GA-A14643
UC-77

*175
3-1-78*

1878

10/16/78

0.20-m (8-in.) PRIMARY BURNER DEVELOPMENT REPORT

by

R. T. STULA, D. T. YOUNG, and J. S. RODE

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

DECEMBER 1977

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

8.00

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-A14643
UC-77**

0.20-m (8-in.) PRIMARY BURNER DEVELOPMENT REPORT

by

R. T. STULA, D. T. YOUNG, and J. S. RODE

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: DECEMBER 1977**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

4

4

4

4

4

ABSTRACT

High-Temperature Gas-Cooled Reactors (HTGRs) utilize graphite-base fuels. Fluidized-bed burners are being employed successfully in the experimental reprocessing of these fuels. The primary fluidized-bed burner is a unit operation in the reprocessing flowsheet in which the graphite moderator is removed. This report presents a detailed description of the development status of the 0.20-m (8-in.) diameter primary fluidized-bed burner as of July 1, 1977.

Experimental work to date performed in 0.10, 0.20, and 0.40 m (4, 8, and 16 in.) diameter primary burners has demonstrated the feasibility of the primary burning process and, at the same time, has defined more clearly the areas in which additional experimental work is required. The design and recent operating history of the 0.20-m-diameter burner are discussed, with emphasis placed upon the evolution of the current design and operating philosophy.

•

•

•

•

•

•

CONTENTS

ABSTRACT	iii
1. INTRODUCTION	1
2. HTGR FUEL AND REPROCESSING FLOWSHEET	3
2.1. HTGR Fuel	3
2.2. HTGR Fuel Reprocessing Flowsheet	3
3. PROCESS DESCRIPTION	10
4. EQUIPMENT DEVELOPMENT	14
4.1. Feed System	14
4.2. Burner Vessel	17
4.3. Gas Distribution	20
4.4. Product Removal	24
4.5. Heating and Cooling	25
4.5.1. Heating System Alternatives	25
4.5.2. Induction Heating System	28
4.5.3. Cooling System	30
4.6. Off-Gas Filter System	35
4.7. Fines Recycle	39
5. OPERATING CYCLE	42
5.1. Startup	42
5.2. Tail-Burn	44
6. EXPERIMENTAL RESULTS	46
6.1. Early Work	46
6.2. Statistical Analysis Experiments	49
6.2.1. Modules 1 Through 4	49
6.2.2. Modules 5 and 6	56
6.2.3. Module 7 - Automation Study	62
6.2.4. Module 7 - Operating Cycle Tests	68
7. EQUIPMENT DESIGN MODIFICATIONS	72
8. SUMMARY AND RECOMMENDATIONS	73
ACKNOWLEDGMENTS	76

REFERENCES	77
APPENDIX A: BURNER OPERATION	A-1
APPENDIX B: SUMMARY OF EARLY BURNER RUNS	B-1
APPENDIX C: DESIGN OF STATISTICAL ANALYSIS EXPERIMENTS	C-1
APPENDIX D: MODULE 1 THROUGH 6 DATA	D-1

FIGURES

1. HTGR fuel element	4
2. Diagrammatic representation of fissile, fertile, and recycle particles for-1150 MW(e) HTGRs	5
3. Reprocessing flow diagram	6
4. 0.20-m-diameter primary burner configuration	15
5. Gravity-pneumatic feeder	16
6. Fresh feed system	18
7. 0.20-m-diameter primary burner vessel	19
8. 0.20-m-diameter primary burner gas distribution	22
9. Induction heater coil and susceptor	29
10. Induction heater power supply system	31
11. Startup transient, 0.20-m-diameter primary burner	33
12. Fin pattern for 0.20-m-diameter primary burner	36
13. Filter venturi	38
14. Three fines recycle systems tested	41
15. Effect of bed height on startup transient	45
16. Pilot plant control instrumentation panels	63
17. Proposed primary burner automatic control	66
18. 0.20-m-diameter primary burner burnthrough	71
A-1. Log sheet	A-27
A-2. Data sheet - module 1	A-28
A-3. Data sheet - module 2	A-29
A-4. Data sheet - module 3	A-30
A-5. Data sheet - module 4	A-31
A-6. Data sheet - module 5	A-32
A-7. Data sheet - module 6	A-33
A-8. Primary burner control panel I	A-34

A-9. Primary burner control panel II	A-35
A-10. 0.20-m-diameter primary burner control room instrumentation . .	A-36
A-11. 0.20-m-diameter primary burner cabinet instrumentation	A-37
A-12. 0.20-m-diameter primary burner system	A-38
A-13. Bed addition auger calibration	A-39
A-14. Explosive limits of carbon monoxide in mixtures of oxygen and carbon dioxide	A-40
A-15. Off-gas analyzer flow diagram	A-41
A-16. Off-gas correction curve - CO ₂	A-42
A-17. Off-gas correction curve - CO	A-43
D-1. Time required to induction heat a fresh feed bed to ignition temperature versus velocity and bed particle size	D-6
D-2. Maximum in-bed axial temperature difference versus superficial gas velocity, bed weight, and particle size	D-7
D-3. Average radial temperature difference versus superficial gas velocity, bed weight, and particle size	D-8
D-4. Particle breakage trends as observed from thorium oxide and particle coatings (SiC hulls) separated from fines samples . . .	D-9
D-5. CO in off-gas versus total in-bed O ₂ and total in-bed gas velocity	D-10
D-6. CO in off-gas versus secondary and total in-bed O ₂ flows	D-11
D-7. O ₂ in off-gas versus secondary and total in-bed O ₂ flows	D-12
D-8. Final bed carbon versus integrated excess O ₂ (off-gas) during tail-burning	D-13
D-9. Maximum in-bed axial temperature difference versus method of fines recycle, secondary O ₂ flow rate, and in-bed O ₂ flow rate	D-14
D-10. Average radial temperature difference versus method of fines recycle, in-bed O ₂ flow rate, and secondary O ₂ flow rate	D-15
D-11. CO in off-gas versus method of fines recycle, in-bed O ₂ flow rate, and secondary O ₂ flow rate	D-16
D-12. Final fines inventory (-355 μm graphite) versus gas velocity/O ₂ flow, recycle system/inlet location, and secondary O ₂ rate . . .	D-17
D-13. Noncombustible (-355 μm) elutriation versus gas velocity/O ₂ flow, recycle system/inlet location, and secondary O ₂ rate . . .	D-18
D-14. Fuel particle loss (breakage) versus gas velocity/O ₂ flow, recycle system/inlet location, and secondary O ₂ rate	D-19
D-15. Particle agglomeration versus gas velocity/O ₂ flow, recycle system/inlet location, and secondary O ₂ rate	D-20
D-16. Final bed carbon versus fines burnout, tail-burn assist, off-gas O ₂ percent, and recycle mode	D-21

TABLES

1.	Average properties of primary burner feed and startup bed . . .	11
2.	Average properties of primary burner fuel particle product . . .	11
3.	Operating guides for primary fluidized bed burner	12
4.	Properties of Hastelloy X	21
5.	Comparison of various heating methods	27
6.	0.20-m-diameter primary burner induction heating coil design parameters	32
7.	0.20-m-diameter primary burner startup requirements	34
8.	Lower cooling jacket design summary	37
9.	0.20-m-diameter primary burner operating cycle (semi-batch) . .	43
10.	0.20-m-diameter primary burner experimental program	50
11.	Primary burner operating levels for minimizing dependent variables	51
12.	Independent variable ranges for 0.20-m-diameter primary burner tests	52
13.	0.20-m-diameter primary burner temperature differentials - averaged experimental results for modules 5 and 6	57
14.	0.20-m-diameter primary burner particle breakage and residual inventory data	58
15.	0.20-m-diameter primary burner statistical analysis of in-bed and above-bed fines recycle with operating levels for minimizing independent variables	60
16.	Primary burner major control functions	64
A-1.	Primary burner operation	A-7
A-2.	Major control functions of primary burner	A-8
A-3.	Gas flow corrections	A-9
A-4.	Run outline	A-16
A-5.	Pre-run checklist A	A-18
A-6.	Pre-run checklist B	A-19
A-7.	Material balance sheet	A-20
B-1.	Summary of early burner experiments	B-2
B-2.	Comparison of perforated conical distributors of varied cone angle	B-17
D-1.	Experimental results - Modules 1, 2, 3, and 4	D-2
D-2.	Experimental results - Modules 5 and 6	D-3
D-3.	Averaged experimental results - Modules 5 and 6	D-4
D-4.	Comparison of above-bed recycle alternatives	D-5

1. INTRODUCTION

The High-Temperature Gas-Cooled Reactor (HTGR) developed at General Atomic Company (GA) is a thermal reactor concept which provides high efficiency in electricity generation, improvements in reactor safety characteristics, and the implementation of an additional energy source by the use of thorium. The HTGR uses helium as the coolant and graphite as the moderator and core structural material. The present fuel cycle employs uranium highly enriched (93%) in U-235 for the initial and makeup fissile material, thorium as the fertile material, and U-233 as the bred material which is recovered for recycle to the reactor. Alternative fuel cycles which offer proliferation resistance are being evaluated.

The technology required for the recycle of the bred U-233 in the HTGR fuel includes reprocessing steps to extract the valuable fissile materials in the spent fuel from the fission product wastes and refabrication to manufacture fuel elements containing the extracted U-233. A program funded by the Department of Energy (DOE), the HTGR Fuel Recycle Development Program, is presently being undertaken by various contractors to develop this technology. The development of technology for reprocessing HTGR fuel is being undertaken primarily at GA.

The basic reprocessing flowsheet is described and discussed in this report. A detailed description is then given of the development and status of the 0.20-m (8-in.) diameter primary fluidized bed burner, a key unit operation which disposes of the bulk of the graphite moderator. Early equipment development in which process feasibility and design criteria were determined is discussed. Major emphasis is given to the most recent activity performed since January 1976. The experimental program during this period was divided into seven groups or "modules," each of which had independent and well-defined objectives. Tests conducted within each module were

devised based on a statistical design of experiments utilizing a fractional factorial analysis technique. Finally, the process automatic control philosophy was developed and tested using a digital process controller.

2. HTGR FUEL AND REPROCESSING FLOWSHEET

2.1. HTGR FUEL

The basic fuel element in the large HTGR is a graphite block 0.793 m (31.4 in.) high with a hexagonal cross section 0.359 m (14.2 in.) across the flats, as illustrated in Fig. 1. The graphite block is drilled lengthwise with three sets of holes: one to allow the passage of helium coolant, the second to contain fuel rods, and the third for burnable poison rods. Fuel rods are formed by the molding of selected blends of fuel particles with a graphite pitch. Each fuel rod is 63.5 mm (2.5 in.) long and has a diameter of 15.8 mm (0.625 in.). The present fuel particles used in the HTGR fuel are schematically shown in Fig. 2. These fuel particles contain either UC_2 (highly enriched in U-235 or recycle U-233) or ThO_2 . The particles shown in Fig. 2 typically have diameters of 500 to 800 μm .

The two particle types used in HTGR fuel are categorized by their coatings (BISO and TRISO coated particles). As shown in Fig. 2, BISO particles are coated with a relatively porous buffer layer of carbon and then with a dense coating of pyrolytic carbon. TRISO coatings, in addition, have a silicon carbide coating placed between two layers of pyrolytic carbon. The silicon carbide layer provides a means of separating these particles from the BISO particles in head-end reprocessing operations and also enhances metallic fission product retention in the fissile particles. BISO coatings are used for particles initially loaded only with ThO_2 , while TRISO coatings are used for particles loaded with uranium carbide.

2.2. HTGR FUEL REPROCESSING FLOWSHEET

A block flow diagram of a flowsheet under development for reprocessing of HTGR fuel as part of the HTGR Fuel Recycle Development Program is shown in Fig. 3. Separation of fission products from fissile materials is

Fig. 1. HTGR fuel element

	FISSILE PARTICLE RECYCLE PARTICLE	(TYPE 1) (TYPE 4)	FERTILE PARTICLE (TYPE 2)	RECYCLE PARTICLE (TYPE 3)
COMPOSITION	$^{235}\text{UC}_2$		ThO_2	UC_2
KERNEL DIAMETER, μm	315		500	356
COATING THICKNESS, μm				
BUFFER	45		85	45
INNER DENSE COATING	25		-	25
SILICON CARBIDE	25		-	25
OUTER DENSE COATING	35		75	35
TOTAL PARTICLE DIAMETER, μm	575		820	616

Fig. 2. Diagrammatic representation of fissile, fertile, and recycle particles for 1150-MW(e) HTGRs

Fig. 3. Reprocessing flow diagram

eventually achieved by solvent extraction from a solution of these materials which is formed by dissolution in nitric acid. Effective dissolution cannot be performed if significant amounts of graphite are present. The reference method of removing this graphite is by combustion, which is most readily achieved in fluidized-bed burners. Experimental tests have shown that a nominal maximum feed size of 4.8 mm (3/16 in.) is required for successful operation in the fluidized-bed burners. The spent HTGR fuel elements received at a reprocessing facility must therefore be reduced to this size before removal of the graphite by combustion.

The initial, or head-end, steps of the HTGR fuel reprocessing flowsheet include fuel element size reduction (by crushing), burning to eliminate the graphite moderator, classification of particle types with additional crushing or grinding as required, and dissolution in nitric acid. The treatment of various fuel types can be traced in Fig. 3. The designs of the various unit operations in the reprocessing flowsheet are based upon the anticipated requirements of a commercial-scale recycle facility. Common requirements for such systems will be:

1. Throughput and capacity.
2. Reliability for operation in a hot cell.
3. Adaptability to remote decontamination and maintenance.
4. Adaptability to automatic operation with control from a remote location.
5. Capability for cleanout to allow material accountability with minimum material holdup.

The purpose of the fluidized-bed burners is to remove the graphite moderator and fuel coatings via oxidation and to oxidize carbide-type fuel kernels in preparation for dissolution. Two types of fluidized-bed burners

are utilized in the head-end reprocessing steps: the crushed fuel element (primary) and the crushed particle (secondary) burners. These burners differ in operating mode and configuration but have similar design requirements.

Design of the primary fluidized-bed burner is based upon process feasibility considerations and anticipated requirements of a demonstration recycle facility (HRDF). The following specific requirements for the demonstration primary burner system have been identified:

1. The crushed fuel element burner must be capable of burning the equivalent of one full-size HTGR fuel element/hour to less than 1% burnable carbon in the product stream.
2. The crushed fuel element burner should minimize TRISO particle breakage.
3. The system configuration of the primary burner should include a means for elutriated fines to be carried out of the burner in the off-gas stream for subsequent recycle.

As of July 1, 1977, experiments have been performed in the 0.1-, 0.2-, and 0.4-m-diameter primary burners and have indicated that the design requirements of the primary burner can be met. These experiments have confirmed the following:

1. System cleanout capabilities.
2. Semi-automatic control of burner temperature and product removal.
3. Acceptably low TRISO particle breakage.
4. Acceptably low carbon content in the product.
5. Conical distribution plate operability.

6. Induction heating capability.
7. Long-term operation at $875^{\circ} \pm 25^{\circ}\text{C}$.
8. Long-term external fines recycle.
9. Product carbon concentrations of less than 1% with TRISO/BISO fuel.

3. PROCESS DESCRIPTION

The primary crushed fuel element burner receives a feed stream of intact fuel particles and crushed graphite produced by a three-stage crushing system. Average properties of the burner feed, nominally -5000 μm , are shown in Table 1. The primary burner must ignite and burn the fuel element graphite, the fuel rod graphite, and the fuel particle pyrolytic carbon at 900°C, producing a product of discreetly separable silicon carbide coated fissile particles and fertile fuel kernel particles containing less than 1 wt % exposed burnable carbon (Table 2). Adequate fluidization of the largest burning graphite and the large, dense fuel particles requires superficial velocities of 1.01 to 1.37 m/s and a carefully designed gas distribution device. Graphite fines (-425 μm), generated both in the crushing process and in the 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.

The primary burner operates in semicontinuous batch cycles. Operating guidelines are summarized in Table 3 and described in more detail in Appendix A. 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 partial bed retained 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 an induction heating 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 to one rich in burned-back fuel particles. Bed bulk density and, hence, bed weight vary by a factor of >5.

TABLE 1
AVERAGE PROPERTIES OF PRIMARY BURNER FEED AND STARTUP BED^(a)

Tap density	1.25 Mg/m ³	
Bulk density	1.08 Mg/m 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

(a) Ref. 1, p. 3.

TABLE 2
AVERAGE PROPERTIES OF PRIMARY BURNER FUEL PARTICLE PRODUCT

Bulk density	2 - 6 Mg/m ³
Size	200 - 870 μm
Exposed burnable carbon	<1%

TABLE 3
OPERATING GUIDES FOR PRIMARY FLUIDIZED BED BURNER

Operating mode	Semicontinuous batch
Startup	Induction heater
Gas distributor	Perforated cone
Feed system	Gravity/rotary valve
Product removal	Gravity/pneumatic
Feed/product control	Metered feed/batched product
Heat removal	Air cooling with annular shroud
Fines recycle	External recycle by gravity to burner from external cyclone/filter system
Temperature	$900^{\circ} \pm 50^{\circ}\text{C}$
Pressure	<200 kPa (15 psig) at all vessel locations
Materials	
Vessel	Hastelloy X
Auxiliaries	304L SS

The major design problems have included: the requirement for a specialized gas distributor and operating techniques to safely burn the large particles and remove the product; combustion of the excessive mass of fine particles elutriated from the bed; and development of a safe, reliable means of operation using automatic controllers.

4. EQUIPMENT DEVELOPMENT

The optimum equipment configuration of the 0.20-m-diameter primary burner, as determined from a development effort spanning several years, is shown schematically in Fig. 4. The development history of the various major equipment components is discussed in the following sections.

4.1. FEED SYSTEM

The primary burner requires a reliable feed system capable of yielding consistent throughput with minimal fuel particle breakage. Several different types of feeders have been tested and evaluated. These include augers, pneumatic valves, and rotary valves.

Augers have generally been successful in conveying feed to the primary burner. However, there are several areas of concern which make the use of an auger system less desirable than other available feed systems. Auger systems have generally exhibited relatively high mechanical wear and fuel particle breakage. In addition, successful operation depends to a large extent on hopper design and flow characteristics, alignment, and pickup efficiency. Inadequacies in the design can lead to significant problems, which could cause complete stoppage of material flow. Examples of such problems include poor material discharge from hoppers due to rat-holing and poor auger alignment. In the latter case, binding of material may result, which could cause significant damage to the auger shaft. While augers have not proven to be the most reliable feed system available, a low-capacity auger feed system has been successfully utilized as a backup feeder for the 0.20-m-diameter primary burner.

A gravity-pneumatic feeder was also developed for testing on the 0.20-m-diameter primary burner. The gravity-pneumatic feeder, shown schematically in Fig. 5, consisted of a feed hopper which discharged into a

Fig. 4. 0.20-m-diameter primary burner configuration

Fig. 5. Gravity-pneumatic feeder

double-elbow section of piping by pneumatic assist. When N_2 flow was initiated (pulse flow), material between the elbows was swept into the burner. The distance between the elbows was set far enough to eliminate the possibility of feed material spilling unassisted into the burner. Since this system had no mechanically moving parts, it was originally considered to be an attractive alternative to the other more complex systems tested. However, testing of the feeder with primary burner feed resulted in frequent bridging of material. Since the feed mass flow rate was somewhat dependent on the diameter of the feeder piping, the pipe diameter had to be kept small to prevent excessive feed flow to the burner. Use of this type of feeder would be considerably more attractive on a larger scale burner where a higher required feed rate would permit utilization of larger feeder piping. Larger feeder piping would minimize or eliminate the feed bridging problems experienced in 0.20-m-diameter primary burner operation.

The final feeder design tested, and the recommended design for the 0.20-m-diameter primary burner feed system, consists of a rotary valve feeder and hopper located above the burner to facilitate gravity flow. This system serves as a metering device for regulation of the feed rate to the burner. Compared with pneumatic and auger feed systems, rotary valves have proven to be much more reliable. Potential mechanical problems are minimal and particle breakage is negligible. In addition, a supplemental knife-gate valve is included in the feed system piping to provide a positive air lock when required. The rotary valve feed system is shown schematically in Fig. 6. The feed hopper includes a 90° aerated outlet to ensure adequate material flow characteristics out of the hopper.

4.2. BURNER VESSEL

The 0.20-m-diameter primary burner vessel (Fig. 7) consists of a 3.048-m length of 0.203-m-I.D. Hastelloy X tubing (Ref. 2). The extreme lower portion of the vessel is tapered from 0.152 m I.D. at the bottom to 0.203 m I.D. at an angle of 10° with vertical. The lower 0.922 m of the 0.203-m-I.D. section of the vessel contains 5400 13.0-mm-long, 5.0-mm-diameter pin fins welded in 108 circumferential rows for increased heat

Fig. 6. Fresh feed system

Fig. 7. 0.20-m-diameter primary burner vessel

transfer capability. Two 50.0-mm penetrations are located higher up on the vessel and are utilized as inlets for the feed and fines recycle streams. The vessel was designed and fabricated to meet the intent of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, which requires the use of Hastelloy X for those portions of the vessel where the metal temperature exceeds 650°C. Hastelloy X is a corrosion-resistant, high-temperature alloy with the properties listed in Table 4 (Ref. 3, p. 6-2).

