7) Off-Gas Handling and Decontamination (117), and (8) Waste Treatment and Disposal (118).

The Head-End Pilot Plant Demonstration will consist of design, construction, and operation of a Head-End Pilot Plant in TURF (ORNL Building 7930). The Head-End Pilot Plant scheme begins with receipt of the spent fuel elements from the reactor and ends with transfer of the fuel values free of the graphite to the Acid Thorex Pilot Plant in ORNL Building 3019. The former shipment is to be made with the fuel shipping cask to be furnished by GGA, and the latter is to be made using either the solids transfer cask to be furnished by ORNL (VPP Waste Carrier No. 2) or the solution transfer carrier. The Head-End Pilot Plant operations will demonstrate recovery of ^{233}U from irradiated fuel and deliver a product ready for reprocessing to the Acid Thorex Pilot Plant. The maintenance philosophy to be used for the Head-End Pilot Plant is remote modular replacement or repair. That is, all equipment will be designed so that the entire apparatus or, where practical, subsections of the apparatus can be removed remotely by cranes and manipulators.

The Head-End Pilot Plant Demonstration (120) steps are: (1) Design (121), (2) Procurement and Testing of Equipment (122), (3) Installation of Equipment (123), (4) Cold Operational Testing of the Head-End Pilot Plant (124), (5) Hot Demonstration of the Head-End Pilot Plant (125), (6) Waste Treatment and Disposal (126), (7) Materials Handling (127), and (8) Process Development Support (128).

The Acid Thorex Pilot Plant Demonstration will consist of modifying and using the existing Thorex Pilot Plant in ORNL Building 3019 for the recovery of uranium and thorium from fuel material being reprocessed. Uranium and thorium separation and decontamination by solvent extraction were chosen for the reference process. This pilot plant will demonstrate the Acid Thorex process and uranium recovery using the product from the Head-End Pilot Plant Demonstration. The Acid Thorex Pilot Plant scheme begins with receipt of the fuel values as oxides or solution from the Head-End Pilot Plant and ends with transfer of the recovered fuel values, as uranyl nitrate.

The Acid Thorex Pilot Plant Demonstration (130) steps are: (1) Design (131), (2) Procurement and Testing of Equipment (132), (3) Installation of Equipment (133), (4) Cold Operational Testing of the Acid Thorex Pilot Plant (134), (5) Hot Demonstration of the Acid Thorex Pilot Plant (135), (6) Waste Treatment and Disposal (136), (7) Materials Handling (137), and (8) Process Development Support (138).

The following definitions are given to assure a common understanding.

fuel element — the loaded graphite block containing coated particles, fuel sticks, and retaining plugs,

fuel block — the empty graphite item containing coolant and fuel holes,

fuel sticks — right circular cylinders made of particles bound together in a carbonaceous matrix. These are inserted into the fuel holes of the fuel block,

fuel particles — coated kernels of fissile and fertile materials or their combinations,

poison particles — coated kernels of neutron absorbing materials,

kernels — uncoated, fissile, fertile, or neutron absorbing materials,

microspheres — kernels made by the Sol-Gel Process,

BT particles — burned TRISO particles that have an exposed SiC coating.

4.2 REPROCESSING DEVELOPMENT SCHEDULE

The schedule for performing the steps of this major task of the development program is shown in Fig. 4.1.

4.3 SUBTASK 110 — HEAD-END REPROCESSING DEVELOPMENT

4.3.1 Purpose

The purpose of this subtask is to obtain the information needed to carry out Subtask 120, Head-End Pilot Plant Demonstration. The fact that all fuel particles will have TRISO coats in the FSVR, whereas it is currently planned that only the ^{235}U-containing particle will have TRISO coats in the 1000-MW(e) HTGR reference fuel, is important to the plans for reprocessing work. As mentioned earlier, the first significant amounts of irradiated fuel available for head-end reprocessing in the pilot plant will be from the FSVR.

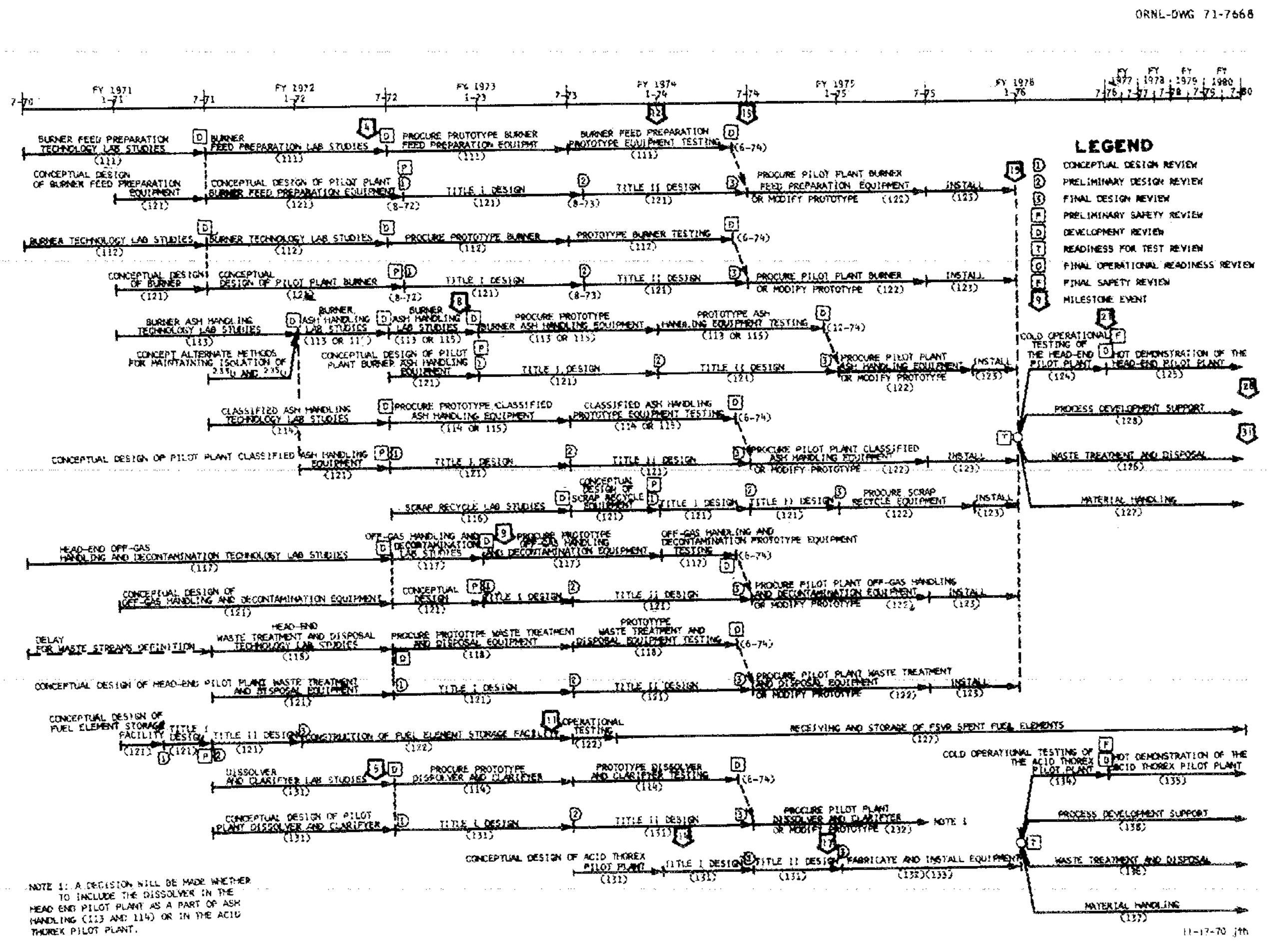

Fig. 4.1. Reprocessing Development Schedule. The numbers of indicated milestone events refer to Table 2.5, pages 10–11.

4.3.2 Requirement

This subtask requires the development of processes and equipment for recovering the fuel values from spent HTGR fuel elements. Recovery of fuel values from HTGR graphite fuel elements has not been demonstrated, although some crushing, tumbling, burning, and grinding studies have been carried out both in cold engineering equipment and in small-scale hot-cell studies.

Uranium-233 is added to or generated in the 1000-MW(e) HTGR fuel element in particles separate from those containing ^{235}U. The reference reprocessing process assumes that the silicon carbide coatings on the burned TRISO particles (BT particles) remain sufficiently intact during reprocessing that they can be separated by screening. Particle breakage or insufficient particle separation can cause crossover. For example, the particles cannot be separated by screening if they stick together in small agglomerates after burning. A cost penalty of about 0.015 mill/kWh has been calculated for a loss of 5% of the ^{233}U to the ^{235}U fraction. The same cost penalty occurs for 10% retention of the ^{235}U (and attendant ^{236}U) by the ^{233}U recycle fraction when reactor equilibrium conditions are assumed (which takes 100 years) and for 25% retention when a 30-year reactor lifetime is assumed. It appears to be reasonable to expect to hold these percentages to such values as those above, or lower.

The bulk of the irradiated ^{235}U must be maintained separate from the ^{233}U (which is to be recycled). While the concepts for recovery and separation of the two fuel components are apparently quite sound, the practice is not developed on any meaningful scale. Potential problems, such as sticking of the alumina powder to SiC coatings, must be studied to determine their severity, and solutions found wherever required. Consequently, it is necessary to establish equipment requirements, evaluate and test the various equipment types, and in some cases perhaps develop new devices rather than modify conventional systems.

Laboratory development of all the significant engineering unit processes must be carried out with unirradiated prototype fuel. Cold fuel elements must be crushed and the crushed product tumbled and screened to determine the practicability of removing the bulk of the carbon from the fuel and poison particles in this way. Several sizes and types of burners and off-gas filters must be evaluated. Particle separation devices and breakage must be studied. Additional irradiated fuel compacts and capsules must be taken through the proposed reprocessing steps in hot cell studies. Realistic particle breakage, fission product release, and fuel reprocessing performance information must be obtained in these studies.

A preliminary head-end process chemical flowsheet is presented in Fig. 4.2. The quantities shown in the flowsheet are based on processing about ten elements per day; this rate corresponds to a meaningful pilot plant scale. Further, the ^{233}U reclaimed daily from these FSVR fuel elements irradiated for two years permits preparation of 10 kg of recycle microspheres having a thorium-to-uranium ratio of 4.25. A generalized diagram of activities in reprocessing development, emphasizing the head-end steps, is presented in Fig. 4.3.

4.3.3 Timing

The various steps of reprocessing development described in the following subtasks will be carried on more or less concurrently and will continue through the mid-1970's. The timing of the subtask is shown relative to the other subtasks in Fig. 4.1 and relative to the overall program in Fig. 2.1, page 5.

4.3.4 Funding

The required funding for this subtask is given in Table 2.1, page 6.

4.3.5 Facilities

No new facilities (in the form of buildings or other items involving major capital investment) will be required. Laboratory development work will be carried out in available chemical and engineering laboratories and hot cell facilities at ORNL. Prototype equipment will be required for development of pilot-plant-scale equipment.

4.3.6 Subtask 111 – Burner Feed Preparation

4.3.6.1 Requirement

A process and its equipment must be developed for preparing the spent fuel element for burning. The process must have a minimum of particle breakage so that mixing of the ^{235}U and ^{233}U can be reduced to a minimum.

The purpose of this subtask is to develop processes and equipment that remove the matrix carbon from the coated particles in such a way that the integrity of the silicon carbide coating is not compromised. This is crucial because it is through the dimensional characteristics and resistance to

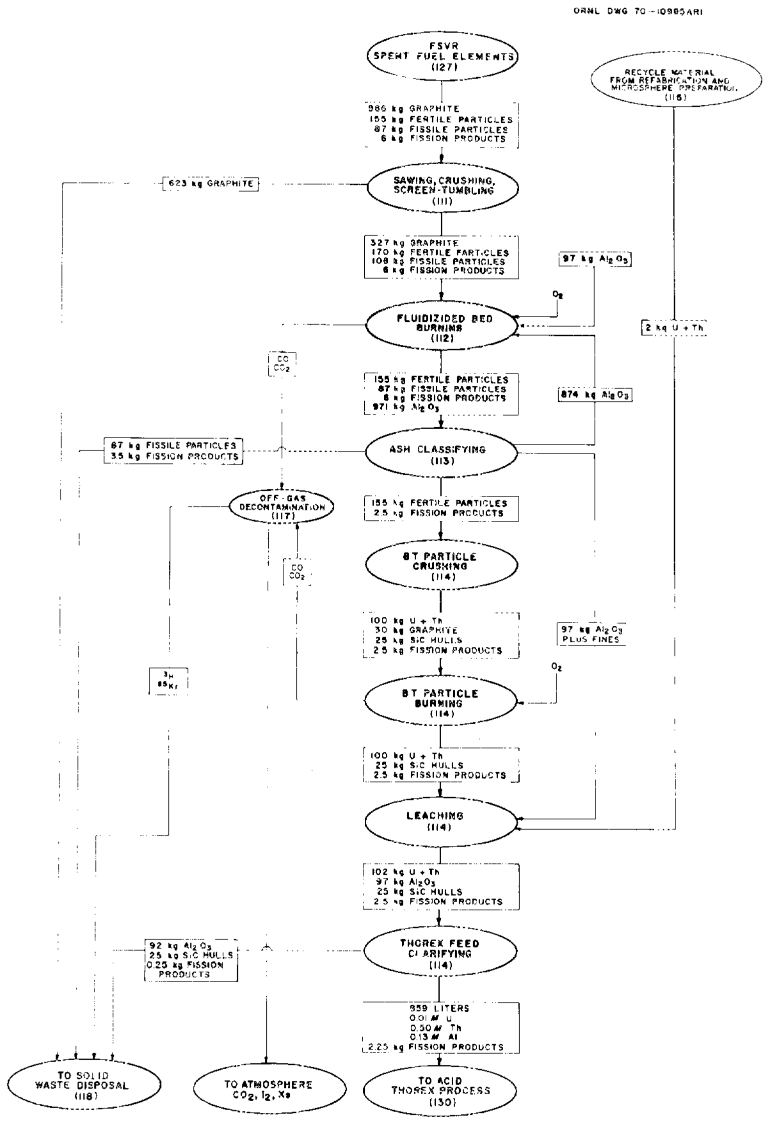

Fig. 4.2. Preliminary Head-End Process Chemical Flowsheet Based on Processing 9.7 First Core FSVR Fuel Elements Irradiated Two Years.

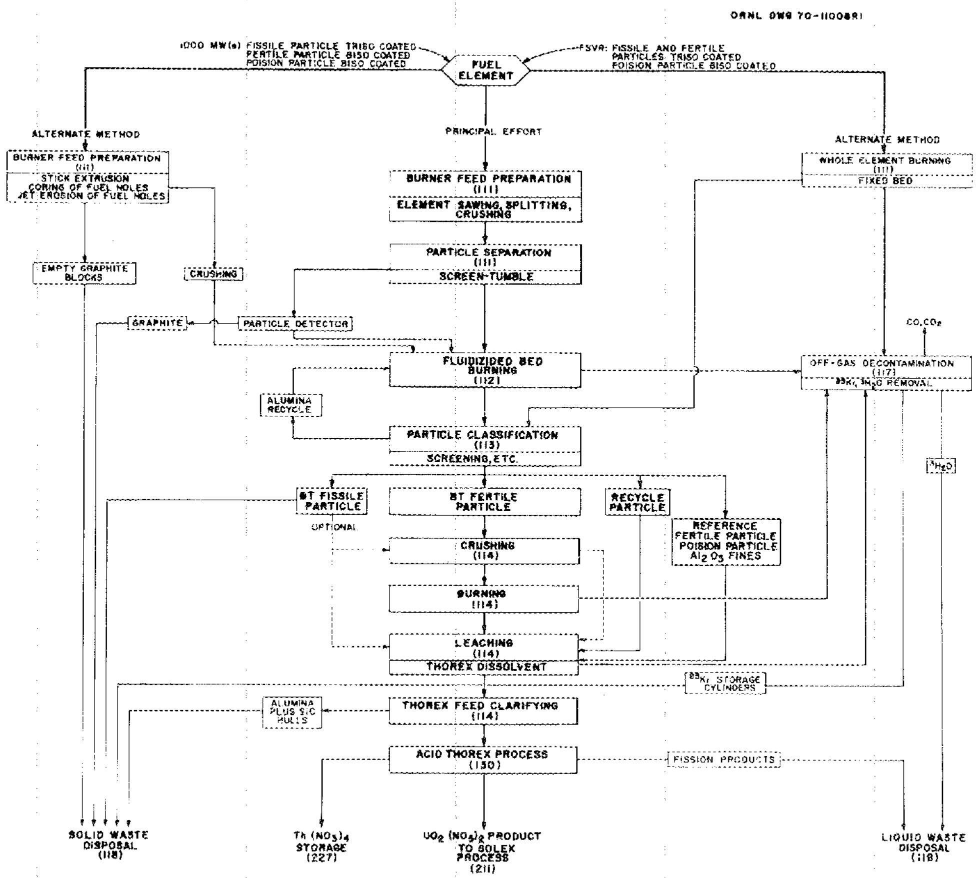

Fig. 4.3. A Generalized Diagram of Activities in the Reprocessing Development, Emphasizing the Head-End Steps.

oxidative attack of the silicon-carbide-coated and recycle particles that particles having various compositions are to be kept separate.

4.3.6.2 Status of Technology

Fuel particles constitute a small fraction of the total material in a fuel element, the major portion being graphite. Further, the fuel element is large (a hexagonal parallelepiped about 14 in. across flats and about 31 in. long) and unsuited for burning in a fluidized-bed burner (and perhaps in a fixed bed also) without breakdown into smaller pieces. Separation of the fuel sticks or preferably the fuel particles from the bulk of the graphite would materially reduce the problems inherent in burning carbon that is contaminated with fission products and which produces a large volume of gaseous waste to be treated and disposed of.

Preliminary tests of simple ways of crushing a graphite fuel element have been accomplished,[1] but it cannot yet be said that a satisfactory system has been developed. This is due, in part at least, to the lack of typical fuel elements. Five approaches that could free the fuel particles from the bulk of the graphite have been considered and have undergone preliminary investigation. These are: (1) water jet erosion of the fuel sticks, (2) core drilling around the sticks, (3) pushing the sticks from the fuel elements, (4) oxygen lance burning, and (5) crushing of the fuel element followed by tumbling. The available information regarding the first four approaches is either inadequate or discouraging.

Recent laboratory-scale research[2] on head-end processes has shown for unirradiated prototype fuel material, one- and 12-fuel-hole cylindrical graphite blocks, that crushing of the fuel element followed by screen-tumbling of the crushed material results in particles separated from graphite with minor particle breakage. However, work with full-size fuel elements is required to establish equipment design parameters, and eventually the results of unirradiated fuel tests must be verified with irradiated fuel.

4.3.6.3 Work Plan

The primary effort will be directed toward determining the optimum method of element comminution to reduce the graphite to a size and configuration such that screening and tumbling will separate particles from the bulk graphite and produce material of a size that can be accepted by a fluidized-bed burner. Techniques to be studied in developing reprocessing of reference HTGR fuel elements include: (1) sawing into segments followed by jaw crushing or hammer milling into small pieces, (2) screening particles from the broken graphite, and (3) tumbling the broken graphite to free the particles. Alternative methods of freeing the fuel from the block, such as pushing the fuel sticks from the fuel holes, should be investigated further because of the advantages of avoiding the difficulty of crushing and burning tons of contaminated graphite. A fuel particle detector will be considered to separate broken pieces of the fuel block, which contain no fuel values and need not be processed further, from broken pieces of the fuel sticks.

Essentially all of this work will be with unirradiated fuel elements prototypical of the reference fuel element. Hot-cell tests will be performed with small amounts of irradiated fuels to verify process and equipment capability.

4.3.7 Subtask 112 — Burner Technology

4.3.7.1 Requirement

Equipment must be developed suitable for burning the graphite contained in the fuel elements. This graphite must be removed before any fissile and fertile material separation based on particle size can be made.

4.3.7.2 Status of Technology

Fluidized-bed burning of approximately 1-in.-diam graphite pieces was developed for use in recovery of ^{235}U from Rover fuel[3–8] and has been extended to processing HTGR fuels at ORNL[9] and at GGA.[10] Control of reaction rate and temperature is good. The process can be an essentially continuous operation; however, scale-up data on fluidized-bed burning are insufficient to permit design of a large-scale unit, such as would be required for head-end reprocessing of HTGR fuel.

The presence of poison particles containing natural boron as B_4C in each of the fuel elements poses questions that must be answered experimentally. The boron is partially converted to lithium by (n,α) reaction, but some remains as B_4C, which would be converted to B_2O_3 in the head-end step. The effect of this B_2O_3 in the burner must be determined and reflected in the design of pilot plant equipment.

4.3.7.3 Work Plan

1. Conduct small-scale hot-cell tests to find the effects of irradiation on particle breakage and the nature and amounts of fission products in the off-gas,
2. determine suitable fuel chunk size for burner feed,
3. determine the packing of fuel chunks as they are fed to the burner,
4. find the better heat transfer medium: Al_2O_3 or fuel particles themselves,
5. determine suitable burner configuration to avoid channeling and to promote heat removal,
6. develop equipment and techniques for product removal without coating breakage,
7. determine the effect of B_4C and fission products such as molybdenum in the fuel elements on the burning operation and devise solutions to problems as required,
8. develop equipment scale-up data and design criteria,
9. develop requirements for operational instrumentation,
10. determine criticality problems,
11. develop methods of off-gas filtration and filter blowback for returning solids to the burner.

Success in one of the methods for removing fuel sticks or fuel particles from the graphite fuel block could vastly reduce the scale of equipment needed for this subtask.

4.3.7.4 Analysis of Alternate Approaches

Fixed-bed burning of entire elements is an alternative to fluidized-bed burning. It was discarded early in the development of the process for recovery of uranium from Rover fuel because of difficulties in temperature control and heat dissipation. It appears that a different approach (dilution of the oxygen with CO_2) might eliminate this problem. Burning graphite on a large scale is a well developed industrial art. Development of suitable equipment for feeding the fuel elements to the burner and withdrawal of the ash (product) would be required. Use of fixed-bed burning could eliminate the need for size reduction of the fuel element.

4.3.8 Subtask 113 - Burner Ash Handling

4.3.8.1 Requirement

Means must be developed and demonstrated to separate fuel materials from poison materials and inert materials and further to classify the fissile and fertile materials into various size components. This separation is necessary to realize the full economic advantage of the HTGR concept.

It must be borne in mind that the initial demonstration of head-end reprocessing will be carried out to a large extent with irradiated fuel elements from the FSVR's first core. These elements contain TRISO-coated $(U,Th)C_2$ and ThC_2 particles. However, the process equipment must also be capable of handling the fuel from the reference 1000-MW(e) HTGR fuel elements, since these are the ones for which the processes are really being developed and demonstrated.

In the case of the reference fuel, both the BT fissile particle and the recycle kernel (which is oxide) will remain intact in the burner ash. These fuel materials must be separated from the Al_2O_3 fluidizing media and any poison material. The separated fuel materials must be classified to separate ^{233}U from ^{235}U. Other kernels that were not coated with SiC, or that had their SiC coatings broken, will be changed from carbides to finely divided oxides in the burner. If the fines contain a significant quantity of ^{235}U along with ^{233}U a process may be required to keep these isotopes apart.

In the case of the FSVR fuel, the BT particles (containing both fissile and fertile materials) will remain intact in the burner ash. They must be separated from the Al_2O_3 fluidizing medium and any poison material. Any broken fuel particles will be converted to fines (as oxides) for the same reason as stated above, and they too must be separated if recovery is necessary.

4.3.8.2 Status of Technology

No significant effort has been expended toward selection and development testing of equipment appropriate for separation and classification of irradiated fuel particles. Presumably the same general type that is suitable for size classification in the fuel refabrication processes (Task 200 of this plan) would be suitable here.

The success of particle classification based on size will depend directly on whether the SiC coatings are ruptured. This coating could rupture in any one or more of several operations: during fuel fabrication, during reactor operation, as a result of mechanical operation during size reduction of the fuel element, by thermal shock during burning, or by mechanical shock during fluidization. If this coating (not to say the entire fuel particle) should break for a substantial fraction of the fuel particles, classification of the fuel particles to adequately separate ^{233}U from ^{235}U will be impossible. However, separation of the ^{235}U from the ^{233}U may be possible by an alternate method (see Subtask 115).

4.3.8.3 Work Plan

Cold and irradiated specimens will be studied in the hot cell to determine the fraction of broken particle coatings and kernels that can be anticipated in the burner ash material.

Equipment suitable for pilot plant operation will be developed to handle the burner ash. Equipment currently used for similar radioactive operations will be reviewed and employed if practical. Use of commercially available devices with modifications as required for hot-cell operation will be emphasized.

4.3.9 Subtask 114 — Treatment of Classified Burner Ash

4.3.9.1 Requirement

The fuel particles in the burner ash must be crushed, reburned, and dissolved, and the solution must be made suitable for recovery of the fuel values by solvent extraction.

4.3.9.2 Status of Technology

Fuel particles from the first core of the FSVR can be crushed to expose the fissile and fertile material to attack by nitric acid or Thorex dissolvent. Under these conditions only relatively small quantities of carbon and SiC will be present. The operation to be accomplished is similar in many respects to the tests involving recovery of thoria from carbon coated sol-gel microspheres by a grind-leach technique.[1, 11–13]

The material to be recovered after head-end treatment of the reference fuel elements will be powdered oxides of poison, fissile, and fertile materials, the intact BT fissile particles, the $(Th,^{233}U)O_2$ recycle particles, and Al_2O_3. The fuel values from the recycle particles will be prepared for recovery by dissolution with Thorex dissolvent. The BT fissile particles can be crushed and dissolved as mentioned above for the FSVR fuel.

4.3.9.3 Work Plan

Laboratory development tests will be performed with both unirradiated and irradiated coated carbide and oxide particles to obtain data for the following:

1. an appropriate equipment design for crushing the SiC coatings,
2. an appropriate equipment design for burning the crushed particles,
3. an appropriate equipment design for dissolution (an essential part of this is the separation of the SiC hulls and any other residue from the dissolver product),
4. the degree of fuel value recovery possible from irradiated fuels (if excessive fissile material is embedded in the inner pyrocarbon shell, an alternate approach will be studied).

Some fission product gases will be entrapped in the solids that reach the dissolver, and a part of the hot-cell tests is to determine the extent of this problem. Methods of handling this radioactive off-gas waste must be developed. This is discussed in Subtask 117.

4.3.9.4 Analysis of Alternate Approaches

If loss of fuel values during dissolution is not excessive, or if the presence of organic acids is acceptable, the separated particles may not need to be burned after crushing to eliminate carbon present in the carbide fuel and in the pyrolytic carbon coatings. To be determined are the appropriate burning system (fixed or fluidized bed) and how to separate the silicon carbide hulls — and any other residue — from the dissolver product. Fixed-bed burning appears to be preferable to fluidized-bed burning for this operation because it will not introduce extraneous materials, such as Al_2O_3, which would require later separation from the dissolver product.

4.3.10 Subtask 115 — Alternate Methods for Maintaining Separation of ^{233}U and ^{235}U

4.3.10.1 Requirement

If SiC breakage should be excessive in the FSVR fuel or if the SiC coating on the ^{235}U particle should break excessively and the recycle particle becomes broken, then a method other than size classification will be required for maintaining separation of ^{233}U and ^{235}U.

4.3.10.2 Status of Technology

Alternative methods of maintaining separation of ^{235}U and ^{233}U have received limited consideration. A possibility for the reference fuel follows.

Apply no silicon carbide coating to any of the particles. All ^{233}U could be incorporated with thorium to make ThO_2-UO_2 particles, and the ^{235}U particles could be formed "undiluted" from either the oxide or carbide kernels. After the pyrolytic carbon coatings are burned off from all particles, the ^{235}U kernels should be readily dissolved in dilute nitric acid, whereas the ThO_2-containing particles will dissolve more slowly. If the ^{235}U kernels are carbides, the ^{235}U could possibly be carried out of the combustion chamber with the combustion products. Removal of ^{235}U oxides from combustion gases has already been demonstrated by Idaho Nuclear Corporation during development of the process for recovering uranium from Rover fuels.

Tests have shown that thorium and uranium carbides are rapidly oxidized to oxide powders if they become exposed to an oxidizing atmosphere. In the fluidized bed burner these oxidized powders would be carried out with the off-gas. If a significant number of particles break in the FSVR fuel during irradiation or during burner feed preparation, an alternate head-end method must be developed to assist in maintaining separation of the ^{235}U and the ^{233}U.

4.3.10.3 Work Plan

If the technique of size classification proves unsatisfactory for maintaining ^{235}U and ^{233}U separate, alternate methods will be studied. Laboratory development tests will be performed with irradiated and unirradiated fuel specimens to establish chemical and mechanical feasibility of processes and equipment for keeping ^{233}U and ^{235}U particles separated. Engineering evaluations will then be made to determine the relative merits of the available approaches. The evaluations will take into consideration the following:

1. effectiveness of maintaining separation,
2. overall cost of process equipment,
3. relative ease of fuel refabrication,
4. desirability from standpoint of reactor physics,
5. desirability from standpoint of fission product release.

