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PROCESS DEVELOPMENT REPORT – 0.20-m PRIMARY BURNER SYSTEM

by
W. S. RICKMAN

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

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GENERAL ATOMIC COMPANY

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ABSTRACT

HTGR reprocessing consists of crushing the spent fuel elements to a size suitable for burning in a fluidized bed to remove excess graphite, separating the fissile and fertile particles, crushing and burning the SiC-coated fuel particles to remove the remainder of the carbon, dissolution and separation of the particles from insoluble materials, and solvent extraction separation of the dissolved uranium and thorium.

Burning the crushed fuel elements is accomplished in a primary burner. This is a batch-continuous, fluidized-bed process utilizing above-bed gravity fines recycle. In gas-solid separation, a combination of a cyclone and porous metal filters is used.

This report documents operational tests performed on a 0.20-m primary burner using crushed fuel representative of both Fort St. Vrain and large high-temperature gas-cooled reactor cores. The burner was reconstructed to a gravity fines recycle mode prior to beginning these tests. Results of two separate and successful 48-hour burner runs and several short-term runs have indicated the operability of this concept. Recommendations are made for future work.

CONTENTS

FIGURES

FIGURES (Continued)

TABLES

1. INTRODUCTION

The HTGR fuel reprocessing flowsheets for Fort St. Vrain and large reactors are shown in Figs. 1-1 and 1-2. Both entail crushing the fuel element, burning the crushed element, and separating the resultant burner product into fissile and fertile particle streams. Those particle streams containing TRISO coated particles (see Fig. 1-3) are then further crushed to expose the carbide kernel and inner carbon coatings. This crushed particle stream is then oxidized in a secondary burner to yield a heavy metal oxide and SiC shell mixture, which is in turn leached to isolate the heavy metals.

The primary burner is a batch-continuous, fluidized-bed reactor with a conical, perforated, inlet gas distributor plate. Fines recycle is presently accomplished using a gravity system, which separates the fines from the off-gas using a cyclone and porous metal filter. Fines flow down to an interim storage bunker from which they are metered back into the burner at a point just above the fluidized bed. A high-temperature rotary valve is used to control fines flow and seal against burner pressure.

Fresh feed containing 83% graphite is also metered in with a rotary valve to a location just above the fluidized bed. Product removal is through a port at the lower vertex of the inlet gas distributor.

Process heat is supplied by an induction heater, and cooling is accomplished by air flow through annular cooling jackets.

The burner cycle is as follows:

1. Add sufficient crushed fuel element material to allow fluidization. Heat to 700°C while fluidizing with an inert gas.

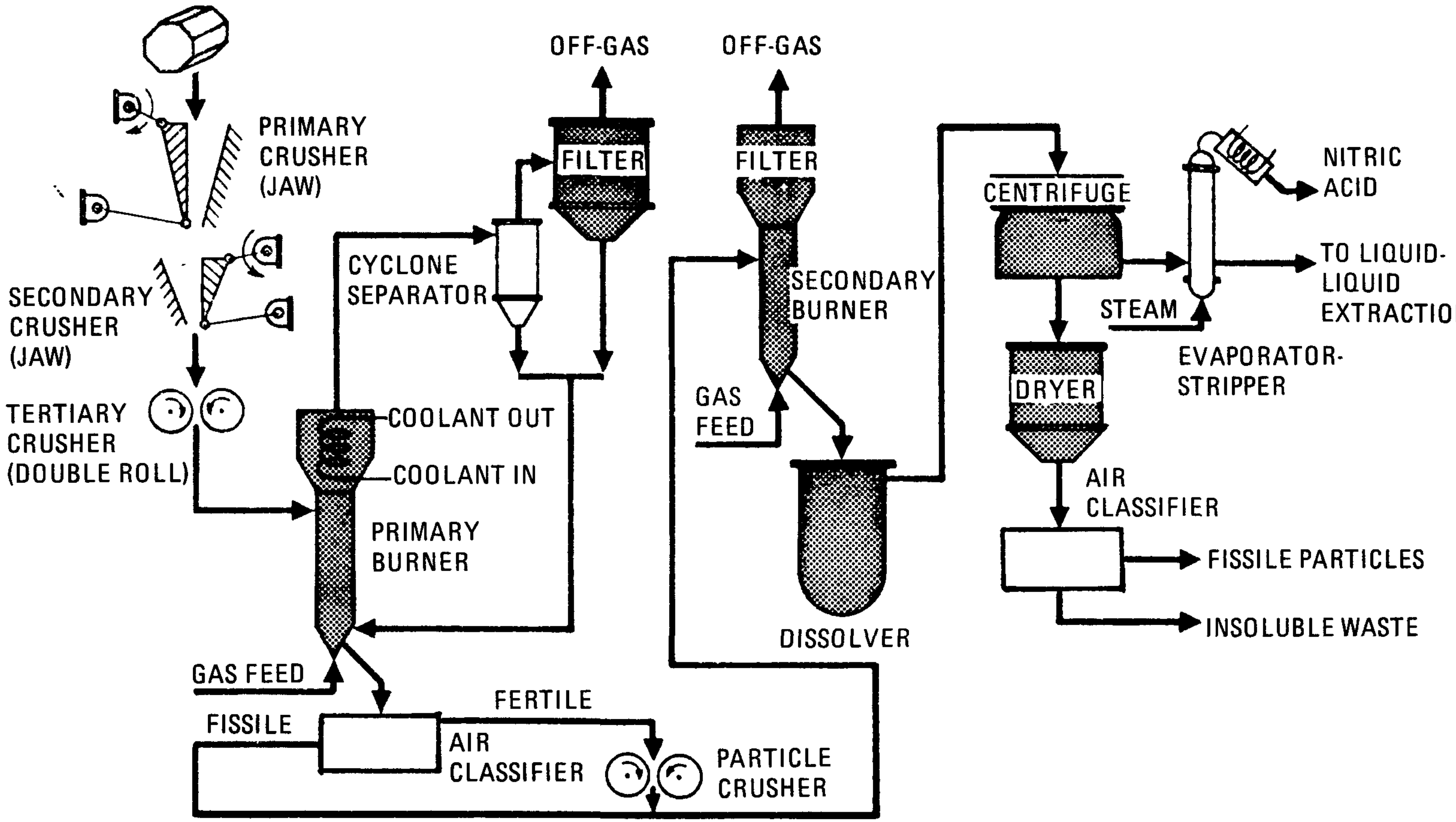


Fig. 1-1. Simplified HTGR head end flow diagram (TRISO-TRISO fuel)

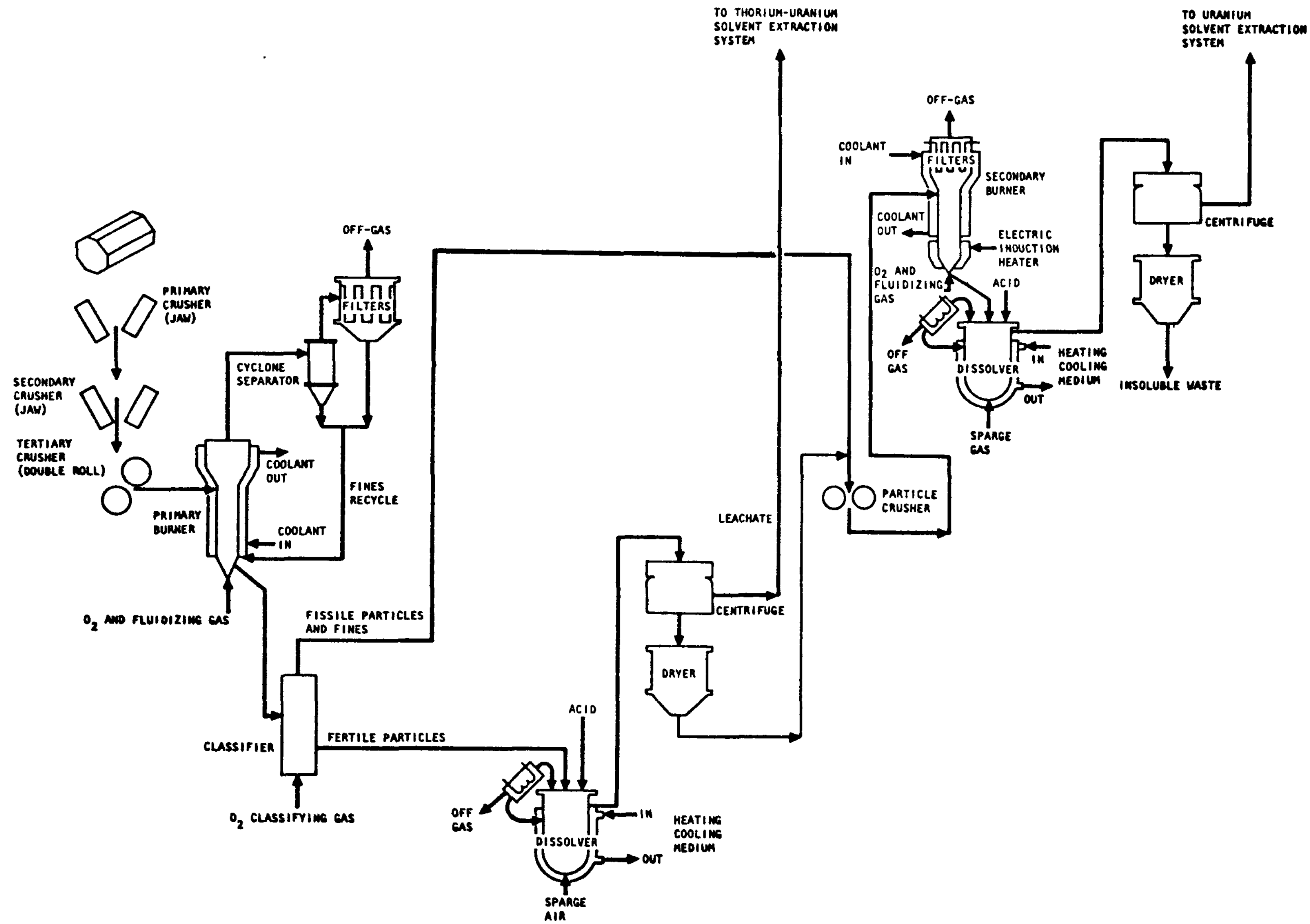
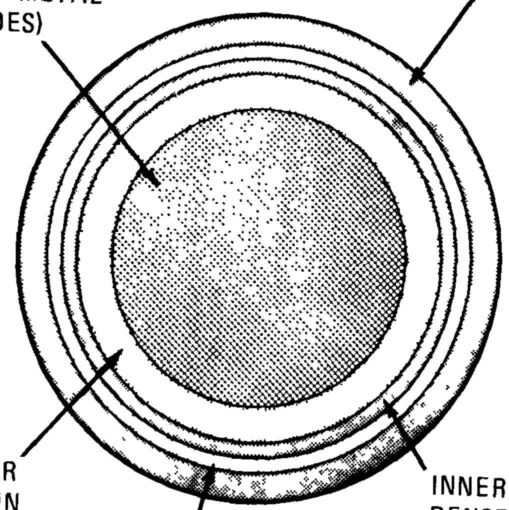


Fig. 1-2. Simplified TRISO-BISO reprocessing flow diagram



MICRONS	FISSILE	FERTILE
KERNEL DIAMETER	175-240	380-450
BUFFER THICKNESS	55	60
INNER DENSE COATING THICKNESS	25	30
SiC THICKNESS	25	25
OUTER DENSE COATING THICKNESS	35	50

Fig. 1-3. Fort St. Vrain TRISO coated fissile and fertile particles

2. Ignite using oxygen in the fluidization gas. Bring the fluidized bed to 900°C and hold there by cooling air modulation.

3. Recycle elutriated fine carbon to the above-bed zone and ignite by initiating above-bed oxygen flow.

4. Start fresh feed addition at a rate close to the burn rate.

5. A large bed of fuel particles will have built up after 15 to 20 hours. Stop fresh feed, and burn all carbon out of the bed and the fines recycle loop. Remove at least half of the fuel particles through the vertex product removal port.

6. Add fresh feed to bring the total fluidized bed carbon content to 20 wt %. Start the cycle again at step 2 until all of the fresh feed has been used.

Development work on 0.10-m and 0.20-m primary burners was begun in 1969-70. Many different modes of operation have been tried since then. One of the main areas of concern has been fine carbon recycle and combustion. Past work has been focused on augurs and pressure tanks for recycle to both above-bed and in-bed locations. Attempts to make this process operable indicated the desirability of a simple gravity fines recycle system.*

For these reasons the work described in this report was undertaken during the past year. This work has been successful in proving the concept of gravity fines recycle and in pointing out areas of future work to help refine that process.

A series of specific experimental tests was carried out to reach this conclusion. Reasons for the selection include fewer mechanical parts that

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*Stula, R. T., D. T. Young, and J. S. Rode, "0.20-m Primary Burner Development Report," DOE Report GA-A14643, General Atomic Company, December 1977.

can wear out, a much smaller effect on the fluidization characteristics of the fuel particle bed, and reduced fuel particle breakage in the fines recycle loop.

Appendixes A and B present the activity plan and operating procedure, respectively, used to operate the 0.20-m primary burner. A summary of the training program and the test used to qualify operators are presented in Appendix C.

2. DESCRIPTION OF EXPERIMENTS

The following summarizes the Activity Plan that describes work to be performed on the 0.20-m primary burner during fiscal year 1978:

1. Rebuild the 0.20-m primary burner including a gravity fines recycle system.

2. Make two shakedown burner runs to test equipment operability.

3. Complete two 48-hour burner runs to establish process operating characteristics with TRISO-BISO and TRISO-TRISO type fuels.

4. Upgrade the inlet gas distributor to minimize fuel particle backflow without sacrificing fluidization performance.

5. Calculate off-gas heat transfer coefficients to aid in future design work.

A series of acceptance criteria detailed the performance levels that would meet the test objectives. They are listed in the Activity Plan, and they are described as part of each experiment discussion.

This section describes in detail all of the burner runs that were made to fulfill the Activity Plan.

2.1. INITIAL BURNING TEST

Completion of burner reconstruction occurred on November 18, 1977. This was followed by a month of burner preoperational checkouts and a month of burner shakedown tests with inert beds. The burner was then judged to be ready for actual combustion operations leading to the ultimate goal of long-term burner runs (more than 20 hours).

The initial test was to determine feeder operability, thermal growth characteristics, cooling capabilities, fines burning capabilities, level sensor operability, and overall burner operability. A fluidized bed typical of equilibrium conditions was added to the burner and ignited for this test, followed by 1 hour of normal fresh feed. This proved more than adequate to test all the aforementioned burner characteristics.

2.1.1. Feed Material

Feed was mixed using product from fiscal year 1977 sequential operations. Proportions were calculated using actual fuel loadings in the 45 fuel elements that are to be used in fiscal year 1988 sequential operations.

