180
7-10-78

Dr 236

GA-A14816
UC-77

PROCESS DEVELOPMENT REPORT: 0.40-m PRIMARY BURNER SYSTEM

by
D. T. YOUNG

MASTER

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

DATE PUBLISHED: APRIL 1978

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$8.00; Microfiche \$3.00

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

GA-A14816
UC-77

PROCESS DEVELOPMENT REPORT: 0.40-m PRIMARY BURNER SYSTEM

by
D. T. YOUNG

MASTER

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

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

**GENERAL ATOMIC PROJECT 3261
DATE PUBLISHED: APRIL 1978**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *fee*

GENERAL ATOMIC COMPANY

ABSTRACT

Fluidized bed combustion is required in reprocessing the graphite-based fuel elements from high-temperature gas-cooled reactor (HTGR) cores. This burning process requires combustion of beds containing both large particles and very dense particles, and it requires in addition combustion of fine graphite particles which elutriate from the bed. Equipment must be designed for optimum simplicity and reliability, as ultimate operation will occur in a limited access hot cell environment.

This report documents the successful long-term operation of the 0.40-m primary burner in burning crushed fuel elements. In this report, the 0.40-m system operation is followed from its first short heatup test in September 1976 to a >40-hr burning campaign that processed 20 LHTGR blocks in September 1977. The 0.40-m perforated conical gas distributor, scaled up from the 0.20-m primary burner, has proven reliable in safely burning even the largest, densest adhered graphite/fuel particle clusters originating from the crushing of loaded fuel elements. Such clusters had never been fed to the 0.20-m system. Efficient combustion of graphite fines using the pressurized recycle technique was demonstrated throughout the long-duration operation required to reduce a high carbon fresh feed bed to a low carbon particle bed. Again, such operation had never been completed on the 0.20-m system from which the 0.40-m burner was scaled.

The successful completion of the tests was due, in part, to implementation of significant equipment revisions which were suggested by both the initial 0.40-m system tests and by results of ongoing development work on the 0.2-m primary burner. These revisions included additional penetrations in the burner tube side-wall for above-bed fines recycle, replacement and deletion of several metal bellows with bellows of more reliable design, and improvements in designs for burner alignment and feeder mechanisms.

CONTENTS

ABSTRACT	iii
1. SUMMARY	1-1
2. INTRODUCTION	2-1
2.1. Objective	2-1
2.2. The Problem	2-1
2.3. Scope	2-5
2.4. Test Descriptions	2-7
2.4.1. A Test Description	2-7
2.4.2. B, C, and D Test Descriptions	2-8
2.4.3. E Test Description	2-9
2.5. Equipment Description	2-10
2.5.1. General	2-10
2.5.2. Burner Vessel	2-10
2.5.3. Heating System	2-16
2.5.4. Cooling System	2-16
2.5.5. Burner Top	2-16
2.5.6. Burner Plenum/Gas Distributor	2-16
2.5.7. Fines Recycle Equipment	2-28
2.5.8. Instrumentation	2-28
3. DISCUSSION OF RESULTS	2-28
3.1. Fines Recycle	3-1
3.1.1. Fines Recycle System Operability	3-1
3.1.2. Fines Burning Efficiency	3-3
3.1.3. Process Effects of Fines Recycle	3-8
3.1.4. Fines Recycle Effects on Equipment	3-11
3.2. Product Characteristics	3-19
3.2.1. Test A	3-19
3.2.2. Tests B, C, and D	3-19
3.2.3. Test E	3-28

3.3.	Temperature Distribution	3-34
3.3.1.	Test A	3-34
3.3.2.	Tests B, C, and D	3-36
3.3.3.	Test E	3-40
3.4.	Bed Fluidization/Cooling	3-44
3.4.1.	Test A	3-44
3.4.2.	Tests B, C, and D	3-45
3.4.3.	Test E	3-49
3.5.	Off-Gas Composition	3-53
3.5.1.	Test A	3-53
3.5.2.	Tests B, C, and D	3-53
3.5.3.	Test E	3-53
3.6.	Feeding	3-59
3.6.1.	Test A	3-59
3.6.2.	Tests B, C, and D	3-62
3.6.3.	Test E	3-64
3.7.	Product Removal	3-64
3.7.1.	Test A	3-64
3.7.2.	Tests B, C, and D	3-66
3.7.3.	Test E	3-66
3.8.	General Equipment Performance	3-67
3.8.1.	Test A	3-67
3.8.2.	Tests B, C, and D	3-69
3.9.	Bed Heights	3-84
3.10.	Induction Heating and Heat Transfer	3-87
3.11.	Automatic Control	3-100
3.12.	Vessel Inspection	3-103
3.13.	Vessel Leak Tests	3-104
3.14.	Semiremote Fixtures	3-104
4.	CONCLUSIONS AND RECOMMENDATIONS	4-1
4.1.	Test A	4-1
4.2.	Tests B, C, and D	4-2
4.3.	Test E	4-4

5. REFERENCES	5-1
6. ACKNOWLEDGMENTS	6-1
APPENDIX A. REQUIREMENTS FOR THE 0.40-m PRIMARY BURNER TESTING . .	A-1
APPENDIX B. SATISFACTION OF SPECIFIED REQUIREMENTS	B-1

FIGURES

2-1. HTGR fuel element	2-2
2-2. HTGR coated fuel particles	2-3
2-3. 0.40-m primary burner assembly.	2-11
2-4. Sequence of 0.40-m primary burner installation	2-12
2-5. Induction heater installation for prototype burners	2-17
2-6. Components of heater assembly	2-18
2-7. Cooling air blower installation in blower vault for prototype burners	2-19
2-8. Upper cooling jacket assembly	2-20
2-9. Exhaust plenum assembly, insulation bonnet assembly, and lower shroud assembly	2-21
2-10. Lower intake plenum	2-22
2-11. Swing bolt clamp installation	2-23
2-12. 0.40-m burner top cap assembly and cross connection elbow . .	2-23
2-13. 0.40-m primary burner perforated cone gas distributor	2-24
2-14. Primary burner plenum and remote clamp	2-25
2-15. Remote clamp heater location	2-26
2-16. Plenum cart for 0.40-m primary burner	2-27
2-17. Primary burner fines recycle system	2-29
2-18. 0.40-m burner arrangement	2-30
2-19. Primary burner system for the HTGR reprocessing cold pilot plant	2-31
2-20. Burner control room instrumentation	2-32
2-21. DIOGENES digital process controller for the HTGR reprocessing cold pilot plant	2-33
3-1. Inlet gas flow in 0.40-m primary burner Test B	3-5
3-2. Inlet gas flow in 0.40-m primary burner Test C	3-6
3-3. Inlet gas flow in 0.40-m primary burner Test D	3-7
3-4. Inlet gas flow for 0.40-m primary burner Test E - Sept 13 . .	3-9

3-5.	Inlet gas flow for 0.40-m primary burner Test E - Sept 20 . .	3-10
3-6.	Bed, filter, and cyclone pressure drops (ΔP) in 0.40-m primary burner Test B	3-12
3-7.	Bed, filter, and cyclone pressure drops (ΔP) in 0.40-m primary burner Test C	3-13
3-8.	Bed, filter, and cyclone pressure drops (ΔP) in 0.40-m primary burner Test D	3-14
3-9.	Filter and cyclone pressure drop (ΔP) for 0.40-m primary burner Test E - Sept 13	3-15
3-10.	Bed, filter, and cyclone pressure drops (ΔP) for 0.40-m primary burner Test E - Sept 20	3-16
3-11.	Recycling fines oxide/hull content and fines sample history for 0.40-m primary burner Test D	3-25
3-12.	Recycling fines oxide/hull content and fines sample history for 0.40-m primary burner Test C	3-26
3-13.	Primary burner BISO/TRISO fuel particle agglomerates (typical)	3-27
3-14.	Material size distribution for 0.40-m primary burner Test B	3-29
3-15.	Material size distribution for 0.40-m primary burner Test C	3-30
3-16.	Material size distribution for 0.40-m primary burner Test D	3-31
3-17.	Recycling fines oxide/hull content and fines sample history for 0.40-m primary burner Test E	3-35
3-18.	System temperatures in 0.40-m primary burner Test B	3-37
3-19.	System temperatures in 0.40-m primary burner Test C	3-38
3-20.	System temperatures in 0.40-m primary burner Test D	3-39
3-21.	System temperatures for 0.40-m primary burner Test E - Sept 13	3-41
3-22.	System temperatures for 0.40-m primary burner Test E - Sept 20	3-42
3-23.	Bed cooling air flow for 0.40-m primary burner Test B	3-46
3-24.	Bed cooling air flow for 0.40-m primary burner Test C	3-47
3-25.	Bed cooling air flow for 0.40-m primary burner Test D	3-48
3-26.	Fuel rod fragments from crushed LHTGR fuel elements (BISO/TRISO fuel particles)	3-50
3-27.	Cooling air flow for 0.40-m primary burner Test E - Sept 13	3-51

3-28.	Cooling air flow for 0.40-m primary burner Test E - Sept 20	3-52
3-29.	Off-gas concentration and bed carbon content in 0.40-m primary burner Test B	3-54
3-30.	Off-gas concentration and bed carbon content in 0.40-m primary burner Test C	3-55
3-31.	Off-gas concentration and bed carbon content in 0.40-m primary burner Test D	3-56
3-32.	Off-gas concentration for 0.40-m primary burner Test E - Sept 13	3-57
3-33.	Off-gas concentration for 0.40-m primary burner Test E - Sept 20	3-58
3-34.	Flow rate into primary burner versus star valve speed setting (ambient conditions)	3-60
3-35.	Variation of flow rate of simulated fresh feed with time . .	3-61
3-36.	0.40-m primary burner showing feed bunker outlet	3-63
3-37.	Material size distribution for 0.40-m primary burner Test E	3-65
3-38.	0.40-m primary burner modified lower seal assembly with inner and outer seals of solid graphite	3-68
3-39.	0.40-m primary burner Peaucellier mechanism	3-70
3-40.	Side deflection of single guide link	3-71
3-41.	0.40-m primary burner connecting link	3-73
3-42.	0.40-m primary burner showing new guide linkage	3-74
3-43.	Primary burner bed level sensor	3-75
3-44.	0.40-m primary burner wall penetrations	3-76
3-45.	Modified lower seal leak locations	3-77
3-46.	Location of failed bellows, 0.40-m primary burner Test C.1	3-80
3-47.	0.40-m primary burner fines recycle system showing 0.10-m i.d. distorted bellows and 0.15-m i.d. bellows replacement .	3-81
3-48.	0.40-m primary burner unguided versus guided bellows	3-82
3-49.	0.40-m primary burner heat balance	3-93
3-50.	Effect of temperature on in-bed heat transfer - 0.40-m primary burner	3-94
3-51.	Effect of temperature on above-bed heat transfer - 0.40-m primary burner	3-95
3-52.	Effect of fluidization velocity on in-bed heat transfer - 0.40-m primary burner	3-97

3-53.	Effect of fluidization velocity on above-bed heat transfer - 0.40-m primary burner	3-98
3-54.	Effect of bed material on in-bed heat transfer - 0.40-m primary burner	3-99
3-55.	Proposed primary burner automatic control	3-102

TABLES

2-1.	Average properties of primary burner feed and startup bed . .	2-4
2-2.	Average properties of primary burner fuel particle product .	2-4
2-3.	Operating guides - primary fluidized-bed burner	2-6
3-1.	Material balance summary for 0.40-m primary burner Tests B, C, and D	3-20
3-2.	0.40-m Test C.2: particle breakage distribution based upon U, Th analysis	3-22
3-3.	0.40 m Test D: particle breakage distribution based upon U, Th analysis	3-23
3-4.	Material balance summary for 0.40-m primary burner Test E . .	3-32
3-5.	0.40-m Test E: particle breakage distribution based upon U, Th analysis	3-33
3-6.	Testing of modified lower seal, 0.40-m primary burner	3-78
3-7.	0.40-m primary burner heatup test results and material balance	3-85
3-8.	0.40-m primary burner heatup test heat transfer data and results	3-89

1. SUMMARY

The primary burning concept was successfully proven in long-term operation of the 0.40-m system at conditions expected to be the most severe in the operating cycle [fresh feed bed startup and subsequent high (≈ 80 wt %) to low (< 20 wt %) bed carbon burning]. Results indicated that in-bed and above-bed pressurized fines recycles were equally effective in burning graphite fines. The above-bed injection resulted in less large particle carryover and fuel particle breakage in the recycle loop and, subsequently, less noncombustible oxide/hull buildup in the fines. With a smaller fines inventory this configuration is potentially capable of higher reliability and more complete fines combustion. Consequently, it was selected as the preferred injection location.

Improvements in equipment configuration were made as the tests progressed, especially in the fines recycle system. The design of bellows was improved, or, where possible, thin-walled bellows were replaced with straight pipe sections. Penetrations were made $\approx 60\%$ up the burner tube side-wall for above-bed O_2 injection after early tests indicated that additional O_2 would increase fines burning efficiency. The penetrations were also used for above-bed fines recycle and for a bed level detection device.

The 0.4-m diameter burner tube length [≈ 4.1 m or length/diameter (L/D) = 10] was adequate for fines burning even when the fines were injected through the side-wall penetration only ≈ 1.6 m from the burner outlet. This tube length did, however, limit the maximum bed L/D to ≈ 4 because the slug heights of taller beds are in excess of the tube $L/D \approx 10$.

The in-bed response to the above-bed recycle indicated that large quantities of the fines entered the bed even when injected above the bed with the high velocities required for pressurized fines transport. The velocities

of pressurized recycle quickly eroded any poorly designed area (e.g., abrupt pipe i.d. change or weak bends in bellows). The severe conditions inherent in the pressurized recycle added motivation for use of the low velocity, gravity recycle technique in the 0.40-m system, should planned long term 0.20-m burner gravity tests prove successful. (The gravity recycle system was very successful in past short-term low carbon tests on the 0.20-m system but must be tested under long-term high carbon conditions on the 0.20-m burner to verify its capabilities.) The severe conditions suggested that if pressurized recycle were to be used further, special attention would have to be given to the transport piping design to reduce wear problems. The above-bed O_2 should be injected through a separate port to reduce both the transport velocity and the possibility of fines burning in the transport tubing.

Many other significant results were noted in the tests. The most important findings are itemized in Section 4. The detailed results are discussed in pertinent subsections of Section 3. Several items that warrant brief mention here are:

1. Breakage of TRISO particles in burning and product transport was much greater than for BISO particles. An average of ~ 13 wt % of TRISO particles fed broke in comparison to ~ 4 wt % for BISO particles (Runs C, D, and E). Overall particle breakage for the BISO/TRISO runs was as high as 9 wt % for in-bed recycle and as low as 2 wt % for above-bed recycle.
2. Significant bed segretation was observed. The dense BISO particles concentrated in the lower bed and most of the Th from BISO particle breakage was found in the plenum. In contrast, the TRISO particles floated in the upper bed and most of the U from TRISO breakage accumulated in the fines system.
3. Internal heat transfer coefficients in the bed ranged from 351 to 602 watts/m²-K (62 to 106 Btu/hr-ft²-°F) in runs without fines

recycle. Superficial velocities lower or higher than ~ 3.3 to ~ 3.6 ft/sec decreased heat transfer, and heat transfer was higher for smaller particles.

Although no measurements were available for fines recycle conditions, the injection of fines seemed to improve heat transfer/bed mixing. Recycling fines carried heat into the upper burner and off-gas system, reducing the bed wall cooling requirements.

4. The single-lead dc circuit level detection device which was developed in-house worked well in the burner vessel and also in the fines hoppers and gravity flow lines.
5. Overall operation of the 0.40-m system (scaled-up from the 0.20-m system) was smoother than 0.20-m operation. In-bed mixing was especially improved in the larger vessel.
6. Drainage of fuel particles through the plenum orifices was high throughout the testing. During test E, drainage amounted to >80 kg of predominantly burned back BISO fuel kernels.

2. INTRODUCTION

2.1. OBJECTIVE

The recovery for recycle of U-233 bred in HTGRs requires reprocessing of the spent graphite-based fuel. This reprocessing involves crushing of the fuel elements, removal of the graphite moderator and the fuel particle outer carbon coatings, separation of fissile and fertile particles, oxidation of fuel particle inner carbon, and dissolution and solvent extraction to separate uranium, thorium, and fission products. The reference method of removing the graphite and carbon is by combustion, which is most readily achieved in fluidized-bed burners. The primary burner system removes over 80 wt % of the graphite and carbon from the crushed fuel elements.

2.2. THE PROBLEM

The primary burner receives a feed stream of fuel particles and crushed graphite produced by a three-stage fuel element crushing system. The fuel element and fuel particles are depicted in Figs. 2-1 and 2-2, respectively. Average properties of the burner feed, nominally -5000 μm , are shown in Table 2-1. The primary burner must ignite and burn the fuel element graphite, the fuel rod matrix, and the fuel particle pyrolytic carbon at 900°C, producing a product of discretely separable silicon carbide-coated fissile particles and fertile fuel kernel particles containing less than 1 wt % exposed burnable carbon (Table 2-2). Adequate fluidization of the largest burning graphite and the large, dense fuel particles requires superficial velocities of 1.01 to 1.37 m/sec and a carefully designed gas distribution device. Graphite fines (-425 μm) generated both in the crushing process during fluidized-bed burning elutriate before they are burned. This carryover of fines is significant, amounting to over 30% of the carbon fed. This large mass of fines presents an expensive nuclear waste disposal problem; hence, combustion of the fines within the burner system is necessary.