4.3. GAS DISTRIBUTION

The gas distributor design (Fig. 8) (Ref. 1, pp. 6 to 9; Ref. 3, pp. 6-4 to 6-15) was a product of development experience with flat perforated plates and single gas inlet cones. It consists of a perforated cone and vertex line. The cone orifice size and angle were experimentally optimized to yield even gas distribution through all perforations, limit plenum drainage, maximize solids mixing at the plate surface, and minimize plate surface temperature. The vertex line was sized for levitation of bed material during normal operation and for free flowing product discharge. Design calculations for perforated cones have developed from scale-up information.

The general distributor functions considered in design were: to support the bed and prevent excessive solid material from flowing down into the plenum chamber; to distribute the gas uniformly over the bed cross section by designing sufficient pressure drop across the plate while maintaining a maximum pressure drop to limit the back pressure on the gas supply system; and to promote rapid particle movement throughout the bed and at the plate and minimize solids stagnation on the plate. Design problems specific to the primary burner included the cyclic burner operation expected (multiple startups and shutdowns). This required a distributor which functioned well over extreme ranges of gas flow and bed height. Avoiding stagnation areas of the burning solids and resultant hot spots in such varied operation was further complicated by the wide range of particle sizes and densities in the mixed heavy metal - carbon beds. The

TABLE 4
PROPERTIES OF HASTELLOY X

Melting temperature range	1260° - 1355°C
Oxidation penetration in dry air at 900°C for 100 h	6.35 μm (0.25 mils)
Typical ultimate tensile strength of sheet at 900°C	2.07 x 10 ⁵ kPa (30,000 psi)
Typical yield strength of sheet at 900°C	1.52 x 10 ⁵ kPa (22,000 psi)
Average stress to cause 0.0001%/h secondary-type creep at 900°C	1.17 x 10 ⁴ kPa (1,700 psi)
Thermal coefficient of expansion	16.3 x 10 ⁻⁶ mm/mm-°C

Fig. 8. 0.20-m-diameter primary burner gas distribution

distributor design also had to be within the constraints of burner configuration dictated by the mechanics of remote maintenance, minimization of high material stress and wear areas, and safety.

Conventional flat perforated plates were tested on the primary burner. Although relatively simple in their design and fabrication, a disadvantage of flat distribution devices was that solids stagnation zones were liable to form between the distributor holes and at the wall-plate juncture. The bed stagnation and resultant fusion of bed solids into defluidized clinkers, or agglomerates, caused gas maldistribution and hot spots in primary burning (Ref. 4). These problems with flat distributor plates were a result of the horizontal geometry of the device and the resultant potential for stagnation of solids.

The subsequent distributor designs tested departed from the flat configuration to circumvent the distributor stagnation failures. These designs utilized sloping surfaces to avoid stagnation of burning solids. A 50° included angle cone with a single vertex inlet gas opening was tested initially. The device worked adequately with feed containing material ($\leq 4760 \mu\text{m}$). However, when a nominal crusher product containing ~5 wt % $>4760 \mu\text{m}$ was fed, intermittent spiked fluctuations of the bed pressure drop (ΔP) occurred. These fluctuations were more than twice the magnitude of the recorded slugging bed ΔP and occurred on ~1-min cycles. The bed ΔP cycles were followed by excursions in bed temperature and off-gas compositions and resulted in formation of agglomerated fuel particles which adhered to portions of the sloping wall of the cone. It was concluded that these operating problems were due to cyclic internal gas spouting caused by the intermittent accumulation of the largest feed material in the cone distributor (Ref. 5). The bed material was apparently in continual transition between spoutable and unspoutable conditions, as described by Mathur (Ref. 6) and Geldart (Ref. 7). This spouting condition could not be allowed in the combustion process due to the local stagnation of burning solids at the cone surface radial to the internal spout.

The merits of the flat perforated plate and the single gas inlet cone were then combined to overcome the problems inherent to the separate devices. The resultant device was a perforated cone with a gas inlet through the cone vertex opening. The vertex gas inlet opening was sized to levitate the largest bed material with ~25 vol % of the total inlet gas flow. The remaining 75 vol % of the total gas flow was allotted to flow to the plenum chamber and through the cone perforations. The device worked well with the largest nominal feed (Ref. 8).

An experimental program was then undertaken to determine the optimum included angle for the cone. Included angle cones of 50°, 90°, and 120° were used in combustion runs at similar conditions. The 90° cone was selected, as the steeper 50° cone surface temperature ran 100° to 150°C hotter than the 90° and 120° cones, and the shallower 120° cone produced solids agglomerates which fused to the cone surface around the periphery of several orifices (Ref. 9).

A 90° perforated cone has proven effective in hundreds of hours of combustion operation on the 0.2-m-diameter burner, including many startups and shutdowns. A scaled-up version has been operated on a 0.40-m-diameter primary burner and has also given good performance.

4.4. PRODUCT REMOVAL

The recommended design of the primary burner product removal system consists of an actuated knife-gate valve located below the perforated conical distributor. Product removal is thus controlled by varying the distributor vertex gas flow rate and the length of time the knife-gate valve is open. A 13.0-mm-I.D. conical distributor vertex allows dumping of high particle concentration beds at up to 0.33 kg/s, but bridges with feed size material. A 26.0-mm-I.D. vertex allows dumping of -5000 μ m feed size material at about 0.17 kg/s with no plugging. Since a burner operating in a production facility must have the capability to dump a charge of fresh feed in case of equipment failure, the 26.0-mm-I.D. vertex was

used in the scale-up design of a 0.40-m-diameter primary burner. However, due to gas flow rate and particle terminal velocity considerations, the 0.20-m-diameter primary burner distributor vertex must be restricted to 13.0-mm-I.D.

Other product removal systems tested included both ball valve and rotary valve designs. Ball valves were unsatisfactory since operation at elevated temperatures and the weight of the particle bed above the valve frequently caused jamming of the valve. Rotary valves were found to be inadequate due to bridging problems, limited and inconsistent throughput, and excessive particle breakage.

4.5. HEATING AND COOLING

4.5.1. Heating System Alternatives

The 0.20-m-diameter primary burner requires a heating system to accomplish the following functions:

1. Ignition of fresh feed material for startup.
2. Re-ignition of the bed materials after bed cooling (or quenching) due to process upsets.
3. Supply of heat to maintain the bed temperature during bed carbon burnout.
4. Evaporation of fission products from the bed materials after bed carbon burnout.

The burner heating methods evaluated can be categorized as follows:

1. Internal heating by:
 - a. Internal CO torch, ignition of coke.

- b. Internal CO torch, direct heating of feed.
 - c. High-temperature fluidizing gas.
2. External heating by:
- a. External flame torch.
 - b. Resistance electric heating.
 - c. Induction heating.

The various heating methods are compared in Table 5 (Ref. 3, p. 6-37) and discussed below:

1. Internal CO Torch to Ignite a Coke Bed. A CO-O₂ torch can be used to ignite a small coke bed, followed by the feeding of -5000 μ m fresh feed to build up an initial bed. This method was used throughout much of the early experimental work with the 0.20-m-diameter primary burner. However, the CO-O₂ torch does not meet the heating system functional requirements listed above except for (1) ignition of feed material for startup. In addition, occasional agglomerate formation has occurred and been attributed to high local temperatures caused by the torch flame. This technique also required additional feed preparation and material transport operations.
2. Internal CO Torch (Direct Heating). Direct heating with an internal CO torch was proposed as a heating method. This technique must be used with high inert fluidizing gas flows in order to promote mixing of the large, cold, fresh feed during startup. Proper fluidization is necessary to eliminate any potential hot spots or particle agglomeration caused by static burning of large graphite.
3. High-Temperature Fluidizing Gas. Compared with other methods in which the heat flux is dependent on the relative surface area per unit bed volume, this method has a distinct advantage

TABLE 5
COMPARISON OF VARIOUS HEATING METHODS

	Startup	Restart	Bed Burnout	Fuel Particle Soaking
Internal heating				
CO torch to ignite coke bed	Fairly fast, agglomeration	Not practical	Not practical	Not practical
CO torch (direct heating)	Relatively fast, agglomeration, difficult to control fluidization	Same as startup	Same as startup	Same as startup
Hot-gas fluidization	Slow, easy to control, has many advantages with a large burner	Same as startup	Difficult to balance fluidizing gas and combustion gas, difficult to control	Same as startup
External heating				
Wide flame torch	Moderately fast, temperature control difficult	Same as startup	Same as startup	Same as startup
Resistance heater	Very slow, needs frequent maintenance	Same as startup	Not suitable due to slow response	Same as startup
Induction heating	Moderately fast, easy to control both temperature and fluidization	Same as startup	Same as startup	Same as startup

in scale-up due to the invariance of the heat flux per unit volume with an increase in the burner diameter. One drawback is the difficulty in controlling the fluidization during bed burnout, although this problem is not insurmountable. A separate combustion chamber for the generation of high-temperature gas is also required. A preliminary evaluation of this method indicates the necessity for further study to determine the operational and economic feasibility.

4. External Flame Torch. The performance characteristics of an external flame torch are similar to those for induction heating. However, the temperature control is more difficult, especially at high temperatures. The change of heating pattern with geometry makes scale-up very difficult. Due to these disadvantages and lack of experience and development, further study of this method was not undertaken.
5. Resistance Heating. Although this method was used for some time in a small crushed particle burner, a number of undesirable aspects were evident, such as a slow response, lack of cooling surface area, and a high maintenance frequency. Therefore, this system was not recommended.
6. Induction Heating. Induction heating was demonstrated on the 0.10-m-diameter crushed particle burner with proven reliability and ease of control. This method was chosen as the heating method for the 0.20-m-diameter primary burner.

4.5.2. Induction Heating System

The induction heating system consists of a solenoid induction coil wound around a metallic susceptor 3.0 mm thick (RA-333 tube), with a solid ceramic insulation between the two components (Fig. 9) and a power supply system. The burner vessel is heated by the radiated heat from the susceptor. An annular gap for cooling air separates the vessel wall from the

Fig. 9. Induction heater coil and susceptor

susceptor so that heat transfer during startup to the vessel wall and subsequently the bed material will be by radiation across the annular gap. To prevent susceping on the end support plate of the cooling shroud, magnetic field cutting coils are used at both ends of the active coil. Water circulating in the coil must maintain a coil temperature around 54°C. The induction coil is held in place with equally spaced transite rib supports. The power to the induction coil is provided by a 250-kW motor-generator set at 1 kHz (Fig. 10). Table 6 shows the 0.20-m-diameter primary burner induction heating coil design parameters.

In addition to having a much higher electrical efficiency, a susceptor acts as a secondary containment for the bed materials in the event of a vessel wall burn-through. Susceptor heating provides more uniform heating of the vessel even with a miscentering of the vessel around the coil and also reduces any thermal shock during a rapid heatup which could result in tube material fatigue.

Because of thermal limitations, the susceptor (RA-333) must not exceed 1100°C. The Hastelloy X burner vessel is maintained at temperatures below 900°C to meet the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII. These two constraints set the maximum operating range for the induction heating system. Figure 11 shows a startup temperature transient which represents the performance of the induction system (Table 7). The control system will automatically heat the susceptor to 1100°C and maintain this temperature until the vessel wall reaches 900°C. From this point on, the susceptor temperature will be gradually decreased to maintain the vessel wall at 900°C. When the bed temperature reaches ~800°C, the induction heater can be turned off. The heater will come on again at the tail-burn period when additional heat is required to maintain the bed temperature at ~800°C.

4.5.3. Cooling System

The heat of combustion in the 0.20-m-diameter primary burner is removed either by the burner off-gas or through the vessel wall by forced

Fig. 10. Induction heater power supply system

TABLE 6
0.20-m-DIAMETER PRIMARY BURNER INDUCTION HEATING COIL DESIGN PARAMETERS

Number of turns	27
Coil size	15.88-mm O.D., 1.65-mm wall
Coil spacing	9.53 mm, even distribution
Coil terminal voltage at full power (250 kW) (a)	700 volts
Support legs	4 each, 50.8-mm by 50.8-mm transite
Capacitors (300 KVAR each)	3
Coil supply	Lead will be held in position by insulating clamps to the coil
Cutting coil	Top/bottom turns
Coil water flow	$\sim 0.68 \text{ m}^3/\text{h}$

(a) Field voltage limiter to provide lower kW.

Fig. 11. Startup transient, 0.20-m-diameter primary burner

TABLE 7
0.20-m-DIAMETER PRIMARY BURNER STARTUP REQUIREMENTS^(a)

Power to coil	100 kW (~80% efficiency)
Coil length (susceptor heated zone)	0.76 m
Bed weight	23 kg
Estimated bed height	~0.92 m from flange
Time required to reach 800°C bed temperature	~0.67 h ^(b)

(b) Axial conduction losses are estimate only and will affect total heatup time.

air cooling shrouds surrounding the burner. The cooling system is sized for a maximum burn rate of 3.33 g C/s (or an equivalent 26 kcal/s). Two cooling shrouds are included. The upper cooling shroud is intended to keep the vessel wall below 900°C but is not expected to have substantial cooling duty. The annular gap for passage of cooling air is 9.5 mm.

The lower cooling shroud, or susceptor, also maintains a 19.0-mm gap from the vessel wall. To accomplish significant heat transfer in this section of the burner (0.914 m), pin fins were added to the vessel wall. A total of 5400 5.0-mm-O.D. by 13.0-mm pins are circumferentially arranged over the 0.914-m section of burner vessel as shown in Fig. 12. The pin layers are staggered to break up boundary layer buildup in an effort to maximize heat transfer. A Buffalo Forge air blower ($1.32 \text{ m}^3/\text{s}$ at 14.9 kPa) is used to supply cooling air to the burner cooling system. A summary of the design parameters for the lower cooling shroud is presented in Table 8.

4.6. OFF-GAS FILTER SYSTEM

The fines recycle loop of the 0.20-m-diameter primary burner consists of the equipment necessary to remove elutriated fines from the process off-gas and to transport them back into the combustion zone of the burner. Elutriated fines are removed from the off-gas by means of a cyclone separator and a pulsed, sintered metal blowback filter system. Approximately 95 to 98 wt % of the elutriated material is removed in the cyclone, with the remaining material proceeding on to the filter system. The filters are cylindrical, sintered stainless steel 70-mm O.D. by 3.2-mm wall by 0.914 m long with a largest pore size of 12 μm and a mean pore size of 5 μm . The filters are capable of removing 100% of 1- μm particles and larger and 98% of 0.4- μm particles and larger.

Blowback of each filter is achieved by the use of a 3.2-mm-diameter orifice located 25.4 mm above a venturi (Fig. 13) (Ref. 10). The blowback gas pulse causes a reverse pumping action as it passes through the venturi, drawing filtered off-gas back through the filters. This increases the effectiveness of the blowback while keeping the volume of gas added to the

Fig. 12. Fin pattern for 0.20-m-diameter primary burner

TABLE 8
LOWER COOLING JACKET DESIGN SUMMARY

Physical dimensions

5.0-mm O.D. by 13.0-mm pin (5400)

Burner heat transfer section = 0.914 m

Vessel wall thickness = 6.4 mm

Heat balance

Burn rate = 26.0 kcal/s (or 3.33 g C/s)

Heat removal rate by air = 22.4 kcal/s

Off-gas loss = 3.6 kcal/s

Heat loss by fines elutriation - not included

Cooling flow parameters

Air flow = 0.258 std.m³/s

Air inlet temperature = 50°C

Air exit temperature = 347°C

Pressure drop

ΔP across shroud = 7.46 kPa

ΔP bends and elbows = 2.49 kPa

ΔP across butterfly valve = 1.12 kPa

Total ΔP = 11.07 kPa

Fig. 13. Filter venturi

system at a minimum. Two different filter system designs were utilized during the course of this work; the two designs are described in more detail in the following section dealing with fines recycle.

4.7. FINES RECYCLE

The elutriated fines removed from the burner off-gas by the cyclone and filter system are subsequently mixed into one stream prior to recycle back to the burner. Disposal of the large mass of fines (~30 wt % of the carbon fed) has been accomplished by returning the fines to the burner for combustion in multiple recycle passes. Various methods for transporting this material have been investigated. Certain physical limitations which make the process somewhat difficult are:

1. The solids/gas ratio in the recycle stream must be large because of fines burning phenomena in the bed and process gas flow rate limitations.
2. The fines must be transported against significant back pressure.
3. Adequate fines hopper flow must be maintained at all times.
4. Equipment and materials must be able to withstand considerable temperature erosion effects.
5. The temperature of the recycled fines must be maintained high in order to minimize the time required for heating them to their ignition temperature once in the burner.

Several dilute-phase methods of pneumatic transport of fines were investigated and found to be unsatisfactory due to the excessive amount of transport gas required for the process. Systems utilizing gas eductors demonstrated poor performance in transport against back pressure. Augers were also investigated, but their capacities were generally limited and insufficient to accommodate typical fines elutriation rates. In addition,

the long residence time in such systems allowed the recycle stream to cool substantially. In order to operate within the physical limitations previously mentioned, the majority of the experimental work was performed utilizing three different fines transport systems:

1. Dual-parallel pressurized hopper dense-phase system.
2. Tri-series pressurized hopper dense-phase system.
3. Single gravity hopper-rotary air-lock system.

With dense-phase transport of fines, only a minimal amount of transport gas is required to transport large mass flow rates of fines. Burner back pressure is easily overcome by pressurizing the fines hopper in excess of this back pressure. The three fines recycle systems tested are shown in Fig. 14. The two multihopper systems utilized a relatively large cyclone and filter vessel with sixteen pulsed blowback filters and venturis. The single-hopper gravity system utilized a smaller cyclone and filter vessel with four pulsed blowback filters and venturis. A parametric study was performed to evaluate the effects of each recycle system on the overall process. Results are presented in later sections.

Fig. 14. Three fines recycle systems tested

5. OPERATING CYCLE

The 0.20-m-diameter primary burner operating mode is a semicontinuous batch (intermittent product discharge and burner restart) operation throughout a campaign. Between batch discharge cycles, the burner has a maximum burn rate of 3.33 g C/s. Table 9 describes operation during the initial startup batch (the first 24 hours of the operating cycle), which represents the worst design conditions experienced in a 6 to 12 day burner campaign. Subsequent inner campaign batches will start up with a small bed of fuel particles and, therefore, will require less energy for fresh feed ignition.

At steady state and at a feed rate of 14.5 kg/h, the maximum bed mass experienced is 67 kg, of which 45 kg is fuel particles. Tail burnout of carbon content with the aid of induction heating will leave a bed mass of 46 kg, which can be partially or wholly dumped from the burner. In the case of partial bed dump, the remaining fuel particles in the bed will serve to start up the next batch in an already partially heated condition, shortening reignition time.

5.1. STARTUP

Startup of the 0.20-m-diameter primary burner is by induction heating with ignition occurring within 1 h. The induction coil design must provide an adequate heat source to ignite a fresh feed bed (which represents the worst startup condition) and also must be able to maintain $\sim 800^{\circ}\text{C}$ during the tail-burn phase of the operating cycle. For proper heat transfer, the bed height must slightly exceed the coil height in both startup and tail-burn situations. However, if the bed level far exceeds the coil height (i.e., the heated zone), excessive heat loss might occur from the

TABLE 9
0.20-m-DIAMETER PRIMARY BURNER OPERATING CYCLE (SEMI-BATCH)

	Time (h)	Fuel Element	Feed		Bed Weight at Time = τ h (kg)	Burn Rate (g C/s)	O ₂ (%)
			kg	kg/h			
Startup	0	0.175	20 to 32 ^(a)	0	20 to 32 ^(a)	0	0
Ignition	≤ 2	0.175	20 to 32 ^(a)	0	20 to 32 ^(a)	~1.98	68
	3.4	0.35	40.3	14.5	27.9	~2.95	77
	4.3	0.46	53.4	14.5	30.7	3.33	79
	18.8	2.27	263.6	14.5	67 ^(b)	3.33	79
	20.2	--	--	--	50.7	3.15	79
	20.5	--	--	--	47.6	2.52	75
	23	--	--	--	46	0	0
Dump	24	--	--	--	--	--	--

(a) Due to uncertainty in fluid bed weight, startup bed may vary from 20 to 32 kg fresh feed.

(b) During batch cycle the maximum bed weight would be 67 kg, of which 45 kg is fuel particles.

bed to the upper portion of the burner vessel (Fig. 15). Moreover, the heat input/bed mass ratio will decrease further, slowing the startup transient.

Due to bed height uncertainty during startup, the initial startup bed weight may vary from 20 to 32 kg. Figure 11 is a transient plot of a 32-kg bed startup and indicates that the bed temperature will reach 800°C in ~40 min. The actual transient may vary somewhat depending on the degree of slugging and how well the burner is insulated.