The initial fluidized bed weighed 60 kg. The composition of the feed material was:

Burned back BISO particles	21 wt %
Burned back TRISO particles	62 wt %
-0.48 cm crushed graphite	17 wt %
	100 wt %

Fresh feed added during combustion weighed 12 kg and had the following composition:

Burned back BISO particles	13 wt %
Burned back TRISO particles	5 wt %
-0.48 cm crushed graphite	82 wt %
	100 wt %

2.1.2. Burner Operations

Figures 2-1 through 2-4 form a graphic "picture" of the burner run. They plot the following variables as a function of time:

1. Fluidized-bed temperature
2. Above-bed temperature
3. Fines recycle bunker temperature
4. Fluidized-bed pressure drop
5. Off-gas filter pressure drop
6. Cyclone pressure drop
7. Off-gas composition
8. Inlet gas flows

The fluidized bed was added by turning the rotary feeder to 3.3 rpm after being CO_2 flow actuated. Burner pressure drop accurately showed fuel particle feed rate (6.3 kg/min) and inventory throughout the run. Heatup began by running the induction heater on a fully automatic mode. When the middle fluidized-bed temperature rose to 300°C, good mixing was assured by turning up the plenum and vertex gas flows to maximum in order to initially mix the bed. After 6 min, the entire bed was up to 300°C so the gas flows were dropped back to normal levels with good mixing noted during the balance of the burner run.

Overall time for heatup to 700°C bed temperature was 40 min. This was followed by a plenum O_2 ramp lasting just under 15 min that yielded a final flow of 290 slpm O_2 and 160 slpm CO_2. Within 10 min, the vertex and mid-reactor O_2 flows were brought up to 65 slpm and 30 slpm, respectively.

During these flow changes, bed temperature rose steadily from 700°C to 900°C. At 820°C, the fines recycle rotary valve was actuated at 2 rpm to heat the fines recycle stream. At 860°C, fresh feed was actuated at a nominal 200 g/min carbon inflow rate. As the burner reached 900°C, the lower cooling air supply was brought on to hold the bed temperature at 900°C.

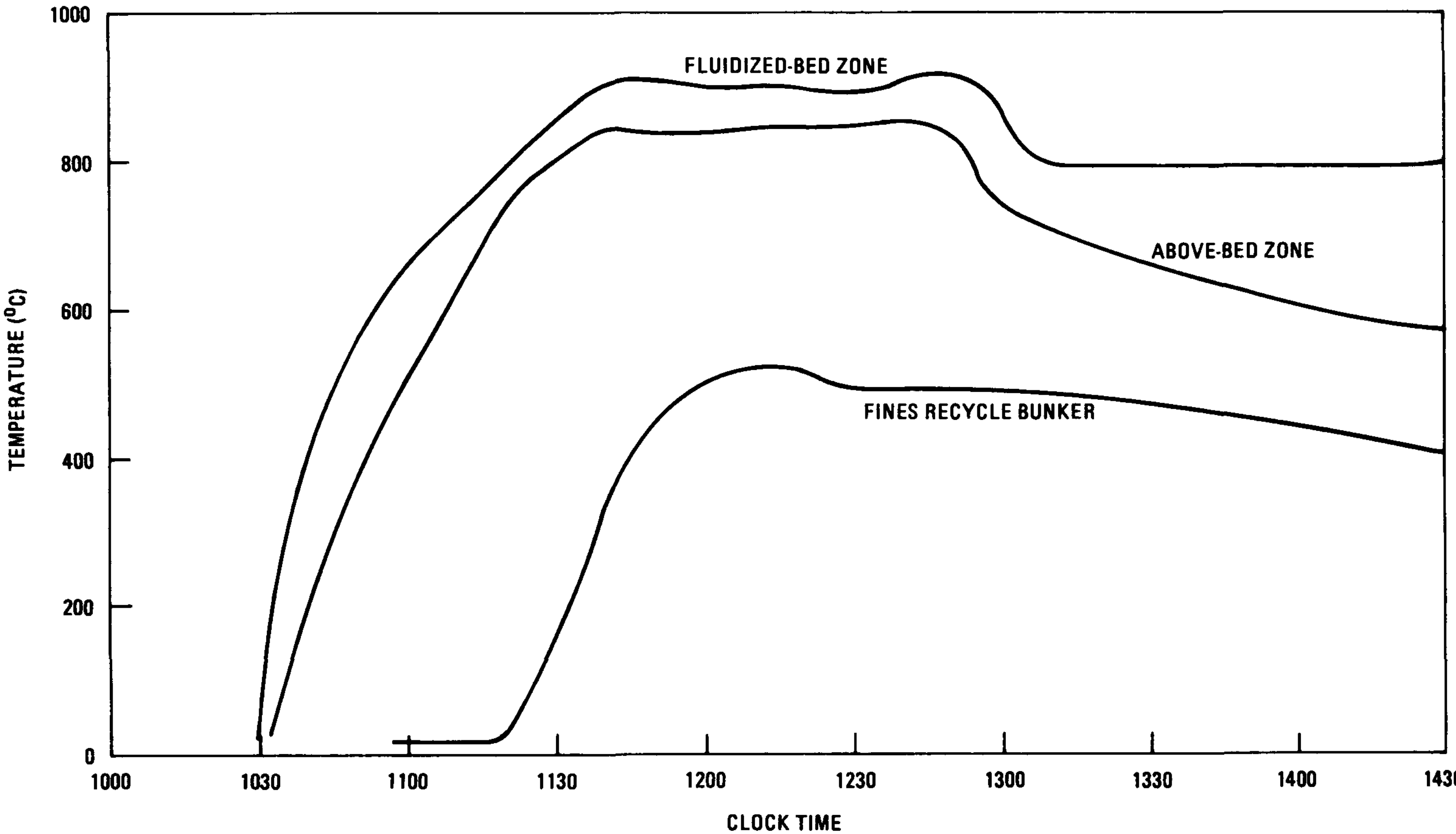


Fig. 2-1. Temperature distribution for 0.20-m primary burner - run 1

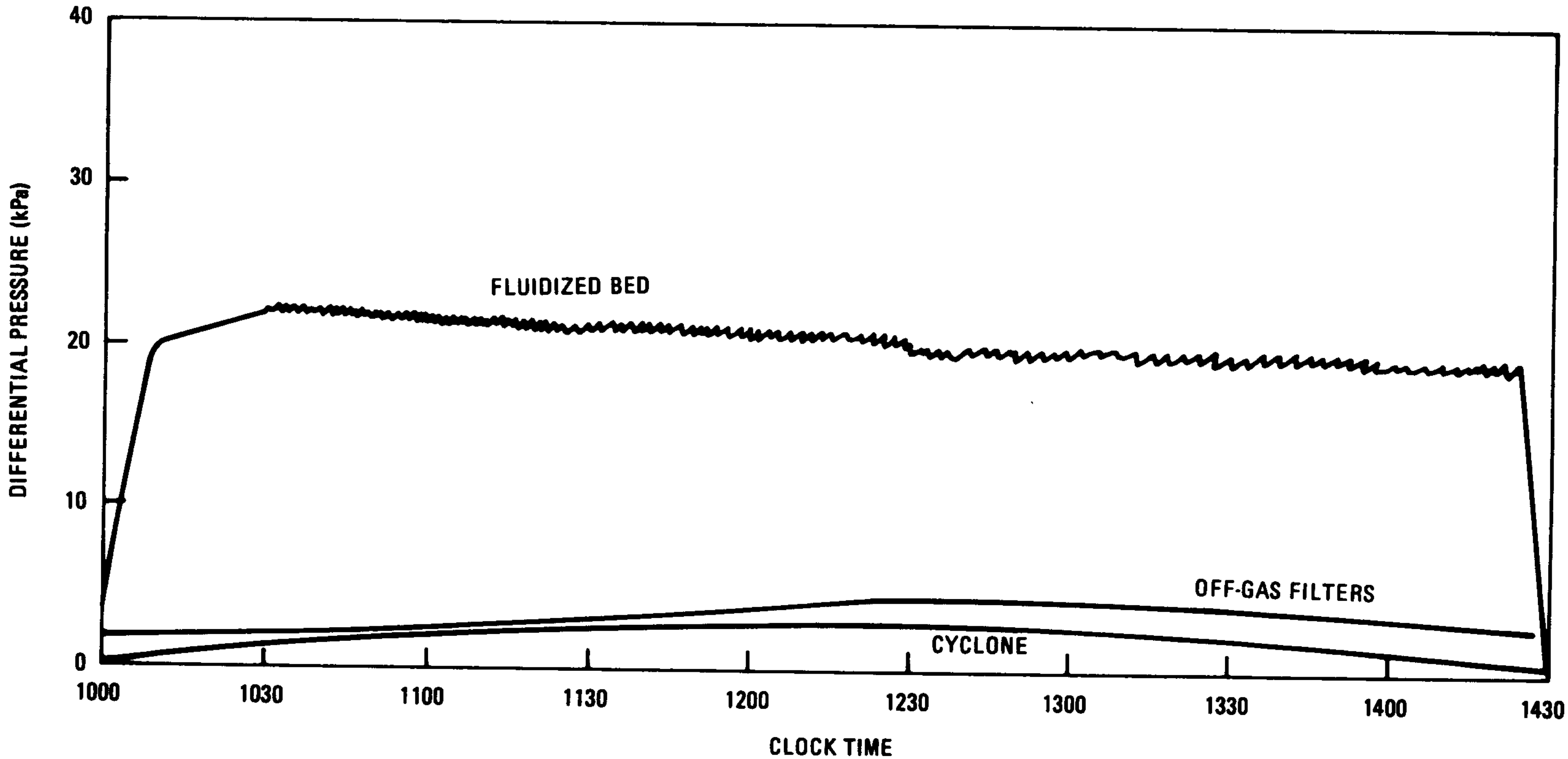


Fig. 2-2. Bed, cyclone, and filter pressure drops for 0.20-m primary burner - run 1

