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HTGR FUEL RECYCLE DEVELOPMENT PROGRAM

**QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING AUGUST 31, 1978**

Prepared under
~~Contract EY-76-C-03-0167~~
Project Agreement No. 53
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: SEPTEMBER 1978

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GENERAL ATOMIC COMPANY

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ABSTRACT

This publication continues the quarterly series presenting results of work performed under the National HTGR Fuel Recycle Development Program at General Atomic Company. Results of work on this program prior to June 1974 were included in a quarterly series on the HTGR Base Program.

The work reported includes the development of unit processes and equipment for reprocessing of High-Temperature Gas-Cooled Reactor (HTGR) fuel, the design and development of an integrated pilot line to demonstrate the head end of HTGR reprocessing using unirradiated fuel materials, and design work in support of Hot Engineering Tests (HET). Work is also described on trade-off studies concerning the required design of facilities and equipment for the large-scale recycle of HTGR fuels in order to guide the development activities for HTGR fuel recycle.

INTRODUCTION

This report covers the work performed by General Atomic Company under Department of Energy Contract EY-76-C-03-0167, Project Agreement No. 53. The work done under this project agreement is part of the program for development of recycle technology for High-Temperature Gas-Cooled Reactor (HTGR) fuels described in the National Program Plan for HTGR Fuel Recycle Development (GCR-76/19).

The objective of the program is to provide the technology development necessary for the recycle of HTGR fuels. The design of an HTGR recycle reference facility including equipment design and operating procedures which are licensable and commercially feasible for the reprocessing and refabrication of spent fuel will be done. Work at General Atomic Company is concentrating on the following National Program tasks: Program Management (Task 000); Studies and Analyses (Task 100); Fuel Handling Task 200); Fuel Reprocessing (Task 300); Fuel Refabrication (Task 500); In-Plant Waste Treatment (Task 600); General Support (Task 800); Major Facilities (Task 900).

Task 000, Program Management. The functions of this task include overall planning, scheduling, budgeting, reporting, management control of the program, and coordination of activities.

Task 100, Studies and Analyses. The purpose of this task is to perform generic studies and analyses in support of the program's developmental tasks and Task 900 projects. The work will include analyses of reactor mass flow and fuel cycle flowsheets; environmental studies and analyses in support of the major facility projects; economic/cost-benefit studies in support of commercialization activities and guidelines to facility design

and developmental tasks; and system integration and design studies to establish equipment availability and maintainability requirements, surge storage, and system-interface design requirements.

Task 200, Fuel Handling. The purpose of this task is to develop the fuel handling and shipping technology that will be needed for the HTGR Recycle Reference Facility (HRRF).

Task 300, Fuel Reprocessing. The purpose of this task is to develop the reprocessing technology required for HRRF. The work will include the development of components and the definition of operating techniques and remote maintenance and/or disassembly techniques. Operations that must be developed include: (1) crushing of the fuel elements, (2) solids transport methods, (3) burning the graphite in a fluidized bed burner, (4) separation of the fertile and fissile particles, (5) crushing the silicon carbide coating on fissile particles, (6) burning the crushed particles, (7) dissolution of thorium, plutonium, and uranium in the burner ash, (8) separation of the undissolved solids (silicon carbide hulls, etc.) from the leachate, (9) separation of the thorium, uranium, and plutonium from the fission products and from each other by solvent extraction, (10) process and facility off-gas treatments to ensure that releases are environmentally acceptable and in compliance with regulations, and (11) the primary treatment of solid, liquid, and gaseous wastes from the process, including recycle of nitric acid and water. Task 300 will also develop the processes and equipment required for thorium storage and management.

Task 500, Fuel Refabrication. The purpose of this task is to develop the refabrication technology that will be needed for HRRF. The work will include the definition of flowsheets, the development of components, the definition of operating techniques, and remote maintenance and/or disassembly techniques. Operations that must be developed include: (1) preparation of uranyl nitrate solution for loading, (2) loading of the uranium onto weak-acid resin particles, (3) carbonization of the loaded resin particles, (4) conversion of these particles to adjust the oxygen

content, (5) application of the buffer, inner low-temperature isotropic, silicon carbide, and outer low-temperature isotropic coatings, (6) blending of the fissile particles with fertile and shim particles, (7) molding the blended particles into fuel rods with the pitch-graphite matrix. (8) loading the rods into fuel elements, (9) carbonizing and annealing the fuel rods in the element, (10) installing end plugs and dowels, and (11) cleaning and inspecting the completed element.

Task 600, In-Plant Waste Treatment. The work to be done by this task will ensure that all radioactive waste from HRRF can be suitably processed and packaged for safe shipment and permanent storage. Where the anticipated HRRF wastes are not suitable for processing by the other waste processes, Task 600 will conduct the necessary research and development to either establish complete treatment or render these wastes suitable for processing by the developed techniques of the other programs.

Task 800, General Support. This task includes the development work required for general plant support functions. This work covers safeguard applications, maintenance systems, and in-plant waste treatment.

Task 900, Major Facilities. The purpose of this task is to design, construct, proof-test, and operate hot engineering and cold prototype test facilities that culminate in the detailed design of an HRRF. These facilities include the Hot Engineering Test Facility (HETF). Hot Engineering Test Waste Facility (HETWF), Cold Prototype Test Facility-Reprocessing (CPTF-Repro), Cold Prototype Test Facility-Refabrication, and Cold Prototype Test Facility-Fuel Handling (CPTF-Fuel Handling). The preconceptual design and early conceptual design of HRRF will guide the development work for reprocessing, refabrication, and waste treatment processes, equipment, and instrumentation for process control of recycle operations.

CONTENTS

ABSTRACT	iii
INTRODUCTION	v
1. SUMMARY	1-1
2. STUDIES AND ANALYSES (TASK 100)	2-1
2.1. Summary	2-1
2.2. Engineering Analysis (Subtask 110)	2-3
2.2.1. Introduction	2-3
2.2.2. Activity	2-3
References	2-16
2.3. Economic/Cost-Benefit Studies (Subtask 130)	2-18
2.3.1. Introduction	2-18
2.3.2. Activity	2-18
2.4. Systems Integration and Design Studies (Subtask 140)	2-20
2.4.1. Introduction	2-20
2.4.2. Activity	2-20
3. FUEL REPROCESSING (TASK 300)	3-1
3.1. Fuel Element Size Reduction (Secondary Subtask 311)	3-1
3.1.1. Summary	3-1
3.1.2. UNIFRAME Wear Analysis	3-2
3.1.3. UNIFRAME Upgrading	3-10
3.2. Crushed Fuel Element Burning (Secondary Subtask 312)	3-21
3.2.1. Summary	3-21
3.2.2. 0.20-m Primary Burner	3-21
3.2.3. 0.40-m Primary Burner	3-43
3.2.4. Primary Burner Automation	3-47
3.2.5. Training Program for Operators	3-52
3.3. Particle Classification, Crushing, and Crushed Particle Burning (Secondary Subtask 313)	3-53

3.3.1.	Summary	3-53
3.3.2.	Fuel Particle Air Classifier	3-53
3.3.3.	Fuel Particle Crusher	3-53
3.3.4.	Secondary Burners	3-54
References		3-58
3.4.	Dry Solids Handling (Secondary Subtask 314)	3-59
3.4.1.	Summary	3-59
3.4.2.	Conveying Line Geometry Test Rig	3-59
3.4.3.	Heat Transfer Test Rig	3-80
References		3-96
3.5.	Dissolution Systems (Subtask 330)	3-97
3.5.1.	Summary	3-97
3.5.2.	Dissolution Studies	3-98
References		3-111
3.6.	Off-Gas Treatment and Retention Processes (Subtask 340)	3-112
3.6.1.	Summary	3-112
3.6.2.	Auxiliary System Design	3-113
3.6.3.	Fabrication and Installation	3-113
3.6.4.	Schedule and Milestones	3-121
3.7.	Separation Processes (Subtask 350)	3-121
3.8.	Rework and Recycle (Subtask 360)	3-133
3.8.1.	Summary	3-133
3.8.2.	HNO ₃ - HF Corrosion Study	3-133
4.	FUEL REFABRICATION (SECONDARY SUBTASK 541)	4-1
4.1.	Summary	4-1
4.2.	Scrap Recovery	4-1
5.	GENERAL SUPPORT (TASK 500)	5-1
6.	MAJOR FACILITIES	6-1
6.1.	Hot Engineering Test Facility	6-1
6.2.	HTGR Recycle Reference Facility (HRRF)	6-2
6.2.1.	Summary	6-2
6.2.2.	Introduction	6-3
6.2.3.	Activity	6-4
APPENDIX A:	TOPICAL REPORTS PUBLISHED DURING THE QUARTER	A-1
APPENDIX B:	DISTRIBUTION LIST	B-1

FIGURES

2.2-1.	HEU segment 10 (23R) neutron multiplication factor as a function of internal water density (monolith)	2-4
2.2-2.	HEU equilibrium (M) neutron multiplication factor as a function of internal water density (monolith)	2-5
2.2-3.	HEU segment 10 (23R) multiplication safety factor as a function of internal water density (monolith)	2-7
2.2-4.	HEU equilibrium (M) multiplication safety factor as a function of internal water density (monolith)	2-8
2.2-5.	Reliability, maintainability, availability growth related to HRRF design and construction	2-17
3.1-1.	Damage caused by tramp metal in secondary crusher	3-3
3.1-2.	Impressions of fuel particles in tertiary roll crusher faces	3-5
3.1-3.	Pitman sleeve installation	3-8
3.1-4.	Graphite bearing installation including sleeve modifications	3-11
3.1-5.	Thermocouple installation for graphite bearing tests	3-12
3.1-6.	Moist gas distribution setup for graphite bearing	3-14
3.1-7.	Graphite bearing test results - no lubricant	3-15
3.1-8.	Graphite bearing test results - water lubricant	3-16
3.1-9.	Graphite bearing test results - saturated	3-17
3.1-10.	Graphite plateout from graphite bearing	3-19
3.1-11.	Oil lubrication pumps	3-20
3.2-1.	Mid-bed temperature	3-23
3.2-2.	Above-bed temperature and O ₂ concentration	3-24
3.2-3.	Bed differential pressure	3-25
3.2-4.	Cyclone pressure	3-26
3.2-5.	Filter pressure	3-27
3.2-6.	Overall view of 0.40-m primary burner - reconstructed to gravity fines recycle mode	3-46
3.2-7.	View of upper 0.40-m primary burner tube and fines recycle bunker	3-46
3.2-8.	Top deck of 0.40-m primary burner with fresh feed bunker and filter chamber	3-46
3.3-1.	Feed and product size distributions from 0.10-m secondary burner test with FSV TRISO ThO ₂ fertile particles	3-57

FIGURES (Continued)

3.4-1.	Conveying line geometry test rig	3-60
3.4-2.	Size distribution of crushed graphite after successive transport operations - test 2	3-62
3.4-3.	Predicted versus measured ΔP as a function of blower power - test 2	3-65
3.4-4.	Predicted versus measured ΔP as a function of acceleration length - test 2	3-66
3.4-5.	Predicted versus measured ΔP as a function of bend radius	3-67
3.4-6.	Predicted versus measured ΔP as a function of blower power - test 3	3-70
3.4-7.	Predicted versus measured ΔP as a function of acceleration length - test 3	3-71
3.4-8.	Predicted versus measured ΔP as a function of bend radius - test 3	3-72
3.4-9.	Predicted versus measured ΔP as a function of acceleration length - test 4	3-74
3.4-10.	Predicted versus measured ΔP as a function of bend radius - test 4	3-75
3.4-11.	Predicted versus measured ΔP as a function of acceleration length - test 5	3-78
3.4-12.	Predicted versus measured ΔP as a function of bend radius - test 5	3-79
3.4-13.	Predicted versus measured ΔP as a function of blower power - test 6	3-82
3.4-14.	Predicted versus measured ΔP as a function of acceleration length - test 6	3-83
3.4-15.	Predicted versus measured ΔP as a function of bend radius - test 6	3-84
3.4-16.	Heat transfer furnace	3-85
3.4-17.	Experimentally determined thermal conductivity of crushed graphite in CO_2 gas	3-87
3.4-18.	Experimentally determined thermal conductivity of HTGR BISO particles in CO_2 gas	3-88
3.4-19.	Experimentally determined thermal conductivity of HTGR WAR TRISO particles in CO_2 gas	3-89
3.4-20.	Experimentally determined thermal conductivity of secondary burner ash in CO_2 gas	3-90

FIGURES (Continued)

3.4-21.	Experimentally determined thermal conductivity of crushed graphite in He gas	3-91
3.4-22.	Experimentally determined thermal conductivity of HTGR BISO particles in He gas	3-92
3.4-23.	Experimentally determined thermal conductivity of HTGR WAR TRISO particles in He gas	3-93
3.4-24.	Experimentally determined thermal conductivity of secondary burner ash in He gas	3-94
3.5-1.	0.13-m dissolver system	3-99
3.5-2.	Iodine volatility during ThO ₂ dissolution	3-102
3.5-3.	0.20-m dissolver system	3-105
3.5-4.	0.20-m secondary burner size distribution of product from sequential operations run	3-107
3.5-5.	Uranium dissolution rate curves for runs 187 and 188 . .	3-108
3.5-6.	Bench-scale dissolution of WAR fissile ash	3-109
3.5-7.	WAR fissile dissolver feed and residue	3-110
3.6-1.	Vessel PbX iodine adsorber	3-115
3.6-2.	Iodine vapor generator off-gas treatment system	3-117
3.6-3.	Condenser/demister off-gas treatment system	3-119
3.6-4.	Single line piping diagram for off-gas	3-123
3.6-5.	Off-gas system vessels	3-125
3.6-6.	Installation of adsorbers and auxiliaries	3-126
3.6-7.	CO/HT oxidizer system	3-127
3.6-8.	Partially completed control room	3-129
3.6-9.	Off-gas design and installation schedule	3-131
3.8-1.	Corrosion test apparatus	3-135
3.8-2.	Corrosion rate in 13.5 <u>M</u> HNO ₃ (liquid)	3-146
3.8-3.	Corrosion rate in 13.5 <u>M</u> HNO ₃ (equilibrium vapor)	3-147
3.8-4.	Nitronic 50 corrosion rate in 13.5 <u>M</u> HNO ₃ during main exposure period	3-148
3.8-5.	316L SS corrosion rate in 13.5 <u>M</u> HNO ₃ during main exposure period	3-149
3.8-6.	Hastelloy C-4 corrosion rate in 13.5 <u>M</u> HNO ₃ during main exposure period	3-150

FIGURES (Continued)

4.2-1.	Perchloroethylene bottoms combustion laboratory-scale test apparatus	4-2
4.2-2.	Standard calibration data plot for perchloroethylene - GC	4-5
4.2-3.	Chromatogram of Texaco NPH 5 μ l sample injection	4-7
4.2-4.	Chromatogram of Texaco NPH perchloroethylene 5 μ l injection	4-8
4.2-5.	Typical temperature excursion profile during perchloroethylene burning tests	4-11
6.2-1.	HTGR/MEU fuel recycle base case reprocessing flowsheet .	6-5
6.2-2.	Functional areas	6-29
6.2-3.	Reprocessing functional facility layout concept	6-30
6.2-4.	Head-end process cells	6-31
6.2-5.	Head-end process flow diagram	6-32
6.2-6.	Head-end facility longitudinal section	6-36
6.2-7.	HRRF heat-end facility general arrangement	6-38
6.2-8.	HRRF functional diagram showing spent and recycle fuel receipt, storage, handling, and shipping	6-41
6.2-9.	Plan of receiving, storage, and shipping facility arrangement - plug well concept	6-45
6.2-10.	Sectional elevation - plug well storage concept	6-46
6.2-11.	Plan of receiving, storage, and shipping facility arrangement - portable well concept	6-47
6.2-12.	Sectional elevation - portable well concept	6-48
6.2-13.	Monolith storage well concept	6-49
6.2-14.	Spent and recycle fuel rail shipping cask (SR-72)	6-53
6.2-15.	Cask fin efficiency	6-55
6.2-16.	Cask fin temperature profile	6-56

TABLES

2.2-1.	Decay heats for MEU equilibrium fuel elements	2-9
2.2-2.	Unscheduled down time distribution	2-13
2.2-3.	Operating cycle assumptions	2-14
2.2-4.	Illustrative availability calculations	2-15

TABLES (Continued)

6.2-6.	Material balance for off-gas system - krypton absorption in liquid CO ₂ (KALC)	6-16
6.2-7.	Material balance for off-gas system - carbon-14 fixation with lime off-gas processing (PF-660-1)	6-17
6.2-8.	Material balance for thorex solvent extraction PF-320-1	6-19
6.2-9.	Material balance for thorex solvent extraction PF-320-2	6-21
6.2-10.	Material balance for thorex solvent extraction PF-320-3	6-22
6.2-11.	Material balance for thorex solvent extraction PF-320-4	6-23
6.2-12.	Material balance for thorex solvent extraction	6-24
6.2-13.	Material balance for thorex solvent extraction PF-350-1	6-25
6.2-14.	Material balance for thorex solvent extraction PF-350-2	6-26
6.2-15.	HRRF remote maintenance requirements	6-28
6.2-16.	General requirements/assumptions for HRRF spent and refabricated fuel storage and handling	6-44
6.2-17.	Summary of results, average spent MEU recycle fuel blocks	6-54

TABLES (Continued)

3.2-1.	48-hour run 1 data	3-35
3.2-2.	48-hour run 2 data	3-36
3.2-3.	Heat gain by cooling air in fines pipe	3-40
3.2-4.	Heat loss by process stream in fines pipe	3-41
3.2-5.	Heat gain by cooling air in cyclone	3-42
3.3-1.	FSV TRISO ThO ₂ fertile particles - size distribution after crushing; used as feed for 0.10-m secondary burner test	3-55
3.3-2.	FSV TRISO ThO ₂ fertile particles - size distribution after 0.10-m secondary burner test	3-56
3.4-1.	Data from test 2 - crushed graphite	3-63
3.4-2.	Data from test 3 - crushed graphite and TRISO kernels . .	3-69
3.4-3.	Data from test 4 - LHTGR BISO fertile particles	3-73
3.4-4.	Data from test 5 - PSC TRISO fissile particles	3-77
3.4-5.	Data from test 6 - crushed graphite and LHTGR TRISO fissile particles	3-81
3.5-1.	Operating conditions for iodine and ruthenium volatility tests	3-100
3.5-2.	Operating parameters for WAR fissile ash dissolution . .	3-104
3.8-1.	Corrosion coupon alloys	3-134
3.8-2.	Corrosion coupon weight loss data	3-137
3.8-3.	Visual inspection of corrosion coupons after 192 hours exposure	3-143
4.2-1.	Gas chromatographic operational parameters	4-4
4.2-2.	Perchloroethylene combustion tests, sweep gas - 0.5 CFH air	4-9
6.2-1.	Material balance for head-end fuel element crush - primary burn - classify (PF-250-1)	6-7
6.2-2.	Material balance for head-end fertile fraction leaching (PF-250-2)	6-9
6.2-3.	Material balance for head-end fissile particle crush- secondary burn-leach (PF-250-3)	6-11
6.2-4.	Material balance for off-gas system - burner off-gas processing (PF-650-11)	6-13
6.2-5.	Material balance for off-gas system - dissolver off-gas processing (PF-650-12)	6-15

1. SUMMARY

Generic engineering studies and analyses are being performed to support the HTGR Fuel Recycle Development Program's developmental tasks. A reprocessing criticality study is being performed to determine physical constraints on spent fuel storage and head-end process equipment. The spent fuel storage analysis has been completed verifying design adequacy for the most reactive fuel element, even when surrounded by water. Analyses are continuing on head-end process equipment. Spent fuel definitions were completed for the reference MEU fuel cycle during the last reporting period, and decay heats have now been calculated for equilibrium spent fuel elements.

Technical assessments were completed for 12 development plan scenarios being evaluated in the National Program Plan Trade-Off and Optimization Study. The next phase of this activity is the value engineering analysis to determine the most cost-effective options.

Statistical calculations based on previous failure mode and effects analyses were completed to determine annual down time and operational availability for individual head-end systems.

The computer cost data base for a commercial-size HTGR recycle plant has been updated for high-gain HEU fuel, and it is now available for developing cost estimates for alternative recycle plant designs.

Little measurable wear has been detected after crushing approximately 6700 kg (14,800 lb) of material in the UNIFRAME. The principal wear, which took place in the oil-lubricated pillow block bearings of both the primary and secondary crushers, resulted from inadequate lubrication at startup. Forced circulation oil pumps have been installed to alleviate this problem.

Macroscopic indentations that have the appearance of being created by silicon-carbide-coated fuel particles were found in both rolls of the tertiary crusher. Fuel particles could be exposed for individual contact with the steel roll faces during UNIFRAME crushing and, given adequate support, could indent the roll surfaces to the extent observed without being crushed. Calculations that compared the observed size of the indents with predicted embedment in the steel indicate that this is probably the case.

Overheating of the pitman bearings of the primary crusher was caused by lack of lubrication due to the improper assembly of the bearing assemblies into the pitman casting. This caused the mislocation of the lubrication oil holes, grooves, and supply galleries resulting in both bearings running with grossly inadequate lubrication. One bronze bushing was damaged and has been replaced, and the other returned to service. Shaft discoloration and scoring were removed by polishing. The bearing assemblies were correctly reassembled into the pitman casting.

A second 48-hour burner run was completed on the 0.20-m primary burner using TRISO fuel particles mixed with crushed graphite. The average burn rate was over 200 g/min. Product removed during the run contained 0.08 wt % carbon, while the final product had 0.25 wt % carbon. This test completes verification testing of gravity fines recycle.

An 11-hour 0.20-m primary burner run was made to test the fines recycle rotary valve operability at 600° to 650°C. Burner operation was simplified by recycling fines near their combustion temperature.

Thirty-five kilograms of Si-BISO type fuel was burned in the 0.20-m primary burner to test the feasibility of reprocessing this type of fuel. Silica material was noted in the fines stream and on some of the TRISO-WAR particles; however, no problems were encountered in the process.

The 0.40-m primary burner modifications were completed on schedule. The work included design, procurement, fabrication, and installation of many items. A graphite heatup test was performed on the reconstructed 0.40-m primary burner. Operation was troublefree and preparations were made for the initial burning test.

Arrangements are underway for testing an electrostatic classifier for the separation of fuel particles during the next fiscal year.

Fort St. Vrain type TRISO ThO_2 fuel particles were crushed and subsequently burned in the 0.10-m secondary burner. Both the crushing and burning processes were successful on this advanced fuel particle type.

A shakedown test using a ZrO_2 granule bed was completed on the 0.20-m secondary burner.

A series of 300 tests in the conveying line geometry test rig have indicated that the conveying line configuration need not be a major design factor in the design of the HTGR Recycle Reference Facility (HRRF).

Data from the heat transfer test rig have shown that actual thermal conductivities of materials encountered in the dry head-end systems are greater by a factor of two to five than those predicted by empirical methods.

The volatility of iodine and ruthenium was examined during the dissolution of ThO_2 kernels in Thorex solution. The pilot plant 0.13-m (5-in.) dissolver system was used for these tests.

Dissolution tests using nitrogen as a sparge gas had less than 10% iodine volatility after 6 hours of dissolution. However, iodine was readily volatilized when nitric oxide (NO) was substituted as the sparge gas. Greater than 98% of the iodine in solution volatilized in 6 hours due to the reduction of the iodate ion by nitric oxide. The pilot plant tests confirm the bench-scale results for iodine and ruthenium volatility during ThO_2 dissolution.

A study has been conducted to assess the behavior of reference weak acid resin (WAR) fissile secondary burner ash during dissolution in dilute nitric acid. As observed in the bench-scale study, the pilot plant operation in the 0.20-m dissolver encountered no foaming and the dissolution rate of uranium was found to be very rapid (98% uranium dissolution in 1-1/2 hours) in boiling 2 moles of nitric acid. The HRRF flowsheet product specification was readily met.

A fissile dissolver operating cycle was proposed for the WAR-derived material. It is recommended that the dissolver should operate below the boiling point in the first part of the cycle to limit the peak off-gas NO_x concentration evolved from the dissolution reaction. A very high NO_x concentration could affect the off-gas NO_x converter operation.

The remodeling of the platform for the off-gas system installation and the expansion of the control room have been completed on schedule. All frameworks for the vessel and auxiliary installation are in place. The completion of system installation has been deferred to FY-79, and only system piping work is continuing at a reduced pace.

All major vessels fabricated have been installed and piping inter-connecting the vessels and other system components such as heaters, heat-exchangers, rotameters, and control valves is being added. Utility piping has been completed to the point where it can be connected to the off-gas system.

A thermal stress analysis has been performed on the off-gas system piping. Metal bellows joints have been added to relieve excessive thermal expansion.

The Diogenes digital process control system and the Hewlett-Packard data acquisition system have been installed. However, all other electrical work has been halted due to a budget reduction.

Shakedown tests for fuel refabrication scrap recovery continued on the combustion of perchloroethylene distillation bottoms. To date mass spectrographic and gas chromatographic analyses indicate combustion is complete at 650°C with a 30% ethanol and 70% perchloroethylene solution.

Since February 27, 1978, all eight FSV test elements were located at the FSV reactor, awaiting insertion with the first refueling operation. ORNL fuel rods are contained in FTE-2, FTE-4, and FTE-6. Relatively high fission gas release data were obtained for these rods after cure-in-place firing; this is believed to be an artifact of obtaining TRIGA rods from an already oversized fuel rod fired in an undersized quality control crucible for subsequent loading into the test elements. All pre- and post-firing metrology data obtained during manufacturing are presently being evaluated for establishing a gap-strain correlation for the as-built FTE fuel rods. Additional firing tests are being carried out to establish the in-situ conditions of ORNL fuel rods, fired in standard size graphite holes as used in the fuel test elements.

PSC submitted Amendment 2 of the test element safety analysis report to NRC. This amendment describes the tentative PIE program under DOE sponsorship. This was the only requirement made by NRC for the approval of the insertion of the test elements into the FSV reactor.

On July 19, 1978, Amendment 3 of the test element SAR was issued. This amendment contains the as-built analysis of the FTE operation under stretch conditions.

Flowsheets and material balances for HRRF reprocessing of spent MEU and recycle fuels were completed. An engineering study subcontract on the GA-proposed remote maintenance concept for the HRRF reprocessing head-end facility was completed by Norman Engineering Company. Their scope of work included: (1) definition of functional requirements and description of major remote maintenance equipment and facilities, (2) identification of governing transfer items for sizing primary transfer equipment

and penetrations, (3) a pictorial presentation of the handling and transfer sequence for remote replacement of a typical head-end equipment item, and (4) supporting drawings such as proposed maintenance facilities and head-end process equipment layouts.

Forced-circulation water cooling concepts were tentatively selected for application to the spent fuel storage area. Natural convection air cooling is acceptable for the refabricated fuel storage area. Preconceptual design layout options for the HRRF tie-in fuel storage area were prepared, along with supporting documentation including: (1) design assumptions, (2) functional flow diagrams, (3) operating requirements by functional area, and (4) a preliminary equipment list for the fuel storage facility. Further evaluation of the storage concept options is required to determine suitability from structural, seismic, and construction standpoints.

Higher fast neutron activity associated with spent MEU fuel relative to HEU fuel was found to require the addition of 6.35 cm (2.5 in.) of neutron shielding to the HEU reference rail-transport spent fuel cask exterior. A preliminary thermal analysis was performed to determine the impact of the neutron shield on the cask thermal characteristics and to establish specific configuration requirements. A copper clad fin was found to provide maximum heat transfer capability while requiring the smallest increase in the cask envelope.

Process flowsheets covering the treatment of reprocessing wastes were completed and distributed for review and comment. A preliminary sampling plan for the HRRF dry head-end, wet head-end, and solvent extraction systems was drafted.

2. STUDIES AND ANALYSES (TASK 100)

2.1. SUMMARY

Generic studies and analyses are being performed to support the HTGR Fuel Recycle Development Program's developmental tasks and Task 900 projects. A reprocessing criticality study is being performed to determine physical constraints on spent fuel storage and head-end process equipment. The spent fuel storage analysis has been completed verifying design adequacy for the most reactive fuel element, even when surrounded by water. Analyses are continuing on head-end process equipment. Spent fuel definitions were completed for the reference MEU fuel cycle during the last reporting period, and decay heats have now been calculated for equilibrium spent fuel elements.

Technical assessments were completed for 12 development plan scenarios being evaluated in the National Program Plan Trade-Off and Optimization Study. The next phase of this activity is the value engineering analysis to determine the most cost-effective options.

Statistical calculations based on previous failure mode and effects analyses were completed to determine annual down time and operational availability for individual head-end systems.

The computer cost data base for a commercial-size HTGR recycle plant has been updated for HEU fuel, and it is now available for developing cost estimates for alternative recycle plant designs.

Simulation code development has been delayed due to personnel turnover and priority assignments resulting from budget reductions.

Proliferation resistance assessments for assigned NASAP fuel cycle cases were completed. Technical support was provided to ORNL in preparing a report on fuel cycle facilities for water reactors, and upgrading a similar report for HTGR fuel cycle cases for input to the International Nuclear Fuel Cycle Evaluation (INFCE) Working Group.

2.2. ENGINEERING ANALYSIS (SUBTASK 110)

2.2.1. Introduction

The objective of this subtask is to perform generic engineering analyses to support developmental tasks and the projects. Results of studies on criticality, spent fuel definition, spent fuel management strategy, and availability allocations are reported in the following sections.

2.2.2. Activity

2.2.2.1. Criticality. The fuel receiving and storage area analysis has been completed. Both as-charged and spent fuel from the LHTGR HEU, LHTGR MEU, and FSV HEU fuel cycles were considered. The 23R element from segment 10 and the equilibrium M element, both from the LHTGR HEU fuel cycle, were found to be the most reactive.

Three fuel storage concepts were included in the analysis: the plug well storage concept, the portable well/rack concept, and the monolith storage well concept. These three concepts are discussed in Section 6.2.3.4. The monolith storage well concept is the most reactive. Figures 2.2-1 and 2.2-2 show the neutron multiplication factor k of the two most reactive elements in monolith storage. It was assumed that the monolith was constructed with ordinary concrete, and that the shipping containers and storage wells were fabricated with type 304 stainless steel and had a combined thickness of 8 mm. Each well was infinitely deep and filled with fuel elements, the wells were arranged with a square pitch, and the storage wells extended to infinity in all lateral directions. To account for the possibility of water filling the fuel element coolant holes (either partially or fully), the monolith was evaluated (1) with the coolant holes dry (i.e., the normal storage condition), (2) completely filled with water at $1/3$ and $2/3$ its normal density (i.e., steam from partial flooding), and (3) full density water (i.e., total flooding).

2-4

Fig. 2.2-1. HEU segment 10 (23R) neutron multiplication factor as a function of internal water density (monolith)

Fig. 2.2-2. HEU equilibrium (M) neutron multiplication factor as a function of internal water density (monolith)

Figures 2.2-3 and 2.2-4 illustrate the multiplication safety factors, $k + 2\sigma - \Delta k$ (Ref. 2.2-1), as functions of the water density in the coolant holes (p) for the most reactive 23R and M fuel elements, respectively. Notice that an adequate margin of safety is present in both situations since the multiplication safety factor is less than 0.97.

The UNIFRAME analysis is approximately 50% complete. Adequate safety margins have been shown to exist under the following conditions:

1. Normal Operations. The UNIFRAME contains one fuel element plus some accumulated (holdup) material. The fissile inventory in the holdup material was conservatively assumed to be 1% of that in a fuel element.
2. Flooding. The UNIFRAME contains one fuel element, the holdup material, and is subjected to all degrees of water moderation.
3. Overbatching. Crushed fuel occupies the entire process flow path of the UNIFRAME (i.e., the primary and secondary crushing cavities, the free volume of the tertiary crusher bounded by a vertical plane passing through each roll crusher axis, and the surfaces of the rolls interior to these planes, the screener, the screener discharge, and the oversize crusher).

2.2.2.2. Fuel Element Definitions. Decay heats were calculated for MEU equilibrium fuel elements at 0.5, 1, 3, and 5 years after discharge. The results are summarized in Table 2.2-1.