Fig. 2-1. HTGR fuel element

(a) TRISO FERTILE PARTICLES ARE SIMILAR BUT LARGER (UP TO $800\mu\text{M}$)

Fig. 2-2. HTGR coated fuel particles

TABLE 2-1
AVERAGE PROPERTIES OF PRIMARY BURNER FEED AND STARTUP BED

Top density:	1.25 g/cm ³
Bulk density:	1.08 g/cm ³
Angle of repose:	35°
Average burnable carbon:	81%
Average particle size:	1378 μm

Size	Wt % of Total Sample	Percent Burnable Carbon in Fraction
-6350 μm + 4760 μm	5	100
-4760 μm + 869 μm	60	100
-869 μm + 550 μm	20	21
-550 μm + 420 μm	5	78
-420 μm + 375 μm	4	97
-375 μm + 250 μm	3	98
-250 μm	3	98

TABLE 2-2
AVERAGE PROPERTIES OF PRIMARY BURNER FUEL PARTICLE PRODUCT

Bulk density:	2 - 6 gm/cc
Size:	200 - 870 μm
Exposed burnable carbon:	<1%

A 90-deg included-angle perforated cone gas distributor with an additional gas inlet/product removal outlet at the cone vertex was developed on the 0.20-m burner system to safely burn crushed fuel elements. Crushed fuel elements are a mixture of large graphite chunks and dense fuel particles. A parallel hopper pressurized fines recycle system was used in the 0.20-m system to burn the smallest graphite fines in multiple recycle passes to the burner. These systems, successful in the smaller 0.20-m burner, were scaled up for the 0.40-m system and had to be proven again.

The primary burner tentatively operates in semi-continuous batch cycles in commercial application. Operating guidelines are summarized in Table 2-3. This operating mode processes an incoming lot of fuel elements in a series of burner runs which are separated by brief fresh feed interruptions for unloading a partial batch of the fuel particle product. The burner temperature is maintained by the thermal inertia of the retained bed and by external induction heating. The burner is completely emptied only after the specified lot of fuel elements is processed. The burner is then restarted by using the induction system to heat the initial crushed fuel element loading from the next customer lot to ignition temperature. Thus, the bed composition ranges from one rich in burnable carbon (>80 wt %) to one rich in burned-back fuel particles (≤ 20 wt %). Bed bulk density, and therefore bed weight, varies by a factor >5 , making this the most demanding portion of this operating cycle. Tests on the 0.20-m burner did not include completion of the entire operating cycle. Consequently the operation of the 0.40-m system had to validate the feasibility of the proposed operating cycle.

2.3. SCOPE

The 0.40-m primary burner development work described progresses from the initial heatup testing without combustion (A Tests), which began in September 1976, through short term combustion tests with in-bed fines recycle (B Test), longer term combustion tests with high to low carbon

TABLE 2-3
OPERATING GUIDES - PRIMARY FLUIDIZED-BED BURNER

	Crushed Fuel Element Burner
1. Operating mode	Semi-continuous batch
2. Startup	Induction heater
3. Gas distributor	Perforated cone
4. Feed system	Gravity/rotary valve
5. Product removal	Gravity/pneumatic
6. Feed/product control	Metered feed/batched product
7. Heat removal	Air cooling via annular shroud
8. Fines recycle	Gravity external recycle to burner via external cyclone/ filter system
9. Temperature	900° ± 50°C
10. Pressure	Less than 15 psig at all vessel locations
11. Materials	
Vessel	Hastelloy X ^(a)
Auxiliaries	304 L SST

^(a) Product of Cabot Corporation.

operation comparing above-bed to in-bed fines recycle (Tests C and D), and finally, completion with the longest operation, which processed 20 LHTGR crushed fuel elements as part of the FY-77 sequential operation of the recycle development pilot plant. This sequential operation was completed on September 20, 1977, about one year after the first A test.

2.4. TEST DESCRIPTIONS

2.4.1. A Test Description

The 0.40-m primary burner had been operated only in preliminary check-out tests of individual subsystems prior to the A series of tests. The burner system required analysis of integrated operation of all systems needed for heating beds to the 700°C ignition temperature. Successful completion of this first heatup test phase was the prerequisite to continuing 0.40-m burner operation into ignition tests and full burner runs. Data obtained in these tests were essential in establishing operating parameters to be used in all subsequent runs and were the basis for future analysis of mixing and heat transfer scale-up differences between the 0.40-m and 0.20-m primary burners.

The 0.40-m A test phase consisted of six burner tests which studied induction coil heating of several types of beds. Four tests were compared for effects of bed depth: Test A-2.1, a heatup using the lower coil to heat a shallow bed of carbon-coated TRISO fertile fuel particles; Test A-2.2, which used the lower and upper coils to heat a deep bed of fuel particles; Test A-3.1, which used a shallow bed lower coil operation with a fresh feed mixture consisting of 83 wt % graphite mixed with 17 wt % fuel particles; and Test A-3.2, a dual coil, deep bed test with the same fresh feed mixture. Tests A-2.1 and A-2.2 concerned tailburning product beds and Tests A-3.1 and A-3.2 startup of fresh feed beds. Two additional tests, the initial graphite bed heatup and an additional particle bed heatup for pneumatic transport study, were not applicable to comparative analysis and were not included in the discussion of experimental results. These tests met the

requirements described in the 0.40-m Primary Burner Activity Plan under Section 3.1, "Heatup Transients," dealing with: 3.1.1 "Crushed Graphite Bed," 3.1.2 "Particle Bed," and 3.1.3 "Fresh Feed" (Ref. 1).

2.4.2. B, C, and D Test Descriptions

This series of tests was planned to test actual burning/fines recycle operation in a step sequence. Low carbon burning and in-bed recycle to a TRISO particle bed was first. Then typical high carbon feed containing BISO/TRISO particles was used with in-bed recycle. Finally, above-bed fines recycle was tested with the BISO/TRISO feed. The burner's capability for long term operation was thereby evaluated.

Test B, as described in the Activity Plan, Section 3.2, "Low Carbon Startup," used a Fort St. Vrain (FSV) TRISO fertile carbon-coated particle bed with low carbon content (~15%) for a startup and a tailburn. In-bed fines recycle was tested in the run but no above-bed O_2 was used for fines burning. The fines recycle was stopped after O_2 utilization had been reduced to zero in tailburning. This served as a checkout to ensure that the burner control loops functioned properly before starting up a typical fresh feed bed.

Test C was the next experiment in the Activity Plan. This test was started up and fed with an equivalent of eight typical high loading BISO/TRISO - crushed graphite blocks (1.5 for a startup bed and 6.5 as feed). One of the typical blocks contained 38 kg of coated BISO/TRISO particles and 80 kg of graphite. In-bed fines recycle was used with above-bed O_2 injection. After all of the blocks were fed, fines recycle was stopped and the product bed was tailburned without induction heating assistance.

Test D completed this phase of tests. It employed the same basic operation as Test C except Test D used above-bed fines recycle through the same injection pipe as was used for above-bed O_2 . This test tailburned both the product bed and the recycling fines to minimum levels, using the induction

heater to assist final burnout. (The ~200 kg product bed of back particles from Test C was added to the ~200 kg product bed of Test D to yield ~400 kg and a volume which filled $\gtrsim 50\%$ of the lower induction coil; this allowed safe induction-heated tailburning in Test D.)

Thus, the parallel, pressurized hopper pneumatic fines recycle system was used for: (1) in-bed recycle during short duration (~4 hr) operation with a low carbon FSV TRISO particle bed in Test B, (2) in-bed recycle during extended duration (~17 hr) operation to a high carbon LHTGR BISO/TRISO particle bed in Test C, and (3) above-bed recycle for Test D with a bed and operating parameters similar to Test C. Test C was shut down and restarted in consecutive days, whereas Test D was operated continuously.

Tests C and D completed the preparations necessary for the 20-block burning campaign of Test E as part of sequential operation of the head-end pilot plant. The results, together with the quantitative results of Test B (low carbon operation with fertile TRISO particles and in-bed fines recycle), indicated the preferred injection location and operating technique for fines recycle in future 0.40-m burner operation.

2.4.3. E Test Description

The burner was prepared to use the above-bed fines recycle location selected in the previous testing to best meet the acceptance criteria as given in Section 4 of the Activity Plan. The operating technique for fines recycle burning was modified to include mid-reactor O_2 increases early in the startup. These mid-reactor O_2 increases brought the flow to $0.25 \text{ m}^3/\text{min}$ (17% of inlet O_2 flow) as rapidly as maintenance of the off-gas $O_2 \lesssim 3 \text{ vol } \%$ would allow.

The 0.40-m burner system processed 20 crushed LHTGR fuel elements (~20 kg of burned back BISO/TRISO particles per block) in Test E, the primary burner portion of the FY-77 sequential pilot plant operation. Burning the 20 crushed blocks (1.5 as startup bed and 18.5 as feed) required >40 hr

of operation. More than 16 hr of this operation had >50 wt % bed carbon. It was thus the most demanding primary burner test to date.

The burner sequential operation Test E was accomplished in two parts. The first part consisted of 24 hr of burning on September 13 and 14; the second part had 20 hr of burning from September 20 to 21. The initial test attempt on September 7 was shut down after ~ 3 hr of burning when the bellows in the mid-reactor fines/ O_2 injection line ruptured. This bellows was replaced by a straight pipe section prior to the remainder of the Test E operation.

2.5. EQUIPMENT DESCRIPTION

2.5.1. General

The 0.40-m primary burner assembly (Fig. 2-3) comprises the burner vessel itself, heating, cooling, insulation, a conical gas distributor, and an assembly from which the vessel hangs. The off-gas passes through a cyclone/filter combination, and the small particulates (or fines) separated from the gas are reinjected into the burner from two pressurized fines hoppers. Feed is metered to the burner by a rotary valve, and the product leaves through a cone gas distributor vertex line to enter a pneumatic transport system.

2.5.2. Burner Vessel

The primary burner vessel is a 0.40-m-i.d., 5-m-high cyclinder. To enhance the heat transfer between the vessel wall and the cooling air which flows through an annular space along the length of the vessel, pin fins are welded to the outside of the wall in a 2-m long array. The burner vessel is installed by lowering it into the heating section (Fig. 2-4).

1. BURNER ASSEMBLY	4. UPPER INTAKE SHROUD ASSEMBLY	7. UPPER LOWER INDUCTION COIL JUNCTION
2. BURNER VESSEL ASSEMBLY	5. HEATER ASSEMBLY	8. PERFORATED GAS DISTRIBUTION CONE
3. INSULATION BONNET ASSEMBLY	6. KNIFE GATE ASSEMBLY	9. CONE VERTEX PRODUCT OUTLET GAS INLET

Fig. 2-3. 0.40-m primary burner assembly

(a)

Fig. 2-4. Sequence of 0.40-m primary burner installation: (a) heater section is connected to upper cooling jacket by means of heater and shroud transfer rails

35-135-189-3

(b)

(c)

Fig. 2-4. Sequence of 0.40-m primary burner installation: (b) 0.40-m primary burner vessel is unloaded from shipping cradle to tilt-down fixture, where vessel can be rotated for thermocouple and insulation installation; (c) finned section of 0.40-m primary burner containing 21,600 pins in a 2-m length of the vessel

35-135-189-8 (d)

35-135-189-12 (e)

Fig. 2-4. Sequence of 0.40-m primary burner installation: (d) 0.40-m primary burner tube on remote handling fixture; (e) vertically erected on tilt-down fixture, the 0.40-m primary burner is ready for transfer to burner platform

2-15

35-135-191-9 (f)

35-135-191-26 (g)

Fig. 2-4. Sequence of 0.40-m primary burner installation: (f) with upper cooling jacket doors swung open, burner vessel is inserted through heater section; (g) completed 0.40-m primary burner vessel installation

2.5.3. Heating System

The bed is heated by an induction heater whose power source is a motor generator set (Fig. 2-5). Current flows through a water-cooled copper coil which suscepts on a thin metal tube that is also the outer boundary of the lower section of the cooling gas annular passage. The susceptor tube radiates heat to the burner vessel wall. The induction coil, shown with some other components in Fig. 2-6, has two zones, allowing heating of both deep and shallow beds.

2.5.4. Cooling System

Cooling air compressed by a rotary blower (Fig. 2-7) passes into the burner assembly via two intake plenum assemblies and leaves via one central exhaust plenum. The amount of air passing through the upper and lower cooling jackets can be independently controlled. The major components of the cooling system are shown in Figs. 2-8 through 2-10.

2.5.5. Burner Top

The top assembly of the burner is held by a swing bolt clamp (Fig. 2-11). The top cap has penetrations for a feed inlet, gas outlet, and thermowell (Fig. 2-12).

2.5.6. Burner Plenum/Gas Distributor

The burner gas distributor is a 90 deg included angle perforated cone with a 0.025-m vertex (Fig. 2-13). The plenum is held in place by a remote clamp (Fig. 2-14) which has its own electric resistance heaters as shown in Fig. 2-15. The clamp heaters prevent excess temperature gradients across the remote clamp. The plenum can be removed using a plenum cart (Fig. 2-16).

Fig. 2-5. Induction heater installation for prototype burners

(a) Heater base plate

(b) Two-zone induction heating coil

(c) Susceptor

Fig. 2-6. Components of heater assembly

Fig. 2-7. Cooling air blower installation in blower vault for prototype burners

Fig. 2-8. Upper cooling jacket assembly

Fig. 2-9. Exhaust plenum assembly, insulation bonnet assembly, and lower shroud assembly

Fig. 2-10. Lower intake plenum

35-135-191-24

Fig. 2-11. Swing bolt clamp installation

35-135-196-12

Fig. 2-12. 0.40-m burner top cap assembly and cross connection elbow

Fig. 2-13. 0.40-m primary burner perforated cone gas distributor

76G1531

Fig. 2-14. Primary burner plenum and remote clamp

Fig. 2-15. Remote clamp heater location

Fig. 2-16. Plenum cart for 0.40-m primary burner

2.5.7. Fines Recycle Equipment

Fines leaving the cyclone and the filter fall down a combined line into two pressurized hoppers (Fig. 2-17). While one hopper is filling, the other is either pressurizing or transporting fines back to the burner. A detailed arrangement drawing of the primary burner is given in Fig. 2-18, and a general view of the upper part of the burner system is given in Fig. 2-19.

2.5.8. Instrumentation

The control room instrumentation is shown in Fig. 2-20. Burner operation draws extensively on the capabilities of a process control computer, DIOGENES (Fig. 2-21). The DIOGENES system is a hard-wired real-time dedicated process controller. Each control loop accepts a 4-20 milliamp dc analog signal from the process and provides a continuous 4-20 milliamp dc analog output signal back to the process. The analog (A) input signals are converted to digital (D) form for interfacing with the computer-based central controller, and the digital feedback instructions from the central controller are reconverted to analog output signals. The A/D and D/A conversion is performed by process interface modules (PIMs); one PIM is required for each DIOGENES channel which has an analog input and/or an analog output.

The configuration of the control loops is set up by the operator beforehand with pins and wire links on a functionally diagrammed diode pin-board called the channel function matrix (CFM). All loops may be digitally controlled by the central controller using an automatic one-second scan arrangement. This is the normal or central control mode of operation. A variation of this mode is the central manual mode, which allows a loop to be manually controlled through the operator's console. In addition, there is a completely separate and independent analog backup control mode, which is effective even if the central controller breaks down.

35-135-194-15

Fig. 2-17. Primary burner fines recycle system

Fig. 2-18. 0.40-m burner arrangement

**OFF - GAS
FILTER**

**FEED
BUNKER**

**OFF - GAS
CYCLONE**

**FINES
RECYCLE
LINE**

**CLAMSHELL
COOLING
JACKET**

**BURNER
VESSEL**

Fig. 2-19. Primary burner system for the HTGR reprocessing cold pilot plant

Fig. 2-20. Burner control room instrumentation

**PROCESS
INTERFACE
MODULES
(PIM'S)**

**OPERATOR'S
CONSOLE**

**CENTRAL
CONTROLLER**

**CHANNEL
FUNCTION
MATRIX
(CFM)
DRAWER**

Fig. 2-21. DIOGENES digital process controller for the HTGR reprocessing cold pilot plant

3. DISCUSSION OF RESULTS

The following sections discuss particular test objectives as outlined in the Activity Plan (Ref. 1). Pertinent results from Test A, Tests B, C, and D, and Test E are reported in sections dealing with specific objectives.

The sections are:

1. Fines recycle
2. Product characteristics
3. Temperature distribution
4. Bed fluidization/cooling
5. Off-gas composition
6. Feeding
7. Product removal
8. General equipment performance
9. Bed heights
10. Induction heating
11. Automatic control
12. Vessel inspection
13. Vessel leak tests
14. Semiremote fixtures

3.1. FINES RECYCLE

3.1.1. Fines Recycle System Operability

3.1.1.1. Test A. No fines were recycled in these heating tests.

3.1.1.2. Tests B, C, and D. The bed temperature cycling for in-bed recycle on the 0.40-m burner ($\pm 10^{\circ}\text{C}$) was less than that observed on the 0.20-m burner ($\pm 50^{\circ}\text{C}$). The recycle mass flow rate was over 10 kg/min

using 50 SLPM transport gas, a 20 to 34 kPa (3 to 5 psig) line pressure drop, and recycle hopper pressures of 270 kPa ($\sim$ 10 psig).

The parallel, pressurized hopper fines transport system operated acceptably in Tests B, C, and D. One significant transport difference was noted in the tests. The fines hopper transport pressure ranged from 70 to 83 kPa (10 to 12 psig) during the in-bed recycle tests, whereas the above-bed recycle transport pressure ranged from $\sim$ 83 to $\sim$ 138 kPa (12 to 20 psig). Tests B and C used in-bed recycle via an $\sim$ 1.4-m length of 14-mm i.d. tube and flex hose. The backpressure on the recycling fines (the fines hopper pressure during transport) included the minimal backpressure of this short transport line and the more significant backpressure of the fluid bed itself. Test D used above-bed recycle via an $\sim$ 5.3-m length of 14-mm i.d. tube, $\sim$ 3.4 m of which was vertical riser. Hence, the bed backpressure was avoided, but the long transport line caused more backpressure with above-bed transport. The highest backpressure in above-bed recycle occurred during the period of peak fines inventory, whereas the lower backpressure occurred at the beginning and end of the test when the fines mass was low.

The hopper inlet valves (0.1-m i.d.) were noted to bind as fines temperatures (recorded in the hoppers) increased through the 375° to 425°C range. The binding stopped at $>425^{\circ}\text{C}$ and did not reoccur when the fines cooled. The cause of this condition and its effects are discussed in Section 3.3.