5.2. TAIL-BURN

The burnout phase at the tail end of the batch cycle is designed to burn out carbon content in the bed. The 46-kg particle bed is adequate to provide heat transfer surfaces for the coil. The maximum temperature that the bed can maintain depends on the bed-to-wall heat transfer coefficient and the heat losses throughout the burner system.

The conditions and heat balance expected in order to maintain a bed at ~800°C are presented in Table 8.

Fig. 15. Effect of bed height on startup transient

6. EXPERIMENTAL RESULTS

6.1. EARLY WORK

The initial experimental work with the 0.20-m-diameter Hastelloy X primary burner consisted of a series of 40 runs in which the primary objectives were equipment component development and provision of scale-up data for a 0.40-m-diameter prototype primary burner. The first six runs were of short duration and were utilized for system shakedown. The results of Runs 7 through 40 are summarized in Appendix B.

Emphasis in Runs 7 through 11 was placed upon improving burner operability by investigating reasons for bed temperature instability and oscillations, characterizing dilute-phase pneumatic fines recycle along with burner response to in-bed fines recycle using an ejector, investigating fines elutriation, and investigating bed carbon burnout capability. Prior to Run 12, a "ball-and-cone" distributor previously used was revised to a perforated cone geometry. Runs 12 through 16 were performed to determine an acceptable startup technique for operation with the perforated conical distributor and to evaluate general performance. Runs 17 through 21 studied the effects of distributor cone angle variation and resulted in the choice of a 90° cone as the optimum angle. A comparison of work with distributors having different cone angles is presented in Appendix B.

Runs 22 through 28 were performed using the dual-hopper dense-phase pressurized fines recycle system. The primary objective of these runs was to investigate fines burning capabilities during recycle to the bottom of both high and low carbon beds. Five shakedown runs were needed in order to achieve reasonable operation of the recycle system. During this work it was found that fines mass flow was very dependent on both hopper outlet line size and hopper pressurizing gas flow rates. Thus, recycle lines

to the burner were sized at 0.0125-m I.D. In addition, it was found that large graphite and/or fuel particles which elutriate and reach the fines hoppers are likely to seriously hamper or block fines flow. As a result, the burner vessel was lengthened from 2.79 m to 3.68 m to provide additional de-entrainment space.

Runs 25 through 28 investigated operation with recycle to both high and low carbon beds. Results showed that fines burning in a high carbon bed without addition of above-bed O_2 is insignificant in that fines generation and accumulation are exceedingly high (~30% to 40% of fresh feed weight). Operation under these conditions is possible provided sufficient fines storage capacity is available. Appreciable fines burning will occur only later in the burner operating cycle after bed carbon decreases significantly. When bed carbon content approaches zero, above bed fines burning will occur as long as fines recycle flow is maintained. Such operation is difficult to control as temperature transients are very rapid. Operation in low carbon beds, however, results in appreciable fines burning during most of the operating cycle. In addition, fines generation is significantly reduced so that fines residence time in the recycle hoppers is short enough to minimize heat loss before reentry to the burner.

Runs 29 through 34 were performed in the 0.20-m-diameter primary burner using fines recycle to the vertex of the 90° perforated conical distributor. The primary objectives of these runs were to investigate:

1. Distributor performance.
2. Effects of vertex fines injection.
3. Fines transport with an improved automatic control system.
4. Effects of a mid-reactor oxygen inlet on fines burning.

Runs 35 through 40 were performed using recycle to various points in the bed. The primary objectives of these runs were to investigate:

1. Ability to burn fines when injected above the static bed (into the slugging zone).
2. Characteristics of fines transport and operation of the fines recycle system with above-bed fines injection.
3. Effects of long-term operation (24 h) on burner components and on the overall process.
4. Differences in effects of long-term operation between vertex and above-bed fines injection.

Operation in Runs 29 through 40 was with low bed carbon content.

The fines recycle system was found to operate exceptionally well in that no significant line plugging or hopper overpressurization was experienced in any of these runs. Final fines hopper inventories at the end of runs with above-bed fines recycle were generally smaller than for operation with vertex fines injection and contained essentially no noncombustible material. Fines burning efficiency with above-bed fines injection was found to be at least as good as that with vertex injection. The use of a mid-reactor oxygen inlet provided a uniform and easily controlled CO/fines combustion zone above the bed. In general, there were no adverse effects due to long-term operation (Runs 38 through 40), with the exception of more small fuel particle agglomeration formation and fresh feed hopper flow inconsistencies.

Following Run 40, the 0.20-m-diameter primary burner was modified to more closely correspond to a half-scale version of a 0.40-m-diameter prototype primary burner. Details of design changes and modifications have been discussed in previous sections of this report. Experimental results of subsequent test work are discussed in the following sections.

6.2. STATISTICAL ANALYSIS EXPERIMENTS

A series of experiments was made on the 0.20-m-diameter primary burner without fines recycle and then with fines recycle using the various recycle systems previously discussed. These tests were devised and analyzed based on a statistical format utilizing a "fractional factorial" analysis technique as described by Hunter (Ref. 11). The series of runs was used to quantify the weighted effects of basic independent process variables such as superficial velocity, particle size, etc., upon burner heatup times, fines elutriation, particle breakage and agglomeration, burner axial and radial temperature profiles, and off-gas compositions. The experimental program was divided into seven groups, or "modules," each of which had independent and well-defined characteristics and objectives as given in Table 10. Module descriptions are presented in more detail in Appendix C.

6.2.1. Modules 1 Through 4

The results of experiments performed during Modules 1 through 4 were correlated using statistical design techniques and are presented in Table 11 in terms of the controlled independent process variable operating levels recommended to reduce the values of the dependent variables. The high (h,h) and low (L,l) terms indicate that the particular independent variable should be high or low within the range of values investigated. These ranges are shown in Table 12. An upper case letter indicates that the independent variable has more than twice as great an impact on the dependent variable as the independent variable with a lower case letter designation.

The results given in Table 11 suggested that the following process control conditions be used:

1. Induction-heated startup (Module 1). Minimum total velocity and bed weight yielded the fastest heating to ignition temperature,

TABLE 10
0.20-m-DIAMETER PRIMARY BURNER EXPERIMENTAL PROGRAM

Module	Type of Operation	Type of Feed	Principal Objective
1	Batch	Crushed fuel elements	Determine startup characteristics with induction heater
2	Batch	Crushed fuel elements	Determine fines elutriation rates from startup bed
3	Semicontinuous	Crushed fuel elements	Determine fines elutriation rates from startup bed
4	Semicontinuous	Crushed fuel elements	Determine effect of induction heated assist on burnout
5	Semicontinuous	Recycle fines	Determine effects of several methods of fines injection on burner performance
6	Semicontinuous	Recycle fines	Determine effect of induction heated assist on burnout
7	Semicontinuous	Crushed fuel elements and recycle fines	Evaluate semi-automatic control of burner

TABLE 11
PRIMARY BURNER OPERATING LEVELS FOR MINIMIZING DEPENDENT VARIABLES

Module and Dependent Variable	Independent Variable									Comments
	Veloc- ity, U_T (m/s)	Average Feed Size, ϕ_F (μ m)	Bed Weight, W_B (kg)	Bed O_2 Total, V_{O_2} (std. m ³ /s)	Bed Carbon, X_C (wt %)	Vertex O_2 (std. m ³ /s)	O_2 Ramp Rate, $\dot{V}_{O_2}$ (std. m ³ /s/s)	Above-Bed O_2 , V_g (std. m ³ /s)	Feed Rate, W (g/s)	
Module 1										Module 1: Induc- tion heated startup and ig- nition { Note inversion
Heatup time	L	H	L							
Axial ΔT	l	L	H							
Radial ΔT	H	H	L							
Fines elutri- ation	L	H	L							
Particle breakage	H	H	H	L						
Agglomeration	H	H	H	L						{ Note agreement
Module 2: High C										Module 2: High carbon, no fresh feed, de- creasing bed car- bon
CO in off-gas	L			H	L	l		l		
Axial ΔT	l			h	L	h	l			
Radial ΔT	h			L	H	h	l			
Fines elutri- ation	l			L	H	h		h		
Particle breakage	h			L	H	H	L			
Agglomeration	h			L	H	H	L			{ Note agreement
Module 2: Low C										Module 2: Low carbon, no fresh feed, decreasing bed carbon
CO in off-gas	l			h	h	h		H		
Axial ΔT	L			h	h	L	l			
Radial ΔT	H			L	l	h	h			
Fines elutri- ation	l			l	L	h		H/L		V_S , H for $X_C > 20\%$ V_S , L for $X_C < 20\%$
Particle breakage	h			L	H	H	L			
Agglomeration	h			L	H	H	L			{ Note agreement
Module 3										Module 3: Fresh feed, constant bed carbon
CO in off-gas	l			h		h		h	L	
Axial ΔT	L			h		L	l		H	
Radial ΔT	h			l		h	h		H	
Fines elutri- ation	l			l	l	h		L	H	≤ 20 wt %
Particle breakage										
Agglomeration										{ See Appendix D
Module 4										Module 4: Tail- burning final bed. See Appendix D
Bed carbon			H	H						
Axial ΔT			H							No significant shift in temp- erature profile with induction heating. No hot spots.
Radial ΔT										

TABLE 12
INDEPENDENT VARIABLE RANGES FOR 0.20-m-DIAMETER PRIMARY BURNER TESTS

Module 1: Heatup and Ignition		
Independent (Controlled) Variable	Level	
	Max.	Min.
Total in-bed gas flow velocity, m/s	1.22	1.10
Type of feed ^(a) (micron averages = d_{RR})	2800	2000
Bed size, kg	36	32
Total in-bed O ₂ flow rate, std. m ³ /s	0.0025	0.0017

Module 2: High-to-Low Carbon Bed Operation (No Fresh Feed)

Dependent Variables

Fines elutriation data
Radial and axial burner temperature distribution
Off-gas composition (CO, CO₂, O₂)
Particle and fines data

Independent Variable	Level			
	High Carbon (>50 wt %)		Low Carbon (<50 wt %)	
	Max.	Min.	Max.	Min.
Bed carbon, wt %	70	50	30	15
Total in-bed gas flow velocity, m/s	1.22	1.10	1.10	1.01
Total in-bed O ₂ flow rate, std. m ³ /s	0.0042	0.0033	0.0058	0.0050
(O ₂) plenum/(O ₂) vertex	∞	4	∞	4
Total O ₂ ramp rate, std. m ³ /s/s	0.004	0.002	0.008	0.004
Secondary O ₂ addition, std. m ³ /s	0.001 ^(b)	0	0.001 ^(b)	0

TABLE 12 (Continued)

Module 3: Constant Low-Carbon (15 to 30 wt %) Bed Operation (Fresh Feed)		
Independent Variable	Level	
	Max.	Min.
Fresh feed rate, g/s	~7.5	~6.67
Total in-bed O ₂ flow rate, std. m ³ /s	0.0058	0.0050
Total in-bed gas flow velocity, m ³ /s	1.10	1.01
(O ₂) plenum/(O ₂) vertex	∞	4
Total O ₂ ramp rate, std. m ³ /s/s	0.004	0.002
Secondary O ₂ addition, std. m ³ /s	0.00083	0
Module 4: Tail-Burning of Final Particle Bed		
Independent Variable	Level	
	Max.	Min.
Tail-burn assist	Yes	No
Percent off-gas O ₂ allowed	10	5
Bed weight, kg	36	32

- (a) The Rosin-Rammler material averages are 66.6% of the R-R plot.
The feed consists of 83% graphite and 17% fertile FSV particle (TRISO).
- (b) Secondary (above-bed) O₂ was added to a maximum quantity limited by off-gas O₂ increases, indicating the additional O₂ was not being consumed.

using minimum O_2 flow rate for ignition reduced particle breakage and agglomeration. Relatively large feed size (up to 2.8-mm diameter on a Rosin-Rammler particle distribution), although not a directly controlled variable, was beneficial in reducing both heatup time and fuel particle breakage and agglomeration.

2. Operation with beds containing 30 to 83 wt % carbon and no fresh feed addition (Module 2). Immediate increase of the total velocity (CO_2 diluent) after ignition and minimal O_2 ramp rates decreased lower bed temperature changes and particle breakage and agglomeration. Use of vertex O_2 yielded decreased particle breakage and agglomeration and reduced fines elutriation; secondary O_2 reduced fines elutriation.
3. Operation with beds containing 15 to 30 wt % carbon and fresh feed addition (Module 3). Secondary O_2 was not beneficial in decreasing fines elutriation with bed carbon weight fractions below 20% and should not be used unless fines are being recycled; maximum rates of top-fed fresh feed were beneficial in dampening fines elutriation and temperature gradients. Other variables should be held as in the above high-to-low carbon phase.
4. Tail-burning final bed (Module 4). Induction heating and allowing maximum off-gas O_2 until off-gas CO was no longer detectable minimized final bed carbon. It also appeared that residual carbon in larger beds was more completely burned out.

The above operating conditions were selected from the results given in Table 11 by ranking the dependent variables in order of importance. The recommended values for the independent variables could then be chosen more easily when opposite effects on the process occurred.

1. Induction-heated startup. For this condition, optimum operation would minimize the following dependent variables: heatup time,

particle breakage and agglomeration, fines elutriation, radial ΔT , and axial ΔT . In recommending process conditions, the importance of each was ranked in the order listed; that is, a reduction of heatup time was considered the most important objective, followed by particle breakage and agglomeration, etc.

2. Operation with beds containing 30 to 83 wt % carbon and no fresh feed addition. For this condition, optimum operation would minimize the following dependent variables: particle breakage and agglomeration, fines elutriation, off-gas CO, radial ΔT , and axial ΔT . As before, in recommending process conditions the importance of each was ranked in the order listed. This ranking assumes no major process upset, such as explosive off-gas CO concentration, and also considers minor increases in fines elutriation to be well within the capacity of a properly functioning recycle system.
3. Operation with beds containing 15 to 30 wt % carbon and fresh feed addition. For this condition, optimum operation would minimize the same dependent variables as for the preceding condition. The ranking of variables was also the same.
4. Tail-burning final bed. For this condition, optimum operation would minimize the fraction of carbon in the final product bed, and this is the most important dependent variable.

Conditions for minimizing the axial ΔT were the inverse of conditions to minimize the radial ΔT , with the exception of very high carbon (>50 wt %) operation in which both ΔT s were minimized by the high vertex O_2 and low O_2 ramp rates.

Other significant results included the general beneficial effect that relatively large feed size and vertex O_2 had on all dependent variables except axial ΔT . Feed size larger than the range investigated (Rosin-Rammler

diameter of 2000 to 2800 μm) and abrupt vertex O_2 introduction to a high carbon bed remain as parameters to be investigated further.

6.2.2. Modules 5 and 6

Experimental work in Modules 5 and 6 was conducted primarily to determine the optimum method of recycle fines transport to the burner. The alternate methods of fines recycle used were (Fig. 14):

1. In-bed (vertex) using the pressurized dual-parallel hoppers.
2. Above-bed using the pressurized dual-parallel hoppers.
3. Above-bed using the pressurized tri-series hoppers.
4. Above-bed with a single gravity hopper-rotary valve.

The runs were all conducted with 32-kg startup beds of simulated fresh feed (~ 83 wt % $< 4800 \mu\text{m}$ graphite and ~ 17 wt % fertile TRISO fuel particles). Startup was performed at ~ 1.10 m/s. These were all optimum conditions established for startup in Modules 1 through 4. The equilibrium O_2 and velocity, as well as the tail-burn off-gas O_2 allowed, were varied in the ranges established in Modules 1 through 4.

The first 9 of 11 planned experiments in Modules 5 and 6 were performed with both in-bed and above-bed fines recycle using the pressurized dual-parallel hopper transport system. Eight of the nine experiments were statistically analyzed to determine preferred control levels and also to select the optimum fines injection point. The above-bed injection was selected as the preferred location with the alternative systems subsequently tested. Details of the test descriptions are given in Appendix C.

Tables 13 and 14 show that in-bed recycle significantly increased fuel particle carryover into the recycle loop, thereby breaking more particles and increasing noncombustible oxide buildup in the fines. Agglomeration of unbroken fuel particles also increased with in-bed fines recycle. In addition to these negative aspects, final bed carbon was highest with

TABLE 13
0.20-m-DIAMETER PRIMARY BURNER TEMPERATURE DIFFERENTIALS -
AVERAGED EXPERIMENTAL RESULTS FOR MODULES 5 AND 6

Measured Variable	Experimental Results	
	In-Bed Recycle	Above-Bed Recycle ^(a)
Module 5 averages		
Axial temperature difference, °C	39	32
Median radial temperature difference, °C	118	112
Module 6 averages		
Axial temperature difference, °C		
Overall	39	36
Not induction heated	35	55
Induction heated	43	27
No fines tail-burn	35	48
Fines tail-burn	43	30
Median radial temperature difference, °C	91	82
Not induction heated	110	120
Induction heated	72	71
No fines tail-burn	80	123
Fines tail-burn	102	70

(a) Gravity and parallel hopper systems. Series runs excluded due to intermittent fines flow and inordinate end-run fines inventory.

TABLE 14
0.20-m-DIAMETER PRIMARY BURNER PARTICLE BREAKAGE AND RESIDUAL INVENTORY DATA

Averages for Modules 5 and 6	In-Bed Recycle	Above-Bed Recycle		
	Vertex Parallel Hoppers	Above-Bed Parallel Hoppers	Above-Bed Series	Above-Bed Gravity
Fines inventory, kg ^(a)	1.4	1.4	6.8	0.21
Particle breakage, wt %	5.3	1.7	0.82	0.56
Noncombustibles in fines (-355 μ m), g	1172	332	222	146
Fuel particles in fines hoppers, g	1609	<3	23	<1
Particle agglomeration, wt %	0.015	0.009	0.006	0.001
Final bed carbon, wt % ^(a)	1.2	0.60	0.39	0.36

(a) Tail-burned results only.

in-bed recycle, indicating poorer bed burnout. Bed heat transfer was affected adversely by in-bed recycle; both the heat transfer zone and the temperature gradients were minimized by above-bed recycle. The final fines inventories for in-bed and above-bed recycle using the parallel pressurized hopper system were similar when fines were burned out. Hence, in-bed recycle using parallel pressurized hoppers will burn fines as well as above-bed recycle, but above-bed recycle is preferable in all other effects on the burner system measured in this study.

Gravity fines recycle resulted in the least final fines inventory; fuel particle elutriation, breakage, and agglomeration; oxide buildup in fines; and final bed carbon of any of the recycle systems tested. The gravity system was the simplest to operate and its single moving part (the rotary valve) increased the reliability of the system. This system is capable of feeding fines with large quantities of fuel particles or fresh feed material. The fabrication cost of the gravity system is less than half the cost of either of the other transport systems. On this basis the gravity system was chosen as the optimum fines recycle technique for further long-term testing.

Table 15 indicates the level at which the independent or "controlled" variables should be held to reduce the values of the dependent or "measured" variables based upon the statistical analysis. The "high-H" and "low-L" terms indicate whether the particular controlled variable should be high or low within the range of values given for each independent variable. The occurrence of an H/L in a row with an L/H means that a "high-H" level of the first variable should combine with "low-L" level of the other variable, and vice versa.

The best fines recycle system tested was gravity above-bed recycle; hence, the levels shown for above-bed recycle were the ones considered. Also considered were qualitative results observed in Module 6, the tail-burning phase which was not statistically analyzed.

TABLE 15
0.20-m-DIAMETER PRIMARY BURNER STATISTICAL ANALYSIS OF IN-BED AND ABOVE-BED
FINES RECYCLE WITH OPERATING LEVELS^(a) FOR MINIMIZING DEPENDENT VARIABLES

Dependent Variable	Independent Variable			
	Bed Velocity, U_T {m/s(ft/s)} L = 1.01(3.3) H = 1.10(3.6)	Secondary O_2 , V_s (std. m ³ /s) L ≤ 0.00067 H ≤ 0.00133	Delay Time ^(b) (s) L = 0 H = 1800	In-Bed O_2 , V_o (std. m ³ /s) L = 0.0050 H = 0.0058
Axial bed ΔT				
Parallel hoppers, vertex recycle	L	L	L	L
Parallel hoppers, above-bed recycle	L	H	L	L
Radial bed ΔT				
Parallel hoppers, vertex recycle	L	L	--	L
Parallel hoppers, above-bed recycle	L	H	--	L
Off-gas				
CO				
Parallel hoppers, vertex recycle	H	L	--	H
O_2				
Parallel hoppers, vertex bed recycle	L	L	--	L
CO				
Parallel hoppers, above-bed recycle	H/L	L/H	--	H/L
O_2				
Parallel hoppers, above-bed recycle	H/L	L/H	--	H/L
Fines inventory				
Parallel hoppers, vertex recycle	H/L	H/L	--	H/L
Parallel hoppers, above-bed recycle	H/L	H/L	--	H/L
Noncombustible fines elutriation				
Parallel hoppers, vertex recycle	L	L	--	L
Parallel hoppers, above-bed recycle	L	L	--	L
Particle breakage (loss)				
Parallel hoppers, vertex recycle	L	H	--	L
Parallel hoppers, above-bed recycle	L/H	L/H	--	L/H
Particle agglomeration				
Parallel hoppers, vertex recycle	L/H	H/L	--	L/H
Parallel hoppers, above-bed recycle	L/H	H/L	--	L/H

(a) L = low within test range and H = high within test range.