2.2.2.3. NPP Trade-off and Optimization Study

2.2.2.3.1. Introduction

During this quarter, the work on this study included the description of the technical issues important to the design, licensing, and operation of the HRRF and the technical assessment of 12 development plan scenarios

Fig. 2.2-3. HEU segment 10 (23R) multiplication safety factor as a function of internal water density (monolith)

2-8

Fig. 2.2-4. HEU equilibrium (M) multiplication safety factor as a function of internal water density (monolith)

TABLE 2.2-1
DECAY HEATS FOR MEU EQUILIBRIUM FUEL ELEMENTS

Decay Time (Years)	Watts/MS Fuel Element			Watts/23 RS Fuel Element		
	Fertile Particles	Fissile Particles	Graphite Block	Fertile Particles	Fissile Particles	Graphite Block
0.5	7.07×10^1	2.05×10^2	1.40×10^{-3}	3.64×10^1	4.88×10^1	1.40×10^{-3}
1	3.07×10^1	1.23×10^2	1.17×10^{-3}	1.58×10^1	2.90×10^1	1.17×10^{-3}
3	9.65	4.37×10^1	9.88×10^{-4}	4.97	1.23×10^1	9.88×10^{-4}
5	5.98	2.62×10^1	8.84×10^{-4}	3.08	8.37	8.84×10^{-4}

proposed as a basis for altering the existing National Program Plan (NPP). This work is part of the methodology described in Ref. 2.2-1. In addition, work started on an estimate of the cost of each development plan and on a discounted-cash-flow assessment of risks with HRRF startup delay and throughput reduction. The next activity is a value analysis of 11 of the 12 development plan scenarios.

2.2.2.3.2. Activity

Twelve development plan scenarios were selected and described in consultation with ORNL as a basis for altering the existing National Program Plan. These scenarios are as follows:

1. Design of the HRRF with detailed design, construction, and cold test of equipment prior to installation in the HRRF.
2. Design and construction of the HRRF with an extensive cold test period during which time the equipment would be modified as required (developed in place).
3. Design and construction of a remote-maintenance test facility, and an expanded cold-engineering development and component test program.
4. Reduced scope of present refabrication cold-prototype facility.
5. Design and construction of the HRRF, preceded by an expanded cold-prototype program and a much reduced cold-engineering and component test program.
6. Hot-engineering tests limited to reprocessing.
7. Hot-engineering tests limited to refabrication.

8. Hot-engineering tests limited to dry head-end reprocessing and refabrication.
9. Hot-engineering tests limited to head-end reprocessing, including off-gas development.
10. An expanded hot-laboratory test program and the Federal Republic of Germany (FRG) Jupiter program.
11. An expanded hot-laboratory test program, the FRG-Jupiter program, and a particle preparation/coating-HET jointly sponsored by other fuel cycle programs.
12. Sequential (nonintegrated) HET test program conducted solely in TURF.

Next, the technical issues in fuel reprocessing, fuel refabrication, off-gas treatment, and primary waste treatment that must be resolved before licensing the HRRF were identified after consultation with ORNL. Approximately 250 issues were so identified. They were later classified according to their potential importance to HRRF licensing.

Each of the 12 development plan scenarios was then evaluated to find out which of the technical issues important to HRRF licensing could be addressed elsewhere in the overall development program as a result of the elimination of part or all of a development phase in the existing NPP. It was determined that only one of the 12 scenarios failed to provide for resolution of all licensing issues.

This scenario would eliminate all fuel reprocessing work from hot-engineering development. It was considered infeasible, primarily because it would fail to verify irradiated-fuel particle behavior (breakage; agglomeration; fission product release, deposition, and removal; and decay heat removal) on a large enough scale to satisfy postulated HRRF

licensing requirements. This scenario was eliminated from further consideration because it failed to meet one of seven assessment criteria agreed upon with ORNL; namely,

An alternative scenario shall be rejected for further consideration if it fails to provide for resolution of any one or more Category I (licensing) issues.

The next step in the methodology is to reduce the number of scenarios by the application of the principles of value analysis. This work was started with the development of a method for estimating the cost of each development plan scenario from the cost of the existing National Program Plan. ORNL was requested to provide some costs for the existing National Program Plan.

In conjunction with estimating alternative development plan costs, GA initiated a sensitivity analysis. This analysis will show the effects on HRRF profitability of postulated delays in plant startup (hot operation), reduction of plant throughput, changes in escalation, and equity/debt ratios.

2.2.2.4. Availability Allocations. Statistical calculations based on previous failure-mode-and-effects analyses (Refs. 2.2-2, 2.2-3) were completed. The resulting downtimes by system per year are shown in Table 2.2-2.

The down time associated with the crushing system (due to screener blinding) was excessive and has been adjusted for availability calculations under the assumption that a design solution will be found for screener blinding. A preliminary planned operating cycle has been calculated for the head end and is shown in Table 2.2-3. Two sets of availability calculations have been developed, one based on total time period (1 year), and one based on the operating cycle shown in Table 2.2-3. The resulting system availabilities are shown in Table 2.2-4. Method of calculation

TABLE 2.2-2
UNSCHEDULED DOWN TIME DISTRIBUTION

System	Fractional Downtime Distribution Parameters (Down Time Hours Per Year)	
	Mean $E(\lambda\tau)$	Std. Dev. $SD(\lambda\tau)$
Fuel element size reduction	<u>3890</u>	3520
Adjusted fuel element size reduction ^(a)	480	--
Fuel element burning	276	220
Particle classification	10	16
Particle crushing and burning	143	93
Dissolution and liquid-solids separation	370	88
Solids handling	<u>55</u>	62
Adjusted head-end total	1334	

(a) Assumes that solution is found for screener blinding.

TABLE 2.2-3
OPERATING CYCLE ASSUMPTIONS
(Planned Operating Time in Hours Per Year)

Total hours per calendar year	8760
Scheduled plant down time (biannual accountability)	720
Planned plant operating time	8040
FUEL ELEMENT SIZE REDUCTION	8040
Customer accountability cleanout ^(a)	912
Scheduled maintenance ^(b)	292
Quality control release time	TBD
Planned operating time	<6836
FUEL ELEMENT BURNING SYSTEM	8040
Customer accountability cleanout	912
Scheduled maintenance	200
Quality control release time	TBD
Planned operating time	<6928
PARTICLE CLASSIFICATION SYSTEM	8040
Customer accountability cleanout	912
Scheduled maintenance	94
Quality control release time	TBD
Planned operating time	<7034
PARTICLE CRUSHING AND BURNING	8040
Customer accountability cleanout	912
Scheduled maintenance	154
Quality control release time	TBD
Planned operating time	<6974
DISSOLVER AND LIQUID SOLIDS SEPARATION SYSTEM	8040
Customer accountability cleanout	912
Scheduled maintenance	66
Quality control release time	TBD
Planned operating time	<7062

(a) Assumes 20,000 fuel elements per year, 19 customers equally divided between 878 MW(e) and 1330 MW(e) plants, two types of fuel per segment, or 38 cleanouts per year.

(b) From Ref. 2.2-2 and other unpublished data.

TABLE 2.2-4
ILLUSTRATIVE AVAILABILITY CALCULATIONS

	Fuel Element Crushing	Fuel Element Burning	Particle Classification	Particle Crushing and Burning	Dissolution and Liquid- Solids Separation
Period hours (total hours/year)	8760	8760	8760	8760	8760
Operating cycle (Planned operating time; period hours - scheduled down time)	6836	6928	7034	6974	7062
Unscheduled down time	491	287	21	154	381
Available hours (operating cycle - unscheduled down time; total hours - scheduled and unscheduled down time)	6345	6641	7013	6820	6681
Operational availability (available hours/period hours)	0.72	0.76	0.80	0.78	0.76
Availability during operating cycle (available hours/operating cycle)	0.93	0.96	0.98	0.98	0.95

and qualifications on the data base are discussed in Ref. 2.2-4. A proposed schedule for upgrading the data base consistent with the HTGR Recycle Reference Facility schedule is shown in Fig. 2.2-5.

REFERENCES

- 2.2-1. "HTGR Fuel Recycle Development Program Quarterly Progress Report for the Period Ending May 31, 1978," DOE Report GA-A15011, General Atomic Company, June 1978.
- 2.2-2. Rode, J. S., and J. B. Strand, "A Preliminary Analysis of the HTGR Dry Head-End Reprocessing Systems," DOE Report GA-A14678, General Atomic Company, November 1977.
- 2.2-3. Stula, R., and H. Yip, "Dissolver-Centrifuge System Maintainability Data," General Atomic Company, unpublished data, February 6, 1978.
- 2.2-4. Holder, N., J. Sharmahd, and J. Rode, "Availability of Reprocessing Systems in an HTGR Recycle Facility," General Atomic Company, to be published.

Fig. 2.2-5. Reliability, maintainability, availability growth related to HRRF design and construction

2.3. ECONOMIC/COST-BENEFIT STUDIES (SUBTASK 130)

2.3.1. Introduction

A conceptual design and cost estimate for the Target Recycle Plant was developed jointly by General Atomic and the R. M. Parsons Co. (RMPCo) in 1975. This cost estimate was stored on a Tymshare data base (RCYCLE) having the capability to report costs in a number of ways useful for cost-benefit and nonproliferation cost studies. This task includes reactivating the data base and updating the costs and plant design to current status.

2.3.2. Activity

The following updating activities have been completed (relative to the 1975 \$336 million direct construction cost estimate):

1. Enter all three-point estimate data originally provided in 1975 and change the reporting basis to mean values instead of most likely values. Net cost effect: \$15 million increase.
2. Escalate material costs according to assigned indexes from July 1975 to June 1977. Net cost effect: \$32 million increase.
3. Escalate labor costs according to June 1977 contract rates in the Tennessee area. Change labor cost basis to full labor crew rates and update productivity factors. Net cost effect: \$108 million increase. (June 1978 contract rates will be applied when June 1978 material escalation indices are published.)
4. Identify quality assurance levels for all hardware items and apply quality assurance cost factors developed by R. M. Parsons Company. Net cost effect: \$15 million increase.

5. Allocate piping, instrumentation, and electrical hardware costs to plant systems, correcting miscellaneous errors and omissions in the 1975 estimates. Revise costs in miscellaneous areas for flowsheet changes occurring since 1975. Net cost effect: \$35 million increase (C-14 fixation, waste glassification, and thorium solidification still to be added).

Preliminary cost estimates by system, material throughput by system, and cell dimensions by system are now available for developing rough order-of-magnitude cost estimates for alternative recycle plant designs.

2.4. SYSTEMS INTEGRATION AND DESIGN STUDIES (SUBTASK 140)

2.4.1. Introduction

The objectives of these studies are to complete the development of a computer code for simulation of reprocessing operating modes, and to assist UCC-ND in the nonproliferation assessment of thorium fuel cycles. Results obtained during this reporting period are summarized in the following sections.

2.4.2. Activity

2.4.2.1. Simulation Code Development. Support personnel for this activity terminated employment at the beginning of the quarter, and only code maintenance work has been performed since. The GASP IV lognormal function has been rewritten to accept reliability and maintainability statistical parameters developed under the availability allocation activity (Section 2.2.2.4). Several validation runs were made to test the lognormal curve fit to the original data estimates (Refs. 2.2-2, 2.2-3). Apparently the triangular distribution previously used as an approximation more closely fits the data. Further tests will be run before a final decision is made on which distribution to use.

2.4.2.2. Nonproliferation Assessment of Thorium Fuel Cycles. Proliferation resistance assessments for Nonproliferation Alternative Systems Assessment Program (NASAP) fuel cycle cases assigned to ORNL/GA were completed and submitted to the Alternate Fuel Cycle Evaluation Program (AFCEP) Office at the Hanford Engineering Development Laboratory for inclusion in the final report on covert facilities. An appendix for the final report was also submitted documenting the design basis for a generic covert processing plant for HTGR high-enriched uranium fresh fuel elements.

Technical support was provided to ORNL in the form of a report on fuel fabrication and the back end of the fuel cycle for water reactors, which was prepared for input to International Nuclear Fuel Cycle Evaluation

(INFCE) Working Group 8. The fuel cycles included three once-through cycles that require only fresh fuel fabrication, shipping, and spent fuel storage; four cycles that utilize denatured uranium-thorium and require all recycle operations; and one cycle that considers the LWR-HWR tandem operation requiring refabrication but no reprocessing. The eight fuel cycles are:

1. LWR - UO_2 fuel; improved, once-through fuel cycle.
2. LWR - denatured (U-235,Th) O_2 fuel with recycle.
3. LWR - denatured (U-235,Th) O_2 fuel with recycle.
4. SSCR* - UO_2 fuel; optimized, once-through fuel cycle.
5. SSCR - denatured (U-235,Th) O_2 fuel with recycle.
6. HWR - UO_2 fuel; once-through fuel cycle.
7. HWR - denatured (U-235,Th) O_2 fuel with recycle.
8. LWR/HWR - UO_2 fuel; tandem fuel cycle.

Technical support was also provided ORNL by updating a similar report on HTGR fuel cycles for input to INFCE. The fuel cycles included three once-through cycles with stowaway of the spent fuel, and five cycles involving recycle options. The three once-through cycles are: (1) the HTGR once-through current MEU/Th cycle, (2) the HTGR once-through optimized MEU/Th cycle and, (3) the HTGR once-through LEU cycle. The recycle options are:

1. MEU-235/Th with uranium recycle.
2. MEU-233/Th with uranium recycle.
3. Pu/Th converter with plutonium recycle and U-233 transfer to other reactor fuel cycles.
4. The well-developed reference HEU-235/Th cycle with uranium recycle and high-enriched U-235 makeup.

*Spectral shift controlled reactor.

5. HEU-233/Th cycle with high-enriched U-233 makeup from an external source.

3. FUEL REPROCESSING (TASK 300)

3.1. FUEL ELEMENT SIZE REDUCTION (SECONDARY SUBTASK 311)

3.1.1. Summary

Little measurable wear has been detected after crushing approximately 6700 kg (14,800 lb) of material in the UNIFRAME. The principal wear, which took place in the oil-lubricated pillow block bearings of both the primary and secondary crushers, resulted from inadequate lubrication at startup. Forced circulation oil pumps have been installed to alleviate this problem.

Macroscopic indentations that have the appearance of being created by silicon-carbide-coated fuel particles were found in both rolls of the tertiary crusher. Fuel particles could be exposed for individual contact with the steel roll faces during UNIFRAME crushing and, given adequate support, could indent the roll surfaces to the extent observed without being crushed. Calculations that compared the observed size of the indents with predicted embedment in the steel indicate that this is probably the case.

Overheating of the pitman bearings of the primary crusher was caused by lack of lubrication due to the improper assembly of the bearing assemblies into the pitman casting. This caused the mislocation of the lubrication oil holes, grooves, and supply galleries resulting in both bearings running with grossly inadequate lubrication. One bronze bushing was damaged and has been replaced, and the other returned to service. Shaft discoloration and scoring were removed by polishing. The bearing assemblies were correctly reassembled into the pitman casting.

A graphite bearing was tested in the primary crusher pillow block.

3.1.2. UNIFRAME Wear Analysis

The primary and secondary crushers, screener, and oversize crusher were removed from the UNIFRAME to permit inspection and analysis of wear on crushing surfaces, bearings, material chutes, and the screener. The wear resulting from crushing approximately 6700 kg (14,800 lb) of scrap graphite, fuel blocks, and loaded fuel blocks in the UNIFRAME crusher has been reviewed and documented for evaluation of component wear rates. In numerous cases, baseline data were established for future comparisons. The primary and secondary crushing faces and cavities were inspected along with the tertiary crushing rolls and the parts in the oversize crusher roll cavity. The chutes and louvers used to direct the crushed product and the cleaning discs from the vibratory screener were also inspected for wear. The pitman shaft pillow block bearings and the toggle groups for each jaw crusher were inspected for wear.

3.1.2.1. Jaw and Roll Crushers. There was little or no measurable wear of the mild steel crushing faces and check plates of the primary and secondary crushers. Original mill plate surfaces and machining marks were still visible, even in areas of greatest crushing activity. The manganese steel rolls of the tertiary crusher showed no measurable wear with the original grinding marks still being evident.

All three crushing stages contained evidence of the passage of miscellaneous tramp metal, predominantly machine fasteners and metal parts. These metal parts are potentially more damaging to crusher components than is normal wear from crushing fuel blocks. The damage caused by these parts is shown in Fig. 3.1-1.

3.1.2.2. Screener, Chutes, and Louvers. The Teflon and two types of aluminum cleaning discs used in the screener exhibited no evidence of wear. The paint on the feeder chutes and louvers has been removed or obliterated, which was the only evidence of material passage.

Fig. 3.1-1. Damage caused by tramp metal in secondary crusher

3.1.2.3. Pillow Block Bearings - Oil Lubricated. Recognized wear of the oil-lubricated pillow block bearings on the pitman shafts of both crushers was found in the lower halves of the split bushings, but only on the drive sides. Bearing wear, which indicates that the bearing is independent of crushing loads, results from insufficient hydrodynamic lubrication during startup and initial operation. In the present design, the lubricant drains from the bearing during standby and is not resupplied until the pickup collar and wiper, coupled with viscous gravity flow, have redistributed the oil. This situation could be improved by pumping the lubricant to the bearings at startup.

3.1.2.4. Toggle Systems - Dry-Film Lubricated. Both toggle shafts from the pitman ends and their mating bushings are original equipment and are still functional. The pushing-block end shafts have either been replaced or locally recoated with dry-film lubricant. One toggle bushing in the primary crusher has been replaced due to severe scoring and galling. One bushing in the secondary crusher has been polished out to minimize the effects of scoring.

The wear in the toggle system was not measurable but was made evident by the burnishing of the solid dry-film lubricant on the shafts. When the coating fails, there is metal-to-metal contact and scoring results. It is significant that two of the original shafts and the original solid-film coating are still serviceable. The pitman end shaft of the primary crusher appeared to have little remaining wear life.

3.1.2.5. Roll Crusher Indentations. During the UNIFRAME wear analysis, uniformly-sized, evenly-spaced spherical impressions and cylindrical gouges were observed on the working faces of both tertiary crushing rolls (Fig. 3.1-2). The source of these impressions was assumed to be the closely packed, spherical fuel particles found in the fuel rods, which have a 55% packing fraction.

Fig. 3.1-2. Impressions of fuel particles in tertiary roll crusher faces

Crushing the fuel rods evidently exposes individual fuel particles to the roll crushing face, where they are supported in a triaxial stress field. The exposed particles are loaded sufficiently during passage through the rolls to become impressed into the steel, and either pass through the roll gap unharmed or become crushed.

The crushing faces of the rolls are, according to the manufacturer, cast Hadfield steel with the following composition: 12.75 wt % Mn, 1.20 wt % C, 0.2 wt % Mo, 0.6 wt % Si, 0.04 wt % (max) P, and Cr residuals. This material has properties similar to the 13 wt % Mn Hadfield steel reported by Howard S. Avery.* It possesses a hardness in the cast and quenched condition of BHN 200 (Rc 19), and a compressive yield strength approximately equal to the tensile yield of 359 MPa (52,000 psi). The hardness of the two tertiary rolls was tested and found to be in the Rc 19 to Rc 20 range.

Assuming that the impressions in the rolls were created by fuel particles, a calculation was made to determine if the silicon-carbide-coated particles could impress the rolls to the observed extent without themselves being crushed. It was found that the sizes of the impressions were not sufficiently large to indicate the crushing of particles. The particles merely indented the rolls, yielding the roll material and subsequently passing through the crusher.

It was assumed that each indentation represented a crushed particle. The indentations were counted in a unit area for each roll and extended to the complete roll crushing surfaces. The sum of these was considered to be the total number of crushed particles generated in the tertiary crusher by all crushing to date. Comparing this total to the total quantity of silicon-carbide-coated particles processed yielded an assumed breakage of 0.33% of the total coated particle throughput to date.

The 0.33% tertiary breakage contribution was compared with the breakage experienced experimentally during fuel element crushing. The results of

*"Work Hardening in Relation to Abrasion Resistance," Symposium Proceedings, Materials for the Mining Industry, July 1974, p. 45.

the UNIFRAME crushing of LHTGR and FSV fuels were normalized to a breakage rate of 2.94%. Thus, the 0.33% represents slightly more than a 10% contribution assuming that each indentation was a broken particle.

The impressions in the tertiary rolls were probably caused by exposed fuel particles that were not crushed by the rolls. However, even if the impressing particles were all crushed in the tertiary crusher, they would not contribute significantly to the total particle breakage.

3.1.2.6. Primary Pitman Bearing Overheating. During testing of the graphite bearing in the primary crusher, one bronze pitman bearing became excessively overheated. Initially, it was assumed that this resulted from a lack of lubrication at startup. An oil pump was installed to supply oil to both pitman bearings from the pitman reservoir. It was noted that no oil entered the overflow lines even though the supply galleries were flooded. The overflow lines were removed; there was no evidence of oil in the lines or casting ports, and the ports dead-ended at the inner pitman sleeve. Disassembly revealed that the two pitman sleeves had been reversed and assembled incorrectly into the pitman casting. Thus the bushing oil groove, supply holes, and the lubrication supply galleries were improperly located rotationally downstream of the load. See Fig. 3.1-3. In this position, the central oil supply wiper was positioned so that the oil had to flow by gravity over a top-dead-center position to get to the oil holes. With the lubrication holes located beyond the position of maximum load, no hydrodynamic oil film could develop between the bushing and shaft, and metal-to-metal contact occurred during rotation. This resulted in no lubrication for the bearings, one of which (the south bearing assembly, farthest from the drive) was severely overheated causing burning and scoring of the shaft and bushing. The other bearing and shaft were slightly discolored and modestly damaged.

Fig. 3.1-3. Pitman sleeve installation

The detailed damages and individual dispositions were as follows:

1. South Bushing

- a. Damage: Severely burned and worn. The "hot" end had shrunk in diameter due to high temperature creep, reducing the shaft-to-bushing clearance and creating a circumferential clearance, sleeve i.d. to bushing o.d., of 0.018 cm (0.007 in.) to 0.043 cm (0.17 in.) (an interference fit is normal).
- b. Disposition: The bushing and oil seal were replaced.

2. South Shaft Journal

- a. Damage: Discolored and scored. The shaft discoloration indicated that the temperature was not sufficiently high to metallurgically damage the SAE 1040 steel shaft. The measured diameter of the shaft was unchanged and the scoring not damaging.
- b. Disposition: The discolored and scored areas were polished and returned to service.

3. North Bearing

- a. Damage: A small discolored area and a locally worn area. The bushing i.d. was measured in 20 places. One region near the oil groove was worn oversize. The burned or "hot" area, which was near the position of maximum apparent load and 45° rotationally ahead of the oil groove, was also worn oversize. A third region located past the oil groove had a smaller than nominal diameter. These conditions combined to produce a maximum diametral clearance of 0.155 cm (0.061 in.) and a minimum of 0.081 cm (0.032 in.) (drawing maximum is 1.07 cm and minimum is 0.10 cm).

- b. Disposition: The changes in diametral clearance were satisfactory for operation if the oil holes and grooves in the bushings were properly positioned and oil was pumped to the bearings at startup. This assembly was returned to service.

4. North Shaft Journal

- a. Damage: Slight scoring with no discoloration.
- b. Disposition: The shaft was polished and returned to service.

After replacement of the bushing and polishing of the shaft journals, the two pitman bearing assemblies were assembled correctly into the pitman casting. The sleeve with the new bushing was assembled into the north side (drive side) of the pitman casting, and the unmodified bearing was placed into the south position. The corrected oil supply will be supplemented by a circulating oil pump drawing from the pitman oil reservoir.

3.1.3. UNIFRAME Upgrading

3.1.3.1. Graphite Bearing Tests. Testing of graphite bearings was terminated after a series of runs involving: an unlubricated, dry bearing; a water-lubricated, dry bearing; and a moist-gas lubricated, dry bearing. The tests involved using the carbon steel pitman shaft of the primary crusher operating in a cylindrical, segmented, mechanical carbon graphite bearing (Pure Carbon Co. - Purebon P-9NR) installed in place of the standard split bronze bushing for one outboard pillow block. A sketch of the bearing installation and steel sleeve modification for water and moist gas additions is shown in Fig. 3.1-4. The graphite bearing segments and the steel sleeve were instrumented with thermocouples connected to a multiple channel recorder. The thermocouples were located as shown in Fig. 3.1-5.

Fig. 3.1-4. Graphite bearing installation including sleeve modifications

NOTE

TC 16 IS IN TOP HOLE
OF SLEEVE AT LEFT
HAND END

Fig. 3.1-5. Thermocouple installation for graphite bearing tests

The primary crusher was operated without crushing loads, starting with all thermocouple temperatures at equilibrium. Testing continued in individual runs until temperatures became excessively high at any one thermocouple, or trends indicated an imminent dangerous temperature at some location.

During dry bearing, water-lubricated tests, measured amounts of pure water were added at 1-min intervals to the three middle bearing segments, through the 0.64-cm (0.25-in.) access holes, with additions continuing until test shutdown.

Figure 3.1-6 shows the apparatus used for adding saturated gas (CO_2) to the bearing segments. The gas, supplied from the plant liquid CO_2 system, passed through a regulator and a gas moisturizer, then to individual bearing segments. Moist gas was furnished continuously to the bearing during testing.

Figures 3.1-7, 3.1-8, and 3.1-9 represent typical temperature versus time data plots for each of the three types of bearing tests. Selected here for observation were thermocouples 3, 4, and 5, which were embedded in the tops of three segments and were located inside the pillow block.

As seen in these figures, there is a gradual frictional heatup of the bearing during operation, as expected. The dry bearing tests were all ended after 20 to 25 min, when the temperatures became too high or it became apparent that they would soon reach unsafe levels.

The addition of water to the bearing did tend to permit operation of the bearing at lower temperatures, although the results were very erratic. The most noticeable change from the dry bearing runs was the rapid temperature rise evident with the introduction of water after 10 min of dry operation (see Fig. 3.1-7).

Fig. 3.1-6. Moist gas distribution setup for graphite bearing

Fig. 3.1-7. Graphite bearing test results - no lubricant

Fig. 3.1-8. Graphite bearing test results - water lubricant

Fig. 3.1-9. Graphite bearing test results - saturated CO₂ lubricant

Supplying moist gas to the bearing had a very satisfactory effect, probably a coupling of cooling with an increased lubricity of the graphite. The temperature rise in the bearing decreased over previous tests. Two tests were completed before tests were discontinued to permit refitting the UNIFRAME for requested plant operation. Both these tests produced similar test data, and each was stopped after only 35 min of operation to prevent excessive heatup of the primary toggle bearings. These results are very encouraging, and suggest additional testing of moist-gas-lubricated, dry-graphite bearings under more closely controlled test conditions.

At the conclusion of testing, the pitman shaft and the graphite bearing were measured for diameter changes. The measurements showed that the shaft diameter increased an average of 0.008 mm (0.003 in.) due to graphite plateout on the journal area. The bearing bore increased in diameter an average of 0.0015 mm (0.0006 in.). Thus there was a net increase in bearing clearance of 0.008 mm resulting from all graphite bearing tests (4.5 h). Figure 3.1-10 shows the pitman shaft with the dark graphite plateout on the journal area readily evident.

3.1.3.2. Oil Lubrication Pumps. Excessive wear has occurred on both the primary and secondary bronze pillow block bearings. The oil to these bearings was supplied by a wiper arrangement which required that the crusher be operating for a short period of time before lubrication would reach the bearings. Since the UNIFRAME remains idle for long periods of time, all of the oil drains out of the bearings and they operate dry during each startup. A forced circulation oil system (Fig. 3.1-11) has been added to lubricate the bearings prior to startup and assure an adequate oil supply during operation.

Fig. 3.1-10. Graphite plateout from graphite bearing

SECONDARY PILLOW BLOCK AND PITMAN BEARINGS

PRIMARY PITMAN BEARINGS

Fig. 3.1-11. Oil lubrication pumps

3.2. CRUSHED FUEL ELEMENT BURNING (SECONDARY SUBTASK 312)

3.2.1. Summary

Using the 0.20-m primary burner, a 48-h burner run was completed on May 4, 1978, 3 months ahead of schedule. Feed material was TRISO fuel particles mixed with crushed graphite. The average burn rate was over 200 g/min. Product removed during the run contained 0.08 wt % carbon, while the final product had 0.25 wt % carbon.

An 11-h 0.20-m primary burner run was made to test the fines recycle rotary valve operability at 600° to 650°C. Burner operation was simplified by recycling fines near their combustion temperature.

Thirty-five kilograms of Si-BISO type fuel was burned in the 0.20-m primary burner to test the feasibility of reprocessing this type of fuel. Silica material was noted in the fines stream and on some of the TRISO-WAR particles; however, no problems were encountered in the process.

The 0.40-m primary burner modifications were completed on schedule. The work included design, procurement, fabrication, and installation of many items.

On July 21, 1978, a graphite heatup test was performed on the reconstructed 0.40-m primary burner. Operation was troublefree and preparations were made for the initial burning test.

3.2.2. 0.20-m Primary Burner

3.2.2.1. 48-h Run Using TRISO Fresh Feed. Activity Plan 524401, Issue E, requires two separate 48-h burner runs to be made on the 0.20-m primary burner. The first, successfully completed on March 30, 1978, is covered in the preceding quarterly. TRISO/BISO fresh feed was used in that run.

3.2.2.1.1. Feed

Feed material was a mixture of 18 wt % FSV type TRISO fertile fuel particles and 82 wt % crushed fuel block graphite (-0.48 cm).

3.2.2.1.2. Run Narrative

Figures 3.2-1 through 3.2-5 give several burner variables as a function of run time. Operating procedure 524301 was followed. Vertex O_2 had been eliminated prior to this run for the purpose of simplification. Vertex CO_2 was maintained at 130 slpm.

The initial fresh feed bed weight was 30 kg, and the maximum particle bed weight was 50 kg. Off-gas filter pressure drop reached a maximum of 6 kPa. Cyclone pressure drop peaked at over 12 kPa during periods of high fines recycle rate.

The fluidized bed temperature was controlled at 900°C during full burn rate periods, and dropped to 750°C during interim product removal steps.

Mid-reactor oxygen flow was maintained at 130 to 170 slpm during full burn rate periods in order to adequately burn recycled fines as well as bed carbon in the ejected slugs that reached the upper burner zone.

Off-gas oxygen concentration averaged 4 vol % during the run, with spikes to 10 vol % during tail burning operations.

Fines and fresh feed flow sensors worked well throughout the run, as did the fresh feed level sensor. The fines bunker level sensor operated, as in the previous run, with fines clumps resting on the probe and giving erroneous indications. Ceramic insulators on the burner level probe cracked and admitted fine carbon dust, which shorted out the unit. Post-run examination indicated that physical damage of the ceramic material may have been caused by hitting the burner wall.

Fig. 3.2-1. Mid-bed temperature

Fig. 3.2-2. Above-bed temperature and O₂ concentration

3-25

Fig. 3.2-3. Bed differential pressure

Fig. 3.2-4. Cyclone pressure

Fig. 3.2-5. Filter pressure

Rotation speed of the fines rotary valve was maintained at 1 to 2 rpm. Fines bunker temperature was kept at 500°C. Thirty hours into the run a slight leak of fine carbon began to show up on one of the rotary valve seals. Tightening the seal follower did not help, so a vacuum duct was placed beside the valve to capture any particulate matter. The seal was a wound graphoil design that had a total of 80 h service time. Disassembly of the seal after the run showed that the inner surface had become loose on the shaft. It is of interest to note that the seal on the other side of the valve did not leak or show any physical wear even though it had the same service time. Reconstruction of the seal is now complete.

Lower burner cooling air flow was used at a low level during full burn rate periods. Fines reentering the bed at 500°C removed the balance of the lower bed heat load. Fines pipe and cyclone cooling air jackets operated at high rates in order to cool elutriated fines to 500°C prior to reentry to the fines bunker.

Four interim product removal steps were made to keep the bed height from becoming excessive. This would have the effect of utilizing too much midreactor oxygen for burning bed carbon, and not enough for recycled fines burning.

3.2.2.1.3. Product

Material removed during the interim product removal phase was bound to contain 0.08 wt % carbon and 1.6 wt % broken particles. Bulk density was 2.3 cm³ while tap density was 2.4 g/cm³. Final product material contained 0.25 wt % carbon and had a bulk density of 2.1 g/cm³ and a tap density of 2.3 g/cm³. Particle breakage was analyzed to be 2.3 wt %.