3.1.1.3. Test E. The above-bed fines injection operation using the parallel, pressurized hoppers was similar to that reported for Test D. The two significant operating characteristics, the high transport pressure and the inlet valve binding, both reoccurred but to a lesser degree than in Test D. The transport pressure in Test E reached 138 kPa (20 psig) but only stayed that high for a short time as compared to Test D. The transport pressure during the bulk of the run time was 110 to 124 kPa (16 to 18 psig). The east fines hopper inlet valve was noted binding only once in the second part of the test. The generally smaller mass of recycling fines throughout Test E as compared to Test D was probably the cause of the reduced operating perturbations.

3.1.2. Fines Burning Efficiency

3.1.2.1. Test B. The final inventory of graphite fines in the fines hoppers after Test B was much larger (5.8 kg) than that observed with the 0.20-m burner (<1 kg). The remainder of the 11.8 kg total final fines hopper contents consisted of ~5.5 kg of oxides mixed with fragments of SiC particle hulls <<335 μm . This oxide/hull content was also much larger than that found in past 0.20-m burner work. This final fines inventory occurred after an extended fines tailburning period at high fines recycle rates.

The difference between the larger final inventory of graphite fines in 0.40-m burner for Test B as compared to prior 0.20-m burner tests may have resulted from some operational discrepancy. However, the Test B extended fines tailburning period with vertex fines recycle was similar to 0.20-m tailburns, which were very successful in burning out the carbon in the recycling fines. Hence, process differences are a possible explanation for the poor fines burnout efficiency.

The process differences between Test B and past 0.20-m vertex recycle work include the very large oxide/hull content of the recycling fines in 0.40-m burner for Test B and the fact that no above-bed source of O_2 was available on the 0.40-m burner. A maximum of ~20 wt % oxide/hull content was noted in 0.20-m vertex recycle test work as compared to the ~50 wt % oxide/hull concentration observed in Test B. The less efficient Test B fines burnout may be associated with this higher oxide/hull concentration in that the greater mass of noncombustible fines may interfere with and limit the reaction kinetics of the recycling graphite fines. Further, the lack of above-bed O_2 throughout Test C compares to past 0.20-m work using above-bed injection of O_2 equivalent to 10 to 20 vol % of the total inlet O_2 . Although this above-bed O_2 is generally not used during tailburning, its use throughout the preceeding equilibrium operation is now thought to be essential to maintaining a low fines inventory and minimizing the fines tailburning period.

Consequently, an injection point for above-bed O_2 was considered necessary prior to operation in Tests C and D. The installation of the side-wall penetration for this O_2 subsystem is discussed in Section 3.8.

3.1.2.2. Tests C and D. Fines burning efficiency for in-bed recycle was similar to that for above-bed recycle during the last part of Tests C and D when bed carbon was <50 wt %. The in-bed recycle of Test C was apparently more efficient than the above-bed recycle of Test D during the early period with >50 wt % bed carbon, since level detectors in the fines hoppers indicated a larger fines inventory in the early period of Test D than during the same period in Test C. Both techniques of fines recycle burned fines at such a rate that the capacity of the existing fines system was never exceeded.

The difference between high carbon fines burning in Tests C and D may be discussed in light of the difference in quantities of mid-reactor O_2 flow used. (As shown in Fig. 3-1, no mid-reactor gas flow was available in Test B.) Figures 3-2 and 3-3 show the levels of O_2 flow in Tests C and D and indicate when mid-reactor O_2 flows were altered. The peak mid-reactor O_2 flow in Test C was 65 SLPM, added during the plenum O_2 ramp increase as the burn rate, fines generation, and burner system temperatures equilibrated. A similarly small amount of mid-reactor O_2 was added during the plenum O_2 ramp of Test D, but the fines buildup noticed after ~1 hr of operation at these O_2 levels indicated that this mid-reactor O_2 level was insufficient for above-bed recycle. The increases in vertex O_2 to ~250 SLPM which occurred early in Test C were replaced in Test D by increases in mid-reactor O_2 (see notes 1 and 3, Figs. 3-2 and 3-3). The fines inventory in Test D was relatively large at this point and required ~4 hr of operation before being reduced below a mass detectable by level devices in the fines system. After the Test D bed carbon wt % had been reduced to <<50 wt %, the mid-reactor and vertex O_2 levels were altered to levels similar to those used throughout Test C (see note 4, Fig. 3-3). In contrast, mid-reactor and vertex O_2 had to be reduced for an ~1.5-hr period during the >50 wt % carbon period of Test C when fines inventory reached

Fig. 3-1. Inlet gas flow in 0.40-m primary burner Test B

Fig. 3-2. Inlet gas flow in 0.40-m primary burner Test C

Fig. 3-3. Inlet gas flow in 0.40-m primary burner Test D

such a low level that burner process conditions were destabilized. The full O_2 levels were reestablished and were held for the remainder of Test C after the recycling fines mass built back up (see note 4, Fig. 3-2).

3.1.2.3. Test E. The fines burning rates in Test E were such that the fines inventory was maintained at less than the 15 to 20 kg capacity of one fines hopper (as indicated by the level probes). This efficiency of fines burning with above-bed injection was similar to that of Test C with in-bed recycle. The fines inventory buildup in the above-bed recycle of Test D was, therefore, definitely caused by insufficient mid-reactor O_2 increases. The mid-reactor O_2 in Test E was increased to $0.25 \text{ m}^3/\text{min}$ (0.17 vol % of the total inlet O_2) well before the plenum O_2 ramp was complete (see Figs. 3-4 and 3-5). The off-gas O_2 was monitored and maintained below ~ 3 vol % to control the rate of mid-reactor O_2 increase.

3.1.3. Process Effects of Fines Recycle

3.1.3.1. Tests B, C, and D. Fundamental differences between non-recycle and recycle periods of the tests and between in-bed and above-bed fines recycle were noted when certain process parameters were compared. The differences involved the final products of the run, the burner system temperature distribution, the bed cooling character, and the off-gas composition. In summary, it was noted that: (1) in-bed recycle resulted in >4 wt % particle breakage in recycle to a TRISO bed and >5 wt % particle breakage in recycle to a BISO/TRISO bed compared with <1 wt % breakage with above-bed recycle to a BISO/TRISO bed; (2) in-bed temperatures were cyclically cooled by both in-bed and above-bed fines transport cycles, with the former having the larger effect; (3) the bed cooling air requirements were reduced by high rates of fines recycle, especially recycle through the bed; and (4) fines recycle generally increased off-gas CO vol % levels and caused intermittent spikes and fluctuations of ± 5 vol % CO. These areas are discussed further in the following sections.

One process parameter response to fines recycle which requires separate mention is the bed pressure drop measured by taps in the vertex gas

Fig. 3-4. Inlet gas flow for 0.40-m primary burner Test E - Sept 13

Fig. 3-5. Inlet gas flow for 0.40-m primary burner Test E - Sept 20

inlet and the burner off-gas outlet. The ΔP trends are plotted in Figs. 3-6, 3-7, and 3-8. The effect on the bed ΔP instrument of the short time lag in establishing fines flow when switching between hoppers is significant. During fines flow the bed ΔP indicates a higher level than it indicates between fines flow. This was used as an accurate monitor of the fines cycle in Tests B and C (see Figs. 3-6 and 3-7). The bed ΔP during the above-bed fines recycle of Test D shows the normal trend (see Fig. 3-8).

3.1.3.2. Test E. The process effects of fines recycle in Test E were:

1. Particle breakage found to be 2 to 4 wt %. (Probable reasons for the higher breakage are discussed in Section 3.2.)
2. Cycling of temperature, especially above-bed TC No. 11 which was for the first time continuously recorded, showing initial $\pm 20^\circ\text{C}$ cycles decreasing to equilibrium $\pm 10^\circ\text{C}$ cycles.
3. Cooling air influences not as marked as in Tests C or D (see discussion in Section 3.4).
4. Fines pockets occurring in the feed later in operation, which caused temporal buildups of fines inventories, off-gas filter ΔP , and bed temperature changes (see Section 3.3 and compare Figs. 3-9 and 3-10).
5. Buildup of oxides/hulls in fines to ≥ 20 wt % measured (more if tailburning was completed) (see Section 3.2).

3.1.4. Fines Recycle Effects on Equipment

3.1.4.1. Tests A through D. No equipment effects directly attributable to fines recycle were noted in Tests A through D.

Fig. 3-6. Bed, filter, and cyclone pressure drops (ΔP) in 0.40-m primary burner Test B

- ① FINES RECYCLE STARTED
- ② ABOVE-BED TEMPERATURE CYCLES ABOVE IN-BED TEMPERATURE
- ③ LOW POINT OF ABOVE-BED TEMPERATURE
- ④ FINES RECYCLE STOPPED

Fig. 3-7. Bed, filter, and cyclone pressure drops (ΔP) in 0.40-m primary burner Test C

Fig. 3-8. Bed, filter, and cyclone pressure drops (ΔP) in 0.40-m primary burner Test D

Fig. 3-9. Filter and cyclone pressure drop (ΔP) for 0.40-m primary burner Test E - Sept 13

Fig. 3-10. Bed, filter, and cyclone pressure drops (ΔP) for 0.40-m primary burner Test E - Sept 30

3.1.4.2. Test E. Three equipment failure incidents during Test E indicated that the pressurized fines recycle had a remarkable ability to erode metal parts, as is recorded below:

1. The first failure occurred at about 1400 on September 7, 1977, when the bellows connecting the mid-reactor fines and gas lines to the burner wall penetration ruptured. The bellows rupture was attributed to the high velocity fines/gas stream eroding through the 0.13 mm (0.005 in.) wall at a flexed-bend point in the bellows. The velocity of the 500°C fines and pneumatic transport gas approaching the bellows was about 26 m/sec (87 fps or 59 mph). Injection of 0.25 m³/min of O₂ just upstream of the bellows added approximately another 33 m/sec (108 fps or 74 mph). Hence, the velocity of the fines/gas stream through the short bellows section and into the burner was at least 59 m/sec (195 fps or 133 mph). This was more than sufficient to wear through a bend in the bellows wall. (In retrospect, it is surprising that the bellows lasted almost 20 hr in such service: 16 hr in Test D and 2 hr in this test.) The bellows was replaced by a straight section of tubing to circumvent bends in this high velocity section. A slot was cut in the upper cooling shroud plate to allow for differential thermal growth of the fines recycle line relative to the burner wall.

This straight pipe section gave no indication of problems throughout the remainder of the run. Thermocouples on the outer wall of the pipe indicated no unusual temperatures, confirming that erosion of the bend in the bellows wall was indeed the failure cause.

2. Indications of a second equipment failure were first noted at about 1350 on September 20, after another 28 hr of Test E operation. Small puffs of fines were seen issuing from the top of the burner thermowell (a 22 mm o.d. x 1.2 mm wall tube, capped at the bottom. Fines recycle was stopped at this time and

mid-reactor and vertex O₂ turned off while the opening in the top of the thermowell was plugged with Sauereisen cement. Fines recycle was restarted at 1511 and full O₂ flow rates were regained by 1553. The fines were no longer leaking, so the run continued.

At 0407 on September 21 (2 hr after the last of the crushed blocks had been fed), indications were that internal burner thermocouples in the thermowell below the point of mid-reactor injection were open or shorted-out. The run was immediately terminated as bed temperature monitoring was no longer possible.

Inspection of the thermowell after the run indicated that the tube had been eroded through by the high velocity fines stream injected perpendicular to the tube. The initial eroded hole (as indicated by the first fines puffs) had grown with the continued operation. Finally, the weakened thermowell tube was snapped by the slugging bed action. The repair had allowed operation to continue well into the tailburning phase. Thus, the unscheduled shutdown did not curtail further sequential operation.

3. The third equipment failure occurred just prior to the thermowell break. At 0345 on September 21, an intermittent leak of fines was seen in the area of the pipe "Y," which joins the two parallel fines hoppers to the common fines recycle transport pipe. Fines recycle was immediately stopped, and this stopped the leak.

This incident would not have curtailed product bed tailburning even though the fines inventory could not be reduced to minimum levels.

Inspection of the pipe "Y" after the run revealed a 1-mm hole eroded in the downstream leg. The "Y" had been contorted (through manufacture or installation) and closer inspection showed that a ridge in the contorted pipe i.d. had presented a perpendicular

face to the erosive fines flow. The recycling fines had finally eroded the hole through this abrupt edge in the many ripsaw cycles at the 26 m/s velocity (the "Y" had serviced almost 100 hr of the cyclic fines transport operation).

Obviously, these incidents draw attention to the severe service of components in pressurized fines recycle and the very careful design, manufacture, and care required for acceptable equipment reliability and longevity.

3.2. PRODUCT CHARACTERISTICS

3.2.1. Test A

Breakage of the carbon-coated TRISO particles attributed to heatup and fluidization averaged 0.9 wt % in the four analyzed A tests. The breakage of the TRISO fuel particles pneumatically conveyed after fluidization averaged 0.53 wt %. These values for breakage of unmixed TRISO particles are a baseline of comparison to the subsequent tests at full-burning fines recycle operating conditions with unmixed TRISO in Test B and mixed BISO/TRISO in Tests C, D, and E.

3.2.2. Tests B, C, and D

The final product from Tests B, C, and D included the product bed, which was pneumatically transported out of the burner, the plenum material, which had been forced through the distributor plate during the slugging bed operation, and the final fines hopper material. Material withdrawn in fines samples during Tests C and D operation gave indication of the fines composition trends leading up to the final fines hopper material.

The fines recycle particle breakage values of >4 , >5 , and <1 wt % for Tests B, C, and D, respectively, were analyzed. The material balance summary for these three runs (Table 3-1) indicates the total particle breakage

TABLE 3-1
MATERIAL BALANCE SUMMARY FOR 0.40-m PRIMARY BURNER TESTS B, C, AND D

Item (a)	Test B		Test C	Test D	Comments
	Hot	Cold			
Combustibles Balance					
1. Carbon in (kg)	82		735	750	1. --
2. Product bed; +850 (kg)	0.04	0.0	0.329	0.065	2. --
3. Product bed; -850, +355(kg)	4.10	1.50	0.665	0.366	3. --
4. Product bed; -355 (kg)	1.20	0.48	2.957	0.033	4. Carbon fines
5. Plenum; +355 (kg)	0.34		1.655	1.033	5. Unburned whole particles
6. Plenum; -355 (kg)	0.22		6.631	5.050	6. Carbon fines and unburned broken particles
7. Final fines hopper; +355 (kg)	0.02		0.012	0.002	7. Graphite, unburned particles
8. Final fines hopper; -355 (kg)	6.30		10.40	0.923	8. No fines tailburn in Test C
9. Total carbon unburned (kg)	14.2		22.65	7.472	9. Sum of 2 through 8
10. Carbon out in fines samples (kg)	None		10.47	11.061	10. --
Noncombustibles Balance					
11. Particles in (kg)	268		197	415	11. --
12. Product bed; +850 (kg)	0	0	0.033	0.260	12. ~0.1 kg of -2000- μ m agglomerates; only in Test D
13. Product bed; -850, +355 (kg)	69.1	156	105.5	328.4	13. Particles (some hulls)
14. Product bed; -355 (kg)	6.29	6.02	2.279	2.947	14. Hulls and oxides (some particles)
15. Plenum;+355 (kg)	5.19		78.84	79.01	15. Particles (some hulls)
16. Plenum;-355 (kg)	0.40		10.63	1.290	16. Oxides and hulls
17. Final fines hopper;+355 (kg)	0.51		0.041	0.099	17. Particles and hulls
18. Final fines hopper;-355 (kg)	4.99		1.280	0.276	18. Oxides and hulls
19. Noncombustibles out in fines samples (kg)	None		0.558	0.071	19. Oxides and hulls
20. Total oxides/hulls out; -355 (kg)	17.7		14.7	4.6	20. 14 + 16 + 18 + 19
21. Total particles out; -850,+355 (kg)	231		184.4	407.5	21. 13 + 15 + 17
22. Particle loss $\left(\frac{\text{No. 11} - \text{No. 21}}{\text{No. 11}}\right) \times 100$ (wt %)	13.8		6.4	1.8	22. Tests B and C low when compared with No. 20 - oxides/hulls
23. Recycle breakage estimate $\left(\frac{\text{No. 16} + 18 + 19}{\text{No. 20}}\right) \times 100$ (wt %)	4.2		5.4	0.6	23. --
24. Final bed carbon $\left(\frac{\text{No. 2} + 3 + 4 = C}{C + \text{No. 12} + 13 + 14}\right) \times 100$ (wt %)	6.6	1.2	3.5	0.14	24. Particle carbon <1 wt % except Test B - Hot (~6%)

(a) 850 and 355 are micron screen sizes.

magnitude as particle loss (item 22). The recycle breakage estimate calculated as shown in Table 3-1 (item 23) is the fraction of that particle loss which is attributable to operation of the primary burner. The difference between item 22 and item 23 is an estimate of breakage from pneumatic transport of the product bed. This analysis is based upon screening; the presence of TRISO hulls in the +355- μ m particle fraction biases the data toward less particle breakage than actually occurred. Microscopic examination of the +355- μ m fractions indicated this to be especially true in the case of Tests B and C. Another biasing factor is that the pneumatically transported product breakage estimate includes some material broken within the fluid bed operation but not yet elutriated into the fines system or pounded into the plenum.

Tables 3-2 and 3-3 show the chemical analysis of the product, plenum, and fines fractions for Tests C and D. The results do indicate an overall 33 to 42% higher breakage than estimated from screening in Table 3-1. This increase in breakage assessment came primarily from the chemical analysis exposure of leachably cracked TRISO particles in the +355- μ m fractions.

It is significant that TRISO particle breakage was more than twice BISO particle breakage in the above-bed recycle of Test D (Table 3-3). The large amount of broken BISO particles found in the plenum after the in-bed recycle of Test C altered this ratio somewhat, but TRISO breakage remained higher overall in Test C (Table 3-2).