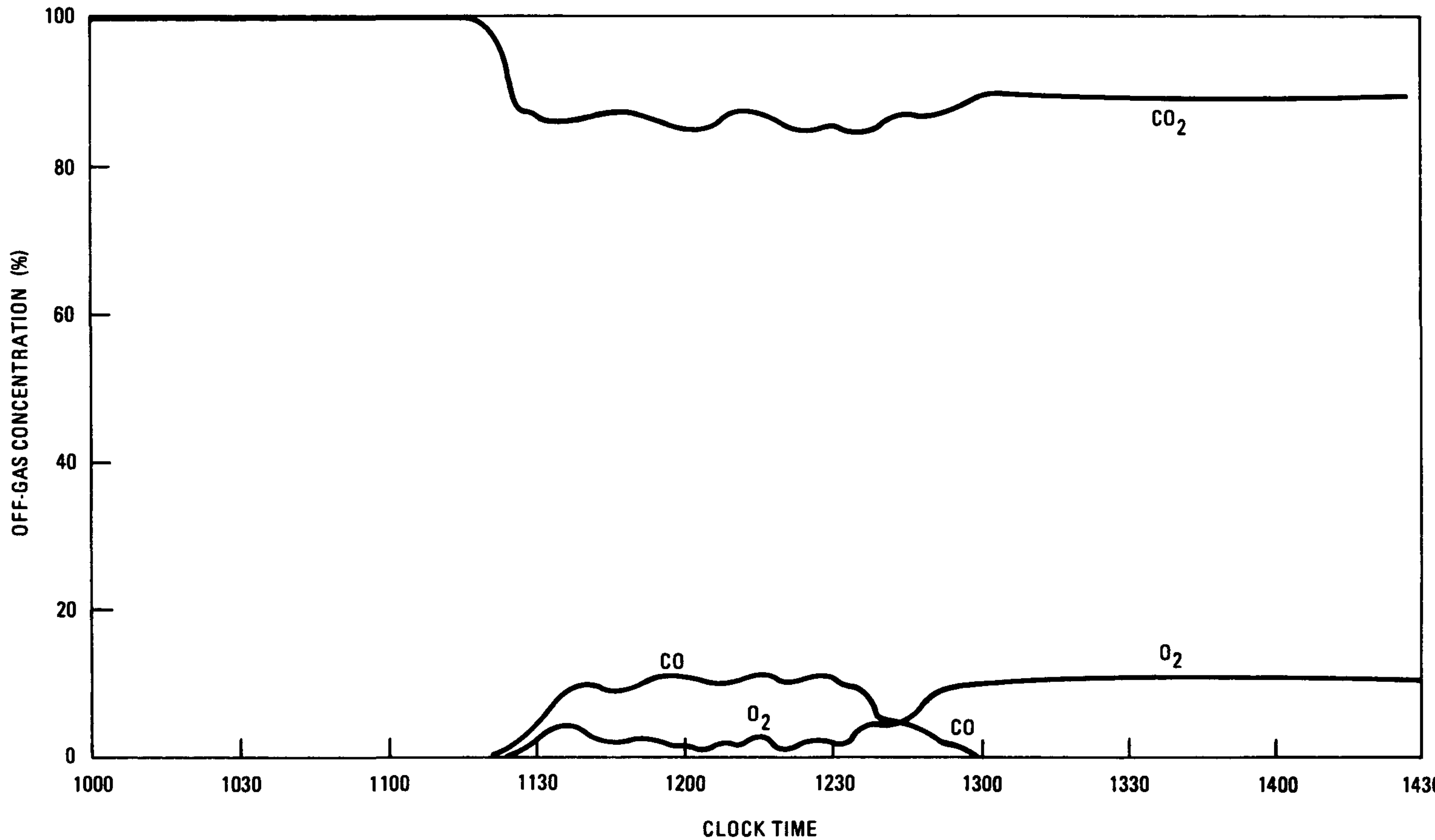


Fig. 2-3. Off-gas composition for 0.20-m primary burner - run 1

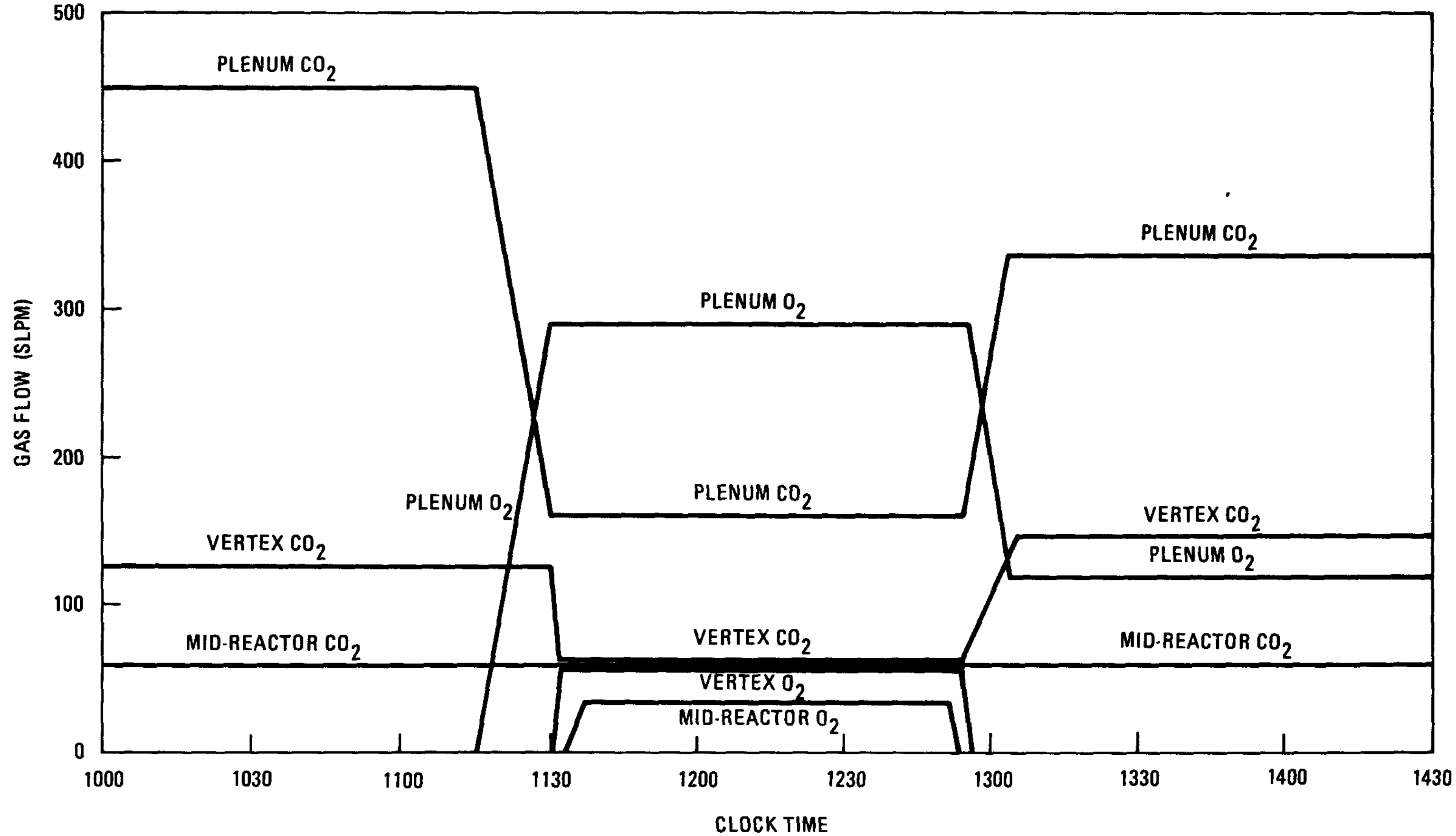


Fig. 2-4. Inlet gas flows for 0.20-m primary burner - run 1

Burner pressure at the vertex entry averaged 28 kPa, oscillating from 20 to 40 kPa overall. Burner distributor pressure drop averaged 4 kPa, but fluctuated constantly, pegging at zero often. Plenum back flow is maximized with this low distributor pressure drop.

About 35 min later, the fines recycle stream had heated the fines valve to 500°C (with attendant baking out of asbestos packing seal), so upper cooling was actuated to prevent any more temperature rise. This worked quite well with very modest cooling air flow rates required, even at the peak burn rate. Lower cooling air supply pressure will be used in future runs to allow a more controllable flow of cooling air to the overall burner. The present 28 kPa supply allowed only a 20% control valve opening for adequate cooling during peak burn rates.

Off-gas filter pressure drop rose to a maximum of 5 kPa while the filters were at 500°C.

Maximum burner growth yielded a 3 cm elongation of the lower burner tube. This was as predicted. No binding problems were noted.

Off-gas carbon monoxide levels stayed between 10% and 12% during the main burning period, decreasing to zero as the bed burned out its remaining carbon. Off-gas oxygen stayed at 2% during the main burning period. As bed carbon decreased, off-gas oxygen began increasing. Mid-reactor and vertex oxygen flow was cut to zero, followed by a 15 min ramp down of plenum oxygen to 120 slpm in order to keep off-gas oxygen levels at 10%. This reduced burn rate caused the induction heater to actuate automatically.

Shutdown was initiated when it was determined that the burn rate had dropped to a negligible level (less than 10 g/min). The fluidized bed was dumped into the product can at 700°C, with an interruption to test partial dump capabilities.

Product flow out of the burner was determined to be 7.5 kg/min during this material load out.

2.1.3. Product

Burner product weighed 50.3 kg with the following composition:

Burned back BISO particles	75 wt %
Burned back TRISO particles	25 wt %
Carbon	0 wt %
	100 wt %

Figure 2-5 contains a size distribution of the burner product. Plenum drainage amounted to 2596 g. This gave further impetus to distributor plate modification studies.

Fines bunker inventory was 1.9 kg. This included filter material dislodged when gas flow was decreased following the run. Carbon content of this material was 95.4%.

2.1.4. Post-Run Burner Examination

Both the fresh feed hopper and the burner tube were found to be empty during inspection. Level sensors were all in excellent condition. Some of them had enough surface carbon dust to indicate electrical contact. This was only a problem in the fines recycle bunker.

2.1.5. Conclusions

Subsystem performance and overall operability of the burner system were found to be excellent. The success of this burner run gave a large degree of confidence in proceeding to the next burner test. This test consisted of igniting and burning a fresh feed bed while adding fuel particles so that, when carbon from the initial bed was depleted, a full

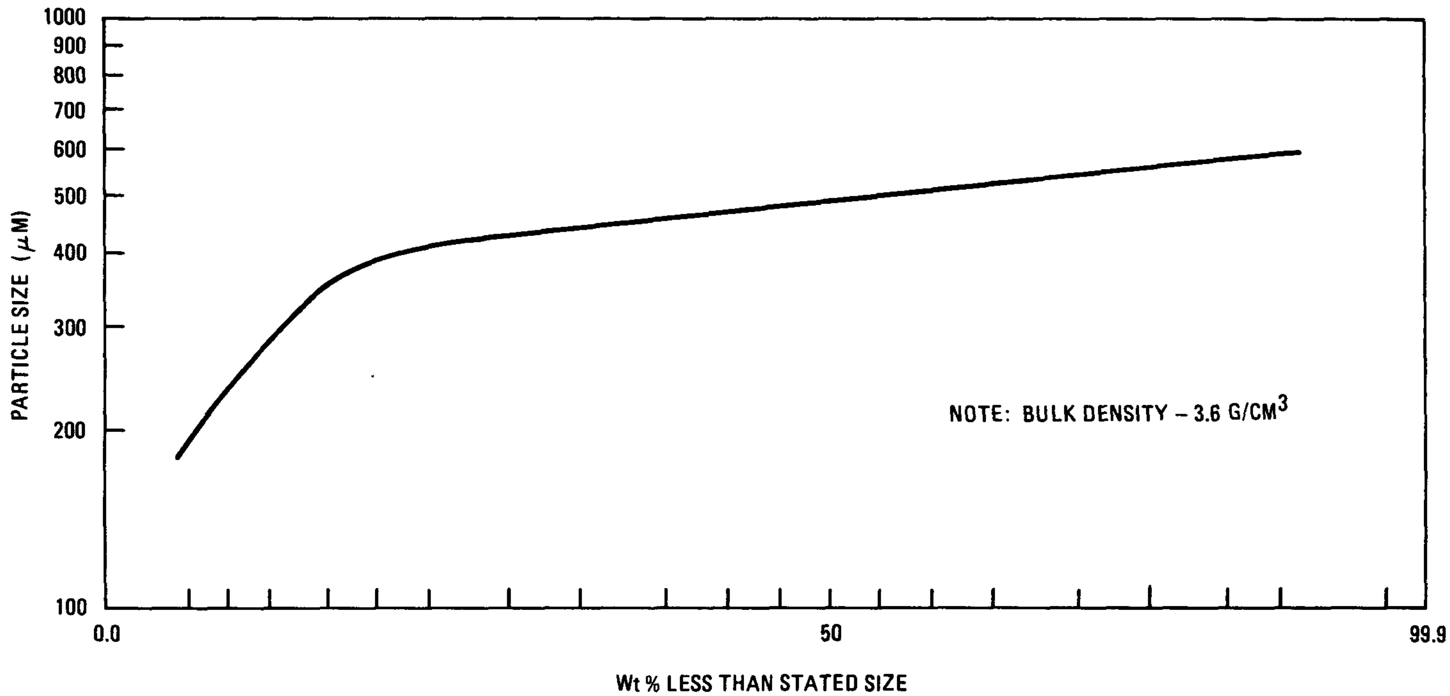


Fig. 2-5. Product size distribution for 0.20-m primary burner - run 1

fuel particle bed was added. The next step is a long-term burner operation using only fresh feed mixed to be representative of the 45 fuel elements that were made for fiscal year 1978 sequential operations.

2.2. FINAL SHORT-TERM BURNING TEST

The purpose of this test was to start up a high-carbon fresh feed bed and add burned back fuel particles to yield a product bed of sufficient volume to allow good heat transfer to the heating and cooling systems.

2.2.1. Feed Material

Feed was mixed using product from fiscal year 1977 sequential operations and crushed scrap graphite. Proportions were calculated using actual fuel loadings in the 45 fuel elements that are to be used in fiscal year 1978 sequential operations.

The initial fluidized bed weighed 26 kg. Its composition was:

Burned back fuel particles	4.36 kg
-0.48 cm crushed scrap graphite	21.64 kg
	26.00 kg

Material added during burning consisted of 46.29 kg of burned back fuel particles.

2.2.2. Burner Operations

Figures 2-6 through 2-11 form a graphic "picture" of the burner run. They are direct plots of data stored by the Hewlett-Packard data acquisition system used.