4.3.11 Subtask 116 – Scrap Recycle

4.3.11.1 Requirement

Undetermined but significant amounts of scrap will be produced in almost every stage of fuel reprocessing and refabrication. A satisfactory, simple method of returning these scrap materials to active use or disposing of them is required for economy of fuel recycle operations. Part of this scrap will come from the refabrication operations. For example, reject microspheres containing ^{233}U and highly radioactive ^{232}U must be recycled.

4.3.11.2 Status of Technology

The status of technology of scrap recycle and the problems to be encountered are roughly the same as for normal fuel reprocessing, with the exception that gross amounts of radioactive fission products will not be present. It is expected that recycle scrap will be, insofar as possible, reprocessed by the same equipment as that used for main line reprocessing of irradiated fuel. The major problem to be considered is that of fissile material accountability. Guidance as to the amount of scrap to be expected from the sol-gel operations may be obtained from a process demonstration run[14] conducted previously at ORNL.

4.3.11.3 Work Plan

The problems of recycle of scrap will be studied. Steps to be taken in the handling of each recycle material and for an appropriate means of accountability will be formulated. Laboratory tests will be conducted to establish the methods and techniques for handling internal recycle of materials.

4.3.12 Subtask 117 – Off-Gas Handling and Decontamination

4.3.12.1 Requirement

An effective and economical means is required for removing radioactive gaseous and volatile fission products from the head-end reprocessing off-gas streams. The fission products may include ^{3}H, Kr, Rb, Mo, Ru, Te, I, Xe, and Cs as major sources of radiation, significant masses of material, or both. The processes and equipment must be selected to take into account the nature of the gas being treated.

4.3.12.2 Status of Technology

Processes and equipment exist for removal of I, Kr, Ru, and ^{3}H from the gases released from dissolvers, but none have been developed specifically for treating gases released during combustion of carbon. Likewise, a process exists for removing ruthenium from waste calcination off-gas streams.[15–16]

The composition of the gas to be treated will depend upon a number of factors, including (1) amount of atmosphere inleakage, (2) diluent used with oxygen to maintain temperature control, (3) composition of combustion reaction products, and (4) temperature of the burner bed.

The method of head-end processing will have an important effect on the point in the process at which specific fission products are released and, therefore, on the method of treatment of the fission-product-containing off-gases. About one-third of the tritium but very little of the other radioactive gases and volatile fission products is expected to appear in the gases produced in burning the graphite from intact SiC-coated particles. Only gases from particles having broken coatings are expected. If fuel values can be satisfactorily dissolved in nitric acid without the need for burning, the off-gas will be quite similar in composition to those previously treated, even if the fuel material is carbide.[17] If burning of the crushed particles before leaching is required, or, more importantly, if significant quantities of volatile fission products are released during crushing and burning the fuel element, or if the particles are not SiC-coated, the gases to be treated will consist largely of carbon dioxide. This is, of course, exactly what will happen to all but the $^{235}UC_2$ particles when reference 1000-MW(e) fuel is reprocessed.

Cesium, ruthenium, and certain other fission products volatilize at high temperature under oxidizing conditions. These materials may be most completely removed by filtration at reduced temperature. Carbon fines over the filter medium appear to be beneficial in that they seem to act as a filter aid.[1]

The major component in the burner off-gas stream will be carbon dioxide. Processes for removing this gas from gaseous streams have existed for many years. These processes range from low-temperature freezing to the use of sorbents. Commonly used sorbents for carbon dioxide removal are potassium hydroxide and alkanolamines. It is, however, by no means certain that chemical sorption is the answer. Condensation should be seriously studied.

It is anticipated that tritium will have to be removed from the off-gas stream before the carbon dioxide. Tritium should be removable from the combustion gases as tritiated water by any process suitable for efficient removal of water from carbon dioxide gas; such processes include (1) sorption on activated charcoal, (2) sorption on molecular sieves, (3) sorption on soda ash, and (4) freezing.

Iodine will be present at such small activity levels after the anticipated 150 or more days of decay that its removal will pose a problem similar to those experienced in processing plutonium production reactor and light water power reactor fuels. However, one difference exists between this situation and that commonly encountered; namely, removal of carbon dioxide from the off-gas stream is required before removal of krypton. This will likely remove the bulk of the iodine.

After removal of carbon dioxide and any other interfering gases, krypton (and xenon) can be trapped by low-temperature sorption on charcoal or molecular sieves, cryogenic distillation, or perhaps sorption in Freon.[18]

4.3.12.3 Work Plan

The work required for this subtask is a strong function of the point of release of fission gases. Hence, extensive effort cannot begin until this is determined. Early information is available from tests with irradiated Dragon Reactor compacts, and more will come from hot-cell studies with irradiation capsules and recycle test elements (RTE's) that will be provided by Task 300. After this determination is made, engineering studies and scouting tests will be performed to determine the best solution. Laboratory development tests will also be carried out to determine the anticipated quantity of atmosphere inleakage into the process equipment and to develop means to reduce the inleakage.

4.3.13 Subtask 118 – Waste Treatment and Disposal

4.3.13.1 Requirement

Radioactive wastes from HTGR fuel reprocessing operations, as from reprocessing of other types of reactor fuel, must be treated and disposed of in a fashion that avoids present or future contamination of the environment.

4.3.13.2 Status of Technology

For HTGR fuels, the three major problems in head-end management of waste fission products are: (1) control and disposal of large amounts of contaminated off-gas from fuel burning operations, (2) disposal of the contaminated SiC hulls and Al_2O_3 from the fluidized bed, and (3) disposal of the SiC-coated

$^{235}UC_2$ particles. Other waste disposal problems are essentially the same as those with the light water reactors (LWR's). Criteria for ultimate disposal will be similar to those for LWR wastes; thus, LWR experience can be used and the procedures and techniques currently under development for LWR's will be adopted.

Concepts are available [15,19–24] and laboratory data are now being derived for the treatment and ultimate disposal of the high-level radioactive solid residues from the fluidized bed-burning step and of the krypton and tritium contained in the off-gases. Disposal of spent fissile particles by storage has been previously studied.[25]

4.3.13.3 Work Plan

The plans for development of treatment processes for gases consisting primarily of CO_2 are discussed under Subtask 117. Burner technology development (Subtask 112) will determine the quantity of Al_2O_3 to be stored and its contamination level. Engineering evaluations of the various alternatives for treatment and small-scale cold laboratory development tests will seek the best method.

Waste treatment and disposal methods developed for wastes from commercial reprocessing plants for reference recycle fuels must be distinguished from the methods developed specifically for the pilot plant demonstrations. While the ultimate objective is to develop processes for the commercial reprocessing plant, attention must be paid to the specific problems that arise in the pilot plant.

4.4 SUBTASK 120 – HEAD-END PILOT PLANT DEMONSTRATION

4.4.1 Purpose

The purpose of this subtask is to develop and demonstrate, on an engineering scale, processes and equipment for head-end reprocessing of HTGR recycle fuels. The Head-End Pilot Plant demonstration will be carried out at the TURF. Equipment must be developed, designed, and built to demonstrate the following operations: (1) receive, store, and prepare fuel elements for reprocessing; (2) crush the fuel elements; (3) burn the graphite in a fluidized bed; (4) screen the resultant discrete fuel particles from fine fuel particle oxides, B_2O_3, and Al_2O_3 and classify them into their respective size fractions; (5) in the case of $(Th,U)C_2$ from FSVR fuel, crush the protective SiC coatings from the BT particles and burn the pyrolytic carbon inner buffer coatings (if necessary); (6) package the product for shipment to the Acid Thorex Pilot Plant; and (7) dispose of solid, liquid, and gaseous wastes from the head-end reprocessing steps.

4.4.2 Requirement

This subtask requires that a sufficient number of recycle fuel elements be taken through the head-end operations to (1) demonstrate that the head-end processes chosen and the equipment designed will perform adequately and (2) obtain sufficient data on both processes and equipment to provide the basis for design of head-end reprocessing equipment for a commercial recycle plant. The scale of this demonstration must be such as to show that full reference-size fuel elements prototypical of the reference fuel design in essential features can be prepared for separation and purification of the fuel values by solvent extraction. This involves a demonstration of element handling, carbon burning, particle size classification, and off-gas treatment using fuel elements irradiated in the FSVR. This subtask will be successfully accomplished when the RTE's (Subtask 302), PTE's (Subtask 303), and a number of spent FSVR fuel elements have been reprocessed. This demonstration should result in at least six months of accumulated operating time of the Head-End Pilot Plant at a rate of nine to ten FSVR fuel elements per 24-hr day. This scale, which is of the order required to process fuel from an HTGR economy totaling 3500 MW(e) operating on a four-year fuel cycle, produces 10 kg/day of recycle particles.

As indicated in Subtask 110, some head-end equipment for operations such as crushing, tumbling, grinding, and burning has been cold tested. However, no significant work has been carried out on the head-end demonstration of prototype pilot plant equipment on highly irradiated graphite fuels of any kind, and irradiation of recycle fuels of the kind described in this program has only just begun. Thus, essentially no truly pertinent pilot plant demonstration of head-end processes and equipment for recycle of HTGR fuels has been carried out.

During this Head-End Pilot Plant demonstration it will be necessary to determine fuel losses, realistic routine equipment down-time for necessary periodic cleanout and maintenance of various equipment pieces, equipment reliability and maintainability, and personnel radiation exposures obtained during routine operation.

4.4.3 Timing

The earliest possible starting date for the Head-End Pilot Plant demonstration is set by the date at which Subtask 110, the head-end reprocessing studies and equipment development, provides the necessary information to start the Head-End Pilot Plant equipment design. The development items that are critical, because of either long equipment procurement times or the necessity for considerable process development, are: element crushing, fluidized-bed burning, SiC coating removal (for FSVR fuel), and gaseous and solid radioactive waste disposal. The operating period of the Head-End Pilot Plant demonstration is set by the availability of sufficient irradiated fuel from the FSVR and the need for the proven technology for the design of a commercial recycle plant. Because the commercial recycle plant design and construction will require about 5.5 years, the pilot plant development and demonstration phase of this program will overlap the commercial plant design. The reprocessing development schedule (Fig. 4.1, page 30) shows the interrelation of the various parts of the Head-End Pilot Plant demonstration subtask, and Fig. 2.1, page 5, relates this task to the overall recycle development program. It would be desirable to perform a single, successful campaign of six-month duration for the hot demonstration, however, experience has snown that this is very unlikely. Therefore, the demonstration has been shown to span several years, reflecting that process and equipment development work is associated with this effort. It is also desirable to have the Head-End Pilot Plant operating during startup of the commercial plant to provide a facility for development support should any unforeseen problems arise.

4.4.4 Funding

An annual breakdown of the operating costs for the Head-End Pilot Plant demonstration is shown in Table 2.1, page 6. The estimated capital expenditure required to accomplish this subtask is itemized in Table 2.2, page 7.

4.4.5 Facilities

Construction of TURF was completed at ORNL in 1968. The facility's major features and capabilities include provisions for receipt, processing, and refabrication of oxide fuel assemblies up to 10 in. in rectangular cross section and 10 ft in length. Major capabilities that are available in TURF and required for the subtask are as follows:

1. shielding to provide biological protection from fission product radiation of sources as large as 35 kg of ^{235}U irradiated to 25,000 MWd/ton and decayed for 90 days; (Allowable exposure in routinely occupied areas is limited to 0.25 mR/hr.)
2. a shielded cell for chemical process equipment development;
3. a cell for mechanical operations on irradiated fuel assemblies, such as dissassembly, incident to reprocessing;
4. a cell to serve as a radiation lock and as a decontamination area; connected to this cell is a glove maintenance room for the repair and maintenance of decontaminated equipment;
5. a lightly shielded equipment storage cell to function as a stand-by storage area for contaminated equipment;
6. a liquid waste disposal system for intermediate level aqueous wastes, such as those from equipment decontamination operations and laboratory wastes;
7. a gaseous waste disposal system for radioactive particulates that accumulate in process vessels, and a gaseous waste disposal system for the cells listed above; (These waste disposal systems are not adequate to handle the radioactive gaseous wastes expected to be evolved from the burned graphite fuel or the other fission product wastes that will be present.)
8. a fuel receiving station and storage basin of limited capacity for irradiated fuel assemblies; included are the enclosing structure and bridge with hoist for handling shipping containers. It should be noted that these facilities cannot accommodate carriers that are more than 12 ft long and 6 ft in diameter without addition of special rigging (see Subtask 127), and they are not adequate for the hot demonstration described in Subtask 125.

Additional fuel receiving, storage, and handling facilities must be provided to meet the requirements of the Head-End Pilot Plant demonstration. A new fuel receiving station is required to handle the fuel shipping cask from the FSVR. A shielded storage vault is required with space sufficient to store approximately 1000 spent fuel elements. Handling facilities are required to transfer spent fuel elements from the receiving station into storage and subsequently to the burner feed preparation equipment.

4.4.6 Subtask 121 – Design

4.4.6.1 Requirement

The Head-End Pilot Plant must be designed. This design must convert the technology obtained from the Head-End Reprocessing Development Subtask (110) into drawings and specifications delineating equipment and systems of the pilot plant. A safety analysis of the Head-End Pilot Plant must be prepared to serve as the basis for hazards evaluation to assure a capability for safe and reliable operation.

4.4.6.2 Status of Technology

The design, construction, and operation of a pilot plant for the head-end reprocessing of unirradiated nuclear rocket (Rover) fuels have been completed by the Idaho Nuclear Corporation. Further, the cost of building a plant to process about 1 ton/day of heavy metal from HTGR's has been estimated on the basis of a conceptual equipment design.[26] However, the technology for nearly all the Head-End Pilot Plant design has yet to be developed.

4.4.6.3 Work Plan

Collection of information already in existence and preparation of chemical and equipment flowsheets will be the first step. Problem areas will be defined and solutions found with necessary support by the persons engaged in the head-end reprocessing development (Subtask 110). Using the results of the development subtasks, equipment and systems will be designed. Facility modifications and additions will make up a large portion of the design to be accomplished under this subtask. Drawings, specifications, and procedures will be prepared from which to construct the Head-End Pilot Plant. Codes and standards applicable to the work will be utilized. Where standards are unavailable or insufficient to supply the needs for future commercial recycle plant design, they will be prepared as a part of the Head-End Pilot Plant design.

The design will be prepared in three phases: conceptual, preliminary (Title I), and final (Title II). As shown on the schedule, these design phases will be coordinated with development subtasks to gain maximum benefit from all efforts.

It is possible, but not probable, that mechanical means will be found to free the fuel particles from the elements and the fuel sticks. In this case, a large burner design would not be necessary. However, it seems most likely that element burning will be required, and design of the burner and related equipment, such as for off-gas handling, will constitute a significant design effort in this subtask.

4.4.7 Subtask 122 - Procurement and Testing of Equipment

4.4.7.1 Requirement

Specialized processing equipment and equipment having long delivery times must be procured early enough to permit development testing before installation. Figure 4.1, page 30, serves as a general guide for procurement, but detailed critical path planning and scheduling studies will have to be made when sufficient information is available from the development subtasks to make them meaningful.

Since all major operations will be carried out for the first time on a significant scale with irradiated HTGR fuels in this pilot plant, it is essential that development testing be carried to the point of confidence in all aspects of the head-end reprocessing. Some of the equipment can be tested cold before installation; other equipment, by its nature, must be tested in the Head-End Pilot Plant itself. An outstanding example is the gaseous waste disposal system, which must demonstrate the capability of separating small amounts of hydrogen (standing in for tritium) and inert gas (for ^{85}Kr) from large volumes of carbon dioxide and oxygen.

4.4.7.2 Status of Technology

Considerable experience in the procurement and testing of prototype head-end equipment will be available through the head-end reprocessing development work by the time this task is to be carried out. At the present time, the experience is that given under various items in Subtask 110.

4.4.7.3 Work Plan

Equipment will be procured according to the program's critical path schedule. Appropriate procurement documents and methods will be developed to secure equipment of adequate quality to perform the required tasks and to provide a basis for procurement of equipment for the commercial recycle plant. As an integral part of procurement activities, each piece of equipment will be tested appropriately to demonstrate and verify its claimed performance capability.

4.4.8 Subtask 123 — Installation of Equipment

4.4.8.1 Requirement

Modifications and additions to TURF must be constructed and the equipment must be installed in the Head-End Pilot Plant. This installation must be performed with the remote handling equipment for in-cell work to demonstrate the applicability of the remote maintenance philosophy and techniques proposed for pilot plant operations. The equipment handling procedures developed during installation must be recorded to facilitate eventual removal of equipment.

4.4.8.2 Status of Technology

TURF provides shielded space and basic facilities for handling, installing, and operating most of the Head-End Pilot Plant equipment items. The philosophy of hot-cell operation and maintenance of complex equipment has been highly developed in connection with the Transuranium Process Plant[27] and the Volatility Pilot Plant, as well as other remotely maintained facilities at ORNL. This experience and knowledge will be brought to bear on the problems of equipment handling and installation.

4.4.8.3 Work Plan

New facilities and modifications to existing facilities required for receiving and storing spent fuel elements must be constructed to achieve the demonstration in this plan. Equipment for handling spent fuel elements will be installed in these new facilities. These facilities must be completed in time to receive fuel from the first discharge of the FSVR core.

Installation of the process equipment requires advanced planning of equipment layout for ease of installation and removal. In some cases this will require mockup studies. These studies will be defined as the design proceeds and equipment dimensions and features become better known. Specifications and procedures will be developed as necessary to guide the installation.

In-cell equipment will be moved into position, anchored, connected to services, and joined to adjacent processing equipment by use of the in-cell crane and manipulator systems. Out-of-cell equipment, including control panels, will be either constructed in place or prefabricated and installed.

4.4.9 Subtask 124 – Cold Operational Testing of the Head-End Pilot Plant

4.4.9.1 Requirement

The remote operability of the Head-End Pilot Plant, its material-handling capabilities, and the adequacy of operational procedures and runsheets must be tested with unirradiated prototype feed materials.

An essential part of operational cold testing any radiochemical processing plant is the training of plant operators. Information gained in the operation of the Head-End Pilot Plant, both cold and hot, will be of direct use in establishing licensing procedures for the commercial recycle plant. One of the requirements of cold operation will be to train the pilot plant operators and to establish training criteria.

4.4.9.2 Status of Technology

Over the past 20 years the cold testing phase of pilot planting a radioactive reprocessing facility has evolved and been proven.

4.4.9.3 Work Plan

Each piece of equipment will be tested in place to verify its operational capability. Individual systems will be tested for leaktightness and functional capability, and the ability of the systems to operate as an integrated pilot plant will be established. Prototype fuel elements will be handled in the fuel receiving station at TURF. These elements will have the same external dimensions as the actual fuel elements. Prototype fuel will be processed by the same procedures that will be followed with actual radioactive fuel. Equipment will be modified where necessary.

Included in this subtask will be plant operating procedure development and personnel training and indoctrination. Specifically this will include the following items: (1) programmed instruction manuals will be prepared to aid the plant operators; (2) formal lectures will be given by the designers of the equipment and by experienced radiochemical operation supervisors; (3) detailed operational procedures will be written and demonstrated; and (4) radiological and conventional safety instruction will be provided by appropriate experts.

4.4.10 Subtask 125 — Hot Demonstration of the Head-End Pilot Plant

4.4.10.1 Requirement

The Head-End Pilot Plant must be operated on hot material until reasonable assurance is gained that all significant problems have been encountered and solved. To assure this, the pilot plant must process highly irradiated fuel elements so as to encounter sufficiently severe manifestations of various irradiation effects. These effects include cracking of SiC and pyrolytic carbon coatings; penetration of fuel into the pyrolytic carbon buffer layer; fission product formation, migration, and segregation; and dimensional changes in the graphite element.

The overriding requirement of the Head-End Pilot Plant hot demonstration is that possible particle size classification be demonstrated with acceptably low ^{233}U losses to nonrecycle streams and acceptably low ^{235}U back-mixing into the fuel recycle stream. Although exact numbers cannot be assigned because of the somewhat arbitrary nature of the acceptable economic penalty, it seems clear that up to 5% ^{233}U loss and 10% ^{235}U back-mixing are tolerable. (Either of these leads to an economical penalty less than 0.015 mill/kWh.)

An important requirement is that the alumina used in the fluidized bed be recycled and that it not react with or stick to the fuel particles.

4.4.10.2 Status of Technology

The head-end treatment of irradiated HTGR recycle fuels has not yet been demonstrated. Graphite fuel burning with nonradioactive Rover fuel has been done successfully and reported.[9] Irradiated Dragon fuel compacts have been handled on a small scale in a series of hot-cell experiments aimed at determining the off-gas composition at each step of the process, particle crushing behavior, effective particle separation and size reduction procedures, and dissolution methods. The GAIL 3A and 3B fuels[13,28] (Peach Bottom Reactor first core prototype fuel) have also been studied in hot-cell tests. With the exception of the small samples of Dragon fuel,[29] the above fuels did not contain SiC barrier coatings. Since particle separation is a key step in the HTGR fuel recycle plan, it is apparent that the crucial experiments for this subtask have only begun.

The only fuel elements with irradiation exposure equivalent to fully irradiated HTGR fuel that will be available before the fall of 1978 are several of the test elements now in the Peach Bottom Reactor, which contain particles with a thorium-to-enriched-uranium ratio of 2. These particles will closely simulate normal six-year burnup conditions after three years of irradiation. Of the test elements in the Peach Bottom Reactor, six are the RTE's (see Subtask 302), which will be available for hot-cell tests and for preliminary work in the Head-End Pilot Plant as soon as the plant is ready to receive irradiated elements. Two additional RTE's should be in the Peach Bottom Reactor by early 1971. No other HTGR fuel suitable for use in the head-end process demonstration of fully irradiated fuel will be available until the first core of the FSVR reaches full burnup in the fall of 1978.

4.4.10.3 Work Plan

The Head-End Pilot Plant hot demonstration will consist of three major parts: (1) studies using part of the RTE's containing thorium-^{235}U fissile particles, which will have been irradiated in the Peach Bottom Reactor, and (2) studies using the PTE's, part of which will have been irradiated in the FSVR to full exposure (the equivalent of six years' exposure at full reactor power), and (3) the reprocessing of 1000 spent FSVR fuel elements. This number of elements will provide an aggregate of four to six months of effective pilot plant operation and will yield sufficient ^{233}U to fabricate about 150 recycle elements. The actual time of pilot plant operation will probably involve several years, reflecting the development character of the demonstration.

Parts of the RTE's will be available for head-end studies by the time they are needed, and they will be the first hot materials processed through the Head-End Pilot Plant. With the exception of possible differences related to the effects of their different irradiation history (and attendant possible differences in element crushing behavior), these elements will be good stand-ins for the reference recycle elements. Their use will enable an early test of the head-end equipment and processes. Process and equipment adjustments will be made as dictated by these results before the first elements from the FSVR are reprocessed.

The irradiated fuel elements will be crushed, some preliminary separation will be carried out, and the crushed materials will be burned in a fluidized bed of Al_2O_3 particles. The efficiency of utilization of the oxygen fed to the system during this step is expected to be greater than 90% for operation at 750 to 800°C. Control of the oxygen feed rate will control the temperature.

Because release of ^3H_2O, ^{85}Kr, and other fission products is expected during these head-end operations, off-gases from the various steps will be treated to remove these isotopes. Existing technology[30] or that developed in future experiments will be used. The burner ash will be separated and classified. The Al_2O_3 will be routed back to the burner for reuse whenever possible. Particles of SiC-coated $^{235}UC_2$ will be processed for storage (following leaching to remove fuel values on their surfaces, if necessary). The fertile particles coated with SiC (from the FSVR) will be crushed to remove the SiC coating and treated by an additional burning step. The classified fractions from the burner ash will be accumulated and dissolved.

It is assumed that the leacher and dissolver will be part of the Head-End Pilot Plant. Whether they will be located in the Head-End Pilot Plant or the Acid Thorex Pilot Plant (Building 3019) will not be finally decided until additional flowsheet and operational feasibility studies have been made.

4.4.11 Subtask 126 — Waste Treatment and Disposal

4.4.11.1 Requirement

The natures and quantities of wastes anticipated in the Head-End Pilot Plant are estimated in Appendix C. An idea of the size of the waste streams and of the magnitude of the problems may be obtained from Fig. 4.2 (page 33), which is based on putting about 10 FSVR fuel elements per day through head-end reprocessing. The ^{233}U contained within these elements is sufficient to prepare 10 kg of recycle particles with a thorium-to-uranium atom ratio of 4.25. Gaseous wastes containing CO_2 and volatile fission products must be made safe before release to the environment.

Liquid waste must be collected and disposed of according to its activity level and type of contamination. Fissile uranium must be diluted with depleted or natural uranium before discharge to the Melton Valley waste system. Tritiated water will require special handling for waste storage.

Solid waste containing radioactivity must be contained and disposed of in controlled areas specifically designated for such wastes. They must be collected, packaged, and identified for storage.

4.4.11.2 Status of Technology

The technology of waste treatment, disposal, and storage is undergoing an extensive revamping in the United States. We must be sufficiently flexible in our plan to accommodate revised criteria that may derive from this situation.

The technology for handling off-gas is discussed under Subtask 117. The TURF off-gas system is suitable for removing particulate materials from the cell and vessel vent gases by filtration. No gas scrubbing equipment is provided.

Liquid waste collection and storage systems exist in TURF. They are adequate for handling high-level wastes that have been made compatible with the type 304L stainless steel lines and tanks that make up the waste system. It is assumed that provisions will be available for permanent disposal of all radioactive wastes. Written procedures and regulations for liquid waste handling are part of the ORNL standard practice procedures.

Solid wastes will be derived from process waste, salvaged equipment, and contaminated clothing. Procedures exist for handling such wastes.

4.4.11.3 Work Plan

Cell ventilation air, process vessel off-gas venting, and incidental waste gases will be disposed of by direct release to the TURF off-gas system, which has a minimum of 10,000 ft/min of air flowing to a 250-ft-tall stack with an average atmospheric dispersion factor of 0.92×10^{-5} sec per cubic meter released. Gaseous products from the burner containing CO_2, CO, and volatile and gaseous fission products will be treated in special cleanup equipment before release to the TURF off-gas stream.

Nonradioactive liquid waste will be handled in the existing TURF process waste system, which is monitored before collection in temporary storage tanks. Such process waste when found to be contaminated can be diverted to ponds that can be drained into the Melton Valley waste disposal system.

Tritiated water will be either packaged for burial or diluted with water to required limits and released to the radioactive hot drain in TURF.

Contaminated clothing, such as shoe covers and gloves, will be bagged for disposal.

Only the radioactive solid process waste will require special equipment for handling and disposal. Doubly enclosed containers for solid waste disposal will be provided. The filled containers will be collected in the shielded processing cells and loaded into a heavily shielded cask for transport to solid waste disposal areas. An existing cask will be modified for solid waste handling. All radioactive waste that requires permanent disposal will be delivered to a central radioactive waste disposal facility at ORNL. It is assumed that this facility, provided by other AEC programs, will be available to support this program. Approximately 15% of the present receiving, handling, storage, and shipping capabilities of TURF will be utilized in the flow of solid wastes.

4.4.12 Subtask 127 – Material Handling

4.4.12.1 Requirement

Materials required to sustain operation of the Head-End Pilot Plant must be handled both entering and leaving the plant. These materials will include both feed and support materials to the process, scrap and off-specification material generated by the process, and the products coming from the process. These materials must be received, handled, stored, or shipped as appropriate. The present TURF capacity is insufficient to accommodate the operations of this subtask necessary to carry out the planned demonstration.

Test fuel elements must be secured for use in development and cold operational testing. About 40 unirradiated FSVR fuel elements will be required for development testing of the Head-End Pilot Plant equipment. Part of these should be shipped in the FSVR Fuel Shipping Cask to simulate hot fuel handling. About half these elements will be needed by January 1974 and the remainder by July 1975.

In addition to these fuel requirements for Head-End Pilot Plant equipment testing, test fuel elements will be required for cold studies of capability and reliability of prototype equipment. Five to ten reference prototype fuel elements will be required each year in 1971 and 1972 and 10 to 20 in 1973.

Spent fuel materials that must be handled from the recycle fuel irradiations Task 300 include RTE's, PTE's, and refabricated test elements containing ^{235}U and ^{233}U. In addition approximately 1000 irradiated FSVR fuel elements must be received, stored, and handled to supply the planned hot demonstration operations.

Products from the Head-End Pilot Plant must be packaged, transferred from the head-end processing cell or shipped from the plant.

Process samples and support materials must also be received, stored, handled, and shipped to support the demonstration.

4.4.12.2 Status of Technology

Experience exists in handling spent fuel elements. The fuel cask and carriers for handling irradiated FSVR materials exist, and operating procedures have been established for their use. However, it may be necessary to develop certain modifications to existing procedures or, in some cases, to establish new handling techniques through mockup tests. Experience also exists for handling the flow of support materials and product from this type of pilot plant.

4.4.12.3 Work Plan

The 60 to 80 FSVR fuel elements required for development testing and cold operations will be fabricated from standard FSVR fuel blocks and loaded with fuel materials prepared during development activities of Subtask 210.

The RTE's will be delivered to ORNL in the Peach Bottom shipping cask. It will be unloaded, the elements will be segmented, and certain parts will be used for postirradiation examination (PIE). Some specimens will be kept for hot-cell development and the remainder will be shipped to TURF for storage and eventual reprocessing.