(b) Delay time to start fines recycle after O_2 ramp.

The combined results indicate that for optimum operation with above-bed gravity fines recycle: (1) fines recycle should be started immediately after the oxygen ramp is completed, (2) total in-bed oxygen, above-bed oxygen, and in-bed velocity should be matched (i.e., at high burn rate, use high above-bed oxygen flow and high in-bed velocity), and (3) induction heating should be used and fines recycle should be continued throughout the final product bed tail-burning.

The suggested operating conditions were selected from the tabulated results by ranking the dependent variables in order of importance, as follows: fines inventory (most important), particle breakage, noncombustible fines elutriation, particle agglomeration, off-gas CO and O₂, radial ΔT , and axial ΔT (least important). [Particle agglomeration was ranked relatively lower than in Modules 1 through 4 because of the very low (<0.02 wt %) amounts of agglomeration formed.]

Fuel particle agglomeration was found to be very much lower in the fines recycle runs than in runs without fines recycle. Nonrecycle run results show agglomeration to be from 0.02 to 0.2 wt % of final beds, while a range of only 0.001 to 0.015 wt % agglomerates was noted in this work. The apparent explanation is that fines recycle (whether in-bed or above-bed) improves bed mixing, thus avoiding any local or temporal stagnation which can allow fuel particles to be fused by eutectic compounds. This mixing improvement was significant as the higher particle breakage resulting from fines recycle should have provided more impurities to form the eutectics which may bond agglomerates.

An average oxygen ramp of 0.00027 std m³/s/s was used in these runs without any noticeable adverse effects (a maximum of 0.00013 std m³/s/s was used in Modules 1 through 4). Ramp rates in excess of ~0.00033 std m³/s/s appeared to cause an initial bed temperature overshoot.

6.2.3. Module 7 - Automation Study

The primary objective of the Module 7 experiments was to implement a postulated automatic control philosophy. The burner automatic control system utilizes a digital process controller with an all analog input/output interface. The system selected is a centralized digital process recorder called Diogenes, manufactured by Rosemount, Inc., of Minneapolis. The Diogenes system is a hand-wired real-time dedicated process controller designed to control up to 100 loops by means of a continuous 1-s scan of the loops. A 20-loop configuration with capacity for expansion to 50 loops was purchased for the primary burner (Fig. 16). The advantages of such a control system to a pilot plant operation are (Ref. 15):

1. Control loop functions and configurations can be changed easily.
2. Control constants, alarm limits, output limits, and scaling constants can be changed easily.
3. Calculation of data and/or interface with a computerized information retrieval system during operation are available.
4. Diagnosis of process control problems is facilitated.
5. Control panel/room space is saved.

There are five principal functions (and many less significant) to be performed or supervised by the primary burner control system. These functions are summarized in Table 16.

Each loop accepts a 4 to 20 ma dc analog signal from the process and provides a continuous 4 to 20 ma 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

Fig. 16. Pilot plant control instrumentation panels

TABLE 16
PRIMARY BURNER MAJOR CONTROL FUNCTIONS

Function	Method of Control	Type of Sensor	Control Criteria
Fluidized-bed heating	Induction heater cascaded to bed/vessel/susceptor temperature	I.S.A. Type K (Chromel-P/Alumel) thermocouples	Heat fresh feed or particle beds to ignition temperatures (700°C) in ≤ 1 h Maintain clamp to hub $\Delta T < 112^\circ\text{C}$ for vessel flanges
Postignition bed temperature control	Adjust oxygen flow	Type-K thermocouples	Control temperatures within 50°C of set points (approx. $\pm 7\%$)
49 Oxygen flow	Equal-percentage control valve	Precision gas flowmeter (SWIRLMETER)	Flow within $\pm 3\%$ of set point
Fluidizing gas (CO ₂) flow	Equal-percentage control valve: adjust CO ₂ flow set point based on bed temperature to maintain a constant total gas flow velocity	Precision gas flowmeter (SWIRLMETER)	Flow within $\pm 3\%$ of set point
Vessel cooling	Adjust cooling air flow and maintain proper cooling air blower discharge pressure	Type-K thermocouples/flow averaging (ANNUBAR) pitot tubes	Maintain full bed at 900°C while burning at 3.3 g C/s Air flow within $\pm 3\%$ of set point Maintain temperatures within $\pm 10^\circ\text{C}$ of set point (approx. $\pm 1\%$)

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 that has an analog input and/or an analog output.

The configuration of the control loops is set up by the operator with pins and wire links on a functionally diagrammed diode pinboard called the channel function matrix (CFM). The various control schemes which can be implemented include cascade, ratio, feedforward, calculating, and multi-variable types. The actual operating parameters for these functions are alterable values entered through an operator's control console and stored in an internal memory. Restructuring of the control schemes is simply a matter of altering the pin and link arrangements on the CFM.

All loops can be controlled digitally by the central controller under the automatic 1-s scan arrangement. This is the normal mode of operation, called the "central" control mode. A variation of this mode is "central manual," which allows a loop to be controlled manually 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.

There are currently 23 out of 50 available channels (CFM) and 13 out of 20 available control loops (PIMs) assigned to the primary burner during the period of initial development work. Possible later changes in the control philosophy to provide greater versatility and more automation will consume up to 39 channels and 16 loops for the primary burner.

The burner control philosophy is shown in Fig. 17. This figure illustrates that the "0. Induction Heater Controller" only supplies power when the bed temperature is $<860^{\circ}\text{C}$. As the induction heater brings the startup bed temperature to its 700°C auto-ignition temperature, the "1. O_2 Ramp Controller" is activated which increases O_2 flow to the plenum gas inlet (the gas then enters the bed through the distributor perforations). The rate of O_2 increase and the maximum level to which the O_2 increases are automatically controlled and can be varied through the "1. O_2 Ramp

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. 17. Proposed primary burner automatic control

Controller." While the O_2 flow is being increased, the "2. Plenum O_2/CO_2 Total Gas Controller" adjusts the plenum CO_2 gas flow to keep the combined total plenum O_2 and CO_2 gas flows constant. This controller functions automatically throughout the run to hold the total gas, hence the superficial velocity, constant even if the O_2 flow controller requires manual operation. At $860^\circ C$ bed temperature the induction heater is automatically deactivated, and at $880^\circ C (\pm 10^\circ C)$ the cooling air flow is activated by the "3. Cooling Controller." The cooling air flow control valve opening is varied to hold the bed temperature at $\sim 900^\circ C$. If the wall cooling is incapable of preventing bed temperature excursions above $930^\circ C$, the "4. High Temperature Plenum O_2 Controller" reduces the plenum O_2 until the bed temperature returns below $\sim 930^\circ C$. The plenum is returned to its preset maximum below $\sim 930^\circ C$. This prevents damage to the vessel wall. During tail-burning the decreased bed carbon allows the O_2 concentration in the off-gas to increase. The "5. Off-Gas O_2 Controller" reduces the plenum O_2 to maintain a preset maximum off-gas O_2 concentration.

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 has been necessary to use manual override during the unstable phase of operation both following fresh feed startup and during the final tail-burning phases. This override consists of manually controlling the O_2 flow and/or the cooling air flow, with all other functions remaining on automatic control.

Fine tuning of the "3. Cooling Air Controller" and the "4. High Temperature Plenum O_2 Controller" is required to further improve the automatic control. Tuning of the "3. 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.

The Diogenes control system has generally been satisfactory in performing its assigned control functions except for an intermittently erroneous temperature signal from the "high bed temperature selector." This function 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 activates the induction heater and deactivates the cooling air. In doing this, the cooling air blower cycles on and off; if this occurs often enough, the blower switch contactor will overheat and fail. The selector problem has hampered studies of fine tuning automatic controls. The reason for 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. Several runs have been made with this corrected function and the high select problem has not been experienced. Proper functioning of the selector will allow continuing fine tuning studies on the remainder of the automatic control system in an effort to reduce the requirement for periods of partial manual control.

Future modifications to control philosophy will include scanning of the axial susceptor and vessel wall temperature profiles for maximum temperature inputs to the induction heater control system. This would better serve to minimize the possibility of overheating the vessel during abnormal operating conditions. Cooling air flow control using wall temperature instead of bed temperature will be studied. A binomial control may also be set up. The binomial would incorporate wall temperature in conjunction with bed temperature in an attempt to improve the response of the "3. Cooling Air Controller."

6.2.4. Module 7 - Operating Cycle Tests

A 48-h run was required as the completion of Module 7 automation studies. This run was not only planned to study the automation system in long-duration operation, but was also an intended study of the proposed

primary burner operating cycle. Five attempts were made to complete this run.

The initial attempt at long-term operation was terminated prematurely primarily because of an erroneous cycling controller signal which caused the burner cooling air blower switch contactor to overheat and fail. Operations during the 12-h run indicated that fluidization of very dense, large-diameter BISO fertile particles mixed with small-diameter, less dense TRISO fissile particles required adjustments to previous process control levels. These levels had been established during prior operation with more homogeneous mixtures of TRISO fuel particles. The BISO fertile particles segregated to the inlet cone distributor region and required a higher total gas velocity and a longer O_2 ramp period to safely burn the carbon coatings. Approximately 4 h was required to ramp the O_2 to its maximum flow rate. As the burned-back inert BISO fuel particles accumulated in the lower burner zone, the operation became more typically smooth.

The succeeding three run attempts demonstrated much smoother startup periods due to the use of longer oxygen ramping time and earlier initiation of fines recycle. However, problems with the off-gas fines filtering system were experienced when high fines generation and accumulation rates resulted from an excessive fresh feed flow rate. Operation of the rotary feed valve at very low speed resulted in a characteristically erratic feed throughput.

The fifth and final run attempt was performed at a reduced feed flow rate. Predictably, this resulted in operation of much longer duration. However, off-gas filter system plugging was eventually experienced because of excessive fines accumulation in the recycle loop.

The majority of the fertile BISO/fissile TRISO particles used in these runs were the large, dense BISO particles which generally exhibited poorer fluidization and bed mixing characteristics than the less dense TRISO particles. Segregation of bed material in the final run attempt was extremely severe with a relatively short bed of BISO particles ($<100^\circ\text{C}$)

occupying the bottom of the burner vessel while a layer of burning graphite existed above. Because of this extreme segregation, an intense burning zone developed at the particle/graphite interface. A deficiency in the automatic control system allowed the induction heater to provide external heat to the burner, which resulted in the formation of a hot spot on the burner vessel. Shortly thereafter a burnthrough resulted, as shown in Fig. 18.

The test failure which occurred identified several required design modifications which will be incorporated during the system reconstruction period. The capability for heating small, segregated beds will be improved, as will the capability of the automatic control system to detect and react to unforeseen abnormal operating situations.

Fig. 18. 0.20-m-diameter primary burner burnthrough

7. EQUIPMENT DESIGN MODIFICATIONS

Following the final 48-h run attempt, the 0.20-m-diameter primary burner system was disassembled in preparation for various equipment repairs and design modifications. The ruptured section of the vessel wall will be repaired by replacement with a 0.30-m length of pinned Hastelloy X tubing. In addition, the induction heating system susceptor design will be reevaluated with particular emphasis given to the feasibility of modifying the configuration to improve overall heating capabilities. Also, the use of a fluidization gas preheater should improve the ability of the system to heat small beds of material.

Concurrent with repairs to the vessel and modifications to the heating system, the fines recycle system will be redesigned. These modifications will include the insulation and cooling capability necessary for proper temperature control of the recycling fines to maintain $<500^{\circ}\text{C}$ fines temperatures at the fines rotary valve. The fresh feed and fines hoppers, as well as the off-gas filter system, will be redesigned and replaced in conjunction with these other repairs and modifications.

Several potential problem areas have been identified which will be investigated, with emphasis on modifying equipment design and operating procedures to accommodate the effects of abnormal operating conditions. Future experimental work will be designed to investigate the effects of the various equipment design modifications on the primary burning process.

8. SUMMARY AND RECOMMENDATIONS

Experimental work to date performed in the 0.20-m-diameter primary burner has demonstrated the feasibility of the primary fluidized-bed burning process by confirming the following:

1. A 90° perforated conical distributor with a 13.0-mm-diameter vertex opening was shown to be the most attractive and flexible gas distribution system available. This design provides adequate fluidization of the primary burner bed solids as well as capability for complete product removal. In addition, the potential for material stagnation and subsequent fuel particle agglomeration is minimized.
2. Semi-automatic control of the burner system has been demonstrated. Significant operating experience with the computer-based Diogenes process controller has allowed continual modification and improvements in the control system.
3. The feasibility of the induction-susceptor heating/cooling technique for bed ignition and temperature control has been verified. Optimum bed size and gas flow rates needed in conjunction with induction-heated startup have been determined.
4. The optimum method of fines recycle to the burner was determined. Gravity-flow fines recycle utilizing a high-temperature rotary valve feeder to an above-bed inlet location was found to be the most promising of the many systems tested.
5. A parametric experimental program was performed to quantitatively determine the effects of various operating variables on the

primary burning process. Optimum operating conditions were determined for the process.

6. Adequate material throughput capacity has been demonstrated. It has been shown that the 0.20-m-diameter primary burner is capable of achieving an average burn rate of 380 kg C/h per square meter of burner inside cross-sectional area. Sufficient external air-cooling capabilities have been demonstrated.
7. The carbon content of primary burner product has been shown to be within the 1% limit imposed by reprocessing flowsheet steps subsequent to the primary burning process.
8. TRISO fuel particle breakage resulting from the steps in the primary burning process has been shown to be acceptably low.
9. Maximum permissible feed size and size distribution of primary burner feed to a $\approx$ 0.20-m-diameter vessel has been determined to be 4800 μ m ring size.
10. Long-term reliability of external fines recycle in the primary burning process has been demonstrated with the use of two different fines recycle systems.

Experimental work to date has shown significant progress toward meeting the primary burning process design requirements, with the result that a scaled-up prototype 0.40-m-diameter primary burner has been designed, built, and successfully operated. However, further work is recommended to meet the following objectives:

1. Improvements and refinements to the digital automatic process control system and philosophy.

2. Increased capability to accommodate abnormal or extreme operating conditions; a gas preheater should be tested for use in heating small or segregated beds of material.
3. Investigation of the system heat removal capability in areas others than through the burner vessel.
4. Improvements and refinements to the fines recycle equipment and off-gas filtering equipment.
5. Improvements in the fresh feed system equipment and instrumentation.
6. Long-term operation and reliability of the overall primary burning process.
7. Ability to process BISO fuel particles.

ACKNOWLEDGMENTS

The work described in this report was supported by the Department of Energy under contract EY-76-C-03-0167. The results proceed from investigations accomplished by technical contributors over a span of several years. The contributors include: D. H. Stallings, M. B. Zacavich, J. C. Narvaez, and R. M. Earle in the fabrication and operation of the 0.2-m-diameter primary burner equipment; H. H. Yip and W. S. Rickman in heat transfer and related analysis and design work on the burner system; and J. W. Allen and R. D. Zimmerman in the leadership of the burner development program.

The parallel pressurized fines recycle hoppers were scaled-up from hoppers originally tested by W. B. Palmer of Allied Chemical Corporation, Idaho Falls, Idaho. Discussions with W. B. Palmer also contributed to the development of the series pressurized hopper system.

REFERENCES

1. Young, D. T., "Fluidized Combustion of Beds of Large, Dense Particles in Reprocessing HTGR Fuel," ERDA Report GA-A14327, General Atomic Company, March 1977.
2. "Thorium Utilization Program Quarterly Progress Report for the Period Ending May 31, 1976," ERDA Report GA-A13949, General Atomic Company, June 30, 1976, pp. 4-25 to 4-26.
3. Stula, R. T., D. T. Young, and H. H. Yip, "Interim Development Report for Primary Burning," ERDA Report GA-A13546, General Atomic Company, January 5, 1976, p. 6-2.
4. "HTGR Base Program Quarterly Progress Report for the Period Ending February 28, 1973," USAEC Report Gulf-GA-A12515, Gulf General Atomic, March 30, 1973, pp. 46-49.
5. "Thorium Utilization Program Quarterly Progress Report for the Period Ending February 28, 1975," ERDA Report GA-A13366, General Atomic Company, May 30, 1975, pp. 4-1 to 4-6.
6. Mathur, K. B., in Fluidization, J. F. Davidson and D. Harrison (eds.), Academic Press, London, 1971, pp. 711-724.
7. Geldart, D., "Types of Gas Fluidization," Powder Technology (7), 290 (1973).
8. "Thorium Utilization Program Quarterly Progress Report for the Period Ending May 31, 1975," ERDA Report GA-A13510, General Atomic Company, August 15, 1975, pp. 4-8 to 4-15.
9. "Thorium Utilization Program Quarterly Progress Report for the Period Ending August 31, 1975," ERDA Report GA-A13593, General Atomic Company, September 30, 1975, pp. 4-1 to 4-8.
10. Rickman, W. S., "Interim Development Report for Secondary Burning," ERDA Report GA-A13540, General Atomic Company, December 25, 1975, p. 33.

11. Hunter, J. S., "Fractional Factorial Designs," in Design of Experiments Course, Vol. 5, Westinghouse, 1968.
12. Rode, J. S., "Process Control of an HTGR Fuel Reprocessing Cold Pilot Plant," ERDA Report GA-A14101, General Atomic Company, October 1976.
13. Snider, J. W., and D. C. Wathin, "An Evaluation of HTGR Primary Burning," USAEC Report ORNL-TM-4520, Oak Ridge National Laboratory, November 1974.

APPENDIX A

BURNER OPERATION

A.1. SCOPE

A.1.1. Modules 1 and 2

The burner was operated with the startup bed (fed in one initial batch load), no fines recycle, and no continuous or intermittent fresh feed. Particles were fed to maintain bed height. The experiments required no more than 6 h duration from ignition to product removal. The equipment involved included combustion/fluidization gas lines, the burner vessel, and batch product removal equipment including the product receiving vessel, a burner cooling system using air as the coolant, the cyclone and filter chamber fines separation equipment, the fines sampling diverter valve, line and receiving vessel, the induction heating system, the off-gas cooling and analysis equipment, and the particle addition system. Instrumentation included the cone plenum, cone vertex, and mid-reactor gas flow controls; the fines sampling controls and fines hopper cycle controls; and recorders for the improvement variables such as in-bed, above-bed, burner-wall, and susceptor temperatures, gas flows, the bed and filter chamber pressure drop, and the off-gas analysis. Where possible, these controls were included in the Diogenes control system. Manual operation in these modules using the Diogenes system was later changed to semi-automatic control in Module 7.

A.1.2. Modules 3 and 4

These experimental phases involved extensions of three Module 1 and 2 runs of approximately 4-h duration each. Fresh feed was added to maintain constant bed carbon (10% to 20%) when the startup bed (83% carbon) had been

burned down to the 10% to 20% carbon level. The fresh feed was used until equilibrium values of off-gas, temperature, and fines elutriation were reached and maintained for about 1 h. The feed was then stopped, supplemental particles were added through the bed addition system, if required, and the bed was allowed to burn out with induction-heated tail-burning optional. Modules 3 and 4 required all equipment and instrumentation used in Modules 1 and 2 in addition to the fresh feed equipment and controls.

A.1.3. Modules 5 and 6

These runs incorporated three separate fines recycle systems: parallel pressurized hoppers, series pressurized hoppers, and gravity rotary valve/hopper recycle. The fines were injected either to the vertex gas line or mid-reactor inlet with the pressurized systems. The gravity system recycled only to the mid-reactor inlet. A total of 11 runs of over 8-h duration (depending upon equilibrium conditions) were involved, with 8 of the runs using the parallel pressurized system to the vertex or mid-reactor inlet. The ninth run incorporated a partial bed removal and restart with vertex recycle. The tenth run tested the gravity system, and the eleventh run tested the series pressurized system to the best injection location selected in the first eight runs. All equipment and instrumentation needed in the prior phases were used in addition to the three fines recycle systems. Fines gas flow was manually controlled. Hopper temperatures and pressures were monitored. (The tenth and eleventh runs were actually the most representative of several shakedown runs of the revised equipment.)

A.1.4. Module 7

This module entailed approximately five short runs (1 to 8 h) to shake down semi-automatic control of the optimum burner operation selected from prior operating alternatives. When the semi-automatic control was deemed satisfactory and all alarm set points and actions had been selected and tested, a long-term run (>48 h) was attempted under full automatic control. This run simulated a reference semicontinuous batch cycle campaign in which product beds are built up, burned out, partially dumped, and restarted.