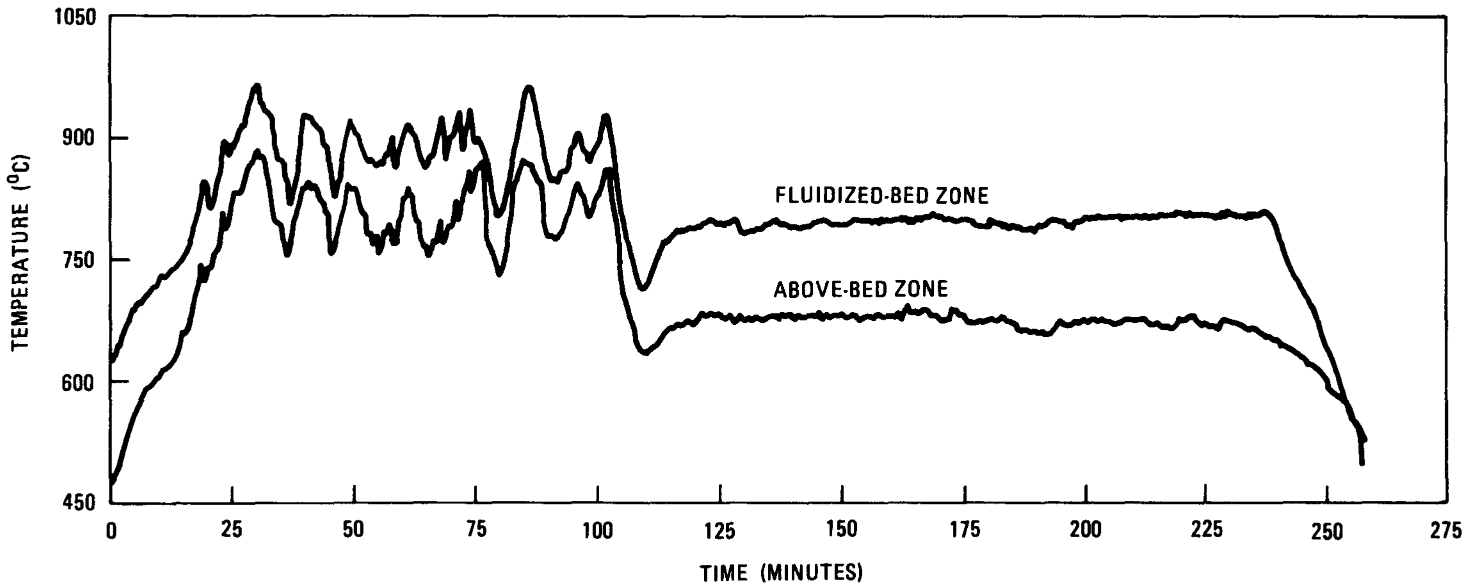


Fig. 2-6. Temperature distribution for 0.20-m primary burner - run 2

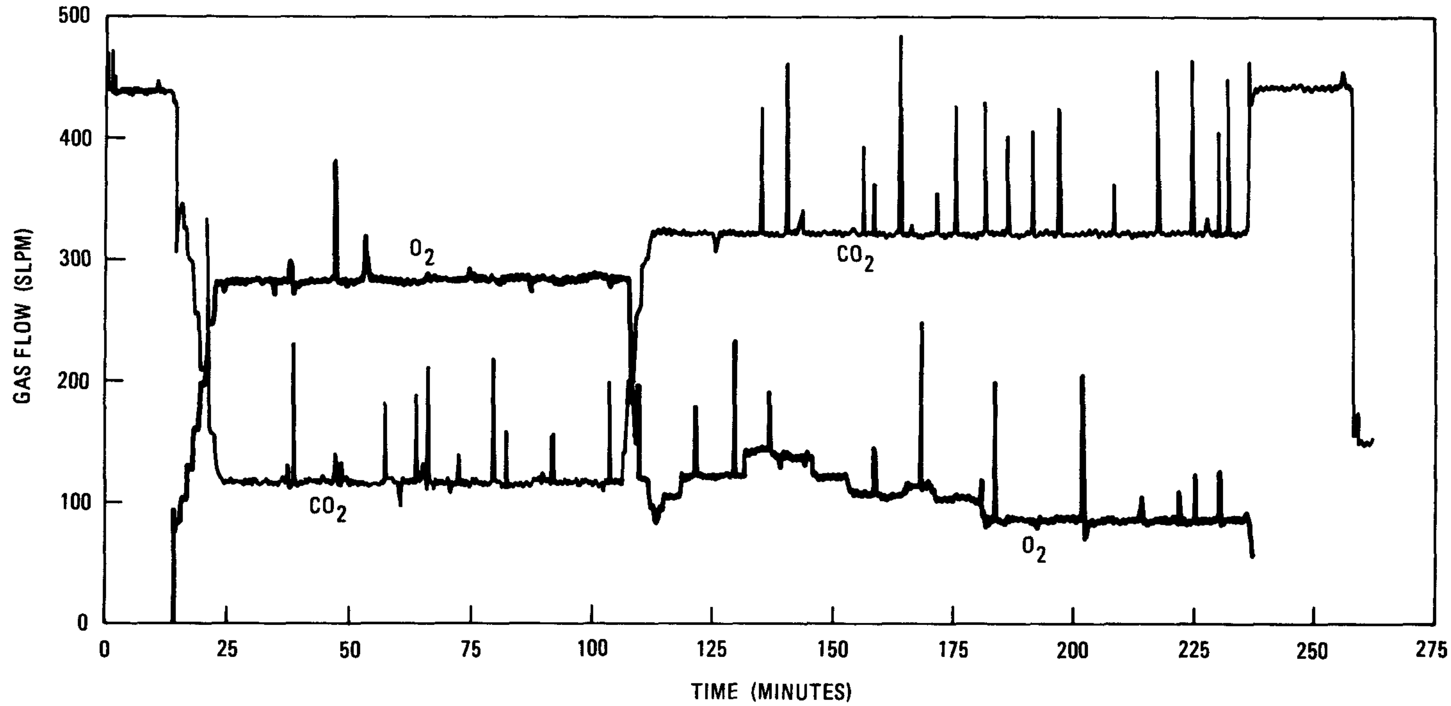


Fig. 2-7. Two-plenum gas flows for 0.20-m primary burner - run 2

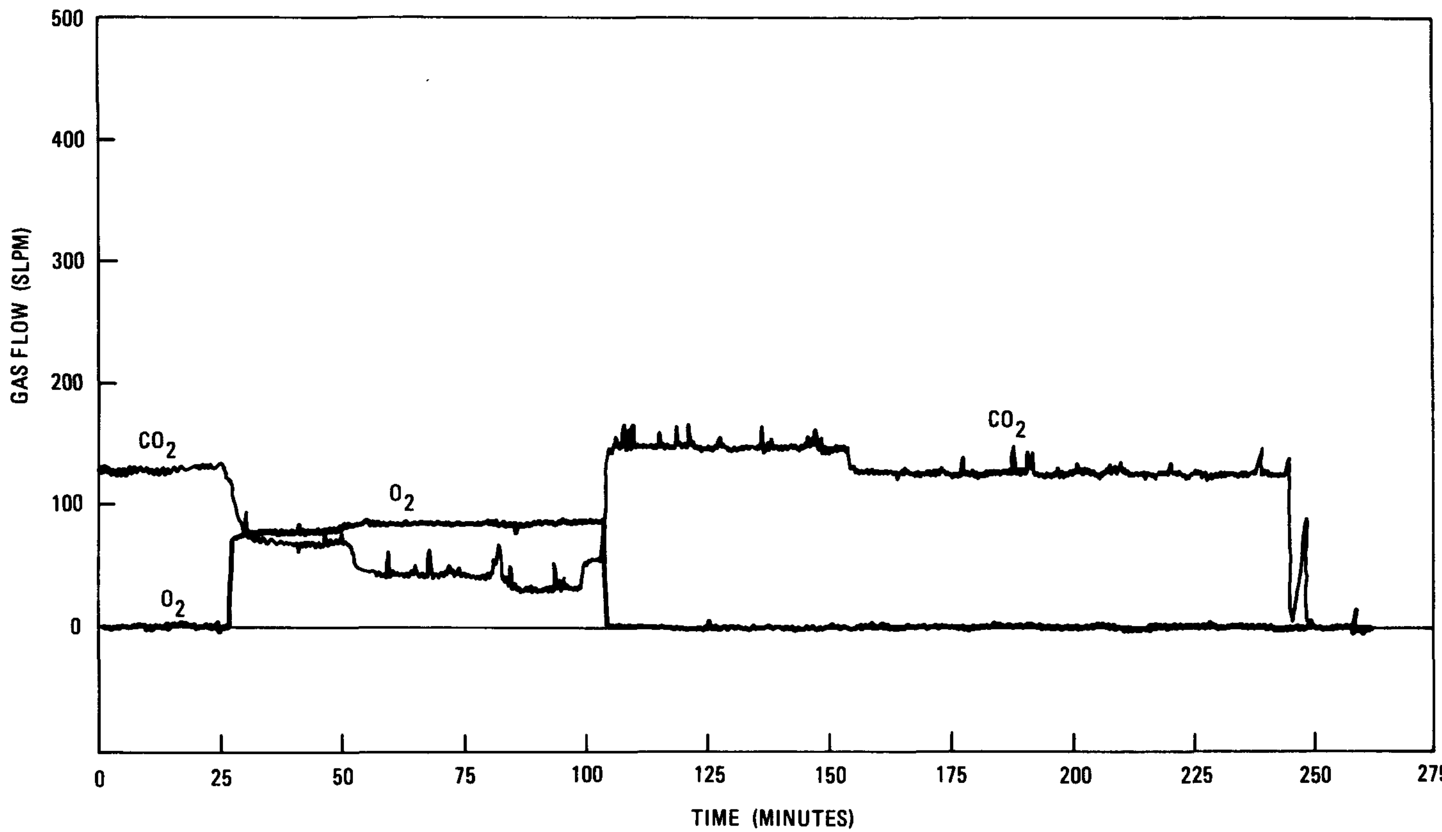


Fig. 2-8. Three vertex gas flows for 0.20 primary burner - run 2

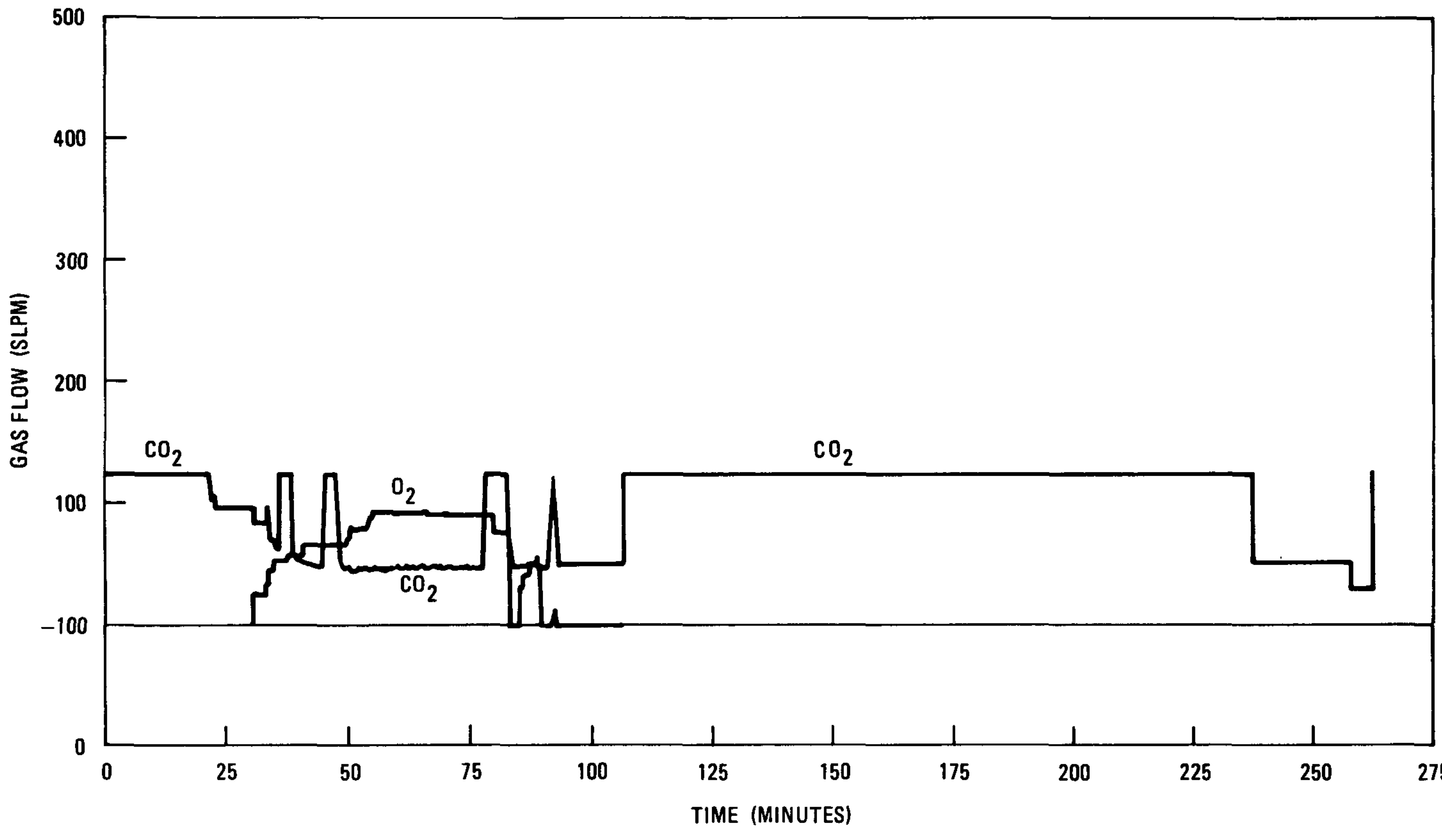


Fig. 2-9. Mid-reactor gas flow for 0.20-m primary burner - run 2

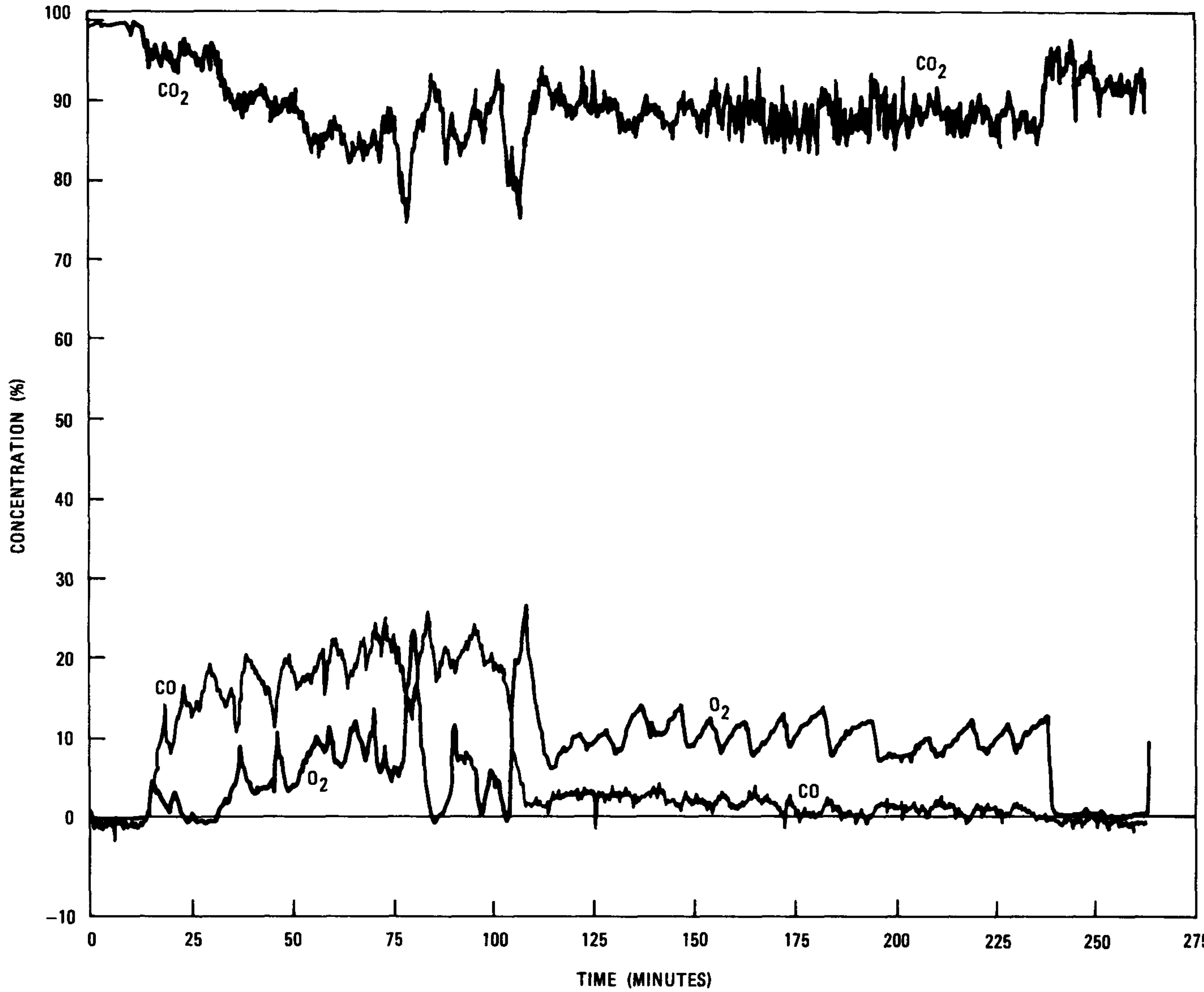


Fig. 2-10. Off-gas composition for 0.20-m primary burner - run 2

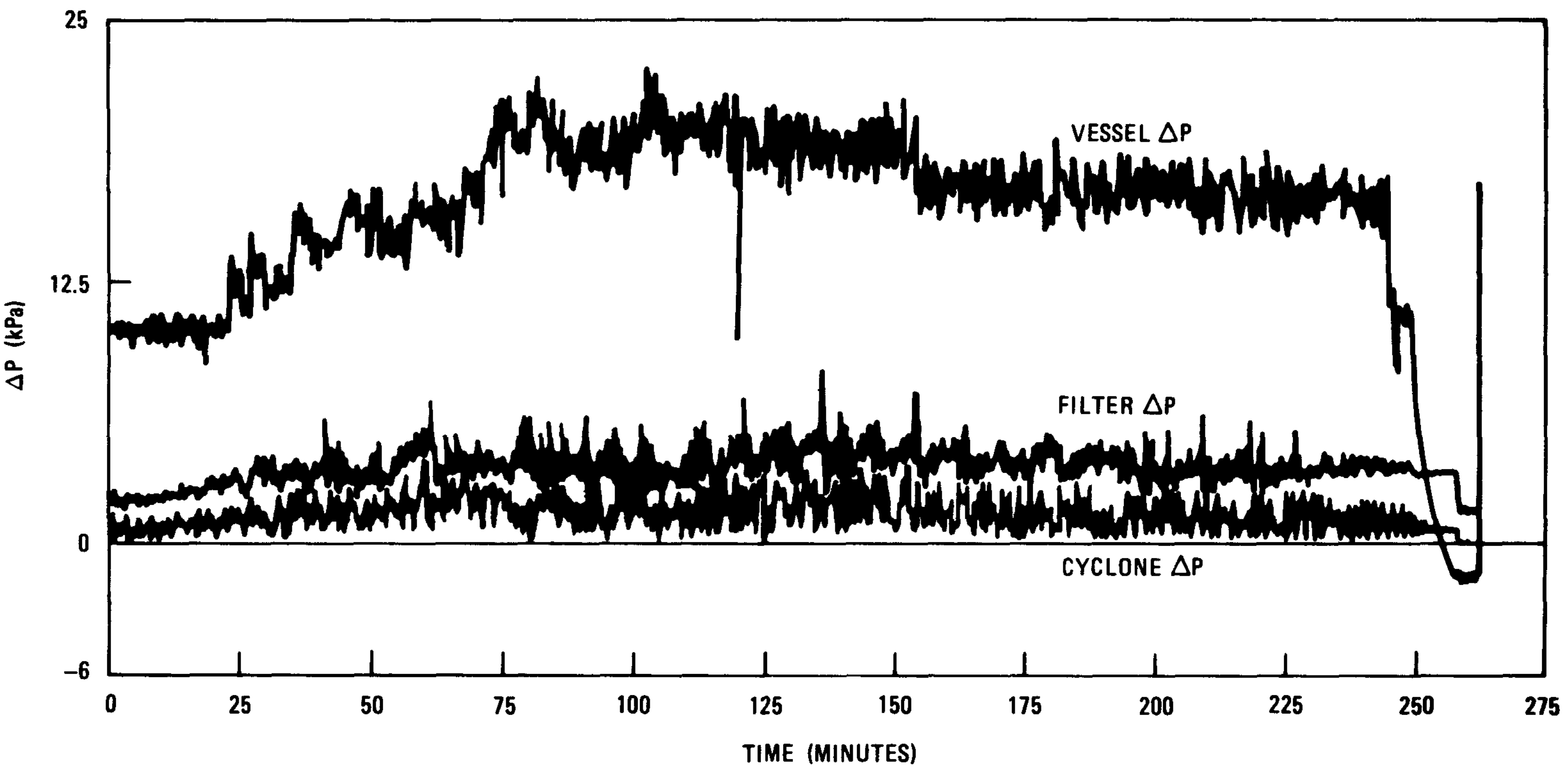


Fig. 2-11. Vessel, cyclone, and filter pressure drops for 0.20-m primary burner - run 2

The fluidized bed was added by turning up the feed rotary valve to 3.3 rpm over a 50-min period. Burner heatup was then started on an automatic mode. Plenum gas flow was raised to maximum when the highest bed temperature reached 375°C; this caused bed mixing to begin. The flow was dropped to normal following reduction of the fluidized bed temperature gradient to 50°C. Total heatup time was 30 min to reach 700°C average bed temperature.