The PTE's, the 1000 FSVR spent fuel elements, and the refabricated test elements containing ^{235}U and ^{233}U will be delivered to ORNL in the FSVR fuel shipping cask. These elements, each weighing approximately 300 lb, will be shipped six at a time inside the fuel shipping cask, which measures about 30 in. in diameter × 18.5 ft long. The cask is hauled on a tractor trailer with overall dimensions 50 ft long × 8 ft wide × 14 ft high. The trailer is 40 ft long but can be collapsed to 30 ft when parked.

The shipping arrangement and the size of the cask make special cask handling equipment and facilities necessary at or near the TURF site. These special facilities include the utilization of space in ORNL Building 7503 for interim spent fuel storage and the construction of a spent fuel receiving, storage, and handling facility, which is to be located near the TURF head-end reprocessing cell. These facilities can receive and handle fuel at a rate sufficient to sustain the head-end processing capacity. They would have dry storage space for storing up to 1000 spent fuel elements in cans 17.5 in. in diameter. A total of 2.1 ft^2 of floor space (at 75% loading) is required to store a column of these cans.

Process support materials such as Al_2O_3, process gas, packaging containers, spare parts, and hardware will be handled through existing facilities at TURF. Process samples will also be handled through these facilities. The flow of samples, support materials, and product, exclusive of spent fuel elements, will require about 25% of the present receiving, handling, storage, and shipping capabilities of TURF.

4.4.13 Subtask 128 — Process Development Support

4.4.13.1 Requirement

As is the case with any pilot plant, unforeseen problems will arise and require rapid solutions. Laboratory and hot-cell tests on actual materials are necessary to give the plant's operators guidance in solving the problems.

4.4.13.2 Work Plan

A process chemist and supporting hot cell facilities will be made available to accomplish the requirement given above. It will be this chemist's and the hot cell operator's function to perform the tests required to provide help to solve the problems. In addition, equipment changes and head-end work on unirradiated elements will be carried out as necessary as a result of deficiencies found after preliminary hot operations with the RTE's or during the other hot operations.

4.5 SUBTASK 130 — ACID THOREX PILOT PLANT DEMONSTRATION

4.5.1 Purpose

The objective of the Acid Thorex Pilot Plant demonstration is to prove that the Acid Thorex Process is adequate to reprocess the uranium-thorium mixture resulting from the head-end reprocessing of irradiated HTGR recycle fuel. The present plan is to process this material at ORNL in Building 3019 (Thorex Pilot Plant) with existing equipment, modified and supplemented as necessary for HTGR Recycle fuel reprocessing. The uranyl nitrate solution resulting from this subtask will then be shipped to the TURF for feed to the Refabrication Pilot Plant. In addition to the primary objective, the secondary objectives of establishing the number of purification cycles required for adequate decontamination from radionuclides and chemical impurities and establishing feed clarification efficiency must be met.

4.5.2 Requirement

Recycle ^{233}U must be separated from fission products and from thorium and other contaminants such as fluoride and boron. The ^{233}U must be recovered with acceptably low losses (usually less than 0.5%) and be suitable for recycle to the Refabrication Pilot Plant.

The required activities of this subtask include modifications and additions to the existing Thorex Pilot Plant. When these modifications are made it will be referred to as the Acid Thorex Pilot Plant. As presently installed, the plant is used as the National ^{233}U Dispensing Facility and is equipped with two complete solvent extraction cycles. Some rerouting of piping is necessary to partition the uranium stream from the thorium and waste streams.

Because of the probable presence of ^{3}H, Kr, I, Ru, Mo, Te, Cs, and Rb in the recycle fuel, their release from process streams may require off-gas treatment system modifications. This possibility is being better defined by the hot-cell studies now in progress, and early indications are that some ^{3}H and ^{85}Kr release is to be expected. To maintain the criticality control necessary for handling ^{233}U and ^{235}U, borated-glass Raschig rings must be installed in expanded column sections.

This demonstration must be on a scale sufficient to show that feed material coming from the Head-End Pilot Plant at the design capacity can be successfully purified. The present capacity of the Thorex Pilot Plant is about 6 kg/day of ^{233}U. The feed to the Acid Thorex Pilot Plant will have a thorium-to-uranium ratio of about 30 according to present flowsheets. Recycle fuel particles for about five 1000-MW(e) reference HTGR fuel elements can be fabricated from 6 kg of ^{233}U. Operating at present capacity the Thorex Pilot Plant will provide recycle capability (^{233}U only) for an HTGR economy of 10,000 MW(e). It is anticipated that the Acid Thorex Pilot Plant will be capable of the same capacity when placed into operation.

A small part of the material from head-end reprocessing of 1000 FSVR elements will have attained full irradiation exposure in FSVR. This will be enough to adequately demonstrate the purification process. It is apparent that the Acid Thorex Pilot Plant will need to be operated on a schedule that will match the schedule of the Head-End and the Refabrication Pilot Plants during their operation.

4.5.3 Timing

The reprocessing development schedule (Fig. 4.1, page 30) shows the interrelation of the various parts of the Acid Thorex Pilot Plant demonstration subtask, and Fig. 2.1, page 5, relates this task to the overall recycle development program.

4.5.4 Funding

The estimated annual operating expenses for the Acid Thorex Pilot Plant are summarized in Table 2.1, page 6. The estimated capital expenditure required for modifying the Thorex Pilot Plant is itemized in Table 2.3, page 8.

4.5.5 Facilities

No new facilities will be required to accomplish this subtask. However, some modifications will be required to Building 3019.

4.5.6 Subtask 131 – Design

4.5.6.1 Requirement

Although the technology of the Acid Thorex Process is established, several equipment modifications and additions must be made to the existing Thorex Pilot Plant for it to process HTGR recycle fuels. The equipment requiring significant design effort includes equipment for handling carriers, the feed charging device, and the off-gas handling systems. In addition to the preparation of detailed component designs and facility modification, criticality calculations must be made and the results integrated into a safety analysis of the Acid Thorex Pilot Plant.

One of the primary concerns in handling HTGR fuels in the purification system is that of nuclear safety. The concentration of uranium in the solvent extraction feed is such (35 g/liter) that the criticality concentration limit of the presently installed equipment is exceeded. For this reason, reliance on soluble and fixed poisons, system geometry, and mass limit control will be required to keep the system subcritical. In addition to the equipment and procedure changes necessary to control criticality, boron and thorium in the Acid Thorex Pilot Plant feed act as soluble neutron poisons.

4.5.6.2 Status of Technology

Throughout the years, the Building 3019 Facility has undergone several design and equipment changes required by the pilot planting of the Purex, Thorex, Redox, and Interim-23 solvent extraction purification processes. Thus, design of solvent extraction plants is a subtask for which the technology is very highly developed.

4.5.6.3 Work Plan

Available information, especially from the hot-cell studies, applicable to the feed preparation and to off-gas treatment, will be collected and evaluated. Flowsheets will be prepared and key areas demonstrated. Specific components (feed preparation system, off-gas handling system) will be designed, procured, and tested. A detailed criticality evaluation will be made, and a preliminary safety analysis of the pilot plant will be prepared and reviewed by the necessary quality assurance and safety committees. Final design of the required Thorex Pilot Plant modifications and additions will be prepared. Drawings, specifications, and procedures will be prepared sufficient to modify the existing plant and to install new equipment. Codes and standards applicable to the work will be utilized. The design will be prepared in three phases, conceptual, preliminary (Title I), and final (Title II).

4.5.7 Subtask 132 – Procurement and Testing of Equipment

4.5.7.1 Requirement

Several new components of process equipment will be required to transform the Thorex Pilot Plant into the Acid Thorex Pilot Plant with capability to perform this demonstration task.

4.5.7.2 Status of Technology

Nothing in this subtask requires development of new technology except the off-gas system. In the case of this system, the basic technology will be developed under Subtask 117, and will be adopted with the changes necessary.

4.5.7.3 Work Plan

Equipment will be procured as dictated by the program's critical path schedule. Appropriate procurement documents and methods will be applied to secure equipment with adequate quality to perform the required operations. As an integral part of procurement activities, appropriate tests will be run on each item of equipment to demonstrate and verify its performance capability.

4.5.8 Subtask 133 – Installation of Equipment

4.5.8.1 Requirement

New components and equipment must be installed and facilities modified concurrently with routine processing of ^{233}U. As stated previously, the Building 3019 Facility also serves the AEC as the National ^{233}U Dispensing Facility.

4.5.8.2 Status of Technology

The extensive experience of changing flowsheets, equipment, and programs in Building 3019 is directly applicable to this program subtask.

4.5.8.3 Work Plan

After the equipment has been procured and proof tested, new components will be installed in the pilot plant. Existing structures, equipment, and systems of the facility will be modified by procedures and techniques that are established for work of this type at ORNL and under ORNL quality assurance and safety controls.

4.5.9 Subtask 134 – Cold Operational Testing of the Acid Thorex Pilot Plant

4.5.9.1 Requirement

To demonstrate the adequacy of the new components as part of the overall plant, cold testing will be required. Specific requirements of cold testing activities include:

1. evaluating the remote operability and the maintainability of the plant and its components. It should be noted that the in-cell equipment in the Acid Thorex Pilot Plant is maintained directly, while that used in the Head-End Pilot Plant is maintained remotely.
2. establishing the actual maximum and minimum plant capacities,
3. determining the effectiveness of the operator training program,
4. validating of the specific operational procedures and hazards evaluation,
5. providing a period of operation to verify process control.

4.5.9.2 Work Plan

Each piece of equipment will be tested to verify its operational capability. Individual systems will be tested for leaktightness and functional capability, and finally the complete Acid Thorex Pilot Plant will be tested to verify its operational readiness. Material that simulates the product from the Head-End Pilot Plant will be purified in the solvent extraction system. Product from the cold testing operations at the Head-End Pilot Plant will be processed. Material handling methods will be studied and optimized to prevent overexposure of personnel when irradiated material is handled.

Included in this subtask will be operating procedure development and personnel training and indoctrination.

4.5.10 Subtask 135 – Hot Demonstration of the Acid Thorex Pilot Plant

4.5.10.1 Requirements

The Acid Thorex Pilot Plant must process hot material to establish requirements of the solvent extraction step for reprocessing HTGR fuels on a commercial scale. Several specific pieces of information must be obtained from the pilot plant's hot demonstration. These include:

1. establishing the number of solvent extraction cycles needed for radiochemical and chemical decontamination,
2. establishing the process losses of fissionable material,
3. assessing the actual amount of process downtime,
4. obtaining adequate personnel radiation exposure records.

4.5.10.2 Status of Technology

The Acid Thorex Process being considered for HTGR fuel reprocessing was developed at ORNL. During the demonstration of the Acid Thorex Process, considerable experience was gained as a total of 40 metric tons of irradiated thorium metal and oxide were processed. Some of the processing involved short-decay fuel (28 days) with 4000 g ^{233}U/ton Th. Adequate decontamination factors were demonstrated.

Recently, both the Hanford and Savannah River sites[31] have employed the Thorex technology to process ton quantities of lightly irradiated ThO_2 to supply the Commission with ^{233}U. In addition to this experience, a report has been prepared[32] wherein the same information has been applied in a proposal to reprocess HTGR fuel in the Nuclear Fuel Services plant. Thus, Acid Thorex technology is developed to a point that scale-up to HTGR fuel reprocessing is feasible.

Since the conclusion of the Thorex program, the equipment and facilities at ORNL have been used as the National ^{233}U Dispensing Facility. Considerable information on shielding requirements and operating experience has been gained during this period. The facilities include shielded wells for storing up to 168 kg of ^{233}U in solid form and tanks that can store 500 kg of ^{233}U in uranyl nitrate solutions at ^{233}U concentrations up to 250 g/liter. Also, a shielded interim storage vault (Building 3100) can hold up to 70 kg of ^{233}U or ^{239}Pu in shipping containers. At present, nine wells for solid storage and five tanks for solution storage are being added to increase the capacity by 80% for solids and by 100% for solutions.

4.5.10.3 Work Plan

The work plan begins with a study of receipt of the product from the Head-End Pilot Plant.

After receipt at the Acid Thorex Pilot Plant, the product will be adjusted to flowsheet conditions by steam stripping. Extraneous solids, such as silica and carbonaceous materials, may be in the feed solution and cause emulsion problems in liquid-liquid extraction systems; therefore, a clarification system may be required.

The adjusted feed solution will be pumped to an extraction-scrub column where the uranium and thorium are separated from the fission products. The column raffinate, which contains the fission products, will probably be transferred to the ORNL high-level waste evaporator for volume reduction. The method chosen for storage of the high-level waste is not yet established and depends on a number of factors currently under study.

The uranium and thorium in the organic phase will be partitioned by adjusting the acid in the second column. Thorium contained in the aqueous phase flowing from this column will be analyzed and routed to metal waste storage. The uranium will be stripped from the organic stream with demineralized water in a third column. After concentration of the uranium product by evaporation, the solution may be recycled to the solvent extraction cycle for additional purification. Ample critically safe storage capacity presently exists for the uranium. This subtask ends with transfer of the ^{233}U as uranyl nitrate solution to the Refabrication Pilot Plant.

The chemical flowsheet is presented in Fig. 4.4.

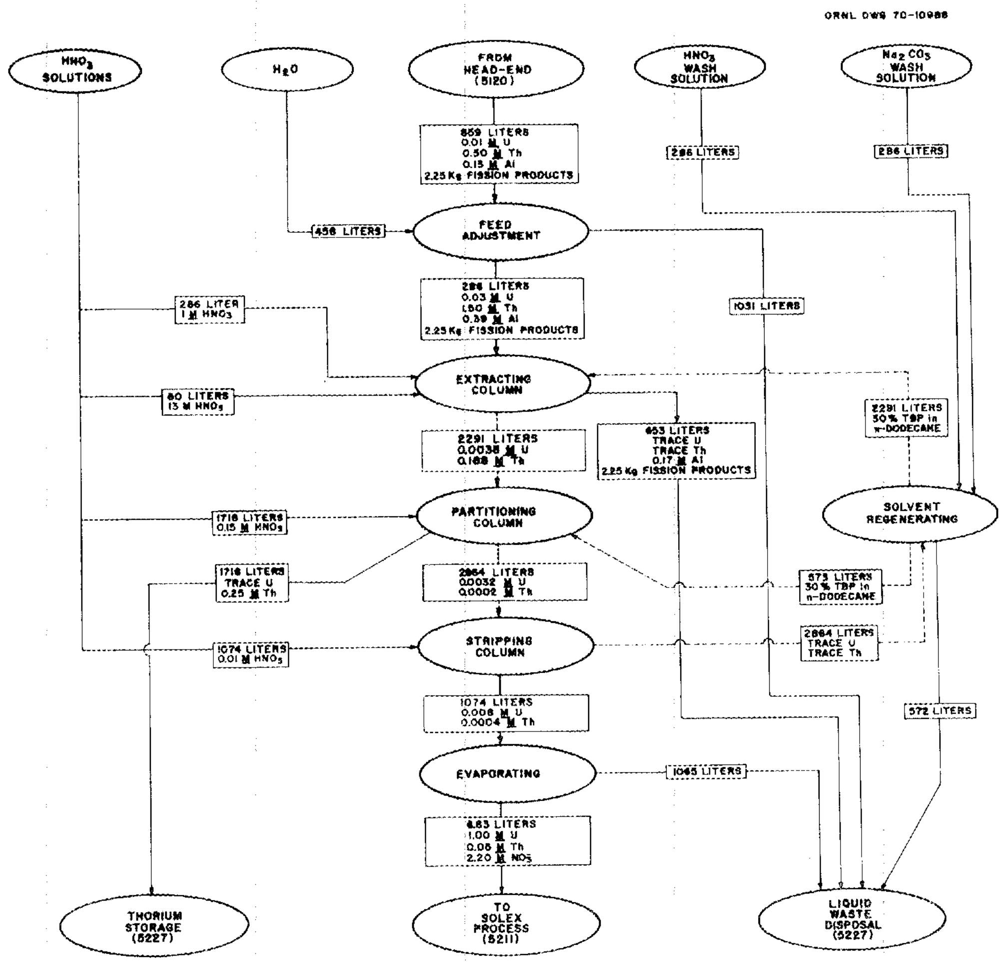

Fig. 4.4. Proposed Acid Thorex Chemical Flowsheet for HTGR Fuel Purification. Basis: 9.7 first-core Fort St. Vrain Reactor fuel elements irradiated two years.

4.5.11 Subtask 136 — Waste Treatment and Disposal

4.5.11.1 Requirement

The natures and quantities of wastes anticipated in the Acid Thorex Pilot Plant are estimated in Appendix C.

Gaseous waste containing volatile fission products from the Process Equipment must be made safe before release to the environment.

Liquid waste must be collected and disposed of according to its activity level and type. Fissile uranium must be diluted with depleted or natural uranium before discharge to the ORNL high-level waste system. Tritiated water will require special handling for waste storage.

Solid waste containing radioactivity must be contained and disposed of in controlled areas specifically designated for such wastes. They must be collected, packaged, and identified for storage.

4.5.11.2 Status of Technology

The technology for handling off-gas is discussed under Subtask 117. The Building 3019 off-gas system is suitable for filtering particulate materials from the cell and vessel exhaust gases. Some gas scrubbing equipment is provided. The TURF does not include gas filtration equipment.

Liquid waste collection and storage systems exist at ORNL. They are adequate for handling high-level wastes that have been made compatible with the type 304L stainless steel lines and tanks that make up the system. Also available will be provisions for permanent disposal of all levels of radioactive wastes. Written procedures and regulations for liquid waste handling are part of the ORNL standard practice procedures.

Solid wastes will be derived from process waste, salvaged equipment, and contaminated clothing.

4.5.11.3 Work Plan

Cell ventilation air will be disposed of by direct release to the 3020 stack, which has a minimum of 38,000 ft/min of air flowing to a 250-ft-tall stack with an average atmospheric dispersion factor of 1.0×10^{-7} sec per cubic meter released. The krypton and xenon will be collected, packaged, and disposed of as a solid waste.

Liquid waste not suspected to contain radioactivity will be handled in the existing ORNL intermediate-level waste system, which is monitored before collection in temporary storage tanks. Contaminated process waste is diverted to the ORNL high-level waste disposal system. Tritiated water will be either packaged for burial or diluted with water to required limits and released to the radioactive hot drain.

Contaminated clothing, such as shoe covers and gloves, will be bagged for burial.

Only the radioactive solid process waste (mainly Al_2O_3) will require special equipment for handling and disposal. Doubly enclosed containers for solids waste disposal will be provided. The filled containers will be collected and loaded into a heavily shielded cask through the carrier charging mechanism for transport to solid waste disposal areas. An existing cask will be modified for solid waste handling.

All radioactive wastes that require permanent disposal will be delivered to a central radioactive waste disposal facility at ORNL. It is assumed that this facility, provided by other AEC programs, will be available to support this program.

4.5.12 Subtask 137 - Material Handling

4.5.12.1 Requirement

Materials required to sustain operation of the Acid Thorex Pilot Plant must be handled both entering and leaving the plant. These materials will include feed and support materials to the process and scrap and the products coming from the process. These materials must be received, handled, stored, or shipped as appropriate.

Transfers of ^{233}U nitrate solution from the Acid Thorex Pilot Plant will contain up to 25 kg of ^{233}U at 250 g/liter.

Process samples and support materials must also be received, store handled, and shipped to support the demonstration.

4.5.12.2 Status of Technology

Experience exists in handling irradiated fuel material, the fuel cask and carriers for handling this material exist, and their operating procedures have been established. However, it may be necessary to modify existing procedures or, in some cases, to establish new handling techniques through mockup tests. Experience also exists for handling the flow of support materials and product from this pilot plant.

4.5.12.3 Work Plan

The existing carriers will be modified to meet the specific requirements of the handling equipment at the Acid Thorex Pilot Plant. Dummy runs will be made with existing casks to test the feed charging mechanism. Practice runs will also be made with empty solution carriers to test the ^{233}U withdrawal equipment and to develop handling procedures.

4.5.13 Subtask 138 – Process Development Support

4.5.13.1 Requirement

Previous pilot plant operational experience indicates that unforeseen problems will arise and require rapid solution. In the case of processing irradiated HTGR fuels, the refining of procedures concerned with feed clarification, decontamination, and product purity and losses may require laboratory and hot-cell tests to assist the plant's operator in solving problems.

4.5.13.2 Work Plan

A process chemist and supporting hot-cell facilities will be made available as needed to follow a particular process and to provide the required support. This individual will be responsible for following the day-to-day operation of the plant and working toward optimizing its operation.

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5. TASK 200 — REFABRICATION DEVELOPMENT

5.1 INTRODUCTION

This task includes the development and demonstration of processes and equipment for fabricating HTGR recycle fuel elements from thorium and ^{233}U nitrate solutions. The reference recycle element contains two particle types as described in detail in Chapter 3. The ThC_2 particle is available commercially; no development of processes or equipment for the refabrication of this particle is planned.

Development of processes and equipment for remotely fabricating recycle fuel is necessary because of the high radioactivity associated with this fuel material. After repeated recycle, the uranium extracted for recycle from the spent fuel elements will contain about 500 ppm ^{232}U, which disintegrates in a short time to isotopes of bismuth and thallium that emit very penetrating gamma radiation.[1–3] Thus, shielding is needed to protect the operators of an HTGR refabrication plant from excessive radiation exposure. The resultant need for remote operation demands that all equipment must be automatic and highly reliable. Provision is required for maintaining the equipment in the high radiation field. At present very little experience exists in remote fabrication of large numbers of fuel elements.

The Refabrication Development task is organized into Refabrication Process Development (Subtask 210) and Refabrication Pilot Plant Demonstration (Subtask 220). The Refabrication Process Development (210) delineated on the flow diagram (Fig. 5.1) includes Sol Preparation (211), Microsphere Preparation (212), Microsphere Coating (213), Fuel Stick Fabrication (214), Fuel Element Assembly (215), and Recycle of Off-Specification Material (216).

The Refabrication Pilot Plant Demonstration (220) includes Design (221), Procurement and Testing of Equipment (222), Installation of Equipment (223), Cold Operational Testing of the Refabrication Pilot Plant (224), Hot Demonstration of the Refabrication Pilot Plant (225), Waste Treatment and Disposal (226), Materials Handling (227), and Process Development Support (228). In addition, process specifications, quality control procedures, and techniques and procedures for fuel handling will be developed where applicable.

The refabrication scheme begins with receipt of the reclaimed ^{233}U, as uranyl nitrate solution, and ends with the shipment of a refabricated fuel element in a shielded carrier to the reactor. Materials handling is an essential part of the refabrication scheme, including the input of nitrate solutions,

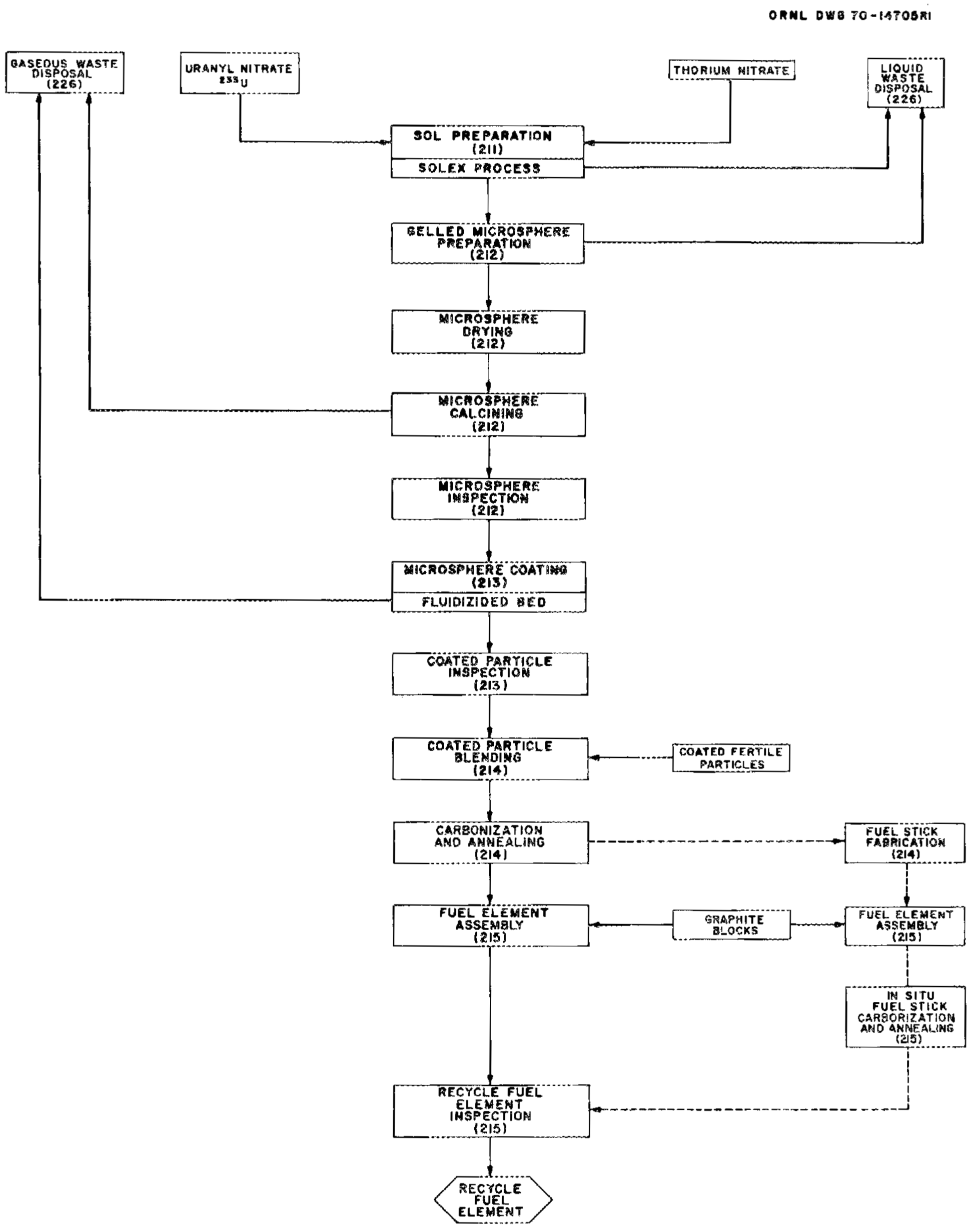

Fig. 5.1. HTGR Fuel Refabrication.

fertile particles, and graphite blocks as well as adequate preparation of all waste streams (gaseous, liquid, and solid) for ultimate disposal.

The equipment will be installed, tested in cold operation, and demonstrated in the refabrication processes in TURF. The in-cell equipment of the Refabrication Pilot Plant is to be maintained by remote modular replacement or repair, although other methods such as decontamination and direct maintenance will be investigated to develop information that may be of value to the design of a commercial fuel recycle plant. Remote modular replacement is particularly suited to TURF with its large hot cells and separate decontamination and repair areas. All equipment for the Refabrication Pilot Plant will be designed so that the entire apparatus or, where practical, subsections of the apparatus can be removed by manipulators and a traveling crane to be replaced or repaired and returned.

5.2 REFABRICATION DEVELOPMENT SCHEDULE

The schedule for performing the steps of this major task of the Development Program is shown in Fig. 5.2.

5.3 SUBTASK 210 — REFABRICATION PROCESS DEVELOPMENT

5.3.1 Purpose

The purpose of this subtask is to develop the processes and equipment needed to remotely refabricate HTGR recycle fuel and fuel elements, starting with the aqueous nitrate solutions of uranium and thorium from the Acid Thorex Pilot Plant and ending with elements ready to be shipped to the reactor.

5.3.2 Requirement

Practical processes and reliable equipment must be developed to convert solutions from the Acid Thorex Pilot Plant to sols, oxide microspheres, coated particles, fuel sticks, and fuel elements as discussed in the following sections. Inspection techniques and process controls to ensure quality of product must also be developed. The quality required will be proven by the radiation tests outlined in Task 300.