Inspection of the fines bunker after the run showed 4.2 kg of fines remaining in the bunker. These fines contained 36 wt % ThO₂ powder. Higher recycle temperatures may be required to reduce this final fines heel when using FSV-type TRISO fuel particles. The high noncombustible

content of the stream imposed undue heating loads on the fines stream, but did not add as much carbon to the recycle loop for more complete oxygen utilization.

3.2.2.1.4. Acceptance Criteria

Activity Plan 524401, Issue E, details eight acceptance criteria. These were all met as shown below:

1. No feed line blockage.
2. Product heel to be less than 0.5 wt %; no heel was observed.
3. Burner heatup time to be less than 2 h; 50 min was required.
4. Off-gas filter pressure drop to be less than 35 kPa; a maximum of 6 kPa was observed.
5. Main burn rate to be at least 200 g/min; the peak burn rate was 232 g/min.
6. Fines heel to be less than 0.5 wt % of throughput; the fines heel was 0.7 wt % of throughput, but only 0.48 wt % was carbon.
7. Product particle breakage to be less than 5 wt %; the actual product breakage was 2.3 wt %.
8. Product carbon content to be less than 1 wt %; the actual average carbon content was 0.17 wt %.

3.2.2.1.5. Conclusions

The success of this run further demonstrated the feasibility of a gravity fines recycle system to burn fines elutriated from a primary

burner. More work should now be focused on operating the fines recycle stream at a higher temperature to improve the fines burnout characteristics when highly noncombustible fines concentrations are present.

3.2.2.2. Si-BISO Turning Test. Si-BISO coatings on the HTGR fertile oxide particles have been proposed to control the rate of fission product migration. The effect of the submicron SiO_2 particles and the heavy metal powder from burned back Si-BISO particles was not known, as there had been no pilot plant experience on reprocessing. Thirty-five kilograms of Si-BISO ThO_2 , the backup fertile particle for the HTGR steam cycle standard plant, were obtained. This was sufficient material for one run in the 0.20-m primary burner, which was adequate to test for any problems that Si particulates might cause when recycling and burning fines.

On July 25, a burner run was successfully completed on the 0.20-m primary burner using a feed material containing Si-BISO type fuel particles. This test was completed over 2 months ahead of schedule. Silica material was noted to build up in the fines stream as a function of run time. Some of the silica deposited on the SiC coatings of burned back TRISO-WAR fuel particles. No process operating problems were encountered during the run. Product carbon content was only 0.1 wt %.

3.2.2.2.1. Feed

The initial fluid bed contained the following materials:

Si-BISO fuel particles	23 kg
Normal BISO fuel particles	18 kg
TRISO coated WAR fuel particles	<u>14 kg</u>
Total	55 kg

This mixture contained 26 wt % burnable carbon as carbon coatings on the particles.

Subsequent feed after ignition of this initial fluidized bed was -0.48 cm crushed graphite.

3.2.2.2.2 Run Narrative

Operating Procedure 524301 was used. Feed was added to the burner over a 10-min period through the feed rotary valve. Heatup of the bed to 700°C took 45 min. Plenum O₂ increases were used to ignite the bed and heat it to 900°C. Bed temperature was held very stable at ±10°C during the rest of the main burning portion of the run. Temperature was controlled by modulating lower cooling air flow.

Fines recycle was initiated during bed ignition. When the fines stream was heated to greater than 200°C, mid-reactor oxygen flow was initiated to begin fines burning. Fines pipe and cyclone cooling air flow was used to keep the fines rotary valve temperature below 650°C.

The carbon burn rate was above 300 g/min for most of the run, and was above 350 g/min for 30 min. These are the highest burn rates yet attained on this burner. The design burn rate is 200 g/min. This was the last burner run of the fiscal year on the burner, so the higher burn rates were pushed for to determine the equipment limitations. No problems were encountered at these higher burn rates.

Off-gas O₂ concentration was less than 0.5% during the main burning portion of the run and was controlled at less than 10% during tail burning. Off-gas CO concentration averaged 15% during the main burning period and less than 1% during tail burning.

Six fines samples were taken during the run at 1-h intervals. They showed increasing concentrations of inert silica material as follows:

<u>Hour No.</u>	<u>Inert Concentrations (%)</u>
1	12
2	15
3	17
4	17
5	27
6	37

3.2.2.2.3. Product

The final fluidized bed contained 0.1 wt % carbon. Microscopic examination of the fuel particle product showed that the BISO kernels (ThO_2 microspheres) were generally very clean, with only occasional surface contamination. The SiC outer surfaces of the burned back WAR-TRISO fuel particles were coated with clumps of material that gave them the appearance of dimpled golf balls. This is in contrast to the normally very smooth burned back TRISO particle surface. This coating is assumed to be a silica deposit from the oxidized Si-BISO coatings. Samples of the product are undergoing analytical chemistry analysis. In addition, microphotographs of the particles are being made.

Final fines bunker inventory was 1 kg. It contained 37 wt % inert silica material.

3.2.2.2.4. Conclusions

Silica associated with Si-BISO particles was found in the fines heel and on the TRISO particle surface at the end of a primary burner run. The product material should be run through the rest of the flowsheet to determine any effects in downstream processes, particularly after the silica enters the aqueous phase as very fine particles. The material is being saved for that purpose.

3.2.2.3. Fines Rotary Valve Test. An 11-h burner run was successfully completed June 22, 1978. The purpose of the run was to test the operability of the fines recycle rotary valve at 600° to 650°C. No problems

were encountered with the valve in that temperature range. Burner operation was simplified by the ability to recycle fines at a temperature close to their combustion threshold. Continued operation of the valve in excess of 600°C is planned during future burner runs.

A TRISO/BISO, 20 wt % carbon fluidized bed was added to the burner for startup. It was heated to 700°C and ignited with plenum O₂. The burn rate was quickly brought to 200 g/min.

Fresh feed was initiated at 250 g/min in order to maintain the bed carbon inventory. Fines recycle was then started at 3 to 4 rpm fines rotary valve speed. Mid-reactor O₂ flow was increased to 160 slpm as the fines stream heated. Fines bunker and rotary valve temperatures were allowed to increase to 630°C by modulating the fines pipe and cyclone cooling air.

It was of interest to note that the fluidized bed temperature profile was much more even than when cooler fines recycle temperatures were used. In this run, the fines stream did not cool the mid and upper fluidized bed as in previous runs. This resulted in a longer time during which fines were hot enough to burn as they passed through the upper burner to the fines upflow pipe. Higher fines burning efficiencies were thus realized.

Final bed carbon burnout proceeded normally. Product carbon content at the end of the run was only 0.1 wt %. The fines heel amounted to about 500 g, which is lower than normal. This low fines heel is certainly associated with the higher fines recycle temperature.

Because of the higher burning efficiency, smoother process characteristics, and continuing physical integrity of the rotary valve, operation of the valve will be in the high temperature range in future burner runs. In this way, longer-term high-temperature operability of the valve may be determined.

3.2.2.4. Fines Heat Transfer Characteristics in the Fines Pipe and Cyclone. Data from the two 48-h runs (March 30 and May 2, 1978) were tabulated and used to make a preliminary estimate of the heat loads and overall heat transfer coefficients for the fines pipe cooling air and cyclone cooling air systems. These data are included as Tables 3.2-1 and 3.2-2.

3.2.2.4.1. Data Tabulation

Data were chosen at times when the process was in a reasonably steady state. A "steady state" was determined by a quick study of the graphs of consolidated data, which showed the general trends of the process variables over the entire 48 h. These graphs are provided in Sections 3.2.2.1.

The process variables chosen were those applicable to the calculation of the heat loads and overall heat transfer coefficients in the area where the fines were being cooled. Although the numerical values of the process variables were taken directly from the raw data recorded during the burner runs, corrections for the cooling air flow rates were made using the calibration curve for the 0.20-m primary burner. The burner gas flow was calculated to be the sum of the inlet O_2 and CO_2 flows. It was assumed that since the concentration of CO in the gas leaving the burner bed was so low during these steady-state periods, any additional volume of gas generated by the production of CO was negligible.

3.2.2.4.2. Estimation of Heat Loads

On the cooling air side, the heat load Q may be expressed as:

$$Q \left(\frac{\text{kcal}}{\text{s}} \right) = \left[\text{cooling air flow} \left(\frac{\text{std m}^3}{\text{s}} \right) \right] \left[\text{cooling air density} \left(\frac{\text{kg}}{\text{m}^3} \right) \right] \\ \left[\text{cooling air } C_p \left(\frac{\text{kcal}}{\text{kg} \cdot ^\circ\text{C}} \right) \right] \left[\text{cooling air } \Delta T \left(^\circ\text{C} \right) \right]$$

TABLE 3.2-1
48-HOUR RUN 1 DATA

	Time (test hour in parentheses)								
	2000 (12)	2200 (14)	0100 (17)	0600 (22)	0800 (24)	1600 (32)	1800 (34)	0300 (43)	0500 (45)
Cooling air (fines flow)									
Flow rate (std m ³ /s)	0.0637	0.0896	0.1038	0.0943	0.0613	0.0943	0.1085	0.0660	0.0060
Outlet temp (°C)	255	225	215	200	250	230	220	255	245
Cooling air (cyclone)									
Flow rate (std m ³ /s)	0.0377	0.0590	0.0660	0.0500	0.0425	0.0590	0.0684	0.0377	0.0377
Outlet temp (°C)	165	145	135	130	155	150	145	165	155
Burner gas flow									
%CO	11	11	11	12	11	11	11	10	10
%O ₂	3	4	2	4	2	0	0	1	1
Flow rate (std liters/s)	15.75	15.77	16.05	15.72	15.37	15.97	16.13	16.07	16.03
Fines pipe									
Inlet temp (°C)	830	875	885	840	895	925	945	885	875
Outlet temp (°C)	600	615	605	580	610	650	685	625	600
Cyclone									
Inlet temp (°C)	600	615	605	580	610	650	685	625	600
Outlet temp (°C)	440	460	450	420	440	455	450	450	445
Fines pipe-wall temp (°C)	430	410	385	360	425	420	395	435	420
Fines flow									
Rotary valve speed (revs/s)	0.022	0.023	0.023	0.025	0.028	0.028	0.029	0.029	0.029

TABLE 3.2-2
48-HOUR RUN 2 DATA

	Time (test hour in parentheses)								
	1530 (6)	1800 (8)	0100 (16)	0300 (18)	0500 (20)	1500 (30)	1700 (32)	2000 (35)	2300 (38)
Cooling air (fines flow)									
Flow rate (std m ³ /s)	0.1509	0.0873	0.1368	0.1368	0.1368	0.1604	0.1557	0.1368	0.0943
Outlet temp (°C)	155	225	185	185	185	175	155	205	225
Cooling air (cyclone)									
Flow rate (std m ³ /s)	0.0967	0.0542	0.0896	0.0896	0.0896	0.0967	0.0967	0.0896	0.0566
Outlet temp (°C)	130	150	120	125	125	145	145	155	140
Burner gas flow									
%CO	15	12	11	11	10	4	1	1	0
%O ₂	4	2.7	3	3	2	3	14	5	9
Flow rate (std liters/s)	17.42	17.08	16.92	16.97	16.97	17.13	16.75	16.88	13.85
Fines pipe									
Inlet temp (°C)	890	905	850	865	875	905	800	890	700
Outlet temp (°C)	610	590	590	595	595	670	545	670	525
Cyclone									
Inlet temp (°C)	610	590	590	595	595	670	545	670	525
Outlet temp (°C)	450	360	430	435	460	510	410	575	465
Fines pipe-wall temp (°C)	300	375	310	315	315	285	315	375	350
Fines flow									
Rotary valve speed (revs/s)	0.022	0.013	0.020	0.020	0.020	0.018	0.013	0.027	0.025

The cooling air ΔT is the difference between the inlet and outlet air temperatures. It was assumed that the temperature of the inlet cooling air remained constant at about 40°C.

The cooling air heat capacity (C_p) was obtained in kcal/kg-°C from tabulated heat capacities for air. An average temperature was used since there is little variation in C_p over the range of temperatures of interest in this calculation.

For the fines pipe cooling air, $T_{av} = 122^\circ\text{C}$. For the cyclone cooling air, $T_{av} = 95^\circ\text{C}$.

The cooling air flow was calibrated in m^3/s at standard conditions. In order to be consistent with units, the cooling air density was also taken at standard conditions.

To double check the value of Q calculated from the cooling air side of the fines pipe, a value of Q from the process side was estimated. On the process side of the fines pipe, Q may be expressed as:

$$Q = \left[(\dot{m} C_p)_{\text{off gas}} + (\dot{m} C_p)_{\text{fines}} \right] \Delta T_{\text{off gas}} ,$$

where

$\Delta T_{\text{off gas}}$ = the difference between inlet and outlet burner gas temperatures of fines pipe, °C,

C_p = heat capacity, kcal/g-°C.

$C_{p_{\text{off gas}}}$ was taken at an average temperature from a table of values listed for carbon dioxide, since the off gas is primarily CO_2 . $T_{av} = 750^\circ\text{C}$. The heat capacity did not vary significantly in the range of temperatures used. An average $C_{p_{\text{fines}}}$ was calculated for $T = 1023 \text{ K}$ using the following equation:

$$C_{p_{\text{fines}}} \left(\frac{\text{cal}}{\text{mol-K}} \right) = 2.67 + (0.0026)T - \left(\frac{117,000}{T^2} \right) .$$

As this equation is based on moles of carbon, the value of C_p must be divided by 12 to convert to a mass basis (cal/g-K).

If $\dot{m}$ is the mass flow rate, $\dot{m}_{\text{off gas}}$ is obtained in the following manner:

$$\dot{m}_{\text{off gas}} \left(\frac{\text{g}}{\text{s}} \right) = \left[\text{volumetric flow rate of burner gas} \left(\frac{\text{std liters}}{\text{s}} \right) \right] \left[\frac{44 \text{ g}}{22.4 \text{ liters}} \right]$$

The mass flow rate of the fines is the amount of fines recycled in a unit of time. $\dot{m}_{\text{fines}}$ is calculated as follows:

$$\dot{m}_{\text{fines}} \left(\frac{\text{g}}{\text{s}} \right) = \left[\frac{\text{volume of fines (cm}^3\text{)}}{\text{revolution of rotary valve}} \right] \left[\rho_{\text{fines}} \left(\frac{\text{g}}{\text{cm}^3} \right) \right] \left[\frac{\text{revolutions}}{\text{s}} \text{ of rotary valve} \right] ,$$

where ρ_{fines} was taken as 0.54 g/cm^3 and volume/revolution was calculated by measuring the dimensions of one pocket of the fines rotary valve, calculating the volume of one pocket then multiplying by the total number of pockets (6) in the rotary valve:

$$\left(\frac{\text{volume}}{\text{revolution}} \right) = (6) (356 \text{ cm}^3) = \frac{2136 \text{ cm}^3}{\text{revolution}} .$$

This method of calculating the heat load from the process side was only valid for the fines pipe flow because in this case both the off-gas and fines were undergoing the same temperature changes and flow patterns between inlet and outlet. In the cyclone, the flow pattern was more complicated, as well as having two separate exit streams. There is presently no means by which the amount of fines in the cyclone exit gas or gas in the fines exit stream can be measured. Thus, this method would yield unreliable results if applied to the process side of the cyclone.

Tables 3.2-1 through 3.2-5 summarize the data.

3.2.2.4.3. Estimation of Overall Heat Transfer Coefficients

For concurrent heat transfer between the cooling air and process stream, the overall heat transfer coefficient U in $\left(\frac{\text{kcal}}{\text{cm}^2\text{-s-}^\circ\text{C}}\right)$ is:

$$U = \frac{Q}{A\Delta T_{1m}} ,$$

where

Q = heat load, kcal/s,

ΔT_{1m} = log-mean temperature difference between inlet streams (ΔT_1)
and exit streams (ΔT_2),

and

ΔT_1 = (process gas temperature in) - (cooling air temperature in),

ΔT_2 = (process gas temperature out) - (cooling air temperature out).

Furthermore,

$$\Delta T_{1m} = \frac{\Delta T_2 - \Delta T_1}{\ln \frac{\Delta T_2}{\Delta T_1}} .$$

If the area for heat transfer A is πDL for a cylinder,

$$A_{\text{fines pipe}} = 2681 \text{ cm}^2 .$$

The diameter used was 5.23 cm, the inside diameter of the fines pipe. The length used was the total length of the pipe from the burner bed exit to the cyclone entrance minus the length occupied by the bellows. This length was estimated to be about 163 cm.

TABLE 3.2-3
HEAT GAIN BY COOLING AIR IN FINES PIPE

RUN 1							
ΔT ($^{\circ}C$)	Flow (std m^3/s)	C_p (kcal/kg- $^{\circ}C$)	ρ ($\frac{kg}{m^3}$)	Q ($\frac{kcal}{s}$)	ΔT_{1m} ($^{\circ}C$)	A (cm^2)	$U \times 10^6$ ($\frac{kcal}{cm^2-s-^{\circ}C}$)
215	0.0637	0.242	1.298	4.30	537	2681	2.99
185	0.0896	0.242	1.298	5.21	585	2681	3.32
175	0.1038	0.242	1.298	5.71	588	2681	3.62
160	0.0943	0.242	1.298	4.74	564	2681	3.13
210	0.0613	0.242	1.298	4.05	572	2681	2.64
190	0.0943	0.242	1.298	5.63	624	2681	3.37
180	0.1085	0.242	1.298	6.14	661	2681	3.46
215	0.0660	0.242	1.298	4.46	575	2681	2.89
205	0.0660	0.242	1.298	4.25	450	2681	3.52
RUN 2							
115	0.1509	0.242	1.298	5.45	632	2681	3.22
185	0.0873	0.242	1.298	5.07	579	2681	3.27
145	0.1368	0.242	1.298	6.23	584	2681	3.98
145	0.1368	0.242	1.298	6.23	593	2681	3.92
145	0.1368	0.242	1.298	6.23	597	2681	3.89
135	0.1604	0.242	1.298	6.80	663	2681	3.83
115	0.1557	0.242	1.298	5.62	555	2681	3.78
165	0.1368	0.242	1.298	7.09	577	2681	4.58
185	0.0943	0.242	1.298	5.48	457	2681	4.47

TABLE 3.2-4
HEAT LOSS BY PROCESS STREAM IN FINES PIPE

RUN 1

$\dot{M}_{\text{fines}}$ (g/s)	$C_{p_{\text{fines}}}$ (kcal/g-°C)	$\dot{M}_{\text{offgas}}$ (g/s)	$C_{p_{\text{offgas}}}$ (kcal/g-°C)	ΔT_{offgas} (°C)	Q (kcal/s)	$U \times 10^6 \left(\frac{\text{kcal}}{\text{cm}^2\text{-s-}^\circ\text{C}} \right)$
25.0	4.35×10^{-4}	30.9	2.94×10^{-4}	230	4.60	3.20
26.9	4.35×10^{-4}	31.0	2.94×10^{-4}	260	5.41	3.45
26.9	4.35×10^{-4}	31.5	2.94×10^{-4}	280	5.87	3.72
28.8	4.35×10^{-4}	30.9	2.94×10^{-4}	260	5.62	3.72
32.7	4.35×10^{-4}	30.2	2.94×10^{-4}	285	6.58	4.29
32.7	4.35×10^{-4}	31.4	2.94×10^{-4}	275	6.45	3.86
33.6	4.35×10^{-4}	31.7	2.94×10^{-4}	260	6.22	3.51
33.6	4.35×10^{-4}	31.6	2.94×10^{-4}	260	6.22	4.03
33.6	4.35×10^{-4}	31.5	2.94×10^{-4}	275	6.57	5.45

RUN 2

25.0	4.35×10^{-4}	34.2	2.94×10^{-4}	280	5.86	3.46
15.4	4.35×10^{-4}	33.6	2.94×10^{-4}	315	5.22	3.36
23.1	4.35×10^{-4}	33.2	2.94×10^{-4}	260	5.15	3.29
23.1	4.35×10^{-4}	33.3	2.94×10^{-4}	270	5.36	3.37
23.1	4.35×10^{-4}	33.3	2.94×10^{-4}	280	5.55	3.47
21.1	4.35×10^{-4}	33.7	2.94×10^{-4}	235	4.49	2.53
15.4	4.35×10^{-4}	32.9	2.94×10^{-4}	255	4.17	2.80
30.8	4.35×10^{-4}	33.2	2.94×10^{-4}	220	5.09	3.29
28.8	4.35×10^{-4}	27.2	2.94×10^{-4}	175	3.60	2.94

TABLE 3.2-5
HEAT GAIN BY COOLING AIR IN CYCLONE

RUN 1

ΔT ($^{\circ}\text{C}$)	Flow (std m^3/s)	C_p (kcal/kg- $^{\circ}\text{C}$)	ρ ($\frac{\text{kg}}{\text{m}^3}$)	Q ($\frac{\text{kcal}}{\text{s}}$)	ΔT_{lm} ($^{\circ}\text{C}$)	A (cm^2)	$U \times 10^6$ ($\frac{\text{kcal}}{\text{cm}^2\text{-s-}^{\circ}\text{C}}$)
125	0.0337	0.241	1.298	1.48	401	974	3.79
105	0.0590	0.241	1.298	1.94	432	974	4.61
95	0.0660	0.241	1.298	1.96	428	974	4.70
90	0.0500	0.241	1.298	1.39	402	974	3.55
115	0.0425	0.241	1.298	1.53	411	974	3.82
110	0.0590	0.241	1.298	2.03	440	974	4.74
105	0.0684	0.241	1.298	2.25	454	974	5.09
125	0.0377	0.241	1.298	1.48	417	974	3.64
115	0.0377	0.241	1.298	1.36	410	974	3.41

RUN 2

90	0.0967	0.241	1.298	2.72	433	974	6.45
110	0.0542	0.241	1.298	1.87	353	974	5.44
80	0.0896	0.241	1.298	2.24	419	974	5.49
85	0.0896	0.241	1.298	2.38	421	974	5.80
85	0.0896	0.241	1.298	2.38	436	974	5.60
105	0.0967	0.241	1.298	3.18	486	974	6.72
105	0.0967	0.241	1.298	3.18	372	974	8.78
115	0.0896	0.241	1.298	3.22	518	974	6.38
100	0.0566	0.241	1.298	1.77	400	974	4.54

The area for heat transfer in the cyclone was estimated using the fact that the cyclone was approximately cylindrical. This assumption tends to increase the area for heat transfer calculated, and therefore yielded a lower value for the overall heat transfer coefficient that was actually occurring:

$$A_{\text{cyclone}} = 974 \text{ cm}^2 .$$

A diameter of 10.15 cm and a length of 30.5 cm were used in this calculation.

3.2.2.4.4. Conclusions

Detailed experimental data have been used to calculate overall heat transfer coefficients. Two separate calculational techniques, one using cooling air heat gain and the other using process stream heat loss, gave heat loads with reasonably close agreement. This checking procedure supported the validity of the experimental technique, measuring devices, and calculational approach used.

3.2.3. 0.40-m Primary Burner

3.2.3.1. Reconstruction. Reconstruction of the 0.40-m primary burner was completed July 14, on schedule. This work included design, procurement, fabrication and installation of the following items:

1. Gravity fines recycle bunker.
2. High capacity filter chamber and off-gas piping.
3. Cooling-air jacketed cyclone separator.
4. Cooling-air jacketed fines upflow pipe.
5. High-temperature fines rotary valve and drive system.

6. Upper level equipment support platform.
7. Feed bunker support cage.
8. Feed bunker tension-type load cells.
9. Feed bunker aeration cone.
10. Feed surge bunker.
11. High throughput feed rotary valve and drive system.
12. Discrete sampler in feed addition pipe.
13. Mid-reactor gravity fines recycle penetration, entering burner tube at 25° angle with 0.10-m diameter Hastelloy-X pipe.
14. Extensive upper cooling air shroud modifications associated with item 13.
15. Y-piping with three bellows to interconnect the mid-reactor penetration with feed and fines rotary valves, and support members for this piping.
16. Cooling air supply and exhaust piping and valving for both cyclone and fines upflow pipe cooling air jackets.
17. Fines bunker and burner tube multiposition level sensors. Feed and fines flow sensors.
18. Rebuilt off-gas analyzer system.
19. Burner tube lower cooling air seal.

20. Inlet conical gas distributor holes were selectively welded closed to minimize plenum material backflow.
21. Rewired lower clamp heater system.
22. Extensive installation of thermocouples, pressure gages, purge rotameter, and differential pressure cells on new equipment.
23. Fines sampler system including vacuum pump and filter receiver.

Figures 3.2-6, 3.2-7, and 3.2-8 show the finished burner system.

Backflow of fuel particles through the plenum gas distributor has been reduced over four orders of magnitude by increasing distributor pressure drop to greater than the maximum slug pressure fluctuation. This was attained by plugging one-fourth of the holes in the distributor plate, thus reducing the number from 946 to 720.

3.2.3.2. Initial Shakedown Run. A graphite heatup test on the recently reconstructed 0.40-m primary burner was completed on July 21, 1978. System operation was smooth and troublefree throughout the test. The burner system is now ready for an initial burning test.

In this test, a 100 kg fluidized bed of -0.48 cm full spectrum graphite was added to the burner. This was then fluidized with CO₂ and heated by the induction heating system to 700°C. The lower coil was used initially to heat the nonexpanded fluidized bed. After the bed was well fluidized (slugging), both induction coils were actuated for a faster heatup rate.

Fines were recycled through the gravity recycle system without any blockages. Off-gas filter pressure drop reached a maximum of 4 kPa.

The fluidized bed was then cooled to 100°C and removed through the pneumatic transport system to the product bunker.

Fig. 3.2-6. Overall view of 0.40-m primary burner - reconstructed to gravity fines recycle mode

Fig. 3.2-7. View of upper 0.40-m primary burner tube and fines recycle bunker

Fig. 3.2-8. Top deck of 0.40-m primary burner with fresh feed bunker and filter chamber

No process difficulties were noted during this initial test. All aspects of the rebuilt burner system are favorable.

3.2.4. Primary Burner Automation

A primary burner automatic operating cycle has been developed to aid in planning short- and long-term automation activities. The burner is assumed to have a gravity fines recycle system.

3.2.4.1. Automatic Operating Cycle

1. Purges on, cooling water on.
2. Plenum, vertex, and mid-reactor CO_2 on at predetermined flow rates.
3. Add fresh feed by opening knifegate(s) and operating rotary valve. Shut off when correct weight has been removed from bunker.
4. Actuate induction; use present control scheme to limit temperature of fluidized bed, burner wall, and susceptor. Turn on filter blowback timer.
5. When the fluidized bed temperature reaches 700°C , begin a plenum O_2 flow ramp to yield a predetermined burn rate (the Hewlett-Packard computer could calculate burn rate and adjust plenum O_2 flow accordingly). Total plenum gas flow is to be kept constant, as is mid-reactor flow.
6. Start fines recycle at a predetermined rate by maintaining the fines rotary valve speed. When the recycling fines have heated to 200°C , begin mid-reactor O_2 flow ramp. This ramp would reach a maximum that is preset. Mid-reactor O_2 flow will be decreased

if off-gas O_2 rises above its set point or if fines cooling air is not sufficient to keep the fines bunker temperature at or below set point. Increases in mid-reactor O_2 flow will be compensated by decreases in plenum O_2 flow to keep burn rate constant.

7. Start fresh feed at preset level to match burn rate.
8. Lower burner cooling air is modulated to maintain the fluidized bed temperature. Cascading of burner wall temperature may be necessary for quick response and low overshoot. Excessive temperatures result in reduction of plenum O_2 flow.
9. Upper burner cooling air is modulated to maintain the fines burning zone temperature. Excessive temperatures result in reduction of mid-reactor O_2 flow, then plenum O_2 flow.
10. Low off-gas CO level or high off-gas O_2 level indicate bed carbon depletion. If the fluidized bed is not yet large enough for an interim dump, increase fresh feed rate to raise bed carbon content.
11. When the fluidized bed is large enough for an interim dump, shut off fresh feed and continue burning as before. As bed carbon is depleted, off-gas O_2 will increase. Turn down mid-reactor O_2 initially; when it is off, turn down plenum O_2 to keep off-gas O_2 concentration below a preset level.
12. Decreased burn rates will require lower cooling air flows and re-initiation of induction heating. This will be done automatically. When the burn rate is less than a certain level, stop fines recycle and empty a predetermined weight of product through the vertex pipe. Vertex flow must be shut off and the product knifegate opened for product removal to proceed.

13. Reestablish vertex flow to the remaining fluidized bed. Add sufficient fresh feed for restart of combustion. Go to step 4 and repeat the cycle. When all feed has been used, step 12 will be a complete fluidized bed removal rather than partial.

3.2.4.2. Carbon Burn Rate. A model has been designed to determine the rate at which carbon reacts with oxygen molecules during combustion in the primary burner as a function of burner process variables. This method may be used in the on-line computer to calculate the carbon burn rate during a burner run, as shown below.

- Model

1. It is assumed that the following reactions occur in the combustion process:

- a. $C + O_2 \rightarrow CO_2$ (Reaction 1)
- b. $2C + O_2 \rightarrow 2CO$ (Reaction 2)

2. The known variables are as follows:

- a. Exit concentration of $O_2 = [O_2]$
- b. Exit concentration of $CO = [CO]$
- c. Total O_2 in slpm = plenum O_2 in + mid-reactor O_2 in
- d. Total CO_2 in slpm = vertex CO_2 in + plenum CO_2 in + mid-reactor CO_2 in + purge CO_2 in
- e. Total flow in = TFI = total O_2 in + total CO_2 in

- f. The corrected value D for the [CO] meter reading in the exit gas is:

$$D = (0.537) [\text{CO}] + (0.451) [\text{CO}]^2$$

This was obtained by fitting a polynomial to the factory-supplied correction curve for the CO analyzer.

3. The burn rate BR can be calculated using the following basic equations:

Reaction 1:

$$\text{BR} = (\text{oxygen used}) \left(\frac{1 \text{ mol}}{22.41} \right) \left(\frac{12 \text{ gC}}{\text{mol}} \right) = \left\{ \text{total } \text{O}_2 \text{ in (slpm)} - \text{total } \text{O}_2 \text{ out (slpm)} \right\} \left(\frac{1 \text{ mol}}{22.41} \right) \left(\frac{12 \text{ gC}}{\text{mol}} \right)$$

Reaction 2:

$$\text{BR} = 2 \left\{ \text{total } \text{O}_2 \text{ in (slpm)} - \text{total } \text{O}_2 \text{ out (slpm)} \right\} \left(\frac{1 \text{ mol}}{22.41} \right) \left(\frac{12 \text{ gC}}{\text{mol}} \right)$$

The total O_2 out is the product of the exit O_2 concentration, $[\text{O}_2]$, and the total gas flow out.

4. By considering each reaction individually, the total flow out for each case can be determined algebraically using material balances:

Case 1: If Reaction 1 is the sole reaction occurring:

$$B = \text{total flow out} = \text{total flow in} = (\text{TFI})$$

Case 2: If Reaction 2 is the sole reaction occurring:

$$C = \text{total flow out} = \left(\frac{\text{TFI} + \text{total } \text{O}_2 \text{ in}}{1 + [\text{O}_2]} \right)$$

5. In the actual process, there is competition between Reactions 1 and 2, so a mixture of byproducts occurs. To combine Reactions 1 and 2, it is necessary to define a new variable X. X is the ratio of carbon-to-oxygen molecules that is consumed in Reaction 2. (1 - X) is the ratio of carbon-to-oxygen molecules which is consumed in Reaction 1.
6. Thus, when Reactions 1 and 2 are combined, the total flow out is:

$$\text{Total flow out} = (1 - X) B + XC$$

7. An expression for X is obtained using the fact that the total flow out, by material balance, is TFI/1-D:

$$X = \frac{1}{2} \left\{ \frac{D(TFI)}{1-D} \right\} \left\{ \frac{1 + [O_2]}{(Total\ O_2\ in) - [O_2] (TFI)} \right\}$$

● Results

For overall reactions ranging from purely Reaction 1 to purely Reaction 2, the carbon burn rate can be calculated using the following equation:

$$\text{Carbon burn rate} = (1+X) \left\{ (total\ O_2\ in) - [O_2] [(1-X)B + XC] \right\} \\ \left(\frac{1\ mol}{22.41} \right) \left(\frac{12\ gC}{mol} \right)$$

The factor (1+X) is included to account for the additional volume of gas generated due to Reaction 2, above and beyond the volume of gas entering the burner.