Ignition was started by a plenum O_2 flow ramp that went from 80 slpm initial flow to 290 slpm over a 10-min period.

As the bed heated to 820°C, the fines rotary valve was turned on at 2 rpm. When the bed reached 860°C, discrete addition of feed was begun. The 46 kg of burned back particles had to be added in spurts of 5 to 7 kg each since they flowed in at about 7 to 10 kg/min. Each discrete addition of particles caused a transient temperature depression that had to be dealt with, which explains why the bed temperature went through nine different cycles.

When the bed reached 900°C, lower cooling air was brought on. Supply pressure had been lowered from 35 kPa to 18 kPa for this run, which made it much more controllable. Vertex flow was then changed to 55% O_2. Mid-reactor gas flow was gradually increased to more than 90 slpm. Upper cooling air was required at this high, above-bed oxygen flow, both to keep the fines upflow line below 900°C and to keep the fines bunker at less than 450°C.

Fines valve asbestos seals were seen to be leaking minute quantities of fines. No counts could be detected on a wipe of the material. The seals were tightened, but that did not help any. After the run, the seals were disassembled; the asbestos had become very hard and nonresilient, which explained the leakage.

A seal was made using 2.5 cm wide by 0.38 mm thick graphite tape. It was wrapped directly onto the rotor shaft until the proper thickness was reached. The valve was then reassembled, and the graphoil packing was compressed using the existing seal follower. An internal pressure of 7.5 kPa was applied, and no leakage was noted. Maximum pressure at the valve during burner operations has been only 4 kPa. In order to further test the seal effectiveness, a "rosebud" heater was used to heat each seal area to 450°C for a 10-min period. After cooling, no leakage was detected using GA's standard "snoop" leak testing fluid.

The maximum off-gas filter pressure drop was 3 kPa. This is quite low and very acceptable. Peak filter temperature was 400°C.

Burner level sensors gave a good graphic display of fluidized bed slugging heights. One of them remained on after apparently building up a graphite coating; this was not a problem in the lower sensors as the particulate fluidized bed kept them cleaned off. Fines flow sensors worked well throughout the run, giving an indication of fines reentering the burner through the downflow pipes. Feed bunker level sensors worked well, giving a definite indication of feed level in the bunker. The upper two fines bunker level sensors indicated a partial "on" condition due to buildup of a layer of fines on their upper surface. The lower two sensors never showed any indication of fines level. The feed flow sensor did not indicate flow, even after rotating it to the pipe wall area. It was subsequently relocated to the inclined pipe section where the feed flow is more localized on the lower pipe surface.

Burnout of the bed carbon inventory was noted when off-gas O_2 raised above 10 vol %. Mid-reactor and vertex O_2 flow were decreased to zero and plenum O_2 gradually decreased to 80 slpm over the tail burning period. Off-gas oxygen was controlled at 10% during this time period.

When burn rate was calculated to be less than 10 g/min, the burner was shut down by quenching with CO_2, cooling to 780°C, and dumping into the product removal can. A partial bed removal, done to test restart capabilities, was followed by removal of the balance of the product material.

2.2.3. Product

Burner product weighed 50.51 kg, including 5.07 kg of plenum drainage. This gave further impetus to studies planned to reduce the backflow of solids through the distributor plate.

Overall carbon content of these streams was less than 0.1 wt %, which means that no carbon was detectable using GA's tray burning technique.

Product density was measured at 3.59 g/cm^3.

The fines bunker access flange was removed just after the burner run without the filters being blown back after gas flow was turned off. A fines heel of 150 to 200 g was observed resting on the knifegate valve. This was quite a reduction from the 1.9 kg found there after the last run. Subsequent filter blowback yielded 1.5 kg of fines. These fines were on the surface of the filters, and they make up the important precoat that stays on the filter during normal operation. It is therefore recommended that the filter blowback system not be operated unless normal process flow is on so that the precoating of fine carbon will not be dislodged from the filter.

2.2.4. Post-Run Burner Examination

Level sensors, the thermowell, the burner cone, and the fines and feed bunkers were all found to be in good condition following this burner run.

2.2.5. Conclusions

Burner shakedown runs demonstrated process feasibility and equipment operability sufficiently to allow long-term burner operations to begin.

Upgrading of the fines rotary valve seal and the gas distributor backflow situation were completed prior to operating the burner for 48 hours.

2.3. 48-HOUR RUN USING TRISO/BISO FRESH FEED (RUN 1)

The Activity Plan called for a 48-hour run to be made on the reconstructed 0.20-m primary burner by June 30, 1978. Feed was to be a mixture of TRISO/BISO fuel particles and graphite in proportions representative of a typical fuel element.

Two 8-hour shakedown runs had already been made on the burner as specified in the Activity Plan. They had proven the operability of the reconstructed burner, including such features as a gravity fines recycle system, a lowered susceptor to increase heating capabilities near the burner distributor, a series of level sensors and flow sensors, a vacuum fines sampler to take discrete samples from the fines bunker, a bellows-sealed burner tube cooling air jacket, a gas inlet distributor modified to reduce plenum particle drainage, and improved instrumentations in many areas.

2.3.1. Feed

A mixture of BISO and TRISO coated fuel particles and -0.48 cm full spectrum graphite was prepared as feed for the burner. The BISO and TRISO fuel particle mix was product from fiscal year 1977 sequential operations on the 0.40-m primary burner. They were burned back to ThO_2 microspheres and SiC-coated WAR type fuel particles as a result of the earlier processing. Composition by wt % was as follows:

TRISO coated WAR-type fuel particles	4.4
ThO_2 microspheres	13.4
Carbon	82.2
	100.0

2.3.2. Run Narrative

Prior to beginning operation, a system operability check was made on the burner. This, as well as the entire burner run, followed the guidelines set forth in the Operating Procedure, which is included as Appendix B.

Figures 2-12 through 2-15 give pertinent burner variables as a function of run time.

Fresh feed, which was started at 3.3 rpm, was maintained for approximately 50 min. During this time, a CO_2 flow of 645 slpm was maintained, with no O_2 flow. The bed differential pressure gave an accurate picture of the bed weight, which during feeding was found to increase steadily. After addition of 26 kg of fresh feed, burner heatup via induction heating was initiated. Wall temperatures increased to their maximum allowable 900°C, but the bed temperature did not respond.

Gradual increases in plenum CO_2 flow were made to promote fluidization. Initial bed mixing occurred suddenly, causing a large rearrangement of the fluidized bed accompanied by a piston effect that ejected about 1 kg of material from the bed. This material plugged the cyclone gas entry and stopped process gas flow. The burner was shut down and the plug removed. It was decided to fully fluidize the bed during feed-in on future runs to eliminate this deep bed rearrangement situation.

The bed was then reheated to 700°C, and the plenum O_2 ramp was begun. The burn rate was averaging 210 g/min.

Filter differential pressure was 4 kPa. Bed differential pressure was 15 kPa, with ±5 to 7.5 kPa fluctuations at 1 to 2 s intervals indicating good slugging behavior.

The burner temperature was controlled very easily using only limited amounts of lower cooling air. Bed temperature kept steady at approximately