5.3.3 Timing

The various development subtasks must be completed according to the schedule in Fig. 5.2 to provide the results needed to design, procure, test,

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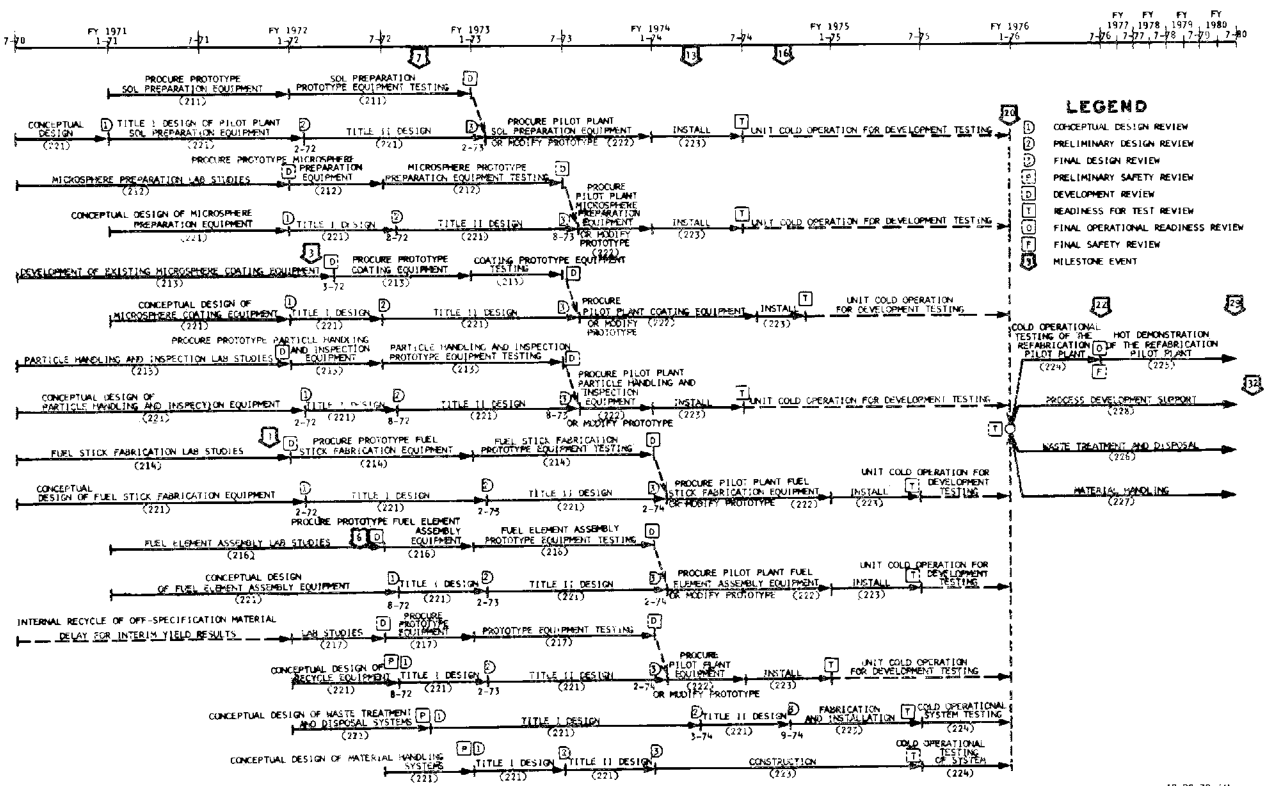

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Fig. 5.2. Refabrication Development Schedule.

and install the necessary equipment and construct modifications to facilities in TURF before the start of cold operational testing of the Refabrication Pilot Plant in January 1976.

5.3.4 Funding

The refabrication processing development will require operating funds as shown in Table 2.1, page 6.

5.3.5 Facilities

The facilities that will be used in the laboratory development are primarily the existing chemical and engineering laboratories and hot cell facilities at ORNL. The available laboratories and facilities provide the services and, in some cases, the capability for providing sols, oxide microspheres, coated particles, and fuel sticks needed for various development aspects of the refabrication process and equipment development.

5.3.6 Subtask 211 – Sol Preparation

5.3.6.1 Requirement

A stable sol of ThO_2-UO_3 suitable for use in forming microspheres must be produced from aqueous nitrate solutions of uranium and thorium. Equipment that can be remotely operated and maintained must be developed to carry out this subtask at about 10 kg/day.

5.3.6.2 Status of Technology

An amine extraction process (Solex Process) for preparing ThO_2-UO_3 sols is in an advanced stage of development.[4–6] Equipment has been designed[7] and operated on a scale at least equal to the approximately 12 kg/day capacity[6] requirement. Figure 5.3 is a chemical flowsheet that is representative of the process that will be used for sol preparation. The work remaining to be done is establishing long-term reliability of key equipment pieces and adaptation of the process to remote operation and maintenance.

5.3.6.3 Work Plan

Development equipment will be fabricated for remote operation and maintenance, and sols will be prepared. The steps in performing this work include the following: (1) units of equipment that perform individual process steps will be adapted for remote operation and maintenance, (2) equipment and process changes will be made as necessary to develop reliable, integrated, remotely

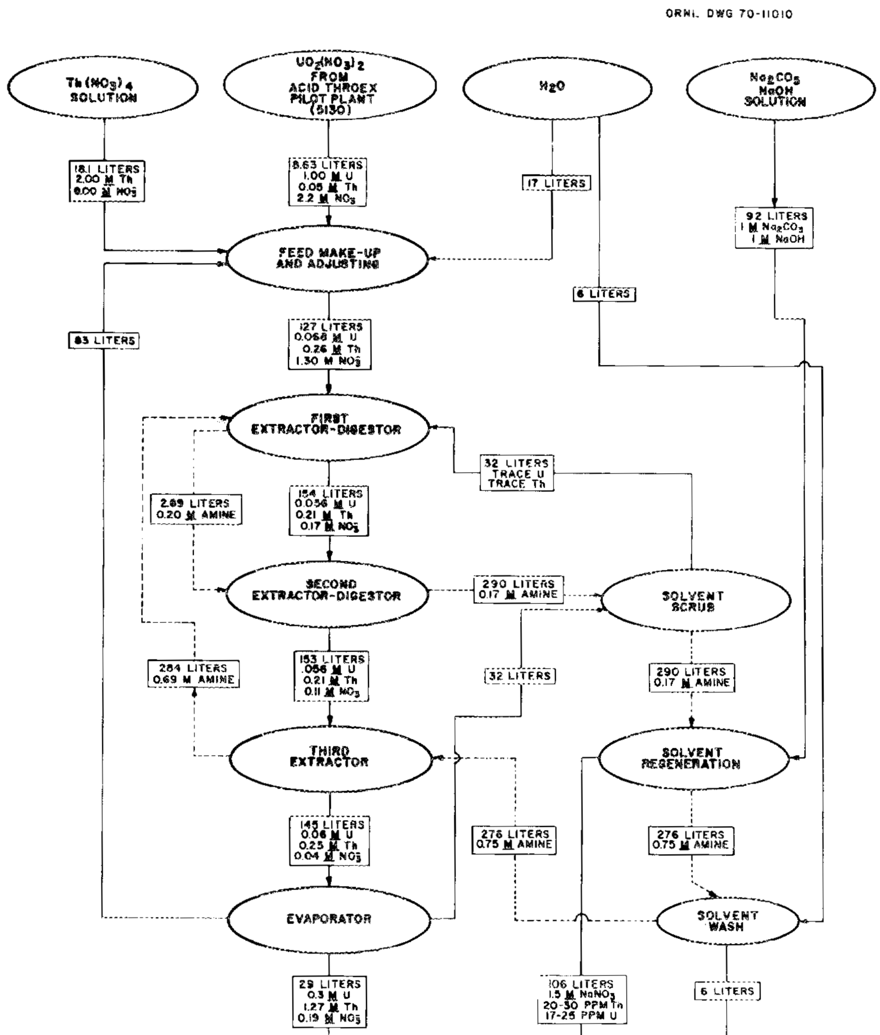

Fig. 5.3. Proposed Solex Process Chemical Flowsheet for the Preparation of Sol for 10 kg/Day of Microspheres with a Thorium-to-Uranium Ratio of 4.25.

operable components and produce sols for use in subsequent operations, (3) the integrated sol-making complex will be operated and maintained remotely over a sufficient period of time to prove reliability, (4) large quantities of sol will be prepared as needed in microsphere-forming laboratory development studies (see Subtask 212), and (5) methods and procedures for evaluating sols will be developed.

5.3.7 Subtask 212 – Microsphere Preparation

5.3.7.1 Requirement

The reference recycle fuel requires remote preparation of a ThO_2-UO_2 microsphere having a thorium-to-fissile-uranium ratio of 4.25 and a 350- ± 25-μm diameter. The microsphere must exceed 95% of the theoretical density and must be strong enough to survive all subsequent fabrication steps. Processes and equipment must be developed to reuse 2-ethyl-1-hexanol, to form gel microspheres, to dry and fire the gel to dense microspheres, and to handle microspheres and transfer them to subsequent fabrication steps. All of these operations must be carried out remotely in equipment that can be remotely maintained and replaced.

5.3.7.2 Status of Technology

About 150 kg of ThO_2-UO_3 as sol and 100 kg of ThO_2-UO_2 as microspheres of the compositions of interest have been produced in pilot-plant-scale equipment during essentially continuous operation.[6] This experience provides the basis for additional laboratory tests to develop methods and equipment for remote operation and to provide the technology necessary to design and construct the microsphere equipment for the Refabrication Pilot Plant. Figure 5.4 is a chemical flowsheet for microsphere preparation. Remote microsphere transfer from the microsphere-forming column to the dryer, and from the dryer into and out of a closed calcining furnace has been demonstrated. Over 30 kg of ThO_2-$^{233}UO_2$, for use in the High-Temperature Lattice Test Reactor,[8] has been prepared semiremotely, as has ThO_2-$^{235}UO_2$ of several thorium-to-uranium ratios and $^{235}UO_2$ microspheres,[8,9] for use in fabricating the eight RTE's for irradiation in the Peach Bottom Reactor. The microsphere-forming column and associated equipment to recycle the 2-ethyl-1-hexanol have not been operated completely remotely.

A major redesign of the dryer that has been under development was shown to be necessary during the preparation of the 100 kg of ThO_2-UO_2 microspheres. Since then a new dryer has been designed, built, installed in the laboratory,

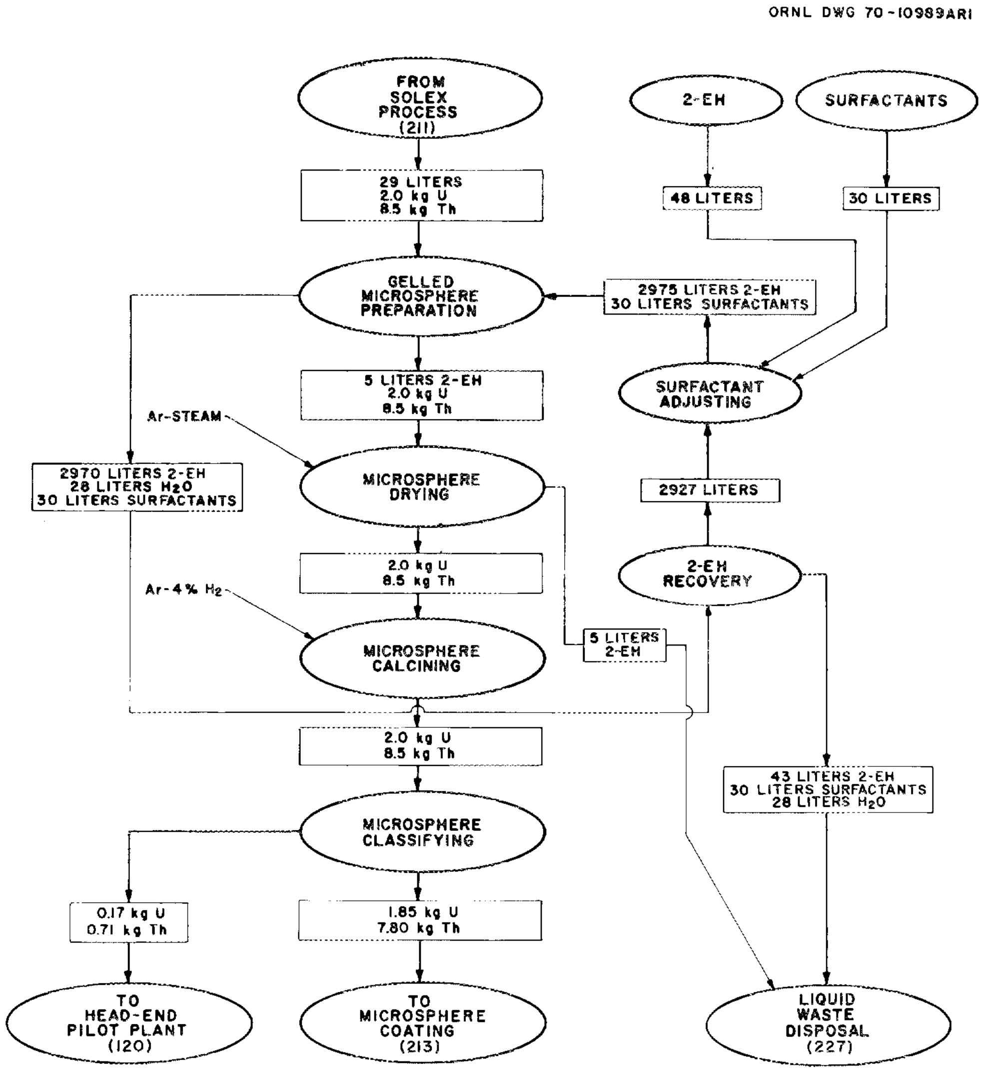

Fig. 5.4. Proposed Chemical Flowsheet for Microsphere Forming for the Preparation of 10 kg/Day of Microspheres with a Thorium-to-Uranium Ratio of 4.25. The abbreviation 2-EH represents 2-ethyl-1-hexanol.

and shown to be satisfactory for use with 20-kg batches of microspheres on a 48-hr cycle. This is equivalent in size to the production rates planned for the Refabrication Pilot Plant. A design for a firing furnace has not been developed; however laboratory tests have shown that no major problems exist in the large-scale firing of ThO_2-UO_2 microspheres. Techniques for the remote inspection of sol droplets and gel microspheres have yet to be developed. Methods of purifying the 2-ethyl-1-hexanol for recycle to the sphere-forming column have been studied in the laboratory and on an engineering scale. Promising processes are being tested on a scale commensurate with direct application to the Refabrication Pilot Plant Equipment.

5.3.7.3 Work Plan

The entire microsphere-forming column operation, from sol feeding to product microsphere removal, will be demonstrated as a remote operation. Both drying and firing operations will be carried out remotely. Additional firing furnace design, fabrication, and testing will be performed.

A periscope for remotely viewing sol droplet formation and loaded column bed behavior will be installed in the laboratory, and its utility will be demonstrated on the existing microsphere forming column. Laboratory equipment for microsphere sampling and singularizing will be installed and tested, and its utility will be determined. Sol handling and feeding equipment will be developed and demonstrated for remote operation.

Microspheres of ThO_2-UO_2 will be prepared as a support activity as needed for other subtasks.

5.3.8 Subtask 213 – Microsphere Coating

5.3.8.1 Requirement

Particles must be remotely transferred between processing stations in the Refabrication Pilot Plant both before and after coatings are applied. The transfer method must not damage the particles and must require only limited remote maintenance. The particles must be inspected, both before and after coating, to verify compliance with specifications.

Microspheres of the reference recycle fuel must be coated with a low-density buffer layer and a high-density isotropic sealer layer of pyrolytic carbon. The coating thicknesses are specified in Table 3.1, page 16. The coating integrity on recycle particles must be equivalent with that on fresh particles. The processes and equipment to produce the required coated particles must be developed along with inspection methods and procedures to ensure the quality of the coatings. Because safety restrictions may require silicon carbide coatings on fuel particles, technology for applying them to recycle fuel must also be developed.

5.3.8.2 Status of Technology

Considerable progress has been made on the development of equipment and processes for particle handling and inspection.[14] After the microsphere preparation step, the dried and sintered microspheres must be fed into a hopper. Development hoppers and feed-control valves have been designed and tested; however, some additional work is needed to improve these items. Microspheres and particles are transported by gravity feeding and pressurized pneumatic feeding. Tests made at ORNL indicate that pneumatic feeding can be used to transfer particles over distances of more than 50 ft with increases in elevation up to 15 ft. Negligible abrasion occurs even on the low-density acetylene-derived particle coatings.

To facilitate these various transfers, diverter valves have been developed to be used in conjunction with storage hoppers. Material enters these diverter valves at the top and travels through a flexible tube, which is then connected to one of two exit tubes by a pneumatic cylinder and cam device. This device has been built and tested.

Before being coated, microspheres must be shape-separated to eliminate any microspheres with a maximum-to-minimum diameter ratio greater than 1.3. The shape separator developed at ORNL is a flat plate that is tilted and vibrated; upon it the nonspherical microspheres are separated from the spherical ones. The spherical microspheres then must be fed to a size classifier, which, as presently conceived, consists of two screens to eliminate the oversize and undersize microspheres in one operation. Next, the acceptable material must be weighed and then dispensed into a sampler. Present plans are to take about a 0.5% sample in-cell and transfer this sample to an analytical glove box facility for analysis of size distribution and if necessary for particle sphericity and density.

The microspheres to be inspected for size distribution are transferred to the particle size analyzer. In this instrument, a light shines across the path of microspheres passing one at a time through a rectangular tube. As a microsphere passes through the channel, a photodetector experiences a dip in current proportional to the size of the microsphere; this dip is then recorded by a pulse-height analyzer. Presently, a 1000-microsphere sample can be recorded in about 3 min. No real effort has been made to speed the operation; hence, considerably faster counting rates may be possible.

If density must be measured, a mercury pycnometer can be used. This apparatus measures the volume of the microspheres by measuring the amount of mercury displaced by them. Then the microspheres can be weighed to give an accurate determination of density. The acceptable microspheres then must be blended and weighed into batches of the proper size for coating.

A 5-in.-diam fluidized-bed coating furnace, similar to the coating furnace planned for the Refabrication Pilot Plant, has been extensively used for pyrolytic carbon coating.[10,11] Coatings of the required types have been produced on a semiproduction scale. A remote coating furnace similar to that required for the pilot plant has been constructed and is currently being tested in the laboratory.

The buffer coating is applied with a mixture of acetylene and inert gas. The isotropic coating is presently applied with propylene but can be applied with propane or methane. No significant differences have been found in coatings produced by these different gases. Coatings can be deposited from propane or propylene in the range 1200 to 1500°C. Methane is more difficult to use because of the higher temperature required (above 1800°C). However, more data are needed on the irradiation performance of propylene-derived coatings before the coating gas can be specified. The coating equipment is being developed to use either gas.

The FSVR most likely will be the only suitable reactor with which to demonstrate HTGR fuel recycle. This reactor requires a silicon carbide coating on all particles to limit the release of fission products that diffuse rapidly through pyrolytic carbon coatings, such as strontium and barium. Hence, to ensure that performance of remotely fabricated thorium-^{233}U fuel can be demonstrated, the processes and equipment to apply SiC coatings are being developed. These coatings are currently applied from mixtures of methyltrichlorosilane and hydrogen, although other silanes can be used. The difficulties involved with SiC coating include the injection of methyltrichlorosilane into the coater (this silane is a liquid at room temperature) and the handling of the HCl produced by the decomposition of methyltrichlorosilane. At ORNL, silicon carbide coatings have been applied in furnaces up to 3 in. in diameter,[12] and prototype equipment for SiC coating has been added to the prototype 5-in.-diam remote coating furnace.

All coating operations involve the production of large volumes of off-gas. This off-gas consists of hydrogen, or hydrogen and HCl, depending on which coating is being applied. In addition, all off-gas must be filtered to remove any radioactive material. Hydrogen chloride is removed by contact with caustic solution. During coating with carbon, no HCl will be in the off-gas, but large quantities of soot may be present. Hence, the off-gas first passes through a bag type roughing filter where the soot is removed. For either coating process the waste gas is passed through absolute filters before being ejected into the atmosphere. Special precautions are used to prevent explosive mixtures of hydrogen and oxygen from occurring in the off-gas equipment.

Both GGA[13] and ORNL* have considerable experience in applying both pyrolytic carbon and silicon carbide coatings. Work has begun at ORNL on adapting the coating process to remote operation.

After each coating operation, the coating thickness has to be measured with the particle size analyzer, and in conjunction with a weight measurement the density is determined. Other inspections needed are: (1) anisotropy, (2) gas content, (3) ^{233}U content, (4) carbon content, (5) thorium content, (6) surface contamination, (7) crushing strength, and (8) uranium content of the coating soot.

Particles from the coating furnace are transferred by gravity to receiving hoppers for cooling. After cooling, the coated particles are weighed and sampled. After analysis, if the particles are acceptable, they are either returned to the coating furnaces for further coating or are sent on to the next step if the coating operations are complete. Rejected material will be transferred to reject storage hoppers.

After the coating operations, the coated particles must be sent to another shape separator and classifier. Again all products have to be weighed, and any reject material is sampled to determine the cause of rejection. At this point in the operation, many batches of particles are accumulated and then blended to produce large homogeneous batches of particles needed for the succeeding steps. The batch blender has been conceptually designed.

5.3.8.3 Work Plan

Laboratory development of the particle handling equipment will be completed. This development includes refinement of the particle classifier to minimize blinding and long-term testing of particle feeding devices. A 0.5% remote sampler will be developed.

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*See list of progress reports in Table 3.3, p. 24.

The inspection techniques are to be refined until the properties of the particles can be determined without delaying the refabrication operation. Further development work will be performed on the feed mechanism for the particle size analyzer and also on improving the calibration method for the particle size analyzer. The techniques for determining anisotropy will be refined, and a procedure for crushing strength determination must be developed. Also, a procedure for determining crystallite size will be developed for particles containing ^{233}U. In addition, a means of determining particle gas content will be developed.

A remotely operable coating furnace has been constructed and is currently being tested in the development laboratory. The effect of operating variables on the coating properties must be determined. These variables include batch size, coating gas composition, flow rate, furnace pressure, and temperature. These variables affect coating rate, sphericity, density, anisotropy, and, in the case of silicon carbide coatings, stoichiometry. Particles are being coated by prototype methods for the irradiation capsules (Subtask 301), for the RTE's (Subtask 302), for the PTE's (Subtask 303), and to provide material for other development subtasks.

5.3.9 Subtask 214 — Fuel Stick Fabrication

5.3.9.1 Requirement

In the particle blending step of the refabrication process, the ThO_2-$^{233}UO_2$ particles must be blended with the ThC_2 particles to produce sticks with less than 10 wt % variance of uranium and thorium in any 1-in. length of the fuel stick and less than 5 wt % U and 6 wt % Th variance from the desired loading in the entire fuel element. The operation must have sufficient loading accuracy so that the uranium and thorium loading of the entire core will vary no more than 1%.

The proper weights of particles must be blended and bonded in a fuel stick of specified dimensions so as to adequately fill a fuel hole in the fuel element. The fuel particles in the recycle fuel will be bonded to the same extent that the particles are bonded in the fresh fuel. That is, the same matrix formulation and carbonization cycle will be used except for such modifications as may be required for remote fabrication. The bonding process for the recycle fuel must not increase the fraction of broken particles nor contaminate the matrix beyond the level specified for the fresh fuel.

5.3.9.2 Status of Technology

Conceptual design of a prototype particle loader-blender is complete. This device will blend up to three types of particles by concurrently pouring into a fuel stick mold measured amounts of the particles from separate hoppers with adjustable orifices. Development work will be required on adjustment methods to ensure homogeneity of the fuel.

Fuel sticks have been made at both GGA[15] and ORNL.[16] However, only limited information is available on the effect of irradiation on the fuel stick matrix material. Also the effects of carbonization and annealing conditions have not been defined. To combat matrix shrinkage during irradiation, which may lead to cracking of the matrix, a bonding agent with greater amounts of carbon can be used. However, when more carbon is added the bonding agent becomes more viscous, thereby increasing the difficulty of injection.

The fuel matrix formulation, particle blending, carbonization, and fuel stick inspection techniques are being developed under the Public Service of Colorado (PSC) project for the FSVR's first core. This core is to be made during 1970 and 1971. It is planned that the recycle program will use the useful techniques and formulations to the maximum extent; however, adoption of the process to remote operations will require considerable development. Present plans are to do the carbonization and annealing of the fuel sticks before placing them into the fuel block during element assembly.

Only a limited amount of work has been done on fuel stick inspection. A combination of attenuation (gamma or x-ray) and gamma emission will be used to determine the relative amounts of ^{233}U and thorium present as a function of position along the fuel sticks. Ultrasonic examination of bond integrity will also be considered.

5.3.9.3 Work Plan

A fuel stick mold filler-blender device is to be fabricated and tested in the development laboratory. If possible the stick bonding method developed for the FSVR's first core will be modified for use in a remotely operated production facility. Development carbonization and annealing furnaces will be constructed and tested. Inspection methods will be developed to nondestructively test for the required loading tolerances, matrix integrity, matrix contamination, and dimensional accuracy of the fuel sticks. Fuel sticks for capsule irradiation will be prepared by prototype processes. In early 1970 fuel sticks were prepared with recycle-type particles for use in eight RTE's for irradiation in the Peach Bottom Reactor. Fuel sticks will also be prepared for use in two PTE's for irradiation in the FSVR.

5.3.10 Subtask 215 — Fuel Element Assembly

5.3.10.1 Requirement

Each graphite block contains some 200 fuel holes that must be loaded with fuel sticks during fuel element fabrication. By the present fuel block design at least two lengths of fuel holes must be filled. Graphite plugs must be placed in each hole and cemented in place as closures. The fuel element must be inspected for transferable contamination to limit buildup of contamination in the reactor.

5.3.10.2 Status of Technology

Some development of processes and equipment for fuel stick loading, element transfer, and element inspection has been done.

The stick loader will use a numerically controlled positioner to align the block under it. It is planned that the loaded fuel element will be transferred between cells in the Refabrication Pilot Plant. During this transfer, the surfaces of the element are inspected for contamination. If any is present, the cooling holes are inspected further to assess the level of contamination, and the element is either cleaned or reprocessed. After inspection, the elements will be canned and prepared for storage or shipment.

5.3.10.3 Work Plan

Various approaches used in industry for similar processes will be investigated.

Basic techniques for handling the fuel sticks and loading them into the graphite block will be developed in the laboratory. A prototype machine for performing the element loading operations will be designed, fabricated, and tested. Inspection methods will be developed for detecting surface contamination on the loaded elements either during intercell transfer or following transfer. Devices for canning a fuel element or elements will be designed along with transfer mechanisms for loading the new elements into the product shipping carrier. A mockup test will be devised to prove the feasibility and reliability of these element canning and handling methods.

Of the eight RTE's for irradiation in the Peach Bottom Reactor, six have been prepared by GGA. The two PTE's for irradiation in the FSVR will be prepared by GGA under this subtask to support other development subtasks. Sufficient quantities of test elements will be fabricated as needed by other subtasks.

5.3.10.4 Analysis of Alternate Approaches

It would be advantageous from the standpoint of remote operation to carbonize the fuel sticks in the fuel blocks after loading. This may be possible if a bonding agent can be developed which does not display excessive shrinkage and gas release during carbonization and annealing. This change would eliminate handling of the fragile carbonized sticks.

5.3.11 Subtask 216 – Recycle of Off-Specification Material

5.3.11.1 Requirement

Fuel materials that do not conform to specification as determined by various inspections or tests must be disposed of in the most economic manner. These materials may include microspheres, coated particles, fuel sticks, and fuel elements.

5.3.11.2 Status of Technology

Particles that have unacceptable pyrolytic carbon coatings are presently put through a fluidized-bed burner for removal of the coating. Other aspects of recycling off-specification material have received no significant study as yet.

5.3.11.3 Work Plan

Only the coated particles that are off-specification could be reworked in the Refabrication Pilot Plant. Since this step would include additional equipment, and only a minor amount of such material is expected, it may be better to send all such material back to the Head-End Pilot Plant for reprocessing. The feasibility of material recycle and the controls and techniques to be used will be studied when some yield information is available from other subtasks.

5.4 SUBTASK 220 – REFABRICATION PILOT PLANT DEMONSTRATION

5.4.1 Purpose

The pilot plant demonstration will prove the technical feasibility of the processes and equipment, provide a test of the maintenance method, and provide economic information concerning refabrication of HTGR fuels.

5.4.2 Requirement

The Refabrication Pilot Plant must be designed, constructed, and operated to demonstrate the equipment and processes required to fabricate HTGR fuel elements. The demonstration must last long enough to determine long-term maintenance requirements for equipment and facilities. To obtain this information, 150 reactor-quality recycle elements must be fabricated and shipped from the plant. The ^{233}U that is processed will be contaminated with adequate radioactivity (^{232}U) to anticipate the problems encountered with levels expected in commercial refabrication plants.

5.4.3 Timing

Equipment design has already begun and will continue until mid-1974. The cold operational testing of the Refabrication Pilot Plant will begin in early 1976, and hot demonstration will begin in mid-1976. The demonstration will continue until fuel refabrication technology has been developed sufficiently to allow preliminary design of large-scale commercial refabrication plants. This result is expected to be attained by 1980.

Two PTE's with ^{235}U as a replacement for ^{233}U will be fabricated by GGA and installed into FSVR by 1972 (Subtask 303). Recycle fuel elements containing ^{233}U will be fabricated beginning in 1976. The first of these elements will be loaded into the FSVR in late 1976 for proof tests (Subtask 304). Another 150 recycle fuel elements will be fabricated during the pilot plant demonstration, which will continue through 1979. The Refabrication Pilot Plant will be kept available after 1979 for development support for the initial commercial refabrication plant or will be disassembled.

5.4.4 Funding

The estimated capital expenditures required to accomplish this subtask are presented in Table 2.4, page 9. The operating cost for the Refabrication Pilot Plant demonstration is summarized in Table 2.1, page 6. These costs do not include such fuel element input materials as coated thorium carbide fuel particles or the machined fuel blocks.

5.4.5 Facilities

The TURF[17,18] will be utilized for the hot demonstration of the Refabrication Pilot Plant. Some modification and additions to the facility will be required to permit all the activities of the Refabrication Pilot Plant Demonstration to be performed. These modifications and additions will include additional fuel element handling, storage, and shipping facilities and process gas handling facilities.

5.4.6 Subtask 221 - Design

5.4.6.1 Requirement

The Refabrication Pilot Plant must be designed. This design must convert the technology obtained from the refabrication process and equipment development subtask (210) into drawings and specifications defining equipment and systems of the Refabrication Pilot Plant. A safety analysis of the pilot plant must be prepared to serve as the basis for hazards evaluation to assure achievement of safe and reliable operation.