The smallest total particle breakage occurred in Test D with above-bed recycle to a BISO/TRISO particle bed. The largest proportion of the breakage in Test D occurred in ambient product pneumatic transport; quantities of broken materials found in the plenum or in the fines were proportionally small as compared to those found in the transported product. The BISO/TRISO particle loss in the in-bed recycle of Test C was, in contrast, predominantly noted in the plenum and final fines hopper and fines sample fractions (see items 16 and 18, Table 3-1, and Tables 3-2 and 3-3). In-bed fines recycle to the pure TRISO-coated particle bed of Test B yielded the highest particle loss of the three tests. The proportionally highest loss

TABLE 3-2
0.40-m TEST C.2: PARTICLE BREAKAGE DISTRIBUTION BASED UPON U, Th ANALYSIS

	Product (a)	Plenum	Fines Hoppers	kg Total Breakage	kg Total Particles In	Total wt % Breakage
kg broken BISO particles (Th equivalent) (b)	1.07	9.87	0.43	11.37	134	8.5
kg broken TRISO particles (U equivalent) (c)	4.64 (d)	1.09	1.07	6.80	63	10.8
Total out		<u>12.46 kg</u>		<u>18.17</u>	<u>197</u>	<u>9.1 (e)</u>
Recycle breakage estimate $\approx \frac{12.46}{18.17}$ (9.1 wt %) ≈ 6.2 wt %						

(a) Includes breakage due to pneumatic transport.

(b) gm Th in fraction $\div 0.88$.

(c) gm U in fraction $\div 0.18$.

(d) 4.3 kg of this fraction leached out of partially cracked +355 μm particles.

(e) Versus the 6.4 wt % "particle loss" calculated from sieve results (Table 3-1).

TABLE 3-3
0.40-m TEST D: PARTICLE BREAKAGE DISTRIBUTION BASED UPON U, Th ANALYSIS

	Product ^(a)	Plenum	Fines Hoppers	kg Total Breakage	kg Total Particles In	Total wt % Breakage
kg broken BISO particles (Th equivalent) ^(b)	2.58	0.89	0.10	3.57	282	1.2
kg broken TRISO particles (U equivalent) ^(c)	6.05 ^(d)	0.42	0.10	6.57	133	4.9
Total out		<u>1.51 kg</u>		<u>10.14</u>	<u>415</u>	<u>2.4</u> ^(e)
Recycle breakage estimate $\approx \frac{1.51}{10.14}$ (2.4 wt %) $\approx$ 0.4 wt %						

(a) Includes breakage due to pneumatic transport.

(b) gm Th in fraction $\div$ 0.88.

(c) gm U in fraction $\div$ 0.18.

(d) 5.7 kg of this fraction leached out of partially cracked +355 μ m particles.

(e) Versus the 1.8 wt % "particle loss" calculated from sieve results (Table 3-1).

as judged by the $-355\text{-}\mu\text{m}$ oxides/hulls was in the transport of the lower 30 wt % of the fluid bed at high ($\sim 650^\circ\text{C}$) temperature. This hot product removal particle breakage was twice the cold product breakage (removed at ambient temperature) on a wt % basis (as a comparison of item 14 with item 13, Test B, Table 3-1 shows). The large quantity of oxides/hulls in the final fines hopper of Test B is discussed in Ref. 2 as a possible inhibitor of fines tailburning efficiency. The short-duration Test B operation yielded the smallest plenum content of noncombustibles of the three tests.

Final bed burnout was best in Test D, in which only 0.14 wt % final bed carbon remained (item 24, Table 3-1). The bed was tailburned using induction heating assistance in Tests B and D, but Test C was tailburned without induction heating. With the exception of the hot product bed of Test B, it was noted that in those final beds in which carbon was >1 wt %, the particle fraction $-850, +355$ was actually <1 wt % carbon (item 3, Table 3-1). The higher carbon in the particle fraction of the hot product bed in Test B apparently resulted from carbon inside TRISO particles which were cracked or partially broken in transport.

Carbon in recycling fines was tailburned to the minimum levels possible only in Tests B and D. The 6.3 kg of carbon remaining in the fines of Test B after the tailburn (item 8, Table 3-1) was mentioned above in the context of burning being inhibited by the 4.99 kg of noncombustible fines also recycling. The tailburn in Test D resulted in only 0.932 kg of remaining carbon fines mixed with 0.276 kg of noncombustible fines. The 10.4 kg of carbon fines mixed with 1.28 kg of noncombustible fines in Test C indicates the in-bed recycling fines composition upon entering the tailburning phase and the generally higher concentration of oxides/hulls (and particles) in circulating fines as compared to that in the above-bed recycle of Test D. The buildup of oxides/hulls in Tests C and D is shown in Figs. 3-11 and 3-12.

A final observation regarding the characteristics of the product was that small ($\leq 2000\text{ }\mu\text{m}$) agglomerates of particles (see Fig. 3-13) were present

Fig. 3-11. Recycling fines oxide/hull content and fines sample history for 0.40-m primary burner Test D

Fig. 3-12. Recycling fines oxide/hull content and fines sample history for 0.40-m primary burner Test C

Fig. 3-13. Primary burner BISO/TRISO fuel particle agglomerates (typical)

in small quantities (<0.100 kg, item 12 in Table 3-1) in Test D. Agglomerates such as these are formed when a local area of marginal mixing occurs coincidentally with the presence of molten metals. Such metals stem from low melting eutectic compounds which are formed from trace levels of impurities released from the broken particles. Similar eutectics may be formed when fission products, present in irradiated particles, are released from broken particles. The local area of marginal mixing is discussed in Section 3.4.

The material size distributions of the feed and products from Tests B, C, and D are shown in Figs. 3-14, 3-15, and 3-16.

3.2.3. Test E

The final product from Test E included five portions: the product bed pneumatically transported out of the bottom of the burner (the lower portion of the final bed), the product bed vacuumed out through the top of the burner (after the broken thermowell plugged the bottom burner vertex outlet), the plenum material pounded through the gas distributor perforations during the slugging bed operation, the final fines hopper material, and the eleven fines samples taken throughout Test E.

The material balance data for Test E are summarized in Tables 3-4 and 3-5. The most significant data indicate that:

1. Particle breakage in Test E (above-bed fines recycle) attributable to the burner and pneumatic transport was 5.1 wt % overall as compared to 2.4 wt % overall in Test D's operation (also above-bed recycle).
2. The TRISO portion of the overall breakage was an order of magnitude higher than the BISO breakage. Table 3-5 shows that 16 wt % of TRISO particles removed were broken compared to only 1.4 wt % of the BISO particles.

Fig. 3-14. Material size distribution for 0.40-m primary burner Test B

Fig. 3-15. Material size distribution for 0.40-m primary burner Test C

Fig. 3-16. Material size distribution for 0.40-m primary burner Test D

TABLE 3-4
MATERIAL BALANCE SUMMARY FOR 0.40-m PRIMARY BURNER TEST E

Item (a)	Top Product Bed	Bottom Product Bed	Comments
Combustibles Balance			
1. Carbon in (kg)	2015.37		
2. Product bed; +850 (kg)	67.66	0.03	Note most of the carbon +850 graphite chunks
3. Product bed; -850, +355 (kg)	18.18	1.29	
4. Product bed; -355 (kg)	3.336	0.019	
5. Plenum; +355(b) (kg)	0.65		
6. Plenum; -355(b) (kg)	1.64		
7. Final fines hopper; +355 (kg)	0.0415		
8. Final fines hopper; -355 (kg)	11.900		No fines tailburn
9. Total carbon unburned (kg)	104.707		Sum of 2 through 8
10. Carbon out in fines samples (kg)	17.129		
Noncombustibles Balance			
11. Particles in (kg)	393		407.6 in crushed blocks - 14.6 pulled for samples
12. Product bed; +850 (kg)	4.14	1.89	} Top of product bed 70% TRISO material } Bottom of product bed 93% BISO material
13. Product bed; -850, +355 (kg)	91.32	109.65	
14. Product bed; -355 (kg)	7.064	1.611	
15. Plenum; +355(b) (kg)	157.97		93% BISO material
16. Plenum; -355(b) (kg)	5.04		93% BISO material
17. Final fines hopper; +355 (kg)	0.0097		99% TRISO material
18. Final fines hopper; -355 (kg)	2.81		99% TRISO material
19. Noncombustibles out in fines samples (kg)	0.764		85% TRISO material
20. Total oxides/hulls out; -355 (kg)	17.289		14 + 16 + 18 + 19
21. Total particles out; -850, +355 (kg)	358.95		13 + 15 + 17
22. Particle loss $\left(\frac{\text{No. 11} - \text{No. 12}}{\text{No. 11}} \right) \times 100$ (wt %)	8.7		
23. Recycle breakage estimate $\left(\frac{\text{No. 16} + 18 + 19}{\text{No. 20}} \right) \times 22 \times 100$ (wt %)	4.33		
24. Final bed carbon $\left(\frac{\text{No. 2} + 3 + 4 = C}{C + \text{No. 12} + 13 + 14} \right) \times 100$ (wt %)	29.56		Particle carbon ~1 wt %; this carbon predominately graphite chunks

(a) 850 and 355 are micron screen sizes.

(b) Includes a small unknown quantity of transported product bed (bottom).

TABLE 3-5
0.40-m TEST E: PARTICLE BREAKAGE DISTRIBUTION BASED UPON U, Th ANALYSIS

	Top Product Bed (a)	Bottom Product Bed (a)	Plenum	Fines Hoppers	kg Total Breakage	kg Total Particles Out	Total wt % Breakage	wt % Broken in Feed	wt % Broken in Burner and Transport
kg broken BISO particles (Th equivalent) (b)	0.76	2.57	2.95	0.21	6.49	286.5	2.3	0.9	1.4
kg broken TRISO particles (U equivalent) (c)	8.27 (d)	6.13 (d)	5.56	<u>2.46</u>	<u>22.42</u>	<u>96.2</u>	<u>23.3</u>	<u>7.3</u>	<u>1.6</u>
Total out			11.18	28.91 kg		382.7	7.6 (e)	2.5	5.1
Recycle breakage estimate $\approx \frac{11.18}{28.91}$ (5.1 wt %) $\approx$ 2.0 wt %									

(a) Top bed includes breakage due to pneumatic transport out through vacuum system; bottom bed includes breakage due to pneumatic transport out through vertex line partially blocked by the broken thermowell.

(b) gm Th in fraction $\div 0.88$.

(c) gm U in fraction $\div 0.18$.

(d) >40% of this fraction leached out of partially cracked +355 μ m particles.

(e) Versus the 8.7 wt % "particle loss" calculated from sieve results (Table 3-4).

3. Although the final bed was not tailburned and total carbon content was ~30 wt %, the carbon coatings on the particles were virtually all burned away. The carbon remaining in the bed was predominately chunks of graphite. Most of this graphite was found floating in the top product bed as shown in Table 3-4.
4. The final fines inventory found in the two hoppers (not tailburned) totalled only 12 kg of carbon fines but also contained 2.8 kg of oxides/hulls (99% TRISO material). This 19 wt % non-combustible oxide/hull content was built up over the run as shown in the "Fines Sample History" section of Fig. 3-17.
5. The distribution of BISO and TRISO material indicated that the TRISO particles float on top of the BISO at the top of the bed (see comments on No. 12 through 14, Table 3-4). Hence, the material pounded into the plenum is predominately BISO (see No. 15 and 16, Table 3-4). The fines material was virtually all from TRISO particle breakage (99%, see No. 17 and 18, Table 3-4), an indication of the higher magnitude of TRISO breakage and the location of the TRISO particles in the upper bed zones from which generated fines easily elutriate.

3.3. TEMPERATURE DISTRIBUTION

3.3.1. Test A

Temperatures measured during heatup and equilibrium heating periods were used to calculate heat transfer coefficients and heat balance values for the varied beds and also to determine minimum static bed levels needed to avoid wall hotspots in the induction heating period. (The latter is crucial to establishing the basis of the burner operating cycle; i.e., how much can be removed in a partial bed removal.)

The heat transfer coefficients obtained are described in detail in Section 3.10.

Fig. 3-17. Recycling fines oxide/hull content and fines sample history for 0.40-m primary burner Test E

No wall hotspots occurred, but it was noted that $>100^{\circ}\text{C}$ -heated zone differential wall temperatures accompanied bed levels which were $<50\%$ of the tube height in the heated zone. Thus, for any induction-heated primary burner operation using interim partial bed removals and restarts, the minimum bed L/D is that bed height which fills at least half of the induction-heated zone of the tube.

3.3.2. Tests B, C, and D

The in-bed temperature and its response to the two modes of fines recycle are illustrated in Figs. 3-18, 3-19, and 3-20. The $<550^{\circ}\text{C}$ fines act as a heat sink as they enter the $\sim 900^{\circ}\text{C}$ bed and cause a brief cooling period during the peak fines flow period. After one fines hopper empties, a short period of time is required before flow from the other hopper is established. The bed heats until the high flow period of the fines cycle reoccurs. The small mass of in-bed recycling fines in the low carbon Test B caused only a $\pm 10^{\circ}\text{C}$ bed temperature cycle (Fig. 3-18). The much larger mass circulating through the bed in the high carbon operation of Test C caused bed temperature cycles as great as $\pm 30^{\circ}\text{C}$ (Fig. 3-19). The above-bed recycle of Test D, which had the largest inventory of fines of the three tests, yielded maximum cycles of $\pm 15^{\circ}\text{C}$ during the peak flow period (between 1500 and 1800 hr) and $< \pm 10^{\circ}\text{C}$ cycles in the remainder of the test (Fig. 3-20). The loss of fines flow from one of the fines hoppers occurred several times early in Test D when the 0.1-m-i.d. inlet ball valve would bind (apparently as a result of non-isothermal conditions between the valve ball and body during the approach to equilibrium temperatures). These losses caused the abrupt bed temperature rises shown in Fig. 3-20 (see note 4). The bed temperature would restabilize after the above-bed fines flow was reestablished.

The above-bed temperature recorded about 0.5 m above the mid-reactor O_2 /fines inlet and approximately 2 m above the upper region of the non-slugging bed is shown as thermocouple No. 11 in Figs. 3-18, 3-19, and 3-20. This temperature rapidly increased upon starting of fines recycle and decreased upon stopping. In the case of in-bed fines recycle, the

Fig. 3-18. System temperatures in 0.40-m primary burner Test B

Fig. 3-19. System temperatures in 0.40-m primary burner Test C

Fig. 3-20. System temperatures in 0.40-m primary burner Test D

above-bed temperature was very sensitive to mid-reactor O_2/CO_2 flows (see Fig. 3-19, notes 2 and 4). The above-bed temperature generally was hotter during in-bed recycle than during recycle above the bed. The abrupt above-bed temperature rise during the fines tailburning period of Test D (note 2, Fig. 3-20) is typical of what occurred in some of the past 0.20-m burner work when in-bed carbon was reduced to a low level. The in-bed O_2 was not utilized, and a large O_2 front abruptly broke through the bed and ignited recycling fines in a flash burn situation. This burning was returned to normal fines tailburning levels by reducing in-bed O_2 and thus the O_2 reaching the fines. (Mid-reactor O_2 had been reduced prior to the flash burn; see notes 5 and 6, Fig. 3-3.)

The minimum recycling fines temperature as recorded in the fines hoppers is given as thermocouple No. 9 in Figs. 3-19 and 3-20. The low fines volume in Test B yielded a maximum fines hopper temperature of $300^\circ C$, and therefore this temperature was not included in Fig. 3-18. The fines hopper temperature peaked at $\sim 570^\circ C$ for the highest fines mass flow period of Test C and at $\sim 530^\circ C$ for Test D.

The in-bed wall temperature is presented as thermocouple No. 15 in Figs. 3-18, 3-19, and 3-20. The general trend, evident especially in the longer Tests C and D, was for the wall temperature to gradually reduce to a 650° to $700^\circ C$ equilibrium temperature. The lower equilibrium temperature applied for the above-bed recycle Test D. Two analogous periods are noted in the Test C and D wall temperature history. The Test C wall experienced an unusual increased bed-to-wall ΔT (dip) between about 1500 and 1700 hr. The Test D wall experienced a similar dip between 2146 and 2300 hr. The significance of this bed-to-wall ΔT perturbation is discussed in the following section.

3.3.3. Test E

In-bed temperature response to fines recycle is shown in Figs. 3-21 and 3-22. The bed temperature cycle induced by the above-bed fines

Fig. 3-21. System temperatures for 0.40-m primary burner Test E - Sept 13

Fig. 3-22. System temperatures for 0.40-m primary burner Test E - Sept 20

injection was $\pm 15^{\circ}\text{C}$ maximum at the beginning of operation and $< \pm 10^{\circ}\text{C}$ for the remainder of the run. The short period of time in which the $\pm 15^{\circ}\text{C}$ cycles occurred as compared to Test D was another indication that the fines mass was significantly lower in Test E. Any curtailment of above-bed fines recycle caused in-bed temperature increases, again demonstrating the heat sink and moderating effect that fines recycle has on the bed.

The above-bed temperature recorded about 0.5 m above the mid-reactor O_2 /fines inlet is shown as "T.C. No. 11" in Figs. 3-21 and 3-22. A continuous strip chart record was kept on T.C. No. 11 in Test E whereas all past work had used only the multipoint to record this above-bed region. The continuous recording revealed that the above-bed temperature also cycles in response to the fines transport cycles, as much as $\pm 20^{\circ}\text{C}$ early in the run as fines temperatures elevate and $\pm 10^{\circ}\text{C}$ in the equilibrium run period.

The recycling fines temperature shown as "T.C. No. 9" in Figs. 3-21 and 3-22 averaged only $\sim 420^{\circ}\text{C}$ during the test; it peaked at $\sim 500^{\circ}\text{C}$ for a very brief period and cycled drastically, many times dropping well below 400°C . These are all indications that the mass of hot fines in the hoppers was generally low, many times so low that the sensing thermocouple lost contact with the hot fines, thus producing the $< 400^{\circ}\text{C}$ cycles.

The wall temperature given as T.C. No. 15 in Figs. 3-21 and 3-22 did not show the well defined gradual reduction trend seen in Test D. A fairly smooth reduction to $\sim 660^{\circ}\text{C}$ was noted in the first half of the test (Fig. 3-21) but the second half of the test had significant wall fluctuations (Fig. 3-21). The fluctuations may be explained by significant changes in the mass of fines recycling which apparently changed the bed-to-wall ΔT and by the fact that fines recycle had to be stopped for > 1 hr in the early part of the September 20 portion of Test E. This stoppage would have allowed fines mass increases and would thus have altered the bed-to-wall ΔT in subsequent operation. Further fluctuations in the filter ΔP (especially in the September 20 operation, Fig. 3-10) indicate that temporary increases in the circulating fines inventory were occurring. This was attributed to pockets of fines in the feed to the burner. Such bursts of additional fines would change the bed-to-wall ΔT .