Based on the model presented, burn rates of carbon can be calculated for any combination of inlet O_2 and CO_2 , where the exit concentrations of O_2 and CO are measured.

3.2.4.3. Automatic Data Logging. The process of adding a real time clock to the Hewlett-Packard instrument measuring system for data logging, on-line calculations, and printout has been completed. This additional capability is now available to all Hewlett-Packard users.

During the Si-BISO run on 25 July, 28 channels of data were scanned and recorded every 15 s. Every 5 min the burn rate was calculated and this value, along with the time and 15 other process variables, was printed out for operator information.

The real time clock provides a means of interrupting the calculator based upon a periodic timing interval, a time match, or a time match with delay. The clock can also be used as a stop watch for counting external events within millisecond accuracy. These functions are in addition to reading the month, day, hour, minute, and second upon request.

3.2.5. Training Program for Operators

A program has been set up to ensure that 0.40-m primary burner operators have a thorough knowledge of the equipment, operating techniques, and process rationale. The program included a revised operating procedure, which served as the basis for a class on burner operating theory and hardware. A hands-on equipment operating session was also given to give operators a good sense of where, when, and how the equipment is to be handled. Finally, a formal testing procedure consisting of a wide range of essay-type questions was given. Four operators were qualified on the 0.40-m primary burner.

3.3. PARTICLE CLASSIFICATION, CRUSHING, AND CRUSHED PARTICLE BURNING (SECONDARY SUBTASK 313)

3.3.1. Summary

Arrangements are underway for testing an electrostatic classifier for the separation of fuel particles during the next fiscal year.

Fort St. Vrain type TRISO ThO_2 fuel particles were crushed and subsequently burned in the 0.10-m secondary burner. Both the crushing and burning processes were successful on this advanced fuel particle type.

A shakedown test using a ZrO_2 granule bed was completed on the 0.20-m secondary burner.

3.3.2. Fuel Particle Air Classifier

Classification studies on selected types and blends of fuel particles have been completed for this fiscal year. The feed compositions operating conditions, feed rates, material balances, and analytical results were reported previously (Refs. 3.3-1, 3.3-2). This equipment is now being readied to complete confirmation of production rates and to establish product specifications with loaded fuel elements during sequential operation of the entire pilot plant.

Arrangements are underway for on-site testing of electrostatic classification for the separation of fuel particles during the next fiscal year using equipment at CarpcO, Inc., Jacksonville, Florida.

3.3.3. Fuel Particle Crusher

Fort St. Vrain type TRISO ThO_2 fuel particles were crushed using the fuel particle crusher with 546 μm (0.0215 in.) gap and a roll speed of about 40 rpm. No unbroken particles were detected. A total of 14.66 kg of these particles were crushed for use in a subsequent

burner test. The bulk and tapped densities and the size distribution of the crusher product are given in Table 3.3-1.

3.3.4. Secondary Burners

3.3.4.1. 0.10-m Secondary Burner. The FSV TRISO ThO_2 fuel particles crushed in the fuel particle crusher (see Section 3.3.3) were used as feed for the determination of parameters for burning this advanced fuel particle type.

The batch burner charge totaled 13.51 kg of these crushed particles. The bulk and tapped densities and the size distribution of the feed are given in Table 3.3-1. Based on the bulk density, the unburned bed height was 67 cm (26.6 in.) with a length to diameter (l/d) ratio of 6.6. After burning, the bed height was 50 cm (20 in.) with an l/d ratio of 5.

During charging and heatup, the particles were kept fluidized with 100 lpm of CO_2 . Heatup to 675°C took about 80 min. At that time oxygen was introduced and ramped up to 55 lpm in 75 min. The CO_2 was ramped down to 30 lpm during the same time. By the end of the ramping period, the bed temperature had risen to 800°C due to combustion. Because of the low carbon content of this type of feed (i.e., 16.6%) the bed remained at 800°C , requiring continuous induction heating throughout the test to sustain combustion. After a few minutes at 55 lpm, it was necessary to reduce the oxygen flow to 40 lpm to maintain safe CO-O_2 concentrations in the off-gas. After 2 h of total run time, the CO concentration in the off-gas began to diminish and the O_2 and CO_2 inlet gases were ramped to 20 and 50 lpm respectively to complete combustion.

The bed was removed without difficulty. The plenum was dropped for a visual inspection of the distributor plate. No heel material was found.

Product material size distribution and bulk and topped densities are given in Table 3.3-2. Comparison of the feed and product size distribution is shown on Fig. 3.3-1.

TABLE 3.3-1
FSV TRISO ThO₂ FERTILE PARTICLES - SIZE DISTRIBUTION
AFTER CRUSHING; USED AS FEED FOR 0.10-m SECONDARY BURNER TEST

Mesh Size (μm)	Wt %	Cum Wt % Less Than
+500	0.2	100.0
-500 +425	50.5	99.8
-425 +355	6.6	49.3
-355 +300	5.4	42.7
-300 +250	8.1	37.3
-250 +180	12.9	29.2
-180 +147	4.2	16.3
-147 +125	2.2	12.1
-125 +90	4.1	9.9
-90 +75	1.1	5.8
-75 +38	2.8	4.7
-38	1.9	1.9

Densities

Description	Bulk (g/cm^3)	Tapped (g/cm^3)
Crushed	2.47	2.74
Crushed & Burned	3.35	3.63

TABLE 3.3-2
FSV TRISO ThO₂ FERTILE PARTICLES - SIZE DISTRIBUTION
AFTER 0.10-m SECONDARY BURNER TEST

Mesh Size (μm)	Wt %	Cum Wt % Less Than
+500	0.1	100.0
-500 +425	62.3	99.9
-425 +355	3.2	37.6
-355 +300	2.0	34.4
-300 +250	3.5	32.4
-250 +180	11.4	28.9
-180 +147	5.3	17.5
-147 +125	2.7	12.2
-125 +90	4.3	9.5
-90 +75	1.0	5.2
-75 +38	3.1	4.2
-38	1.1	1.1

Densities

Bulk (g/cm^3)	Tapped (g/cm^3)
3.34	3.93

Fig. 3.3-1. Feed and product size distributions from 0.10-m secondary burner test with FSV TRISO ThO_2 fertile particles

The final bed material contained no burnable carbon detectable by our analytical procedures.

The product from this test has been retained and is available for leaching studies.

3.3.4.2. 0.20-m Secondary Burner. A shakedown test of the 0.20-m secondary burner was completed. The purpose of the test was to improve familiarization with operation of the equipment, calibration of gas flow instrumentation, and to discover problem areas.

The bed consisted of 47.51 kg of granular ZrO_2 . During charging, the bed was fluidized with 500 lpm of CO_2 . This flow was reduced to 385 lpm during heatup to 600°C. All major equipment functioned satisfactorily during the test. Only minor instrumentation problems were encountered. These have been corrected with the exception of two noncritical faulty thermocouples.

At the conclusion of the shakedown and after cooling, the bed was discharged and pneumatically transported using the upgraded product removal system. Total recovery was 47.70 kg after thorough cleanout of the transport system and product bunker. This was an increase of 0.19 kg resulting in 0.4% unaccounted for material.

REFERENCES

- 3.3-1. "HTGR Fuel Recycle Program Quarterly Progress Report for the Period Ending February 28, 1978," DOE Report GA-A14878, General Atomic Company, March 1978.
- 3.3-2. "HTGR Fuel Recycle Program Quarterly Progress Report for the Period Ending May 31, 1978," DOE Report GA-A15011, General Atomic Company, June 1978.

3.4. DRY SOLIDS HANDLING (SECONDARY SUBTASK 314)

3.4.1. Summary

A series of 300 tests in the conveying line geometry test rig have indicated that the conveying line configuration need not be a major design factor in the design of the HTGR Recycle Reference Facility (HRRF).

Data from the heat transfer test rig have shown that actual thermal conductivities of materials encountered in the dry head-end systems are greater by a factor of two to five than those predicted by empirical methods.

3.4.2. Conveying Line Geometry Test Rig

A series of tests were run using the solids handling test rig (Fig. 3.4-1) to determine the effect of conveying line geometry on transport properties and product degradation.

Tests were performed using the following feed materials while varying the bend radius R , acceleration length L , and the conveying velocities:

<u>Test</u>	<u>Material</u>
1	Crushed graphite
2	Crushed graphite
3	Crushed graphite and TRISO kernels
4	LHTGR BISO fertile particles
5	PSC TRISO fissile particles
6	Crushed graphite and LHTGR TRISO particles

3.4.2.1. Test 1 - Crushed Graphite. A series of 134 tests using crushed graphite were made to check out the test rig and correlate the effect of the changes in test rig geometry with system pressure drop.

Fig. 3.4-1. Conveying line geometry test rig

Reduction of the data revealed that charges in system differential pressure due to geometry changes were overshadowed by changes caused by the bag filtering system used. The system was redesigned to use sintered metal tubular filters to eliminate this problem.

3.4.2.2. Test 2 - Crushed Graphite. A series of 75 tests using crushed graphite were made. The bend radius was varied from 0.076 m to 0.406 m, and the acceleration length was varied from 0.71 m to 3.20 m. The blower power, which varies the conveying velocity, was also varied over a range of 30% to 40%. This covered the range of expected velocities during normal plant operation.

The graphite was recirculated through the test loop many times so periodic samples were taken to determine any degradation in particle size. The screen analysis of samples (Fig. 3.4-2) indicated that no appreciable degradation occurred.

The method chosen to correlate the data was to compare the system differential pressure predicted by the Engineering Equipment Users Association method (Ref. 3.4-1) with the measured differential pressure. Since this prediction method does not use acceleration length or bend radius as independent variables, any change in system pressure drop due to changing these variables should be evident.

The system feed rate was measured by weighing the amount of material transport in a given time. The test rig was instrumented with differential pressure gages to measure pressure drops.

The results of this test are presented in Table 3.4-1 and Figs. 3.4-3, 3.4-4, and 3.4-5. As can be seen in these figures, changing the bend radius or acceleration lengths caused no noticeable change in system pressure drop.

Fig. 3.4-2. Size distribution of crushed graphite after successive transport operations - test 2

TABLE 3.4-1
DATA FROM TEST 2 - CRUSHED GRAPHITE

Run No.	Acceleration Length (m)	Bend Radius (m)	Blower Power (%)	Feed Rate (kg/s)	Measured ΔP (in. H ₂ O) ^(a)	Predicted ΔP (in. H ₂ O) ^(a)	Velocity (m/s)
1	0.71	0.406	40.00	0.196	24.0	19.5	16.1
2	0.71	0.406	35.00	0.196	19.0	18.3	13.9
3	0.71	0.406	30.00	0.196	17.5	17.5	11.3
4	0.71	0.305	40.00	0.323	21.0	30.7	16.5
5	0.71	0.305	35.00	0.323	18.5	31.0	16.8
6	0.71	0.305	30.00	0.323	12.0	27.5	10.8
7	0.71	0.203	40.00	0.323	22.0	29.3	14.8
8	0.71	0.203	35.00	0.323	19.0	28.1	12.8
9	0.71	0.203	30.00	0.323	20.0	27.5	10.4
10	0.71	0.152	40.00	0.196	24.0	18.8	14.8
11	0.71	0.152	35.00	0.196	21.0	17.7	12.4
12	0.71	0.152	30.00	0.196	18.0	17.3	10.4
13	0.71	0.076	40.00	0.196	22.0	18.8	14.8
14	0.71	0.076	35.00	0.196	18.0	17.6	11.9
15	0.71	0.076	30.00	0.196	17.0	17.6	11.9
16	1.32	0.076	40.00	0.196	22.0	18.8	14.8
17	1.32	0.076	35.00	0.196	20.0	17.7	12.4
18	1.32	0.076	30.00	0.196	18.0	17.3	9.9
19	1.32	0.152	40.00	0.196	22.0	18.4	14.0
20	1.32	0.152	35.00	0.196	18.0	17.6	11.9
21	1.32	0.152	30.00	0.196	20.0	17.4	11.0
22	1.32	0.203	40.00	0.196	22.0	18.8	14.8
23	1.32	0.203	35.00	0.196	21.0	17.7	12.4
24	1.32	0.203	30.00	0.196	18.0	17.3	9.9
25	1.32	0.305	40.00	0.196	19.0	18.4	14.0
26	1.32	0.305	35.00	0.196	17.5	17.6	11.9
27	1.32	0.305	30.00	0.196	17.0	17.3	9.9
28	1.32	0.406	40.00	0.196	20.0	18.4	14.0
29	1.32	0.406	35.00	0.196	17.5	17.5	11.4
30	1.32	0.406	30.00	0.196	20.0	17.5	8.8
31	2.15	0.406	40.00	0.196	23.0	17.7	12.4
32	2.15	0.406	35.00	0.196	20.0	17.3	10.5
33	2.15	0.406	30.00	0.196	25.0	17.7	8.2
34	2.15	0.305	40.00	0.196	18.0	17.7	12.3
35	2.15	0.305	35.00	0.196	17.0	17.3	10.4
36	2.15	0.305	30.00	0.196	25.0	17.7	8.2
37	2.15	0.203	40.00	0.196	17.0	18.0	13.2
38	2.15	0.203	35.00	0.196	17.0	17.4	10.9
39	2.15	0.203	30.00	0.196	20.0	17.4	9.4
40	2.15	0.152	40.00	0.196	18.0	18.0	13.2
41	2.15	0.152	35.00	0.196	17.0	17.5	11.4
42	2.15	0.152	30.00	0.196	18.0	17.4	9.4
43	2.15	0.076	40.00	0.196	24.0	17.9	12.9
44	2.15	0.076	35.00	0.196	21.0	17.3	10.5

TABLE 3.4-1 (Continued)

Run No.	Acceleration Length (m)	Bend Radius (m)	Blower Power (%)	Feed Rate (kg/s)	Measured ΔP (in. H ₂ O) (a)	Predicted ΔP (in. H ₂ O) (a)	Velocity (m/s)
45	2.15	0.076	30.00	0.196	23.0	17.4	9.4
46	2.74	0.076	40.00	0.196	25.0	19.4	15.9
47	2.74	0.076	35.00	0.196	21.0	18.0	13.2
48	2.74	0.076	30.00	0.196	18.0	17.4	10.9
49	2.74	0.152	40.00	0.196	21.0	19.4	15.8
50	2.74	0.152	35.00	0.196	19.0	18.0	13.2
51	2.74	0.152	30.00	0.196	17.0	17.4	10.9
52	2.74	0.203	40.00	0.196	21.0	19.2	15.5
53	2.74	0.203	35.00	0.196	18.0	18.0	13.2
54	2.74	0.203	30.00	0.196	17.0	17.3	10.4
55	2.74	0.305	40.00	0.196	22.0	19.4	15.8
56	2.74	0.305	35.00	0.196	18.0	18.0	13.2
57	2.74	0.305	30.00	0.196	19.0	17.3	10.5
58	2.74	0.406	40.00	0.196	18.0	18.8	14.7
59	2.74	0.406	35.00	0.196	21.0	17.7	12.4
60	2.74	0.406	30.00	0.196	20.0	17.3	10.5
61	3.20	0.406	40.00	0.196	24.0	18.8	14.8
62	3.20	0.406	35.00	0.196	20.0	17.7	12.4
63	3.20	0.406	30.00	0.196	17.0	17.8	8.1
64	3.20	0.305	40.00	0.196	18.0	18.4	14.0
65	3.20	0.305	35.00	0.196	17.0	17.6	11.9
66	3.20	0.305	30.00	0.196	17.0	17.3	9.9
67	3.20	0.203	40.00	0.196	17.0	18.4	13.9
68	3.20	0.203	35.00	0.196	16.0	17.9	12.7
69	3.20	0.203	30.00	0.196	16.0	17.3	9.9
70	3.20	0.152	40.00	0.196	18.0	17.5	11.4
71	3.20	0.152	35.00	0.196	18.0	17.3	9.9
72	3.20	0.152	30.00	0.196	17.0	17.4	9.3
73	3.20	0.076	40.00	0.196	23.0	18.2	13.7
74	3.20	0.076	35.00	0.196	19.0	17.4	11.0
75	3.20	0.076	30.00	0.196	18.0	17.4	9.4

(a) 1 in. H₂O = 249 Pa.

Fig. 3.4-3. Predicted versus measured ΔP as a function of blower power - test 2

Fig. 3.4-4. Predicted versus measured ΔP as a function of acceleration length - test 2

Fig. 3.4-5. Predicted versus measured ΔP as a function of bend radius

3.4.2.3. Test No. 3 - Crushed Graphite and TRISO Kernels. A series of 19 tests were made using buffer coated TRISO kernels mixed with crushed graphite. The buffer-coated TRISO kernels were mistakenly believed to be fully coated TRISO particles, and particle breakage was to have been measured by chemical analysis (Ref. 3.4-2); however, this was not possible with uncoated particles.

In this series of tests, again the three variables (bend radius, acceleration length, and blower power) were varied.

The results of this test are presented in Table 3.4-2 and Figs. 3.4-6, 3.4-7, and 3.4-8. There was no noticeable effect on system pressure drop.

3.4.2.4. Test 4 - LHTGR BISO Fertile Particles. A series of 6 runs were made with LHTGR BISO fertile particles varying the bend radius and acceleration lengths. Particle breakage was monitored by screening the fuel particles after the test and assuming that all of the material in the -425 μm fraction was broken fertile particles. The results are presented below.

<u>Run No.</u>	<u>% Breakage</u>
1	0.010
2	Not measured
3	Not measured
4	0.350
5	0.075
6	0.272

As can be seen, no significant breakage ($>0.5\%$) occurred during any of the runs.

The results of this test are presented in Table 3.4-3 and Figs. 3.4-9 and 3.4-10. Again there was no noticeable effect on system pressure drop.

TABLE 3.4-2
DATA FROM TEST 3 - CRUSHED
GRAPHITE AND TRISO KERNELS

Run No.	Acceleration Length (m)	Bend Radius (m)	Blower Power (%)	Feed Rate (kg/s)	Measured ΔP (in. H ₂ O)	Predicted ΔP (in. H ₂ O)	Velocity (m/s)
1	3.20	0.076	45.00	0.279	31.0	28.4	18.2
2	3.20	0.076	35.00	0.249	22.0	22.0	12.3
3	3.20	0.203	45.00	0.248	24.0	25.4	18.0
4	3.20	0.203	35.00	0.269	20.0	23.7	12.7
5	3.20	0.406	45.00	0.215	25.0	20.8	15.6
6	3.20	0.406	35.00	0.248	18.0	21.9	12.4
7	2.36	0.406	45.00	0.220	25.0	23.0	18.1
8	2.36	0.406	35.00	0.224	19.0	20.0	12.3
9	2.36	0.203	45.00	0.225	25.0	23.4	18.1
10	2.36	0.203	35.00	0.229	21.0	20.5	12.8
11	2.36	0.076	45.00	0.224	29.0	23.4	18.2
12	2.36	0.076	35.00	0.246	18.0	21.9	12.7
13	0.71	0.406	45.00	0.232	26.0	24.1	18.1
14	0.71	0.406	35.00	0.249	23.0	22.2	12.8
15	0.71	0.203	45.00	0.250	27.0	25.7	18.2
16	0.71	0.203	35.00	0.250	22.0	22.2	12.8
17	0.71	0.076	45.00	0.250	28.0	25.0	17.2
18	0.71	0.076	35.00	0.250	21.0	22.1	12.4
19	0.71	0.076	60.00	0.250	41.0	35.1	27.5

Fig. 3.4-6. Predicted versus measured ΔP as a function of blower power - test 3

Fig. 3.4-7. Predicted versus measured ΔP as a function of acceleration length - test 3

Fig. 3.4-8. Predicted versus measured ΔP as a function of bend radius - test 3

TABLE 3.4-3
DATA FROM TEST 4 - LHTGR
BISO FERTILE PARTICLES

Run No.	Acceleration Length (m)	Bend Radius (m)	Blower Power (%)	Feed Rate (kg/s)	Measured ΔP (in. H ₂ O)	Predicted ΔP (in. H ₂ O)	Velocity (m/s)
1	3.15	0.152	40.00	0.245	27.0	24.3	16.9
2	3.15	0.076	40.00	0.224	28.0	22.4	16.9
3	2.34	0.152	40.00	0.215	26.0	21.1	16.1
4	0.71	0.152	40.00	0.229	27.0	22.0	15.6
5	0.71	0.152	40.00	0.229	28.0	21.3	14.5
6	3.15	0.152	40.00	0.224	26.0	20.3	13.2

3-74

Fig. 3.4-9. Predicted versus measured ΔP as a function of acceleration length - test 4

Fig. 3.4-10. Predicted versus measured ΔP as a function of bend radius - test 4

3.4.2.5. Test 5 - PSC TRISO Fissile Particles. Six runs were made with PSC TRISO fissile particles. Particle breakage was monitored using chemical analysis. The particle breakage results are presented below.

<u>Run No.</u>	<u>% Breakage</u>
1	6.03
2	17.60
3	2.69
4	13.36
5	1.23
6	3.23
Control	17.48
Control	18.76

The results of this analysis are suspect as none of the transported samples, with the exception of sample 2, exhibited a breakage as high as the untransported control samples.

The results of this test are presented in Table 3.4-4 and Figs. 3.4-11 and 3.4-12. There was no noticeable effect on system pressure drop.

3.4.2.6. Test 6 - Crushed Graphite and LHTGR TRISO Fissile Particles. Twenty-seven runs were made with LHTGR TRISO fissile particles mixed in crushed graphite. Particle breakage was determined using chemical analysis. The particle breakage data are presented below:

<u>Sample No.</u>	<u>% Breakage</u>	<u>Sample No.</u>	<u>% Breakage</u>	<u>Sample No.</u>	<u>% Breakage</u>
1	0.044	10	0.047	19	0.046
2	0.093	11	0.047	20	0.216
3	0.046	12	0.041	21	0.046
4	0.045	13	0.044	22	0.044
5	0.045	14	0.044	23	0.041
6	0.091	15	0.094	24	0.088
7	0.093	16	0.046	25	0.225
8	0.046	17	0.047	26	0.045
9	0.090	18	0.044	27	0.086

TABLE 3.4-4
DATA FROM TEST 5 - PSC
TRISO FISSILE PARTICLES

Run No.	Acceleration Length (m)	Bend Radius (m)	Blower Power (%)	Feed Rate (kg/s)	Measured ΔP (in. H ₂ O)	Predicted ΔP (in. H ₂ O)	Velocity (m/s)
1	3.25	0.152	40.00	0.229	35.0	23.5	17.7
2	3.25	0.076	40.00	0.218	39.0	22.1	17.2
3	2.36	0.152	40.00	0.227	33.0	22.9	17.1
4	0.71	0.152	40.00	0.230	33.0	21.7	14.9
5	0.71	0.152	40.00	0.233	33.0	22.9	16.4
6	3.25	0.152	40.00	0.230	33.0	22.5	16.2

Fig. 3.4-11. Predicted versus measured ΔP as a function of acceleration length - test 5

Fig. 3.4-12. Predicted versus measured ΔP as a function of bend radius - test 5

There was no significant ($>0.5\%$) particle breakage observed in any of the tests.

The test data are presented in Table 3.4-5 and Figs. 3.4-13, 3.4-14, and 3.4-15. Again, there were no significant changes in system pressure drop.

3.4.2.7. Conclusions. Bend radius, blower power, and acceleration length do not appear to affect system performance over the range of material transport velocities expected in plant operation. There is also no noticeable effect on particle breakage. Equipment layout in the HRRF can be based on other considerations, and the transport piping bend radii and acceleration distances will not be a major design problem.

3.4.3. Heat Transfer Test Rig

3.4.3.1. Summary. Data from the test runs were used to calculate the thermal conductivities of crushed graphite, HTGR BISO particles, WAR TRISO particles, and secondary burner ash, using CO_2 and He as the interstitial gases. The purpose of these experimental heat transfer studies is to verify design methods for fission product decay heat removal.

3.4.3.2. Test Equipment. The heat transfer test apparatus is an annular furnace with a bed length of 0.91 m, an inner radius of 0.016 m, an outer radius of 0.077 m, and a bed volume of $1.6 \times 10^{-2} \text{ m}^3$. Five thermocouples are located in the axial center of the bed with $1.27 \times 10^{-3} \text{ m}$ spacing. The furnace has a central heating rod and external cooling jackets. A diagram of the furnace is presented in Fig. 3.4-16.

3.4.3.3. Calculation of Thermal Conductivities. Temperature distributions were found by monitoring the five thermocouples in the bed. The difference between the equilibrium temperatures of adjacent thermocouples was used to compute the corresponding thermal conductivity, k_{ab} :

TABLE 3.4-5
DATA FROM TEST 6 - CRUSHED GRAPHITE
AND LHTGR TRISO FISSILE PARTICLES

Run No.	Acceleration Length (m)	Bend Radius (m)	Blower Power (%)	Feed Rate (kg/s)	Measured ΔP (in. H ₂ O)	Predicted ΔP (in. H ₂ O)	Velocity (m/s)
1	3.25	0.406	55.00	0.188	35.0	26.4	25.8
2	3.25	0.406	45.00	0.194	26.0	22.4	20.4
3	3.25	0.406	35.00	0.190	19.0	17.9	14.0
4	3.25	0.203	55.00	0.184	33.0	25.1	24.9
5	3.25	0.203	45.00	0.203	25.0	23.0	20.1
6	3.25	0.203	35.00	0.211	20.0	19.7	14.1
7	3.25	0.076	55.00	0.206	37.5	25.4	22.7
8	3.25	0.076	45.00	0.200	28.5	20.4	17.0
9	3.25	0.076	35.00	0.196	21.0	18.4	14.1
10	2.36	0.076	55.00	0.224	39.0	26.8	22.2
11	2.36	0.076	45.00	0.207	31.0	20.6	16.4
12	2.36	0.076	35.00	0.217	23.0	20.2	14.1
13	2.36	0.203	55.00	0.210	32.0	27.4	24.4
14	2.36	0.203	45.00	0.214	27.0	21.6	16.9
15	2.36	0.203	35.00	0.222	21.0	20.6	14.1
16	2.36	0.406	55.00	0.203	34.0	26.8	24.4
17	2.36	0.406	45.00	0.221	26.5	24.8	20.2
18	2.36	0.406	35.00	0.219	20.0	20.3	14.1
19	0.71	0.406	55.00	0.205	32.0	24.8	22.0
20	0.71	0.406	45.00	0.200	25.0	20.4	16.9
21	0.71	0.406	35.00	0.214	20.0	19.9	14.1
22	0.71	0.203	55.00	0.205	33.0	25.2	22.5
23	0.71	0.203	45.00	0.189	24.0	21.5	19.9
24	0.71	0.203	35.00	0.179	16.5	17.0	14.0
25	0.64	0.076	55.00	0.189	36.0	25.4	24.6
26	0.64	0.076	45.00	0.182	25.0	21.1	20.2
27	0.64	0.076	35.00	0.183	17.0	17.4	14.1

Fig. 3.4-13. Predicted versus measured ΔP as a function of blower power - test 6

Fig. 3.4-14. Predicted versus measured ΔP as a function of acceleration length - test 6

Fig. 3.4-15. Predicted versus measured ΔP as a function of bend radius - test 6

Fig. 3.4-16. Heat transfer furnace

$$T_a - T_b = \frac{Q}{2\pi k_{ab} L} \ln \frac{r_b}{r_a} .$$

T_a and T_b are the equilibrium temperatures of the thermocouples at r_a and r_b , respectively. An average temperature value was computed as $1/2(T_a + T_b)$. Solving the above equation for k_{ab} :

$$k_{ab} = \frac{Q}{2\pi L(T_a - T_b)} \ln \frac{r_a}{r_b} .$$

The heat generation rate Q is a function of the power stat setting P :

$$\frac{Q}{L} = \frac{-1.8796 P + 2.7886 P^2 - 0.019577 P^3}{0.1944} .$$

Q is expressed in watts/m; hence, a unit length of 1 m is chosen for L .

The average temperature value T_M and the corresponding thermal conductivity k_M were fitted to first and second order polynomials, then plotted with T_M as the independent variable. Since the second order linear regression did not provide a better fit, only the first order curves are shown. Each material required two graphs, one each for CO_2 and He. These graphs are shown in Figs. 3.4-17 through 3.4-24.

3.4.3.4. Results. The effective thermal conductivity of a packed bed with stagnant fluid is predicted by the Kunii-Smith correlation (Ref. 3.4-3).

$$\frac{k_e^o}{k_g} = \epsilon \left(\frac{1 + h_{rv} d_p}{k_g} \right) + \frac{1 - \epsilon}{\frac{1}{\phi} + \frac{d_p h_{rs}}{k_g} + \frac{k_g}{k_s}} ,$$

where k_e^o = effective thermal conductivity of packed bed with stagnant fluid,

*Wong, Hin Wai, "Thermal Analysis of Reprocessing Particle Hoppers," ERDA Report GA-A14094, General Atomic Company, October 15, 1976.

Fig. 3.4-17. Experimentally determined thermal conductivity of crushed graphite in CO₂ gas

Fig. 3.4-18. Experimentally determined thermal conductivity of HTGR BISO particles in CO_2 gas

Fig. 3.4-19. Experimentally determined thermal conductivity of HTGR WAR TRISO particles in CO_2 gas

Fig. 3.4-20. Experimentally determined thermal conductivity of secondary burner ash in CO₂ gas

Fig. 3.4-21. Experimentally determined thermal conductivity of crushed graphite in He gas

Fig. 3.4-22. Experimentally determined thermal conductivity of HTGR BISO particles in He gas

Fig. 3.4-23. Experimentally determined thermal conductivity of HTGR WAR TRISO particles in He gas

Fig. 3.4-24. Experimentally determined thermal conductivity of secondary burner ash in He gas

ϵ = voidage,
 d_p = mean particle diameter,
 k_g, k_s = thermal conductivities of the interstitial gas and the solid, respectively,
 ϕ = effective thickness of fluid film adjacent to contact surface of two particles = $\phi(\epsilon, k_s/k_g)$,
 h_{rv}, h_{rs} = heat transfer coefficients of thermal radiation between voids and solid surfaces, respectively.

Experimental results for graphite were approximately twice those predicted by the Kunii-Smith correlation. The only data available for fuel particles are that for a mixture of fertile and fissile particles. Experimental BISO and TRISO runs were conducted separately, but since their respective thermal conductivities differ by only 0.6 W/m-K, it is expected that a comparison with the data predicted for a mixture is still valid. Values for BISO particles were a bit more than twice the Kunii-Smith results, while TRISO values were approximately five times those predicted.

Good results were obtained when CO₂ was used as the interstitial gas. Data from the helium runs showed a significant amount of scatter, apparently caused by convective cooling. It is recommended that further tests be conducted with He, using convection barriers in the bed (such as graphoil).

The overall thermal conductivity measured in the bed, k_e^0 , is very sensitive to the thermal conductivity of the interstitial gas k_g . The k_e^0 of the same bed may be increased to about four times its original value by replacing CO₂ with He. Since the contribution of the gas to the thermal conductivity of the material is measurable, additional helium runs with only one or two of the experimental packing materials used here should be sufficient. If the actual results from the new He tests compare favorably with the values predicted by the CO₂ relation, then that corrective factor will provide appropriate results for the remaining materials.

REFERENCES

- 3.4-1. Engineering Equipment Users Association (EEUA), Pneumatic Handling of Powdered Materials, Constable and Company, Ltd., London, 1963.
- 3.4-2. "Thorium Utilization Program Quarterly Progress Report for the Period Ending November 30, 1977," DOE Report GA-A14738, General Atomic Company, December 1977.
- 3.4-3. Wong, Hin Wai, "Thermal Analysis of Reprocessing Particle Hoppers," ERDA Report GA-A14094, General Atomic Company, October 15, 1976.

3.5. DISSOLUTION SYSTEMS (SUBTASK 330)

3.5.1. Summary

The volatility of iodine and ruthenium was examined during the dissolution of ThO_2 kernels in Thorex solution. The pilot plant 0.13-m (5-in.) dissolver system was used for these tests.