5.4.6.2 Status of Technology

Arrangement drawings of the Refabrication Pilot Plant equipment in the TURF have been prepared. Some components of the particle handling equipment have been conceptually designed. A feed storage tank has already been designed and fabricated. Laboratory development of other microsphere preparation and coating equipment has reached a stage sufficient to allow conceptual design of these pilot plant equipment items to start any time.

Some operations, such as stick making, will be on a smaller scale in the Refabrication Pilot Plant than in future commercial plant requirements, while others will approach commercial plant scale. As much as possible, automatic equipment will be used in the Refabrication Pilot Plant to permit realistic scale-up. The Refabrication Pilot Plant scale of other equipment, such as the coating furnace, may be at a maximum critically safe size for recycle fuel fabrication. Hence, commercial recycle plants would use a larger number of pieces of the same size equipment.

Because of the extensive use of automatic equipment and the requirements for constant material control for accountability and criticality, a computer-based data handling system must be used. This system, tied to the operational control of the plant, will ensure that fissionable material does not accumulate to unsafe amounts in any area and will provide a fissile inventory check at any required time.

5.4.6.3 Work Plan

The collection of information already in existence and the preparation of process and equipment flowsheets will be the first steps. Conceptual designs will be prepared for each unit of Refabrication Pilot Plant equipment as each development subtask provides sufficient information. These conceptual designs will be developed sufficiently to allow procurement and testing of prototype equipment. Based upon results from development subtasks, equipment and systems of the Reprocessing Pilot Plant will be designed. Drawings, specifications and procedures will be prepared sufficient to construct the Refabrication Pilot Plant. Codes and standards applicable to the work will be utilized. Where standards are unavailable or are insufficient to supply the needs for future commercial refabrication plant design, they will be prepared as a part of the Refabrication Pilot Plant design.

The overall Refabrication Pilot Plant design will be prepared in three phases: conceptual, preliminary (Title I), and final (Title II). As shown on the refabrication development subtask schedule (Fig. 5.2, page 79), these phases will be coordinated with the development subtasks to provide them with maximum support and to utilize maximum results from those activities.

5.4.7 Subtask 222 - Procurement and Testing of Equipment

5.4.7.1 Requirement

Refabrication Pilot Plant equipment must be procured and proof tested before its installation. In some cases prototype equipment procured for development testing may be adaptable for actual installation in the Refabrication Pilot Plant. When such is the case, the equipment must be modified as necessary and proof tested to verify that after modification it complies with functional requirements.

5.4.7.2 Status of Technology

Several items of development equipment have been procured and are currently being tested. Some of the inspection equipment may be modified for Refabrication Pilot Plant use. By the time the major part of this subtask is to be carried out considerable experience will have been established in the procurement and testing of prototype equipment.

5.4.7.3 Work Plan

Detailed critical path plans and schedules will be prepared for procurement of Refabrication Pilot Plant equipment. Equipment will be procured according to these schedules, with emphasis given to specialized equipment or long-delivery items. Appropriate procurement documents and methods will be applied, not only to secure equipment of adequate quality but also to develop industrial capability sufficient to support the design and construction of commercial refabrication plants. As an integral part of these procurement activities appropriate tests will be run on each piece of equipment to demonstrate and verify its performance capability.

5.4.8 Subtask 223 — Installation of Equipment

5.4.8.1 Requirement

Modifications and additions to TURF must be constructed and the equipment must be installed in the facilities designated to house the Refabrication Pilot Plant. The equipment must be installed with the remote handling equipment for in-cell work to demonstrate the application and techniques of remote maintenance. The equipment handling methods and procedures developed during installation must be recorded to facilitate eventual remote removal or replacement of equipment.

5.4.8.2 Status of Technology

The TURF provides space and basic facilities for handling, installing, and operating the various Refabrication Pilot Plant equipment items. The methods of hot-cell operation and maintenance of similar complex equipment have been developed to a high level of proficiency at ORNL in connection with the High Radiation Level Examination Laboratory, the High Radiation Level Analytical Laboratory, and previous operations in TURF and other remotely maintained facilities. This experience and knowledge will be utilized to establish the Refabrication Pilot Plant maintenance program and therefore will guide the equipment installation procedures.

5.4.8.3 Work Plan

Advanced planning will begin during the preparation of conceptual designs. Equipment layouts will be developed for ease of installation and removal. Methods will be established for anchoring and joining equipment, and in some cases mockup tests will be conducted to establish space limits, configuration restraints, and handling procedures. The required mockup studies will be defined and executed as the design progresses and equipment dimensions and features are better known. Specifications and procedures to guide the installation will be prepared as necessary. These will stress the preservation of the quality designed and fabricated into the equipment and systems.

In-cell equipment will be moved into position, anchored, connected to services, and joined to adjacent processing equipment with the use of the in-cell crane and manipulator systems. Out-of-cell equipment, including control panels, will either be constructed in place or prefabricated and installed.

New facilities and modifications to existing facilities required for storage and shipment of new fuel elements will be constructed. Equipment for handling new fuel elements will be installed in these new facilities.

5.4.9 Subtask 224 - Cold Operational Testing of the Refabrication Pilot Plant

5.4.9.1 Requirement

The entire Refabrication Pilot Plant must be performance tested with prototype feed material before operation with irradiated material begins. These tests are to demonstrate the remote operability and material handling capabilities of the plant as well as the adequacy of operational procedures and runsheets.

Pilot plant operators must be trained in equipment operation and safety procedures. Their proficiency in carrying out operations and controls must be demonstrated. From this information criteria must be established for operator qualification and training to be used in licensing procedures for commercial refabrication plants.

5.4.9.2 Status of Technology

The methods and techniques of preoperational testing and startup of fuel refabrication facilities have been developed at ORNL over the past several years. This technology has been developed and proven in the Kilorod Facility,[19] the Transuranium Processing Plant,[20] and previous operation in TURF with molten-salt fuel.[21]

5.4.9.3 Work Plan

Each piece of equipment will be tested to verify its operational capability. Individual systems will be tested for leaktightness and functional capability, and finally the complete Refabrication Pilot Plant will be tested to verify its operational readiness.

Prototype feed material will be handled in the fuel receiving, handling, storing, and shipping facilities of TURF. Prototype fuel will be fabricated by the same procedures to be followed with recycle radioactive material. During these operations test fuel elements will be produced in support of Task 300 for irradiation studies. Potential problem areas in the Refabrication Pilot Plant will be identified and corrected to minimize failure or malfunction of equipment and procedures.

Included in this subtask are operating procedure development and personnel training and indoctrination. Specifically this will include the preparation of programmed instruction manuals to aid plant operators, formal lectures by the designers of equipment and by experienced hot-cell facility supervisors, radiological and conventional safety instruction by appropriate authorities, and the preparation and trial use of operating procedures.

5.4.10 Subtask 225 — Hot Demonstration of the Refabrication Pilot Plant

5.4.10.1 Requirement

The Refabrication Pilot Plant must be operated with hot material to demonstrate the equipment and processes required to fabricate HTGR fuel elements. The demonstration must be of sufficient duration to determine long-term maintenance, materials handling, and waste disposal requirements. The demonstration is estimated to require hot operation of the Refabrication Pilot Plant through 1979, with possible later use for development support for the first commercial plant.

5.4.10.2 Status of Technology

The technology for the refabrication of irradiated HTGR recycle fuels is not yet developed. Only technology for fabrication of HTGR fuels containing ^{235}U currently exists, and it is being applied in unshielded facilities by GGA to fabricate the FSVR core. The large quantities of ^{232}U in recycle fuels will require heavily shielded refabrication facilities with remote operation and maintenance.

For physics parameter measurements in the High-Temperature Lattice Test Reactor 32 kg of ^{233}U containing less than 5 ppm ^{232}U has been formed into microspheres and coated with pyrolytic carbon.[8] Considerable experience exists in the handling of ^{233}U nitrate solutions at the National Uranium-233 Dispensing Facility located in ORNL Building 3019.

Approximately 30 kg of ^{233}U containing about 200 ppm ^{232}U (this is comparable to the first HTGR recycle fuels) was fabricated into molten-salt fuel in the TURF.[21] Approximately 600 kg of ^{233}U will have been fabricated into $(Th,U)O_2$ fuel for a core loading of the Shippingport Reactor as a part of the LWBR Program by 1975. Applicable technology from these programs will be applied to this demonstration subtask.

5.4.10.3 Work Plan

After successful completion of cold operational testing of the Refabrication Pilot Plant, feed material containing ^{233}U will be introduced to start the hot demonstration. This will continue until reasonable assurance is gained that all significant problems have been encountered and solved. In mid-1976 the pilot plant will begin fabrication of fuel elements containing ^{233}U. The demonstration will include the refabrication of 150 reference recycle fuel elements containing the reference fuel. These elements must be produced to verify adequacy of operating procedures, accountability procedures, remote equipment maintenance methods and techniques, shielding, and radiation and contamination control requirements.

After 1979, the Refabrication Pilot Plant may be used for development support for the first commercial refabrication plant, or it will be disassembled so the hot cells in TURF can be prepared for a new development program.

5.4.11 Subtask 226 – Waste Treatment and Disposal

5.4.11.1 Requirement

Wastes anticipated in the Refabrication Pilot Plant are estimated in Appendix C.

Gaseous waste containing hydrocarbons and radionuclides must be made safe before release to the environment. Hydrogen from the coating furnace must be made safe for handling and disposal.

Liquid waste must be collected and disposed of according to the type and level of contamination. Fissile uranium must be diluted with depleted or natural uranium before discharge to the Melton Valley waste system. All liquid waste must be neutralized to be handled in the TURF stainless steel system and subsequently in the Melton Valley hot-waste handling system. Halogen compounds, such as chlorides and fluorides, are to be avoided where possible. Halogens in the liquid-waste system must be complexed with a metal to prevent corrosion; for example aluminum ions in aluminum nitrate complex fluoride.

Solid waste containing radioactivity must be contained and disposed of in controlled areas specifically designated for such wastes. It must be collected, packaged, and identified for storage.

5.4.11.2 Status of Technology

The TURF off-gas system is suitable for filtering particulate materials from the cell and vessel vent gases. No gas scrubbing equipment is provided.

Liquid waste collection and storage systems exist in the TURF. They are adequate for handling high-level wastes that have been made compatible with the type 304L stainless steel lines and tanks that make up the system. Also available will be provisions for permanent disposal of all levels of liquid wastes. Written procedures and regulations for liquid waste handling are part of the ORNL standard practice procedures.

Solid wastes will be derived from process waste, salvaged equipment, and contaminated clothing.

5.4.11.3 Work Plan

Cell ventilation air, process vessel off-gas venting, and incidental waste gases will be disposed of by direct release to the TURF off-gas system, which has a minimum of 10,000 scfm of air flowing to a 250-ft-tall stack with an average atmospheric dispersion factor of 0.92×10^{-5} sec/m^3 released.

Gaseous products from dryers and furnaces will be treated in special cleanup equipment before release to the TURF gaseous waste disposal system. The off-gas from the coater will be treated in equipment designed for handling and disposing of gases containing hydrogen and halogens.

Liquid waste not suspected to contain radioactivity will be handled in the existing TURF process waste system, which is monitored before collection in temporary storage tanks. Contaminated process waste is diverted to ponds that can be drained to the Melton Valley waste disposal system.

Special equipment for handling and disposal of both solid and liquid wastes will be provided. Contaminated equipment and clothing, such as shoe covers and gloves, will be bagged for burial.

Enclosed containers for both solid and liquid wastes will be provided. The filled containers will be collected in the shielded processing cells and loaded into a heavily shielded cask for transport to solid-waste disposal areas. An existing cask will be modified for this purpose.

All radioactive waste that requires permanent disposal will be delivered to a central radioactive waste disposal facility at ORNL. It is assumed that this facility, provided by other AEC programs, will be available to support this program.

It is estimated that about 20% of the present receiving, handling, storage, and shipping capabilities of TURF will be utilized in the flow of solid wastes from this pilot plant.

5.4.12 Subtask 227 - Material Handling

5.4.12.1 Requirement

Materials required to sustain operation of the Refabrication Pilot Plant must be handled both entering and leaving the plant. These materials will include both feed and support materials to the process, scrap and off-specification material generated by the process, and the products coming from the process. These materials must be received, handled, stored, or shipped as appropriate.

Coated fertile particles and fuel blocks must be secured for development, cold-operational testing, and the hot demonstration of the Refabrication Pilot Plant. Thorium must be secured for the fertile component of the recycle particles. The ^{233}U product from the Acid Thorex Pilot Plant must be received. All of these feed materials must be received, stored, and handled in the TURF.

The product from the Refabrication Pilot Plant must be packaged, transferred from the refabrication cells, stored, and shipped from the plant. These product shipments will be handled in the same carrier used to transfer the spent fuel elements from the FSVR to the TURF.

Test fuel elements prepared for use in development and cold-operational testing must be stored and handled. At the present time about 40 unirradiated FSVR fuel elements will be required for development testing of the Head-End Pilot Plant equipment. Part of these should be shipped from the Refabrication Pilot Plant in the recycle element shipping carrier to simulate hot fuel handling. Half of these elements will have to be handled by January 1974, and the remainder by July 1975. Process samples and support materials must also be received, stored, handled, and shipped to support the demonstration.

5.4.12.2 Status of Technology

Technology and equipment exist for handling thorium as coated particles and as thorium nitrate tetrahydrate and for handling ^{233}U nitrate solutions. However, modifications to both the equipment and the handling procedures may be needed to accomplish this subtask. Experience also exists for handling the flow of test fuel elements, support materials, and similar items that will be associated with this pilot plant.

Experience does not presently exist for shipping recycle fuel elements. These elements will be too radioactive to ship without shielding but will be less radioactive in spent elements. Technology does exist for shipping unirradiated initial FSVR fuel elements, and applicable parts of this technology will be applied to the handling and shipping of recycle fuel elements.

5.4.12.3 Work Plan

The handling of test materials will be planned and scheduled as required to support other subtasks. Procedures and work instructions will be prepared for handling these items. The feed materials for the Refabrication Pilot Plant will be planned and scheduled, handling procedures will be prepared, and equipment will be provided. The equipment and handling procedures will be tested to prove their adequacy.

Operating procedures and handling techniques will be established for the recycle fuel shipping carrier, and its performance capability will be proven.

Process support materials such as process gas, packaging containers, spare parts, and hardware will be handled through existing facilities at TURF. Process samples will also be handled through these facilities.

The flow of samples and support materials should require about 30% of the present receiving, handling, storage, and shipping capabilities of TURF. This does not include handling the recycle fuel elements produced.

5.4.13 Subtask 228 — Process Development Support

5.4.13.1 Requirement

As is the case with any pilot plant, unforeseen problems will arise and require rapid solution. Laboratory and hot-cell tests on actual materials are necessary to guide the plant operators in solving the problems.

5.4.13.2 Work Plan

Development engineers and laboratory facilities will be available to accomplish the requirement given above. Their function will be to perform the tests required to provide help to solve the problems. In addition, equipment changes may be necessary as the result of deficiencies found after preliminary hot operations with the RTE's or during the other hot operations.

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6. TASK 300 – RECYCLE FUEL IRRADIATIONS

6.1 INTRODUCTION

This section of the program plan describes the type and schedule of irradiation tests required to develop and demonstrate a satisfactory recycle fuel. These tests are essential in the National HTGR Recycle Development Program to accomplish two major objectives: (1) to provide irradiated fuel for development and demonstration of reprocessing and (2) to verify the performance capability of the recycle fuel developed and produced in other tasks of this program. The accomplishment of these two objectives requires a series of irradiation tests ranging from very small quantities (grams) in capsule tests to reference 1000-MW(e) HTGR fuel elements irradiated under reference conditions of time, temperature, and fluence. Each irradiation test contributes to both objectives, since a portion of the irradiated fuel is subjected to postirradiation evaluation of its performance, and the remainder of the irradiated fuel is provided for reprocessing development or demonstration.

Because of the time required for irradiation tests (ranging from one to six years), early scheduling and implementation of these tests are vital to the success of the recycle development program. The scheduling of fuel irradiations must also take cognizance of (1) the refinements of fuel element design, (2) changes in the fuel element arising from developments on reprocessing and refabrication processes, and (3) the schedule and availability of reactor test space. Accelerated testing of fuel can be accomplished by capsule irradiations in ETR and ATR. Prototype fuel elements will be irradiated in the Peach Bottom Reactor and full-size fuel elements in the FSVR.

The capsule irradiations are designed to accelerate the burnup rate of the fuel and the fast fluence exposure of the coating and stick bonding. These accelerated conditions expedite the determination of fuel performance capability as well as provide small quantities of irradiated fuel for laboratory-scale reprocessing development. The capsule irradiations are especially useful in evaluating small quantities of material produced in laboratory development equipment.

The first series of these capsule tests will contain fuel used in Peach Bottom irradiation tests and will provide fuel for early reprocessing studies. The second series will give an accelerated test of the fuel produced for the proof test elements.

The results of these tests can be available in time to guide the selection of reprocessing and refabrication processes and equipment for installation in the reprocessing pilot plants.

The Peach Bottom Reactor is being used to irradiate engineering-scale quantities of recycle fuel for evaluation of performance capabilities and for development of processes and equipment to be demonstrated in the reprocessing pilot plants. These tests are designated as the Recycle Test Elements (RTE's). The installation of the second core of the Peach Bottom Reactor was completed in June 1970, and the reactor was available for full power irradiation starting in July 1970. Postirradiation results of the RTE fuel will be available in 1972 and will be used in support of development subtasks of this program.

The Proof Test Element (PTE) irradiations in the FSVR will determine the performance capability of large quantities of reference recycle fuel. By use of the information gained from capsule and engineering-scale tests of recycle fuel particles and recycle fuel sticks, the PTE's will be designed and scheduled for insertion with the first reloading of the FSVR; this reloading should occur late in 1972. Starting in the fourth quarter of 1974 and annually thereafter, some of these elements can be unloaded for postirradiation examination and subsequent use as feed material to the reprocessing pilot plants.

During pilot plant demonstration a number of fuel elements containing ^{235}U and ^{233}U fissile particles that meet FSVR fuel specifications will be produced. Some or all of these elements will be loaded for irradiation testing in the FSVR during the normal refueling operations. These full-scale recycle demonstration fuel elements will be irradiated from 4 to 6 years in the FSVR and will serve as proof tests of the refabrication technology.

6.2 RECYCLE FUEL IRRADIATION SCHEDULE AND TIMING

The schedule for performing the steps of this task of the development program is shown in Fig. 6.1. These irradiations will be carried on concurrently with the reprocessing and refabrication development effort as shown in Fig. 2.1, page 5.

6.3 FUNDING

The required funding for this task is given in Table 2.1, page 6.

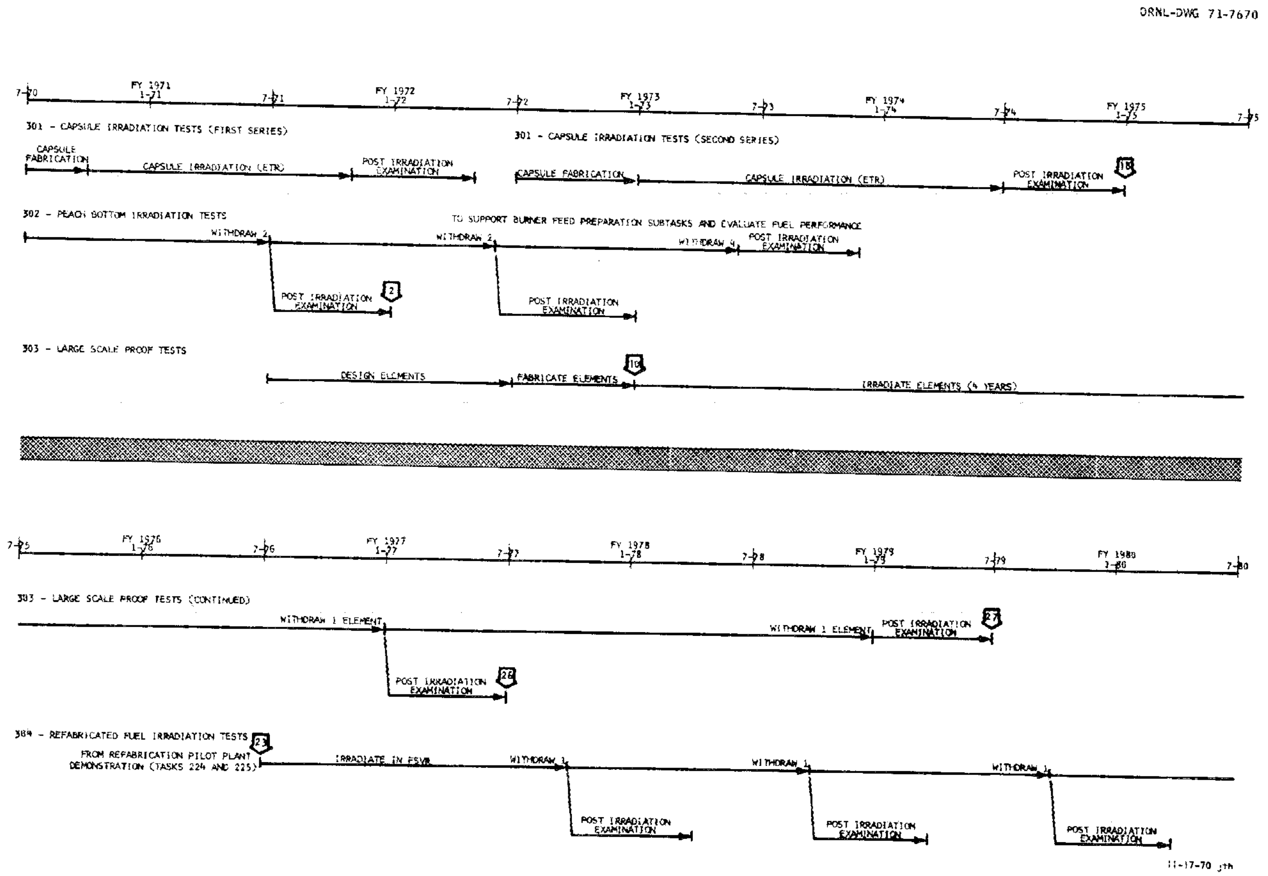

Fig. 6.1. Recycle Fuel Irradiation Schedule.

6.4 SUBTASK 301 — CAPSULE IRRADIATION TESTS

6.4.1 Requirement

The purpose of this subtask is to conduct the initial irradiation testing of coated particles and fuel sticks prepared by processes intended for use in the recycle pilot plants. Gram quantities of irradiated recycle fuel are required for head-end process development and hot-cell tests. The capsule irradiations are intended to test refabrication processes, qualify fuel for the proof test elements to be inserted in the FSVR, and provide material for laboratory-scale development on head-end processes and equipment.

Two sets of capsules shall be irradiated to determine the behavior of the reference recycle coated particles and bonded beds or fuel sticks prepared by recycle processes and equipment. Process and equipment changes will occur as work progresses on the recycle development program, and capsule irradiation tests provide the quickest and most direct means of determining the effects of these changes on the behavior of the resultant coated particle fuels and fuel sticks. To satisfy the requirements of large HTGR's these irradiation tests must be conducted to exposures that include 20% FIMA burnup, 4 to 8×10^{21} neutrons/cm^2 fast neutron fluence, and temperatures ranging from 750 to 1300°C.

6.4.2 Status of Technology

Extensive capsule irradiation testing of various types of coated particle fuel has been conducted during the past several years by both ORNL[1–6] and Gulf General Atomic.[7–10] The objectives of these irradiation tests in recent years have been to develop and proof test coated particle fuels intended for the FSVR and larger HTGR's. These highly sophisticated tests of coated particle fuel have been conducted to high temperature, high burnup, and high flux exposures under closely controlled and monitored conditions. Excellent capabilities for the postirradiation examination of the fuel materials in these capsules also exist at both sites.

The results of these irradiation tests to date have demonstrated that properly designed and prepared coated particles of both the BISO (two-layer pyrolytic carbon coating) and TRISO (multilayered pyrolytic carbon and SiC coating) varieties have excellent irradiation stability under the operating conditions of HTGR's. Both carbide and oxide kernels have been found suitable as the substrates for these coated particles. The performance of BISO coated particles has been demonstrated to the full maximum design operating conditions of the FSVR — namely, greater than 20% FIMA burnup, 8×10^{21} neutrons/cm^2 fast (> 0.18 MeV) neutron fluence, and temperatures to 1300°C. The performance of BISO coated particles has also been demonstrated to greater than 50% FIMA at high temperature but at lower fast neutron fluences. TRISO coated particles have been successfully demonstrated to burnups of greater than 20% FIMA and to fast neutron fluences of greater than 4×10^{21} neutrons/cm^2.

Mathematical models have been developed[11–14] for calculating the stresses induced in the coating of BISO and TRISO coated particles during irradiation. Good correlations have been obtained between irradiation test results and the stress levels predicted by the models. These models are now routinely applied to the design of coated-particle fuel for HTGR's and used in conjunction with all capsule irradiation tests.

Limited irradiation tests of fuel sticks containing coated particles have been conducted during the past year or two. The results of these tests have shown that the fuel sticks retain their integrity to high burnup (approximately 20% FIMA) at fast neutron fluences of about 4×10^{21} neutrons/cm^2. Fuel sticks containing simulated (unfueled) coated particles have also been successfully tested to fluences of 4 to 8×10^{21} neutrons/cm^2 in the HFIR.[15,16] Many additional irradiation tests[10] of various types of fuel sticks to both high fast neutron fluence and high burnup are in progress as part of the FSVR and large HTGR research and development programs. These tests will provide an excellent foundation in both materials behavior and capsule irradiation capabilities before the start of this program's capsule irradiations.

No irradiated reference recycle fuel samples for head-end process development has been made available; however, many irradiations of a similar nature have been and are being performed in the USAEC's and GGA's programs for HTGR fuel development. This technology and small amounts of irradiated material are available to the recycle development program, but no samples of irradiated recycle-type fuel are available. Some head-end tests of crushing, burning, sieving, grinding, and leaching have been performed at ORNL on irradiated Dragon compacts. The results have been generally favorable in showing the feasibility of the reference head-end process, but again they do not include the reference recycle fuel.

6.4.3 Work Plan

Each capsule irradiation experiment requires about 1 to 1.5 years to complete, including capsule design, preparation, preirradiation evaluation, capsule construction, irradiation, and postirradiation examination. In each series two essentially identical capsules will be prepared containing both fuel particles and fuel sticks, and the first series of these capsules will test four particle combinations at four temperatures to fast fluences of 8×10^{21} neutrons/cm^2. These capsules will be irradiated in the ETR. The second series of tests will be similar to the first.

Fuel sticks containing recycle coated particles will be prepared by the candidate processes and evaluated in these capsule irradiation tests. The fuel sticks for these irradiation experiments will be short (about 2-in.-long) segments of full-scale (nominally 0.5-in.-diam) fuel sticks. The fuel sticks will be contained in graphite holders during irradiation so that the sample environment is representative of that of an HTGR fuel element. The temperature and temperature gradients in the fuel stick samples will be representative of those expected in the commercial reactor.

The normal pre- and postirradiation examinations will be conducted on the fuel to assess the effects of irradiation on its behavior and to evaluate its capability for satisfactory performance in an HTGR. These tests will include microradiography, metallography, and such other tests as may be warranted.

The fuel particles and sticks resulting from the capsule irradiation tests will be available as test material for head-end process development following the postirradiation examination.

6.4.4 Facilities

The capsules will be prepared at ORNL and irradiated in the ETR or ATR, depending on availability. The capsule preparation and postirradiation examination will be conducted in existing facilities at ORNL.

6.5 SUBTASK 302 – PEACH BOTTOM IRRADIATION TESTS

6.5.1 Requirement

The RTE irradiations will provide kilogram quantities of irradiated fuel, similar to the reference recycle fuel, for performance evaluation and head-end process and equipment development. Various fuel elements must be operated for one, two, and three years to provide fuel particles with the required burnups and fast flux exposures. These irradiations are being conducted in the Peach Bottom Reactor to provide fuels tested in an HTGR environment at the earliest possible point in the program. The range of burnups and fluences to be obtained will permit the examination of the effects of these parameters on both the performance of recycle fuel particles produced in laboratory equipment and on the recycle processes under development.

6.5.2 Status of Technology

No large-scale irradiations of HTGR fuels have been carried out to provide material in quantities adequate for engineering-scale development testing. In addition, no recycle-type fuels prepared in prototypic equipment have been tested in a true HTGR environment. Only limited irradiation tests of fuel sticks have been conducted to date (see discussion under Subtask 301). However, numerous tests of fuel sticks are in progress at both ORNL and GGA, so that the procedures and techniques for fabrication and postirradiation evaluation will be developed before similar work is required by the HTGR Recycle Development Program. Techniques for disassembly of graphite elements have been developed and used in the Peach Bottom postconstruction research and development program.

6.5.3 Work Plan

Eight fuel recycle test elements similar to the FSVR elements will be irradiated in the Peach Bottom Reactor to the required burnup and fast fluence by mid-1974. These elements are designed to simulate recycle and makeup fuel fabricated with ^{235}U. At least eight particle types will be tested in nine different two-particle combinations to evaluate all of those fuels of primary interest for large HTGR's. Under the HTGR Base Program design analysis on the fuel element, fuel stick compositions have been specified, core locations have been selected, and information has been provided for the safety analysis.