3.4. BED FLUIDIZATION/COOLING

3.4.1. Test A

Fluidization of beds in the 0.4-m i.d. tube was quite different than that experienced in 0.20-m i.d. vessels. Only ~ 0.3 m/sec (1 ft/sec) velocity was required to initiate heat flux into the shallow fresh feed bed of single coil heatup Test A3.1. This minimum heatup velocity was 50% of the ~ 2 ft/sec required to initiate mixing and heat flow to fresh feed beds in earlier 0.20-m burner work. The decreased wall effects (or increased wall diameter/particle diameter ratio) apparently allowed the fresh feed particles to mix more readily in the 0.40-m tube as compared to the 0.20-m tube. This has been explained in other fluidization studies as decreased gas bypassing in bubbles at the wall. This bypassing effect was shown to decrease rapidly as tube diameters increased from 0.10 to 0.20 m and to reach a minimum at 0.40 to 0.50 m diameter and larger tubes (Ref. 2).

This improved mixing substantially simplified heatup. Adjustments to total gas flow to compensate for bed temperature increases were not required, as those increases are at high velocities. This reduces the probability of operator error causing excessive bed carryover through slow or incorrect flow adjustments. It also reduces the complexity of the system automation.

The improved mixing and concurrent increase in potential heat transfer may allow reductions in the superficial velocities required at peak burn-rate. This would increase the maximum slug height, plant gas flows, and required burner height. However, this improvement is dependent upon the effect of bed diameter on heat transfer. With the 0.40-m burner the additional CO_2 diluent may be required for cooling rather than for mixing.

No cooling air was used in this series of heatup tests.

3.4.2. Tests B, C, and D

The overall bed fluidization quality during heatup and combustion in Tests B, C, and D was excellent. The 85 wt % TRISO/15 wt % -3/16-in. graphite bed of Test B began heating at 0.33 m/sec superficial inlet gas velocity and had an overall bed ΔT of $<10^{\circ}\text{C}$ during the heatup. The 85 wt % -3/16-in. graphite/15 wt % BISO/TRISO particle bed required a slightly higher (~ 0.39 m/sec) velocity for heating and had an overall bed ΔT of $<20^{\circ}\text{C}$ during heatup in Tests C and D.

The bed fluidization quality during combustion may be roughly assessed from the in-bed ΔT and the bed-to-wall ΔT and from the quantity of final bed agglomeration (which results partly from poor local mixing). As discussed above, the recycling fines cause a general cycling of the bed temperature. However, the overall bed ΔT can still be a valid monitor of successful mixing. The average in-bed ΔT in the tests was 10° to 20°C . The peak in-bed ΔT observed was $\sim 40^{\circ}\text{C}$ and occurred in Tests C and D concurrently with the wall temperature dips mentioned in the previous section. The bed ΔT and wall ΔT increase in these runs, occurring at a period when fines inventory was known to be low, indicated that mixing quality degenerated with reduction of recycling fines. Inversely, fines recycle improved in-bed mixing, resulting in better in-bed and bed-to-wall heat transfer. The presence of a minor quantity of agglomerates in Test D may indicate that mixing quality (at least at some local area) is lower when fines recycling takes place above the bed.

The cooling requirements for each run are given in Figs. 3-23, 3-24, and 3-25. Test C required much less external bed cooling air than Test D or B. The temperature distributions discussed previously indicated that the heavy mass of in-bed recycling fines carried more heat axially into the above-bed and fines system zones of the burner. The result was less heat dissipation radially to the cooling air. The cooling air requirements were generally less than expected for the full burn rate in all of the tests with fines recycle. The cooling air flow trends showed a general increase as a test proceeded.

Fig. 3-23. Bed cooling air flow for 0.40-m primary burner Test B

3-47

Fig. 3-24. Bed cooling air flow for 0.40-m primary burner Test C

3-48

Fig. 3-25. Bed cooling air flow for 0.40-m primary burner Test D

3.4.3. Test E

The bed fluidization character of crushed LHTGR fuel elements called for a higher gas velocity during the initial startup than was required in earlier tests. The probable reason that the Test E initial heatup period required higher fluidization velocity was the presence of small quantities of fuel rod fragments ($\approx 3/16$ in.), i.e., chunks of particles fused by fuel rod binder, in the fresh feed startup bed. Figure 3-26 is a photograph of such fragments, which result from crushing fueled fuel elements (Fig. 2-1). In earlier tests, crushed fuel elements were simulated by mixing crushed graphite and loose particles.

With crushed fuel elements, a gas velocity well in excess of 0.43 m/sec (1.4 ft/sec) (flow meters were pegged) was required to yield isothermal startup bed temperatures. The bed ΔT was as high as 75°C in the earliest portion of the heatup when bed temperatures were <400°C and superficial velocities <0.61 m/sec (2 ft/sec). The bed ΔT reduced to <15°C after bed temperatures reached >400°C and velocities >0.61 m/sec, indicating excellent fluidization quality at the 1.1-m/sec (3.5-ft/sec) operating superficial velocity. No agglomerates of fuel particles were found in Test E's product bed (as were found in minor quantities in Test D).

Over 80 kg of fuel particles were found in the plenum after the run. The slugging fluid bed had created pressure variations larger than the distributor pressure drop. This caused instantaneous reverse gas flow and thus a flow of fuel particles through the gas distributor holes.

The cooling air requirements in Test E (Figs. 3-27 and 3-28) showed an increase as the run progressed. This trend was not as distinct as in Test D, perhaps because of the fines mass perturbations in the second part of the run (discussed earlier). Also, the Test E bed was not completely tail-burned whereas Test D was. This difference in reduction of bed heights and bed carbon concentrations would account for part of the difference in cooling air needs.

Fig. 3-26. Fuel rod fragments from crushed LHTGR fuel elements
(BISO/TRISO fuel particles)

Fig. 3-27. Cooling air flow for 0.40-m primary burner Test E - Sept 13

Fig. 3-28. Cooling air flow for 0.40-m primary burner Test E - Sept 20

3.5. OFF-GAS COMPOSITION

3.5.1. Test A

Test A had no combustion; this aspect is not applicable to them as the off-gas was CO₂.

3.5.2. Tests B, C, and D

Figures 3-29, 3-30, and 3-31 show the vol % CO off-gas monitored during Tests B, C, and D, respectively. The vol % O₂ is also plotted. The remainder of the off-gas, CO₂, may be obtained by subtraction.

The most significant off-gas result was the response of the CO vol % to starting and stopping of fines recycle. Starting the cyclic mass flow of fines into the burner started cyclic spikes and fluctuations in the vol % of off-gas CO (see note 1, Figs. 3-29, 3-30, and 3-31). These fluctuations averaged ± 3 vol % with spikes as large as ± 5 vol %. Stopping fines recycle abruptly reduced the overall CO vol % and resulted in decreased fluctuations (see note 5, Fig. 3-30).

The O₂ breakthrough and resulting above-bed flash burn of fines is seen in the off-gas response (note 3 of Fig. 3-31). The high-temperature fines burning generated the pulse of CO (see Section 3.3).

3.5.3. Test E

The CO and O₂ off-gas concentrations for Test E are plotted in Figs. 3-32 and 3-33 (CO₂ may be obtained by difference to a total of 100%).

The cyclic spikes of off-gas CO with the cycling fines recycle was again apparent (as for Test D). The effect of stopping fines recycle was again abrupt reduction of off-gas CO. This effect was much less significant in the mid-run period than in the tailburning period. The in-bed burning

Fig. 3-29. Off-gas concentration and bed carbon content in 0.40-m primary burner Test B

Fig. 3-30. Off-gas concentration and bed carbon content in 0.40-m primary burner Test C

Fig. 3-31. Off-gas concentration and bed carbon content in 0.40-m primary burner Test D

Fig. 3-32. Off-gas concentration for 0.40-m primary burner Test E - Sept 13

Fig. 3-33. Off-gas concentration for 0.40-m primary burner Test E - Sept 20

must account for a larger portion of the CO concentration when the carbon level is high than when the carbon level is low.

The level of O_2 in the burner off-gas began increasing slightly at ~2330 hr on September 20 and cycled between 1 and 3 vol % in much the same way that the CO vol % cycles with fines flow cycles. This continued until ~0330. At this time, the O_2 returned to 0 vol % concurrent with indications that a large mass of fines had entered with the final feed quantity. Apparently the circulating fines mass was being depleted between 2330 and 0330 hr to a quantity which was marginal in consumption of all of the mid-reactor O_2 .

The final O_2 blip occurred immediately after fines recycle was stopped and before mid-reactor O_2 was reduced. Subsequent reductions of mid-reactor O_2 from $0.25 \text{ m}^3/\text{min}$ to $0.10 \text{ m}^3/\text{min}$ kept the off-gas $O_2 < 3 \text{ vol } \%$ and avoided the above-bed fines flash burn situation encountered during Test D.

3.6. FEEDING

3.6.1. Test A

Input of fresh feed using the 0.05 m nominal size rotary feeder was calibrated at ambient conditions as shown in Fig. 3-34. The ~1-kg/min feed rate required at equilibrium 800 gram/min burn rate was achieved by an ~15% power setting. The ~150-kg fresh feed startup bed was fed in ~40 min at the 3.8-kg/min maximum power setting of ~110%.

Figure 3-35 shows the decrease in mass flow of feed as a batch of feed is unloaded at constant feed rate. This phenomenon indicates that a degree of segregation of the dense fuel particles to the bottom of the feed bunker occurs which yields an initially high mass flow. This segregation profile in the bunker equilibrates somewhat after an initial period of feeding as shown by the approach of the feed rate to a constant level. Such segregation can cause fluctuations in burner bed temperature and feed rate requirements and therefore should be recognized by burner operators, and controls should be set to compensate.

Fig. 3-34. Flow rate into primary burner versus star valve speed setting (ambient conditions)

Fig. 3-35. Variation of flow rate of simulated fresh feed with time

3.6.2. Tests B, C, and D

Although the feeding system performed acceptably for Test B's high particle concentration feed, the feed system became plugged or bridged with graphite fines in the initial attempt at Test C. Just as the dense fuel particles tended to segregate to the bottom of the feed bunker, the light graphite fines tended to segregate to the top of the bunker. These pockets of fines are known to bridge during gravity flow if the pipe length to diameter ratio is $\gtrsim 1$.

The bridging of graphite fines in the feed bunker outlet was thought to result from an apparently excessive length of pipe coupling the aerated bunker outlet to the rotary feed mechanism. This pipe section (Fig. 3-36) was removed and the rotary valve installed directly under the knife-gate valve in the feed bunker outlet prior to Test C.

The fresh feed system experienced no flow inconsistencies during Tests C and D. The mechanism of the bridging which had occurred previously was apparently removed when the outlet piping of the feed bunker was revised. The rotary valve gave adequate feed metering performance.

A setting of 25 to 30% speed was used in the equilibrium operation as compared to the 15% speed predicted in ambient calibration. Apparently the hot gas upflow tended to slow the feed throughput in full burning operation as compared to ambient operation.

The feed bunker maximum capacity during the runs was $\lesssim 1.5$ blocks. This was the high limit of the load cell device weight-measuring range. Burner feeding was interrupted for 4 to 10 min during refill of the feed bunker. Loss of the fresh feed flow into the burning bed caused 10° to 30°C elevations in the bed temperature. The bed temperature was restabilized when feeding resumed.

Fig. 3-36. 0.40-m primary burner showing feed bunker outlet

3.6.3. Test E

The fresh feed system performed acceptably during the test. The segregation of fines to the top of the bunker and thus to the end of each feed batch did not appear to cause bridging in the feed system.

The <10 min stoppages of fresh feed flow during feed bunker refill again caused 10° to 30°C bed temperature increases which abated after feeding resumed.

The size distribution of the feed and the material removed from both fines hoppers are shown in Fig. 3-37. Material withdrawn in fines samples during operation gave indication of the fines composition trends leading to the final fines hopper material. Feed material was also sampled prior to putting it in the burner. These samples indicated particle breakage as a result of crushing operation (Table 3-5).

3.7. PRODUCT REMOVAL

3.7.1. Test A

Removable in-line orifices were used in series with an on/off knife-gate for this series of tests.

The following removal rates were recorded: 0.16 to 0.23 kg/sec for fuel particles, 0.84 to 1.0 kg/sec for simulated feed, and 0.57 to 0.88 kg/sec for graphite.

All material flowed acceptably out of the 2.54 cm cone vertex opening with the exception of the crushed graphite used in Test A-1. Periodic bridges occurring at the cone vertex stopped outflow. These bridges were probably caused by the presence of cohesive fines. The bridges were broken and flow restarted by cycling the product take-off valve below the vertex from an open to a closed position with the vertex gas on. This effected an intermittent blast of gas through the vertex and dislodged the

Fig. 3-37. Material size distribution for 0.40-m primary burner Test E

bridge, allowing the rearranged solids to flow. This procedure is not expected to be required in the future, as the 100% graphite which bridged is not a typical bed material.

No bed material holdup was found in the burner upon plenum removal after the six runs. A few grams of fines dust were noted on the cone surface. These fines probably were dislodged from the upper burner wall when a jackhammer was used to loosen the plenum assembly for plenum removal.

Ten kg of product were found in the plenum. This further emphasizes the particle drainage problem of severely slugging beds noted in 0.20-m work. Plenum drains have been incorporated into future designs, and mechanisms to reduce drainage are being investigated.

3.7.2. Tests B, C, and D

A variable position knifegate valve was installed beneath the primary burner prior to primary burner Test B. This device allowed for independent control of the product removal flow rate into the pneumatic transport line, thus avoiding potential plugging problems in the transport system (Ref. 3).

This variable position knifegate valve was used successfully to control flow rates of product removed in Tests B, C, and D. The Fort St. Vrain TRISO particle product was conveyed both at 700°C and at ambient temperatures during Test B. Burned-back BISO/TRISO fuel was transported at 600°C during Test C and at ambient temperatures after Test D.

3.7.3. Test E

The lower ~114 kg of the 305-kg product bed was removed (at a curtailed rate) through the cone vertex product removal system. The remainder of the bed was vacuumed out through a hose dropped down from the top of the burner. The lower section of the broken 22.2 mm (7/8-in.) o.d. thermowell had plugged the 25.4-mm (1-in.) i.d. vertex opening and prevented complete bed removal.

3.8. GENERAL EQUIPMENT PERFORMANCE

3.8.1. Test A

The system equipment performed acceptably through the six heatup tests.

On inspection of the burner after the A tests, the Grafoil seal, which prevents cooling air from leaking out of the cooling jacket, was found damaged. An inspection report (IR29876) was issued documenting the damage. One layer of the seal was completely peeled off, leaving a 1/8-in. gap between the sealing surfaces. This condition was expected to allow excessive air leakage to the clamp heater. A repair method was evaluated by the design group.

A metal seal was made to replace the outer Grafoil ring seal. This seal proved inadequate because it did not conform to the Grafoil seal segments, which were out of round. A graphite seal was then fabricated to replace the Grafoil seal after design review indicated this would have a minimum schedule impact in terms of redesign of the seal.

The modified seal arrangement shown in Fig. 3-38 was mounted in a fashion identical to the Grafoil seal mounting and was installed without removal or repositioning of the burner or burner shrouds. The inner and outer seal elements were segmented solid graphite machined to contour and were retained by pinning or containment. The horizontal parting line of the inner seal facilitated assembly and eliminated direct leak paths for the cooling air. The outer seal incorporated annular grooves to minimize conductive heat transfer and to reduce leakage through an increased resistance to gas flow.

Performance of the semiremote plenum clamp and removal cart is discussed in Section 3.14.

Fig. 3-38. 0.40-m primary burner modified lower seal assembly with inner and outer seals of solid graphite

3.8.2. Tests B, C, and D

3.8.2.1. Test B. Two major areas of the burner mechanical system requiring modification were identified during Test B. First, the horizontal deflection of the burner within the constraints of the Peaucellier mechanisms was unacceptable [~ 9.5 mm ($\sim 3/8$ in.)]. Second, breathing of the unstiffened surface of the filter chamber caused surface deformations.

The Peaucellier mechanisms (Fig. 3-39) were installed to provide restraint against lateral movement of the burner tube. However, the end of the burner was observed to move an estimated 9.5 mm (0.375 in.) at maximum displacement, whereas the structural platform to which it is attached appeared not to deflect. From post-test examination it was concluded that the stack-up of tolerances in the multiple pin joints amplified by the particular arrangement of linkages permitted the observed deflection to occur. This degree of motion, which would be detrimental to the lower sliding seal between the burner and the shroud, had to be eliminated. Two solutions were considered:

1. Rework of the existing Peaucellier mechanisms to reduce the lateral deflection.
2. Replacement of the Peaucellier mechanisms with simpler single-bar linkage.

The Peaucellier cell was adopted to provide theoretically perfect straight line guidance as the bottom of the burner grows downward. As shown in Fig. 3-40, the maximum theoretical horizontal deflection which resulted from using a 250-mm (9.83-in.) long single link connection was 0.7 mm (0.028 in.).

The 0.7-mm horizontal deflection was acceptably small and consequently the simpler and less expensive single linkage was selected over a more costly precision remachining and reassembly of the existing Peaucellier

Fig. 3-39. 0.40-m primary burner Peaucellier mechanism

$$\theta \approx \frac{0.75}{9.83} = 0.076 = 0.076 \left(\frac{180}{\pi} \right) \approx 4.35^\circ$$

$$\begin{aligned} \text{MAXIMUM LATERAL DEFLECTION} &= 9.83 (1 - \cos \theta) \\ &= 9.83 (1 - \cos 4.35^\circ) \\ &= 0.028 \text{ in. (0.7 mm)} \end{aligned}$$

Fig. 3-40. Side deflection of single guide link

cells. The new connecting linkage design is shown in Fig. 3-41 and the installation is shown in Fig. 3-42.