Semi-automatic product removal was incorporated in this series as well as the systems of the prior module and the selected optimum fines recycle system. Control room indication of the product removal valve position was included in instrumentation, as well as a manual open/close switch for this valve. Circuitry was tested that will either operate the product removal valve on bed ΔP low level indication or on a preset timer switch. The product removal by gravity required a 50.8 mm (2 in.) knife-gate slide valve and a 38.1 mm (1.5 in.) line from the burner to the product bunker. The semi-automatic capabilities of the Diogenes controller were required in this series.

A.1.5. General Control Instrumentation

Although the full capability of the Diogenes system was not called on until Module 7, the semi-automatic controller was at least partially utilized throughout each module.

A.1.6. Corrosion Studies

Banks of corrosion coupon disks were spaced axially on the burner bed thermowell. A series of these coupons was removed after 500 h and the remainder will be removed after the program is completed and the maximum time is accumulated. Sulfur was added to the graphite feed to simulate projected conditions of burner corrosion atmospheres.

A.2. NORMAL OPERATION

The startup procedure in initial experimental studies varied gas flows, feed size, and bed weights using the peak induction heater power input allowed by wall temperatures. Thereafter, the startup followed the optimum procedure established in the first experiments. Startup involved the period from initiation of gas flows through startup bed addition and induction system bed heatup, to the point where bed temperature was sustained by bed graphite ignition.

The steady-state operation occurred from the time when the bed was ignited and sustained at 900°C until the time when the shutdown procedure was initiated. This was not a true steady state as equilibrium parameters varied from module to module and within some modules as tests were being conducted.

The shutdown operation commenced when bed carbon had been burned to a low level such that off-gas O_2 concentration increased and gas flows required adjustment to limit the O_2 breakthrough. This occurred at some finite time ($0.25 \text{ h} \lesssim t \lesssim 3 \text{ h}$, depending on bed carbon level) after fresh feed had been stopped. This phase varied in the modules as induction-heated tail-burning was used or not used, and as two levels of "off-gas O_2 allowed" (5% and 10%) were controlled in the bed carbon burnout. Burnout of recycling fines also altered the operating parameters and time required in the shutdown phase.

Modules 1 through 7 refer to separate phases or modes of operation in which analysis emphasis differed, as follows:

1. Module 1 studied "startup."
2. Module 2 studied "steady state" as bed carbon burned to zero wt %.
3. Module 3 studied "steady state" as feeding of graphite maintained constant bed carbon.
4. Module 4 studied the "shutdown" of the prior modules.
5. Module 5 studied "steady state" with fines recycle incorporated into Module 3 type operation.
6. Module 6 studied "shutdown" of Module 5.
7. Module 7 incorporated semi-automatic control into Module 5 and 6 operation.

Modules 1 through 4 were studies in the first eight burner runs. The startup phase of each of the eight experiments was considered in the Module 1 analysis.

The subsequent burnout of the startup bed was considered in Module 2 as the steady state with emphasis on fines elutriation changes and O_2 ramp rates allowable as the bed carbon level was reduced. The operation did not include fresh feed, but required adding "supplemental" particles to maintain the bed weight constant. Module 2 was divided into "high-carbon" and "low-carbon" phases of data acquisition to allow less constrained selection of values for controlled variables and to yield better data analysis. The approximate "breakpoint" carbon level which separates the phases was high > 50 wt % > low.

Module 3 provided a comparison steady state with Module 2 with fresh feed maintaining an approximate 15% bed carbon level after the bed carbon had burned down from the 83% carbon startup bed. Module 3 operation was an extension of certain Module 1 and 2 runs, with the initiation of fresh feed indicating the end of the Module 2 portion and the beginning of Module 3 analysis.

Module 4 was an induction heating "tail-burning" analysis that was an extension of certain Module 2 and 3 runs.

Module 5 involved fines recycle steady state using different injection points and fines transport mechanisms. It was a separate set of experiments from those conducted in Modules 1 through 4. The startup was the optimum selected in Module 1. The steady state involved using burn rates and bed carbon levels similar to the "low-carbon" levels used in the prior Modules 2 and 3. Time of fines recycle initiation and the use of supplemental above-bed O_2 were other variables investigated in the "steady state" of Module 5.

Module 6, an extension of Module 5 runs, was an induction heating "tail-burning" analysis with fines recycle incorporated.

Module 7 operation was the nearest approach to a true "steady state" of all the modules. It used the optimum startup, steady-state, and shut-down techniques found in earlier experiments and applied the full capabilities of the Diogenes semi-automatic controller to maintain smooth equilibrium burner operation.

These modules are described in Appendix C in terms of the specific measured (dependent) variables studied with the values selected for controlled (independent) variables given at two operating levels - maximum and minimum.

Logging of selected variables was done during the run at periods of special significance in process analysis (e.g., before and after O_2 ramps, feed changes, etc.). This log supplemented the process log shown in Fig. A-1* and the continuously recorded data on strip-chart recorders. The selected variables are shown in Figs. A-2 through A-7. Fines samples were taken during the logging period.

Information pertaining to burner operation, control, and instrumentation is given in Tables A-1 through A-3 and Figs. A-8 through A-13.

A.3. ABNORMAL OPERATION

A.3.1. Upsets and Transients

1. Burner in-bed temperature elevation to $\geq 930^\circ\text{C}$ (alarm at 930°C) or less than 880°C (alarm at 880°C) required commencing corrective action. The probable conditions and corrective actions are listed below in order of most probable to least probable occurrence.

*Figures appear at the end of Appendix A.

TABLE A-1
PRIMARY BURNER OPERATION

First Campaign Startup

1. Turn on power
2. Establish CO₂ flows
3. Load burner with initial bed
4. Open O₂ isolation valves
5. Turn on induction heater

First and Inter-Campaign

-
1. Initiate O₂ flow to plenum
 2. Reduce CO₂ flow to plenum
 3. Turn off induction heater
 4. Start flow of cooling air
 5. Initiate O₂ flow to vertex
 6. Reduce CO₂ flow to vertex
 7. Start fines recycle (as appropriate)
 8. Adjust cooling air flow
 9. Start fresh feed on demand
 10. Stop fresh feed on demand
 11. Stop fines recycle on high above-bed temperature
 12. Reduce cooling air flow
 13. Reduce O₂ flow on high off-gas concentration
 14. Increase CO₂ flows
 15. Dump bed to low level
 16. Re-establish bed with fresh feed

Final Tail-Burn

1. Stop fresh feed
 2. Reduce O₂ flows
 3. Increase CO₂ flows
 4. Increase cooling air flow
 5. Shut off O₂ on high off-gas concentration
 6. Increase CO₂ flows to shutdown level
 7. Dump entire bed
-

TABLE A-2
MAJOR CONTROL FUNCTIONS OF PRIMARY BURNER

Function	Method of Control	Type of Sensor	Basis for Selection
Bed heating	Induction heater cascaded to bed/vessel/susceptor temperature	Type-K thermocouples	Better control Allows independent fluidization control Longer burner life Easier to maintain Better safety, reliability
Postignition bed temperature control	Adjust oxygen flow	Type-K thermocouples	Fast response
Oxygen flow	Equal-% (linear) Control valve	Swirlmeter	High accuracy Wide rangeability
Fluidizing gas flow	Equal-% (linear) control valve to hold total gas flow constant	Swirlmeter	High accuracy Wide rangeability Prevents bed stagnation
Vessel cooling	Adjust cooling air flow	Type-K thermocouples/ Annubar pitot tube	Avoid criticality
Combustion off-gas oxygen concentration	Reduce oxygen flows	Paramagnetic oxygen analyzer	Oxygen deleterious to off-gas treatment system Minimize explosion hazard Prevent high filter temperatures CO/CO ₂ ambiguous
Bed inventory	Start/stop feed/product flows	Differential pressure transmitter	Control bed level Control disengagement height Minimize particle carryover
Feed rate	Variable speed rotary valve	Tachometer	Allows control and feed rate estimation
Product rate	Remote-manual on/off	Timer	Allows low-carbon product Controls transport loading to minimize breakage
Fines recycle	Dual parallel hopper pressurized recycle to burner	Timing system	0.20-m-diameter primary burner experience

TABLE A-3
GAS FLOW CORRECTIONS

Velocity Corrections for Temp./Gas Flow in the 0.20-m-Diameter Primary Burner					Rotameter Back-pressure Gas Flow Corrections	
Temp. (°C)	SLPM for Velocity of				Back Pressure (psig)	Rotameter Reading Correction
	2.2 ft/s	3.3 ft/s	3.7 ft/s	4.2 ft/s		
25	1200				2	0.97
200		1130			3	1.00
300		940	1060	1180	4	1.03
400		800	890	1020	5	1.06
450		750	840	950	6	1.08
500		700	800	890	7	1.11
550		650	740	840	8	1.13
600		610	690	780	9	1.16
650		580	650	730	10	1.18
700		550	620	690	11	1.21
750		525	580	660	12	1.23
800		500	560	630	13	1.25
850		480	530	610	14	1.27
875		460	520	590	15	1.30
900		450	510	580	20	1.40
925		440	500	570	25	1.50
950		430	490	560	30	1.59
					35	1.67
					40	1.76
					45	1.84
					50	1.91
					60	2.05

High In-Bed Temperature

<u>Condition</u>	<u>Corrective Action</u>
a. O ₂ ramp or total O ₂ flow rate too high for the cooling air flow rate.	a. Stop any O ₂ ramp and increase cooling air; if the temperature does not begin decreasing at maximum cooling, see (b), (c), etc.
b. Total O ₂ flow rate in excess of maximum cooling capabilities - usually due to "intense" combustion in which excessive burning is localized in a small area (such as with a high weight percent carbon bed and larger graphite segregation to the distributor area or, if the bed height becomes too low for good heat transfer, this may be accompanied by increasing off-gas CO).	b. Increase the CO ₂ /O ₂ feed gas ratio by O ₂ decreases with equivalent CO ₂ increases (maintain constant total velocity). Increase the bed height if this action appears necessary.
c. Local bed temperature cycling above adjacent bed temperatures - usually due to a very large "oversize" fraction of graphite feed gravitating in waves to the distributor area and burning semi-statically.	c. If cycles exceed 930°C, increase the CO ₂ /O ₂ ratio by O ₂ reductions. Make up with excess CO ₂ such that the total velocity is increased ~5%. Repeat this procedure until cycles diminish to <930°C.
d. Separating bed temperatures with elevation of a local area to >930°C - usually due to insufficient gas velocity for complete bed mixing.	d. Increase the total velocity by 5% increments using increases in plenum CO ₂ .

Low In-Bed Temperature

<u>Condition</u>	<u>Corrective Action</u>
a. An overall bed temperature reduction due to too much cooling air for the O ₂ /CO ₂ feed gas ratio and bed height and bed percent carbon conditions.	a. Decrease cooling air. If a decrease to minimum does not increase temperatures, increase the O ₂ and reduce the CO ₂ feed gas. Do not allow ~840°C.
b. Local reduction of temperature with remainder of bed stable - usually due to local cooling effects of ambient fresh feed entering the bed.	b. No corrective necessary unless general cooling occurs. If so, lower cooling air rate and (or) reduce fresh feed rate and stabilize temperatures.

2. Burner above-bed temperature elevation to $\approx 930^{\circ}\text{C}$ (alarm at 950°C) may occur especially if fines recycle is in operation and lowered weight percent bed carbon allows excess O_2 to reach the above-bed fines burning zone.

High Above-Bed Temperatures

<u>Condition</u>	<u>Corrective Action</u>
a. O_2 breakthrough from a low carbon bed elevating temperature in the fines burning zone below the mid-reactor gas inlet.	a. Reduce the vertex, then plenum O_2/CO_2 ratio for 900°C stable above-bed temperature. Add carbon to the bed if applicable.
b. O_2 breakthrough from a low carbon bed elevating temperature above the mid-reactor gas inlet.	b. Reduce the mid-reactor gas O_2/CO_2 ratio, then the vertex and plenum O_2/CO_2 ratio for 900°C stable temperatures. Add carbon to the bed if applicable.
c. Excessive O_2 from the mid-reactor gas inlet	c. Reduce the mid-reactor gas O_2/CO_2 ratio.

3. Fresh feeder mechanism blockage can occur if large foreign material enters the feeder. This can stop the feeder rotation and may even shear the drive shaft. An rpm gauge in the control room will indicate any such problem

<u>Condition</u>	<u>Corrective Action</u>
a. Fresh feeder malfunction - the bed carbon will start reducing and bed temperatures will elevate and/or off-gas O_2 will begin increasing.	a. Turn on the bed addition system with supplemental "backup" fresh feed. Correct the fresh feed rotary problem after determining cause, i.e., fix pin, hand reverse drive the rotor to clear, etc. When clear, turn on fresh feeder and turn off bed addition.

4. Increasing off-gas O_2 during low carbon operation calls for more bed carbon. Increase the fresh feed rate in small increments until off-gas O_2 decreases. Low bed temperatures may cause the

off-gas O_2 percent to increase (see A.3.1, item 1). If off-gas O_2 percent increases with bed $\lesssim 900^\circ C$, add fresh feed.

5. An induction heater system cut out requires pushing the "MG Protect Reset and Start" switches as given in the Induction Heater Operating Procedure after determining and correcting the cause of the heater cut out.
6. Loss of power will automatically flood the burner with CO_2 (fail open valves) and eliminate O_2 (fail closed valves).
7. Loss of cooling air blower will require reducing the burn rate by decreasing the O_2/CO_2 feed gas ratio to maintain $900^\circ C$ bed temperatures while maintaining constant velocity. If the blower cannot be recovered, a normal shutdown may be advisable.
8. Thermocouples often give erroneous or "open" (pegged) readings. Confirm the error with adjacent thermocouples and off-gas CO stability and then call on electronics technician support to trace and correct the fault.
9. The bed ΔP cell lines have plugged in the past. The present vertex gas line tap has not given such plugging fault but if it occurs, open the line at the ΔP cell on the west cabinet wall and blow out with short bursts of plant air.
10. Obvious faults in recorders should be corrected by electrician support with care given to parameters that are clouded by the erroneous instrument (i.e., if the CO recorder fails, balance the CO_2 and O_2 readings to approximate).

Always operate on the "safe side." If an upset in instrumentation threatens continuation of safe operation, shut the system down.

A.3.2. Emergencies

1. Emergency shutdown: turn off the "Plenum O₂" and "Vertex O₂" solenoids; increase the vertex CO₂ to >0.0017 std.m³/s and the plenum CO₂ to >0.0075 std.m³/s; and turn the cooling air off. Do not enter the burner cabinet until visual check indicates the area clear of dangerous leakage or hot materials.

<u>Condition</u>	<u>Corrective Action</u>
"Hotspots" in the bed or above the bed which are not correctable under "Upsets and Transients" procedures above. These "overtemperatures" will usually be accompanied by off-gas CO increases to the explosive range (see Fig. A-14).	The emergency shutdown described above.
2. Explosive off-gas CO, O ₂ , CO ₂ mixtures (recorder CO ₂ below 68% coupled with O ₂ recorder above 8%, see Fig. A-14) require immediate correction. Increase CO ₂ and decrease O ₂ until the condition is corrected.	
3. A leak in a flange seal that is not an emergency shutdown condition should be analyzed for severity. If shutdown is deemed advisable, ramp out O ₂ with CO ₂ makeup but to a limit of 0.0017 std.m ³ /s vertex CO ₂ and 0.0050 std.m ³ /s plenum CO ₂ .	
4. A leak in the induction system cooling water coils calls for immediate shutdown of the induction system.	

A.3.3. Faults

A fault involves a burner, cyclone, filter chamber, or connecting piping failure such that a hole is burned through the containing wall.

A fault situation calls for the emergency shutdown described above, except that all gas sources to the burner should be shut off when the bed cools below 600°C.

A.4. SAFETY REQUIREMENTS

The cognizant engineer will ensure that all operators are familiar with the normal and emergency conditions in the burner operations. Successful completion of the Radiological Safety Orientation Course is a mandatory prerequisite. The Flammable Liquids Course is advisable.

A basic rule-of-thumb is "be cautious and ask if you don't know." The cognizant engineer will be responsible for explaining and correcting (if possible) any unsafe operation. Bring any unsafe condition to the attention of the cognizant engineer. The following are normal hazardous conditions and corrective actions encountered in day-to-day operation; operators will be trained per DP-143-5.

<u>Safety</u>	
<u>Condition</u>	<u>Corrective Action</u>
a. The materials handled (thorium, graphite, silicon, insulation materials, etc.) are not to be ingested or spread into uncontrolled areas.	a. Wear respirators and appropriate protective clothing and follow all radiological safety procedures. Limit "dusting" in materials handling by use of dust covers, shrouds, vacuum assists, vent hoods, etc.
b. The induction system carries 100 volts and 500 amps. <u>This can kill you.</u>	b. The east door and corridor adjacent to the burner will be locked and a flashing red light will designate induction system operation. Entry is not allowed to the east corridor.
c. The fines sample cans and hoppers are hot during operation.	c. Wear gloves when removing the fines sample can and avoid contact with the hoppers.

Safety (Continued)

<u>Condition</u>	<u>Corrective Action</u>
d. The burner product is hot (100°C) when removed from the system and the product removal vents some dust.	d. Allow product to cool and do not stay in the cabinet area when dumping product (the induction system will be secured prior to product removal).
e. An "overpressure" condition >330 kPa (>25 psig) may theoretically occur in the burner tube if the off-gas line is somehow blocked.	e. None. The condition probability is zero as the off-gas line has no sealing valves and cannot be plugged by process conditions. Hence, a continuous vent (under vacuum) is provided.

A.5. 0.2-m-DIAMETER PRIMARY BURNER PREOPERATIONAL CHECKLIST AND PROCEDURE

A.5.1. General

1. All operators will be familiar with the equipment, piping layouts, control systems, and support systems. No one will operate the equipment without a formal checkout by the responsible lead engineer.
2. Operators are required to take adequate radiological and general safety precautions.
3. The principal operator is responsible for the operation of the equipment and for fulfilling the run objectives and directives of the lead engineer for the 0.2-m-diameter primary burner.
4. The run will be made following the procedures outlined by the lead engineer. The run objective, required materials, and pertinent comments will be recorded on the Run Outline (Table A-4). It is the responsibility of the lead engineer to provide a Run Outline for each run and to make clear the objective, expected results, and behavior of each run.

TABLE A-4
 RUN OUTLINE: MATERIALS FOR RUN _____
 (RECORD ON MATERIAL BALANCE SHEET: RUN _____)

I. Objective

		kg	Grams ^(a) S-Coke	Special Remarks
II. Startup Bed:	Graphite	_____	_____	_____
	Particles	_____	_____	_____
	Total	_____	_____	_____
III. Supplemental Bed-Addition:	Graphite	_____	_____	_____
	Particles	_____	_____	_____
	Total	_____	_____	_____
IV. Fresh Feed:	Graphite	_____	_____	_____
	Particles	_____	_____	_____
	Total	_____	_____	_____

V. Additional Materials:

VI. Comments:

(a) Coke containing sulfur added to all graphite material to yield
 _____ wt % sulfur.

5. The lead engineer and operators will record preliminary steps, startup steps, and material balance data on the following forms: Run Outline, Table A-4; Pre-Run Checklist A, Table A-5; Pre-Run Checklist B, Table A-6; and Material Balance Sheet, Table A-7.

A.5.2. Preliminary

1. One Day Prior to Operation

- a. Weigh out the quantity and type of feed specified for the startup bed in the Run Outline (Table A-4) and place in a "bed-addition" hopper; attach the hopper to the bed-addition auger with valves on the auger and hopper closed.
- b. Weigh out the quantity and type of supplemental or backup feed specified in the Run Outline and place in another bed-addition hopper (sealed in plastic bags if necessary), and put the hopper near the bed-addition auger system for easy access during the run.
- c. Weigh out the quantity and type of fresh feed specified in the Run Outline. After ensuring that the feed line valve into the burner is closed, add the fresh feed to the fresh feed hopper:
 - (1) Place the graphite portion in a barrel and start fresh feed transport vacuum pump; initiate suction of graphite into the fresh feed hopper as the valve of the particle can (filled with the particle portion) is opened to the hopper.
 - (2) Close inlet valve after all graphite and particles are in the feed hopper.