Dissolution tests using nitrogen as a sparge gas had less than 10% iodine volatility after 6 h of dissolution. However, iodine was readily volatilized when nitric oxide (NO) was substituted as the sparge gas. Greater than 98% of the iodine in solution volatilized in 6 h due to the reduction of the iodate ion by nitric oxide. The pilot plant tests confirm the bench-scale results for iodine and ruthenium volatility during ThO_2 dissolution.

A study has been conducted to assess the behavior of reference weak acid resin (WAR) fissile secondary burner ash during dissolution in dilute nitric acid. As observed in bench-scale study, the pilot plant operation in the 0.20-m dissolver encountered no foaming and the dissolution rate of uranium was found to be very rapid (98% uranium dissolution in 1-1/2 hours) in boiling 2 M nitric acid. The HRRF flowsheet product specification was readily met.

A fissile dissolver operating cycle was proposed for the WAR-derived material. It is recommended that the dissolver should operate below the boiling point in the first part of the cycle to limit the peak off-gas NO_x concentration evolved from the dissolution reaction. A very high NO_x concentration could affect the off-gas NO_x converter operation.

There was no activity on the 0.50-m (20-in.) dissolver-centrifuge system during this quarter.

3.5.2. Dissolution Studies

3.5.2.1. Iodine and Ruthenium Volatility During Pilot Plant Scale Dissolution

3.5.2.1.1. Introduction

Iodine and ruthenium are potentially volatile fission products that are released from spent ThO_2 kernels during dissolution. Iodine will volatilize throughout the process system unless it can be driven off at one point, such as the dissolver. This will eliminate the problem of treating iodine in a wide variety of off-gas streams. Ruthenium, on the other hand, is so highly radioactive that large concentrations pose a serious handling problem. Therefore, ruthenium should be contained in solution until it is removed in dilute concentrations in the waste stream of the solvent extraction process.

The behavior of these radioactive elements during dissolution must be determined to define the off-gas requirements for the dissolver vessel. Methods of promoting iodine volatility while suppressing ruthenium volatility during ThO_2 dissolution are the developmental objectives of this effort.

3.5.2.1.2. Experimental

The 0.13-m dissolver system, shown in Fig. 3.5-1, was used for the iodine and ruthenium volatility tests. Modifications of the dissolver system were reported in Ref. 3.5-1. The operating conditions for each test are given in Table 3.5-1. Samples of the dissolver solution were taken periodically throughout each test, and at the end of the test a sample was taken from the off-gas trap. The samples were examined with a Ge-Li counter for total gamma counts of I-131 and/or Ru-103. Differences in total gamma counts for the samples determines the percent volatility for iodine and ruthenium during dissolution.

Fig. 3.5-1. 0.13-m dissolver system

TABLE 3.5-1
OPERATING CONDITIONS FOR IODINE AND RUTHENIUM VOLATILITY TESTS

Run No. (a)	Trap Medium (b)	N ₂ Sparge (ℓ/min)	NO Sparge (ℓ/min)	Temp. (°C)	Dissolution Time (h)	No. Trap Stages
179	C	3.8	0	119	6	5
183	AgZ	0	3.8	116	6	2
189	AgZ	1.9	1.9	106	6	2

- (a) ● Run 179 initial dissolver contents: 12ℓ Thorex, 5.28 kg ThO₂ kernels, 1.81g normal I + 0.4 mCi I-131 tracer.
- Run 183 initial dissolver contents: 12ℓ Thorex, 3.17 kg ThO₂ kernels, 1.85g normal I + 0.1 mCi I-131 tracer, 4.3g normal Ru + 0.2 mCi Ru-103 tracer.
- Run 189 initial dissolver contents: 12ℓ of 1M Th(NO₃)₄ solution, 4.3g normal Ru + 0.15 mCi Ru-103 tracer.
- (b) ● C refers to Type AE activated carbon from Barneby-Cheney, 4 x 6 nominal mesh size.
- AgZ refers to silver zeolite from Coast Engineering Laboratory, 0.48 cm x 0.12 cm (3/16 in. x 1/16 in.) pellet size.

3.5.2.1.3. Results and Discussion

The iodine volatility test (Run 179) using nitrogen as a sparge gas resulted in only 10% volatility of iodine after 6 h of dissolution. However, when nitric oxide (NO) was substituted as the sparge gas in Run 183, 98.8% iodine volatility occurred during the 6-h test. Figure 3.5-2 compares the percentage of iodine volatility with dissolution time for the nitrogen sparged and nitric oxide sparged dissolution runs. Bench-scale tests for iodine volatility during ThO_2 dissolution, as reported in Refs. 3.5-2 and 3.5-3, agree with the pilot plant scale results. Bench-scale tests found that NO gas reduces the iodate ion formed during dissolution, and thus allows the iodine to escape into the off-gas stream. The effect of the increased NO_x load on the off-gas treatment system, especially the NO_x converter, is not known and needs to be determined (Ref. 3.5-4).

Detection of Ru-103 in the Run 183 samples was obscured by the high background activity, including I-131. Therefore, in Run 189, the iodine tracer was not included in the test so that the Ru-103 tracer could be detected in the silver zeolite in the off-gas trap. The result of Run 189 was that no detectable level ($<0.23\%$) of Ru-103 was found in the trap. This also agrees with the results of the bench-scale ruthenium volatility tests reported in Ref. 3.5-3.

3.5.2.2. Pilot Plant Dissolution of WAR Fissile Secondary Burner Ash

3.5.2.2.1. Introduction

Two types of fissile secondary burner ash are currently available for dissolution study: WAR-derived and FSV. The FSV fissile particle has a thorium-to-uranium ratio of 4 to 1 and, therefore, requires the use of Thorex. Since the uranium dissolution rate in Thorex for FSV fissile burner ash is moderated by the ThO_2 present, no unmanageable reaction is expected. The bench-scale study at GA (Ref. 3.5-2) indicated no violent reaction and that ThO_2 dissolution is rate-controlling for FSV fissile ash.

Fig. 3.5-2. Iodine volatility during ThO_2 dissolution

Therefore, in the pilot plant study particular emphasis was placed on determining the rate of uranium dissolution for WAR-derived fissile material and its characteristics in dilute nitric acid.

During secondary burner operations, the crushed uranium oxycarbide WAR fissile particles are converted to finely divided U_3O_8 . By dissolving this ash in nitric acid, the uranium can be recovered by a modified Purex solvent extraction process. The flowsheet specification in HRRF for the reference fissile fuel is 0.035 M uranium in 2 M HNO_3 . The dissolution reaction in the dissolver is:

The evolution of nitrogen dioxide in the dissolver operation is potentially troublesome because violent evolution of NO_2 may cause foaming in the dissolver and may possibly upset the off-gas treatment system downstream.

Bench-scale dissolution of WAR fissile ash has shown that (1) no foaming was observed on addition of 2 M HNO_3 to the ash or during subsequent heating to boiling, and (2) over 98% uranium was dissolved within 1 h of dissolution at the boiling point. It was the objective of the pilot plant test (1) to verify the bench-scale result on reaction rate, (2) to look for scale-up effects, and (3) to evaluate potential operating problems with reference WAR fissile ash.

3.5.2.2.2. Experimental

Leach runs 187 and 188 were conducted in the pilot plant 0.20-m dissolver. For each run, 0.55 kg of WAR fissile ash was charged to the dissolver, followed by addition of 14 liters of 2 M nitric acid. Fine ash particles have a tendency to float on solutions, resulting in poor mixing and perhaps being carried into the overhead condenser should foaming occur. To prevent this problem, the acid solution was poured on top of the ash rather than ash onto acid. The operating conditions for each run are given in Table 3.5-2. Figure 3.5-3 shows a schematic of the 0.20-m dissolver system.

TABLE 3.5--2
OPERATING PARAMETERS FOR WAR FISSILE ASH DISSOLUTION

Parameter	Run 187	Run 188
Dissolver diameter, m	0.20	0.20
Ash weight, kg	0.55	0.55
2 <u>M</u> HNO ₃ volume, liters	14	14
Sparge rate, liters/min	3.8	3.8
Operating temperature, °C	19	103
Time to reach 84% dissolution, h	0.3	7.0

Fig. 3.5-3. 0.20-m dissolver system

The WAR fissile ash (batch R-0002, No. 1) used for these tests originated from Sequential Run E (FY-77) in the 0.20-m secondary burner. The uranium content in the ash is 21.5% by weight. Size distribution of the product (or feed to dissolver) is given in Fig. 3.5-4.

3.5.2.2.3. Results and Discussion

The total leaching time as a function of percentage uranium undissolved is shown in Fig. 3.5-5 for Runs 187 and 188. Bench-scale results of similar WAR fissile ash leaching experiments are given in Fig. 3.5-6. Figure 3.5-7 shows the appearance of the WAR fissile ash before and after dissolution.

The total leaching time to dissolve greater than 98% of the uranium in the WAR fissile ash, for Run 188, was approximately 1-1/2 h. A boiling temperature of 103°C was reached 15 min after the acid was charged to the dissolver. It is believed that foaming did not occur during boiling because analysis of the condensate stream revealed only insignificant amounts of uranium and SiC hulls in the overheads. Bench-scale experiments with WAR fissile ash at boiling temperature agree with the pilot plant results; i.e., more than 98% uranium dissolution in 1-1/2 h (Ref. 3.5-2).

3.5.2.2.4. Conclusion

There is little scale-up effect in dissolving crushed WAR fissile particles. The reaction of 2 M nitric acid with U_3O_8 is controllable and encounters no foaming.

Based on this study, a batch fissile dissolver operating cycle is proposed. Solids feed to the dissolver should be by batch, and due to its low bulk density (1.3 g/cm^3), solids should be added before the introduction of dilute nitric acid at 25°C to avoid poor mixing and to prevent rapid foam producing reactions. Continuous metering of feed could be utilized, but it has the potential disadvantage of bridging at the feed chute, especially if the fissile ash is wetted by condensation from boiling nitric acid.

Fig. 3.5-4. 0.20-m secondary burner size distribution of product from sequential operations run

Fig. 3.5-5. Uranium dissolution rate curves for runs 187 and 188

Fig. 3.5-6. Bench-scale dissolution of WAR fissile ash

Fig. 3.5-7. WAR fissile dissolver feed and residue. Top photo shows WAR fissile secondary burner ash before dissolution (x20) Bottom shows WAR fissile dissolver residue after dissolution (x20)

In actual spent fuel, the decay heat generation in the ash will probably cause the fissile dissolution to occur above ambient temperature. The estimated decay heat for WAR fissile (Segment 9 fuel) is 164 W/FE (560 Btu/h-FE), which could raise the dissolver solution temperature to 30° to 40°C with no cooling. The projected dissolution rate is in the envelope bounded by the curves at boiling (103°C) and at room temperature (19°C). The ambient temperature curve represents the lowest reaction rate. If peak NO_x concentration in the off-gas treatment system must be limited to less than 10,000 ppm (Ref. 3.5-4) in the NO_x converter, we should operate at lower temperature (i.e., below boiling) at least in the first few hours of the cycle to control reaction rate by temperature. After the bulk of uranium is dissolved, the solution temperature can be brought to the boiling point to dissolve as much residue as possible and to volatilize iodine. Since the dissolution curves at ambient and boiling are widely separated, using temperature to control NO_x evolution is relatively effective.

Spurge gas is required to promote mixing, especially in the nonboiling portion of the cycle. The spurge gas would at the same time dilute the NO_x evolved in the reaction.

The dissolver solution will be cooled down to less than 35°C before initiating slurry transport with the steam jet.

REFERENCES

- 3.5-1. "HTGR Fuel Recycle Development Program Quarterly Progress Report For The Period Ending May 31, 1978," DOE Report GA-A15011, General Atomic Company, June 1978.
- 3.5-2. "HTGR Fuel Recycle Program Quarterly Progress Report For The Period Ending November 30, 1977," DOE Report GA-A14738, General Atomic Company, December 1977.
- 3.5-3. "HTGR Fuel Recycle Development Program Quarterly Progress Report For The Period Ending February 28, 1978," DOE Report GA-A14878, General Atomic Company, March 1978.
- 3.5-4. Park, U. S., General Atomic Company, private communication, May 15, 1978.

3.6. OFF-GAS TREATMENT AND RETENTION PROCESSES (SUBTASK 340)

3.6.1. Summary

Design of all auxiliaries and electrical schematics for instrumentation have been completed. The process flow (PF) and piping and instrument (P&I) diagrams have been revised, updated, and issued. A thermal stress analysis has been performed on system piping. Metal bellows joints have been added to relieve excessive thermal expansion.

The remodeling of the platform for the system installation and the expansion of the control room have been completed on schedule. All framework for the vessel and auxiliary installation is in place.

Fabrication of major system vessels, i.e., adsorption columns for I_2 , I_2 back-up, SO_2 , Rn, HTO, Kr/ CO_2 , and moisture adsorption and a NO_X catalytic converter has been completed. Fabrication of CO/HT oxidizer and auxiliaries such as PbX iodine adsorber, iodine generator, dissolver off-gas (DOG) humidifier, and DOG condenser-demister is continuing.

All major vessels fabricated have been installed and piping for inter-connection of the vessels and other system components such as heaters, heat exchangers, rotameters, and control valves is being installed. Utility piping has been completed to the point where it can be connected to the off-gas system.

The Diogenes digital process control system and the Hewlett-Packard data acquisition system have been installed. However, all other electrical work has been halted due to a budget reduction.

The completion of system installation is deferred to FY-79, and only system piping work is continuing at a reduced pace.

3.6.2. Auxiliary System Design

Design of auxiliary systems, i.e., PbX iodine adsorption column for I_2 bed regeneration, dissolver off-gas (DOG) humidifier, and DOG condenser-demister, has been completed. The components and vessels are under fabrication.

I_2 and I_2 back-up beds are regenerated at 500°C with H_2 . The effluent gas consisting mainly of H_2 and small amount of HI is passed through a PbX (lead exchanged molecular sieve 13X) bed at 150°C. HI adsorbs on PbX, and the hydrogen is recycled back to the I_2 bed. This will enable us to reuse the expensive silver exchanged molecular sieves (Zeolon 900 and 13X), and at the same time will provide valuable information on regeneration characteristics of silver zeolites (AgZ and AgX) and adsorption characteristics of HI on PbX.

The iodine generator is essentially a packed bed of iodine kept in a constant temperature water bath. A small amount (0.5 scfm) of sweep gas, i.e., CO_2 for burner off-gas (BOG) and N_2 for DOG, is passed through the packed bed of iodine and the iodine saturated gas mixes into the main BOG or DOG stream. The temperature of the water bath is controlled to give a desired iodine vapor pressure in the main gas stream.

Figures 3.6-1 through 3.6-3 show the details of the PbX I_2 adsorber, iodine vapor generator, and DOG condenser-demister.

3.6.3. Fabrication and Installation

Fabrication of major vessels, i.e., adsorption columns for I_2 , I_2 backup, SO_2 , Ru, HTO, Kr/ CO_2 and moisture adsorption, and a NO_x catalytic converter has been completed. Fabrication of the CO/HT oxidizer has been delayed due to a material shrinkage during welding and a design modification to increase the catalyst bed length. Completion of the CO/HT oxidizer unit is expected by August 31, 1978. All other auxiliary vessel fabrication is continuing.

NOTES:

ALL FLANGES TO BE ASA D16.5 150LB RAISED
FACE. GASKET FACE TO BE SMOOTH TO 100
MICROINCHES & FLAT WITHIN $\pm .001$

72 GASKET DIMENSIONS TO CONFORM TO
REQUIREMENTS OF ASA B16.21 FOR
150 LB RAISED FACE STEEL FLANGES
SOURCE: UNION CARBIDE CARBON PROD.
120 SO. RIVERSIDE PLAZA
CHICAGO, ILL., 60606

1. NORMAL OPERATING CONDITIONS:
16.7 PSIA @ 302°F
2. FABRICATE IN ACCORDANCE WITH SECTION
VIII OF ASME B + PV CODE. STAMP
IS NOT REQUIRED.
3. PRESSURE TEST WITH 50 PSIG HE LEAK RATE TO
CONFORM TO QDI LTH-3801A
4. SOLVENT CLEAN AND SEAL OPENINGS
PRIOR TO SHIPPING
5. VESSEL WT = (LATER)
CONTENTS : LEAD ZEOLITE = 25 LBS.
GROSS WT = (LATER)
6. POSITION ITEM 5 FOR BOLTS TO CLEAR
ITEM 16, MARKED P
7. WELD BY GMA OR GTA PROCESS
8. PENETRANT INSPECT PER QDI-PT3801
9. DESIGN CONDITIONS, 50 PSIG @ 930°F
10. SOURCE : LADISH

				4	26		5/8-11 HEX NUT	SST 316	SA-194 B-8M
				8	25		5/8-10 HEX NUT	SST 316	SA-194 B-8M
				1	24	5650121-22	SCREEN ASS'Y.		
				4	23		5/8 LOCKWASHER	SST 316	FFW-84
				4	22		5/8-PLAIN WASHER	SST 316	FFW-84
				4	21		5/8-11UNC-2A x 2 1/4 LG. HEX. HD.	SST 316	SA-193 B-8M
12				1	20	G 4769	GASKET, 2" FLANGE 1/16 THK.	ONE GRAFLOL SST 316	
				8	19		3/4 LOCKWASHER	SST 316	FFW-84
				8	18		3/4 PLAIN WASHER	SST 316	FFW-84
				8	17		3/4-10UNC-2A x 3 LG. HEX. HD.	SST 316	SA-193 B-8M
				5	16		ROUND, 1 1/2 φ	SST 316L	SA-479
10				1	15		BLIND FLANGE 2"-150°	SST 316L	SA-182
				2	14	5650121-14	BRACKET, MTG.		
				1	13	5650121-23	SCREEN		
12				1	12	G 4772	GASKET, 6" FLANGE 1/16 THK	ONE GRAFLOL SST 316	
10				1	11		BLIND FLANGE 6"-150°	SST 316L	SA-182
				1	10		CAP, 6" SCH. 10S	SST 316L	SA-182
				2	9		PIPE, 1/2" SCH 10S	SST 316L	SA-312
10				2	8		FLANGE, SLIP-ON 1/2"-150°	SST 316L	SA-182
				1	7		PIPE 2" SCH 10S	SST 316L	SA-312
10				1	6		FLANGE, SLIP-ON 2"-150°	SST 316L	SA-182
				1	5		FLANGE, SLIP-ON 6"-150°	SST 316L	SA-182
				1	4		PIPE, 6" SCH 10S	SST 316L	SA 312
				1	3	5650121-21	SCREEN ASSY		
				1	2	5650120-11	BASKET, SAMPLING ASSY		
				1	1		ASSEMBLY		
				-1					
				ITEM	PART NO.		DESCRIPTION	MATL	
							LIST OF MATERIAL		

Fig. 3.6-1. Vessel PbX iodine adsorber

NOTES:
 1 SOURCE: SHAWGLAX, SAN DIEGO VALVE, 1295-C, NORTH, S.D. CAL. 92110
 2 SOURCE: MOTT, A.G. ANDERSON, 4022 PLANN DRIVE, LA PALM, CAL. 90623
 3 SOURCE: BLUE M. ELECTRIC, BLUE ISLAND, ILLINOIS, 60406

ITEM	PART NO.	DESCRIPTION	MATL.
23			
22			
21			
20			
19	1210-7-8	CONNECTOR, 3/8"	
18	810-7-4	CONNECTOR, 1/2"	
17	1210-6	UNION, 3/4"	
16	810-6	UNION, 1/2"	
15		SHEET, 24 GA	304 SS ASTM-A-276
14		TUBE, 1/2 I.D. X 13 WALL	304 SS ASTM-A-276
13		TUBE, 1/2 I.D. X 12 WALL	304 SS ASTM-A-276
12		TUBE, 1/2 I.D. X 13 WALL	304 SS ASTM-A-276
11	1210-1-8	CONNECTOR, 3/4"	304 SS
10	810-1-6	CONNECTOR, 1/2"	304 SS
9	3" TUBING	FILTER, POROUS METAL, 1/2"	316 SS
8		PLATE, 1/4"	304 SS ASTM-A-276
7		CAP, 2" SCH 40	304 SS ASTM-A-312
6		PIPA, 2" SCH 40	304 SS ASTM-A-312
5		GENERATOR ASSY	
4		COIL, 1/2 I.D. X 12 WALL	304 SS ASTM-A-276
3	MPI-AE	COVER	
2	MPI-11502	WATER BATH	
1		ASSY	

Fig. 3.6-2. Iodine vapor generator off-gas treatment system

- NOTE 5:
- 1 SOURCE: SWAGelok, S.D. VALVE, 1295-C MORENA, SAN DIEGO, 92110
 - 2 SOURCE: DUCONNIN, 1300 WILSON, SAN DIEGO CAL. 92051
 - 3 SOURCE: LADISH, KIPPEN APP, 7510 CARROLL CANYON, S.D. 92121
 - 4 MAX. DESIGN PRESSURE: 50 PSIA MAX. DESIGN TEMP: 100°C
MAX. OPERATING PRESSURE: 25 PSIA MAX. OPERATING TEMP: INLET 65°C
OUTLET 25°C
 - 5 FLEXITALLIC, INDUSTRIAL SUPPLY, 23018 NORMANDIA, TORRANCE, CALIFORNIA, 90502

ITEM	PART NO	DESCRIPTION	MATL
1	21	CG-10	
1	20	GASKET, 8"	
2	19	TUBE 1/2" OD x 0.049 WALL x 6	304 SS ASTM A-276
2	18	FL, 90°, 1/2"	304 SS
2	17	MALE CONNECTOR	304 SS
2	16	TUBE 1/2" OD x 0.049 WALL	304 SS ASTM A-276
2	15	PIPE, 2 SCH. 40	304 SS ASTM A 312
2	14	FLANGE, 2, 150° ASME	304 SS
2	13	FLANGE, 2, 150° ASME	304 SS
2	12	WASHER, 3/16" FLAT	304 SS
2	11	NUT, 3/4-10	304 SS
2	10	BOLT, 3/4-10 x 1	304 SS
2	9	TYPE O WOOD, STAPLE (STAINLESS)	
2	8	MESH #12	
2	7	SCREEN	
2	6	TUBE, 5/16" OD x 10mm	ASTM A-276
2	5	FINNED TUBE CLEANING	
2	4	TUBE 1/2" OD x 0.049 WALL	ASTM A-276
2	3	PLATE 500x400x1/4	ASTM A 270
2	2	PLATE 1/2"	ASTM A 270
2	1	NIPPLE, 1 SCH. 40 x 1.5	ASTM A 312
2	0	PIPE, 2 SCH. 40	304 SS ASTM A 312
2	0	ASSY	

Fig. 3.6-3. Condenser/demister off-gas treatment system

In order to facilitate the piping installation and to evaluate thermal stresses, especially during a regeneration cycle, a piping diagram has been developed (Fig. 3.6-4). The results from a thermal analysis of the piping system revealed possible overstress to several pipe joints. Metal bellows joints have been added to these points. All materials are on order.

Installation of major vessels received has been completed as shown in Fig. 3.6-5. Piping for the vessels and system components such as rotameters, heaters, heat exchangers, and control valves is progressing well as shown in Fig. 3.6-6. Figure 3.6-7 shows the CO/HT oxidizer system arrangement to be added next. Due to a budget reduction, however, less activity in system installation is expected for the remainder of FY-78.

The Diogenes digital process controller and the Hewlett-Packard data acquisition and analysis system have been installed (Fig. 3.6-8). All other activities in electrical system installation were halted in July due to a budget cut; these activities have been deferred into FY-79.

3.6.4. Schedule and Milestones

All major design and purchase orders have been completed and receipt of purchased items is continuing. Installation of system vessels, electrical works, and instrumentation work have progressed well so far. Due to a budget reduction, however, all activities except the piping installation have been curtailed and deferred into FY-79. The piping installation is continuing, however, at a reduced pace. Figure 3.6-9 shows an up-to-date schedule on system installation.

The completion of engineering off-gas system installation (Milestone No. 50) accordingly has been deferred into FY-79.

3.7. SEPARATION PROCESSES (SUBTASK 350)

No experimental work was performed during the quarter on HTGR solvent extraction or HTGR solvent extraction feed adjustment.

NOTES
 1. LINES & VALVES SHOWN PER P&ID SHEET 1
 FOR ADDITIONAL INFORMATION SEE SHEET 2
 2. INDICATES 2 IPS
 3. DIME SIZE
 4. SLSXXX INDICATES VESSEL Y-1000
 5. SEE ADJACENT TO VALVE INDICATES L&T TYPE
 6. DIME SIZE ON P&ID SHEET

Fig. 3.6-4. Single line piping diagram for off-gas

Fig. 3.6-5. Off-gas system vessels. From left to right: Kr/CO_2 , Rn , H_2O , SO_2 , I_2 backup, and I_2 adsorbers. Three tall vessels (over 10 ft) extend to lower floor through a cutout.

Fig. 3.6-6. Installation of adsorbers and auxiliaries. The support framework and heat exchanger blower for CO/HT oxidizer are shown behind the person.

Fig. 3.6-8. Partially completed control room. Diogenes digital computer controller, PIM's and HP data acquisition system are shown. Recorders, indicators, and alarms are to be installed on the panels (arrow mark).

NOTES:
 ▲ PURCHASE CONTINGENT ON FY79 BUDGET LEVEL
 ▲ INSTALLATION COMPLETION MILESTONE REVISED TO 12/31/78 FROM 9/30/78 DUE TO BUDGET.
 RE- TELECOPY ALLEN TO LOTT, JULY 14, 1978.

Fig. 3.6-9. Off-gas design and installation schedule

3.8. REWORK AND RECYCLE (SUBTASK 360)

3.8.1. Summary

Bench-scale corrosion work designed to evaluate corrosion rates of candidate metals for the nitric acid fractionator was completed.

3.8.2. HNO₃ - HF Corrosion Study

3.8.2.1. Corrosion Coupon Preparation. Corrosion coupons from samples of 316L stainless steel, Hastelloy C-4, and Nitronic 50 were prepared for use in this work. Welded and unwelded coupons were used. The welded type consisted of two strips of identical metal welded lengthwise. Table 3.8-1 provides information on the metal alloys used.

All cutting operations during fabrication were performed by shearing since this did not result in as severe a thermal treatment of the metal as flame cutting or friction sawing. For the welded coupons, the metal pieces to be welded were secured to a welding fixture with an argon purge gas constantly applied to the underside of the weld area. A gap of 1.6 mm was set between the edges for Hastelloy C-4 and 316L stainless steel and a gap of 3.2 mm was set for the Nitronic 50 so that a full weld penetration could be obtained. Both sides were welded using weld rods or wires of identical composition in each case. Coupons were cut to approximately 25.4 mm x 50.8 mm after which a 6.35 mm hole was drilled through the center of each coupon for mounting purposes. Each coupon was then polished on a stainless steel grinding wheel to remove any weld slag or discoloring prior to being measured for surface area.

3.8.2.2. Equipment. The test apparatus consisted of a 254-mm length of 152.4-mm-diameter Teflon bar stock machined to a 127 mm inner diameter and sealed at either end with threaded Teflon caps (Fig. 3.8-1). Coupons were suspended on four 6.35 mm Teflon rods in the liquid solution or vapor space of the apparatus. The system was vented to atmosphere by an 11.1-mm-

TABLE 3.8-1
CORROSION COUPON ALLOYS

Alloy	Heat No.	Density (g/cm ³)	Approximate Dimensions (mm)	Weld Filler
316L SS	50447	8.04	25.4 x 50.8 x 4.76	316L SS
Hastelloy C-4	245550834	8.64	25.4 x 50.8 x 3.97	Hastelloy C-4
Nitronic 50	37286-ID	7.88	25.4 x 50.8 x 4.76	Nitronic 50

Fig. 3.8-1. Corrosion test apparatus

diameter Teflon tube routed through a condenser. The entire apparatus to the condenser was inserted into an oven where a constant temperature was maintained for the duration of each experiment.

3.8.2.3. Experimental Procedure. Corrosion tests were performed with 24 coupons at a time in the apparatus. Eight coupons of each metal (four welded, four unwelded) were spaced symmetrically through the liquid and vapor regions. Each test was performed with an identical experimental procedure except for the variation in environmental conditions from test to test. Prior to installation, coupons were individually scrubbed with a soap solution and stainless steel wire brush and then weighed on an analytical balance. Once proper positioning of the coupons was achieved, the acid solution was heated to operating temperature and added to the test apparatus, which was then inserted into a preheated oven. Operating conditions used were 13.5 M HNO_3 , 10^{-4} to 5×10^{-3} M HF, and 60° to 100°C.

3.8.2.4. Discussion of Results. Sufficient accuracy for comparative work may usually be obtained by neglecting corrosion over the first 48 h.* This initial period allows for any film formation on the metal and may be considered a preparation for the final test. In this study, each test was interrupted after 48 h to obtain intermediate weighings. A new acid solution was then added to the apparatus after reinsertion of the coupons. The second corrosion period lasted 144 h, after which a final weighing and visual examination of the coupons were performed.

Data pertaining to the weight loss and resultant corrosion rate of each coupon tested are given in Table 3.8-2. Visual observations are presented in Table 3.8-3. In general, corrosion in and around weld areas of the coupons appeared less severe than that of surrounding surfaces. Little, if any, effect was noticed as to knifeline attack at the weld base interface or weld bead decay. Most coupons showed some degree of discoloration ranging from a brownish or blackish tint at low fluoride concentrations

*Perry's Chemical Engineers' Handbook, fourth edition, pp. 23-69.