The normal pre- and postirradiation examination of the particles and bonded fuel sticks will be performed to provide information on fuel performance and characterization of the fuel subsequently furnished for laboratory- and engineering-scale reprocessing development.

6.5.4 Facilities

The fuel particles and bonded fuel sticks have been prepared at GGA (carbide particles) and at ORNL (oxide recycle-type particles). The fuel elements were assembled at GGA and shipped from there to the Peach Bottom Reactor for irradiation. The elements will be returned to ORNL for postirradiation examination (PIE) and utilization in head-end development. No new facilities are required to perform this subtask. However, some new disassembly and handling equipment will be required at ORNL for the PIE.

6.6 SUBTASK 303 — LARGE-SCALE PROOF TESTS

6.6.1 Requirement

The irradiation of these FSVR Proof Test Elements (PTE's) will demonstrate the performance characteristics of kilogram quantities of recycle-type HTGR fuels prepared in recycle processes and equipment and irradiated under typical HTGR conditions.

Two PTE's shall be produced and irradiated in the FSVR. These elements shall be produced by processes and equipment similar to those that are intended for demonstration in the Refabrication Pilot Plant. The elements shall be postirradiation examined to evaluate the performance of the fuel and verify the adequacy of the process and equipment planned for reprocessing operations.

6.6.2 Status of Technology

No large-scale irradiations of recycle fuel have been conducted. Smaller quantities will have been irradiated under Subtasks 301 and 302.

6.6.3 Work Plan

The PTE's will be identical in design to the FSVR fuel elements except that recycle-type fuel (fabricated with ^{235}U instead of ^{233}U) will be used. The principal effort of this subtask will be to perform an analysis on the fuel element, specify the fuel compositions, select the core locations, and provide information for the safety analysis.

After irradiation the fuel elements will be examined to determine the dimensions and integrity of the graphite element and the fuel sticks therein. Removal of some fuel sticks from the fuel elements will probably be attempted by drilling out the top plugs and sliding the sticks out of the element. If this fails the graphite below the fuel stick will be drilled out and attempts will be made to push the fuel stick from the element. Detailed examination of the fuel sticks will supply the required information on integrity to guide the refabrication and head-end reprocessing subtasks.

6.6.4 Facilities

The existing fuel facilities at ORNL and GGA will be utilized in the fabrication of these fuel elements. The fuel handling and storage facilities required by other subtasks of the program will also be utilized by this subtask.

6.7 SUBTASK 304 — REFABRICATED FUEL IRRADIATION TESTS

6.7.1 Requirement

These irradiations will proof test the fuel elements produced in the Refabrication Pilot Plant during both cold and hot operations, and will determine the adequacy of the processes and equipment for production of acceptable recycle fuel elements.

A proof test of the ^{235}U-base fuel produced in the cold startup operation of the Refabrication Pilot Plant is required as a part of the reprocessing demonstration. Irradiation testing of the ^{233}U-base fuel produced in the hot demonstration is required to establish the performance reliability of the ultimate product of the recycle facility. Postirradiation examinations shall be performed to verify performance of these materials.

6.7.2 Status of Technology

These will be the first full-size fuel elements produced in the pilot plant equipment, although similar fuel particles and fuel sticks will have been produced in developmental equipment and tested in earlier tests. Only limited postirradiation evaluation of full-size FSVR fuel elements will have been conducted. Peach Bottom first core elements will have been examined at GGA, and numerous evaluations of fuel elements will have been performed as part of this task at both ORNL and GGA. The procedures and techniques for the postirradiation examination of fuel elements will be well developed before similar work is required by this subtask.

6.7.3 Work Plan

A number of fuel elements will be produced during the cold operational testing and hot demonstration of the Refabrication Pilot Plant. Those elements that meet the FSVR specification will be loaded into the reactor for irradiation testing for one to five years. Each of the fuel elements will receive postirradiation examination to evaluate its performance.

Test fuel elements containing ^{233}U will be fabricated during hot demonstration operations. Their irradiation will establish the performance capability of recycle fuel developed in this program. These elements will be irradiated for three and four years in the FSVR, postirradiation examined, and reprocessed.

6.7.4 Facilities

The pilot plants will be utilized for the production of these test elements; therefore, no additional facilities are needed for this subtask.

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7. TASK 400 – COMMERCIAL RECYCLE PLANT STUDIES

7.1 INTRODUCTION

The goal of this task is to prepare a conceptual design for a commercial recycle plant such that the plant may be designed, constructed, and placed into operation by 1984. This task will be performed concurrently with other program tasks and will both utilize the results of other task efforts and guide the performance of the other tasks in order that all efforts will be directed toward the achievement of program objectives. The work performed under this task will consist primarily of collecting and coordinating the data from the other tasks and providing the body of defined technology required to establish the base for commercial recycle operations. The task of actually designing, constructing, and operating a commercial recycle plant is, of course, a follow on to this development program and will be carried on by private industry.

The studies performed under this task differ from the effort of tasks 100 and 200 primarily as to emphasis. Tasks 100 and 200 consist of operation of laboratory and pilot plant equipment to obtain data on the process variables and equipment performance. The pilot plants are not expected to be optimized systems; rather, they are used to obtain information needed for design, construction, and operation of a commercial plant.

This task is organized into Engineering and Economic Studies (Subtask 410) and Conceptual Design of a Commercial Recycle Plant (Subtask 420). The Engineering and Economic Studies include Process Evaluations (411), Fuel Shipping Methods and Costs (412), Irradiated Fuel Storage (413), and Waste Management and By-Product Recovery (414). The conceptual design activities include plant layouts, equipment and systems designs, and the preparation of a conceptual design report.

The studies of this task will be performed to coordinate all aspects of the recycle research and development effort into the most economical plant for the selected processes and equipment for the overall fuel recycle system. The program will emphasize (1) the review of the preferred schemes to see if alternatives are needed for the large plant, (2) liaison among the various research and development establishments involved in the research program, (3) correlation of operating and equipment data for the commercial plant design, (4) comparison of the effect of equipment scale-up versus duplication on economics and maintenance, (5) study of spent and refabricated fuel shipping and storage, and (6) study of the waste disposal problems of the HTGR recycle plant.

7.2 COMMERCIAL RECYCLE PLANT STUDIES SCHEDULE

The schedule for performing the steps of this major task of the development program is shown in Fig. 7.1.

7.3 SUBTASK 410 — ENGINEERING AND ECONOMIC STUDIES

7.3.1 Purpose

The purpose of the commercial recycle plant engineering and economic studies is to guide the development program from the viewpoint of overall recycle needs and thus (1) obtain an economical HTGR fuel recycle method for early recovery and use of bred ^{233}U, (2) assure that the information required for conceptual plant design (Subtask 420) is obtained, and (3) provide a firm basis for private industry to make decisions on building a commercial plant.

7.3.2 Requirement

It is vital that processes and equipment be developed for the economic reprocessing and refabrication of HTGR fuel with a minimum expenditure of development resources. It is required, therefore, that the development effort and its results be continuously evaluated with respect to the scale-up and other needs of commercial plant design, construction, and operation. Continuous interaction of the development and evaluation efforts is expected, with particular emphasis on review of the preferred reprocessing or refabrication schemes to determine if process alternatives should be substituted for those giving trouble or found to be uneconomical.

7.3.3 Timing

The engineering and economic studies will be carried on concurrently with the reprocessing and refabrication development effort as shown in Fig. 2.1, page 5, and with commercial plant conceptual design as shown in Fig. 7.1.

7.3.4 Funding

The required funding for this subtask is included in Table 2.1, page 6.

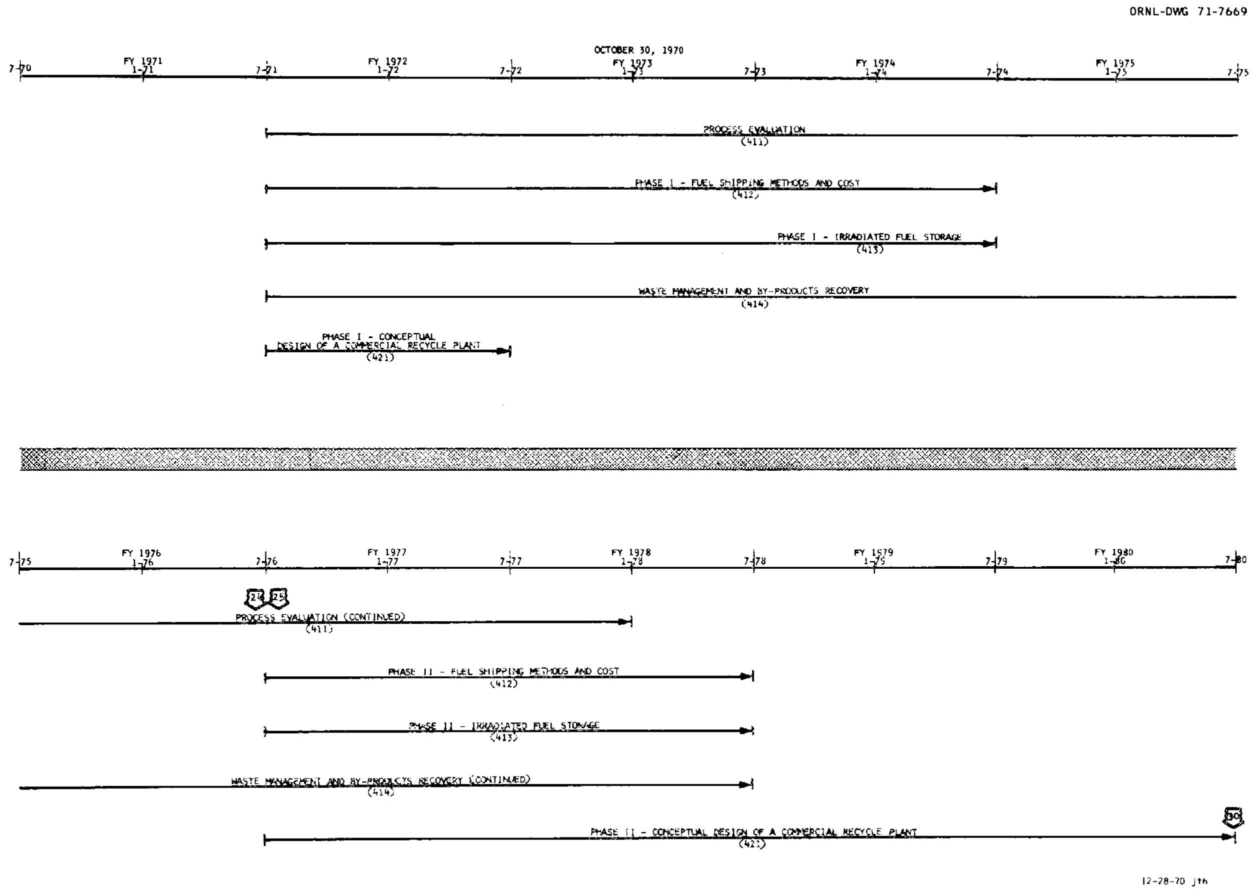

Fig. 7.1. Commercial Recycle Plant Studies Schedule.

7.3.5 Facilities

No additional facilities will be required to perform this subtask.

7.3.6 Subtask 411 – Process Evaluation

7.3.6.1 Requirement

To guide the development effort and to aid in selecting economical processes for the commercial recycle plant, reprocessing and refabrication methods and combinations of methods developed in the laboratory and pilot plant studies must be evaluated. Liaison must be established with various development groups and sites performing related studies to gain maximum benefit from the efforts being expended. Data needed for commercial plant design must be collected and correlated to define areas where further research and development are needed. Computer codes must be prepared for rapid evaluation of commercial plant design changes evolving from variations of process and business conditions.

7.3.6.2 Status of Technology

Based on work of the National Laboratories and GGA, a number of studies of the costs of reprocessing and refabricating recycle fuel have been or are being performed. Head-end reprocessing at the reactor site has been investigated.[1] Costs of central plants for HTGR fuel reprocessing[2–6] and refabrication[7–9] have been estimated. All of these cost studies have been performed under the HTGR Base Program.

7.3.6.3 Work Plan

Data from the development tasks will be evaluated and correlated to determine its adequacy in support of commercial plant applications. Changes that are determined as needed in the development task will be formulated and fed back to the development efforts. The design and demonstration efforts will be monitored to determine that factors such as scale-up are given appropriate consideration during development efforts.

7.3.7 Subtask 412 – Fuel Shipping Methods and Costs

7.3.7.1 Requirement

The methods and equipment used in shipping both spent fuel to the reprocessing plant and refabricated fuel from the refabrication plant must be integrated into the design of both the commercial recycle plant and the reactor. In general, spent fuel shipping has received more previous attention; however, the commercial recycle plant must also consider the problems of both shielding recycle fuel and assuring intact transit of refabricated fuel elements. Shipping containers, loading and unloading facilities, and cask all require more study to determine an economical shipping technique that meets AEC and DOT licensing requirements.

7.3.7.2 Status of Technology

Under the HTGR Base Program, GGA has determined preliminary spent fuel shipping costs for several combinations of cask size, shipping distance, and shipping media.[10] Shipping refabricated HTGR fuel has received little attention thus far.

7.3.7.3 Work Plan

Methods for shipping both irradiated and recycle fuel will be studied. Parameters studied will include selection of shielding materials, economic shipment size, packaging requirements, alternative modes of transportation, separate shipment of reflectors and spent fuel, and common cask usage for both irradiated and recycle fuel. Available computer codes will be utilized or improved as necessary for rapid evaluations of the parameters. Periodic cost evaluations of spent fuel and refabricated fuel shipping requirements will be made, and plant cost estimates will be updated as necessary.

7.3.8 Subtask 413 — Irradiated Fuel Storage

7.3.8.1 Requirement

The optimum timing and size of both storage facilities and recycle plants must be determined from a projection of the HTGR economy. Use of storage as a fuel management method as opposed to early construction of recycle plants must be evaluated and reevaluated as reprocessing development information becomes available and plant data are being developed. Methods and costs for storage must be developed.

7.3.8.2 Status of Technology

On-site fuel storage has been studied briefly by GGA under the HTGR Base Program.[11] Storage at the reprocessing plant site has been included in the reprocessing plant cost studies.[2–5] Interim storage of spent fuel has been studied briefly.[12] Alternatives have yet to be studied to any extent.

7.3.8.3 Work Plan

Alternative methods of fuel storage will be examined, including storage at the reactor site, storage independent of the recycle plant, and storage designed for later use as part of the reprocessing plant. The methods and practices of each type of storage will be studied from viewpoints of both safety and economics.

7.3.9 Subtask 414 – Waste Management and By-Product Recovery

7.3.9.1 Requirement

Disposal methods for gaseous, solid, and liquid radioactive wastes from the commercial recycle plant must be reviewed to determine the applicability of standard methods and to determine if problems unique to the HTGR fuel will arise.

By-products such as neptunium, plutonium, and tritium may become more in demand. The techniques and costs of recovery and concentration of by-products should be considered in the preparation of the commercial plant design. Investigation of the limitations on disposal of krypton and ^{14}C to the atmosphere is required to determine their effects on processing techniques, plant size, and plant location.

7.3.9.2 Status of Technology

The problems of disposal of wastes from reprocessing plants for water reactors have been studied and reported extensively.[13–17] By-product recovery from these plants has also been studied. The technology of water reactor waste disposal and by-product recovery can without doubt be applied to the wastes from reprocessing HTGR fuel. However, before application to design of recycle plants for HTGR fuel, much review and evaluation are required.

7.3.9.3 Work Plan

The waste disposal problems unique to HTGR fuel reprocessing and refabrication will be emphasized. The first efforts will be directed toward the treatment of off-gas derived from burning the graphite and the carbon coatings on particles. Secondary efforts will be directed toward the disposal of the solid residues from the head-end operations. Liquid waste disposal problems will be related to those from water reactor fuel reprocessing. Disposal methods will be analyzed for economics on the basis of results of the development program and related techniques for water reactor fuels. Results of the analyses will be used to guide the development program and the conceptual design of the commercial recycle plant.

7.4 SUBTASK 420 – CONCEPTUAL DESIGN OF A COMMERCIAL RECYCLE PLANT

7.4.1 Purpose

The purpose of preparing a conceptual design is primarily to guide the development tasks, evaluate their results for commercial plant application, and determine economic processes and equipment for the commercial recycle plant. The conceptual design provides the basis for developing estimates of the capital and operating costs of commercial recycle plants. During the conceptual design, data will be collected and correlated, needed missing data identified, and the results and conclusions derived from the design and cost estimates fed back to guide the development tasks toward the most efficient use of the available development time and money.

7.4.2 Requirements

A conceptual plant design must be prepared based upon the reprocessing and refabricating processes and equipment that are developed under other tasks of this program. The completed conceptual design must include the effects of fuel management, materials handling, and waste treatment and disposal methods on the commercial recycle costs. The conceptual plant design is required to guide decisions on investment in a commercial recycle plant and is required to provide the basis for the preliminary design.

7.4.3 Timing

The conceptual design will be prepared concurrently with reprocessing and refabrication pilot plant design, construction, and operation as shown in Fig. 2.1, page 5, and with the engineering and economic studies as shown in Fig. 7.1.

7.4.4 Funding

The required funding for this subtask is included in Table 2.1, page 6.

7.4.5 Facilities

No additional facilities will be required to perform this subtask.

7.4.6 Work Plan

The first step in the preparation of a conceptual design will be development of process flowsheets and equipment layouts. These will be based upon the HTGR economy projections and use of the reference fuel described in Chapter 3. The priorities and emphasis in preparing the conceptual design will depend on the time of first discharge of spent fuel from the first large HTGR. However, the capacity of the first commercial plant is determined by the number of HTGR's on line, in construction, and expected to be built. A decision on the capacity will be deferred as late as practical and until needed in the preliminary plant design. Based on sales predictions and reactor locations (two smaller commercial plants might be more economical than one large plant), size and siting will be studied as part of the conceptual design.

Plant safety, reliability and maintenance considerations will be a part of each step in the conceptual plant design effort. Information on equipment quality, operation, performance, and maintenance requirements, as obtained from the cold and hot pilot plants, will be incorporated into the conceptual plant design.

The preparation of the conceptual design will include defining the design in descriptions, on drawings, and in specifications and procedures. The design will include the identification of nationally accepted codes and standards that are appropriate for application to the design, construction, and operation of commercial plants. The design will also include the identification of areas where AEC-RDT or other government codes and standards should be applied or where additional standards should be developed to define the technical and quality assurance requirements that must be satisfied to attain practical, reliable, and economical HTGR fuel recycle on a commercial basis.

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APPENDIX A

CHOICE OF FUEL CYCLE

Basis for Fuel Cycle Comparisons

The neutronics and economics of the HTGR with alternative fuel cycles have been studied[1–5] by several groups, and some of the results are compared below.

Economic factors important in evaluating fuel cycle costs are the unit costs for fuel element fabrication, recovery or storage of spent fuel, uranium ore and enrichment, and the value of fissile material removed from the system.

In the HTGR, the fuel fabrication cost can be divided into a particle production component, which is proportional to the fissile and fertile metal loading, and a second component associated with such items as graphite cost, graphite machining cost, and fuel rod production cost, which are independent of loading. Each step has its associated inspection and quality assurance aspects. The fuel cycle cost for the second component is insensitive to the particular fuel cycle and depends mainly on the fuel residence time for a given power density and fuel rating. It is important to treat the fabrication in this fashion, as the alternative fuel cycles result in large variations in fissile and fertile loadings.

Recovery costs include the cost of shipping the spent fuel to a reprocessing facility and the cost of recovering the fuel values. If shipping and reprocessing the fuel is too expensive relative to the value of the recovered fuel, the spent fuel can simply be stored either for future recovery or for permanent disposal. The shipping cost to a recycle plant assumes a 1000-mile distance and amounts to about $230* per fuel element. Storage costs include the cost of shipping the spent fuel to a storage facility as well as the appropriate storage cost. As the storage facility can be quite near the reactor, the combined costs of storage and shipping are taken as equal to the shipping cost for a reprocessing cycle. Equal reprocessing costs* of $65/kg (Th+U+Pu) have been taken for all the fuel cycles. The cost factors used in this study are summarized in Table A-1.

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*These costs and other costs in this appendix are consistent with each other but may change with further study.

Table A-1. Summary of Cost Bases for HTGR Fuel Cycle Assessments

Item	Value
U_3O_8 cost, \$/lb	8
Separative work cost, \$/kg U	26
$^{233}U/^{235}U$ value ratio	14/12
Fissile Pu/^{235}U value ratio	10/12
Finished graphite cost, \$/block[a]	1000
Particle fabrication cost, \$/kg[b]	60
Fuel shipping cost, \$/block	230
Reprocessing cost, \$/kg	65
Storage cost, \$/block	230

[a]About 3.6 blocks per megawatt (electrical). Finished cost includes machining, assembly, and inspection.

[b]Value is a weighted average for thorium and ^{235}U particles for the thorium cycle or $^{235}U/^{238}U$ particles for the uranium cycle; handling costs of recycle fuel increase this about \$10/kg.

A meaningful comparison of alternative fuel cycles requires that the same physical limitations (i.e., maximum temperature, reactor characteristics, and cost information) apply to all designs. The temperature criteria include fuel particle temperatures, structural graphite temperatures, and outlet coolant temperatures. One way to ensure a reliable comparison, in this regard, in the HTGR is to require that all calculations be limited to the same age-peaking factor (the power-peaking effect arising from differences in power densities in adjacent fuel elements exposed to the same neutron flux where the fissile material concentration of older fuel is low relative to that in new fuel). Further, one should use the same pressure drop and thermal efficiency since all fuel cycles gain in a similar way from improved cooling. These criteria have been applied in the cost comparisons presented below.

Alternative Fuel Cycles

The particular HTGR fuel cycles that have received significant attention are discussed below. In all cases equilibrium fueling conditions are assumed.

1. Reference thorium cycle with selective recycle ($^{235}U + ^{233}U/^{232}Th/^{233}U$)*

Here the ^{233}U produced by capture in thorium is processed separately from the ^{235}U, ^{236}U and used as recycle feed material. The reference cycle retires the "burned" ^{235}U, which is diluted with ^{236}U and ^{238}U in about the ratio 1:2:0.5 (i.e., an enrichment of about 30%). The recovery of the uranium from the spent fissile particle uses processes similar to those used for the recovery of ^{233}U from the recycle and fertile particles. Thus, the recovery of this material should not add significantly to the cost of the recycle program. The retired material should be worth recovering since it contains considerable quantities of ^{237}Np and ^{238}Pu; further, the uranium can be blended with about 12 times as much natural uranium to make 3%-enriched uranium for light water reactor fuel. If the blended fuel were assigned full value, the discharge ^{235}U would be worth \$9.60/g as compared to the scheduled value of \$10.70/g ^{235}U for 30%-enriched material. Considering this relatively small difference in potential values, the small quantity of material to be sold (i.e., about 10% of the initial makeup ^{235}U), and the potential value of the contained ^{238}Pu and ^{237}Np, taking full credit for this retired uranium seems reasonable. Further, the actual value has only a relatively small impact on the total fuel recycle cost.

2. Thorium cycle with nonselective recycle ($^{235}U + ^{233}U/^{232}Th/^{233}U$)

Here the discharged ^{233}U and ^{235}U together with the parasitic absorber ^{236}U are reprocessed together and fed back into the reactor.

3. Thorium cycle without recycle ($^{235}U/^{232}Th/^{233}U$)

Here the spent fuel is discarded at end of life with zero value. A realistic evaluation cannot take full credit over the long term for the discharged ^{233}U if it is not recycled back to the reactor. Further, the total fuel cycle cost is quite sensitive to the actual value of the material to be sold.

4. Plutonium makeup cycle ($Pu + ^{233}U/^{232}Th/^{233}U$)

The plutonium makeup cycle, in which the ^{235}U feed material is replaced by ^{239}Pu, is currently being investigated in depth at GGA under an EEI/GGA cooperative program. Results to date indicate an indifference value of \$9 to \$10/g

*(x/y/z) denotes fissile feed material/fertile material/bred fissile material.

of fissile plutonium for this use of plutonium. However, the plutonium makeup cycle requires the use of ^{233}U recycle and makes many of the same demands (except for particle separation in the head end) as the reference cycle.

5. Uranium cycle ($^{235}U/^{238}U/^{239}Pu$)

This is a low-enrichment cycle. It can be used with or without reprocessing depending on the value of the recovered plutonium and the cost of its recovery. It does not require particle separation in the head-end step of the reprocessing or in refabrication.

Comparison of Fuel Cycles

The fuel cycle costs for the reference thorium cycle (cycle 1) in a 1000-MW(e) HTGR, and for the thorium cycle without recycle (cycle 3), are shown in Figs. A-1 and A-2, respectively, as functions of carbon-to-thorium ratio and fuel residence time. The fuel cycle costs for the low-enrichment cycle (cycle 5) in a 1000-MW(e) HTGR, with and without spent fuel recovery, are shown in Fig. A-3 as a function of carbon-to-^{235}U ratio and fuel residence time. All of these costs are appropriate to a six-month refueling interval, as such data were readily available for this summary. The various fuel cycles gain from shorter refueling intervals, but studies[5] to date indicate they all improve by similar amounts. The fuel cycle costs for the thorium cycle without selective recycle (cycle 2) are not shown in detail, but early in the HTGR Base Program, studies[6] indicated that the long-term recycle of all the discharged uranium was disadvantageous because of the continued buildup of ^{236}U and ^{237}Np. However, it was determined that the fuel could be selectively recycled by placing the various constituents (thorium, recycle ^{233}U, and makeup ^{235}U) in fuel particles that could be separated from each other in the head-end portion of the reprocessing plant. These studies have been updated,[7] and some of the results are summarized below.

The age-peaking factors for the various fuel cycles are shown in Fig. A-4. The large HTGR, unlike the Fort St. Vrain, does not use variable orifices to distribute the coolant and thus must make more stringent limits on the peak to average power density ($\hat{P}/\bar{P}$). Currently, $\hat{P}/\bar{P}$ has been set at 1.6 (FSVR design limit is 1.83), which limits the age peaking to about 1.4; the remaining margin in the peaking factor must cover the cross radial power distribution and any flux tilting from asymmetrics and inserted control rods. In effect, this limit

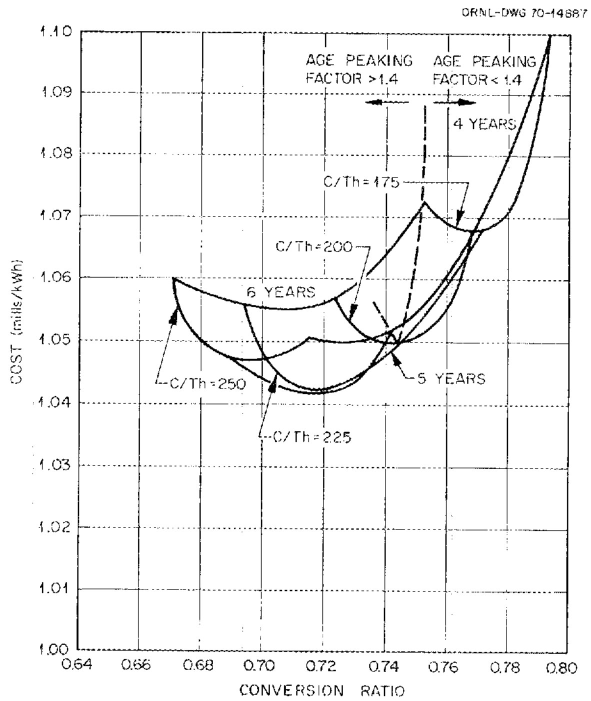

Fig. A-1. Equilibrium Fuel Cycle Costs for the Reference Thorium Cycle.

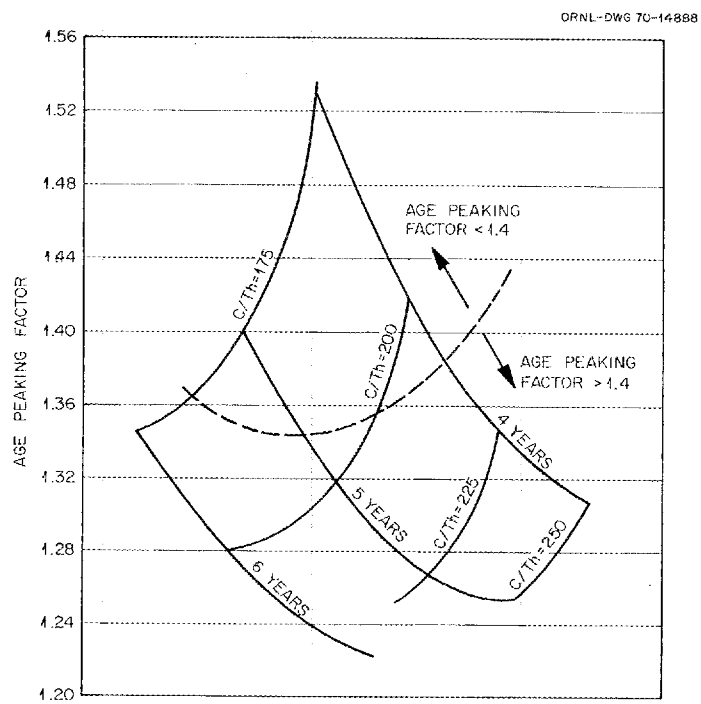

Fig. A-2. Equilibrium Fuel Cycle Cost for the Thorium Cycle Without Recycle.