TABLE A-5
PRE-RUN CHECKLIST A
(ONE DAY PRIOR TO OPERATION)

Item	Initial/ Date
1. Startup bed weighed, sampled, placed in a bed-addition hopper, valves closed; record data on Material Balance Sheet: Run _____.	/
2. Supplemental Feed: (Same as 1 above)	/
3. Fresh Feed: (Same as 1 except using fresh feed hopper system)	/
4. Check CO ₂ supply [____/10 full (call for refill at 3/10)]	/
5. Check O ₂ supply [____/10 full (call for refill at 3/10)]	/
6. Check cooling air blast gates ensuring that 0.20-m-diameter primary are open and all others closed	/
7. Check and open burner off-gas blast gate and burner cabinet ventilation blast gate	/
8. Check all multipoints in operation to see that there are no faulty thermocouple connections	/
9. Check ink and paper in all multipoints and recording instruments for sufficient supply	/
10. Check the gas flow control valves and the perforated distributor magnehelix ΔP , the bed ΔP cell, and the filter ΔP cell with vertex and plenum CO ₂ and O ₂ flow to ensure proper operation: (distributor ΔP at 0.0067 std. m ³ /s plenum CO ₂ flow = _____ in. H ₂ O)	/
11. Check the fines diverter sampling system for proper valve and timer operation	/
12. Check the cooling air blower and butterfly valves for proper operation	/

TABLE A-6
PRE-RUN CHECKLIST B
(IMMEDIATELY PRIOR TO OPERATION)

Item	Initial/ Date
1. Turn on panel power and off-gas analysis recorders and calibrate the off-gas analyzer as detailed in "Gas Analyzer Operating Procedure." Check that the gas sample selector valve is turned to "0.20-m-diameter primary burner" (located on I-beam next to the 0.1-m-diameter secondary burner).	/
2. Turn on multipoints and recorders not yet operating and check for proper operation.	/
3. Spot check all blast gates and feed valves to ensure they are positioned as prepared on the day prior; check the positions of the fines sample diverter valve, cooling air butterfly valve, and gas supply (O ₂ , CO ₂) solenoid valves to ensure closed orientations (panel lights and physical position).	/
4. Open the O ₂ and CO ₂ supply hand valves located on the west side of the burner cabinet, and set the regulators to 60 psig.	/
5. Prepare the induction system for heating as given on the "Induction Heater Operating Procedure - 0.20-m-diameter primary" but <u>do not close contactor</u> (I.C. of Procedure).	/
At this point the burner operational preliminaries are complete.	

TABLE A-7
MATERIAL BALANCE SHEET: RUN _____

Sample	No.	Time	Weight (kg)		% Carbon (% Combustible)	% Broken Particles (% <550 μ m after tray burn)
			Total	Sample		
Startup bed	--					
Supplemental feed	--					
Fresh feed	--					
Products	1					
	2					
	3					
	4					
	5					
	6					
Fines	1					
	2					
	3					
	4					
	5					
Fresh feed hopper ^(a)	--					
Bed-addition hopper ^(a)	--					
North fines hopper ^(a)	--					
South fines hopper ^(a)	--					

(a) Taken at the end of the run.

Additional Materials:

NOTES

1. All of the above materials are to be sampled, sieved, and burned back for size distribution, carbon content, and particle breakage. These data are to be recorded on the Material Balance Sheet: Run ____ (Table A-7).
 2. Add sulfur containing coke to all graphite mixtures as per the Run Outline.
- d. After the above has been done, note on the Pre-Run Checklist A (Table A-5) and follow the remaining procedures on Checklist A.

2. Immediately Prior to Operation

See Pre-Run Checklist B (Table A-6) for items to be covered immediately prior to operation of the 0.2-m-diameter primary burner.

This completes the preliminary steps necessary for the operation of the 0.2-m-diameter primary burner.

A.6. 0.2-m-DIAMETER PRIMARY BURNER INDUCTION HEATER OPERATING PROCEDURE

A.6.1. Startup

1. Open water supply valves to yield the following supply pressures:

MG set	240 kPa (20 psig)
Autotransformer	515 kPa (60 psig)
Coil	377 kPa (40 psig)
Capacitor	240 kPa (20 psig)

Check sight ports to assure return water flow.

2. At outside control station:

- a. Close 600A circuit breaker.
 - b. Select 0.2-m primary on 3-position switch.
 - c. Push "MG Protect Reset" switch.
 - d. Start motor with key switch; wait 1 minute for loud click.
 - e. Switch field on; wait for time delay to kick relay in.
 - f. Push start button - this lights the top light in the control room which shows that the system is operating and ready to supply heat.
3. Close the contactor from the control room - this allows heat to be supplied as field voltage is increased. It also actuates a flashing red light at the burner.
4. Field voltage is increased by a demand controller in Diogenes, which can be operated manually.

A.6.2. Steady-State Operation

During normal steady-state operation, no adjustments to the system are necessary.

A.6.3. Shutdown

1. Decrease field voltage to zero on Diogenes.
2. Open contactors from control room.

3. Turn off field, motor generator, and 600A circuit breaker.
4. Close water valves only after equipment has cooled to ambient (may take several hours).

A.7. OFF-GAS ANALYSIS

Analysis of off-gas is performed continuously to indicate the concentrations of CO_2 , CO, and O_2 . The off-gas is sampled at a point between the outlet of the off-gas filter and the inlet of the off-gas cooler. The pressure and temperature of the sample off-gas are atmospheric and ambient, respectively. The gas is filtered before admission into the analyzers.

An infrared analyzer (LIRA Model 300, Mine Safety Appliances Company) is used to detect and indicate the concentrations of the carbon oxides. The operation of this analyzer is based on the comparative absorption of infrared radiation by a known gas and the unknown gas; differences in infrared absorption spectra in the area of the "component of interest" are detected by a sensitive membrane, electronically amplified, and recorded. This analyzer is a low-sensitivity instrument which can respond quickly (90% of final reading within 5 s) to concentrations of CO and CO_2 in the percent range. The range of gases is typically 70% to 90% for CO_2 and 0% to 15% for CO.

The oxygen analyzer (International Bio-Physics) operates on a polarographic principle: oxygen in the sample gas diffuses through a semi-permeable membrane and is electrolytically reduced; the flow of current is measured and related to oxygen concentration. The analyzer covers ranges of 0% to 100% and 0% to 25%. Linearity around calibrated oxygen concentrations is $\pm 1\%$.

A.8. GAS ANALYZER OPERATING PROCEDURE

A.8.1. General

1. Off-gas from fluid bed burners is continuously analyzed for O_2 , CO , and CO_2 by pumping a bleed stream through a particulate filter into the electronic analyzers. The flow patterns of gas are shown in Fig. A-15, as are valve numbers and equipment items.
2. The system should be calibrated prior to each day of use due to drift of the analyzers. Calibration is performed using gases of known concentration.
3. The filter should be replaced at least every 6 months, depending on usage.

A.8.2. Calibration

1. Switch selector valve to burner desired.
2. Turn valve 11 to sample and valve 3 to sample.
Close valves 4 and 5.
Open valves 1, 2, 9, and 8.
Turn on sample pump.
Adjust valves 6 and 7 to give readings of 0.3 and 3 on the rotameters.

Note the pressure gauge reading (P); it will be used throughout the calibration because the analyzers are very sensitive to their operating pressure.

3. Close valves 8 and 9.
Open zero bottle.
Switch valve 3 to calibrate.
Open valve 5.

Adjust valves 6 and 7 to give 0.3 and 3 on
rotameters. } Repeat until
Adjust valve 10 to give P on pressure gauge. } stable

Set zero on O_2 analyzer, CO analyzers, and CO_2 analyzer.
Shut off zero gas. Close valve 5.

4. Switch valve 3 to sample.
Switch valve 11 to O_2 line.
Adjust valve 6 to give 0.3 on rotameter. } Repeat until
Adjust valve 10 to give P on pressure gauge. } stable

Set 100% span on O_2 analyzer.
Switch valve 3 to calibrate.
Switch valve 11 to sample.

5. Turn on CO_2 span gas bottle.
Open valve 4.
Adjust valve 7 to give 3 on CO_2 rotameter. } Repeat until
Adjust valve 10 to give P on pressure gauge. } stable
Set span on CO_2 and 10% CO analyzers.
Close CO_2 span gas bottle.

6. Open CO span gas bottle.
Adjust valve 7 to give 3 on CO_2 rotameter. } Repeat until
Adjust valve 10 to give P on pressure gauge. } stable
Set span on 30% CO analyzer.
Close CO span gas bottle.

7. Close valve 4. Open valves 8 and 9.
Switch valve 3 to sample.
Adjust valves 6 and 7 to give 0.3 and 3 on rotameters.

8. The analyzer system is now ready for use for about 1 day before recalibration is required. It should be noted that the operating pressure reading P is different for all the burners due to sample line restrictions being widely divergent.

PRIMARY BURNER RUN #										DATE:										ENTERED BY									
TIME	PLENUM FLOW		VERTEX FLOW		MID-RX FLOW		DIST. ΔP (in. H ₂ O)	FEED (% dial)		COOL AIR (% dial)	HOPPER PRESS GAS		ROTA READ AT () psig						MID RX PURGE CO ₂ P7	REMARKS STARTUP BED ADDITIONAL PARTICLES ADDITIONAL FRESH FEED									
	SLPM/psig	SLPM/psig	SLPM/psig	SLPM/psig	SLPM/psig	SLPM/psig		FRESH	BED		SLPM/psig	NOT INTO BURNER			INTO BURNER														
	O ₂ /BACK PRESS.	CO ₂ /BACK PRESS.	O ₂ /BACK PRESS.	CO ₂ /BACK PRESS.	O ₂ /BACK PRESS.	CO ₂ /BACK PRESS.		FEED	ADD																				
	N th	S th	P1	P2	P3	P4		P5	P6																				

Fig. A-1. Log sheet

(ft/s) TOTAL IN-BED GAS FLOW VELOCITY (A) _____

TYPE OF FEED (B) _____

(kg) BED SIZE (C) _____

(SLPM) TOTAL IN-BED O₂ FLOW RATE (D) _____

MAX

[illegible]

g PARTICLES TOTAL

Fig. A-2. Data sheet - Module 1

0.20 m DIAMETER RUN DATA SHEET

MODULE 2 RUN

HIGH LOW CARBON

DATE

ENTERED BY

OPERATING CONDITIONS DESIRED (INDEPENDENT VARIABLES)

		HIGH CARBON			LOW CARBON		
(wt %)	BED CARBON	(A) _____	☐ MAX	☐ MIN	(A) _____	☐ MAX	☐ MIN
(ft/s)	TOTAL BED GAS FLOW VELOCITY	(B) _____	☐ MAX	☐ MIN	(B) _____	☐ MAX	☐ MIN
(SLPM)	TOTAL BED O ₂ FLOW RATE	(C) _____	☐ MAX	☐ MIN	(C) _____	☐ MAX	☐ MIN
	(O ₂) PLENUM/(O ₂) VERTEX	(D) _____	☐ MAX	☐ MIN	(D) _____	☐ MAX	☐ MIN
(SLPM/min)	TOTAL O ₂ RAMP RATE	(E) _____	☐ MAX	☐ MIN	(E) _____	☐ MAX	☐ MIN
(SLPM)	SECONDARY O ₂ ADD	(F) _____	☐ MAX	☐ MIN	(F) _____	☐ MAX	☐ MIN

ACTUAL CONDITIONS

INDEPENDENT VARIABLES						MEASURED VARIABLES DURING RUN																	REMARKS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
TIME	wt % CARBON (A)	ft/s VEL (B)	SLPM BED O ₂ (C)	(O ₂) _p / (O ₂) _v (D)	SLPM/min O ₂ RAMP (E)	SLPM 2ND O ₂ (F)	BED TEMP (°C) AT TC								WALL TEMP (°C) AT TC					FINES SAMPLE		OFF GAS (°)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
							1	2	3	4	5	6	7	8	14	15	16	17	18	#	g/min	O ₂		CO ₂	CO																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			</

MEASURED DEPENDENT VARIABLES AFTER RUN

PARTICLE EFFECTS

FINAL BED wt % BREAKAGE _____

FINAL BED wt % AGGLOMERATION _____

_____ g PARTICLES IN FINES SAMPLE _____

_____ g PARTICLES IN FINES SAMPLE _____

_____ g PARTICLES IN FINES HOPPERS _____

_____ g PARTICLES TOTAL

Fig. A-3. Data sheet - Module 2

OPERATING CONDITIONS DESIRED (INDEPENDENT VARIABLES)

HIGH CARBON

(g/min.)	FRESH FEED RATE	(A)	_____	☐ MAX	☐ MIN
(SLPM)	TOTAL BED O ₂ FLOW RATE	(B)	_____	☐ MAX	☐ MIN
(ft/s)	TOTAL BED GAS FLOW VELOCITY	(C)	_____	☐ MAX	☐ MIN
	(O ₂) PLENUM/(O ₂) VERTEX	(D)	_____	☐ MAX	☐ MIN
(SLPM/min)	TOTAL O ₂ RAMP RATE	(E)	_____	☐ MAX	☐ MIN
(SLPM)	SECONDARY O ₂ ADD	(F)	_____	☐ MAX	☐ MIN

ACTUAL CONDITIONS

INDEPENDENT VARIABLES						MEASURED VARIABLES DURING RUN																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
TIME	(g/min) FEED RATE (A)	SLPM BED O ₂ (B)	(ft/s) VEL. (C)	(O ₂) _p / (O ₂) _v (D)	SLPM/min. O ₂ RAMP (E)	SLPM 2ND O ₂ (F)	BED TEMP (°C) AT TC								WALL TEMP (°C) AT TC					FINES SAMPLE		OFF GAS (%)			REMARKS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
							1	2	3	4	5	6	7	8	14	15	16	17	18	-	g/min	O ₂	CO ₂	CO																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										

MEASURED DEPENDENT VARIABLES AFTER RUN

PARTICLE EFFECTS

FINAL BED wt % BREAKAGE _____

FINAL BED wt % AGGLOMERATION _____

_____ g PARTICLES IN FINES SAMPLE _____

_____ g PARTICLES IN FINES SAMPLE _____

_____ g PARTICLES IN FINES HOPPERS _____

_____ g PARTICLES TOTAL

Fig. A-4. Data sheet - Module 3

☐ 5.

[illegible]

MEASURED DEPENDENT VARIABLES AFTER RUN

_____g PARTICLES TOTAL

Fig. A-5. Data sheet - Module 4

OPERATING CONDITIONS DESIRED (INDEPENDENT VARIABLES)

METHOD OF FINES RECYCLE

SECONDARY O₂ ADDITION

TIME OF RECYCLE INITIATION

(SLPM) TOTAL O₂ FLOW RATE TO BED

(ft/s) TOTAL IN BED GAS FLOW VELOCITY

HIGH CARBON

(A) _____ ☐ MAX ☐ MIN(B) _____ ☐ MAX ☐ MIN(C) _____ ☐ MAX ☐ MIN(D) _____ ☐ MAX ☐ MIN(E) _____ ☐ MAX ☐ MIN

ACTUAL CONDITIONS

INDEPENDENT VARIABLES						MEASURED VARIABLES DURING RUN																			
TIME	FINES METHOD (A)	SLPM 2ND O ₂ (B)	TIME RECYCLE (C)	SLPM BED O ₂ (D)	(ft/s) VEL (E)	BED TEMP (°C) AT TC								WALL TEMP (°C) AT TC					FINES SAMPLE		OFF GAS (%)			REMARKS	
						1	2	3	4	5	6	7	8	14	15	16	17	18	=	g/min	O ₂	CO ₂	CO		

MEASURED DEPENDENT VARIABLES AFTER RUN

PARTICLE EFFECTS

FINAL BED wt % BREAKAGE _____

FINAL BED wt % AGGLOMERATION _____

_____ g PARTICLES IN FINES SAMPLE _____

_____ g PARTICLES IN FINES SAMPLE _____

_____ g PARTICLES IN FINES HOPPERS _____

_____ g PARTICLES TOTAL _____

Fig. A-6. Data sheet - Module 5

OPERATING CONDITIONS DESIRED (INDEPENDENT VARIABLES)

TAIL-BURN ASSIST (A) _____

☐ YES☐ NOOFF-GAS O₂ ALLOWED (B) _____☐ 10%☐ 5%

FINES BURNOUT (C) _____

☐ YES☐ NO

ACTUAL CONDITIONS

TIME	INDEPENDENT VARIABLES			MEASURED VARIABLES DURING RUN																				REMARKS																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
	TAILBURN ASSIST (A)	OFF-GAS O ₂ ALLOWED (B)	FINES BURNOUT (C)	BED TEMP. (°C) AT TC								WALL TEMP (°C) AT TC						SUSCEPTOR TEMP (°C) AT TC				OFF GAS (%)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
				1	2	3	4	5	6	7	8	14	15	16	17	18	1'	2'	3'	4'	O ₂	CO	CO ₂																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							</

MEASURED DEPENDENT VARIABLES AFTER RUN

PARTICLE EFFECTS

FINAL BED wt % BREAKAGE _____

FINAL BED wt % AGGLOMERATION _____

_____ g PARTICLES IN FINES SAMPLE # _____

_____ g PARTICLES IN FINES SAMPLE # _____

_____ g PARTICLES IN FINES HOPPERS # _____

_____ g PARTICLES TOTAL

WT % CARBON IN FINAL BED _____

Fig. A-7. Data sheet - Module 6

Fig. A-8. Primary burner control panel I

Fig. A-10. 0.20-m-diameter primary burner control room instrumentation

Fig. A-11. 0.20-m-diameter primary burner cabinet instrumentation

A-12. 0.20-m-diameter primary burner system

Fig. A-13. Bed addition auger calibration

Fig. A-14. Explosive limits of carbon monoxide in mixtures of oxygen and carbon dioxide

Fig. A-15. Off-gas analyzer flow diagram

MSA Lira Data Sheet

Customer Name Gulf Energy MSA Order No. 378508
 Model Number 303 115 VAC 60 HZ Analyzer Serial Number 30932
 Thermostat Temp: 140 to 145 °F. Sample Flow: 1-4 SCFH at 0 PSIG
 Customer Order No. 503939 Absorption: 24 % By 100% CO2
 Span Check Reading: _____ Amplifier Gain: X- 10 Non Linearity: 9 % F.S.
 Sample Cell: Length 0.026" Cell Material AL Source Windows Caf2 w/CFQ S.
 Sample Filter Cell: Length 4.474" Windows Caf2 Gas 50% CO/50% IC4
 Comparison Cell: Length 5.5" Windows Caf2 Gas 50% CO/50% IC4
 Detector: Dryer Dehy. Windows Caf2 Gas 100% CO2
 Interrupter: Metal Oscillator Volts: 10.4 VDC Zeroing Gas: 100% N2
 Amplifier Response: 5 Sec. Zero Setting: 5 Span Setting: 5

A373 REV 2

GAS CONCENTRATION

893324

Fig. A-16. Off-gas correction curve - CO₂

MSA Ltd Data Sheet

Customer Name Gulf General Atomics MSA Order No. 830919
 Model Number 303 120 VAC 60 HZ Analyzer Serial Number 31944
 Thermostat Temp: 140 to 145 °F. Sample Flow: 1-4 SCFH at 0 PSIG
 Customer Order No. 500543 Absorption: 14 % By 100% CO
 Span Check Reading: None Amplifier Gain: X- 10 Non Linearity: 12 % F.S.
 Sample Cell: Length .06 Cell Material AL Source Windows Caf2 w/CFQ
 Sample Filter Cell: Length 4.9" Windows Caf2 Gas 50% CO2 in IC4
 Comparison Cell: Length 5.5" Windows Caf2 Gas 50% CO2 in IC4
 Detector: Dryer Sod. Windows Caf2 Gas 50% CO in A
 Interrupter: Metal Oscillator Volts: 8.5 VDC Zeroing Gas: N2
 Amplifier Response: 5 Sec. Zero Setting: 5 Span Setting: 5

CALIBRATION CURVE

A373 REV 2

GAS CONCENTRATION

883324

Fig. A-17. Off-gas correction curve - CO

APPENDIX B
SUMMARY OF EARLY BURNER RUNS

TABLE B-1
SUMMARY OF EARLY BURNER EXPERIMENTS

Run	Objectives	Observations/Conclusions
7	<p>Test dilute phase fines recycle premixed with gas to cone bottom; Penberthy ejector on bottom of fines hopper. Fines introduced late in run to observe effects on equilibrium operation. Ball/cone distributor</p> <p>Test operation using startup that adds significant quantity of particles initially to maintain cone area material size average as low as possible.</p>	<p>Limited fines transport was noted visually. Sampling of fines circulation was disrupted by cyclone bridging and fines salt-out in horizontal lines. Effects of fines injection were reduction of in-bed temperature and increase in above-bed temperatures.</p> <p>No operating problems or agglomerates as seen in prior runs. The cone temperature was lower than temperatures higher on the bed, indicating high particle concentration in the cone, hence decreased spouting potential.</p>
8	<p>Test longer duration of dilute phase fines recycle premixed with cone gas. Ejector on bottom of fines hopper, fines introduced during startup. Better fines circulation monitoring with N₂ purges to overhead lines to curtail bridging.</p>	<p>Material balance indicated about 50% of generated fines were burned at average bed back pressure of 38 in. H₂O. Partial blockage of ejector by pieces of the diverter valve plastic seal was thought to be the limiting factor in mass transport. Premixed fines injection again lowered in-bed temperature and increased above-bed temperatures.</p>
9	<p>Further study dilute, pneumatic fines recycle; fines recycle as in Run 8. Fines sample diverter valve seat resurfaced with metal to improve fines circulator monitoring.</p>	<p>Negligible fines burning. Fines ejector was blocked by bed material backflow during initial fines transport gas introduction; called for reorientation of the ejector on the fines hopper to prevent material buildup and also a change in fines transport introduction. Fines ignited above the bed as bed carbon burned out.</p>
10	<p>Recycle fines with ejector on the side of the fines hopper and abrupt fines introduction to preclude bed material backing up and blocking ejector.</p>	<p>Fines lowered bed temperature and hence oxygen consumption and ignited above the bed. The run was shut down to prevent thermowell burn-through. Abrupt fines introduction not desirable. Need to bring in fines during startup with a continuous ejector bypass gas purge to prevent bed material backflow and to stabilize fines introduction.</p>