The surfaces of the filter chamber were stiffened with the "X" cross braces.

The need for an above-bed O_2 injection source to increase fines burning efficiency was noted after Test B, as discussed in Section 3.1. Also, successful application of a bed level sensor in the 0.20-m burner suggested that a similar sensor (Fig. 3-43) would be beneficial in the 0.40-m burner. Penetrations for the above-bed O_2 and for the bed level sensor were therefore installed in the sidewall of the 4.1-m long burner tube after Test B. The penetrations were made 2.5-m up the tube from the distributor.

Designs for the addition of a mid-reactor gas line and a level sensing probe to the 0.40-m burner are shown in Fig. 3-44. The studed bosses welded to the burner wall were of Hastelloy X and were identical for both penetrations. The mid-reactor gas line through the shroud was a stainless steel braided bellows to allow for differential thermal expansion between the shroud and the vessel. The shroud penetrations were 88.9-mm diameter stainless steel tubes.

A final area of equipment performance noted during Test B operation was the cooling air shroud sliding seal leakage. A room temperature cooling air leak test of the sliding seal indicated that modest alterations were required to reduce the cooling air leakage to an acceptable level. Figure 3-45 and Table 3-6 identify the detected leaks, the corrective actions taken, the results when using $1.18 \text{ m}^3/\text{sec}$ and 34 kPa cooling air at room temperature. Leakage during subsequent combustion tests was similar to the room temperature findings and was considered acceptable.

3.8.2.2. Tests C and D. The first attempt at Test C was shut down after 6.5 hr of operation when a rupture occurred in a fines recycle bellows. The 0.15-m-i.d. failed bellows was in the connection between the cyclone

Fig. 3-41. 0.40-m primary burner connecting link

Fig. 3-42. 0.40-m primary burner showing new guide linkage

0.0635-m-OD STAINLESS STEEL PROBE EXTENDING
OUT THROUGH BURNER WALL

Fig. 3-43. Primary burner bed level sensor

Fig. 3-44. 0.40-m primary burner wall penetrations

Fig. 3-45. Modified lower seal leak locations (see Table 3-1 for description of leak locations, corrective action, and room-temperature leakage)

TABLE 3-6
TESTING OF MODIFIED LOWER SEAL, 0.40-m PRIMARY BURNER

Leak No. (see Fig. 3-45)	Location	Corrective Action	Room Temp. Leakage (a)
1	Between seal elements (o.d./i.d. leak)	Reduce outer seal circumference	Minimal
2	Between shroud and seal elements	Install ceramic cloth (SiO ₂) to fill longi- tudinal gap	None
3	Between butt ends of inner seal segments	Install spline bridging butt ends of top members	None
4	Between gasket and mounting plate	Regasket	None
5	Between shroud and burner tube	Apply fillet of high- temperature cement	None
6	At expansion joint of seal ring assembly	Pack with ceramic cloth detained by shim clamped by clamp ring	None
7	At slipjoint between seal ring assembly elements	None feasible	Small

(a) Blower air test at 1.18 m³/sec (2500 cfm) and 34 kPa (5 psig)
(burner).

and filter chamber discharge line and the fines hopper inlet (see Fig. 3-46). The average fines recycle hopper temperature had reached $\sim 440^{\circ}\text{C}$ at the time of the bellows failure, as compared to temperatures of $\sim 260^{\circ}\text{C}$ in the low carbon combustion Test B. The bellows collapsed when the inner sleeve impinged upon and tore the bellows wall.

Additional mechanical problem areas in the incompletd test were: the bed bunker outlet configuration, which induced bridging of fines (discussed previously in Section 3.6) and the bellows in the 0.10-m-i.d. fines hopper inlet pipes, which were found to be distorted (Fig. 3-47).

The failure of the fines recycle bellows was attributed to the uneven thermal expansion caused by the flow pattern of the hot fines in the piping above the bellows in combination with some initial misalignment. This caused radial movement of the inner sleeve of the bellows. A metal bellows design using a fully enclosed and guided expansion joint was procured and installed (see Fig. 3-47). Figure 3-48 shows the difference between the unguided failed bellows and the guided design installed to alleviate the inner sleeve impingement failure mode.

The distortion of the 0.10-m i.d. bellows in the fines hopper inlet pipes was attributed to slippage of a hopper brace and uneven loading. These bellows were high risk failure areas based on the observed distortion and the failure of the 0.15-m bellows discussed above. These bellows and the fines hopper outlet 13-mm bellows were installed for the load cell system. The load cells did not provide accurate hopper weights because of the effect of pressure surges inherent in the pressurized fines system. Therefore, their high probability of failure combined with their lack of utility suggested that these bellows be replaced with rigid pipe sections. This was implemented.

Tests C and D were then both completed with no mechanical problems. The fully enclosed, guided bellows which replaced the ruptured 0.15-m i.d. fines system bellows gave satisfactory performance through Tests C and D.

APPROXIMATE POINT OF FAILURE OF 0.15-m-ID
FINES RECYCLE SYSTEM BELLOWS

0.10-m FINES
HOPPER INLET
BELLOWS
FOUND DIS-
TORTED AFTER
RUN C.1
(SEE FIG. 3-2)

WEST
FINES
HOPPER

Fig. 3-46. Location of failed bellows, 0.40-m primary burner Test C.1

Fig. 3-47. 0.40-m primary burner fines recycle system showing 0.10-m i.d. distorted bellows and 0.15-m i.d. bellows replacement

Fig. 3-48. 0.40-m primary burner unguided versus guided bellows

The 0.10-m i.d. fines system bellows that were found distorted after the initial Test C attempt were replaced with flange pipe sections, which also gave trouble-free performance in the operations.

The performance of the single bar linkage which replaced the Peaucellier burner alignment mechanism was acceptable and the level sensors used in Tests C and D in the fines bunkers and in the burner performed well.

The dual-bellows off-gas line from the burner to the cyclone was noted to be a high-risk failure area during the long-duration Tests C and D. The line was initially installed with about 13 mm offset. During the burner tests, this line was heated to about 700°C. The resulting thermal expansion increased the initial offset and caused the fines to impinge on the bellows corrugations.

The offset in the dual-bellows off-gas line was corrected prior to Test E by shortening the horizontal section of the line by 13 mm. A sleeve was designed and installed to fit inside the bellows in the vertical run. The sleeve extended well beyond the convolutions of the bellows to eliminate any possibility of impingement.

One additional equipment change was made prior to Test E. The binding of the fines hopper inlet valves (Section 3.1.1) during the rise of the circulating fines to their >500°C operation temperature was apparently caused by the higher temperature of the valve internals as compared to the valve body temperature. The valves were insulated on the outside to decrease the heat loss and the nonisothermal temperature binding condition.

3.8.2.3. Test E. The provisions to protect the dual-bellows off-gas line discussed above were effective. The corrected off-set and the sleeve installed inside the bellows prevented the fines impingement and the formation of hot spots on the bellows wall.

The problems concerning the erosion of bends, in-line wall perturbations, and the thermowell by the pressurized fines recycle have been discussed in Section 3.1.4.

All other system equipment performed acceptably in Test E.

3.9. BED HEIGHTS

The two possible bed heights for startup were studied specifically in fresh feed bed heatup Test A3.1 (lower coil) and Test A3.2 (lower and upper coil). The lower and then the lower and upper coil tailburning studies were carried out by heatup of fuel particle product beds in Tests A2.1 and A2.2, respectively.

Tests B, C, D, and E used only the lower coil for heating with beds having >50% of the lower coil height (as recommended by the Test A studies).

Table 3-7 shows that the heatup times were similar for single and double coil heating, but that significant detrimental conditions of product bed particle breakage and bed carryover (Test A2.1 versus Test A2.2) and initial fresh feed bed ΔT (Test A3.1 versus Test A3.2) resulted from use of the deeper beds required in dual coil heating. The deep particle bed used in Test A2.2 had more than twice the wt % particle breakage and almost two orders of magnitude more particle carryover than the single coil shallow bed used in Test A2.1.* This resulted from the greater slugging action inherent in deeper beds.

The values for material carryover and breakage for the fresh feed fluidization tests, A3.1 and A3.2, show a trend opposite to that described above. It is assumed that higher breakage occurred with the deeper slugging fresh feed bed, although the data do not clearly show this. The breakage

*About 220,000 cc of static material caused bed carryover at 1.08 m/sec. Using a safety factor of 20% reduces the maximum bed volume to ~175,000 cc.

TABLE 3-7
0.40-m PRIMARY BURNER HEATUP TEST RESULTS AND MATERIAL BALANCE

Test	Material into Burner (kg)	Induction Coil Use	Material Elutriated				Particle Breakage ^(a) (wt % of fed)	Bed Material Transport (kg)
			$\gtrsim 850 \mu\text{m}$ (kg)	$\gtrsim 425 \mu\text{m}$ (kg)	$\lesssim 425 \mu\text{m}$ (kg)	Oxides (kg)		
A2.1	180 (f.p.) ^(b)	Single	0.055	0.074	1.047	0.277	0.31	$\lesssim 120$
A2.2	470 (f.p.) ^(b)	Double	0.002	16.478	3.427	1.849	0.78	$\lesssim 448$
A3.1	130 (f.f.) ^(c)	Single	Nil	0.008	9.231	0.105	1.5	$\lesssim 120$
A3.2	220 (f.f.) ^(c)	Double	Nil	0.002	5.261	0.25	1.0	$\lesssim 214$

TABLE 3-7 (Continued)

Test	Overall In-Bed Heat Transfer Coefficient ^(d) (W/m ² -K)	Internal In-Bed Heat Transfer Coefficient ^(d) (W/m ² -K)	Overall Above-Bed Heat Transfer Coefficient ^(d) (W/m ² -K)	Internal Above-Bed Heat Transfer Coefficient ^(d) (W/m ² -K)	Initial Velocity Required for Heatup (m/sec)	Heatup Time to 700°C (min)	Comments
A2.1	523	602	47.7	48.5	0.55	120	Heating delayed ~60 min because of feeder problems
A2.2	381	423	142.2	149.3	0.46	140	Heatup delayed ~50 min to replace a blown fuse
A3.1	414	456	48.5	49.4	0.305	90	Lower to upper bed $\Delta T < 15^\circ\text{C}$ (excellent startup)
A3.2	322	351	84.1	86.6	0.34	60	Poor mixing as upper bed 600°C hotter than lower bed in initial 15 min of heating

(a) Calculated based on:
$$\frac{(\text{gm oxides elutriated with fines}) \left(\frac{\text{Total particle weight}}{\text{Weight of ThO}_2 \text{ in particle}} \right)}{(\text{weight of material fed to burner})(\text{fraction of particles in feed})}$$

(b) (f.p.) = carbon-coated TRISO "A" fertile particles (bulk density ~ 2 gm/cc; diameter ~ 600 to 850 μm).

(c) (f.f.) = 83% $\lesssim 3/16$ in. ring size graphite + 17% TRISO fertile fuel particles.

(d) From induction heating of in-bed walls in runs at comparable temperature, velocity, and gas flow rate (Ref. 2).

NOTE: Divide heat transfer results by 5.68 to yield Btu/hr-ft²-°F.

data were based upon a calculated value for the weight of particles in the bed. Prior to these two tests, the feed hopper was filled with sufficient feed for the deeper bed. Part of this material was used for Test A3.1 and was subsequently reused in Test A3.2 along with the additional hopper contents. This obscured the data because (1) the material segregates by density in the hopper and consequently more particles were in the bed in Test A3.1 than were calculated, making the calculated breakage number too high; and (2) reusing the material from Test A3.1 preferentially removed particles with defective coatings and any oxides on external particle surfaces.

The upper half of the deep fresh feed bed used in Test A3.2 experienced a radical temperature divergence from the lower half of the bed during the initial 15 min of heating. The upper bed reached 625°C before the lower half began heating. Glassware studies have shown that as velocity increases (or temperature increases in the heatup situation) the general fresh feed bed mixing pattern is to achieve "significantly better quality of mixing in the upper 1/3 to 1/2 of a bed than below" (Ref. 4). This normally causes a <100°C bed ΔT . The deeper bed of Test A3.2 aggravated this zonal mixing, causing a >600°C bed ΔT . This, in turn, caused the wall of the heated zone to diverge $\sim 175^\circ\text{C}$.

These negative conditions imposed by the deep particle and fresh feed beds all indicated that future use of the dual coil heating option should be avoided.

3.10. INDUCTION HEATING AND HEAT TRANSFER

Induction heating in the A tests was successful in heating beds to 700°C in less than 2 hr with either the single or dual coil system. The major differences between single and dual coil heating were discussed above. An additional interesting point was that $\sim 100\%$ more power was required in initially heating the deep beds, but power to maintain the equilibrium 700°C temperature of similar bed material was only 10 to 30% more for the deep beds than for the shallow beds. This indicates that the

overall heat loss for deep beds without fines recycle is 10 to 30% greater than for shallow beds.

Only single coil induction heating was used in the B, C, D, and E tests, and it was acceptable.

The overall and internal heat transfer coefficients given in Table 3-7 are results obtained at comparable values of temperature, velocity, and gas flow which aid in the evaluation of heatup or tailburning for shallow versus deep beds. (More complete results are reported in Table 3-8.) The "Initial Velocity Required for Heatup" of Table 3-7 is the velocity required to initiate sufficient mixing of ambient startup material to transfer wall heat into the bed.

The values given in Table 3-7 for in-bed heat transfer at comparable process conditions show that deeper beds limit the bed solids' capability to pick up and retain heat from the wall. This is an indication of a decrease in bed solids mixing in the radial bed to wall direction and an increase in the axial heat loss from solids slugging out of the heated zone. This axial heat loss increase is reflected in an increase of the above-bed heat transfer coefficient.

The four individual heatup tests A2.1, A2.2, A3.1, and A3.2 were used to provide heat transfer data. All data were obtained at steady-state conditions; for each point, power input data, temperature readouts, and gas flow rates were recorded. In the case of Test A2.1, five individual data points were recorded at varied power rates, temperatures, and gas flow rates (velocities).

The mean overall heat transfer coefficient $\bar{U}$ between the burner wall and fluid bed is calculated using the following equation:

$$\bar{U} = \frac{Q}{A\Delta T} \quad , \quad (3-1)$$

TABLE 3-8
0.40-m PRIMARY BURNER HEATUP TEST^(a) HEAT TRANSFER DATA AND RESULTS

Test	Time	CO ₂ Flow Rate (std m ³ /sec)	In-Bed Gas Velocity (m/sec)	Mean Wall Temp. (Heated) (°C)	Bed Temp. (°C)	Mean Wall-Bed ΔT (°C)	Induction Power (kW)	Net Heat Input, Q (kW)	Wall Area Heated, A (m ²)
{ A2.1	1313	0.0463	1.23	800	670	130	98.6	68.6	1.151
{ A2.1	1510	0.0382	1.03	779	680	99	82.9	59.4	1.151
{ A2.1	1642	0.0340	0.92	792	685	107	81.8	56.7	1.151
{ A2.1	1837	0.0492	1.27	770	640	130	98.6	71.5	1.151
{ A2.1	2003	0.0538	1.22	655	530	125	82.9	57.8	1.151
{ A2.2	1449	0.0386	1.05	778	690	88	100.8	77.3	2.302
{ A3.1	1342	0.0388	1.06	817	695	122	87.4	58.0	1.151
{ A3.2	1310	0.0390	1.05	769	680	89	94.1	66.1	2.302

TABLE 3-8 (Continued)

Test	Time	$\bar{U}_{\text{(heated)}}$ (W/m ² -K)	$\bar{h}_{i\text{(heated)}}$ (W/m ² -K)	$T_{\text{CO}_2, \text{in}}$ (°C)	$C_{P\text{CO}_2, \text{out}}$ (J/kg-K)	$T_{\text{CO}_2, \text{out}}$ (°C)	$C_{P\text{CO}_2, \text{out}}$ (J/kg-K)	$\dot{m}_{\text{CO}_2}$ (kg/sec)
{ A2.1	1313	460	523	20	825	505	1155	0.0909
{ A2.1	1510	523	602	20	825	490	1147	0.0749
{ A2.1	1642	460	523	20	825	483	1143	0.0668
{ A2.1	1837	477	544	20	825	496	1151	0.0966
{ A2.1	2003	402	452	20	825	445	1126	0.1056
{ A2.1	1449	381	423	20	825	524	1163	0.0759
{ A3.1	1342	414	456	20	825	469	1139	0.0763
{ A3.2	1310	322	351	20	825	505	1155	0.0767

TABLE 3-8 (Continued)

Test	Time	$Q_{\text{CO}_2, \text{out}}$ (kW)	Heat Loss Above Coil, Q_{AC} (kW)	Wall Area Above Coil (m^2)	Wall-Bed $\bar{\Delta T}_{\text{AC}}$ ($^{\circ}\text{C}$)	$\bar{U}_{\text{(above coil)}}$ ($\text{W}/\text{m}^2\text{-K}$)	$\bar{h}_{\text{i(above coil)}}$ ($\text{W}/\text{m}^2\text{-K}$)
{ A2.1	1313	51.5	17.1	3.989	100	42.7	43.5
{ A2.1	1510	40.9	18.5	3.989	97	47.7	48.5
{ A2.1	1642	35.7	21.0	3.989	96	54.8	56.1
{ A2.1	1837	53.5	18.0	3.989	99	45.6	46.4
{ A2.1	2003	51.1	6.7	3.989	94	17.9	18.0
{ A2.2	1449	45.0	32.3	2.838	80	142.2	149.3
{ A3.1	1342	39.4	18.6	3.989	96	48.5	49.4
{ A3.2	1310	43.4	22.7	2.838	95	84.1	86.6

(a) Data for bracketed tests obtained at comparable in-bed operating conditions (temperature, velocity, gas flow rate).

where Q/A = heat flux through the wall (W/m^2-K),

$\bar{\Delta T}$ = mean difference between the outside wall temperature and fluid bed temperature ($^{\circ}C$).