ORNL-DWG 70-14889

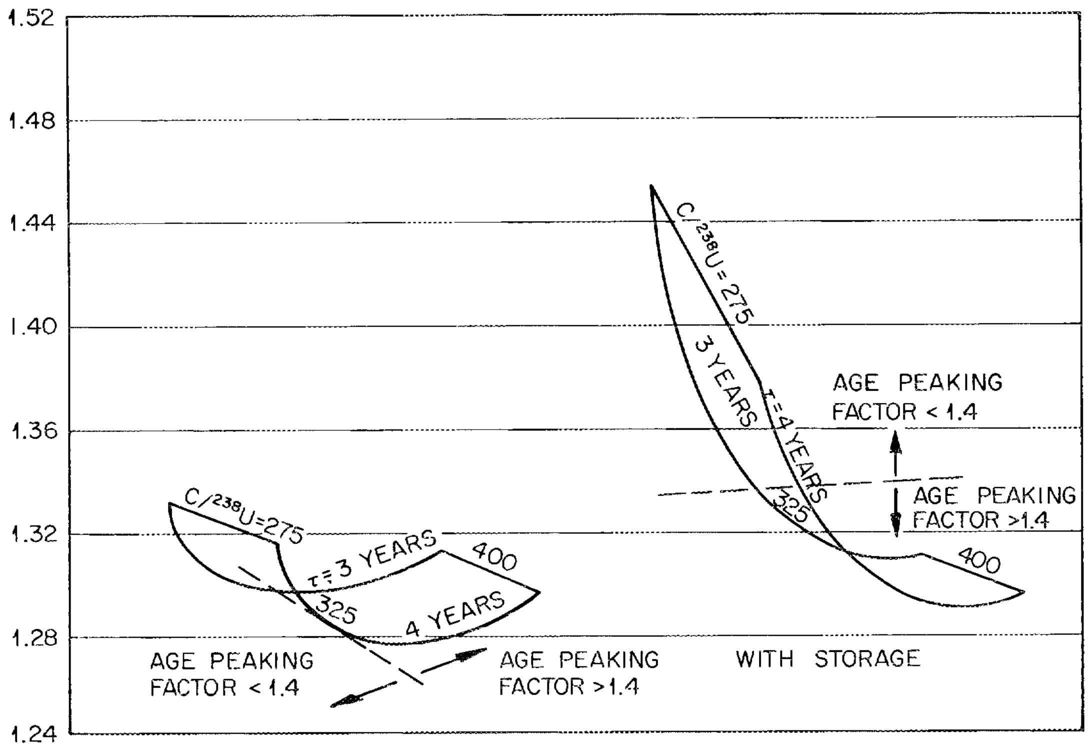

Fig. A-3. Equilibrium Fuel Cycle Cost for the Low-Enrichment Uranium Cycle.

ORNL-DWG 71-6864

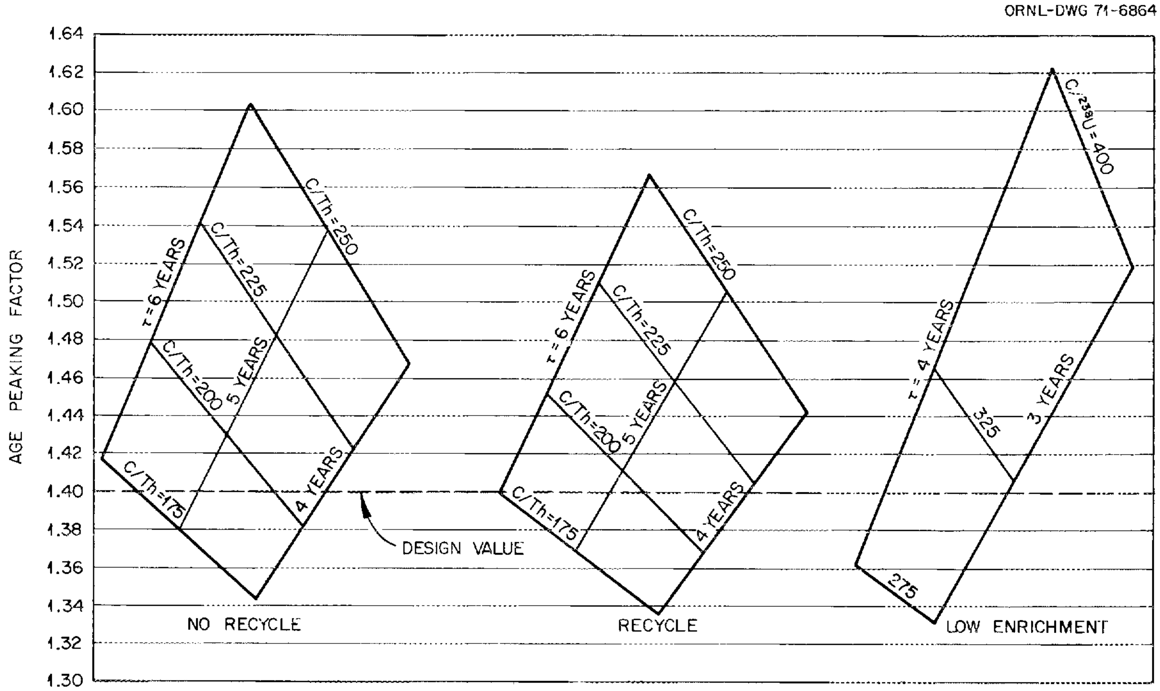

Fig. A-4. Age-Peaking Factor for Various Fuel Cycles.

makes many of the lowest cost fuel cycles unavailable. Within this restriction on age-peaking factor, the minimum practical equilibrium fuel cycle costs for the alternative cycles are:

Reference thorium cycle with selective recycle	1.05 mills/kWh
Thorium cycle without recycle	1.34 mills/kWh
Uranium cycle with reprocessing	1.30 mills/kWh
Uranium cycle without reprocessing	1.34 mills/kWh

The minimum fuel cycle cost differences for equilibrium conditions as a function of conversion ratio for various forms of recycle are shown in Fig. A-5. We see that if the retired fuel carries zero value, full recycle is advantageous over no recycle but is itself 0.19 mill/kWh more expensive than selective recycle.

The equilibrium fuel cycle cost advantage of the reference thorium cycle with selective recycle over the thorium cycle without recycle is at least 0.26 mill/kWh. Further, by comparison with the light water reactor, only the reference cycle exhibits significant potential savings in both fuel cost and uranium ore requirements. A recent evaluation[8] indicated that in the mid-1980's light water reactors will obtain fuel cycle costs of 1.3 to 1.4 mills/kWh. Some of the fuel cycle characteristics of the alternative fuel cycles, based on designs which have age peaking factors within 10% of the design value, are shown in Table A-2.

All of the above comparisons are based on fuel cycle costs calculated at equilibrium conditions. Although previous studies[9] have shown that equilibrium fuel costs are indicative of the relative value of various fuel cycles, one should also consider the relative cost advantage of the reference cycle relative to the nonselective recycle case during approach to equilibrium. Such a comparison is necessary because equilibrium is not achieved in the nonselective recycle fuel cycle in a single 30-year reactor lifetime, and technical forecasts beyond this time period are open to question.

Recent calculations by GGA indicate that the cost advantage of the reference thorium cycle over the thorium cycle with nonselective recycle averaged over the first 30 years of reactor operation is about 0.06 mill/kWh. In the final year of operation the nonselective cycle will have generated about two-thirds of the equilibrium quantity of parasitic ^{236}U, and the cost advantage of the selective recycle system for that year will be about 0.15 mill/kWh.

An additional complication in the comparison of the two recycle schemes is that, in a multiple-reactor economy based on nonselective recycle, a new reactor might well receive reprocessed fuel from an older and hence more heavily poisoned system. The effects of such cross contamination have not been calculated in detail, but it should make the nonselective recycle process less attractive.

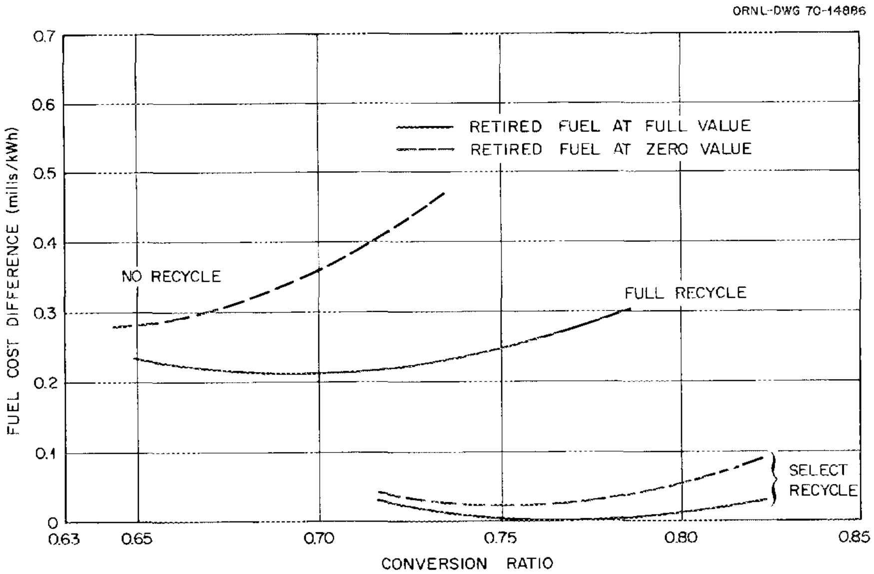

Fig. A-5. Minimum Fuel Cycle Cost Difference as a Function of Conversion Ratio for Various Forms of Recycle.

Table A-2. Fuel Cycle Characteristics for Alternative Fuel Cycles

Fuel Cycle	Reference Thorium Cycle	Thorium Cycle Without Recycle	Uranium Cycle
Carbon-to-thorium ratio (carbon-to-^{238}U ratio)	225	200	(325)
τ, years	4	5	3
Conversion ratio	0.74	0.69	0.53
Average specific power, MW/kg fissile	1.9	1.6	2.7
Fissions per initial fissile atom	1.5	1.5	1.2
Age-peaking factor	1.41	1.47	1.42
Thorium charged, kg/year	9130	8200	
Uranium makeup, kg/year	273	557	8920
Makeup enrichment, %	93.5	93.5	6.95
Uranium recycle, kg/year	388		
Recycle enrichment, %	64		
Thorium retired, kg/year	8550	7600	
Uranium retired, kg/year	71	374	8030
Retired uranium enrichment, %	29	62	0.90
Plutonium retired, kg/year			60
Retired plutonium enrichment, %			55.4
Fuel cycle cost, mills/kWh			
With reprocessing	1.05		1.30
Without reprocessing		1.32	1.34

If the reference cycle is adopted, then in the head-end process one can expect some mixing of the uranium scheduled for recycle with that scheduled for retirement as a result of imperfections in either the process or the particles. The contents of broken particles can be collected by leaching the products of the fuel block burner. If the resultant solution is mixed with the uranium scheduled for recycle, no ^{233}U will be lost from the system to within the capabilities of the screening process. Figure A-6 shows the increase in fuel cycle costs, again at equilibrium conditions, that result from mixing either stream into the other. If the screening process is at least 98% effective, the loss of recycle uranium from the system will add less than 0.005 mill/kWh to the equilibrium fuel cost. Mixing retired uranium with the recycle uranium results in even smaller cost increase, and breakage of even 10% of the uranium particles adds only 0.016 mill/kWh to the equilibrium fuel cycle costs.

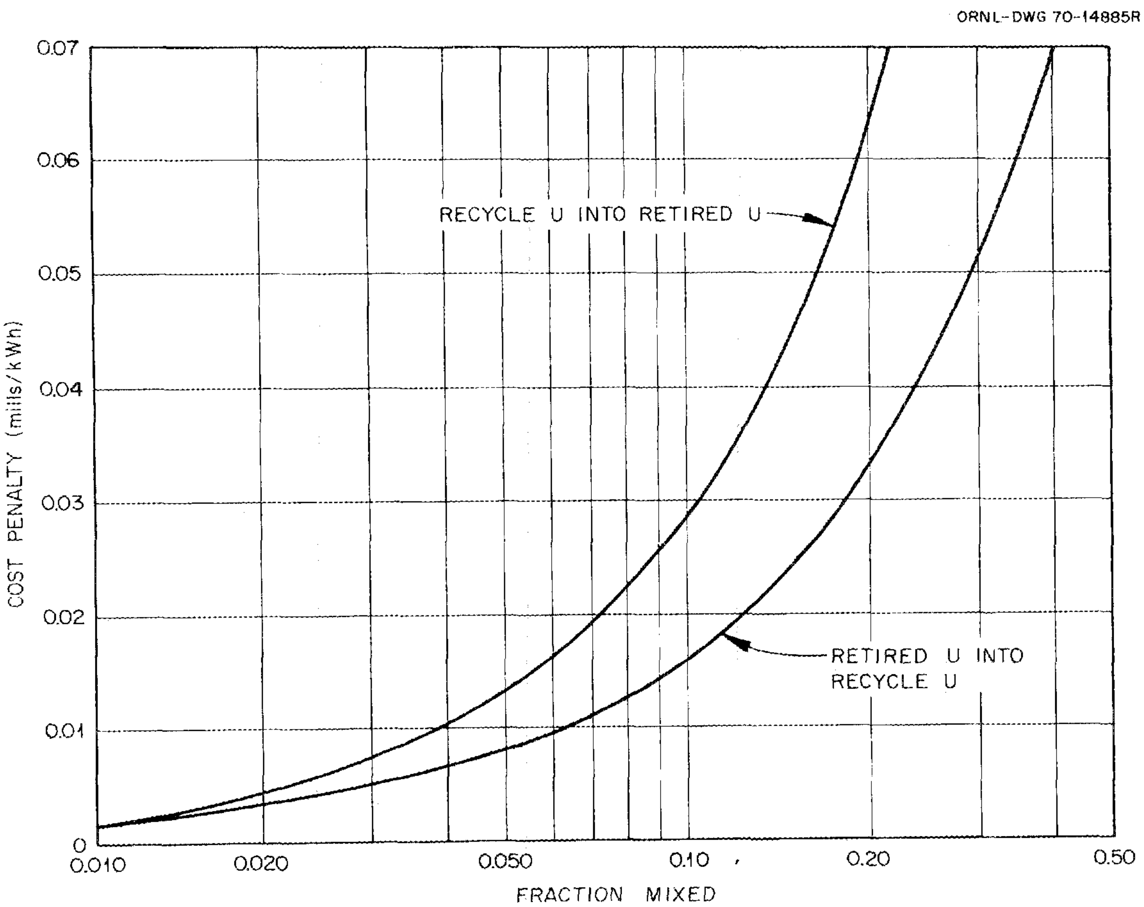

Fig. A-6. Cost Penalty for Mixing Recycled ^{235}U and ^{233}U in HTGR.

Conclusions

These results indicate that while selective recycle is advantageous to HTGR nuclear performance, a 10% crossover of "burned" fissile into "bred" fissile does not add a significant cost penalty even under equilibrium fueling conditions. Taking time dependence into account would increase the permissible crossover significantly.

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APPENDIX B

FUEL ELEMENT DESIGN FOR FSVR AND LARGE HTGR'S

The following is a revision of the paper by R. F. Turner, W. V. Goeddel, and E. O. Winkler, "HTGR Fuel Design," pp. 31–48 in <u>Symposium on Sol-Gel Processes and Reactor Fuel Cycles, Gatlinburg, Tennessee, May 4–7, 1970</u>, CONF-700502.

HTGR FUEL DESIGN

R. F. Turner
W. V. Goeddel
E. O. Winkler

ABSTRACT

The hexagonal block fuel element has been established as the design concept for large HTGR power plants in the United States. Summary descriptions of this fuel element and typical reactor core assemblies are presented. The element contains spherical fuel particles which are very amenable to fabrication by the sol-gel process. Extensive irradiation test data to high burnups and to high fast fluences confirm the good integrity of reference fuel materials for the HTGR. The Th-U^{233} fuel cycle appears most favorable economically for the HTGR. Fuel particles are fabricated in such a way that recycled U^{233} can be kept segregated from make-up U^{235} in order to avoid the buildup of parasitic U^{236}.

INTRODUCTION

The fuel element for large HTGR reactors is a hexagonal graphite block containing rods of coated fuel particles. Helium coolant flows through vertical cylindrical holes within the block. This fuel element design was evolved from the long cylindrical graphite element used in Peach Bottom. The hex block element is the design used for the Fort St. Vrain Nuclear Power Station[1] and is the reference design for larger HTGR power plants.

The fuel particles are in the form of uranium-thorium carbide or oxide kernels coated with pyrolytic carbon and with silicon carbide layers included on some particle types. Because these kernels are small and spherical in shape, they are very amenable to fabrication by the sol-gel processes.

DESCRIPTION OF CORE DESIGNS

Summary descriptions of important core parameters are shown in Table 1 for two large HTGR plants, the 330 MWe Fort St. Vrain and an 1100 MWe design. In each case the active core is approximately a right circular cylinder made up of arrays of the hex block fuel elements. A plan view of the FSV core assembly is shown in Fig. 1, while a vertical view of a section of the core assembly is shown in Fig. 2. The active core is surrounded by graphite reflectors which have effective thickness of 3.3 ft at the top and 3.8 ft at the bottom and along the sides. The core is contained in a steel core barrel which provides lateral restraint and support for the fuel and reflector columns. The fuel and reflector element columns are laterally positioned at the top and bottom planes of the core by radial keys. The top keys and keyways are designed to allow axial movement of individual columns to provide for relative dimensional changes arising from thermal expansion or irradiation induced contraction of the graphite fuel elements.

Each of the hexagonal fuel elements is 14.2 in. across flats and about 31 in. long. The standard fuel element assembly is shown in Fig. 3. The fuel columns are grouped into fuel regions, each containing seven columns, except for some regions at the core periphery which contain five columns. The minimum nominal gap between individual columns is 0.040 in. when the reactor is shut down for refueling.

Each fuel region is located directly below a refueling penetration in the prestressed concrete pressure vessel. During reactor operation each of these penetrations houses a control rod drive and orificing assembly. The central column of fuel elements in each region has three parallel channels through the top reflector and the active fuel zones, as shown in Fig. 2. Two of the channels are occupied by control rods that move as a unit. The third channel is available for the insertion of boron carbide reserve shutdown material. The central fuel column in each region is displaced axially downward about 7.5 in. relative to the fuel elements in the surrounding six columns, thereby preventing the possibility of shear motion across fuel element interfaces in the core.

Table 1. Summary Descriptions:
Fort St. Vrain and 1100 MWe HTGR's

	Fort St. Vrain	1100 MWe
Thermal power, MW(t)	842	2804
Effective core diameter, ft	19.5	27.15
Active core height, ft	15.6	20.8
Number of fuel elements	1482	3800
Number of fuel columns	247	475
Reflector thickness (avg.), ft	3.8	4.2
Number of refueling regions	37	73
Number of control rods, pairs	37	73
Fuel lifetime, years	6	4
Fraction of core replaced each year	1/6	1/4
Fuel cycle	Uranium/Thorium	Uranium/Thorium
Initial loadings:		
Thorium, kg	19,500	40,700
U-235, kg	870	2,000
Average power density, watts/cc	6.3	8.2
Average outlet gas temperature, °F	1440 (770°C)	1398 (760°C)
Average inlet gas temperature, °F	760 (400°C)	630 (330°C)
Core pressure drop, psi	8.4	7.4
Maximum fuel temperature, °F	2300 (1260°C)	2380 (1300°C)
Volume median fuel temperature, °F	1500 (830°C)	1440 (780°C)
Volume median moderator temperature, °F	1350 (750°C)	1300 (700°C)
Maximum fast fluence (E < .18 mev), nvt	8×10^{21}	8×10^{21}
Average fast fluence (E < .18 mev), nvt	5×10^{21}	5×10^{21}
Maximum burnup, MWd/tonne	200,000	180,000
Average burnup, MWd/tonne	100,000	92,000

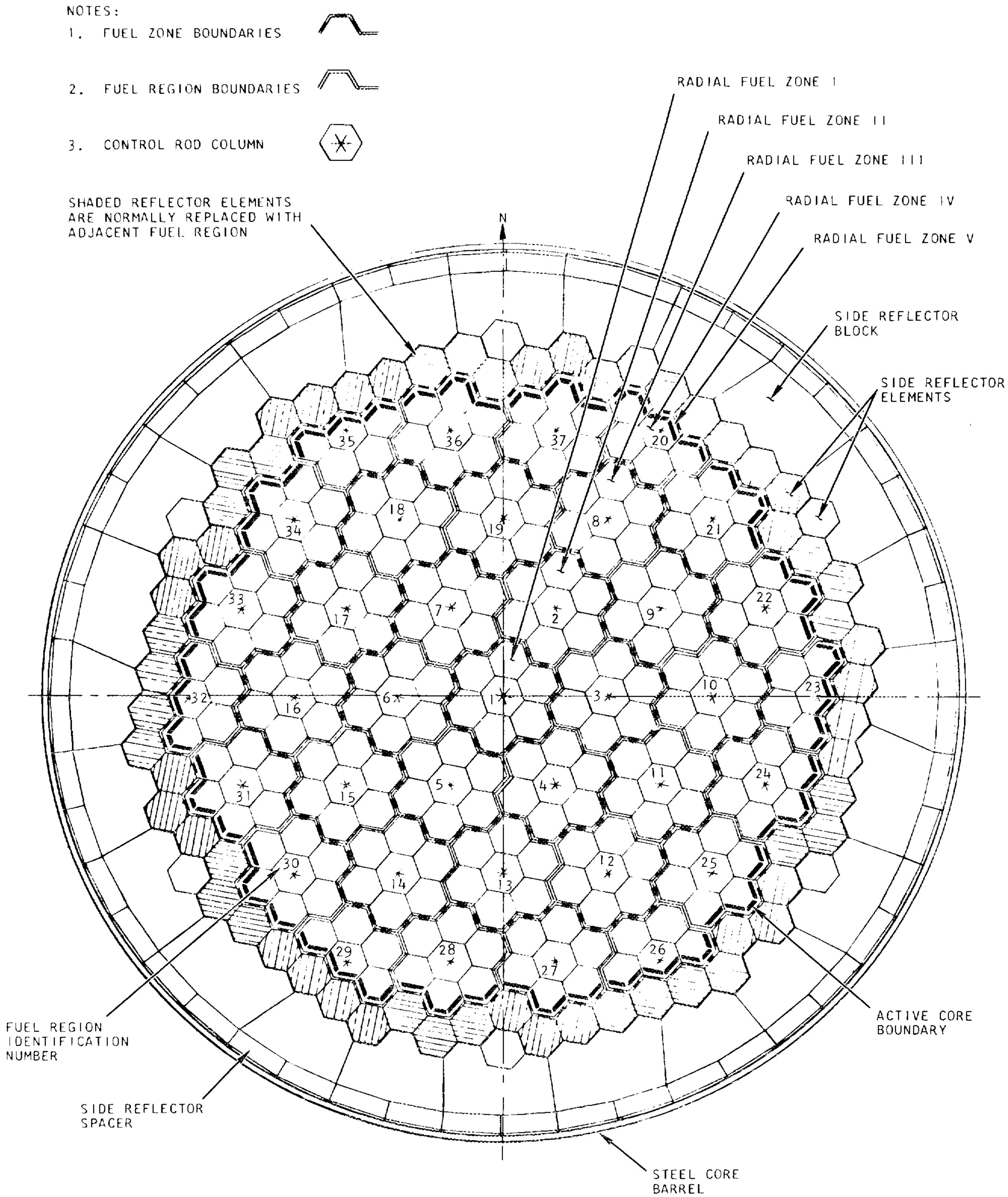


Fig. 1. Core plan view - Fort St. Vrain HTGR.

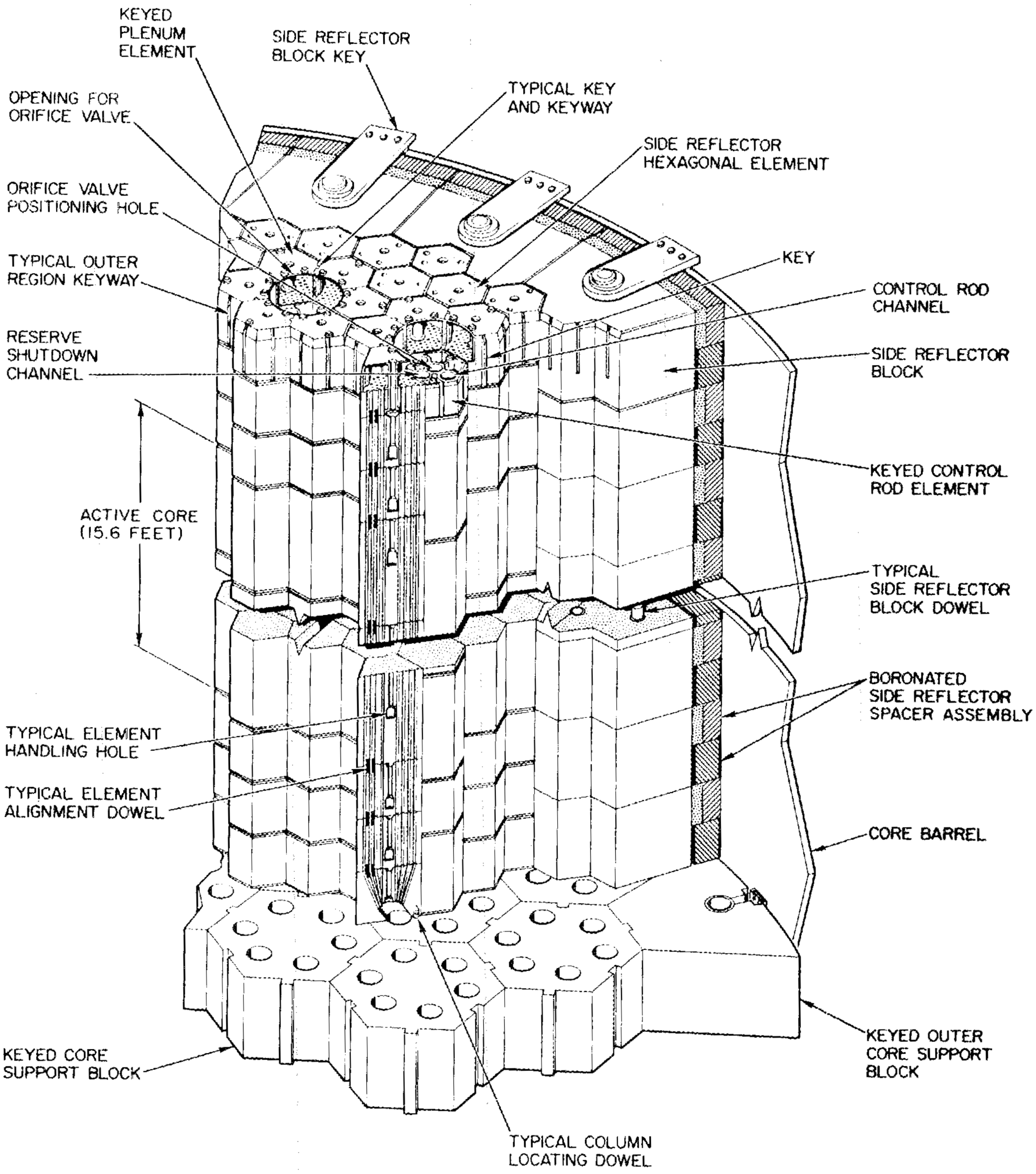


Fig. 2. Core arrangement - Fort St. Vrain HTGR.