TABLE B-1 (Continued)

Run	Objectives	Observations/Conclusions
11	Recycle fines tangentially to cone with ejector bypass purge, rather than vertical premixed injection as in prior runs. Fines recycle introduced during startup by increasing fines transport gas while decreasing purge gas.	Fines flow initially high but decreased as bed level was increased. About 15% fines burning at average bed back pressure of 52 in. H ₂ O. No material in ejector which represented optimum; hence, this method is unacceptable. Tangential injection yielded smoother in-bed temperature effects with less significant temperature decreases.
12	Test initial operation with perforated cone distributor. Startup with full-sized fresh feed. No fines recycle.	<p>Cone area temperature excursions during startup with the full-sized fresh feed thought to be due to defluidized burning of the large graphite under limited startup gas flow rate conditions. Cone area temperature excursions as bed carbon burned out thought to be due to decreased heat transfer to large graphite remaining in the cone at bed burnout.</p> <p>Small (<4000 μm) agglomerates were found in the final bed, amounting to 0.5% of the total final bed weight. These fused particles were thought to be formed during the temperature excursions.</p>
13	Further test perforated cone with full-sized fresh feed for startup. Initial O ₂ introduction made through cone perforations instead of vertex inlet as in Run 12. No fines recycle.	Temperature excursions occurred as in Run 12. Excursions as bed burned out were less significant. This was thought to be due to a larger quantity of final bed particles in Run 13 than in Run 12 and resultant better heat transfer. Agglomerates (<4000 μ m) constituted 0.45% of the final bed

TABLE B-1 (Continued)

Run	Objectives	Observations/Conclusions
14	Avoid startup temperature excursion using an initial feed of -1400 μ m graphite mixed with particles prior to full-sized fresh feed addition. Perforated cone distributor. No fines recycle.	No startup cone area temperature excursions seen. Smooth operation with large fresh feed. Cone area temperatures again increased as bed carbon burned out. Agglomerates were found but in less than half the quantity seen in Runs 12 and 13 (0.2% of final bed).
15	Perform longer run with product take-off during operation to pinpoint time of any agglomerate formation. Perforated cone distributor. No fines recycle. Increase diluent flow at bed burnout to improve large graphite circulation in the cone area and to dampen temperature effects of immobile large graphite burning. Test full batch dump at end of the run.	No significant cone area temperature excursions during startup or shutdown. No agglomerates found in mid-run products or in the final bed. Twenty-five kilograms of final bed material were dumped in approximately 2 minutes with no problems.
16	Test 50° included angle perforated conical distributor with a larger bed weight of "oversize" feed (the feed was "oversize" based on fluidization criteria established in the 0.1-m-diameter burner using a ball/cone distributor). Introduce pure O ₂ to vertex of perforated cone early in run.	34-kg final bed was high in carbon especially in the upper region. Lower 32.6 kg (17.8% carbon) dumped through 12.7-mm vertex at 15 kg/min. Top 1.4 kg (62.7% carbon) contained some fresh feed size graphite and bridged at the 12.7-mm opening. The 0.4-m-diameter prototype distributor design was subsequently revised to allow enlarging the diameter of the cone vertex opening. Vertex O ₂ injection was too abrupt as it was accompanied by a bed temperature excursion. Revised system for incremental O ₂ /CO ₂ ratio adjustments later in the run.

TABLE B-1 (Continued)

Run	Objectives	Observations/Conclusions
16.1 16.2 16.3	Test torch startup with varied amounts of fresh feed size graphite and particle beds using new high-capacity CO ₂ diluent system.	The large bed material volume and the high CO ₂ gas rates required to fluidize the bed created heat losses greater than the heat input available with the torch system. Standard small bed/coke startup to be used until induction system installation.
17	Further study burner response to oversize feed with revised thermocouple locations including an in-cone thermocouple.	In-cone temperature cycling 10° to 30°C above bulk bed temperature. Cycling analogous to cyclic spouting seen with the single inlet ball/cone distributor and thought to be a result of the larger fraction of the fresh feed graphite periodically gravitating into the cone. The larger graphite chunks were possibly less mobile than the smaller bulk of the graphite and hence the decreased convective particle heat transfer caused temporal increases in local cone temperature. These oscillations dampened as the run progressed. This was attributed to an increase in in-cone fuel particle concentration and resultant dampening of locally intense combustion of larger graphite.
	Study gas distributor vertex/cone perforation gas balance with revised capability to ramp CO ₂ /O ₂ flows in small increments.	Burner operated in pure O ₂ with no problem when O ₂ level was increased in small increments as the run progressed and the bed particle concentration increased.
	Test bed burnout using the new high-capacity CO ₂ diluent system. Increase diluent flow during bed burnout phase to allow cooling air reductions (instead of increases in cooling air as necessary in past runs with low-capacity N ₂ diluent system).	Bed burnout very successful with revised operating procedure. About 0.07% carbon in the final bed.

TABLE B-1 (Continued)

Run	Objectives	Observations/Conclusions
18	<p>Characterize operation with a higher particle concentration bed using "oversize" feed similar to Run 17.</p> <p>Duplicate bed burnout of Run 17 to recheck diluent increase/cooling air decrease procedure.</p>	<p>No in-core temperature oscillations noted; apparent verification of fuel particle dampening effects on local temperature problems and indication that equilibrium operation should be smooth compared with the difficult initial period of operation with high bed carbon content.</p> <p>Bed burnout to less than 0.1% carbon.</p>
19	<p>Test operation with an oversize feed specially sieved to fall on 100-mm ball/cone poor fluidization line [$\sim 3\% > 4.76 \text{ mm}$ (3/16 in.)].</p> <p>Bed burnout with $\sim 20\% \text{ CO}_2$ diluent to study limiting off-gas O_2 concentration (prior successful burnouts used 100% O_2 in feed gas).</p>	<p>Operation acceptable. In-cone temperature cycling of 10° to 30°C every 90 to 120 s disappeared as run progressed (after about 2 h of operation).</p> <p>Final bed carbon again less than 0.1%</p>
20	<p>Test operation with an oversized feed [$5\% > 4.76 \text{ mm}$ (3/16 in.)].</p> <p>Increase CO_2 diluent/O_2 ration (66% CO_2 feed gas) to test effects of limiting off-gas O_2 at burnout (18% O_2 in off-gas).</p>	<p>Same as Run 19</p> <p>Top bed carbon 0.93% and bulk bed carbon 0.2% indicating some decrease in burnout and graphite "floating" on top of particle bed when using low O_2/CO_2 feed gas ratio.</p>
21	Test operation with a 120° included angle distributor cone.	Operation acceptable. Temperature cycling up to 20°C on a 1 to 2 minute cycle was experienced on the underside of the cone early in the run. The cycling dampened to 5° to 10°C as the run progressed but never completely disappeared. In-cone material packing with intense slugging was evident.

TABLE B-1 (Continued)

Run	Objectives	Observations/Conclusions
21 (cont)	Determine burnout characteristics.	Final bed contained 0.18 wt % agglomerated particles with additional agglomerates and single particles found fused and sunk into the shallow cone surface. Results indicated a dangerous stagnation potential with a shallow cone.
22A,B,C, 23, 24	Shakedown dense-phase pressurized dual-parallel hopper fines recycle system.	Fines mass flow rate found to be heavily dependent on both hopper outlet line size and hopper pressurizing gas flow rates. Recycle lines sized at 0.0125-m I.D. Large graphite and/or fuel particles which elutriated were likely to seriously hamper or block fines flow. Burner vessel was lengthened from 2.79 to 3.68 m to increase de-entrainment space.
25	Test operation with dense-phase pressurized fines recycle to a high carbon bed.	Bed temperature cycled $\pm 15^{\circ}$ to 60°C throughout the run period prior to fines burnout. This was due to intermittent fines recycle flow. Fines burning in a high-carbon bed was found to be insignificant; fines generation and accumulation was exceedingly high ($\sim 40\%$ of fresh feed weight).
	Determine bed/fines burnout characteristics.	Temperature control became much more difficult during fines burnout period. Appreciable above-bed fines burning occurred only late in the operating cycle after fresh feed flow was terminated and the bed carbon significantly decreased. End-of-run hopper material contained approximately 20 wt % noncombustibles (whole and broken fuel particles).
	Test operation with a 0.021-m-I.D. pulsed, pneumatic fresh feeder.	Fresh feed flow was generally consistent. Occasional bridging was experienced.

TABLE B-1 (Continued)

Run	Objectives	Observations/Conclusions
26	<p>Test operation with dense-phase pressurized fines recycle to a low-carbon bed.</p> <p>Determine bed/fines burnout characteristics.</p> <p>Test operation with a 0.021-m I.D. pulsed, pneumatic fresh feeder.</p>	<p>Fines generation was significantly reduced by low-carbon operation. Operation was considerably smoother and easier to control than high-carbon operation. Lack of excessive fines generation resulted in decreased residence time of the fines in the hoppers; recycled fines were hotter and caused less thermal cycling in the bed.</p> <p>Control of end-of-run above-bed fines burning much easier with fewer recycling fines. Wall temperatures remained below 900°C without cooling during the above-bed fines burning period.</p> <p>Run terminated when the bed was extinguished by a lack of bed carbon caused by inconsistent feed flow.</p>
27	<p>Test operation with dense-phase pressurized fines recycle to a low-carbon bed.</p> <p>Determine bed/fines burnout characteristics.</p> <p>Test operation with automatic control of the fines recycle system.</p>	<p>End-of-run fines inventories were less than the original hopper inventories indicating that more fines were burned than accumulated in low-carbon operation. Off-gas CO concentration of 20% to 25% throughout run indicated significant fines burning. CO off-gas concentration cycled in unison with intermittent fines recycle flow and cycling bed temperatures.</p> <p>End-of-run hopper contents showed no large graphite but significant amounts of whole and broken particles, oxides, hulls, and graphite fines. Graphite fines were extremely small and cohesive due to numerous passes through the recycle loop; fines bulk density was 0.22 Mg/m³.</p> <p>Timers were utilized to provide smooth control of hopper switching frequency.</p>

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
28	<p>Test operation with dense-phase pressurized fines recycle to a low-carbon bed; determine bed/fines burnout characteristics.</p> <p>Test operation with addition of mid-reactor oxygen introduced to the burner.</p>	<p>Similar to Run 27. End-of-run fines hopper material contained approximately 70 wt % noncombustibles.</p> <p>Fines burning was aided by mid-reactor O_2. Mid-reactor O_2 accounted for ~3% of total carbon burned during run.</p>
29	<p>Test low-carbon operation with fines recycle to the distributor cone vertex gas line (90° cone).</p> <p>Test operation with an improved fines recycle automatic control system.</p> <p>Test operation with a rotary valve fresh feeder</p>	<p>Plugging of bed ΔP lines resulted in a bed of unknown weight and higher than planned bed carbon. Inadvertent reversal of gas line connections to the distributor resulted in excessive flow to the cone vertex, which caused particle breakage in the bed of ~80 wt %.</p> <p>New timing equipment resulted in more efficient operation of the fines recycle system. Less bed thermal cycling was evident.</p> <p>Rotary valve fresh feeder performed acceptably with no blockage of materials.</p>
30	<p>Test performance of 90° perforated conical distributor.</p> <p>Investigate effect of fines recycle to the distributor vertex.</p> <p>Test a recycle hopper switching system (electrical).</p>	<p>The 90° distributor allowed better operation than with the previously used 50° and 120° cones. Operating temperatures below the cone were cooler and no bed solids fusion was noted on the cone surface.</p> <p>Fines recycle equipment worked well against 122 to 136 kPa (3 to 5 psig) back-pressure. No line plugging occurred.</p> <p>Recycle of fines through the bed caused only minimal thermal cycling.</p>

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
30 (cont)		<p>"Superfines" were evident during the final stages of the run but were burned with no difficulty.</p> <p>Complete control of in-bed and above-bed temperatures was maintained by varying the inlet O_2/CO_2 ratio.</p>
31	Investigate operation with secondary oxygen inlets located above the bed.	<p>Run was shut down prematurely due to foreign obstruction in fresh feed rotary valve.</p> <p>The final bed and fines inventory were allowed to burn out in typical fashion with ~300 g fines remaining in the hoppers at the end.</p>
32	Investigate operation with secondary oxygen inlets located above the bed.	<p>Secondary oxygen was introduced either into the bed slugging zone (above static bed) or completely above the bed.</p> <p>Greater oxygen utilization was achieved with the lower tap.</p> <p>Definite evidence of above-bed CO/fines burning was seen in the burner temperature profile and off-gas concentration.</p> <p>Control of above-bed temperatures was not a problem. A stable burning zone was maintained as long as fines recycle flow and elutriation were reasonably continuous.</p> <p>Toward the end of the run, ~4 kg "superfines" fell back into the bed. These extremely small and cohesive fines apparently stick to the upper vessel surfaces.</p>

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
32 (cont)		"Superfines" remained clumped in the bed after falling back and exhibited burning characteristics similar to larger in-bed graphite.
33	Investigate further operation with secondary inlets located above the bed.	All process characteristics and phenomena observed in previous run were essentially duplicated.
	Investigate further the various phenomena observed in the previous run.	~7 kg superfines fall-back occurred.
		Final fines inventory was <200 g.
34	Test operation of an improved hopper pressurization sequencing system.	The improved electrical fines recycle controls provided an almost uniform fines flow to the vertex with only minimal thermal cycling in the bed.
	Investigate fines burning characteristics with secondary above-bed oxygen and improved fines recycle flow.	The initial fines inventory was reduced considerably within a few hours and remained low for the rest of the run.
		Superfines fall-back occurred toward the end of the run. Immediate shutdown verified the existence of a large mass of clumped fines which floated on top of the final bed.
35	Investigate effect of operation with fines recycle to a point above the bed (into the bed slugging zone above the static bed).	The recycle equipment worked very well against a lower back-pressure [<108 kPa (<1 psig)] with no plugging and an almost uniform fines flow.
	Investigate characteristics of fines transport and operation of the fines recycle system (dense phase) with above-bed fines injection.	In-bed and above-bed temperature control was good with essentially no thermal cycling in either zone.

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
35 (cont)	Determine fines burning capabilities with this configuration.	<p data-bbox="1166 343 1991 434">Above-bed temperature, and hence oxygen utilization, was adversely affected by external cooling of the burner above the bed.</p> <p data-bbox="1166 472 1953 500">Superfines fall-back occurred as in previous runs.</p> <p data-bbox="1166 538 2013 690">After the large in-bed graphite in the final bed was completely consumed, the particle bed temperature decreased to a final temperature with 400°C while the above-bed fines burning zone was sustained at ~900°C (~50 min).</p> <p data-bbox="1166 728 1991 913">Above-bed fines burn rate during tail-burning was significantly decreased (<100 g/min) due to higher temperatures associated with dilute phase fines burning and the inability to remove process heat as quickly as from a particle bed; hence, the O_2/CO_2 ratio was reduced.</p> <p data-bbox="1166 951 2013 1103">The fines inventory throughout the run was at its maximum early when recycle flow was initially started. It then steadily decreased to ~4 kg at the start of the final fines burning period. This represented <5% of the total graphite fed to the burner.</p> <p data-bbox="1166 1141 1885 1202">Final fines hoppers contained only 79 g (~25% noncombustible) after shutdown.</p> <p data-bbox="1166 1240 1991 1331">Above-bed recycle apparently results in suppression of bed solids slugging and decreased particle carry-over (compared with vertex injection).</p>

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
35 (cont)		As in previous runs, the jack-hammering effect of the slugging bed resulted in appreciable drainage of fuel particles into the distributor plenum chamber.
36	Verify operation and results of previous run. Start with initial fines heels in the recycle hoppers to test operation with a large fines inventory.	The larger fines inventory had no effect on operation of the fines recycle equipment. The fines inventory decreased as the run progressed. Superfines production was higher than usual because of the initial fines inventory. Superfines result from many recycle passes through the burner. Superfines fall-back occurred in significant amounts at least three separate times. Final fines hopper inventories showed only ~180 g (~25% noncombustible). Drainage of whole and broken particles into the distributor plenum chamber amounted to ~800 g. Results of Run 35 were essentially duplicated.
37	Obtain more data and operating experience with above-bed fines recycle. Determine effects of increased secondary above-bed oxygen flow on off-gas CO (attempt to reduce percent CO)	Results were generally similar to Runs 35 and 36. Increased above-bed oxygen flow resulted in increased above-bed fines burning. CO off-gas concentration actually increased as above-bed oxygen flow increased. This indicated appreciable fines burning rather than CO oxidation.

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
38	<p>Investigate effects of long-term operation (24-h) on burner components and on the over-all process.</p> <p>Test long-term operation of recycle equipment and determine fines generation and burning characteristics.</p>	<p>Recycle equipment operated successfully throughout the run with no change in operating characteristics.</p> <p>Fines accumulation was not excessive at any time.</p> <p>Fresh feed hopper flow inconsistencies were encountered. Future installation of an aeration screen will remedy this problem.</p> <p>Several superfines fall-backs as in previous runs.</p> <p>The run was terminated prematurely (after 22 h) by an excessive increase in external cooling initiated by operator error. Subsequent remedial action was insufficient to maintain combustion.</p> <p>End-of-run materials indicated ~9 kg fines (~7 kg superfines resting on top of the bed and ~2 kg fines in the hoppers). This fine carbon together with ~4 kg fresh feed carbon in the bed (13% carbon bed) indicate a typical "equilibrium" situation. A total of 11 kg carbon explains >1 h burnout needed in these fines recycle runs.</p> <p>~1400 g particle drainage into the distributor chamber.</p>
39	Same as Run 38	<p>Results on Run 38 were essentially duplicated.</p> <p>The run was concluded after 25-1/2 h by burnout of the end-of-run fines inventory and bed carbon (~2.5 h low burn-rate burnout).</p> <p>Final fines inventory was ~840 g (<1% noncombustible).</p>

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
39 (cont)		<p>~900 g particle drainage into the distributor chamber.</p> <p>~380 g <2000 μm agglomerates in the final bed. (Compares with <50 g agglomerates in 8-h runs; increased agglomerates due to longer run with reused, cracked particles.)</p> <p>There were essentially no serious effects of long-term operation on either equipment performance or on overall process characteristics.</p>
40	<p>Investigate effects of long-term operation (24 h) on burner components and on the overall process using fines recycle to the vertex.</p> <p>Test long-term operation of recycle equipment and determine fines generation and burning characteristics with fines recycle to the vertex.</p>	<p>Recycle equipment operated successfully throughout with no change in operating characteristics.</p> <p>With the use of above-bed oxygen, fines burning characteristics were comparably to those with above-bed recycle.</p> <p>Fines accumulation was not excessive at any time.</p> <p>Fines recycle to the vertex results in somewhat more bed thermal instability and potential for serious process upset than does above-bed recycle.</p> <p>Superfines fall-backs occurred as in previous runs.</p> <p>The final fines hopper inventory was ~2000 g (93% noncombustible particles, hulls, and ThO_2). Particles found salted-out in fines recycle lines into the burner and high ThO content of fines indicate elutriation, recycle, and possibly jet-grinding of particles using vertex fines recycle.</p>

TABLE B-1 (continued)

Run	Objectives	Observations/Conclusions
40 (cont)		~2000 g agglomerates in the final bed. This agglomeration relates to breakage mechanism. ~400 g particle drainage into the distributor chamber.

TABLE B-2
COMPARISON OF PERFORATED CONICAL DISTRIBUTORS OF VARIED CONE ANGLE

CONE ANGLE	RUN	CONE TEMPERATURE (°C)		WT % AGGLOMERATES IN FINAL BED	MINIMUM DISTRIBUTOR GAS FLOW (std. m ³ /s)	COMMENTS
		SURFACE	PLENUM			
50°	17	>750 (touch- ing)	450 (mid- plenum)		0.0064	Surface temperature recorded by thermo- couple touching underside of cone. Plenum temperature in middle of plenum chamber. Red iron oxide tinge on surface indication of high temperatures.
50°	18	>700+	400		0.0060	High bed particle concentration yielded lower temperatures.
50°	19	>600	400		0.0061	Red tinge increased in coverage. Surface thermocouple not touching in this run.
50°	20	>625	425	0.06 (≤4000 μm)	0.0042	Low plenum flow when particles first intro- duced probable cause of agglomerates.
120°	21	<725 (embedded)	<425 (mid- plenum)	0.18	0.0050	Embedded surface thermocouple cycled 5° to 15°C around 725°C as larger fresh feed burn- ed. Agglomerates relatively large in quan- tity and several fused to plate surface in- dicating insufficient slope.
90°	30	<700 (embedded)	<400 (mid- plenum)	0.03	0.0040	Cycling plate temperature 5° to 10°C before fines recycle, 10° to 30°C during recycle.
90°	31	700 ±15	350	See comments	0.0048	Fuel particles fused to droplet-shaped stainless steel (110 g total weight). The cyclone internal was checked and found to have stalactite-like projections from section burned in Run 25. The section was ground smooth.
90°	32	700 ±20	350	See comments	0.0041	Reduced amount of stainless steel droplet- particle agglomerates (12 g) evidently residual in system.