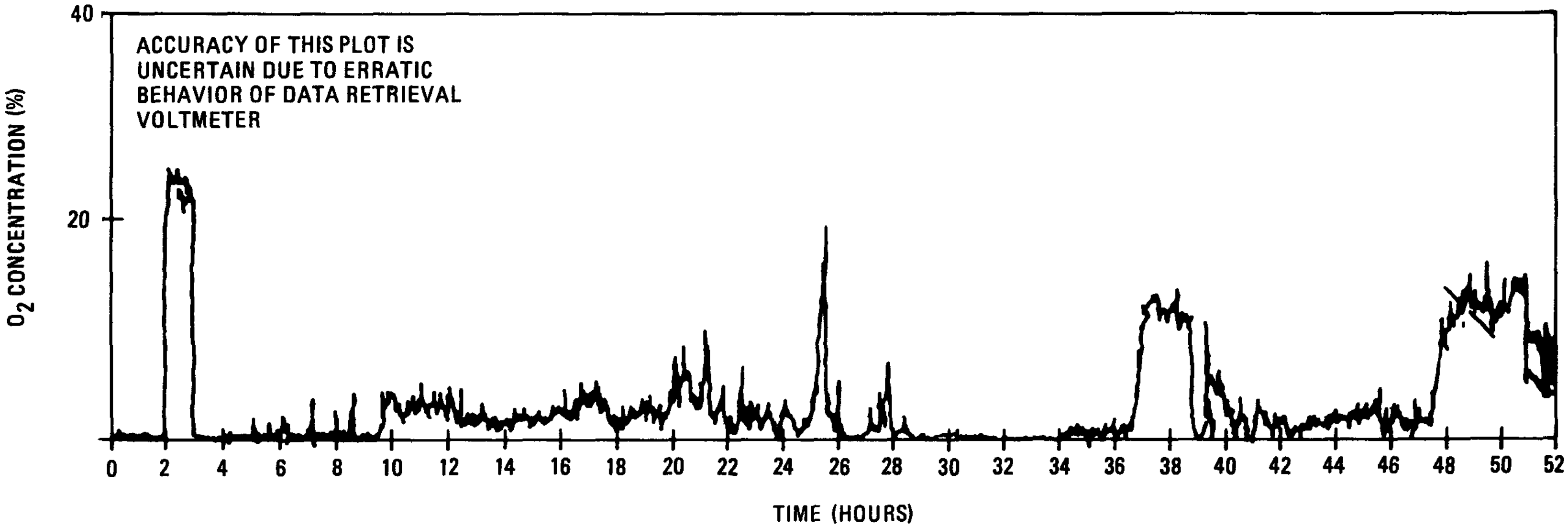


Fig. 2-12. CO concentration for 0.20-m primary burner, 48-h run

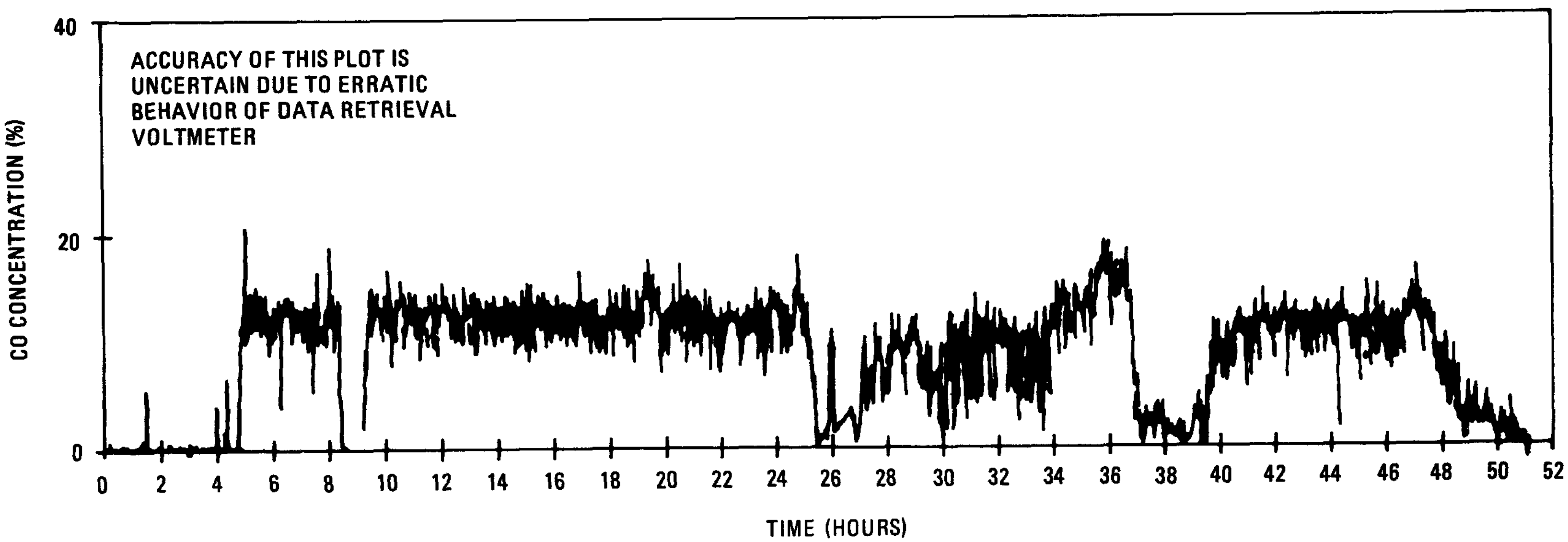


Fig. 2-13. Off-gas concentration for 0.20-m primary burner, 48-h run

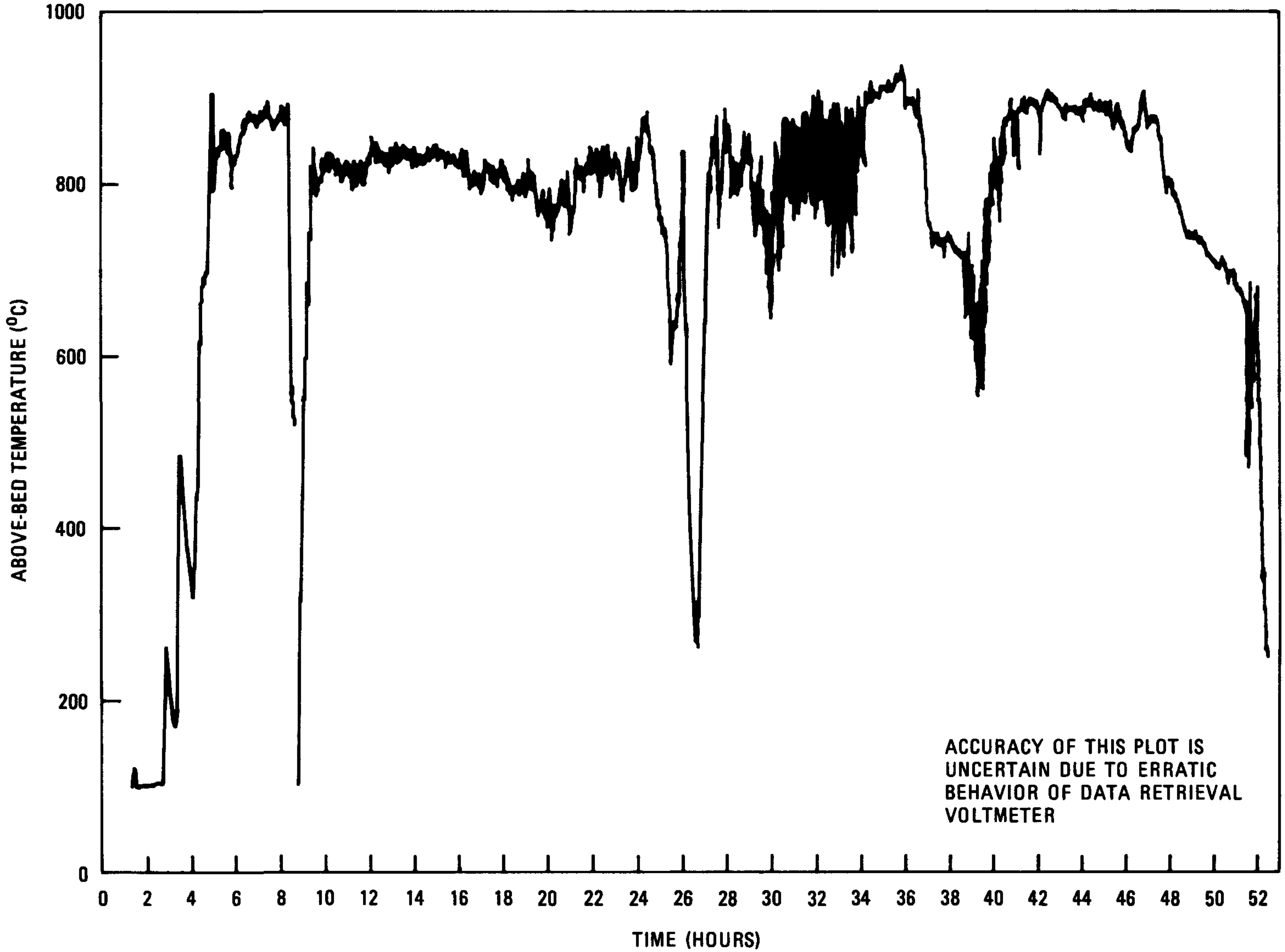


Fig. 2-14. Above-bed temperatures for 0.20-m primary burner, 48-h run

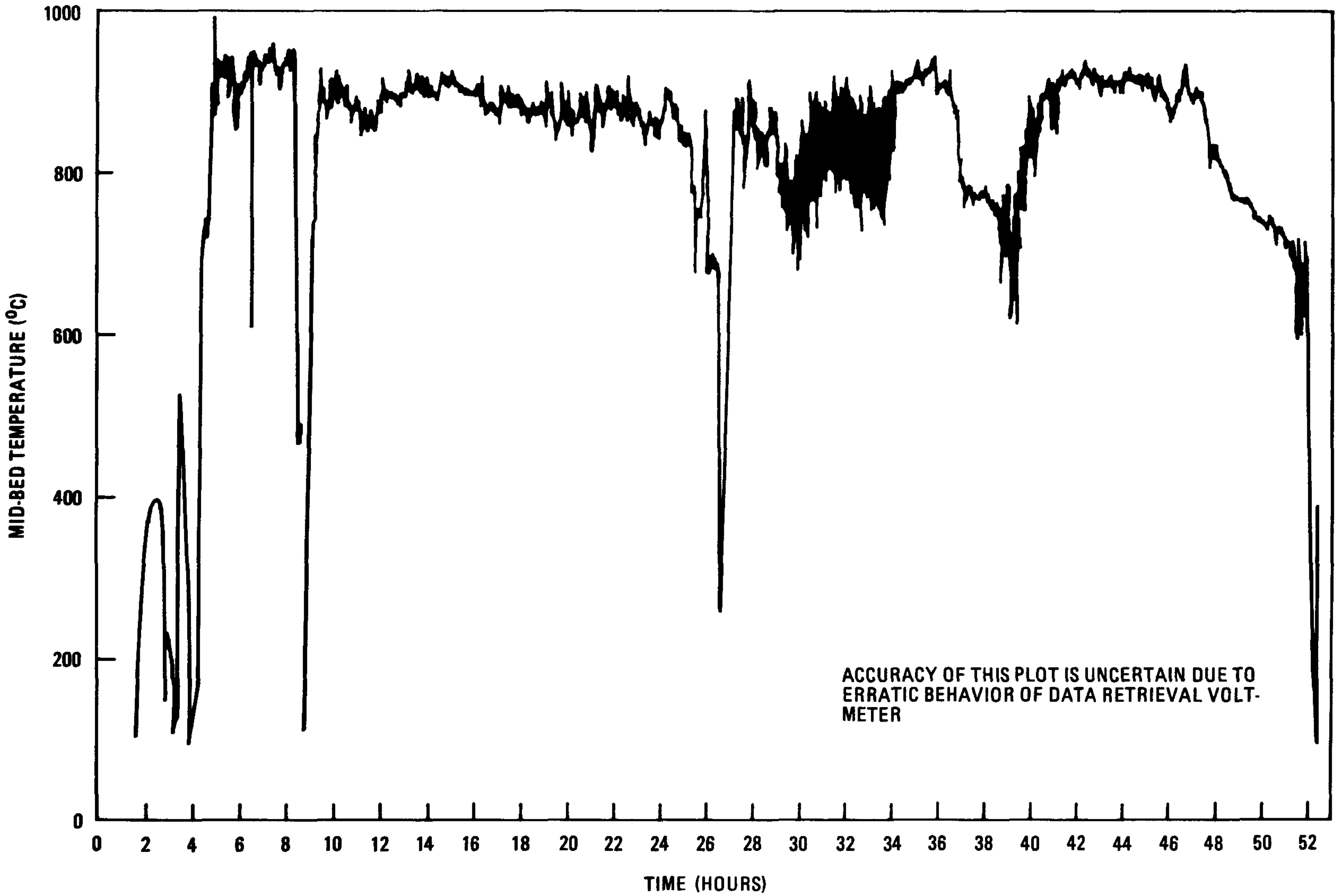


Fig. 2-15. Mid-bed temperatures for 0.20-m primary burner, 48-h run

900°C. Upper cooling air was used to keep the fines recycle line cool. The fines rotary valve was maintained below 500°C at all times.

The upper cooling air can be directed three ways: (1) fines pipe, (2) cyclone, and (3) above bed. During this run, no above-bed cooling air was necessary. The fines entered the fines upflow pipe at about 725°C. The fines pipe was cooled at the rate of 9 m^3/min air flow. Just prior to entering the cyclone, the internal temperature was 630°C. The cyclone, cooled at the rate of 5.6 m^3/min, further lowered the temperature to 450°C. As the fines reentered the burner, they were cooled to 400°C. These cold fines entering the burner in effect cooled the bed temperature, which implied that the fines were entering the bed and mixing in.

At this point, the gas flows were being held constant: plenum CO_2 at 175 slpm, vertex CO_2 at 75 slpm, mid-reactor CO_2 at 60 slpm; plenum O_2 at 180 slpm, vertex O_2 at 50 slpm, and mid-reactor O_2 at 70 slpm.

The fines rotary valve seals held up well with no leaks occurring throughout the run. Approximately 8 hours into the run, a slight leakage near the burner gas exit was noted during visual inspection. A gasket allowed leakage through a flange. No contamination occurred during this time period. At this point, it was decided to shut down to fix the flange. The fines bunker was then inspected and found to contain 15 kg of fines. These were sampled and found to be 99% carbon. At the end of the run, the fines bunker was again examined and found to contain only 1.5 kg.

Restart of the 48-hour run proceeded smoothly. Bed fluidization was ensured prior to heat-up. Startup proceeded in the same way. The temperature of the bed increased to 700°C, at which time the plenum O_2 ramp began. Fines recycle was initiated at 820°C. Fresh feed was established at somewhat less than the burn rate so that a particle bed could be built up while the carbon level decreased. This was done with the fresh feed rotary valve operating at 1.5 rpm.

In-bed temperature response showed a well defined temperature distribution. Thermowell temperatures stayed within the 900° to 940°C range throughout operation, with the exception of the lowest thermocouple, which indicated a temperature of about 870°C. This thermocouple was located directly above the point where vertex gas entered, which produced a cooling effect. The thermocouple located near the opening through which the recycled fines entered the burner was also a few degrees cooler, which demonstrated the moderating effect that fines recycle has on the bed. The fines bunker temperature varied between 400° and 500°C. Temperature profile and level sensors indicated a maximum fines inventory of approximately 15 kg. The temperature of the fines rotary valve stayed under 450°C for the entire run.

Temperatures were controlled easily throughout this portion of the operation. Lower cooling air was at a minimum, and above-bed cooling was found unnecessary. Cyclone and fines pipe cooling were used when necessary. Cyclone cooling air varied from 0 to 4.8 m^3/min, and fines pipe cooling from 2.8 m^3/min to 6.3 m^3/min. Heat transfer throughout the fines recycle loop was large as evidenced by the fact that the fines left the burner at about 850°C and entered the fines bunker at less than 500°C. Heat transfer to the fines line and cyclone can be controlled by adjusting the fines recycle rate.

O_2 concentration was maintained below 5% during most of the run. The O_2 off-gas concentration graph shows a sharp increase at 25 hours. At this point, the bed had apparently burned to a low carbon state. Fresh feed rate was increased and the situation was immediately under control.

Almost simultaneously, the upper burner tube outlet gasket began to leak again. Apparently the thermal cycling, which this flange was exposed to during the bed temperature drop, caused the bolts to loosen. The bolts were tightened and the run continued as before. Plans to change the gasket design have been made.

Thirty-nine hours into the run an interim product dump was effected. Prior to the product dump, fresh feed was stopped, and the carbon was depleted out of the bed. As the carbon content decreased, O_2 breakthrough occurred. When the bed was very low in carbon, combustion-generated heat was no longer sufficient to maintain 900°C bed temperatures. The induction heater kept the bed at 850°C, and when the burn rate dropped to less than 10 g/min, an interim dump of 25 kg was made. Analytical results later revealed a carbon content of less than 0.1%. Fresh feed was once again continued, and the burner was restarted. Figure 2-14 shows off gas O_2 rose again at 48 hours, which was the start of the tailburn. Here again the bed carbon was burned out. The level of O_2 in the burner off-gas during the run was noted to increase slightly when the bed cooled slightly. Thus, strict control of bed temperature is important for the vessel as well as for control of off-gas composition.

Gas flows were held constant: plenum O_2 at 230 slpm, vertex O_2 at 62 slpm, and mid-reactor O_2 at 80 slpm; plenum CO_2 flow was 240 slpm, vertex CO_2 75 slpm, and mid-reactor CO_2 42 slpm. About 35 hours into the run it was decided to try to increase fines burning. Mid-reactor O_2 flow was increased to 115 slpm. This proved to be very effective, and no difficulties were encountered. Vertex O_2 flow was then stopped to determine if burner operation would be affected. Since no change in burner operation occurred, vertex O_2 will be eliminated as plenum and mid-reactor oxygen can perform as well. Also, operator control will be simplified.

Bed differential pressure reached a maximum of 36 kPa. Throughout operation it gave an accurate reading which easily translated into bed weight. Filter differential pressure stayed around 3.8 kPa.

Level sensors were installed in the burner, feed hopper, and fines bunker. The level sensors in the bed gave an accurate picture of the slugging material. They were located at four depths, and as the bed height increased and slugging occurred, lights on an indicator panel in the control room showed what was happening. Similarly, the level sensor in the feed bunker gave an indication of the volume of material it contained. Fines bunker level sensors were found to give erroneous indications of fines level due to material resting on top of the horizontal sensors.

Both bunkers have aeration pads to help keep the level constant. The fresh feed bunker material tended to cone in the middle despite aeration because the graphite was in larger chunks. The fines bunker maintained an even level.

Flow sensors were located in the pipes from the fines bunker and from the feed bunker. These pipes joined together in a Y and entered into the burner. Flow sensors in this area indicated whether or not feed or fines were flowing. Fines flow sensors worked well throughout the run, but the feed sensor showed flow intermittently. This was probably due to the nature of the granular feed material as it bounced down the feed pipe.

2.3.3. Product

Material was removed during the final bed removal (84.5 kg) and during an interim product dump (23.3 kg). Final bed carbon content was 0.1 wt %, while interim product carbon content was 0.03 wt %. These are both far below the design criteria level of 2 wt % carbon content. Product bulk density was measured at 3.7 g/cm^3. Size distributions are shown in Fig. 2-16.

The fluidized bed was "slumped" twice during the run for flange tightening, and 1.8 kg of particles were found in the plenum drain can.

Three fines samples were taken 10, 20, and 40 hours into the run. Each weighed about 200 g. Carbon content was 99%, 97.7%, and 99.2%, respectively. This may have been due to the relative cleanliness of the feed fuel particles (they went in unbroken), which kept the noncombustible fines generation due to broken particles low.