TABLE 3.8-2
CORROSION COUPON WEIGHT LOSS DATA

Coupon Identification	Environment	Temp. (°C)	HF (M)	Initial Weight (g)	Initial Surface Area (mm ²)	48-Hour Weight Loss (g)	Next 144 Hour Weight Loss (g)	48-Hour Corrosion Rate mm/yr (mils/yr)	144-Hour Corrosion Rate mm/yr (mils/yr)
<u>Hastelloy C-4</u>									
H-1W ^(a)	Liquid	60	0.0001	44.3178	2995.9	0.0423	0.0512	0.298 (11.8)	0.120 (4.7)
H-2W	Vapor	60	0.0005	44.3360	3014.8	0.0354	0.0661	0.248 (9.8)	0.154 (6.1)
H-3W	Liquid	60	0.0005	43.9990	2984.0	0.0500	0.1084	0.354 (13.9)	0.256 (10.1)
H-5W	Vapor	60	0.0005	43.7672	3017.2	0.0348	0.0718	0.244 (9.6)	0.168 (6.6)
H-6W	Liquid	60	0.0005	48.2156	3310.3	0.0539	0.1196	0.344 (13.6)	0.255 (10.0)
H-7W	Vapor	60	0.0001	43.8900	3009.0	0.0285	0.0267	0.200 (7.9)	0.063 (2.5)
H-8W	Vapor	100	0.005	43.7854	3018.5	0.4952 ^(b)	1.3129 ^(c)	3.541 (139.4)	3.119 (122.8)
H-9W	Liquid	100	0.005	43.9404	3017.6	0.7943 ^(b)	1.8406 ^(c)	5.564 (219.0)	4.373 (172.2)
H-11W	Vapor	100	0.005	44.7520	3018.6	0.4619 ^(b)	1.2467 ^(c)	3.303 (130.0)	2.961 (116.6)
H-12W	Liquid	100	0.005	49.8576	3377.2	0.8766 ^(b)	2.0232 ^(c)	5.603 (220.6)	4.295 (169.1)
H-13W	Liquid	60	0.0001	44.3128	3007.2	0.0445	0.0507	0.313 (12.3)	0.119 (4.7)
H-14W	Vapor	60	0.005	43.6369	3014.4	0.1398	0.3022	0.980 (38.6)	0.706 (27.8)
H-15W	Liquid	60	0.005	43.6770	3004.4	0.2268	0.4691	1.596 (62.8)	1.100 (43.3)
H-17W	Vapor	60	0.005	44.1279	3035.0	0.1318	0.2846	0.918 (36.1)	0.661 (26.0)
H-18W	Liquid	60	0.005	48.7878	3330.7	0.2531	0.5217	1.606 (63.2)	1.104 (43.4)
H-19W	Vapor	60	0.0001	45.3558	3043.0	0.0294	0.0228	0.204 (8.0)	0.053 (2.1)
H-20W	Vapor	100	0.0001	44.7960	3028.2	0.2275	0.6563	1.588 (62.5)	1.527 (60.1)
H-21W	Liquid	100	0.0001	44.7543	3033.8	0.4164	1.1329	2.901 (114.2)	2.631 (103.6)
H-23W	Vapor	100	0.0001	44.7721	3038.1	0.2224	0.6429	1.547 (60.9)	1.491 (58.7)
H-24W	Liquid	100	0.0001	49.6088	3322.5	0.4384	1.2265	2.789 (109.8)	2.601 (102.4)
H-1	Liquid	60	0.0001	41.2391	2938.8	0.0333	0.0516	0.240 (9.4)	0.124 (4.9)
H-2	Vapor	60	0.0005	41.2885	2943.2	0.0241	0.0644	0.173 (6.8)	0.154 (6.1)
H-3	Liquid	60	0.0005	41.5964	2946.1	0.0442	0.1111	0.317 (12.5)	0.266 (10.5)
H-5	Vapor	60	0.0005	41.6025	2962.4	0.275	0.0748	0.196 (7.7)	0.178 (7.0)

TABLE 3.8-2 (Continued)

Coupon Identification	Environment	Temp. (°C)	HF (M)	Initial Weight (g)	Initial Surface Area (mm ²)	48-Hour Weight Loss (g)	Next 144-Hour Weight Loss (g)	48-Hour Corrosion Rate mm/yr (mils/yr)	144-Hour Corrosion Rate mm/yr (mils/yr)
<u>Hastelloy C-4</u> (cont'd)									
H-6	Liquid	60	0.0005	45.8701	3221.1	0.0474	0.1211	0.311 (12.2)	0.265 (10.4)
H-7	Vapor	60	0.0001	42.7806	3012.9	0.0171	0.0330	0.120 (4.7)	0.077 (3.0)
H-8	Vapor	100	0.005	42.5292	3018.6	0.4821 ^(b)	1.2367 ^(c)	3.448 (135.7)	2.938 (115.7)
H-9	Liquid	100	0.005	42.4246	3012.1	0.7935 ^(b)	1.7723 ^(c)	5.687 (223.9)	4.219 (166.1)
H-11	Vapor	100	0.005	42.6198	3022.7	0.4684 ^(b)	1.2036 ^(c)	3.275 (129.0)	2.855 (112.4)
H-12	Liquid	100	0.005	46.6728	3294.8	0.8733 ^(b)	1.9349 ^(c)	5.602 (220.6)	4.211 (165.8)
H-13	Liquid	60	0.0001	42.4786	2994.2	0.0362	0.0505	0.256 (10.1)	0.119 (4.7)
H-14	Vapor	60	0.005	42.3924	2988.8	0.1455	0.2693	1.029 (40.5)	0.635 (25.0)
H-15	Liquid	60	0.005	42.2134	2983.2	0.2247	0.4652	1.592 (62.7)	1.099 (4.3)
H-17	Vapor	60	0.005	42.1873	2993.4	0.1247	0.2904	0.881 (34.7)	0.684 (26.9)
H-18	Liquid	60	0.005	47.0498	3276.6	0.2496	0.5192	1.610 (63.4)	1.116 (44.0)
H-19	Vapor	60	0.0001	42.4150	2990.6	0.0179	0.0258	0.127 (5.0)	0.061 (2.4)
H-20	Vapor	100	0.0001	42.3953	3021.4	0.2364	0.6239	1.654 (65.1)	1.455 (47.3)
H-21	Liquid	100	0.0001	42.2460	2992.3	0.3873	1.0333	2.736 (107.7)	2.433 (95.8)
H-23	Vapor	100	0.0001	42.4725	3023.7	0.2246	0.5952	1.570 (61.8)	1.387 (54.6)
H-24	Liquid	100	0.0001	47.1985	3327.9	0.4183	1.1180	2.657 (104.6)	2.367 (93.2)
H-25	Vapor	100	0.0001	42.5035	2988.6	0.2295	0.6078	1.623 (63.9)	1.433 (56.4)
H-26	Liquid	100	0.0001	42.3088	2980.0	0.3850	1.0312	2.731 (107.5)	2.438 (96.0)

TABLE 3.8-2 (Continued)

Coupon Identification	Environment	Temp. (°C)	HF (M)	Initial Weight (g)	Initial Surface Area (mm ²)	48-Hour Weight Loss (g)	Next 144-Hour Weight Loss (g)	48-Hour Corrosion Rate mm/yr (mils/yr)	144-Hour Corrosion Rate mm/yr (mils/yr)
<u>Nitronic 50</u>									
N-1W	Liquid	60	0.0001	52.1771	3135.4	0.0207	0.0105	0.153 (6.0)	0.026 (1.0)
N-2W	Vapor	60	0.0005	52.3504	3135.0	0.0233	0.0307	0.172 (6.8)	0.076 (3.0)
N-3W	Liquid	60	0.0005	51.9547	3130.0	0.0287	0.0372	0.213 (8.4)	0.092 (3.6)
N-5W	Vapor	60	0.0005	51.5829	3149.1	0.0218	0.0303	0.160 (6.3)	0.074 (2.9)
N-6W	Liquid	60	0.0005	56.3984	3437.6	0.0316	0.0417	0.213 (8.4)	0.094 (3.7)
N-7W	Vapor	60	0.0001	50.5169	3087.2	0.0150	0.0080	0.113 (4.4)	0.020 (0.8)
N-8W	Vapor	100	0.005	50.3429	3088.4	0.2537 ^(b)	0.4385 ^(c)	1.944 (76.5)	1.116 (43.9)
N-9W	Liquid	100	0.005	50.2225	3090.8	0.2875 ^(b)	0.4290 ^(c)	2.202 (86.7)	1.091 (43.0)
N-11W	Vapor	100	0.005	50.8400	3132.1	0.2435 ^(b)	0.3992 ^(c)	1.840 (72.4)	1.002 (39.4)
N-12W	Liquid	100	0.005	58.7699	3560.8	0.3326 ^(b)	0.4912 ^(c)	2.211 (87.0)	1.085 (42.7)
N-13W	Liquid	60	0.0001	50.5946	3096.9	0.2222	0.0120	0.166 (6.5)	0.030 (1.2)
N-14W	Vapor	60	0.005	49.9899	3086.0	0.1188	0.1521	0.892 (35.1)	0.381 (15.0)
N-15W	Liquid	60	0.005	49.9859	3091.3	0.1432	0.1653	1.074 (42.3)	0.413 (16.3)
N-17W	Vapor	60	0.005	49.8201	3123.0	0.1238	0.1533	0.919 (36.2)	0.379 (14.9)
N-18W	Liquid	60	0.005	57.1967	3469.9	0.1584	0.1870	1.058 (41.7)	0.416 (16.4)
N-19W	Vapor	60	0.0001	51.3922	3104.7	0.0166	0.0097	0.124 (4.9)	0.024 (1.0)
N-20W	Vapor	100	0.0001	51.3710	3150.6	0.2278	0.2321	0.1676 (66.0)	0.569 (22.4)
N-21W	Liquid	100	0.0001	51.0400	3083.9	0.0841	0.0739	0.632 (24.9)	0.185 (7.3)
N-23W	Vapor	100	0.0001	50.8233	3097.2	0.2200	0.2221	1.646 (64.8)	0.554 (21.8)
N-24W	Liquid	100	0.0001	57.7418	3456.4	0.0898	0.0783	0.602 (23.7)	0.175 (6.9)
N-1	Liquid	60	0.0001	48.6395	3065.9	0.0130	0.0113	0.098 (3.9)	0.028 (1.1)
N-2	Vapor	60	0.0005	48.1125	3067.3	0.0205	0.0452	0.155 (6.1)	0.114 (4.5)
N-3	Liquid	60	0.0005	48.0221	3046.0	0.0326	0.0519	0.248 (9.8)	0.132 (5.2)

TABLE 3.8-2 (Continued)

Coupon Identification	Environment	Temp. (°C)	HF (M)	Initial Weight (g)	Initial Surface Area (mm ²)	48 Hour Weight Loss (g)	Next 144-Hour Weight Loss (g)	48-Hour Corrosion Rate mm/yr (mils/yr)	144-Hour Corrosion Rate mm/yr (mils/yr)
<u>Nitronic 50</u> (cont'd)									
N-5	Vapor	60	0.0005	48.7246	3190.3	0.0202	0.0454	0.147 (5.8)	0.110 (4.3)
N-6	Liquid	60	0.0005	55.4079	3439.6	0.0347	0.0550	0.234 (9.2)	0.124 (4.9)
N-7	Vapor	60	0.0001	49.2157	3103.0	0.0081	0.0056	0.060 (2.4)	0.014 (0.5)
N-8	Vapor	100	0.005	49.4915	3092.1	0.2809 ^(b)	0.4062 ^(c)	2.150 (84.7)	1.033 (40.7)
N-9	Liquid	100	0.005	49.6746	3106.5	0.3195 ^(b)	0.4373 ^(c)	2.434 (95.8)	1.107 (43.6)
N-11	Vapor	100	0.005	49.6144	3095.7	0.2579 ^(b)	0.3820 ^(c)	1.972 (77.6)	0.970 (38.2)
N-12	Liquid	100	0.005	55.0965	3392.5	0.3420 ^(b)	0.4701 ^(c)	2.386 (93.9)	1.089 (42.9)
N-13	Liquid	60	0.0001	49.7606	3068.9	0.0119	0.0118	0.090 (3.5)	0.030 (1.2)
N-14	Vapor	60	0.005	49.4446	3083.7	0.1422	0.1692	1.069 (42.1)	0.424 (16.7)
N-15	Liquid	60	0.005	49.6771	3091.4	0.1620	0.1791	1.214 (47.8)	0.448 (17.6)
N-17	Vapor	60	0.005	48.8978	3074.1	0.1365	0.1741	1.029 (40.5)	0.438 (17.2)
N-18	Liquid	60	0.005	55.0026	3436.4	0.1813	0.1961	0.223 (48.1)	0.441 (17.4)
N-19	Vapor	60	0.0001	50.2022	3108.9	0.0077	0.0051	0.057 (2.3)	0.013 (0.5)
N-20	Vapor	100	0.0001	49.8538	3091.3	0.2169	0.2185	1.626 (64.0)	0.546 (21.5)
N-21	Liquid	100	0.0001	49.2580	3064.2	0.0748	0.0674	0.566 (22.3)	0.170 (6.7)
N-23	Vapor	100	0.0001	48.8634	3062.8	0.2081	0.2113	1.575 (62.0)	0.533 (21.0)
N-24	Liquid	100	0.0001	54.5208	3410.0	0.0800	0.0671	0.544 (21.4)	0.152 (6.0)
N-25	Vapor	100	0.0001	50.1400	3099.5	0.2151	0.2183	1.608 (63.3)	0.544 (21.4)
N-26	Liquid	100	0.0001	49.9237	3124.8	0.0774	0.0700	0.574 (22.6)	0.173 (6.8)

TABLE 3.8-2 (Continued)

Coupon Identification	Environment	Temp. (°C)	HF (M)	Initial Weight (g)	Initial Surface Area (mm ²)	48-Hour Weight Loss (g)	Next 144-Hour Weight Loss (g)	48 Hour Corrosion Rate mm/yr (mils/yr)	144-Hour Corrosion Rate mm/yr (mils/yr)
<u>316L SS</u>									
S-1W	Liquid	60	0.0001	43.4971	2940.7	0.0136	0.0058	0.105 (4.1)	0.015 (0.6)
S-2W	Vapor	60	0.0005	43.5955	3004.5	0.0153	0.0235	0.116 (4.6)	0.059 (2.3)
S-3W	Liquid	60	0.0005	43.6229	2972.8	0.0211	0.0324	0.161 (6.3)	0.083 (3.2)
S-5W	Vapor	60	0.0005	44.1611	2999.5	0.0149	0.0271	0.113 (4.4)	0.068 (2.7)
S-6W	Liquid	60	0.0005	48.0039	3263.0	0.0214	0.0354	0.149 (5.9)	0.082 (3.2)
S-7W	Vapor	60	0.0001	42.5984	2945.6	0.0091	0.0017	0.070 (2.8)	0.004 (0.2)
S-8W	Vapor	100	0.005	42.6730	2946.2	0.2736 ^(b)	0.6871 ^(c)	2.154 (84.8)	1.797 (70.7)
S-9W	Liquid	100	0.005	42.8866	2953.8	0.3202 ^(b)	0.7223 ^(c)	2.515 (99.0)	1.884 (74.2)
S-11W	Vapor	100	0.005	43.0934	2995.5	0.2537 ^(b)	0.6356 ^(c)	1.965 (77.4)	1.635 (64.4)
S-12W	Liquid	100	0.005	47.0851	3227.0	0.3408 ^(b)	0.7531 ^(c)	2.450 (96.5)	1.798 (70.8)
S-13W	Liquid	60	0.0001	42.7149	2975.3	0.0107	0.0053	0.082 (3.2)	0.013 (0.5)
S-14W	Vapor	60	0.005	42.6874	2974.3	0.0928	0.2178	0.709 (27.9)	0.554 (21.8)
S-15W	Liquid	60	0.005	43.4353	2996.1	0.1294	0.2628	0.981 (38.6)	0.664 (26.1)
S-17W	Vapor	60	0.005	44.0564	3023.1	0.0957	0.2257	0.719 (28.3)	0.565 (22.3)
S-18W	Liquid	60	0.005	48.1646	3259.6	0.1414	0.2829	0.985 (38.8)	0.657 (25.9)
S-19W	Vapor	60	0.0001	43.5786	2978.7	0.0100	0.0021	0.076 (3.0)	0.005 (0.2)
S-20W	Vapor	100	0.0001	43.7586	3011.1	0.2269	0.5273	1.712 (67.4)	1.326 (52.2)
S-21W	Liquid	100	0.0001	44.1400	3006.1	0.0464	0.5848	0.351 (13.8)	1.473 (58.0)
S-23W	Vapor	100	0.0001	43.9253	3017.9	0.2233	0.4899	1.681 (66.2)	1.229 (48.4)
S-24W	Liquid	100	0.0001	45.9247	3160.1	0.0515	0.5956	0.370 (14.6)	1.427 (56.2)
S-1	Liquid	60	0.0001	41.8194	2962.5	0.0042	0.0040	0.032 (1.3)	0.010 (0.4)
S-2	Vapor	60	0.0005	41.7053	2972.3	0.0053	0.0230	0.041 (1.6)	0.059 (2.3)
S-3	Liquid	60	0.0005	41.8932	2975.6	0.0121	0.0332	0.092 (3.6)	0.084 (3.3)

TABLE 3.8-2 (Continued)

Coupon Identification	Environment	Temp. (°C)	HF (M)	Initial Weight (g)	Initial Surface Area (mm ²)	48-Hour Weight Loss (g)	Next 144-Hour Weight Loss (g)	48-Hour Corrosion Rate mm/yr (mils/yr)	144-Hour Corrosion Rate mm/yr (mils/yr)
<u>316L SS</u> (cont'd)									
S-5	Vapor	60	0.0005	42.8359	3089.1	0.0075	0.0267	0.055 (2.2)	0.065 (2.6)
S-6	Liquid	60	0.0005	46.6863	3281.4	0.0137	0.0354	0.095 (3.7)	0.082 (3.2)
S-7	Vapor	60	0.0001	41.4533	2947.6	0.0028	0.0003	0.022 (0.8)	0.001 (0.03)
S-8	Vapor	100	0.005	41.7747	2971.4	0.2781 ^(b)	0.6780 ^(c)	2.171 (85.5)	1.758 (69.2)
S-9	Liquid	100	0.005	41.7127	2984.5	0.3155 ^(b)	0.7547 ^(c)	2.452 (96.5)	1.948 (76.7)
S-11	Vapor	100	0.005	42.0447	2992.4	0.2461 ^(b)	0.6983 ^(c)	1.908 (75.1)	1.798 (70.8)
S-12	Liquid	100	0.005	44.8697	3168.0	0.3313 ^(b)	0.7819 ^(c)	2.426 (95.5)	1.902 (74.9)
S-13	Liquid	60	0.0001	41.8048	2955.2	0.0042	0.0025	0.032 (1.3)	0.006 (0.3)
S-14	Vapor	60	0.005	42.3954	2999.6	0.0804	0.2431	0.609 (24.0)	0.614 (24.2)
S-15	Liquid	60	0.005	42.4586	3011.0	0.1145	0.2708	0.864 (34.0)	0.681 (26.8)
S-17	Vapor	60	0.005	42.7615	3030.7	0.0842	0.2523	0.631 (24.8)	0.630 (24.8)
S-18	Liquid	60	0.005	44.9540	3168.8	0.1233	0.2834	0.884 (34.8)	0.677 (26.7)
S-19	Vapor	60	0.0001	42.7255	3009.3	0.0031	0.0005	0.023 (0.9)	0.001 (0.05)
S-20	Vapor	100	0.0001	42.3338	2995.2	0.2177	0.5012	1.651 (65.0)	1.267 (49.9)
S-21	Liquid	100	0.0001	42.9037	3044.4	0.0537	0.6566	0.401 (15.8)	1.633 (64.3)
S-23	Vapor	100	0.0001	42.7083	3024.5	0.2041	0.4718	1.533 (60.3)	1.181 (46.5)
S-24	Liquid	100	0.0001	45.5403	3210.1	0.0481	0.6449	0.340 (13.4)	1.521 (59.9)
S-25	Vapor	100	0.0001	41.5171	2956.4	0.2225	0.4811	1.710 (67.3)	1.232 (48.5)
S-26	Liquid	100	0.0001	42.0882	2995.9	0.0583	0.6303	0.442 (17.4)	1.593 (62.7)

(a)_W denotes welded coupon.(b)₄₇ hours.(c)_{141.5} hours.

TABLE 3.8-3
VISUAL INSPECTION OF CORROSION COUPONS AFTER 192 HOURS EXPOSURE

60°C, 0.0001 M HF

Nitronic 50 coupons showed only slight degradation of flat surfaces and edges with welded areas appearing unaffected. Very slight brownish discoloration.

SS 316L corrosion appeared similar in magnitude to Nitronic 50 but with slightly more attack at the edges. Very slight discoloration.

Hastelloy C-4 surfaces appeared smooth and shiny with no apparent color change or corrosion despite higher weight loss than other metals.

100°C, 0.0001 M HF

Nitronic 50 coupons showed moderate pitting on flat surfaces and edges with blackish discoloration. Welded areas showed a lesser degree of corrosion, particularly in the borders around the welds. Vapor coupons showed more apparent corrosive attack and discoloration than liquid coupons.

SS 316L corrosion appeared more severe than Nitronic 50, particularly at the coupon edges. As with Nitronic 50, the weld areas appeared to maintain better integrity than the remaining coupon surfaces. Vapor coupons appeared to show more attack than liquid coupons with both exhibiting blackish discoloration.

Hastelloy C-4 surfaces showed less apparent corrosive action despite higher weight losses than the other metals. Liquid coupon corrosion appeared more severe than that of vapor coupons. No discoloration evident.

60°C, 0.005 M HF

Nitronic 50 coupons showed moderate pitting with weld areas only slightly affected. Coupons exhibited a shiny, whitish surface.

SS 316L coupons showed moderate corrosive attack but less than coupons of other alloys. Weld areas only slightly affected with coupon surfaces again exhibiting a shiny, whitish appearance.

Hastelloy C-4 coupons exhibited more corrosive attack than the other alloys with weld areas less affected. As the others, the coupons showed shiny, whitish surfaces. Vapor coupons also exhibited a greenish coating which was easily washed off with water.

TABLE 3,8-3 (Continued)

100°C, 0.005 M HF

Nitronic 50 coupons showed more pitting than at 60°C with the weld areas less affected than the remaining surfaces. Coupons exhibited shiny, whitish appearance.

SS 316L coupons showed significant attack but less than Nitronic 50. Weld areas less affected than the remaining surfaces. Coupons exhibited shiny, whitish appearance.

Hastelloy C-4 coupons appeared severely corroded with weld areas less affected than other surfaces. Coupons showed shiny, whitish surfaces. Vapor coupons exhibited a greenish coating (more than at 60°C) which was easily removed with water.

to a shiny, whitish appearance at the higher fluoride concentrations. In addition, a greenish deposit (nickel-based compound) was found on the Hastelloy C-4 vapor coupons at high fluoride concentrations. Despite exhibiting a somewhat smoother and shinier appearance than the other alloys, Hastelloy C-4 coupons showed the greatest corrosion as determined by weight loss. With a few exceptions, coupons of all three alloys exhibited less corrosion by weight loss in the equilibrium vapor space of the apparatus than in liquid solution.

The calculated corrosion rates for coupons both in solution and in the vapor are shown graphically in Figs. 3.8-2 and 3.8-3 for the main exposure period (after 48 h). Data are presented as a function of temperature and HF concentration. Figures 3.8-4, 3.8-5, and 3.8-6 show the data for each individual alloy as a function of all operating variables. In all cases, corrosion rates increased with increasing temperature or fluoride composition. In addition, in almost every case corrosion rates were higher during the preliminary 48-h exposure period than in the subsequent exposure period. In the main exposure period, 316L stainless steel showed higher rates for unwelded coupons while Hastelloy C-4 showed higher rates for welded coupons. No discernible trend was evident between welded and unwelded coupons of Nitronic 50.

3.8.2.5. Conclusions. From Figs. 3.8-2 and 3.8-3, it can be seen that Hastelloy C-4 is the least acceptable of the three candidate metals for use in the fractionator. In the main exposure period, Nitronic 50 exhibited the lowest corrosion rates at all operating conditions. In addition to apparent superior corrosion resistance, Nitronic 50 is considerably stronger and has better mechanical properties than conventional 300 series steels. Of the three alloys tested, Nitronic 50 appears to be the most suitable for the range of conditions tested.

Fig. 3.8-2. Corrosion rate in 13.5 $\underline{\text{M}}$ HNO_3 (liquid)

Fig. 3.8-3. Corrosion rate in 13.5 M HNO_3 (equilibrium vapor)

Fig. 3.8-4. Nitronic 50 corrosion rate in 13.5 M HNO₃ during main exposure period

Fig. 3.8-5. 316L SS corrosion rate in 13.5 M HNO₃ during main exposure period

Fig. 3.8-6. Hastelloy C-4 corrosion rate in 13.5 M HNO₃ during main exposure period

4. FUEL REFABRICATION (SECONDARY SUBTASK 541)

4.1. SUMMARY

Shakedown tests continued on the combustion of perchloroethylene distillation bottoms. To date mass spectrographic and gas chromatographic analyses indicate combustion is complete at 650°C with a 30% ethanol and 70% perchloroethylene solution.

4.2. SCRAP RECOVERY

Perchloroethylene (tetrachloroethylene $\text{Cl}_2\text{-C=CCl}_2$) is used for scrubbing off-gases in the HTGR fuel refabrication process. After distillation, the perchloroethylene is recycled leaving the distillation bottoms to be treated for disposal and nuclear material recovery. Currently, a molten salt technique is the method of treatment. As an alternative to this method, combustion in a fluidized bed is being considered for study. Initial tests are being conducted in a laboratory-scale tube reactor to determine the feasibility and reduce the uncertainties of using a fluidized-bed combustion system.

The laboratory-scale apparatus, which was initially constructed as described in the previous quarterly report,* was modified to conform with analytical techniques developed at General Atomic Company and current successful combustion techniques used at the Rocky Flats plant. A schematic of this modified apparatus is shown in Fig. 4.2-1. Modifications included: (1) replacing the sodium carbonate (Na_2CO_3) bed with a two-stage bed of Na_2CO_3 and a chromic trioxide coated alumina catalyst, (2) replacing the evacuated chromatographic sample tube with diverter

*"HTGR Fuel Recycle Program Quarterly Progress Report for the Period Ending May 31, 1978," DOE Report GA-A15011, General Atomic Company, June 1978.

Fig. 4.2-1. Perchloroethylene bottoms combustion laboratory-scale test apparatus

valves and a sample bulb, and (3) replacing the perchloroethylene bubbler with a Texaco normal paraffin hydrocarbon (NPH) (kerosene) bubbler.

The perchloroethylene sample is injected from a hypodermic syringe through a septum into a heated, moving air stream. The air stream transports the vaporized sample into a heated, packed bed of Na_2CO_3 granules. The Na_2CO_3 reacts with the HCl formed by combustion, producing sodium chloride (NaCl). Products of combustion that have not been completely converted to CO_2 and H_2O are converted in the heated catalytic bed. Parallel piping and diverter valves allow the off-gas to be passed through a sample bulb for the purpose of obtaining a sample at a selected point in time. The off-gas then passes through a cooling coil into a kerosene bubbler. Uncombusted perchloroethylene is trapped in the kerosene. The remaining off-gas is scrubbed in a water bubbler prior to venting into a hood.

A method has been developed for chromatographic analysis of perchloroethylene in kerosene. A Varian Model 3700 gas chromatograph equipped with a thermal conductivity detector was used in this study.

The perchloroethylene-kerosene separation was accomplished in a 1.83 m (6 ft) long x 0.64 cm (0.25 in.) diameter free fatty acid phase (FFAP) column operated in a programmed temperature mode. Details of the operational parameters are given in Table 4.2-1. Four standards were prepared containing 0, 25, 50, and 100 μl of perchloroethylene distillation bottoms supplied by ORNL in 25 ml of kerosene. One standard was prepared with 100 μl of reagent grade perchloroethylene in 25 ml of kerosene. Aliquots (5 μl) of each standard were injected into the chromatograph's column, the temperature program was activated, and corresponding chromatograms were obtained. A calibration plot of the standard data is shown in Fig. 4.2-2. Comparison of the pure perchloroethylene standard's result with the ORNL perchloroethylene distillation bottoms standard's result shows a perchloroethylene content of about 89 vol % in the ORNL material.

TABLE 4.2-1
GAS CHROMATOGRAPHIC OPERATIONAL PARAMETERS

1. Attenuation: 0.1
2. Carrier: helium
3. Carrier flow rate: 20 ml/min
4. Column packing: FFAP^(a)
5. Column dimensions: 1.83 m x 0.64 cm
6. Temperature program data:
 - a. Initial temperature = 85°C
Time = 4 min
 - b. Program temperature rise = 10°C/min
 - c. Final temperature = 225°C
Time = 2 min

^(a) Free fatty acid phase

Fig. 4.2-2. Standard calibration data plot for perchloroethylene - GC

The chromatogram of the pure kerosene is shown on Fig. 4.2-3. A typical chromatogram of kerosene containing perchloroethylene is shown in Fig. 4.2-4. From this figure it can be seen that the perchloroethylene has a retention time of about 5.5 min, and is adequately resolved from a minor component of the kerosene (possibly undecane) for detection.

This analytical method is expected to permit detection of as little as 0.03% "breakthrough" of perchloroethylene during combustion of 1.0 ml of reagent grade or distillation bottoms solutions in the laboratory apparatus.

To determine if melting or fusing of the Na_2CO_3 could occur due to uneven furnace heating, two shakedown tests were made. The first used a pure Na_2CO_3 bed purged with air at 575°C . Some friable agglomerates were produced, but no melting or fusing was detected. The large quantity of fines in this unscreened Na_2CO_3 may have contributed to the agglomeration, and larger granules may perform better. The second test used a mixture of 90% Na_2CO_3 and 10% NaCl purged with air at 575°C to simulate a bed composition during combustion. No melting or fusing was apparent, but similar friable agglomerates were again formed.

Subsequent to the initial shakedown tests, 16 tests using perchloroethylene have been completed to establish parameters for combustion. A summary of these parametric studies is given in Table 4.2-2.

In the initial two tests (P-1 and P-2), 100 μl samples of reagent grade perchloroethylene were injected at a 550°C bed temperature. Heating tape was added to the inlet gas line between the first and second tests to ensure vaporization of the sample. No perchloroethylene was detected in the kerosene bubbler in either test. Later tests indicated that this was because it was below detectable limits rather than due to complete combustion.

In the third test (PC-3) a 1 ml sample of reagent grade perchloroethylene was injected. Through an oversight, the temperature had not

Fig. 4.2-3. Chromatogram of Texaco NPH 5 μ l sample injection

Fig. 4.2-4. Chromatogram of Texaco NPH perchloroethylene 5 μ l injection

TABLE 4.2-2
PERCHLOROETHYLENE COMBUSTION TESTS, SWEEP GAS - 0.5 CFH AIR

Test No	Feed Description	Feed Volume	Bed Temp (°C)	Results		Remarks
				Chromatograph	Mass Spec	
PC-1	100% perchloroethylene (reagent)	100 µl	550	No perchloroethylene detected	Not taken	Perchloroethylene in off-gas may have been below detectable limits
PC-2	100% perchloroethylene (reagent)	100 µl	550	No perchloroethylene detected	Not taken	Heat tape added to inlet Perchloroethylene in off-gas may have been below detectable limits
PC-3	100% perchloroethylene (reagent)	1 ml	430	11% perchloroethylene in kerosene bubbler	Not taken	
PC-4	100% perchloroethylene (reagent)	1 ml	550	11% perchloroethylene in kerosene bubbler	Not taken	
PC-5	100% perchloroethylene (reagent)	1 ml	550	18% perchloroethylene in kerosene bubbler	Not taken	
PC-6	100% perchloroethylene (reagent)	1 ml	750	0.8% perchloroethylene in kerosene bubbler	Not taken	Some combustion evident
PC-7	90% perchloroethylene (reagent) + 10% ethanol	1 ml	550	14% perchloroethylene in kerosene bubbler	Not taken	
PC-8	80% perchloroethylene (reagent) + 20% ethanol	1 ml	650	4% perchloroethylene in kerosene bubbler	Not taken	Some combustion evident
PC-9	70% perchloroethylene (reagent) + 30% ethanol	1 ml	650	0.9% perchloroethylene in kerosene bubbler	Not taken	Increased combustion over 80% ethanol
10	70% perchloroethylene distillation bottoms (ORNL) + 30% ethanol	1 ml	650	0.6% perchloroethylene in kerosene bubbler	Not taken	
PC-11	70% perchloroethylene distillation bottoms (ORNL) + 30% ethanol	1 ml	650	0.1% perchloroethylene in kerosene bubbler	Off-gas was air minus O ₂ plus 21% CO ₂ , No hydrocarbons or Cl ₂	No perchloroethylene in off-gas
PC-12	70% perchloroethylene distillation bottoms (ORNL) + 30% ethanol	1 ml	650	0% perchloroethylene in kerosene bubbler	Off-gas was air + CO ₂ , O ₂ , no CCl ₂ or hydrocarbons	CO ₂ level in off-gas was lower at this point.
PC-13	70% perchloroethylene distillation bottoms (ORNL) + 30% ethanol	1 ml	650	0.5% perchloroethylene in kerosene bubbler	Off-gas was air + CO ₂ , O ₂ , no Cl ₂ hydrocarbons, trace H ₂ possible	
PC-14	70% perchloroethylene distillation bottoms (ORNL) + 30% ethanol	1 ml	650	1.4% perchloroethylene in kerosene bubbler	1st Sample Off-gas was air, trace CO ₂ , ~15% O ₂ 2nd Sample Off-gas was air	
PC-15	70% perchloroethylene distillation bottoms (ORNL) + 30% ethanol	1 ml	550	1.4% perchloroethylene in kerosene bubbler	1st Sample Off-gas was air + 16.5% CO ₂ - O ₂ . 2nd Sample Contained trace of a high mol. wt hydrocarbon	Incomplete combustion
PC-16	80% perchloroethylene (reagent) + 20% ethanol	1 ml	550	0.3% perchloroethylene in kerosene bubbler	1st Sample Off-gas was air + 15% CO ₂ - O ₂ . 2nd Sample Definite indications of a high mol. wt hydrocarbon.	Incomplete combustion, perchloroethylene breakthrough evident.

reached the desired 550°C level at the time of sample injection, but was at 430°C. Perchloroethylene was evident in the kerosene bubbler.

In the fourth test (PC-4) at 550°C and the fifth test (PC-5) at 650°C, breakthrough of perchloroethylene was still evident. In the sixth test (PC-6) at 750°C, the quantity of perchloroethylene breakthrough was substantially less. Temperature excursions were observed in all three tests (i.e., 41° at 550°C, 20° at 650°C, and 18° at 750°C).

Since combustion was obviously incomplete at these temperatures with pure perchloroethylene, a solution of 90% perchloroethylene and 10% ethanol was used in the seventh test (PC-7) with a bed temperature of 550°C. Breakthrough was evident; therefore, for the next test (PC-8) both the ethanol concentration and temperature were increased (i.e., 20% ethanol and 650°C). Breakthrough was again evident, but in a smaller quantity than in test PC-7. At 650°C and 30% ethanol (test PC-9) only a small quantity (0.9%) of perchloroethylene breakthrough was detected.