From Eq. 3-1 the mean internal bed to wall heat transfer coefficient $\bar{h}_i$ may be calculated:

$$\bar{U} = \frac{1}{1/\bar{h}_i + t/\bar{k}} \quad , \quad (3-2)$$

where $\bar{h}_i$ = mean internal bed to wall coefficient (W/m^2-K),

t = wall thickness (m),

$\bar{k}$ = mean wall conductivity (W/m^2-K).

For the 0.40-m burner, $t = 6.35 \times 10^{-3}$ m (1/4 in.) and

$$\begin{aligned} k \text{ (Hastelloy X)} &= 27.3 \text{ W/m-K at } 900^{\circ}C \quad , \\ &= 25.1 \text{ W/m-K at } 800^{\circ}C \quad , \\ &= 23.0 \text{ W/m-K at } 700^{\circ}C \quad . \end{aligned}$$

The total induction heat input into the fluid bed Q is determined by actual power measurement during steady-state operation and then subsequently corrected for conduction and electrical losses. Conduction losses were calculated based on temperature data, whereas electrical losses were calculated as insignificant. Mean bed-to-wall temperature differences were determined using a step-wise integration procedure utilizing thermocouples at various elevations both in the burner and on the outer wall.

Table 3-8 presents the experimental heat transfer data and results. Once $\bar{U}$ and $\bar{h}_i$ are determined for the heated section of the vessel, an overall heat balance (Fig. 3-49) may be performed to determine the $\bar{U}$ and $\bar{h}_i$ for the section of the vessel above the active heating coil(s).

Figures 3-50 and 3-51 present data taken during Test A2.1 at two different steady-state points. The gas velocity through the bed opposite the

Fig. 3-49. 0.40-m primary burner heat balance

Fig. 3-50. Effect of temperature on in-bed heat transfer - 0.40-m primary burner

Fig. 3-51. Effect of temperature on above-bed heat transfer - 0.40-m primary burner

lower coil (Fig. 3-50) was essentially constant for these two points. Results show an increase in $\bar{h}_1$ as temperature increases over the range of 540° to 670°C. Similarly, Fig. 3-51 shows an increase in $\bar{h}_1$ as temperature increases at constant velocity for the section of wall above the lower induction coil. With relatively few bed particles in the space above the lower coil, a significant decrease in $\bar{h}_1$ would be expected in this region. Calculations show $\bar{h}_1$ to be approximately 10 times greater for the heated wall than for the non-heated wall, as expected for a dilute solids phase heat transfer.

Figures 3-52 and 3-53 show the effect of fluidization velocity (i.e., mixing, slugging, bed porosity, etc.) on $\bar{h}_1$ at three different steady-state points. In the case of the heated section of wall and bed solids (Fig. 3-52), a maximum in the curve is observed. As velocity is increased from a low value, the bed goes from a static condition to one of minimum fluidization and expansion and then to a bubbling condition. As these changes occur, the primary result is a continually increasing degree of solids mixing and particle-to-wall contact. The internal heat transfer coefficient $\bar{h}_1$ increases until a certain velocity is reached, whereupon it starts to decrease. This occurs as bubble size and the degree of solids slugging increase. Slug height increases with velocity; therefore, increased bubble size and slugging result in a decreased particle density in the lower heated section of the burner. Particle-to-wall contact in this region occurs less frequently and heat transfer is adversely affected.

The effect of gas velocity on $\bar{h}_1$ above the heated wall is shown in Fig. 3-53 for three different steady-state points in Test A2.1. As mean gas velocity increases, $\bar{h}_1$ decreases. This is explained by the fact that as velocity is increased, slugging characteristics change from axisymmetric formation to asymmetric. Horizontal gas voids as well as wall slugging become more prevalent, which results in decreased particle-to-wall contact in the upper section of the vessel.

Figure 3-54 shows the effect of bed material on $\bar{h}_1$. All four tests were performed at comparable bed temperature and gas velocity. Power input

Fig. 3-52. Effect of fluidization velocity on in-bed heat transfer - 0.40-m primary burner

Fig. 3-53. Effect of fluidization velocity on above-bed heat transfer - 0.40-m primary burner

Fig. 3-54. Effect of bed material on in-bed heat transfer - 0.40-m primary burner

to the bed was varied to maintain the desired bed temperature. The results show that for runs utilizing a greater heat transfer area and bed size (double coil runs), $\bar{h}_1$ was significantly smaller. In addition, $\bar{h}_1$ decreased as average bed particle size increased, independent of bed weight or heat transfer area.

3.11. AUTOMATIC CONTROL

Automatic control in the 0.40-m tests was limited to DIOGENES control of induction heating, the O_2 ramp, and the plenum O_2/CO_2 total gas flow.

Most of the automatic control study to date has been done on the 0.20-m burner, but extensive studies were curtailed by a problem with the DIOGENES system. The problem involved an intermittently erroneous temperature signal from the high bed temperature selector, which is normally used to scan the axial bed temperature profile and to provide a high-temperature signal to several other controllers. This erroneous signal briefly activated the induction heater and deactivated the cooling air, causing the cooling air blower to cycle on and off; when this had occurred often enough, the blower switch contactor overheated and failed. The cause of the high select channel randomly selecting a low temperature was traced to a software problem in the system "read-only-memory" (ROM). Programming changes were subsequently made to the ROM and it was reinstalled in the DIOGENES system. The 0.40-m burner Test C was then completed; Tests D and E were also conducted after the programming changes and the problem did not reoccur. However, because of the requirement that Tests C and D provide data to compare in-bed and above-bed recycle and that Test E provide sequential operation data, no additional automation studies were conducted in these 0.40-m tests. Extensive automation studies will be done in future 0.20-m and 0.40-m burner work.

Preliminary results of the automation study indicated that the postulated automation philosophy can control the primary burner in the initial heatup, in the O_2 ramp used for startup, and in the major steady-state

portion of the run. It was necessary to use manual override during the unstable phase of operation both following fresh feed startup and during the final tailburning phases (0.20-m burner tests). This override consisted of manually controlling the O_2 flow and the cooling air flow, with all other functions remaining on automatic control.

The control philosophy is shown in Fig. 3-55. This figure illustrates that the induction heater controller (0) only supplied power when the bed temperature was $<860^\circ\text{C}$. As the induction heater increased the startup bed temperature to its 700°C auto-ignition temperature, an O_2 ramp controller (1) was activated which increased O_2 flow to the plenum gas inlet. (The gas then entered the bed through the distributor perforations.) The rate of O_2 increase and the maximum level to which the O_2 increased were automatically controlled and varied through the O_2 ramp controller. While the O_2 flow was being increased, the plenum O_2/CO_2 total gas controller (2) adjusted the plenum CO_2 gas flow to keep the combined total plenum O_2 and CO_2 gas flows constant. This controller functioned automatically throughout the run to hold the total gas, and thus the superficial velocity, constant even if the O_2 flow controller required manual operation. At the 860°C bed temperature the induction heater was automatically deactivated, and at 880°C ($\pm 10^\circ$) the cooling air flow was activated by the cooling air controller (3). The cooling air flow control valve opening was varied to hold the bed temperature at $\sim 900^\circ\text{C}$. If the wall cooling was incapable of preventing bed temperature excursions above 930°C , the high temperature plenum O_2 controller (4) reduced the plenum O_2 until the bed temperature returned below $\sim 930^\circ\text{C}$. The plenum gas was returned to its preset maximum below $\sim 930^\circ\text{C}$, which prevents damage to the vessel wall. During tailburning the decreased bed carbon allowed the O_2 concentration in the off-gas to increase. The off-gas O_2 controller (5) reduced the plenum O_2 to maintain a preset maximum off-gas O_2 concentration.

This control philosophy has been very beneficial in simplifying the burner operator's duties and in providing safer, more constant operating conditions. Fine tuning of the cooling air controller and the high temperature plenum O_2 controller is required to further improve the automatic

0. INDUCTION HEATER CONTROLLER – ADJUSTS INDUCTION POWER AND RESULTANT HEAT INPUT INTO BURNER IF BED TEMPERATURE IS $< 860^{\circ}\text{C}$, LIMITS WALL TEMPERATURE $\leq 900^{\circ}\text{C}$ AND (OR) SUSCEPTOR TEMPERATURE $\leq 1080^{\circ}\text{C}$
1. O_2 RAMP CONTROLLER – INCREASES PLENUM O_2 AT A PRESET RATE, STOPS O_2 AT A PRESET MAXIMUM FLOW
2. PLENUM O_2/CO_2 TOTAL GAS CONTROLLER – ADJUSTS TO MAINTAIN CONSTANT TOTAL PLENUM GAS FLOW – $\text{O}_2\uparrow, \text{CO}_2\downarrow$
3. COOLING AIR CONTROLLER – ADJUSTS COOLING AIR FLOW TO MAINTAIN 900°C BED TEMPERATURE; TURNS COOLING AIR ON AND OFF AT PRESET TEMPERATURE
4. HIGH-TEMPERATURE PLENUM O_2 CONTROLLER – REDUCES PLENUM O_2 IF BED TEMPERATURE EXCEEDS 930°C
5. OFF-GAS O_2 CONTROLLER – ADJUSTS PLENUM $\text{O}_2\downarrow + \text{CO}_2\uparrow$ SO THAT OFF-GAS $\text{O}_2 < 7\%$

Fig. 3-55. Proposed primary burner automatic control

control. Tuning of the cooling air controller appears to be the most difficult. The slow response of bed temperature to wall cooling and the dependence of this response upon bed-to-wall heat transfer, which can fluctuate with fluidization conditions, complicate the control of the cooling air flow. Automation is discussed in added detail in Ref. 5.

3.12. VESSEL INSPECTION

Vessel inspection after the initial (Test A.1) and sixth thermal cycle (Test A3.3) centered around the plenum assembly as specified in the maintenance manual (MM 524401). Problems with the Grafoil cooling air seal have been discussed in detail previously and need not be expanded here. All visual and dye penetrant examinations were approved and signed off by the QA department.

The vessel inspection following Test E (which represents 12 thermal cycles from ambient to full operating temperature) has yet to be completed. However, visual inspection of the process side of the distributor cone from the top of the vessel indicates that there are no significant effects.

A visual examination of the primary burner interior wall opposite the fines recycle penetration also revealed no detectable damage.

A 75-Watt drop light was lowered into the vessel, and the interior side wall surface was observed through the top and through the two burner wall penetration holes. A fiber optics boroscope was also inserted through the penetration holes and used for a close look at the interior surfaces. No detectable damage was apparent. There were small pock marks or indentations on the wall surface, but these are potentially characteristic of the surface. Also, a discolored region was visible on the interior surface opposite to the fines penetration when the drop light was held in a certain position. This discoloration, about 4 in. round in size, was perhaps a slightly worn spot or only a surface discoloration; it did not appear to have any measurable depth.

3.13. VESSEL LEAK TESTS

Vessel leak tests were performed after the plenum was reassembled to the burner tube via the Gray Tool Company seal and clamp prior to the B, C, D, and E test series. Leakage was determined by a pressure decay test beginning at a vessel pressure of 12 psig. The leakage from the Gray seal and any blinds or plenum flanges or connections was determined to be $\sim 1.9 \times 10^{-2}$ SLPM (9.5×10^{-4} vol % of the 2000 SLPM nominal gas flow) in a 3-day decay from 12 to 9.75 psig. Leakage through the product removal slide valve and its packing was found to be ~ 3.5 SLPM (0.175 vol % of the process flow of 2000 SLPM) in a 50-min decay from 12 to 7.25 psig. Both of these leak rates were considered acceptable for operation.

General bubble leak tests prior to each test indicated excessive leakage from the filter chamber flanges and from the fresh feed rotary valve shaft seal. The filter leakage was reduced by installing "C" clamps. The shaft seal leakage could not be reduced as no adjustment is available.

3.14. SEMIREMOTE FIXTURES

Semiremote fixtures involved use of the plenum cart and disconnection of the Gray clamp. Difficulty was encountered in separating the plenum assembly from the burner tube despite the fact that the plenum assembly weighed approximately 500 kg. Apparently the seal ring undergoes sufficient plastic deformation when the clamp is made up to hold the plenum and the burner tube together after removal of the clamp. A jackhammer was required to vibrate the plenum assembly loose from the seal ring. The plenum cart functioned as required in disassembly and reassembly.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. TEST A

The following conclusions and recommendations have been reached:

1. Lower induction coil heating was preferable to use of a dual coil/deeper bed operation. At least 50% of the coil height should be filled with bed material to avoid upper heated zone hot-spots. Heatup to the 700°C bed ignition temperature required <2 hr.
2. Internal heat transfer coefficients ranged from 351 to 602 W/m²-K in the bed and from 18 to 149 W/m²-K (3 to 26 Btu/hr-ft²-°F) above the bed in non-fines recycle testing. Heat transfer was generally higher at higher temperatures and for smaller particles. In-bed heat transfer peaked at about 1.05 m/sec velocity for TRISO fertile particle beds, with much lower heat transfer at 0.92 and 1.24 m/sec.

Every type of primary burner bed material apparently has a different peak heat transfer/velocity relationship. The 1.1 m/sec velocity nominally used in the primary burners seems acceptably within the peak area and should be used until further study warrants change.

3. Despite the high temperature coating on the seal ring, considerable difficulty was experienced in removing the 14-in. high temperature remote flange for maintenance following high temperature operation. Consideration should be given to either improving the removability of this flange or relocating the connection to improve maintainability for remote operation.

4. The sliding seal between the burner wall and cooling air shroud is a potentially low reliability component. Future design efforts should deal with either integration of the cooling jacket and burner to eliminate the need for the peak at this location or redesign of the separable cooling shroud to simplify the sealing requirements.

4.2. TESTS B, C, AND D

The following conclusions and recommendations have been reached:

1. In-bed fines recycle via the perforated cone vertex caused excessive particle carryover and subsequent particle breakage in the recycle loop. Above-bed fines recycle through the side-wall (injected at a point ~60% up the 4.1-m tube) burned fines as efficiently as in-bed recycle if mid-reactor O_2 flow was increased to ~17 vol % of total O_2 inlet flow as quickly as possible. The limitation to this rate of mid-reactor O_2 increase was maintaining off-gas O_2 vol % at <3%. Even with this constraint, the mid-reactor O_2 could be increased to its maximum long before the in-bed O_2 ramp was complete.

The use of above-bed recycle is recommended in conjunction with the rapid increases of mid-reactor O_2 .

2. The Peaucellier mechanisms have excessive linkage play inherently and should be replaced by simpler devices such as the single link mechanism.
3. The rotary valve feeder performed acceptably in the tests only after it was flanged directly to the aerated conical bottom of the feed hopper. Its shaft seals leak excessively.

A line $L/D < 1$ should always be maintained between a gravity hopper and a metering mechanism. The present fresh feed valve

(a 510-mm Pulva Corporation unit modified with brass insert blades having ~ 4.7 -mm clearance between the blade and the housing) should be revised or replaced with an equivalent unit capable of shaft sealing against 69 kPa.

4. The 0.40-m burner's $L/D = 10$ length was adequate for burning fines injected above the bed if sufficient mid-reactor O_2 was used. This tube length limits the static bed height to $L/D \lesssim 4$.
5. Large amounts of the fines entered the bed when fines were recycled above the bed.
6. Fines recycle improved bed mixing and bed-to-wall heat transfer and drastically reduced the expected lower burner wall cooling requirements by carrying heat into the upper burner, the off-gas line, and the cyclone.
7. The breakage of TRISO particles was as much as twice that of BISO particles; segregation of the BISO particles to the lower bed resulted in much of the Th from BISO breakage occurring in the plenum, as the BISO particles were pounded through the distributor perforations, whereas the U from broken TRISO particles floating near the top of the bed was found in higher concentration in the fines recycle loop.
8. Off-gas CO averaged as high as 18% with $\pm 5\%$ spikes following the ~ 1 -min cycle of the fines flow from the switching hoppers.

Off-gas treatment systems should incorporate a surge tank of a volume sufficient to contain ~ 5 min of burner off-gas. This surge volume would line out the fluctuations in CO that would otherwise be difficult to adjust for in the CO oxidizer.

4.3. TEST E

The following conclusions and recommendations have been reached:

1. The minute quantities (<1 wt %) of fuel rod fragments resulting from crushing loaded fuel blocks require ≈ 2 ft/sec startup velocity but pose no apparent problems during combustion.
2. No problem of accumulation of fines with above-bed recycle occurs if mid-reactor O_2 is increased to ~ 17 vol % of total O_2 as fast as maintaining off-gas O_2 at $\lesssim 3$ vol % will allow. (Above-bed fines recycle burning effectiveness equals that of in-bed recycle.)
3. Pressurized recycle erodes any poorly designed area (weak bend, bellows, abrupt i.d. well change). Also, combining of fines transport gas and mid-reactor O_2 injection into the burner should be avoided if pressurized recycle is to be used further.
4. Gravity fines recycle should be used if it is found acceptable under all expected burning conditions in future 0.20-m burner tests.
5. The higher particle breakage in Test E as compared to Test D may be a result of two basic differences between the Test D and E operations. First, Test D lasted <24 hr whereas Test E lasted >40 hr. The additional time would add to particle breakage. Second, Test D fuel particles were not put through a crusher and the additional handling associated with crushing. Although the Test E burner breakage values were adjusted for breakage of particles in the feed, fuel particles that were weakened (though not broken) would add to subsequent breakage within the burner system.

6. Breakage of TRISO particles was much greater than was breakage of BISO particles; the natural segregation of TRISOs and BISOs to the top and bottom of the burner bed respectively tends to place most oxides from BISO breakage in the plenum chamber and most oxides from TRISO breakage in the fines system.
7. The simple single-lead dc circuit level detect device worked well in the fines hoppers, the gravity flow lines, and the burner, and its use should be continued and extended to the fresh feed bunker.
8. The gas distributor requires redesign and further development to reduce fuel particle drainage into the plenum. The plenum design should incorporate provisions for removal of accumulated particles.