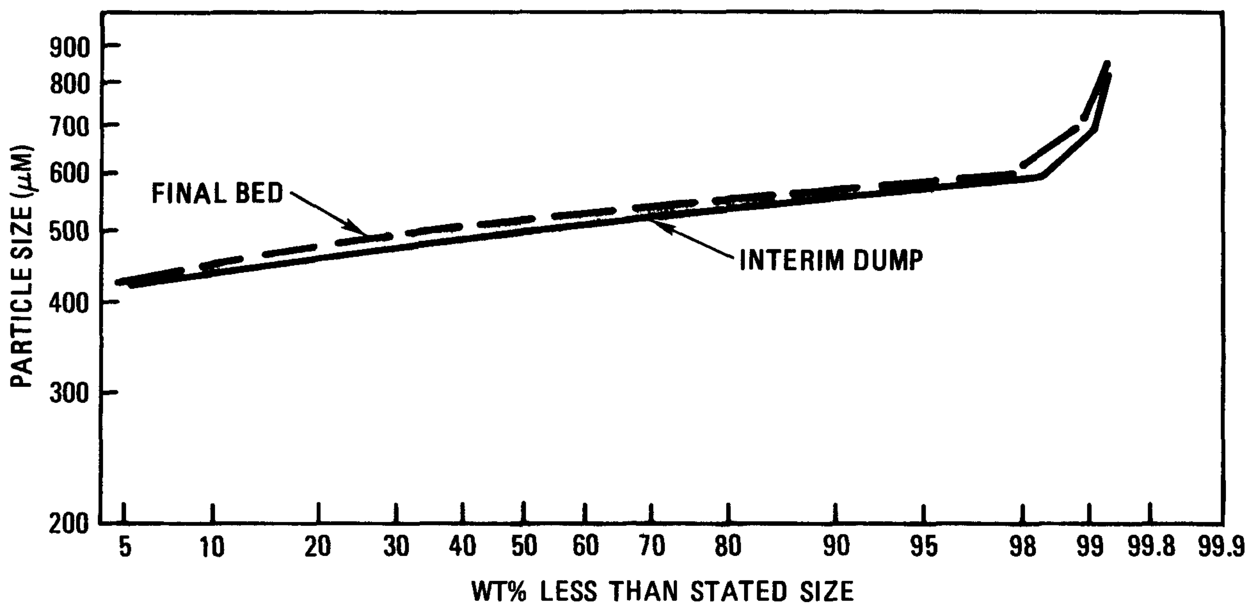


Fig. 2-16. Product size distribution for 0.20-m primary burner, 48-h run

Fines bunker inventory after the run was 1.5 kg. This was observed 4 days after the burner run was over. This meant that many filter fines were dislodged in time due to normal platform vibrations.

A small proportion of agglomerates was found. Slumping the fluidized bed three different times could have contributed to agglomeration of fuel particles.

2.3.4. Acceptance Criteria

The Activity Plan detailed eight acceptance criteria. They were all met as shown below:

1. No feed line blockage.

2. Product heel to be less than 0.5 wt %; no heel was observed.

3. Burner heatup time to be less than 2 hours; 45 min was required.

4. Off-gas filter pressure drop to be less than 35 kPa; a maximum of 4.2 kPa was observed.

5. Main burn rate to be at least 200 g/min; the peak burn rate was 240 g/min.

6. Fines heel to be less than 0.5 wt % of throughput; the fines heel including filter coating was only 0.3 wt % of throughput.

7. Product particle breakage to be less than 5 wt %; visual examination indicated less than 2 wt % breakage.

8. Product carbon content to be less than 1 wt %; actual carbon content was 0.1 wt %.

2.3.5. Conclusions

The success of this run indicated that gravity fines recycle can be used to burn elutriated fines from a primary burner system. One of the important results was that the fines rotary valve held up well at the nominal 450°C fines recycle temperature; no seal leakage was noted, and the high temperature bearings worked well throughout the run.

2.4. 48-HOUR RUN USING TRISO FRESH FEED

The Activity Plan required two separate 48-hour burner runs to be made on the 0.20-m primary burner. The first, using TRISO/BISO fresh feed, was successfully completed on March 30, 1978.

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

2.4.1. Feed

The feed material was a mixture of 18 wt % Fort St. Vrain type TRISO fertile fuel particles and 82 wt % crushed fuel block graphite (-0.48 cm).

2.4.2. Run Narrative

Vertex O_2 had been eliminated prior to this run for the purpose of simplification. Vertex CO_2 was maintained at 130 slpm.

Figures 2-17 through 2-21 give several burner variables as a function of run time.