At this point, the perchloroethylene distillation bottoms were substituted for the reagent grade perchloroethylene in solution with 30% ethanol (test PC-10). The kerosene bubbler solution was reused for this test. In the previous tests, fresh solution was used for each test. A similar concentration of perchloroethylene was detected in the bubbler solution indicating no breakthrough. The test was repeated (PC-11) and an off-gas sample was taken at the peak of the first temperature excursion for mass spectrographic analysis. During the three tests with 70% perchloroethylene and 30% ethanol at 650°C, two separate temperature excursions were observed. The first, which occurred as the 1 ml of solution was being injected, was 41°C in magnitude; the second, which occurred about 4 min after injection, was about 12°C in magnitude. A typical plot of these excursions is shown in Fig. 4.2-5. Perchloroethylene concentration in the kerosene bubbler did not increase over that found in the previous tests, indicating no breakthrough.

Fig. 4.2-5. Typical temperature excursion profile during perchloroethylene burning tests

Analysis of the off-gas indicated complete oxygen utilization, CO₂ formation, and no hydrocarbons or chlorine at the peak of the first temperature excursion.

Conditions of test PC-11 were repeated in three more tests (PC-12, -13, and -14). During these tests, off-gas samples were taken at the end of the first temperature excursion, at the peak and end of the second temperature excursion, and about 5 min after the second temperature excursion. Sample points are shown in Fig. 4.2-5. These samples indicated combustion was complete and occurred over a period of 8 min after injection of the perchloroethylene solution. Analysis of the kerosene bubbler solution substantiated that combustion was complete since breakthrough of perchloroethylene was not evident.

For the next test (PC-15) the temperature was lowered to 550°C. Off-gas samples were taken at the end of the first and second temperature excursions. The second sample contained a trace of a high molecular weight hydrocarbon, indicating incomplete combustion. However, breakthrough of perchloroethylene was not detected.

In the final test completed to date (PC-16), the ethanol concentration was lowered to 20%; off-gas samples were taken at similar points with similar results.

These initial tests have shown that complete combustion of pure perchloroethylene is not accomplished at temperatures up to 750°C. However, with the addition of 30% ethanol, combustion occurs at 650°C but not at 550°C. The parameters for combustion will be further defined in future tests.

5. GENERAL SUPPORT (TASK 500)

FSV FUEL TEST ELEMENTS

Since February 27, 1978, all eight test elements were located at the FSV reactor, awaiting insertion with the first refueling operation. ORNL fuel rods are contained in FTE-2, FTE-4, and FTE-6. Relatively high fission gas release data were obtained for these rods after cure-in-place firing; this is believed to be an artifact of obtaining TRIGA rods from an already oversized fuel rod fired in an undersized quality control crucible for subsequent loading into the test elements. All pre- and post-firing metrology data obtained during manufacturing are presently being evaluated for establishing a gap-strain correlation for the as-built FTE fuel rods. Additional firing tests are being carried out to establish the in-situ conditions of ORNL fuel rods, fired in standard size graphite holes as used in the fuel test elements.

The quality control release data package, submitted to ORNL on June 28, 1978, contains all test results obtained for the test elements in support of the QC release earlier this year.

PSC submitted amendment 2 of the test element safety analysis report to NRC. This amendment describes the tentative PIE program under DOE sponsorship. This was the only requirement made by NRC for the approval of the insertion of the test elements into the FSV reactor.

On July 19, 1978, Amendment 3 of the test element SAR was issued. This amendment contains the as-built analysis of the FTE operation under stretch conditions.

6. MAJOR FACILITIES

6.1. HOT ENGINEERING TEST FACILITY

With publication of the Conceptual Design Report Addenda II during the last report period, all tasks were completed for FY-78. No activities were scheduled for the third and fourth quarters of FY-78.

6.2. HTGR RECYCLE REFERENCE FACILITY (HRRF)

6.2.1. Summary

Flowsheets and material balances for HRRF reprocessing of spent MEU and recycle fuels were completed. An engineering study subcontract on the GA-proposed remote maintenance concept for the HRRF reprocessing head-end facility was completed by Norman Engineering Company. Their scope of work included: (1) definition of functional requirements and description of major remote maintenance equipment and facilities, (2) identification of governing transfer items for sizing primary transfer equipment and penetrations, (3) a pictorial presentation of the handling and transfer sequence for remote replacement of a typical head-end equipment item, and (4) supporting drawings such as proposed maintenance facilities and head-end process equipment layouts.

Forced-circulation water cooling concepts were tentatively selected for application to the spent fuel storage area. Natural convection air cooling is acceptable for the refabricated fuel storage area. Preconceptual design layout options for the HRRF tie-in fuel storage area were prepared, along with supporting documentation including: (1) design assumptions, (2) functional flow diagrams, (3) operating requirements by functional area, and (4) a preliminary equipment list for the fuel storage facility. Further evaluation of the storage concept options is required to determine suitability from structural, seismic, and construction standpoints.

Higher fast neutron activity associated with spent MEU fuel relative to HEU fuel was found to require the addition of 6.35 cm (2.5 in.) of neutron shielding to the HEU reference rail-transport spent fuel cask exterior. A preliminary thermal analysis was performed to determine the

impact of the neutron shield on the cask thermal characteristics and to establish specific configuration requirements. A copper clad fin was found to provide maximum heat transfer capability while requiring the smallest increase in the cask envelope.

Process flowsheets covering the treatment of reprocessing wastes were completed and distributed for review and comment. A preliminary sampling plan for the HRRF dry head-end, wet head-end, and solvent extraction systems was drafted.

6.2.2. Introduction

The objectives of this subtask are to perform engineering feasibility studies and to develop and evaluate preliminary HRRF Reprocessing Facility concepts, leading to the definition of HRRF design requirements. The objectives include updating of prior HRRF Reprocessing Facility concepts to MEU fuel recycle.

During the preceding quarter, updated MEU fuel recycle reprocessing flowsheets were issued, and the reprocessing head-end material balance was completed. The Ralph M. Parsons Co. subcontract to update the Target Recycle Plant (TRP) cost data base was completed. A remote maintenance concept for HRRF-Reprocessing was developed, and requirements for integrated remote maintenance handling and support equipment were established. An engineering support study subcontract was initiated with Norman Engineering Co. to assist GA in the design development of HRRF-Reprocessing Head-End remote maintenance equipment systems and facilities. A number of previously investigated spent fuel storage concepts were reviewed for applicability to the HRRF Feasibility Study. Choosing between water and air-cooling systems for spent fuel storage was identified as a major design issue.

6.2.3. Activity

6.2.3.1. HTGR/MEU Cycle Reprocessing Flowsheet. Material balance data for the updated solvent extraction and head-end off-gas treatment flowsheets were calculated, completing the FY-78 flowsheet and material balance updating activity for HRRF reprocessing of spent MEU and recycle fuels.

The reprocessing flowsheet schematic for the HTGR/MEU fuel recycle base case is shown in Fig. 6.2-1. The MEU cycle base case entails the use of 20% enriched U-235 initial and makeup fuel elements and nondenatured U-233 recycle elements. At equilibrium, the ratio of recycle to makeup elements is approximately 1:2. Fertile particles from both types of elements are reprocessed for recovery of bred U-233, as are the fissile particles from spent recycle elements. The fissile particles from spent makeup elements are separated from burned-back fertile particles, then immobilized in an inert matrix and packaged for disposal in a waste repository. Tables 6.2-1 through 6.2-14 summarize the material balance data for the HTGR/MEU fuel recycle base case reprocessing flowsheets.

6.2.3.2. Reprocessing Facility Configuration and Cost Basis. No significant activity occurred during the reporting period.

6.2.3.3. HRRF Remote Maintenance Systems. Norman Engineering Co. completed the support study subcontract, initiated May 5, 1978, for the development of a conceptual facility arrangement to accommodate remote maintenance functions for the HRRF reprocessing system. This study particularly concentrated on a conceptual design of head-end process cell equipment arrangements, including remote handling equipment, on maintenance facilities and on the interface between the process cell and maintenance facilities. Norman Engineering made a final presentation to cognizant representatives of both ORNL and GA at GA on July 27, 1978.

Fig. 6.2-1. HTGR/MEU fuel recycle base case reprocessing flowsheet

TABLE 6.2-4
MATERIAL BALANCE FOR OFF-GAS SYSTEM - BURNER OFF-GAS PROCESSING (PF-650-11)

	Primary Burner Off-gas (PBOG)	To Semivolatile FP Removal	To Iodine Removal Unit	To Sulfur Removal Unit	To CO/HT Oxidizer	To Tritium Removal Unit	To Radon Holdup Unit	To KALC Surge Tank	Secondary Burner Off-gas (SBOG)	To Semivolatile FP Removal	To Iodine Removal Unit	To CO/HT Oxidizer	To Tritium Removal Unit	To Radon Holdup Unit From SBOG	To KALC Process
Stream No.	101	104	107	111	113	117	120	123	151	152	155	159	162	164	167
Type of flow	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Semicont.	Batch	Batch	Batch	Batch	Batch	Batch	Batch
Avg operating h/d ^(a)	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Avg gas flow, slpd/1000 ^(b)	16,311 ^(e)	16,311	16,311	16,311	16,311	16,325	16,325	16,325	416 ^(e)	416	416	416	416	416	416
Heat load, W/1 ^(c)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Activity, Ci/1	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>2.4 (-4)	>1.5 (-4)	>1.5 (-4)	>3.4 (-2)	>3.4 (-2)	>3.4 (-2)	>3.4 (-2)	>3.4 (-2)	3.4 (-2)	3.4 (-2)
O ₂ , slpd/1000	49	49	49	49	49	62.7	62.7	62.7	58	58	58	58	58	58	58
CO ₂ , slpd/1000	14,892	14,892	14,892	14,892	14,892	16,235	16,235	16,235	340	340	340	340	358	358	358
CO, slpd/1000	1,370	1,370	1,370	1,370	1,370	27.4	27.4	27.4	18	18	18	18	0.4	0.4	0.4
NO _x , slpd/1000															
Air, slpd/1000															
NH ₃ , slpd/1000															
N ₂ , slpd/1000															
Sulfur, g/1	5.6 (-5)	5.6 (-5)	5.6 (-5)	5.6 (-5)	5.6 (-7)	5.6 (-7)	5.6 (-7)	5.6 (-7)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)	1.1 (-5)
Carbon-14, g/1 ^(d)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)	8.3 (-7)
Radon, g/1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Tritium, g/1	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-9)	9.1 (-12)	9.1 (-12)	6.4 (-8)	6.4 (-8)	6.4 (-8)	6.4 (-8)	6.4 (-8)	6.4 (-11)	6.4 (-11)
Krypton, g/1	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	2.4 (-6)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)	5.6 (-4)
Xenon, g/1	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	2.1 (-5)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)	5.8 (-3)
Iodine, g/1	6.3 (-7)	6.3 (-7)	6.3 (-7)	6.3 (-10)	6.3 (-10)	6.3 (-10)	6.3 (-10)	6.3 (-10)	1.9 (-4)	1.9 (-4)	1.9 (-4)	1.9 (-7)	1.9 (-7)	1.9 (-7)	1.9 (-7)
Other FP, g/1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Other particulates, g/1	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

(a) Exclusive of rework - based on 233 equivalent operating days per year.
(b) Exclusive of filter blowback and bed regeneration CO₂ additions. Not including impurity volumes.
(c) Decay heat only (exclusive of process heating or cooling).
(d) Carbon-14 level has increased by 80% in PBOG and 127 times in SBOG as a result of using recycle CO₂ from KALC system.
(e) Value has been adjusted to include miscellaneous gas stream inputs; e.g., transport gas bleed or coolant purge.

TABLE 6.2-3
MATERIAL BALANCE FOR HEAD-END FISSILE PARTICLE CRUSH-SECONDARY BURN-LEACH (PF-250-3)
(SPENT 23 ELEMENTS)

Stream No.	Spent 23R Element Fissile Particle Transport	Fissile Crusher Feed	Fissile Crusher Product	Particle Burner Feed	Burner Feed Gases	Particle Burner Off-gas	Particle Burner Product	Burner Product Transport	Fissile Leacher Feed	Poisoned Nitric Acid Solution	Off-gas	Condensate Return	Fissile Leacher Off-gas	Fissile Leacher Product	Centrifuge Solution	Centrifuge Solids	Poisoned Dilute Acid	Repulping Product	Centrifuge Solution	Fissile Leaching Product to SX	Centrifuge Solids	Insols Dryer Product	High Level Liquid Waste	Insols Dryer Off-gas
Type of flow	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Batch
Avg operating h/d ^(a)	0.1	2.8	2.8	2.8	12.0	12.0	1.6	0.1	7.0	7.0	14.0	14.0	14.0		0.5				0.3			0.06		
Avg solids flow, kg/d	113.6	113.6	113.6	113.6	0	TBD	66.6	66.6	66.6					53.4	0.1 ^(b)	53.3		53.1		0.1	53.1	53.1	Negl.	Negl.
Avg gas/vapor flow, slpd/1000	14.0				208.3	209.7		15.0			211.4		211.3											TBD
Avg liquid flow, l/d										469.0		0.24		469.0	463.7	5.3	380.0	385.3	380.0	463.7	5.3	--	5.3	
Heat load, W/l ^(c) or W/kg	TBD	TBD	TBD	TBD		TBD	TBD	TBD	TBD		Negl.		Negl.	TBD	TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD	TBD
Activity, Ci/l or Ci/kg	TBD	TBD	TBD	TBD		TBD	TBD	TBD	TBD		Negl.		Negl.	TBD	TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD	TBD
Burned-back fissile particles, kg/d	99.9	99.9	1.0	1.0			0.9	0.9	0.9					0.9		0.9		0.9			0.9	0.9		
Broken fissile particles, kg/d	6.2	6.2	105.1	105.1			--	--	--					--				--			--	--		
SiC hulls, kg/d	3.7	3.7	3.7	3.7				50.0	50.0	50.0				50.0		50.0		50.0			50.0	50.0		
Burned-back fertile particles, kg/d	1.7	1.7	1.7	1.7				1.7	1.7	1.7				1.7		1.7		1.7			1.7	1.7		
U ₃ O ₈ , kg/d								4.44	4.44	4.44				0.15	--	0.15		0.1			0.1	0.1		
Other solids, kg/d ^(e)	2.0	2.0	2.0	2.0			9.6 ^(d)	9.6	9.6					0.6	0.1	0.5		0.4		0.1	0.4	0.4		
In Solution:																								
Uranium, g/l														8.0	8.0	8.0		0.2	0.2	8.0	0.2		TBD	
Thorium, g/l														Negl	Negl.	Negl.		Negl.	Negl.	Negl.	Negl.		TBD	
Plutonium, g/l														0.4	0.4	0.4		0.01	0.01	0.4	0.01		TBD	
Other heavy metals, g/l														0.4	0.4	0.4		0.01	0.01	0.4	0.01		TBD	
Fission Products																								
³ H, Kr, I, Xe, Rn, g/l								TBD	TBD	TBD	Negl.			Negl.	Negl.	Negl.		Negl.	Negl.	Negl.	Negl.		TBD	
Other, g/l								TBD	TBD	TBD				11.7	11.7	11.7		0.3	0.3	11.7	0.3		TBD	
Boron, g/l														0.09	0.09	0.09		0.001	0.001	0.09	0.001		TBD	
HNO ₃ , M										2.5				2.0	2.0	2.0	0.2	0.2	0.2	2.0	0.2		TBD	
Cd ⁺⁺ , M										0.075				0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075		TBD	
Total NO ₃ ⁻ , M										2.5				2.5	2.5	2.5	0.3	0.3	0.3	2.5	0.3	TBD	TBD	
O ₂ , slpd/1000					94.1	29.1																		
CO ₂ , slpd/1000	14.0				114.2	171.6	TBD	15.0																TBD
CO, slpd/1000						9.0																		
NO _x , slpd/1000													0.24	0.11								TBD		
Air, slpd/1000											211.2		211.2											TBD

(a) Exclusive of rework. Based on 233 equivalent operating days per year.
(b) 25% of the insoluble carbon is assumed to go in solution (E from both centrifuges all shown in stream 320).
(c) Decay heat only (exclusive of process heating or cooling)
(d) All unburned carbon exterior to SiC coatings included in "other solids." All actinides and fission products associated with SiC Hulls included with hulls. B₂O₃ included in other solids.
(e) Unburned graphite, B₂O₃, and other oxygen associated with fission products and heavy metal oxides from broken fissiles from primary burn.

TABLE 6.2-2
MATERIAL BALANCE FOR HEAD-END FERTILE FRACTION LEACHING (PF-250-2)
(SPENT MAKEUP ELEMENTS)

	Fertile Leacher Feed	Thorex Acid Solu- tion	Fertile Leacher Product	Leacher Off-Gas			Centri- fuge Product Solution	Centri- fuge Product Solids	Poisoned Dilute Acid	Repulping Product	Centri- fuge Product Solution	Fertile Leach Product to SX	Centri- fuge Product Solids	Insols Products	Insols to Classify	Dryer Off- Gas	High Level Liquid Waste
Stream No.	202	203	204	205	206	207	209	210	211	212	214	218	219	220	221	225	226
Type of flow	Batch	Batch	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Batch	Batch	Semi- cont.	Semi- cont.	Batch	Batch	Batch	Batch	Semi- cont.	Semi- cont.
Avg operating h/d(a)	0.2		8-12	8-12	8-12	8-12	0.6				0.03			0.003	0.003	TBD	
Avg solids flow, kg/d	179.6		7.1				0.03 ^(b)	7.1		6.4	^(b)	0.03 ^(b)	6.4	6.4	6.4		
Avg gas/vapor flow, slpd/1000 ^(c)	44.2			408.1	407.4									0.7	0.7	TBD	
Avg liquid flow, l/d ^(c)		585.6	585.6			0.7	585.1	0.5	49.0	49.5	49.0	633.6	0.5				0.5
Heat load, W/l ^(d)			TBD				TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD		TBD
Activity, Ci/l			TBD	TBD	TBD		TBD	TBD		TBD	TBD	TBD	TBD	TBD	TBD		TBD
Fissile particles, kg/d	6.0		6.0					6.0		6.0			6.0	6.0			
Fertile particles kg/d	173.6																
Carbon, g/l			0.2				0.04	150.0		1.5		0.05	150.0	0.11	0.11		
Uranium, g/l			10.4				10.4	60.9		0.6	0.6	9.7	0.3	0.0002	0.0002		0.006
Thorium, g/l			232.0				230.9	1357.2		13.7	13.1	214.2	80.0	0.06	0.06		0.13
Fission products, g/l ^(e)			14.0	0.005	0.005		13.5	585.0		5.9	0.4	12.5	540.0	0.4	0.4		0.06
HNO ₃ , <u>M</u>		13.0	8.5				8.8		0.2	0.2	0.2	7.9	0.2				0.2
F ⁻ , <u>M</u>		0.05	0.05				0.05					0.05					
Al ⁺⁺⁺ , <u>M</u>		0.1	0.1				0.1					0.1					
Cd ⁺⁺ , <u>M</u>		0.075	0.075				0.075		0.075	0.075	0.075	0.075	0.075				0.075
Total NO ₃ ⁻ , <u>M</u>		13.4	13.4				13.4		0.3	0.3	0.3	12.4	0.3				0.3
NO _x , slpd/1000				1.2	8.15												
CO ₂ , slpd/1000																	
Air, slpd/1000				406.9	399.3											TBD	

(a) Exclusive of rework. Based on 233 equivalent operating days/year.
(b) 25% of free carbon assumed to be in final product (all shown in first centrifuge product).
(c) Operating flow rate.
(d) Decay heat only (exclusive of process heating or cooling).
(e) Includes other heavy metals.

TABLE 6.2-1
MATERIAL BALANCE FOR HEAD-END FUEL ELEMENT CRUSH - PRIMARY BURN - CLASSIFY (PF-250-1)
(SPENT MAKEUP ELEMENTS)

	Crusher Feed	Crusher Product	Material Transport	Burner Feed	Burner Product	Material Transport	Burner Off-gas	Material Transport	Classifier Feed	Classifier Bottoms	Fertile Fraction Transport	Classifying Gas Return	Classifier Overheads	Fissile Fraction Transport	Burner Feed Gases
Stream No.	101	102	104	105	106	107	110	114	115	123	124	126	129	131	135
Type of Flow	Batch	Batch	Batch	Semi- cont.	Batch	Batch	Semi- cont.	Batch	Batch	Batch	Batch	Batch	Batch	Batch	Semi- cont.
Avg operating h/d ^(a)	11.0	11.0	3.2	20.24	0.4	0.4	24.0	0.4	4.3	4.3	0.2	4.3	4.3	0.1	24.0
Avg solids flow, kg/d	4952.7 ^(b)	4952.7	4952.7	4952.7	516.5	516.5	TBD	516.5	516.2	179.6	179.6	TBD	336.8	336.8	--
Avg gas flow, slpd/1000		663.7	663.7			80.4	12,300	80.4	--	--	--	726.0	--	27.0	11,500
Heat load, W/kg ^(c)	2.4 ^(d)			2.44	23.4				23.4						
Activity, Ci/kg	579.0 ^(d)			579.0	5552.0				5552.0						
Bulk density, g/cm ³	1.29			1.12	2.7				2.7						
Physical Components															
Fissile particles															
Whole, kg/d	443.2	431.6	422.7 ^(e)	422.7		15.14		18.20	18.2				19.7	19.7	
Broken, kg/d	3.12	14.73	23.7	23.7	12.05	305.6		302.5	302.5	6.0	6.0		295.0	295.0	
Burned-back, kg/d					308.7	10.86		10.9	10.9				10.9	10.9	
SiC hulls, kg/d					10.86										
Fertile particles															
Whole, kg/d	311.8	309.3	308.7 ^(e)	308.7		2.94		3.20	3.2	0.8	0.8		2.4	2.4	
Broken, kg/d	1.25	3.76	4.4	4.38	2.68	176.23		175.74	175.4	172.8	172.8		2.6	2.6	
Burned-back, kg/d															
Graphite, matrix, shim, and boron, kg/d	4193.0	4193.0	4193.0	4193.0	6.2	6.2		6.2	6.2				6.2	6.2	
Chemical Components															
Burnable carbon, kg/d	4429.0	4432.0	4434.0	4434.0	6.0	7.0		8.0	8.0	{0.1	0.1}		8.0	8.0	
Bound carbon, kg/d	112.7	109.8	107.5	107.5	102.7	101.7		100.7	100.7	27.3	27.3		100.6	100.6	
Bound oxygen, kg/d	41.3	41.3	41.3	41.3	38.7	38.7		38.7	38.7	2.0	2.0		11.4	11.4	
Silicon carbide, kg/d	113.5	113.5	113.5	113.5	113.5	113.5		113.5	113.5				111.5	111.5	
Heavy metal															
U (w/U-233), kg/d ^(f)	4.73	4.73	4.73	4.73	4.73	4.73		4.73	4.73	4.6	4.6		0.13	0.13	
U (w/U-235), kg/d ^(g)	79.55	79.55	79.55	79.55	79.55	79.55		79.55	79.55	1.49	1.49		78.06	78.06	
Thorium, kg/d	138.5	138.5	138.5	138.5	138.5	138.5		138.5	138.5	135.9	135.9		2.6	2.6	
Other, kg/d	3.21	3.21	3.21	3.21	3.21	3.21		3.21	3.21				3.21	3.21	
Fission Products															
³ H, Kr, I, Xe, Rn, kg/d	4.007	4.007	4.007	4.007	3.6	3.6	0.4	3.6	3.6	2.2	2.2		1.4	1.4	
Other, kg/d	25.68	25.68	25.68	25.68	25.68	25.7	25.7	25.7	25.7	6.0	6.0		19.7	19.7	
Sulfur	0.9	0.9	0.9	0.9			0.9								
Boron	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2				0.2	0.2	
O ₂ , slpd/1000							24.6								
CO ₂ , slpd/1000							10,829.0	80.4			44.2	726.0		27.0	7,676
CO, slpd/1000							1,446								3,824

(a) Exclusive of rework - based on 233 equivalent operating days per year.

(b) LHTGR standard makeup fuel element basis (for 10,000 fuel element/yr throughput).

(c) Decay heat only (excludes process heating and cooling effects).

(d) 180-day cooled fuel elements discharged at reload 5.

(e) Total transport breakage from crusher to burner.

(f) Total uranium in the fertile particle.

(g) Total uranium in the fissile particle.

TABLE 6.2-5
MATERIAL BALANCE FOR OFF-GAS SYSTEM - DISSOLVER OFF-GAS PROCESSING (PF-650-12)

	Fertile Fraction Dissolver Off-Gas	Fissile Ash Dissolver Off-Gas	Insol Dryer (Fertile Dissolution)	Insol Dryer (Fissile Dissolution)	To Dissolver Off-Gas Processing	To NO _x Converter	Ammonia Addition	To Iodine Removal	To KALC Process
Stream No.	501	502	503	504	506	512	513	519	530
Type of flow	Semi-cont.	Batch	Semi-cont.	Batch	Semi-cont.	Semi-cont.	Semi-cont.	Semi-cont.	Semi-cont.
Avg operating h/d ^(a)	14	8-12	TBD	TBD	14	14	14	14	14
Avg gas flow, slpd/1000 ^(b)	407.4	211.3	TBD	TBD	618.7	618.7	8.2	617.4	617.4
Heat load, W/l ^(c)	TBD	TBD	TBD	TBD	TBD	TBD	0	TBD	TBD
Activity, Ci/l	>2.1 (-2)	>9.0 (-4)	TBD	TBD	>1.4 (-2)	>1.4 (-2)		>1.4 (-2)	>1.4 (-2)
NO _x , slpd/1000 ^(d)	8.1	0.11			8.2	8.2	0	8.2 (-2)	8.2 (-2)
CO ₂ , slpd/1000	399.3	211.2			610.5	610.5	0	610.5	610.5
NH ₃ , slpd/1000	--	--			--	--		8.2 (-2)	8.2 (-2)
N ₂ , slpd/1000	0	0			0	0	0	6.9	6.9
Radon, g/l	TBD	TBD			TBD	TBD	--	TBD	TBD
Krypton, g/l	2.9 (-4)	1.2 (-5)			2.0 (-4)	2.0 (-4)	--	2.0 (-4)	2.0 (-4)
Xenon, g/l	1.7 (-3)	7.1 (-5)			1.1 (-3)	1.1 (-3)	--	1.1 (-3)	1.1 (-3)
Iodine, g/l	1.0 (-4)	4.9 (-6)			6.8 (-5)	6.8 (-5)	--	6.8 (-5)	6.8 (-8)

(a) Exclusive of rework - based on 233 equivalent operating days per year.

(b) Exclusive of moisture content.

(c) Decay heat only (exclusive of process heating or cooling).

(d) 2% NO_x from fertile dissolver is assumed since the fertile dissolver is sparged with NO with CO₂ (composition TBD).

TABLE 6.2-6
MATERIAL BALANCE FOR OFF-GAS SYSTEM - KRYPTON ABSORPTION IN LIQUID CO₂ (KALC)
OFF-GAS PROCESSING (PF-650-3)

	From SBOG and DOG Off-Gas Treatment	From PBOG Off-Gas Treatment	To KALC Compressors	To Absorber/ Fractionator	To MS-CO ₂ Removal	To Krypton Storage	To Stack	To Carbon-14 Fixation
Stream No.	200	201	202 ^(a)	208 ^(b)	218	233	237	245
Type of flow	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.	Semi- cont.
Avg operating h/d ^(c)	24	24	24	24	24	24	24	24
Avg gas flow, slpd/1000 ^(d)	<1035	16,325	17,360	17,360	357.1	0.2	5.9 (-1)	8623.9
Heat load, W/l ^(e,f)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Activity, Ci/l ^(f)	2.2 (-2)	1.5 (-4)	1.45 (-3)	1.45 (-3)	7.0 (-2)	125	TBD	2.92 (-5)
O ₂ , slpd/1000	58	62.7	120.7	120.7	3.8 (-1)	Negl	Negl	120.7
CO ₂ , slpd/1000	969	16,235	17,204	17,204	5.84	Negl	Negl	8468.3 ^(g)
CO, slpd/1000	0.4	27.4	27.8	27.8	8.8 (-2)	Negl	Negl	27.8
N ₂ , slpd/1000	6.9	0	363.3	363.3	350.1	0.1	Negl	363.3
Krypton, slpd/1000	9.45 (-2)	1.03 (-2)	1.05 (-1)	1.05 (-1)	1.04 (-1)	0.1	1.0 (-3)	1.05 (-3)
Xenon, slpd/1000	5.37 (-1)	5.86 (-2)	5.96 (-1)	5.96 (-1)	5.9 (-1)	5.0 (-3)	5.9 (-1)	5.96 (-3)
NO _x , slpd/1000	8.2 (-2)	0	8.2 (-2)	8.2 (-2)	Negl	Negl	Negl	8.2 (-2)
NH ₃ , slpd/1000	8.2 (-2)	0	8.2 (-2)	8.2 (-2)	Negl	Negl	Negl	8.2 (-2)
Sulfur, g/l ^(h)	4.4 (-6)	5.6 (-7)	7.9 (-7)	7.9 (-7)	TBD	Negl	Negl	TBD
Carbon-14, g/l	1.3 (-6)	1.6 (-6)	1.6 (-6)	1.6 (-6)	1.63 (-6)	Negl	Negl	1.6 (-6)
Radon, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Tritium, g/l	Negl	9.1 (-12)	8.6 (-12)	8.6 (-12)	TBD	Negl	Negl	TBD
Krypton, g/l	3.4 (-4)	2.4 (-6)	2.3 (-5)	2.3 (-5)	5.5 (-2)	1.90	6.4 (-3)	4.6 (-7)
Xenon, g/l	3.0 (-3)	2.1 (-5)	2.0 (-4)	2.0 (-4)	4.9 (-1)	1.5 (-1)	5.8	4.0 (-6)
Iodine, g/l	1.2 (-7)	6.3 (-10)	7.7 (-9)	7.7 (-9)	TBD	Negl	Negl	TBD
Other FP, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Other particulates or contaminants, g/l	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

(a) ">" and "<" designations have been dropped in 202 and following stream as insols; gas dryer flows are considered negligible in the large system.

(b) All terms expressed in terms of standard temperature and pressure throughout.

(c) Exclusive of rework -- based on 233 equivalent operating days.

(d) Exclusive of filter blowback and bed regeneration CO₂ additions.

(e) Decay heat only (excludes process heating and cooling).

(f) Exclusive of any activity contributed by any semivolatiles still in stream.

(g) Excluding CO₂ makeup (220).

(h) Exclusive of any SBOG sulfur content.