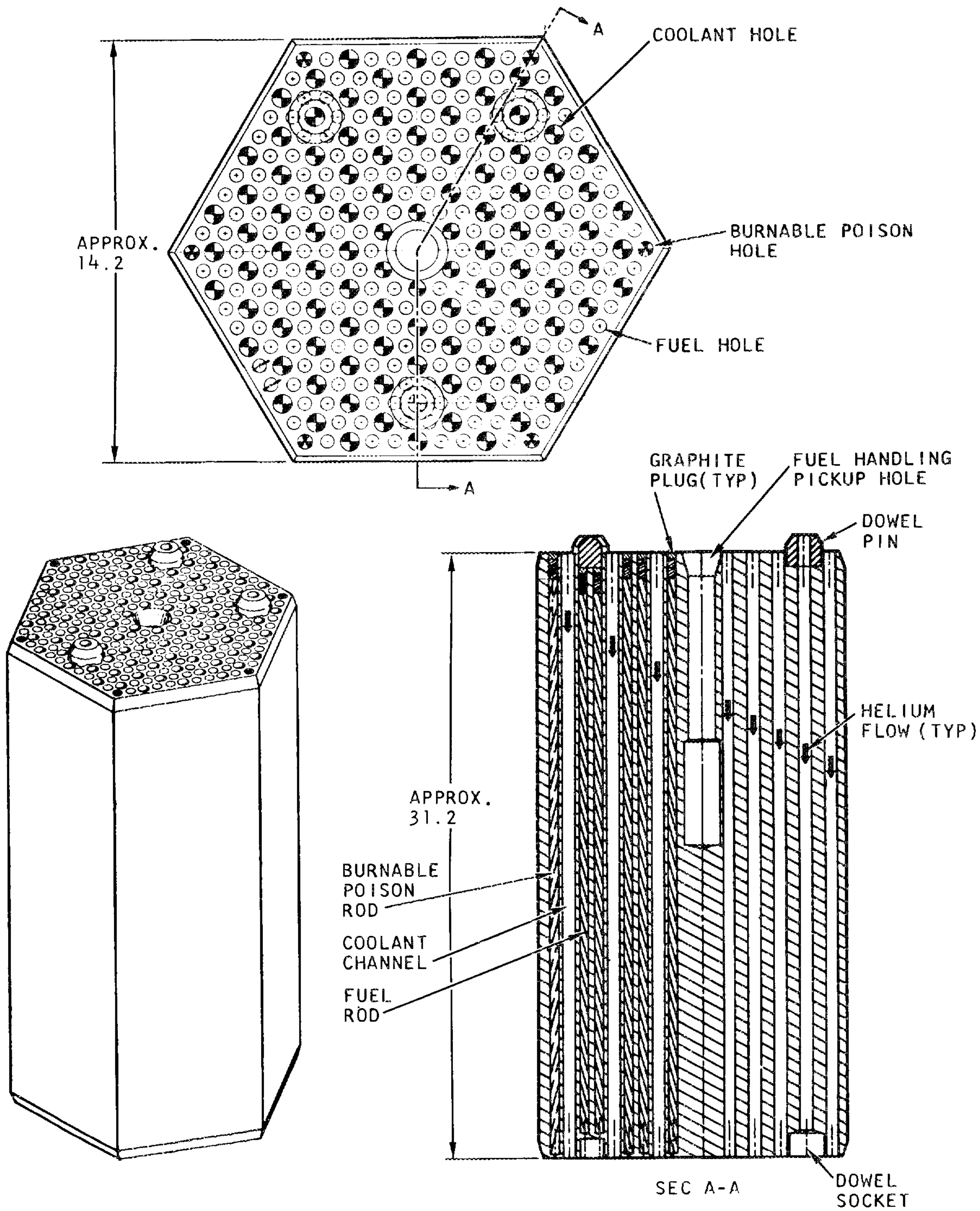


Fig. 3. Standard hex block fuel element for large HTGR's.

Three dowels at the end of each fuel element engage with adjacent elements, thereby maintaining alignment of the coolant holes.

The fuel is contained in the graphite blocks as bonded rods of coated fuel particles in a carbonaceous matrix. There are 210 fuel holes and 108 coolant holes in each standard element. A criterion of the design is that relative changes in dimensions of the fuel rod and the graphite block due to irradiation effects will not result in any unusual stresses on the coated fuel particles. This simple fuel element design lends itself to ease of fabrication and assembly.

Conventional nuclear grade extruded needle coke graphite is being used for the fuel and reflector blocks. The graphite has anisotropic characteristics in directions parallel and perpendicular to the extrusion axis. Mechanical properties of the production material, shown in Table 2, exceed design requirements. Fast neutron fluence causes contraction in both the parallel and the perpendicular directions over the full range of core temperature and exposure conditions. The maximum shrinkage in any fuel element is expected to be approximately 3% in the parallel (axial) direction and 1% in the perpendicular (radial) direction. Expansion of the graphite in the perpendicular direction is not expected under HTGR operating conditions.

Temperature and flux gradients across the blocks, particularly at the core edge, can cause some small amount of bowing of the blocks. Local temperature gradients around the fuel and coolant holes can induce local stresses in the graphite blocks because of the temperature dependence of the irradiation contraction. These ligament stresses are generally tensile adjacent to the fuel holes and compressive adjacent to the coolant holes. The stress is higher at shutdown than during operation because a thermal stress component becomes additive to the contraction stress at that time. However, the peak calculated stresses are at most one-half the measured tensile strength of the graphite material.

Table 2. Properties of Production Graphite Utilized for the Fort St. Vrain Fuel Blocks

	Design Criteria	Average Measured Value
Density, g/cm	1.70 min.	1.77
Tensile strength, psi		
Longitudinal mean	1500	1920
Longitudinal minimum	1000	1690[a]
Transverse mean	1000	1160
Transverse minimum	600	1010
Compressive strength, psi		
Longitudinal	3000	4400
Transverse	3000	4700

[a]Based on 100% testing of 752 logs; the σ value is 360 psi.

COATED PARTICLES

The coated particle fuel, called the TRISO and BISO types, is a dominant feature of the fuel element. Two types of TRISO particles are used in the Fort St. Vrain reactor, as shown schematically in Fig. 4. Fissile particles contain a mixture of thorium and uranium carbide in the kernel, while larger fertile particles contain only thorium carbide. The TRISO particle has a four layer coating. The inner layer is a porous pyrolytic carbon which is used to absorb fission recoils and to provide space for the holdup of gaseous fission products. This layer is referred to as a "buffer layer." The next layer is a high density isotropic pyrocarbon which is surrounded by a thin layer of silicon carbide. The silicon carbide is highly impervious to metallic fission products. The outermost layer is a strong isotropic pyrocarbon layer that supplies strength to the composite coating. The BISO particle is similar to the TRISO, except the SiC layer is not present (see Fig. 5). Typical dimensions for the Fort St. Vrain TRISO coated particles are shown on Fig. 4.

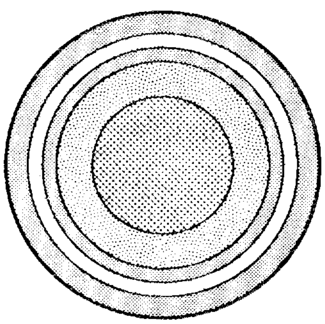
Manufacturing experience has shown that less than 0.1% of the particle coatings have defects following fabrication. Furthermore, irradiation test data indicate that less than 1% of the particles should lose their coating integrity during operation. The primary coolant cleanup system is designed to accommodate the fission product activity associated with a failure of 5% of the particles in the complete core, with a maximum of 10% failed in the oldest fuel regions.

REQUIREMENT FOR PARTICLE SEPARATION

The fuel cycle for HTGR's is based upon the uranium-235 thorium fuel cycle with recycle of bred uranium-233. Graded refueling is used; the fuel lifetime is from 4 to 6 years and one-fourth or one-sixth of the core is replaced each year, respectively. This fuel cycle will involve at least two modes of operation over the lifetime of the plant, as illustrated in Fig. 6.

TRISO COATED PARTICLES PSC REFERENCE DESIGN

FISSILE		FERTILE
$(Th,U)C_2$	FORM	ThC_2
4.25	Th:U RATIO	(ALL Th)
6 YEARS	LIFETIME	6 YEARS
1260°C	TEMPERATURE (MAX)	1260°C
20% FIMA	BURNUP (MAX)	7% FIMA
8.0×10^{21} N/CM^2	FAST FLUX EXPOSURE (MAX)	8.0×10^{21} N/CM^2
200 ± 75μ	PARTICLE SIZE	400 ± 100μ
50μ	BUFFER COATING	50μ
20μ	ISOTROPIC PyC COATING	20μ
20μ	SiC COATING	20μ
30μ	ISOTROPIC PyC COATING	40μ
120μ	TOTAL COATING	130μ



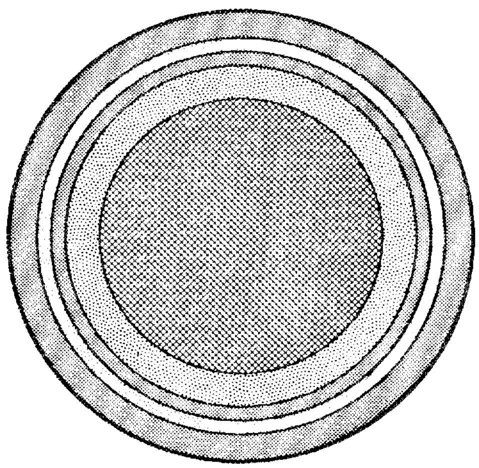


Fig. 4. Fissile and fertile TRISO coated particles for the Fort St. Vrain HTGR.

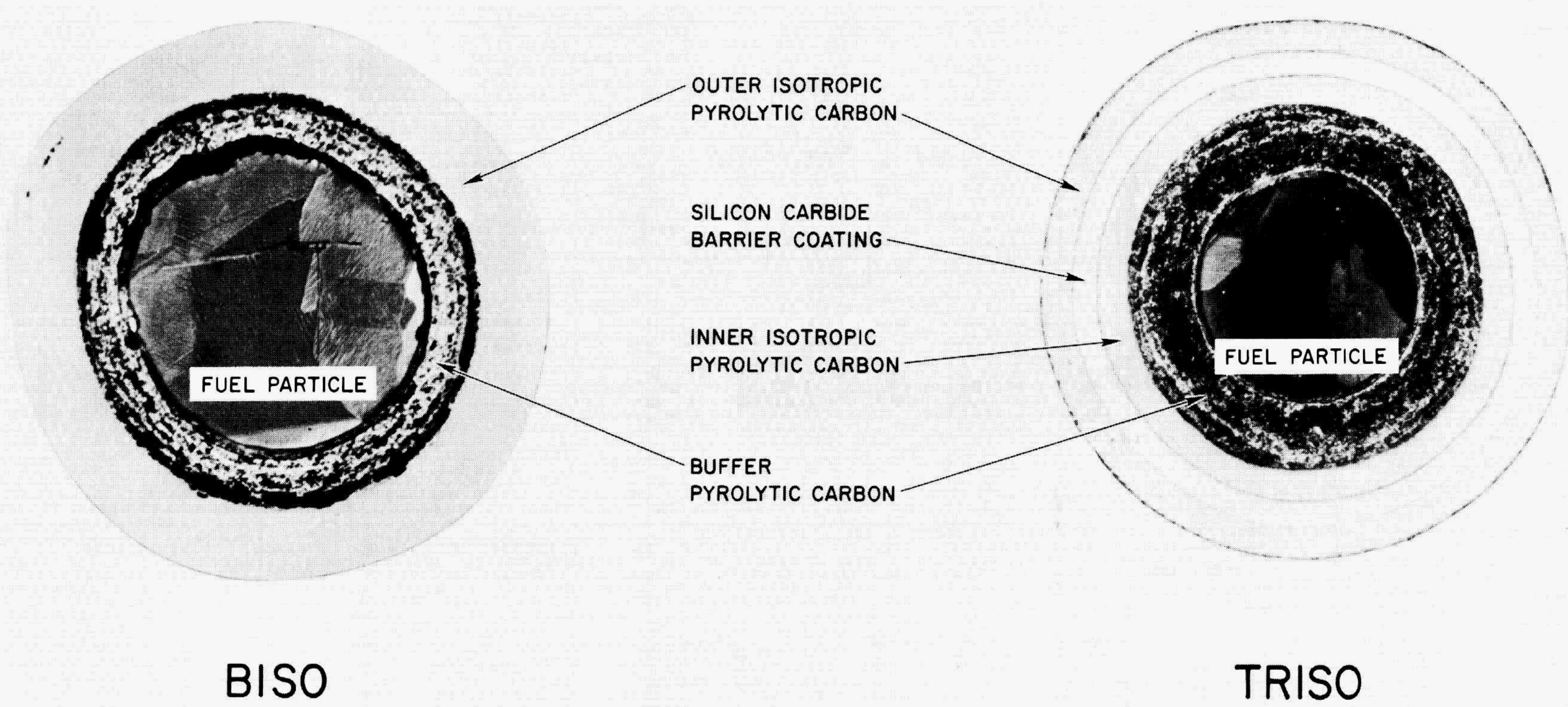


Fig. 5. BISO and TRISO coated particles.

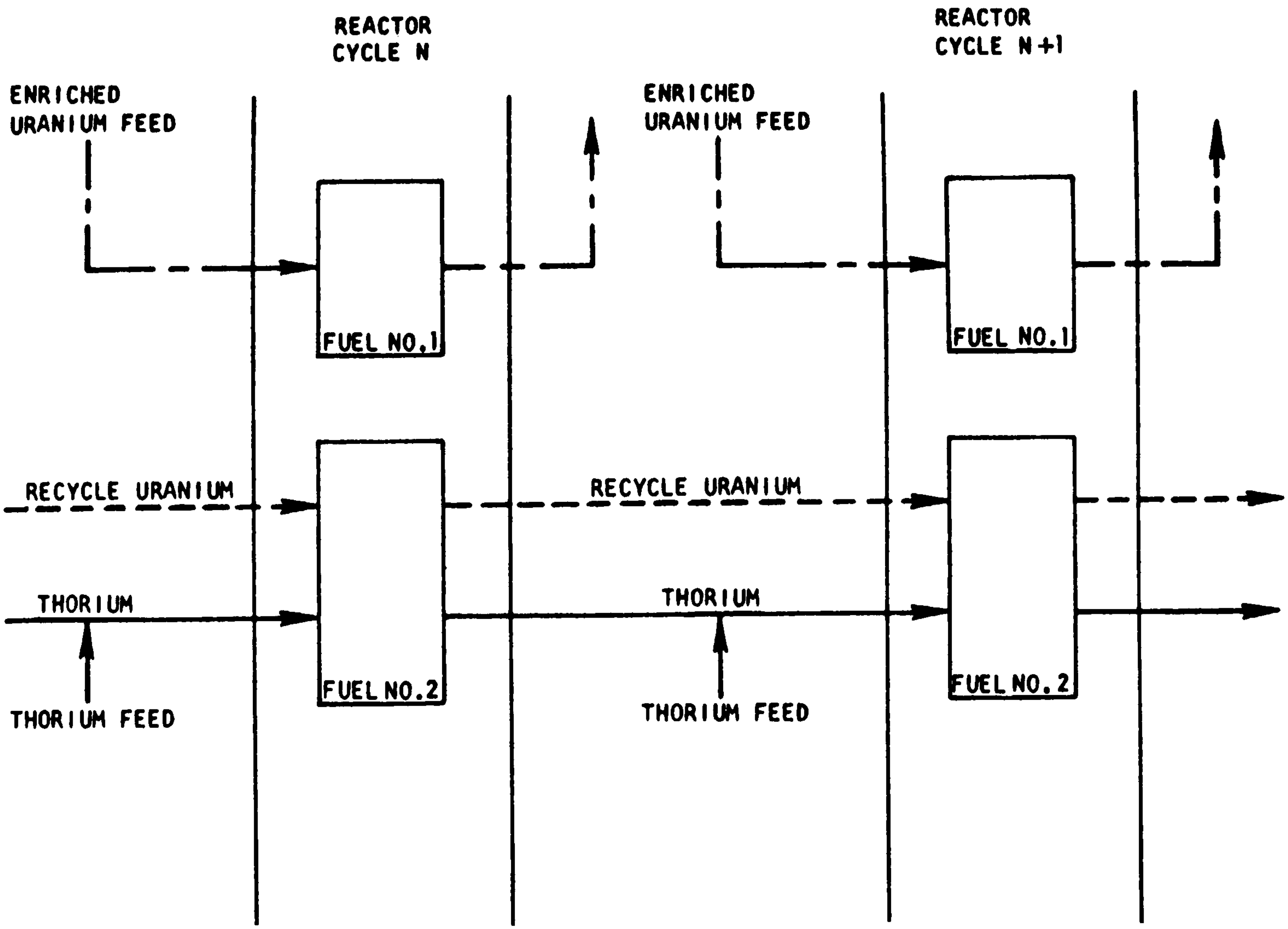


Fig. 6. $U^{235}/Th/U^{233}$ fuel cycle modes.

1. Non-recycle operation, in which fuel removed from the core is placed in storage awaiting reprocessing and recycle. Core operation is sustained by the introduction of additional fresh fully enriched fuel.

2. Recycle operation in which the fuel removed from the core is reprocessed and the U^{233} is fed back into the core along with sufficient makeup U^{235}.

It is desirable that the U^{235} fuel particles be segregated from the U^{233} bearing particles primarily becuase the buildup of U^{236} and Np^{237} would impose a neutron penalty since these nuclides are undesirable neutron poisons. This segregation will be accomplished in the large HTGR power plants by using three types of coated particles:

1. Fissile particles containing only U^{235}.

2. Fertile particles containing only Th^{232}.

3. Mixed particles containing U^{233} plus Th^{232}.

The fissile particles will be physically separated from the fertile and mixed particles prior to processing to recover the U^{233}.

The fuel particle type most desirable for sol-gel fabrication is the mixed U^{233}-Th^{232} particle. Because of the presence of some U^{232} in the recycled U^{233}, this fuel must be fabricated remotely. The relatively simple sol-gel process appears favorable for fabrication in remotely operated facilities.

IRRADIATION TEST RESULTS

A great many irradiation tests conducted over the past several years have confirmed the feasibility and stability of the HTGR fuel materials and components under the most severe design operating conditions envisioned for HTGR plants. Over 175 samples of BISO coated particles have been irradiated in Gulf General Atomic capsule experiments. (Each sample contains approximately 2000 to 3000 coated particles, all of which are examined before and after irradiation.) In these tests, BISO coated particles have survived burnups up to 59% FIMA, fast fluences up to

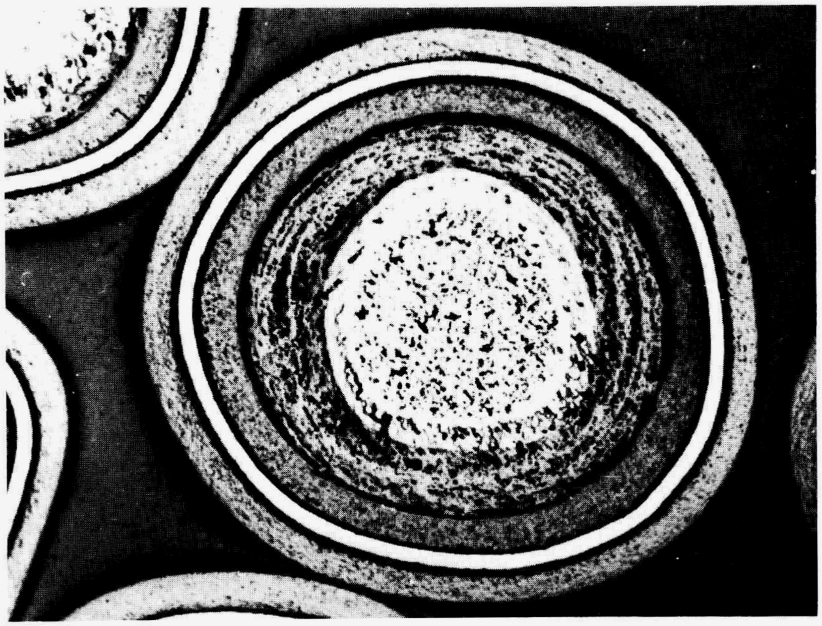
8.4×10^{21} n/cm^2, and temperatures up to 1450°C. Similar tests of over 110 samples of TRISO coated particles have demonstrated the stability of this design to burnups up to 27% FIMA, fast fluences up to 8.7×10^{21} n/cm^2, and temperatures up to 1300°C. These test results on BISO and TRISO coated particles include many samples prepared in full-scale production equipment. Photomicrographs of TRISO and BISO coated particles tested under conditions more severe than the peak design operating conditions envisioned for HTGR plants are shown in Fig. 7. The extent of the successful demonstration of Gulf General Atomic coated particle performance is given in Table 3.

The fuel rods consist of close-packed beds of coated particles bonded together with a carbonaceous matrix. This matrix has been designed for stability under irradiation in order to avoid the deleterious effects that have been observed with less stable fuel body matrices. Design features of the fuel rods include use of graphitizing binder in conjunction with high heat treatment temperatures and irradiation-stable graphitic filler material. Tests to 6×10^{21} n/cm^2 at 1250°C have shown that these fuel rods have excellent stability under irradiation. No evidence of coating breakage or of deleterious interaction between the matrix and the particle coatings has been observed. Photos and photomicrographs of irradiated fuel rods are shown in Figs. 8 and 9.

SUMMARY

The hexagonal block fuel element with coated fuel particles is the concept planned for future large HTGR plants. This is essentially the same fuel element as used in the Fort St. Vrain HTGR. The fuel element is simple and promises to be economic to fabricate and reprocess. The sol-gel process may be an important step in the remotely operated fabrication lines for recycle fuel.

TRISO



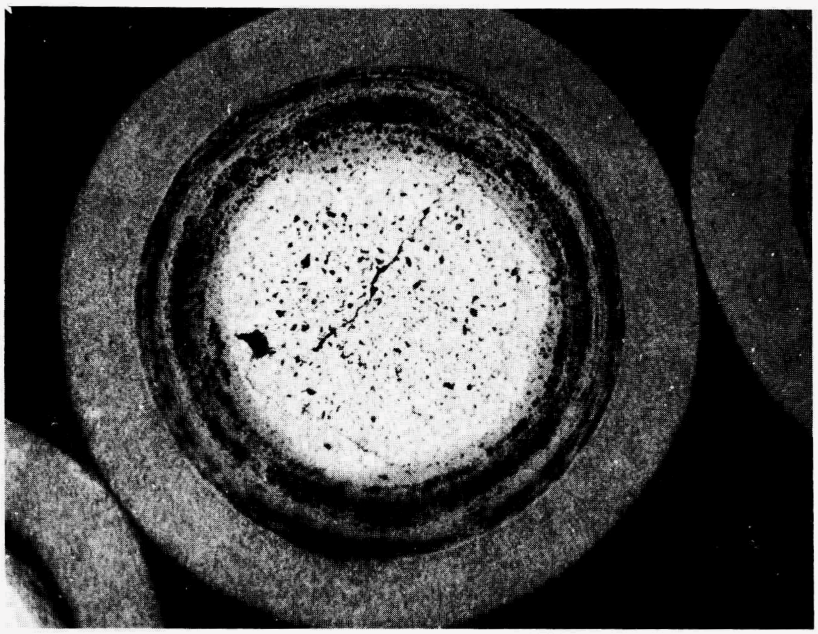
27% FIMA

1300°C (MAX)

8.7×10^{21} NVT

M251-94 (P20) 175X

BISO



22% FIMA

1300°C (MAX)

8.4×10^{21} NVT

M275-48 (P18) 200X

Fig. 7. Irradiated coated particles tested to greater than HTGR maximum exposures.

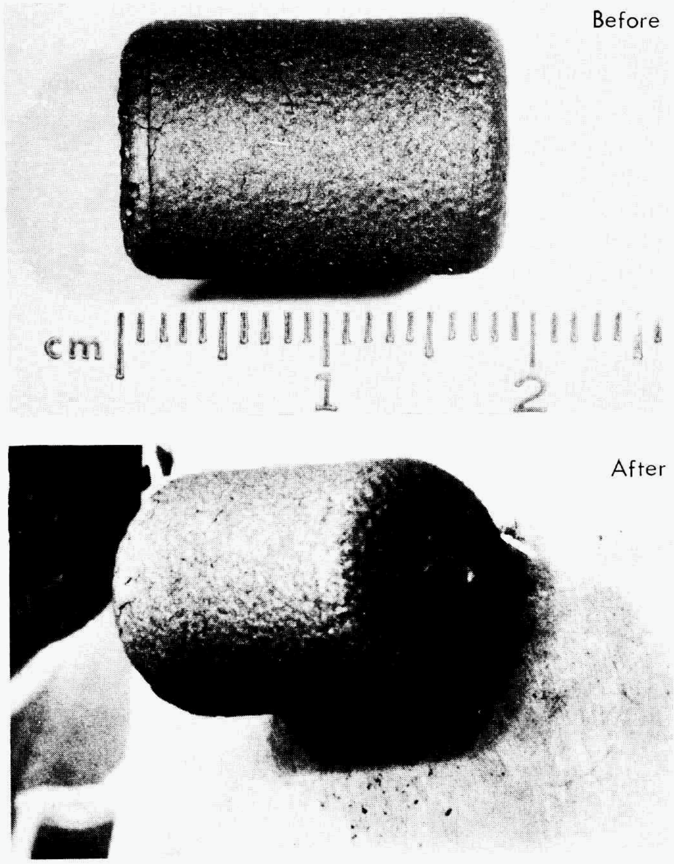


Fig. 8. Fuel rod before and after irradiation to 5.7 x 10^{21} n/cm^2 and 18% burnup at 1250°C. This fuel rod is 0.5-in. diameter by 0.75-in. long. The end of a severed thermocouple tube projects from the end of the irradiated rod.

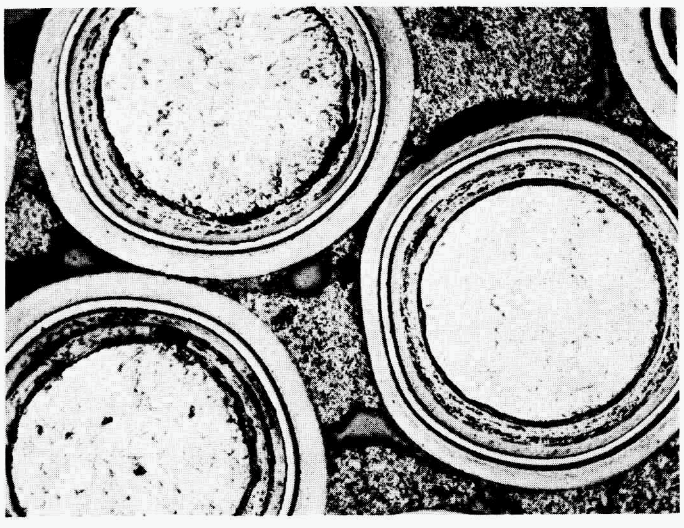


Fig. 9. No deleterious effects were noted in the coated particles in this fuel rod after irradiation to 5.7 x 10^{21} n/cm^2 and 18% FIMA burnup at 1250°C.

Table 3. Number of Coated Particle Samples Successfully Tested to Indicated Exposure

Fast Fluence (x 10^{21} n/cm^2)

	1	2	3	4	5	6	7	8
BISO samples*	31	18	31	16	13	9	2	9
TRISO samples*	21	21	19	22	3		5	5
								↑ FSV max

Burnup (% FIMA)

	≤2	4	6	8	10	12	14	16	18	20	>20
BISO	9	11	22	9	2	8	9	5	12	5	37
TRISO	11	2	8	7	8	19	9	6	8	1	17
										↑ FSV max	

Temperature (°C)

	500	600	700	800	900	1000	1100	1200	≥1300
BISO		1	3	3	9	11	1	14	90
TRISO	6	3	3		19	14	6	9	36
								↑ FSV max	

*In all cases, each sample consisted of 2000-3000 coated particles.

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APPENDIX C

ESTIMATED WASTES FROM THE FUEL RECYCLE PILOT PLANTS

Table C-1. Estimated Wastes from the Head-End Pilot Plant

Title	Composition	Quantity Generated (per day)
	High-Level Wastes	
Kr - Xe	Krypton Xenon	1.3 ft^3
Fissile particles	Graphite Silicon carbide Uranium Thorium Fission products	87 kg 15 liters 1900 W-day
	Low- and Intermediate-Level Wastes	
Barren graphite	Carbon	624 kg
Dust collector off-gas	Oxygen Nitrogen	500 ft^3
CO_2 removal off-gas	Carbon dioxide	21 ft^3
Tritiated water	Water	17 Ci
Dust collector off-gas	Oxygen Nitrogen	10 ft^3
Iodine to storage	Iodine	1.2 Ci 18 g (total)

Table C-2. Estimated Wastes from the Acid Thorex Pilot Plant

Title	Composition	Quantity Generated (per day)
	High-Level Wastes	
Raffinate I-AW	Uranium (trace) Thorium (trace) Fission products (2.5 kg/day) HNO_3 (1.5 M) Aluminum (0.18 M) Fluoride (0.02 M)	653 liters
Thorium-solution I-BT	Uranium (trace) Thorium (99.6 kg/day) Fission products (trace) Nitrate (1.29 M) Acid (0.3 M)	1720 liters
Filter cake	Uranium (trace) Thorium (trace) Fission products (trace) Silicon carbide hulls (25 kg/day) Alumina (92 kg/day)	117 kg
	Low- and Intermediate-Level Wastes	
Empty cans	Aluminum	14 kg
Condensate	Nitric acid (3.5 M)	1030 liters
Condensate	Nitric acid (0.086 M)	1070 liters
Na_2CO_3 to waste	Sodium carbonate/nitrate (1 M Na)	286 liters
HNO_3 to waste	Nitric acid (0.1 M)	2860 liters

Table C-3. Estimated Wastes from the Refabrication Pilot Plant[a]

Title	Composition	Quantity Generated (per day)
	Sol Formation	
Spent carbonate	Sodium carbonate/nitrate (2.6 M Na)	106 liters
	Microsphere Preparation	
Alcohol waste from IX column	2-ethyl-1-hexanol Ethyl alcohol Surfactants	1.7 liters
NH_4OH waste from IX column	Ammonium hydroxide (1.0 M)	4 liters
Wash water from IX column	Water	36 liters
Vaporizer waste stream	2-ethyl-1-hexanol Surfactants	72 liters
Waste water from still	Water (trace alcohol)	28 liters
Condensate	Water Alcohol (trace surfactants)	25 liters
	Microsphere Coating	
Coating furnace off-gas	Hydrogen, HCl	127 m^3
Used reaction cones from coating furnace	Graphite	10 kg
	Fuel Stick Fabrication	
Solvent with pitch and graphite flour		2.5 liters

[a]No high-level wastes are produced in the Refabrication Pilot Plant.

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