5. REFERENCES

1. Rickman, W. S., "Activity Plan: 40-cm Primary Burner" (revised by D. T. Young), General Atomic Company unpublished data, June 1977.
2. Werther, Joachim, "Influence of the Bed Diameter on the Hydrodynamics of Gas Fluidized Beds," AICHE Symposium Series on Fluidization 70 (1974) pp. 53-62.
3. "HTGR Fuel Recycle Program Quarterly Progress Report for the Period Ending August 31, 1977," ERDA Report GA-A14583, General Atomic Company, September 1977, pp. 7-16 to 7-22.
4. Stula, R. T., "Fluidization Studies in the Cold 20-cm Glass Primary Burner," General Atomic Company unpublished data, September 1976.
5. "0.20-m (8-in.) Primary Burner Development Report," DOE Report GA-A14583, General Atomic Company, December 1977, pp. 62-68.

6. ACKNOWLEDGMENTS^{*}

The work described in this report was the result of a team effort by many talented technicians, designers, and engineers. The technicians involved in the equipment construction included R. M. Earle, M. D. True, and M. B. Zacavich. The experience and enthusiasm of T. D. Wright in guiding the technician effort was a key to the smooth installation. The engineer in charge of piping and instrumentation runs and responsible for the induction heater design and shakedown was W. S. Rickman. W. S. Rickman was also responsible for the original activity plan and for compiling the inputs for the maintenance manual and the operating procedure. H. H. Yip was responsible for the early heat transfer analysis together with Dr. U-Sun Park. H. H. Yip was also responsible for supervising the burner tube and off-gas system fabrication and installation. R. T. Stula was responsible for scale-up of the 0.20-m burner fines recycle subsystem to the 0.40-m burner and for supervising its installation. R. T. Stula also participated in the long hours of monitoring burner operation and in data reduction and heat transfer analysis. J. S. Rode was involved in procurement, especially in analysis of automatic controllers and selection/procurement of the DIOGENES system, and also wrote portions of the maintenance manual.

Technician support during operation and data analysis involved G. W. Cox, P. L. Knoll, J. W. McClean, J. C. Narvaey, E. Simmons, R. W. Wheatly, and M. B. Zacavich. Special appreciation again goes to T. D. Wright for his coordination of the technicians and especially for his contribution in plugging a leak during sequential operation, which was indeed beyond the call of duty. The solids handling section engineers, whose contributions included the continuous surveillance of feed equipment during long operations, were E. J. Cook, J. M. McNair, and especially P. C. Richards, who

^{*}Note: The parallel pressurized fines recycle hoppers were scaled-up from hoppers originally tested by W. B. Palmer of Allied Chemical Corporation, Idaho Falls, Idaho.

also added to the smooth planning that made the sequential operation successful. R. D. Crabtree was responsible for instrumentation, and his engineering and coordination of instrument technicians was of great assistance. C. A. Ederle's help in data reduction and graph production was also helpful.

The long list of team members also includes the design group's input from the beginning of the 0.40-m concept throughout the equipment alterations during the year of operation. J. W. Baer and N. W. Johanson contributed both in engineering design and in practical equipment guidance and suggestions. Also, the design-drafting of R. S. Huston, which kept him out with the equipment almost as much as at his board, was essential.

Leadership of the development program came from J. W. Allen and R. D. Zimmerman.

APPENDIX A
REQUIREMENTS FOR THE 0.40-m PRIMARY BURNER TESTING

The documentation of requirements which pertains to the subject matter of this report includes:

1. "AP524401D, Activity Plan: 40-cm Primary Burner" dated June 16, 1977, by W. S. Rickman (revised by D. T. Young).
2. "MM524401B, Maintenance Manual: 40-cm Primary Burner," dated January 20, 1977, by W. S. Rickman (revised by D. T. Young).
3. "OP524401A, Operating Procedure: 40-cm (Prototype) Fluidized Bed Crushed Fuel Element Burner," dated April 28, 1976, by W. S. Rickman (revised by D. T. Young).

The requirements in these documents are most clearly stated in the following excerpts from the Activity Plan "Objectives" and "Acceptance Criteria" sections:

2.0 OBJECTIVES

In this series of experiments, data will be gathered to define burner operating characteristics in the HRDF reference operating cycle. This will serve to verify design calculations and obtain design data. Maintenance and reliability data will be taken for HRDF input. These include burner minimum design life verification, thermal gradients, and gas leakage rates. Adequacy of remote tooling for partial burner assembly/disassembly will be determined during maintenance inspections. These plans are described in the Maintenance Manual (MM 524407).

Independent variables (gas flows, bed weights, feed rates and fines recycle rates) will be set based on input from the 0.20-m primary burner activity plan. That plan incorporates a statistical variation of independent variables to determine the optimum values for those variables. The purpose of that burner is to provide scale-up data for the 0.40-m primary burner on an economical scale.

Because of the two zone induction heating coil feature of the 0.40-m burner, there are two possible bed heights for both starting and tail burning. Each will be investigated.

The specific operating characteristics to be determined are as follows:

2.1 Induction Heating

Heat up transients with startup beds of fresh feed; tail burning capability with a particle bed. The wall and susceptor temperatures will be controlled to 900°C and 1100°C, respectively. Within these constraints, the ability to heat the fresh feed to ignition temperature (700°C) will be tested.

2.2 Feeding

Usefulness of rotary feeder for initial bed addition and subsequent continuous feeding. Feed rates will be recorded and any blockages or holdups noted.

2.3 Fluidization

Superficial velocities required for adequate bed circulation (max. bed $\Delta T = 100^\circ\text{C}$) over the range of bed compositions. Preliminary indications are that high velocities (>3.3 ft/sec) are required for mixing fresh feed beds. This will be tested by noting bed temperature gradients during heatup.

2.4 Off-gas Composition Throughout the Run

This will be an input for off-gas processing work. It serves as a continuous indication of bed reaction conditions and allows burning efficiencies to be calculated.

2.5 Temperature Distribution In the Bed and Throughout the Vessel

These are used to monitor heating and cooling efficiencies, bed fluidization quality and burner tube thermal gradients for input to thermal modeling work for stress analysis.

2.6 Cooling

Internal and external heat transfer coefficients as functions of gas velocity and temperature. Both of these variables are continuously recorded and will allow calculations on pin fin cooling effectiveness and internal transport of heat from the bed to the tube.

2.7 Fines Recycle

Fines elutriation rate from a high carbon startup bed and fines burning efficiency as a function of bed composition and height. Continuous readout of fines recycle bunker weights will allow instantaneous mass rates of fines elutriation and recycle to be determined. These will yield an insight into the nature of fines burning that has not been possible previously.

2.8 Product Removal

Rate of discharge into the transport system, and material holdup in the burner. After this rate of discharge is known, partial emptying of the burner may be accomplished using a timed interval of removal. This will allow an interface with the pneumatic transporter during

interim product removal operations. Material holdup figures will be useful in future accountability calculations.

2.9 Automatic Control

Effectiveness in controlling variables around set points. Each control loop will be tuned by an empirical method to yield optimum control characteristics.

2.10 Product Characteristics

Determine particle breakage and product carbon content after each run. This will yield a preliminary product specification.

2.11 Vessel Inspection

The maintenance manual describes inspections to be made on the vessel following the initial thermal cycle. This will take the form of a liquid dye penetrant examination at specified locations. In addition, a liquid dye penetrant inspection for cracks is to be made after Run A1, Run A5, and Run E.

2.12 Vessel Leak Test

Pressure decay tests using CO₂ gas are to be made preceding operation and following preassembly after the sixth and tenth thermal cycles. This will dictate whether seals are effective &/or gasket replacement is necessary.

2.13 Semi-Remote Fixtures

The burner distributor spool piece will be removed as required in MM 524401 using the semi-remote removal cart. Removal of the burner assembly is not planned during the activity plan period.

4.0 ACCEPTANCE CRITERIA

As per the design criteria, the following are the levels of variables which will be acceptable if met:

4.1 Induction Heating

Ability to heat fresh feed or particle beds to 700°C using the 250 kW power supply; maintaining clamp to hub $\Delta T < 112^\circ\text{C}$ for Gray flanges and 900°C maximum wall temperature. Heatup shall take not more than two hours.

4.2 Fluidization

Ability to adequately mix (max. bed $\Delta T = 100^\circ\text{C}$) the bed during all normal phases of operation.

4.3 Feeder

Ability to feed within 5% of nominal feed rate.

4.4 Off Gas

Ability to keep out of the CO-O₂ explosion envelope, removal of particulates < 1 micron, cooling to less than 66°C.

4.5 Cooling

Ability to keep the bed at 900°C while burning at 800 gC/min - with full bed only (to top of pin-fin area).

4.6 Fines Recycle

Ability to recycle and burn fines continuously through the run including tailburning without the line plugging and result in a heel of fines < TRDg. Fines accumulation shall be < TBDg.

4.7 Product

Ability to remove beds of 17-100% particle concentration without blockage, product carbon content <1%.

4.8 Automatic Control

Ability to hold measured variables within the following limits:

Process Gas Flow - $\pm 3\%$ of set point

Cooling Air Flow - $\pm 3\%$ of set point

Temperature - $\pm 7\%$ of set point

4.9 Remote Fixtures

Ability to remove and replace cone-plenum assembly routinely.
If necessary for maintenance, the vessel removal steps must lead to safe burner removal and reinstallation.

APPENDIX B
SATISFACTION OF SPECIFIED REQUIREMENTS

The content of this document and of the work described completely fulfills the requirements of the Activity Plan in each specified section with one possible exception. The degree of progress hoped for in automatic control was hampered by the DIOGENES controller problem. Additional studies on both the 0.20-m and the 0.40-m system are required to extend the present level of automatic control.

The maintenance manual specified inspection and reporting techniques with quality assurance sign-offs. Examples of these are shown in Figs. B-1 and B-2.

The successful, safe long-term operation of the burner over the year's testing reflects not only adherence to proper operating procedure as specified in the operating plan but also prudent in-process adaptation and revision of those procedures to fulfill the objectives. Figure B-3 reflects documentation of such revisions, which were necessary to achieve efficient fines burning with the use of above-bed fines recycle.

General Atomic Company

No. 31261

Pri Burner

INSPECTION REPORT

☐ SKETCH ATTACHED

PAGE 1 OF 1

NOMENCLATURE		DWG/PART NO.		REV.	LOT/SERIAL NO.	DATE
Outlet spool connecting to the 40cm Burner Cyclone Lower Flange		5244105 Part #16				7/13/77
PROJECT	W.O./P.O./S.O. NO.	TRAVELER NO.	OPER/P.O. ITEM NO.	LOCATION		
3225				E. BLDG Pilot Plant		
NEXT ASS'Y NO.	QAL	SUPPLIER	LOT SIZE	QTY INSP	QTY NOT ACC	PREVIOUS REPORT NO
5244002	III	G. A.	1	-	-	-
RESPONSIBILITY	DISCOVERED IN:		INSPECTION CRITERIA		OTHER (EXPLAIN)	
	☐ REC'G ☐ IN-PROCESS ☐ TEST ☒ FIELD		☒ DWG ☐ SPEC. ☐ I.I. ☐		NO. _____	
DISCREPANCY			DISPOSITION			
ITEM	CL OF CHAR	DESCRIPTION	OCCUR.	PRELIM. DECISION	MRB DECISION	INSP. DATE
1		In bubble leak test in preparation for RUND, a pin-hole leak was found in the lower flange of the spool which connects the cyclone to the pipe leading to the fines hoppers.			The pin hole will be repaired by welding in place and another leak test will be made to check the repair.	DTY 7/13/77
				Actions: (D.T. Young) T.D. Wright		
				Distributions: NWT RCR TDW DTY Project File		
INITIATOR	DATE	INSP. SUPERVISOR	DATE	MFG. REPRESENTATIVE		DATE
D.T. Young	7/13/77	John Williams	7/13/77			
CAUSE OF DISCREPANCY		CORRECTIVE ACTION				
A poor in-house weld which was weakened by the heat of operation		None Rec'd				
SIGNATURE _____ DATE _____						
MRB			INSPECTION			
QUALITY ENGINEER	DATE	CUSTOMER REPRESENTATIVE	DATE	QTY ACC.	QTY NOT ACC.	COMPLETED DATE
George Chandler	7/13/77					
DESIGN ENGINEER	DATE	A.I.A. REPRESENTATIVE	DATE	NEW IR NO.		
Dwain T. Young	7/13/77					

Fig. B-1. Inspection and reporting techniques

GA 1232 (1, 2/75)

GENERAL A. MIC COMPANY

DOCUMENT NO. MM 524401 ☐ Receiving ☐ Source Inspection Plan No. TEST Issue
 Component Name 40-CM (PROTOTYPE) PRIMARY BURNER Unit Serial No. 524404 Page 1 of 3
 Supplier GA Location E-183 Prepared by N. W. Johanson Date

Item	Inspection Operation	Inspection Method	Clarifying Details-e.g. identify of key documents reviewed or used, exactly what verified, witnessed, etc.	Initial	Date
1	Bellows Body	Visual	D/No. 5244011- Item 5		
2	Bellows Attachment Weld	PT	Figure 1-1, Item (1)		12/7/76
3	Distributor Cone	Visual	D/No. 5244011- Item 3		
4	Surface From Upper Access Port/Hub Weld to Hub Tapper	PT	Figure 1-1, Item (2)		12/7/76
5	Cover Plate Bolts	Hand-Tight	D/No. 5244012 - Item 6		
6	Accessible Surfaces of Clamp	Visual	D/No. 5244010 - Item 5		
7	Concave Surface of Clamp	PT	Figure 1-1, Item (3)		
8	Circum. Weld Plus 1/2 Inch Strip Either Side	PT	Figure 1-1, Item (4)		
A.	Internal				12/7/76
B.	External				
9	Exter. Surface of Hub-to-Hub Transition	PT	Figure 1-1, Item (5)		
10	Cone/Hub Circum. Weld	PT	Figure 1-1, Item (6)		12/7/76
A.	I.D., 1/2" Below, 1" Above	PT			
B.	Ø.D., Weld & Radius	PT			

This page verified complete by _____ Approved for filing _____
 Customer Verification Date _____ Date _____ (Cognizant Quality Engineer)

Fig. B-2. Inspection and reporting techniques

ENGINEERING CHANGE ORDER		CHANGE REQUEST NUMBER		Date								
See back of form for instructions		00512		10/17/77								
6	2 Originator: <i>D. Young</i>	3 Document No. <i>OP52440/A</i>	Sheet 1 of 1									
Notification Required: Leave blank if not applicable ☐ ACC ☐ ORNL ☐ ERDA-RRD ☐ PROCUREMENT REP ☐ A-E ☐ ID-ORO	4. DESCRIPTION OF CHANGE <i>Page 20, 21 under B. start-up insert underlined changes -</i> 1. Open the vertex, plenum, and mid-reactor gas supply solenoids. 2. ... increases above 700°C → <u>860°C</u> . <i>insert new</i> → 9. Start mid-reactor fines recycle when the bed temperature reaches <u>5820°C</u> (press the pressurizing depress switch and set to 905.5m) 10. Start fresh feed at a rate approximately equal to the burn rate (on a carbon balance) when the bed temperature reaches <u>5860°C</u> . Increase the feed rate to maximum concurrent with the burn rate increase (O ₂ ramp).											
7	Schedule Effect: Leave blank if no change											
5. REASON FOR CHANGE: <i>Cancel, and update based upon present information</i>												
9 OTHER DOCUMENTS <table border="1"> <thead> <tr> <th>Title, Change Description</th> <th>Number</th> <th>Issue</th> <th>Level</th> </tr> </thead> <tbody> <tr> <td colspan="4"> 11. Turn on cooling air at a bed temperature <u>5890°C</u> and place on automatic. to regulate the The cooling air flow will be varied automatically to maintain a <u>900°C</u> bed temperature. (optionally use manual control of the cooling air flow) <div style="border: 1px solid black; padding: 5px; margin: 10px 0;"> delete B. 9. and B. 10.; C. 1 and C. 2, C. 4-revise numbering as necessary </div> 12. Start mid-reactor O₂ at <u>705m</u> and turn off mid-reactor CO₂ when fines temperatures measured in the fines hoppers exceed <u>200°C</u>. Manually increase the mid-reactor O₂ to <u>250 SCFM</u> as quickly as allowed by the off-gas O₂ remaining <u><3 mol %</u>. </td> </tr> </tbody> </table>					Title, Change Description	Number	Issue	Level	11. Turn on cooling air at a bed temperature <u>5890°C</u> and place on automatic. to regulate the The cooling air flow will be varied automatically to maintain a <u>900°C</u> bed temperature. (optionally use manual control of the cooling air flow) <div style="border: 1px solid black; padding: 5px; margin: 10px 0;"> delete B. 9. and B. 10.; C. 1 and C. 2, C. 4-revise numbering as necessary </div> 12. Start mid-reactor O ₂ at <u>705m</u> and turn off mid-reactor CO ₂ when fines temperatures measured in the fines hoppers exceed <u>200°C</u> . Manually increase the mid-reactor O ₂ to <u>250 SCFM</u> as quickly as allowed by the off-gas O ₂ remaining <u><3 mol %</u> .			
Title, Change Description	Number	Issue	Level									
11. Turn on cooling air at a bed temperature <u>5890°C</u> and place on automatic. to regulate the The cooling air flow will be varied automatically to maintain a <u>900°C</u> bed temperature. (optionally use manual control of the cooling air flow) <div style="border: 1px solid black; padding: 5px; margin: 10px 0;"> delete B. 9. and B. 10.; C. 1 and C. 2, C. 4-revise numbering as necessary </div> 12. Start mid-reactor O ₂ at <u>705m</u> and turn off mid-reactor CO ₂ when fines temperatures measured in the fines hoppers exceed <u>200°C</u> . Manually increase the mid-reactor O ₂ to <u>250 SCFM</u> as quickly as allowed by the off-gas O ₂ remaining <u><3 mol %</u> .												
8	Cost Effect: Leave blank if no change											
10	Distribution: RDZ LO. 3 GC. (QA) WSR. CAE. PCR.											
11	ASSIGNED Approval Level: <u>2</u>											
12	APPROVALS Cog. Engineer <i>[Signature]</i> Level 1 Sect. Leader <i>[Signature]</i> Level 2 Br. Mgr. <i>[Signature]</i> Level 3 Dept. Mgr. <i>[Signature]</i>											

Fig. B-3. Documentation of burner revisions