TABLE 6 2-7
MATERIAL BALANCE FOR OFF-GAS SYSTEM - CARBON-14 FIXATION WITH LIME OFF-GAS PROCESSING (PF 660-1)

	From KALC Absorber	Vent to Filters and Stack	Reactor Product	Slaked Lime Slurry	Filtrate	Moist Cake	Moisture To Vent	Dried Product	Lime To Slaker	Water To Slaker	Makeup Water	To Disposal
Stream No	501	504	505	508	509	510	511	512	513	514	515	516
Type of flow	Semi-cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Cont	Batch
Avg operating h/d ^(a)	24	24	24	24	24	24	24	24	24	24	24	24
Avg gas flow, slpd/1000 ^(b)	8623 9	482 3	Negl									
Avg slurry/solids flow, kg/d			270,994	254,531		65,490		39,607	22,744	231,787		39,607
Avg fluid flow kg/d					205,504		25,883					
Heat load, W/l or W/kg ^(c)	TBD	TBD	TBD			TBD	Negl	TBD				TBD
Activity, Ci/l or Ci/kg ^(d)	2 92 (-5)	5 27 (-4)	TBD			TBD	Negl	TBD				TBD
O ₂ , slpd/1000	120 7	120 7	Negl									
CO ₂ , slpd/1000	8468 3	84 7	Negl									
CO, slpd/1000	27 8	27 8	Negl									
N ₂ , slpd/1000	363 3	363 3	Negl									
Krypton, slpd/1000	1 05 (-3)	1 05 (-3)	Negl									
Xenon, slpd/1000	5 96 (3)	5 96 (-3)	Negl									
NO _x , slpd/1000	8 2 (-2)	4 1 (-2)	Negl									
NH ₃ , slpd/1000	8 2 (2)	8 2 (-2)	Negl									
sulfur, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Carbon 14, kg/d	1 6 (-6)	1 6 (-8)	1 6 (-6)			1 6 (-6)		1 6 (6)				1 6 (6)
Radon kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Tritium, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Krypton, kg/d	4 6 (-7)	4 6 (-7)	Negl			Negl		Negl				Negl
Xenon, kg/d	4 0 (6)	4 0 (-6)	Negl			Negl		Negl				Negl
Iodine, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Other FP, kg/d	TBD	TBD	TBD			TBD		TBD				TBD
Other particulates or contaminants, kg/d	TBD	TBD	682	682		682		682	682			682
CaO, kg/d									22,062			
H ₂ O, kg/d		4 8	230,037	223,305	204,114	25,923	25,883	40		230,396	26,282	40
Ca(OH) ₂ , kg/d			2,848	30,544	1,390	1,458		1 458		1,391		1,458
CaCO ₃ , kg/d			37,427		TBD	37,427		37,427				37,427

(a) Exclusive of rework Based on 233 equivalent operating days/yr

(b) Exclusive of filter blowback and bed regeneration CO₂ additions Not including insol dryers air contribution

(c) Decay heat only (excludes process heating and cooling) Excludes contribution of any 'TBD' products

(d) Excludes contribution of any 'TBD' products

ASSUMPTIONS

- 1 99% CO₂ removal
- 2 5% Ca(OH)₂ (unreacted) in the product
- 3 40% H₂O in filter cake
- 4 3% solid impurity in CaO
- 5 0.1 wt % moisture in product

TABLE 6.2-8
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-1

	From Fertile Account- ability	From Waste Recovery	H ₂ O Addition	To HLW	Formic Acid Addition	Demin. Water Addition	Denitrator Product	From Waste Rework	Cold Chem Add	1A Column Feed	Dilute Acid	1 M Acid	Waste Recovery Product	Conc. Acid	Solvent From No. 1 Treat.	Aqueous Waste	Waste Solvent	High Level Waste	1A Column Product	To Vessel Off-Gas
Stream name				1AD						1AF	1AIS	1AS	WRP	1AA	1AX	1AW		1AW	1AP	
Stream No.	100	101	103	104	105	134	106	109	110-112	114	115	116	117	118	119	120	121	122	124	133
Relative flow rate	162.5		325	411	23.6		100			100	25	125	225	33.3	1192	283.3		283.3	1417	
Avg flow, l/d (a,b)	561.3	TBD	1122.6	1420	81.4	TBD	345.5	TBD	TBD	345.5	86.4	431.9	777.4	115.2	4118	979	TBD	979	4895	TBD
Oper. flow rate, l/hr (b)	23.4		46.8	59.2	3.4		14.4			14.4	3.6	18.0	32.4	4.8	171.6	40.8		40.8	204	
Design flow rate, l/hr (b)	47.0		94.0	118.5	6.8		29.0			29.0	7.5	36.5	65.5	9.7	344	82		82	410	
Heat load, W/l (c)	TBD			TBD			TBD			TBD			TBD			TBD		TBD	TBD	TBD
Activity, Ci/l	TBD			TBD			TBD			TBD			TBD			TBD		TBD	TBD	TBD
Carbon, g/l	0.05						0.08			0.08						0.03		0.03		
Uranium, g/l	9.7						15.8			15.8			Trace			Trace		Trace	1.1	
Thorium, g/l	214.2						348.2			348.2			Trace			0.1		0.1	24.6	
Pu, g/l	0.002						0.003			0.003						Trace		Trace	Trace	
Other H.M., g/l	0.03						0.05			0.05			Trace			0.02		0.02	Trace	
Fission products, g/l	12.5			0.025			20.2			20.2			Trace			7.2		7.2	Trace	TBD
HNO ₃ , M	7.9			2.88			1.0			1.0	0.01	1.0	0.15	13.0		2.3	Trace	2.3	0.15	
F ⁻ , M	0.05			0.0006			0.075			0.075						0.03		0.03		
Al ⁺⁺⁺ , M	0.1						0.15			0.15						0.06		0.06		
Cd ⁺⁺ , M	0.075						0.12			0.12						0.04		0.04		
HCOOH, M				1.3	23.0															
TBP-NPH, V/O TBP													30		30				30	
NO _x (slpd)				1.2																
H ₂ O (slpd)																				

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.
(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.
(c) Decay heat only.

TABLE 6.2-9
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-2

	1BX Feed	Dilute Acid Addition	1BX Uranium Product	1BX Thorium Product	Solvent From No. 1 Treat.	Return To 1A	1BS Thorium Product	Dilute Acid Addition	1C Uranium Product	Nitric Acid Addition	2A Feed	To Solvent Recovery	To Vessel Off-Gas
Stream name	1AP	1BX	1BU	1BXT	1BS	1BSU	1BT	1CX	1CU		1CU	1CW	
Stream No.	200	202	203	204	206	207	208	213	215	216	217	214	226
Relative flow rate	1417	850	1700	850	283.3	283.3	850	708	708	208	916	1700	
Average flow, l/d ^(a)	4895	2937	5874	2937	979	979	2937	2446	2446	720	3166	5874	TBD
Oper. flow rate, l/h ^(b)	204	122.4	244.8	122.4	40.8	40.8	122.4	102	102	30	132	244.8	
Design flow rate, l/h ^(b)	410	245	492	245	82	82	245	205	205	60	265	492	
Heat load, W/l ^(c)	TBD		TBD	TBD			TBD		TBD		TBD	TBD	
Activity, Ci/l	TBD		TBD	TBD			TBD		TBD		TBD	TBD	
Uranium, g/l	1.1		0.92	0.12		0.35	0.001		2.2		1.7	0.001	
Thorium, g/l	24.6		0.002	41			41		0.005		0.004	0.002	
Pu, g/l	Trace		Trace	0.0004			0.0004		Trace		Trace	Trace	
Other H.M., g/l	Trace			Trace			Trace		Trace		Trace	Trace	
Fission products, g/l	Trace		Negl.	0.0002			0.0002		Trace		0.0002	Trace	
HNO ₃ , M	0.15	0.2	0.02	0.44		0.10	0.41	0.01	0.058	13.0	3.0	Trace	
F ⁻ , M		0.005		0.005			0.005						
TBP-NPH, % TBP	30		30		30		Trace					30	
Fe ⁺⁺ , M		0.0006		0.0006			0.0006						
N ₂ H ₄ , M		0.005		0.005			0.005						

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE 6.2-10
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-3

	2A Feed	Dilute Acid Addition	Solvent From No. 2 Treat.	2A Waste	2A Uranium Product	2B Feed	Dilute Acid Addition	2B Uranium Product	To Solvent Recovery	Nitric Acid Addition	3A Feed	To Vessel Off-Gas
Stream name	2AF	2AS	2AX	2AW	2AU	2BF	2BX	2BU	2BW		2BU	
Stream No.	302	303	304	306	305	312	313	315	314	316	317	325
Relative flow rate	916	100	254	1016	254	254	170	170	254	50	220	
Average flow, l/d ^(a)	3166	346	878	3512	878	878	587	587	878	171	758	TBD
Oper. flow rate, l/h ^(b)	132	14.4	36.6	146.4	36.6	36.6	24.5	24.5	36.6	7.1	31.6	
Design flow rate, l/h ^(b)	265	29	74	284	74	74	49	49	74	14.3	63.3	
Heat load, W/l ^(c)	TBD				TBD	TBD		TBD	TBD		TBD	
Activity, Ci/l	TBD				TBD	TBD		TBD	TBD		TBD	
Uranium, g/l	1.7			0.0015	6.1	6.1		9.1	0.006		7.05	
Thorium, g/l	0.004			Trace	0.0015	0.0015		Trace	Trace		Trace	
Pu, g/l	Trace			Trace								
Other H.M., g/l	Trace											
Fission products, %/l	0.0002			Trace	Trace	Trace		Trace	Trace		Trace	
HNO ₃ , M	3.0	0.3		2.72	0.05	0.05	0.01	0.085	Trace	13.0	3.0	
F ⁻ , M												
TBP-NPH, % TBP			30		30	30			30			
Fe ⁺⁺ , M		0.005		0.0005								
H ₂ , M		0.005		0.0005								

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE 6.2-11
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-4

	3A Feed	Dilute Acid	1 M Acid	Solvent From No. 2 Treat.	To Low Level Waste	3A Uranium Product	3B Feed	Dilute Acid	To Solvent Recovery	3B Uranium Product	Solvent Addition	Wash Rework	Conc. Feed	To Vessel Off-Gas
Stream name	3AF	3AIS	3AS	3AX	3AW	3AU	3BF	3BX	3BW	3BU	3WS	3WW	3BU	
Stream No.	402	403	404	405	406	408	409	410	411	412	415	416	419	428
Relative flow rate	220	20	5	65	245	65	66	51	66	51	0.3	0.3	51	
Average flow, l/d ^(a)	758	68.3	17.1	224	844	224	225	174	225	174	1.0	1.0	174	TBD
Oper. flow rate, l/h ^(b)	31.6	2.85	0.7	9.3	35.2	9.3	9.4	7.25	9.4	7.25	0.04	0.04	7.25	
Design flow rate, l/h ^(b)	63.3	5.7	1.45	18.7	70.5	18.7	18.8	14.5	18.8	14.5	0.1	0.1	14.5	
Heat load, W/l ^(c)	TBD				Negl	TBD	TBD		Negl	TBD			TBD	
Activity, Ci/l	TBD				TBD	TBD	TBD		TBD	TBD			TBD	
Uranium, g/l	7.05				0.005	23.8	23.7		0.024	30.6		Trace	30.6	
Thorium, g/l	Trace				Trace	Negl	Negl		Negl	Negl			Negl	
Pu, g/l														
Other H.M., g/l					Trace									
Fission product, g/l	Trace				Trace	Negl	Negl			Negl			Negl	
HNO ₃ , M	3.0	0.1	1.0		2.71	0.03	0.03	0.01	Trace	0.049		Trace	0.049	
F ⁻ , M														
TBP, %				30		30	30		30			Trace		
NPH, %				70		70	70		70		100	100		

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE 6.2-12
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-320-5

	Conc. Feed	Conc. Over- Heads	Conc. Uranium Product	Product to Refab	To Vessel Off-Gas
Stream name	3BU		3UC	3UC	
Stream No.	500	504	503	510	517
Relative flow rate	51	46	5	5	
Average flow, 1/d ^(a)	174	157	17	17	TBD
Operating flow rate, 1/h ^(b)	7.25	6.5	0.7	0.7	
Design flow rate, 1/h ^(b)	14.5	13.1	1.4	1.4	
Heat load, W/l ^(c)	TBD		TBD	TBD	
Activity, Ci/l	TBD		TBD	TBD	
Uranium, g/l	30.6		313	313	
Thorium, g/l	Negl		Negl	Negl	
Fission products, g/l	Negl		Negl	Negl	
HNO ₃ , <u>M</u>	0.049	0.02	0.32	0.32	

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE 6.2-13
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-350-1

	IBT Conc. Feed	Conc. Over- Heads	Conc. Prod.	2D Denit. Feed	Steam Add		Formic Acid Add	To HLW	Denit. Prod.	Demin. Water	Feed Adj.	2D Feed	To Vessel Off-Gas
Stream name	1BT											2DF	
Stream No.	101	103	102	105	104	106	107	111	108	109	113-114	117	125
Relative flow rate	850	TBD	850	850	TBD	1275	29.8	2115	39.4	110.6	TBD	150	
Average flow, l/d ^(a)	2937		2937	2937		4406	102.8	7298	148.3	370.7		519	TBD
Oper. flow rate, l/h ^(b)	122.4		122.4	122.4		183.6	4.3	304	6.2	15.4		21.6	
Design flow rate, l/h ^(b)	245		245	245		367.1	8.6	608	12.4	30.9		43.3	
Heat load, W/l ^(c)	TBD		TBD	TBD				TBD	TBD	TBD		TBD	
Activity, Ci/l	TBD		TBD	TBD				TBD	TBD	TBD		TBD	
Uranium, g/l	0.002		0.002	0.002					0.04			0.01	
Thorium, g/l	41.0		41.0	41.0					812			232	
Pu, g/l	0.0004		0.0004	0.0004					0.008			0.002	
Other H.M., g/l	Trace		Trace	Trace					Trace			Trace	
Fission products, g/l	0.0002		0.0002	0.0002				Trace	0.004			0.001	
HNO ₃ , M	0.39		0.39	0.39					-0.35			-0.1	
F ⁻ , M	0.005		0.005	0.005				Trace	0.1			0.03	
HCOOH, M							23	0.32					
TBP-NPH, V% TBP	Trace	Trace											
Fe ⁺⁺ , M	0.0006		0.0006	0.0006					0.012			0.0035	
N ₂ H ₄ , M	0.005		0.005	0.005					0.1			0.03	

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

TABLE 6.2-14
MATERIAL BALANCE FOR THOREX SOLVENT EXTRACTION PF-350-2

	2D Feed	Dilute Acid	5 M Acid	Solvent From No. 2 Treat.	Conc. Acid	2D Product	2D Waste	To HLW	2E Feed	2E Product	2E Waste	Dilute Acid	2ET Concen. Feed	Conc. Over- heads	2ET Product	To Th Store	To Vessel Off-Gas	2E Scrub
Stream name	2DF	2DS	2DIS	2DX	2DA	2DT	2DW		2EF	2ET	2EW	2EX	2ET		2THN	2THN		2ES
Stream No.	200	202	201	203	236	204	205	208	210	213	212	211	216	219	218	223	235	237
Relative flow rate	150	125	25	1159	25	1159	325	325	1159	680	1301	680	680	605	75	75		142
Average flow, l/d ^(a)	519	432.5	86.5	4010	86.5	4010	1124.5	1124.5	4010	2352	4501	2352	2352	2093	259	259	TBD	491
Oper. flow rate, l/h ^(b)	21.6	18	3.6	167	3.6	167	46.8	46.8	167	98	187.5	98	98	87	11	11		20.5
Design flow rate, l/h ^(b)	43.3	36	7.2	334	7.2	334	93.7	93.7	334	196	375	196	196	174	22	22		41
Heat load, W/l ^(c)	TBD					TBD	TBD	TBD	TBD	TBD	TBD		TBD		TBD	TBD		
Activity, Ci/l	TBD					TBD	TBD	TBD	TBD	TBD	TBD		TBD		TBD	TBD		
Uranium, g/l	0.01					0.001	Trace	Trace	0.001	0.001	Negl		0.002		0.015	0.015		
Thorium, g/l	232					30	0.11	0.11	30	51.1	0.027		51.1		464	464		
Pu, g/l	0.002					Negl	0.001	0.001	Negl	Negl	Negl		Negl		Negl	Negl		
Other H.M., g/l	Trace					Negl	Trace	Trace	Negl	Negl	Negl		Negl		Negl	Negl		
Fission products, g/l	0.001					Negl	0.0005	0.0005	Negl	Negl	Negl		Negl		Trace	Trace		
HNO ₃ , M	-0.1	0.01	5.0		13.0	0.05	1.16	1.16	0.05	0.10	Trace	0.01	0.10	Trace	0.5	0.5		
F ⁻ , M	0.03						0.014	0.014										
HCOOH, M																		
TBP-NPH, V% TBP				30		30			30		30							30
Fe ⁺⁺ , M	0.0035	0.045					0.019											
N ₂ H ₄ , M	0.03						0.014											

(a) Exclusive of rework. Based on 263 equivalent operating days/yr.

(b) Based on processing 10,000 fuel elements/yr. Design flow rate is 20,000 FE/yr exclusive of excess required for rework.

(c) Decay heat only.

Design guidance for this study was based upon previously prepared remote maintenance requirements (see Table 6.2-15), functional facility layouts (Figs. 6.2-2 and 6.2-3), facility and equipment descriptions, and various conceptual drawings such as shown in Fig. 6.2-4. The objectives of the Norman Engineering study were to develop a feasible design for the head-end cell remote maintenance interface, and to define the major remote handling equipment and the associated facilities that are required to support the remote maintenance of head-end process equipment.

Using the applicable information provided in a GA-supplied data package, Norman Engineering first prepared an updated flow diagram (Fig. 6.2-5) of the HRRF head-end process system including surge storage capability. This flow diagram represents a single, independent head-end system capable of handling 10,000 fuel elements per year, or one-half of the total HRRF fuel capacity of 20,000 elements. Each of the double cells shown in Fig. 6.2-4 would therefore contain the equipment shown in the flow diagram.

This flow diagram was then used in conjunction with equipment outline specifications to prepare an equipment arrangement layout of the head-end process equipment (see Fig. 6.2-6) and provided a first look at the overall configuration of both process equipment and remote maintenance equipment. An isometric view of the double head-end cell configuration is shown in Fig. 6.2-7.

All components within the head-end cell will be capable of remote maintenance, including the process and remote maintenance equipment, service piping, instrumentation, special structural supports, and lighting fixtures. The remote cranes and manipulator systems are stored at one end of the cell behind a gamma shield door (no seals) to minimize radiation damage to this equipment when they are not in use. All equipment items leaving the cell for repair or replacement are moved to the radiation lock area, and then are transferred up and out of the cell through a single access port in the roof to the remote repair cell.

TABLE 6.2-15
HRRF REMOTE MAINTENANCE REQUIREMENTS

1. Equipment within the process cell will be maintained remotely by: total replacement; minor repair in place; or removal for repair and reinstallation.	11. Install all head-end process equipment in either a single cell or double cell. Example: Incorporate two separate process systems at 10,000 elements/yr each - 50%/system.
2. Provide alpha-tight facility to prevent contamination spread.	12. Centralize maintenance equipment and facilities to serve reprocessing system.
3. Transfer equipment horizontally via aisle to single access port in roof.	13. Provide means to diagnose failures and test after repairs.
4. Incorporate gas-tight liner; no roof slabs.	14. Maximize use of floor access ports rather than using sealed vertical doors.
5. Install equipment in tiers to allow effective use of gravity feed.	15. Standardize and modularize components.
6. Provide facilities to remotely repair, decontaminate, store, and ship process equipment.	16. Match interfaces to installation-fixtures and gages.
7. Don't skimp on quality of maintenance equipment. Use best tools available to assure high equipment availability.	17. Perform maintenance operations in a criticality-safe manner.
8. Incorporate bilateral servo force-reflecting manipulator system with high-resolution TV.	18. Provide capability to remove and replace all reprocessing equipment.
9. Over-design remote handling equipment.	19. Locate pumps, valves, motors, etc., in adjacent limited-access cells.
10. Provide viewing equipment to observe all components and cell areas including windows, periscopes, TV, and lighting.	20. Completely check out all components and maintenance operations in mockup facility prior to final installation.

Fig. 6.2-2. Functional areas

PLAN VIEW

Fig. 6.2-3. Reprocessing functional facility layout concept

Fig. 6.2-4. Head-end process cells

Fig. 6.2-5. Head-end process flow diagram (Sheet 1 of 4)

Fig. 6.2-5. Head-end process flow diagram (Sheet 4 of 4)

Fig. 6.2-6. Head-end facility longitudinal section (Sheet 1 of 2)

Fig. 6.2-6. Head-end facility longitudinal section (Sheet 2 of 2)

Fig. 6.2-7. HRRF head-end facility general arrangement

In the remote repair cell, highly contaminated process equipment items can be subjected to dry decontamination operations and/or they can be completely disassembled remotely for repair and then reassembled and tested for reinstallation back into the process cell. Components requiring contact repair are transferred out of the repair cell to a specially designed decontamination cell that allows wet decontamination operations to be performed remotely followed by semi-contact repair in a glove box enclosure system.

Direct contact repair on the equipment could be accomplished in an adjacent cell, but only if complete decontamination operations have been successful in reducing contamination to acceptable levels for direct repair. Hot equipment storage is provided in each of the repair areas.

6.2.3.4. Spent Fuel Receiving, Storage, and Handling. This activity has the objective of preparing a design concept for MEU spent fuel receiving, storage, and handling. Previous storage and fuel handling concepts for both the reprocessing and reactor plants were reviewed for applicability to the MEU fuel cycle. This review in conjunction with establishment of the general requirements/assumptions shown in Table 6.2-16 was used as the basis for developing three concepts for the HRRF spent fuel receiving, storage, and handling areas. In addition, a functional flow diagram was prepared (Fig. 6.2-8) to identify material flow patterns and functional area interfaces.

The major design issue identified is the choice between water or air cooling systems for the storage areas. The cooling mode selection will be based primarily on the spent fuel heat load requiring dissipation, although structural and safety considerations are also important. The spent fuel heat load could not be firmly established since final fuel thermal data and reactor storage (decay) time have not been defined. Also, the number of reactors and their discharge rates were not available for determination of specific HRRF storage capacity requirements.

Fig. 6.2-8. HRRF functional diagram showing spent and recycle fuel receipt, storage, handling, and shipping

In order to prepare concepts, assumptions were made relative to these parameters based on the standard industry practice of providing storage for one-fourth (90 days) of the HRRF throughput at 100% availability and assuming an equilibrium fuel cycle involving receipt of 100-day-old spent fuel. (See Table 6.2-16.)

Based on these assumptions, it was felt that forced circulation water cooling should be employed for the spent fuel storage while natural convection air cooling was acceptable for the refabricated fuel storage area. It was judged that the high heat load combined with the desirability of closely spaced wells to minimize the storage area size could be handled by the higher efficiency water cooling system. It was further desirable to minimize the volume of air requiring cleanup to meet overall plant site air quality standards. Since water pools and cleanup systems are employed exclusively throughout the LWR fuel cycles, this technology is well known. Additionally, it was felt that a water cooling system provided greater safety should a loss of cooling medium circulation occur. With air cooling systems, extensive back-up systems would be required to assure adequate air circulation at all times. For the water system, however, backup systems can be minimized since the pool provides an adequate heat sink even if allowed to boil. Emergency makeup water can readily be supplied and a considerable response time is available to effect corrective action before any serious fuel heatup problem would be encountered.

The three storage concepts prepared are shown in Figs. 6.2-9 through 6.2-13. The overall facility arrangement for all of the concepts is basically the same except for specific size and operational differences between the plug well and portable rack concepts.

6.2.3.4.1. Plug Well Concept (Figs. 6.2-9 and 6.2-10)

This storage concept follows previous concepts used on the prior Target Recycle Plant design, except that water cooling is used and fuel handling has been greatly simplified. It can be seen from Fig. 6.2-10 that the wells provide containment and isolation of the fuel containers

TABLE 6.2-16
GENERAL REQUIREMENTS/ASSUMPTIONS FOR HRRF SPENT AND REFABRICATED FUEL
STORAGE AND HANDLING

1. Three rail loading ports (spent and refabricated sides).	16. Automatic indexing to storage well.
2. Two truck loading ports (spent and refabricated sides).	17. Crane handling of shipping casks (truck and rail).
3. Rail turnaround: 24 hours/cask.	18. Major maintenance done in plant maintenance cells.
4. Truck turnaround - 12 hours/cask.	19. No special handling of leaking containers.
5. 24-hour turnaround for two rail casks.	20. Separate off-gas treatment for storage areas.
6. 24-hour turnaround for four truck casks.	21. Storage based on two containers/well.
7. Spent fuel storage (equivalent to 90-day plant throughput) - 7800 elements.	22. Water cleanup/cooling system for spent storage pool.
8. Refabricated fuel storage (equivalent to 90-day plant throughput) $\approx$ 3500 elements.	23. Physical separation of spent and refabricated operations.
9. Storage for 150 rejected refabricated elements in spent fuel storage area.	24. Separate spent and refabricated loading ports.
10. Storage area handling rate - two containers/hour/handling system.	25. Double containment for water cooling.
11. Container opening cell handling rate - one per hour.	26. Individual container handling.
12. Container loading cell handling rate - one per hour.	27. Facility seismically stable.
13. Container refurbishment handling rate - one per hour.	28. Major utilities and services (except off-gas) from plant.
14. Water cooling in spent fuel storage.	29. No segregation of loaded containers (refabricated U-233 or U-235).
15. Natural convection air cooling in refabricated fuel storage.	30. Container and cask closure seal replacement done manually.
	31. Receipt of 100-day cooled fuel.

Fig. 6.2-9. Plan of receiving, storage, and shipping facility arrangement - plug well concept

Fig. 6.2-10. Sectional elevation - plug well storage concept

Fig. 6.2-11. Plan of receiving, storage, and shipping facility arrangement - portable well concept

Fig. 6.2-12. Sectional elevation - portable well concept

Fig. 6.2-13. Monolith storage well concept

from the water cooling medium and each well provides storage for two shipping containers. In this concept, fuel handling operations would be fully remote and personnel access to the area over the storage pool would not be permitted. A further consideration is that cleanup of the air in the fuel handling cell, cask unloading area, and the annulus directly over the pool water would require off-gas treatment. A stainless steel pool liner and heavy shield floor over the wells would also be required. It is envisioned that the storage wells would be remotely replaceable should this be required for any reason.

The refabricated fuel storage area is similar in arrangement to the spent fuel area except it utilizes natural convection air cooling in lieu of water since the heat load for this fuel is very low.

6.2.3.4.2. Portable Well Concept (Figs. 6.2-11 and 6.2-12)

This concept utilizes rack storage of fuel similar to LWR storage schemes. This concept also reduces the volume of air requiring cleanup, and permits personnel access and utilization of the area directly over the storage wells. Double containment (isolation of the fuel containers from the cooling water) is provided as with the plug well concept. In the portable well concept, the wells, with a capacity of two containers each, are carried to an overhead port for loading and returned to the storage rack when filled. A stainless steel pool liner is also required in this concept; however, the floor over the pool can be somewhat lighter than for the plug well arrangement since it is not heavily loaded by storage wells. It is envisioned that both the racks and the wells can be replaced if required.

The refabricated fuel storage area is similar in arrangement to the spent fuel area except it utilizes natural convection air cooling in lieu of water.

It should be noted that both the plug well and portable rack concepts could be used if an air cooling system were found to be acceptable. This

may result if the at-reactor storage time were increased from the assumed 100 days to 5 or more years, which is currently under consideration.

6.2.3.4.3. Monolith Concept (Fig. 6.2-13)

This concept is based on a prior concept developed for reactor spent fuel storage. In this concept the cooling water is circulated in pipes embedded in concrete and positioned between the storage wells. Since the water is isolated totally from the fuel, no cleanup is required and a once-through system would likely be used. Fuel handling, gas cleanup, etc., would be similar to that described for the plug well concept.

Refabricated fuel storage would be arranged in a similar manner; however, no cooling tubes would be required assuming an adequate heat sink is provided by the concrete shield.

This spent fuel storage concept is limited to a water cooling system and will require careful consideration of backup circulation systems in the event of loss of cooling water flow.

Future design activities will include a detailed evaluation of these storage concepts to determine their suitability from the structural, seismic, and construction standpoints. Once confirmation of these features is made and final fuel parameters and fuel logistics are defined, a final facility arrangement and detailed equipment designs can be undertaken.

6.2.3.5. Reprocessing Waste Treatment Requirements. Update and revision of reprocessing waste treatment process flowsheets was completed. A total of 21 flowsheets were prepared, reflecting the HRRF functional system/subsystem breakdown (HRRF chart of accounts). The process flowsheets were distributed for review and comment by ORNL and GA.

6.2.3.6. Radioactive Materials Shipping. This activity has the objective of preparing a design concept for MEU spent fuel rail transport. The shipping cask concept previously established for the transport of the HEU spent fuel (Fig. 6.2-14) was analyzed for suitability to transport MEU spent fuel.

The higher fast neutron activity associated with the MEU fuel, resulting from increased quantities of Cm-242, Cm-244, Pu-238, and Cf-252 isotopes in the spent fuel, indicates that neutron shielding will be required on the rail cask to maintain total dose levels within acceptable regulatory limits. Table 6.2-17 shows the results of the preliminary analysis, indicating that for the reference cycle involving 100 days of decay 6.35 cm (2.5 in.) of RICORAD* (a dry hydrogenous shield) or an equivalent and 0.635 cm (0.25 in.) of steel must be added to the cask exterior to maintain a satisfactory transport dose of less than 10 mrem/h at 1.8 m (6 ft) from the edge of the vehicle.

The addition of the neutron shielding has a significant impact on the cask envelope and heat transfer capability. A preliminary thermal analysis was performed to determine the impact of the neutron shield on the cask thermal characteristics and to establish specific configuration requirements. An effort was made to optimize the fin material/configuration to minimize the resulting envelope and weight increase while maximizing the heat transfer capability.

Figures 6.2-15 and 6.2-16 show the results of the thermal analysis. These results indicate that a copper clad fin provides the maximum heat transfer capability while requiring the smallest increase in the cask envelope. Detail calculations to determine final cask weights and shipping envelopes are now in process.

*Trademark by Reactor Experiments, Inc.

**72 ELEMENT CAPACITY
LOADED WT. (160 TONS)**

Fig. 6.2-14. Spent and recycle fuel rail shipping cask (SR-72)

TABLE 6.2-17
SUMMARY OF RESULTS, AVERAGE SPENT MEU RECYCLE FUEL BLOCKS

Decay Period	Railroad Cask Shielding Required	Gamma and Neutron Source Terms	Afterheat ($\frac{\text{Btu/h}}{\text{block}}$)
1 d	NA	NA	11,050
100 d	Same as Fig. 6.2-14 except 6.35 cm (2.5 in.) RICORAD and 0.635 cm (0.25 in.) steel added.	1.39 (+10) γ MeV/cm ³ -s 159 n/cm ³ -s	1,790
150 d	Same as Fig. 6.2-14 except 5.08 cm (2 in.) RICORAD and 0.635 cm (0.25 in.) steel added.	9.62 (+9) γ MeV/cm ³ -s 152 n/cm ³ -s	1,300
180 d	NA	7.92 (+9) γ MeV/cm ³ -s 147 n/cm ³ -s	1,120
1 yr	NA	3.56 (+9) γ MeV/cm ³ -s 130 n/cm ³ -s	622
5 yr	Same as Fig. 6.2-14 except 5.08 cm of DU removed, and 5.08 cm RICORAD and 0.635 cm steel added.	1.05 (+9) γ MeV/cm ³ -s 120 n/cm ³ -s	143

Fig. 6.2-15. Cask fin efficiency

Fig. 6.2-16. Cask fin temperature profile

6.2.3.7. Miscellaneous Activities. The draft of a preliminary sampling plan for the HRRF dry head-end, wet head-end, and solvent extraction systems was prepared. The sampling plan identifies sampling points and associated sampling frequency, and it defines the type of analytical data required for process control.

Tentative work scopes for FY-79 HRRF subtask activities were drafted in joint ORNL/GA working sessions during the week of July 10, 1978.

Information regarding functional and operational requirements of the fuel element size reduction system was furnished by GA to the Boeing Company. Boeing will incorporate this information in the requirements guideline that is being prepared as part of the HRRF Project Summary Plan.

APPENDIX A
TOPICAL REPORTS PUBLISHED DURING THE QUARTER

Strand, J. B., and G. T. Cramer, "HTGR Fuel Element Size Reduction System - Interim Development Report," DOE Report GA-A14838, General Atomic Company, June 1978.

Strand, J. B., "Design Evaluation of the HTGR Fuel Element Size Reduction System," DOE Report GA-A14859, General Atomic Company, June 1978.

Holder, N. D., B. B. Haldy, and M. Jonzen, "Spent Fuel Reprocessing System Availability Definition by Process Simulation," DOE Report GA-A14910, General Atomic Company, May 1978.

"HTGR Fuel Recycle Development Program - Quarterly Progress Report for the Period Ending May 31, 1978," DOE Report GA-A15011, General Atomic Company, June 1978.

Strand, J. B., "Particle Classifier for HTGR Reprocessing - Engineering-Scale Unit Interim Development Report," DOE Report GA-A14930, General Atomic Company, July 1978.

Olguin, L. J., "Continuous Solvent Extraction Feed Adjustment for HTGR Fuel Reprocessing - Interim Development Report," DOE Report GA-A15014, General Atomic Company, June 1978.

Wilbourn, R. G., "Solvent Extraction in HTGR Reprocessing - Interim Development Report," DOE Report GA-A15030, General Atomic Company, July 1978.

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