APPENDIX C
DESIGN OF STATISTICAL ANALYSIS EXPERIMENTS

The "factorial design" approach (Ref. 11) was utilized in designing an experimental program for the 0.2-m-diameter primary burner. This analytical method offers the following advantages:

1. Forces consideration of all possible independent variables and their effects on the system.
2. The value of the experiments is maximized; i.e., the maximum amount of useful data is obtained from a given number of experiments.
3. Information is obtained on the effects of interaction of variables.
4. An estimate of the experimental error can often be made, preventing unwarranted conclusions.

The experimental program for the 0.2-m-diameter primary burner was designed to achieve the following five major objectives:

1. Heating/cooling - Verify the feasibility of the induction-susceptor heating/cooling technique for bed ignition and temperature control and obtain heat transfer coefficients.
2. Fines recycle - Determine the optimum method of recycle fines injection into the burner.

3. Fines carryover - Carry out a parametric program to determine quantitatively the causes and effects of fines elutriation from the burner.
4. Off-gas composition - Determine off-gas composition as a function of burner operation.
5. Automatic control - Verify the feasibility of remote-automatic control of the burner system and gain experience with the computer-based process controller (Diogenes).

The first step in the statistical design of experiments was to develop a more detailed characterization of the seven proposed modules, determining both the measured (dependent) variables and the process alternatives (independent variables) for each module.

Module 1: Heatup and Ignition

Dependent (Measured) Variables

Heatup time
 Radial and axial burner temperature distribution
 Particle breakage/agglomeration/elutriation
 Fines elutriation data

Independent (Controlled) Variables	Symbol	Level	
		Max.	Min.
Total in-bed gas flow velocity, m/s	A	1.21	1.10
Type of feed ^(a) (micron averages = d_{RR})	B	2800	2000
Bed size, kg	C	36	32
Total in-bed O ₂ flow rate, std. m ³ /s	D	0.0025	0.0017

(a) The Rosin-Rammler material averages are 66.6% of the R-R plot. The feed consists of 83% graphite and 17% fertile FSV particle (TRISO).

Module 1 consisted of eight runs of ~4-h duration each. Since the purpose of this module was to determine the burner startup characteristics with induction-heated bed ignition and temperature control, data collected during the first hour or so were of most interest. The eight experiments in this module were devised to determine the effects of four independent variables, at two levels, on burner startup characteristics (measured variables) such as bed heatup time, radial and axial bed temperature distributions, and particle breakage, accumulation, and agglomeration. During each of the eight experiments, the values of the four independent variables were fixed at maximum or minimum levels. Data taken during Module 1 included the following:

Characterize induction heating	1. Heatup time. 2. Power required. 3. Heater control [temperature profiles throughout the heated zone (susceptor, vessel, and bed) to determine optimum thermocouple location].
Determine bed size and gas flow rates needed for optimum induction-heated startup	4. Isothermal axial conditions in heated zone: a. Bed heatup below heated zone - based on cold benchwork, determine optimum gas flow rate and a distributor vertex/plenum flow rate to provide sufficient mixing to heat lower bed solids below the heated zone of the bed. Verify hot. b. Bed size for isothermal upper heated zone - based on cold benchwork, determine minimum bed weight which provides good heat transfer throughout heated zone under gas flow conditions which accomplish (a) above. Verify hot.
Determine causes for small (<2000 μm) agglomerate formation	5. Particle breakage and/or particle agglomeration.

Module 2: High-to-Low Carbon Bed Operation (No Fresh Feed)

Dependent Variables

Fines elutriation data
Radial and axial burner temperature distributions
Off-gas composition (CO, CO₂, O₂)
Particle and fines data

Independent Variables	Symbol	High Carbon (>50%)		Low Carbon (<50%)	
		Max.	Min.	Max.	Min.
Bed carbon, wt %	A	70	50	30	15
Total in-bed gas flow velocity, m/s	B	1.21	1.10	1.10	1.01
Total in-bed O ₂ flow rate, std.m ³ /s	C	0.0042	0.0033	0.0058	0.0050
(O ₂) plenum/(O ₂) vertex	D	∞	4	∞	4
Total O ₂ ramp rate, std.m ³ /s/s	E	0.004	0.002	0.008	0.004
Secondary O ₂ addition	F	Yes ^(a)	No	Yes ^(a)	No

(a) Secondary (above-bed) O₂ will be added to a maximum quantity limited by off-gas O₂ increases indicating the additional O₂ is not being consumed.

Module 2 consisted of the same eight runs as in Module 1, except that the independent variables were re-identified and adjusted. Data taken during Module 2 were used to determine the effects of the eight stated independent variables on fines elutriation rate, radial and axial bed temperature distributions, and combustion off-gas composition (CO, CO₂, O₂).

Module 3: Constant Low-Carbon Bed Operation (Fresh Feed)

Dependent Variable

Fines elutriation data
Radial and axial burner temperature distributions
Off-gas composition (CO, CO₂, O₂)
Particle and fines data

Independent Variables	Symbol	Max.	Min.
Fresh feed rate, g/s	A	~7.5	~6.67
Total in-bed O ₂ flow rate, std. m ³ /s	B	0.0058	0.0050
Total in-bed gas flow velocity, m/s	C	1.10	1.01
(O ₂) plenum/(O ₂) vertex	D	∞	4
Total O ₂ ramp rate, std. m ³ /s/s	E	0.004	0.002
Secondary O ₂ addition	F	Yes ^(a)	No

(a) Secondary (above-bed) O₂ will be added to a maximum quantity limited by off-gas O₂ increases indicating the additional O₂ is not being consumed.

Module 3 consisted of three runs of approximately 8-h duration. The first two runs were 4-h extensions of two runs from Module 2; the third run was an extension of the second run of this module. The independent variables were the same as in Module 2, except that "fresh feed rate" was substituted for "bed carbon." Values of these variables in the third run were identical with the second run except that secondary oxygen was added. Data taken during Module 3 were used to determine the effects of the six independent variables on the same measured variables as in Module 2.

Module 4: Tail-Burning of Final Particle Bed

Dependent Variables

Bed carbon

Radial and axial burner temperature distributions

Independent Variable	Symbol	Level	
		Max.	Min.
Tail-burn assist	A	Yes	No
Off-gas O ₂ allowed, %	B	10	5

No additional runs were planned for Module 4, the purpose of which was to determine the effect of the induction heater power usage during "tail-burning" on bed burnout. Bed carbon and bed temperature distributions were monitored at the end of the Module 3 test, with induction power on or off and two different values of off-gas O₂ allowed. Supplemental fuel particles were added near the end of these tests to allow induction-heated tail-burning with a full particle bed.

Module 5: Fines Recycle Alternates Tests

Dependent Variables

Fines inventory
Fines elutriation data
Particle data - elutriation, breakage, and agglomeration
Radial and axial burner temperature distributions
Off-gas composition (CO, CO₂, O₂)

Independent Variables [for each method of fines recycle ^(a)]	Symbol	Level	
		Max.	Min.
Secondary O ₂ addition	B	Yes ^(b)	No ^(b)
Time of recycle initiation	C	Immediately after O ₂ ramp	30 min after O ₂ ramp
Total O ₂ flow rate to bed, std. m ³ /s	D	0.0058	0.0050
Total in-bed gas flow velocity, m/s	E	1.10	1.01

(a) (1) Dual-parallel hopper pressurized fines recycle to cone vertex ("Max." level); (2) dual-parallel hopper pressurized fines recycle to above-bed ("Min." level); (3) single hopper - rotary valve gravity fines recycle above-bed (level 3); (4) tri-hopper series pressurized fines recycle (level 4).

(b) The "yes" maximum level will be the maximum secondary (above-bed) O₂ that does not increase off-gas O₂ or otherwise hamper safe operation. The "no" minimum level is 50% of the maximum secondary O₂ level.

Module 5 consisted of 10 runs of approximately 6 to 8 h duration and one additional run of 8 to 12 h duration. The purpose of the tests was to determine the optimum method of fines recycle injection into the burner. The startup bed (83 wt % carbon, 17 wt % fuel particles) was maintained at its initial bed height by fresh feed addition in these runs. This ensured sufficient heat transfer area to maintain the required burn rate while the bed reduced in carbon content. The 10 experiments in Module 5 were devised to determine the effects of four independent variables, at two levels, on the measured dependent variables shown. The additional run extended the study of the burner operating cycle by incorporating a partial (~20%) bed

removal and a restart. This run used the vertex fines recycle configuration with the pressurized dual-parallel hoppers and LHTGR (TRISO/BISO) feed.

The first eight experiments in Module 5 were conducted with dual-parallel hopper pressurized fines recycle to either the distributor vertex or above the bed. The ninth run was conducted with the single-hopper rotary valve gravity fines recycle system; the tenth run utilized the tri-hopper series pressurized fines recycle system with above-bed entry to the burner. Data obtained in the eleventh run were used primarily for qualitative comparison to the statistically analyzed 10-run series.

Module 6: Tail-Burning

Dependent Variables

Bed carbon

Radial and axial bed temperature distributions

Independent Variables	Symbol	Level	
		Max.	Min.
Tail-burn assist	A	Yes	No
Off-gas O ₂ allowed, %	B	10	5
Fines burnout	C	Yes	No

No additional runs were planned for Module 6, the purpose of which was to determine the effect of the induction heater power usage during "tail-burning" on bed burnout with recycling fines. Bed carbon and bed temperature distributions were monitored at the end of the Module 5 tests, using induction heating in some tests and nonassisted tail-burning in others.

Module 7

Dependent Variables

Radial and axial bed temperature distributions
Vessel wall temperature
Burner pressure
Fines elutriation rate
Off-gas composition (CO, CO₂, O₂)
Carbon content of final bed

Independent Variables

Gas controller scaling data
Air controller scaling data
Power controller scaling data
Alarm setpoints
Delay times

Once the optimum mode of burner operation was selected based on Modules 1 through 6, Module 7 tests were conducted as follows:

Develop automatic control for the entire operating cycle and compare with scale-up data	Short shakedown runs of automatic control - a series of 1 to 8 h runs to fine tune the controller (approximately five runs).
	Long-term (48 h) run with automatic control - using prior knowledge, apply primary burning process to long-term operation simulating an actual semicontinuous batch cycle campaign.

Data collected during Module 7 included gas, air, and power control loop scaling data; alarm set points based on system response to transients and upsets; and delay times. However, Module 7 was actually a proof test of the optimum burner system derived from previous test results and, as such, did not lend itself to simple quantitative analysis.

APPENDIX D
MODULE 1 THROUGH 6 DATA

TABLE D-1
EXPERIMENTAL RESULTS - MODULES 1, 2, 3, 4

Measured Variable	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8A	Average
<u>Module 1</u>									
Heatup time, h	0.77	0.77	0.75	0.87	0.84	0.97	0.73	0.87	0.82
Radial temp. difference (range), °C									
Susceptor-to-bed	132-436	107-460	151-445	99-377	103-445	114-477	115-420	99-403	115-433
Vessel-to-bed	62-293	48-324	73-312	60-251	40-322	35-343	44-301	42-282	51-304
Axial temp. difference, °C	60	28	80	80	35	18	35	55	48.9
Fines elutriation rate, g/s	0.12	0.13	0.13	0.27	0.25	0.30	0.08	0.25	0.19
<u>Module 2 (high-carbon level)</u>									
Fines elutriation rate, g/s	1.50	0.63	1.53	1.13	2.17	0.92	2.17	0.97	1.38
Radial temp. difference (range), °C	37-110	85-150	50-70	55-80	85-212	28-48	60-190	83-170	63-129
Axial temp. difference, °C	30	75	40	100	23	25	25	110	53.5
Off-gas composition, %									
CO ₂	88.5	88.0	87.7	88.5	97.0	91.0	91.5	86.2	89.8
CO	11.5	12.0	12.3	11.5	3.0	9.0	8.5	13.8	10.2
O ₂	0	0	0	0	0	0	0	0	0
<u>Module 2 (low-carbon level)</u>									
Fines elutriation rate, g/s	1.37	1.63	1.80	3.25	1.58	2.50	1.67	1.43	1.90
Radial temp. difference (range), °C	105-250	120-280	125-300	15-86	170-340	170-322	70-170	115-270	111-252
Axial temp. difference, °C	18	22	20	35	20	25	50	20	26.3
Off-gas composition, %									
CO ₂	88.0	92.0	91.0	87.0	92.0	91.0	87.0	91.0	89.9
CO	9.0	6.0	9.0	13.0	8.0	8.0	11.0	6.0	8.75
O ₂	3.0	2.0	0	0	0	1.0	2.0	3.0	1.35
<u>Module 3</u>									
Fines elutriation rate, g/s	1.33					(a) 1.92			1.63
Radial temp. difference (range), °C	145-330					125-280			135-305
Axial temp. difference, °C	25					22			23.5
Off-gas composition, %									
CO ₂	87.0					85.0 ^(b)			86.0
CO	6.0					11.0			8.5
O ₂	7.0					4.0			5.5
<u>Module 4</u>									
Bed carbon, wt %	0.52	1.12	2.80	0.86	0.37	0.33	0.40	1.82	1.03
<u>Modules 1 through 4 inclusive</u>									
Particle breakage, wt % of final bed	1.20	0.28	0.31	0.26	0.21	0.46	0.23	0.65	0.45
Agglomeration, wt % of final bed	0.20	0.05	0.08	0.12	0.03	0.04	0.02	0.04	0.07

(a) Without secondary O₂; value changed to 2.17 g/s with 0.00083 std. m³/s secondary O₂.

(b) Without secondary O₂; values changed to 83% CO₂, 10% CO, and 7% O₂ with 0.00083 std. m³/s secondary O₂.

TABLE D-2
EXPERIMENTAL RESULTS - MODULES 5 AND 6

Measured Variable	Run 1VTX (a,b)	Run 2VTX (a)	Run 3VTX (b)	Run 4VTX	Run 1AB (a,b)	Run 2AB (a)	Run 3AB (b)	Run 4AB	SERIES-1 (c)	SERIES-3	GRAV-3 (d)	GRAV-4
Module 5												
Axial temp. difference, °C	30	40	30	55	35	20	35	30		55	20	55
Radial temp. difference (range), °C	46-176	45-180	20-90	73-312	73-230	40-120	30-65	40-235		80-225	50-200	45-180
Off-gas compositions (avg.), vol % CO ₂	84.5	84	86	79	92	89.5	86	79		84	74	84
CO	12.5	14	14	19	8	8.5	10	18		11	17	14
O ₂	3.0	2	0	2	0	2.0	4	3		5	9	2
Module 6												
Axial temp. difference, °C	30	40	40	45	75	20	35	15		10	35	35
Radial temp. difference (range), °C	40-150	20-110	50-200	30-125	75-250	40-125	30-125	35-110		50-100	40-125	25-65
Modules 5 and 6												
Fines inventory, kg	3.18	2.00	1.68	1.16	1.93	8.56	1.59	1.30	9.67	4.00	0.21	0.20
Particle breakage, wt %	6.71	4.15	4.45	5.74	1.27	3.19	1.25	1.00 ^(d)	1.39	0.24	0.60	0.52
Noncombustibles in fines (-355 µm), g	1266	1166	1084	1170	290	489	292	256	259	186	50	142
Fuel particles in fines hoppers, g	1635	2272	1244	1285	<1	9	<1	<1	29	16	<1	<1
Particle agglomeration, wt %	0.010	0.006	0.014	0.032	0.001	0.001	0.012	0.022	0.006	0.007	0.001	0.001
Final bed carbon, wt %	2.5	1.3	1.4	1.0	0.8	0.9	1.3	0.3	0.51	0.27	0.35	0.37

(a) No fines tail-burning in these runs.

(b) No induction-heated tail-burn in these runs.

(c) SERIES-2 and Runs GRAV-1 and -2 were shakedown.

(d) Estimated value.

TABLE D-3
AVERAGED EXPERIMENTAL RESULTS - MODULES 5 AND 6

Measured Variable	Experimental Results			
	In-Bed Recycle	Above-Bed Recycle (Excludes SERIES) ^(a)		
<u>Module 5 averages</u>				
Axial temp. difference, °C	39	32		
Median radial temp. difference, °C	118	112		
<u>Module 6 averages</u>				
Axial temp. difference, °C, overall	39	36		
Not induction heated	35	55		
Induction heated	43	27		
No fines tail-burn	35	48		
Fines tail-burn	43	30		
Median radial temp. difference, °C	91	82		
Not induction heated	110	120		
Induction heated	72	71		
No fines tail-burn	80	123		
Fines tail-burn	102	70		
	In-Bed Recycle	Above-Bed Recycle		
	Vertex Parallel Hoppers	Above-Bed Parallel Hoppers	Above-Bed SERIES	Above-Bed GRAVITY
<u>Module 5 and 6 averages</u>				
Fines inventory, kg	1.4	1.4	6.8	0.21
Particle breakage, wt % of particles fed	5.3	1.7	0.82	0.56
Noncombustibles in fines (-355 µm), g	1172	332	222	146
Fuel particles in fines hoppers, g	1609	<3	23	<1
Particle agglomeration, wt % of particles fed	0.015	0.009	0.006	0.001
Final bed carbon, ^(b) wt % of final bed	1.2	0.60	0.39	0.36

(a) SERIES runs excluded due to intermittent fines flow and inordinate end-run fines inventory.

(b) Tail-burned results only.

TABLE D-4
COMPARISON OF ABOVE-BED RECYCLE ALTERNATIVES

Run	Fines Inventory (kg)	Noncombustible in Fines (-355 μ m)		Particle Breakage (loss) (wt %)	Particle Agglomeration (g)	Final Bed Carbon (wt %)
		Elutriation (g)	Total Inventory (g)			
1-AB	2.0 ^(a)	170	290	1.27	0.4	0.82 ^(a)
4-AB	1.30	185	256	1 (est.)	8 (est.)	0.35
GRAV-3, -4 ^(b)	0.20	58	146	0.56	0.5	0.37
SERIES-1, -3 ^(c)	6.84	172	223	0.82	2.25	0.39

(a) No fines burnout or tail-burning as for other runs in table.

(b) Values are the average of values from Runs GRAV-3 and GRAV-4.

(c) Values are the average of values from Runs SERIES-1 and SERIES-3.

Fig. D-1. Time required to induction heat a fresh feed bed to ignition temperature versus velocity and bed particle size

Fig. D-2. Maximum in-bed axial temperature difference versus superficial gas velocity, bed weight, and particle size (induction-heated fresh feed bed)

Fig. D-3. Average radial temperature difference versus superficial gas velocity, bed weight, and particle size (induction-heated fresh feed bed)

Fig. D-4. Particle breakage trends as observed from thorium oxide and particle coatings (SiC hulls) separated from fines samples (runs M1 through M6)

Fig. D-5. CO in off-gas versus total in-bed O₂ and total in-bed gas velocity (60 wt % bed carbon)

Fig. D-6. CO in off-gas versus secondary and total in-bed O₂ flows (<30 wt % bed carbon, 1.05 m/s total in-bed superficial gas velocity)

Fig. D-7. O_2 in off-gas versus secondary and total in-bed O_2 flows
(30 wt % bed carbon)

Fig. D-8. Final bed carbon versus integrated excess O₂ (off-gas) during tail-burning

Fig. D-9. Maximum in-bed axial temperature difference versus method of fines recycle, secondary O₂ flow rate, and in-bed O₂ flow rate (in-bed velocity)

Fig. D-10. Average radial temperature difference versus method of fines recycle, in-bed O₂ flow rate, and secondary O₂ flow rate

Fig. D-11. CO in off-gas versus method of fines recycle, in-bed O₂ flow rate, and secondary O₂ flow rate

Fig. D-12. Final fines inventory (-355 μm graphite) versus gas velocity/ O_2 flow, recycle system/inlet location, and secondary O_2 rate

Fig. D-13. Noncombustible ($\sim 355 \mu\text{m}$) elutriation versus gas velocity/ O_2 flow, recycle system/inlet location, and secondary O_2 rate

Fig. D-14. Fuel particle loss (breakage) versus gas velocity/ O_2 flow, recycle system/inlet location, and secondary O_2 rate

Fig. D-15. Particle agglomeration versus gas velocity/ O_2 flow, recycle system/inlet location, and secondary O_2 rate

Fig. D-16. Final bed carbon versus fines burnout, tail-burn assist, off-gas O₂ percent, and recycle mode