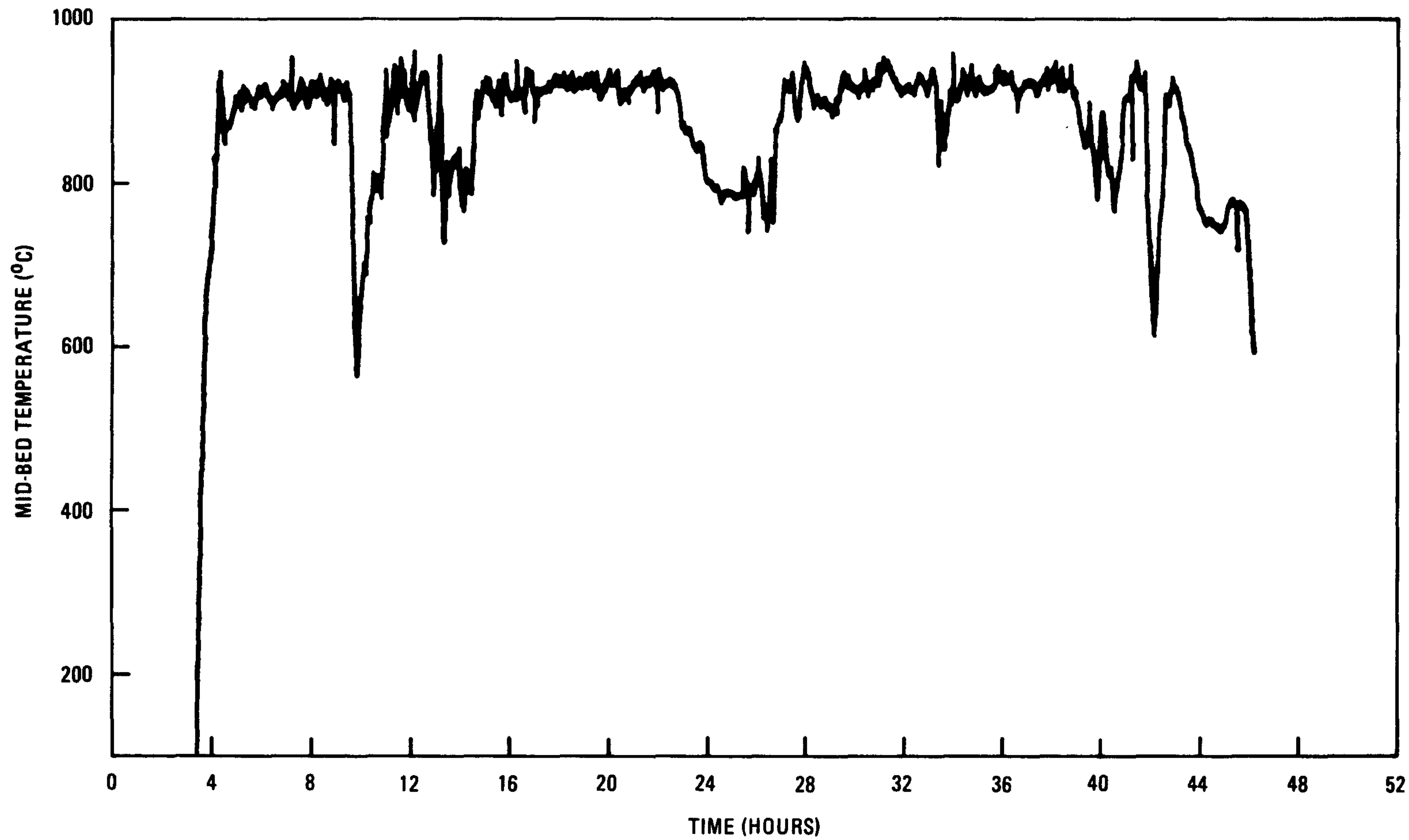


Fig. 2-17. Run 1 mid-bed temperature

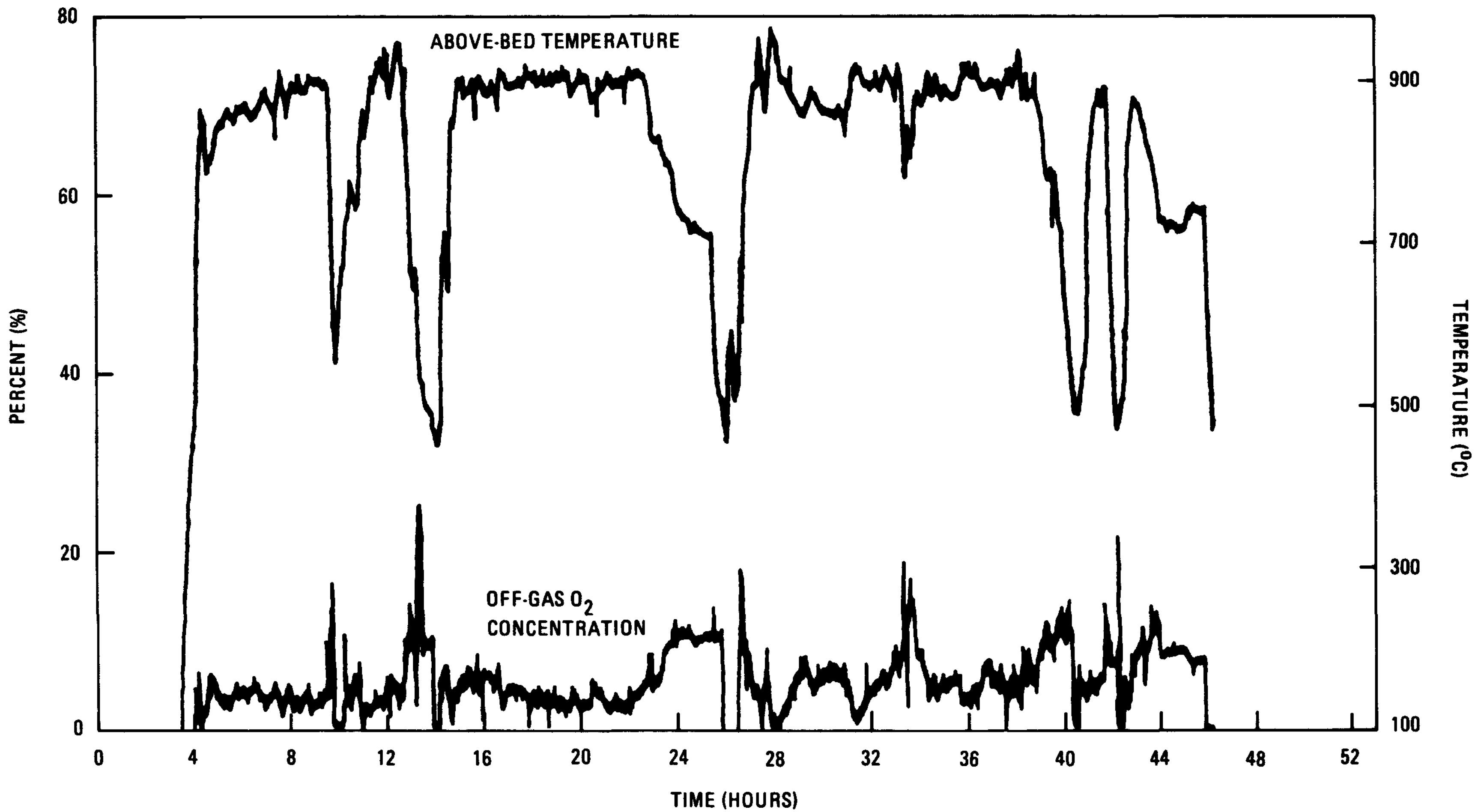


Fig. 2-18. Run 1 above-bed temperature and O_2 concentration

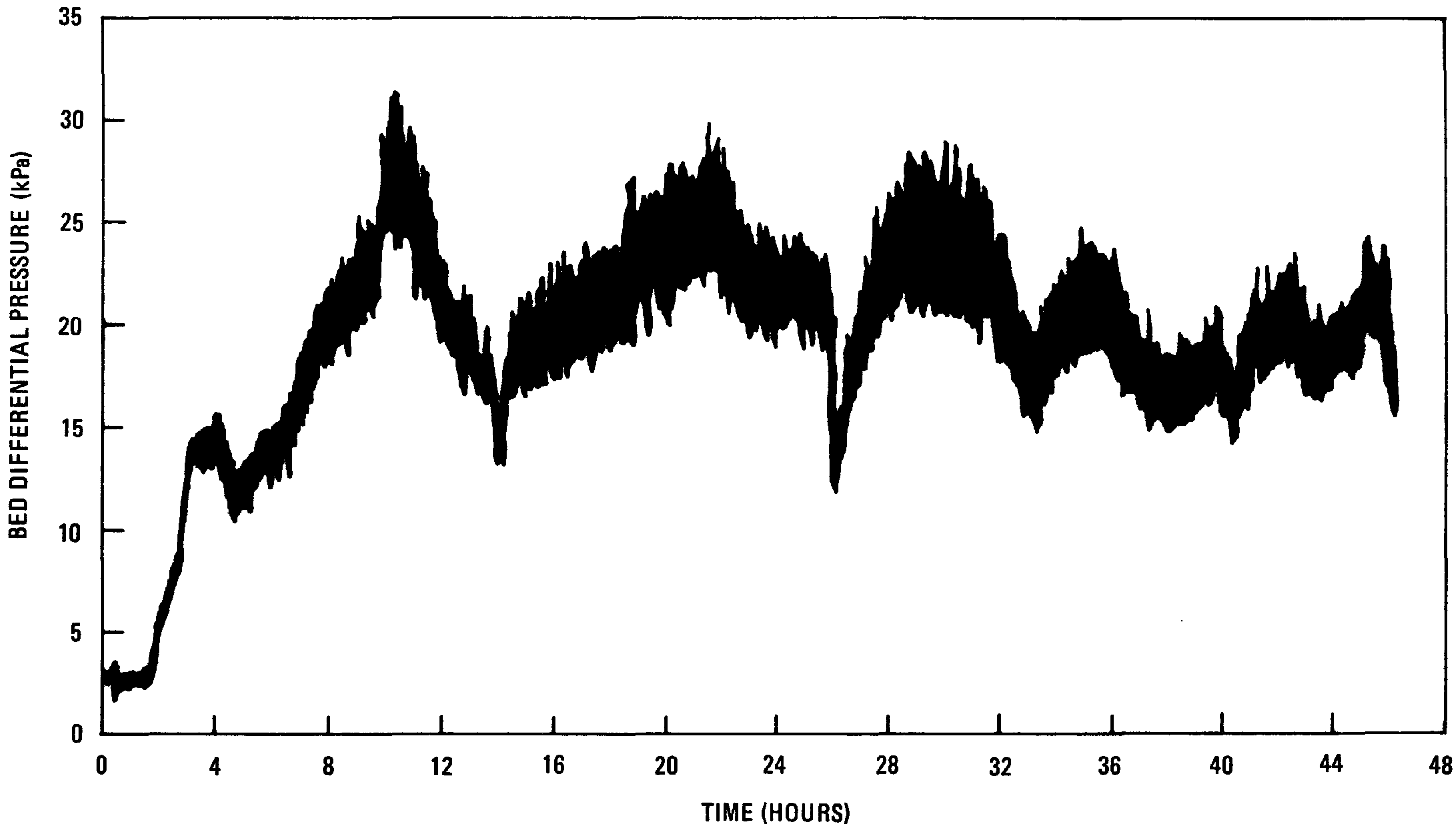


Fig. 2-19. Run 1 bed differential pressure

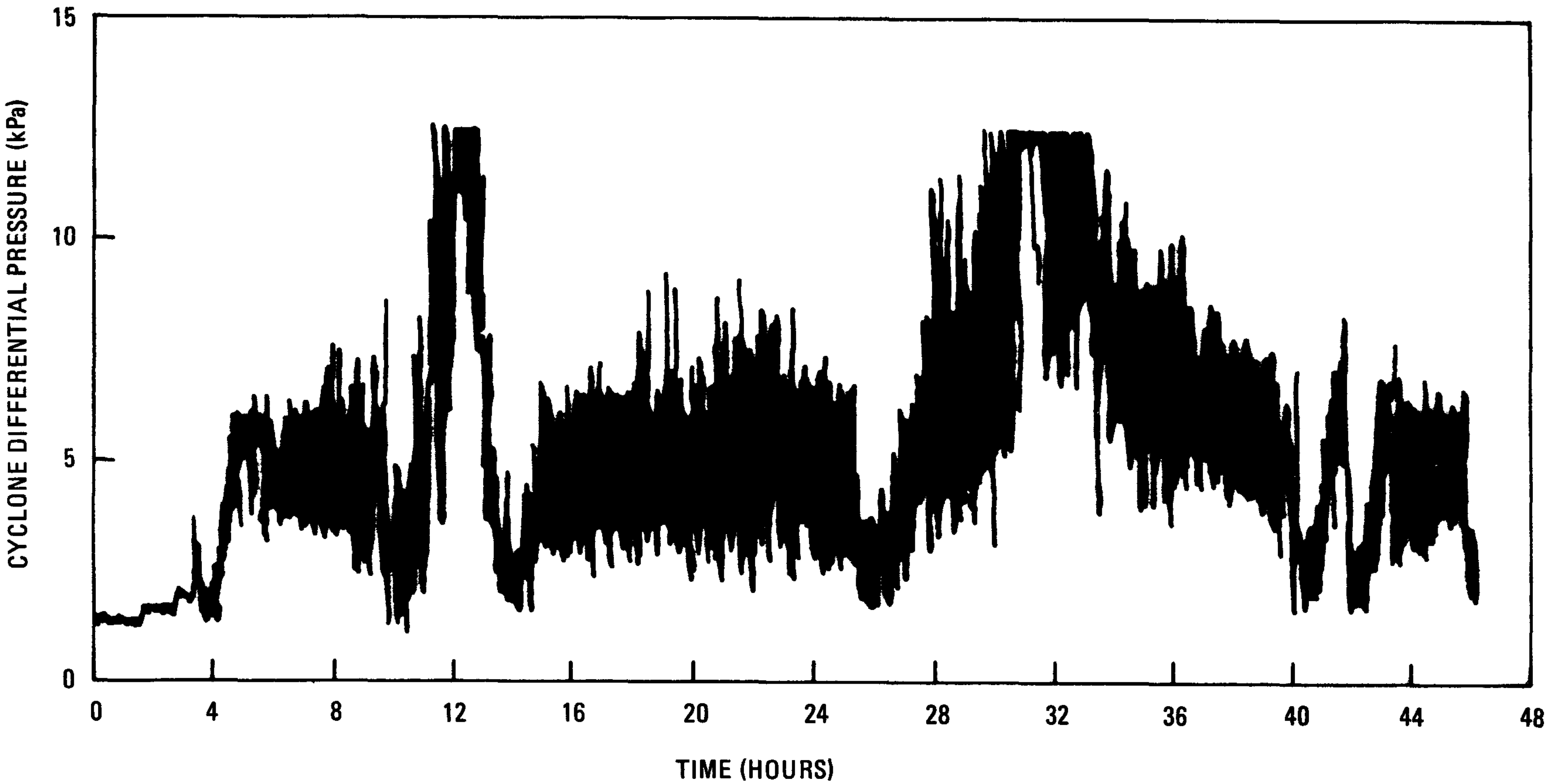


Fig. 2-20. Run 1 cyclone pressure

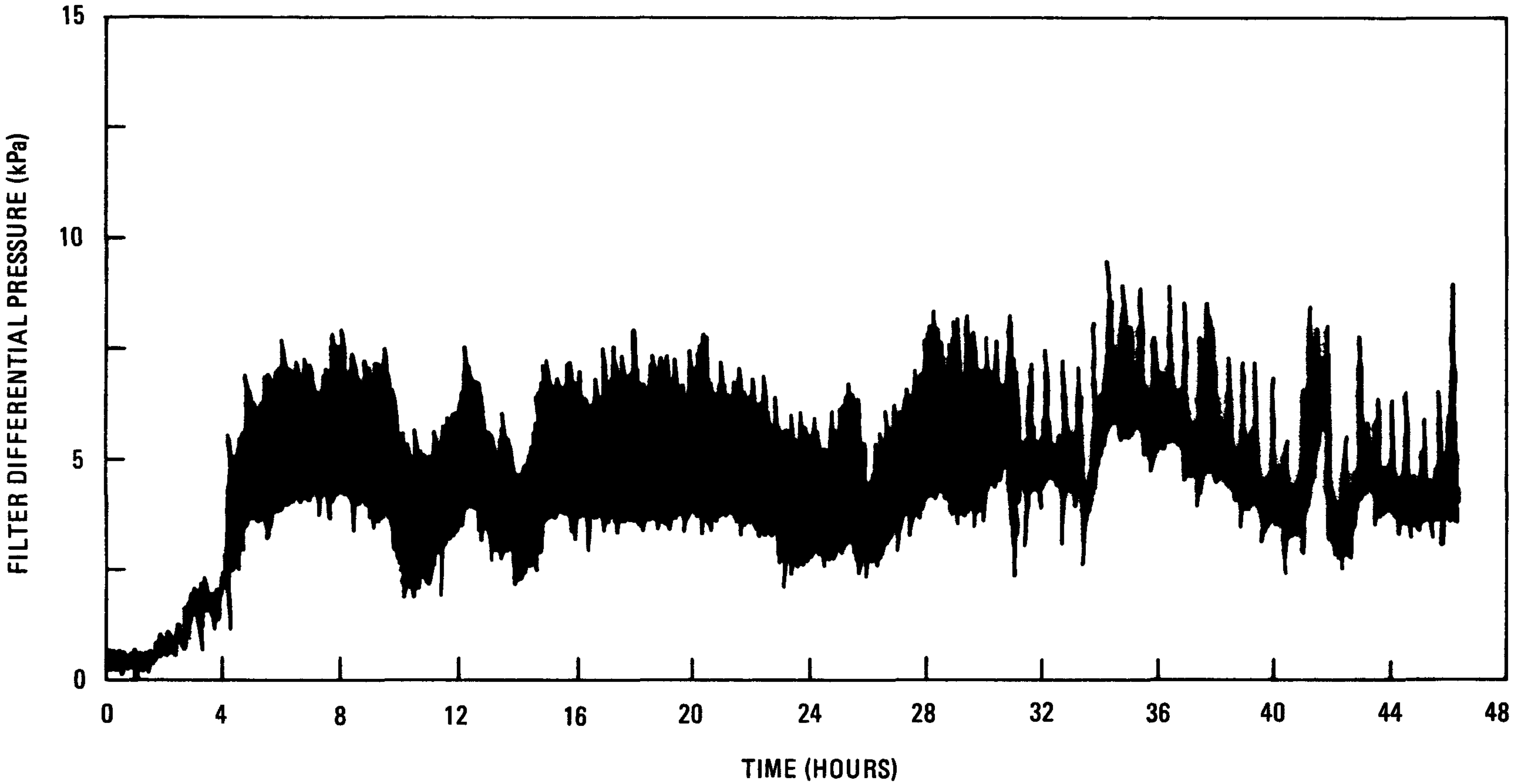


Fig. 2-21. Run 1 filter pressure

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

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

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

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

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

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

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

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

2.4.3. Product

Material removed during the interim product removal phase was found to contain 0.08 wt % carbon and 1.6 wt % broken particles. Bulk density was 2.3 g/cm^3 while tap density was 2.4 g/cm^3. The final product material contained 0.25 wt % carbon and had a bulk density of 2.1 g/cm^3 and a tap density of 2.3 g/cm^3. Particle breakage was analyzed to be 2.3 wt %.

Inspection of the fines bunker after the run showed 4.2 kg of fines remaining in the bunker. These fines contained 36 wt % ThO_2 powder. Higher recycle temperatures may be required to reduce this final fines heel when using Fort-St.-Vrain-type TRISO fuel particles. The highly noncombustible content of the stream imposed undue heating loads on the fines stream, but did not add as much carbon to the recycle loop; this allowed for more complete oxygen utilization.

2.4.4. Acceptance Criteria

The Activity Plan detailed eight acceptance criteria. They were all met as shown below:

1. No feed line blockage.

2. Product heel to be less than 0.5 wt %; no heel observed.

3. Burner heatup time to be less than 2 hours; 50 min was required.

4. Off-gas filter pressure drop to be less than 35 kPa; a maximum of 6 kPa was observed.

5. Main burn rate to be at least 200 g/min; the peak burn rate was 232 g/min.

6. Fines heel to be less than 0.5 wt % of throughput; the fines heel was 0.7 wt % of throughput, but only 0.48 wt % was carbon.

7. Product particle breakage to be less than 5 wt %; the actual product particle breakage was 2.3 wt %.

8. Product carbon content to be less than 1 wt %; the actual average carbon content was 0.17 wt %.

2.4.5. Conclusions

The success of this run further demonstrated the feasibility of a gravity fines recycle system to burn fines elutriated from a primary burner system. More work was then focused on operating the fines recycle stream at a higher temperature to improve the fines burnout characteristics when highly noncombustible fines concentrations are present.

2.5. FINES HEAT TRANSFER CHARACTERISTICS IN THE FINES PIPE AND CYCLONE

Data from the two 48-hour runs were tabulated and used to make a preliminary estimate of the heat loads and overall heat transfer coefficients for the fines pipe-cooling air and cyclone-cooling air systems. These data are included as Tables 2-1 and 2-2.

TABLE 2-1
48-HOUR RUN 1 DATA

	Time (test hour in parentheses)								
	2000 (12)	2200 (14)	0100 (17)	0600 (22)	0800 (24)	1600 (32)	1800 (34)	0300 (43)	0500 (45)
Cooling air (fines flow)									
Flow rate (std m^3/s)	0.0637	0.0896	0.1038	0.0943	0.0613	0.0943	0.1085	0.0660	0.0060
Outlet temp (°C)	255	225	215	200	250	230	220	255	245
Cooling air (cyclone)									
Flow rate (std m^3/s)	0.0377	0.0590	0.0660	0.0500	0.0425	0.0590	0.0684	0.0377	0.0377
Outlet temp (°C)	165	145	135	130	155	150	145	165	155
Burner gas flow									
%CO	11	11	11	12	11	11	11	10	10
$\%O_2$	3	4	2	4	2	0	0	1	1
Flow rate (std liters/s)	15.75	15.77	16.05	15.72	15.37	15.97	16.13	16.07	16.03
Fines pipe									
Inlet temp (°C)	830	875	885	840	895	925	945	885	875
Outlet temp (°C)	600	615	605	580	610	650	685	625	600
Cyclone									
Inlet temp (°C)	600	615	605	580	610	650	685	625	600
Outlet temp (°C)	440	460	450	420	440	455	450	450	445
Fines pipe-wall temp (°C)	430	410	385	360	425	420	395	435	420
Fines flow									
Rotary valve speed (revs/s)	0.022	0.023	0.023	0.025	0.028	0.028	0.029	0.029	0.029

TABLE 2-2
48-HOUR RUN 2 DATA

	Time (test hour in parentheses)								
	1530 (6)	1800 (8)	0100 (16)	0300 (18)	0500 (20)	1500 (30)	1700 (32)	2000 (35)	2300 (38)
Cooling air (fines flow)									
Flow rate (std m^3/s)	0.1509	0.0873	0.1368	0.1368	0.1368	0.1604	0.1557	0.1368	0.0943
Outlet temp (°C)	155	225	185	185	185	175	155	205	225
Cooling air (cyclone)									
Flow rate (std m^3/s)	0.0967	0.0542	0.0896	0.0896	0.0896	0.0967	0.0967	0.0896	0.0566
Outlet temp (°C)	130	150	120	125	125	145	145	155	140
Burner gas flow									
%CO	15	12	11	11	10	4	1	1	0
$\%O_2$	4	2.7	3	3	2	3	14	5	9
Flow rate (std liters/s)	17.42	17.08	16.92	16.97	16.97	17.13	16.75	16.88	13.85
Fines pipe									
Inlet temp (°C)	890	905	850	865	875	905	800	890	700
Outlet temp (°C)	610	590	590	595	595	670	545	670	525
Cyclone									
Inlet temp (°C)	610	590	590	595	595	670	545	670	525
Outlet temp (°C)	450	360	430	435	460	510	410	575	465
Fines pipe-wall temp (°C)	300	375	310	315	315	285	315	375	350
Fines flow									
Rotary valve speed (revs/s)	0.022	0.013	0.020	0.020	0.020	0.018	0.013	0.027	0.025

2.5.1. Data Tabulation

Data were chosen at times when the process was in a reasonably steady state. A "steady state" was determined by a quick study of the graphs of consolidated data, which showed the general trends of the process variables over the entire 48 hours. These graphs are provided in Sections 2.3 and 2.4.

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

2.5.2. Estimation of Heat Loads

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

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

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

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

For the fines pipe cooling air, T_{av} = 122°C. For the cycline cooling air, T_{av} = 95°C.

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

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

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

where

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

Cp = heat capacity, kcal/g-°C.

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

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

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

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

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

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

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

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

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

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

Tables 2-1 through 2-5 summarize the data.

TABLE 2-3
HEAT GAIN BY COOLING AIR IN FINES PIPE

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

TABLE 2-4
HEAT LOSS BY PROCESS STREAM IN FINES PIPE

RUN 1

$\dot{M}_{fines}$ (g/s)	Cp_{fines} (kcal/g-°C)	$\dot{M}_{offgas}$ (g/s)	Cp_{offgas} (kcal/g-°C)	ΔT_{offgas} (°C)	Q (kcal/s)	$U \times 10^6 \left(\frac{kcal}{cm^2\text{-}s\text{-}°C}\right)$
25.0	4.35×10^{-4}	30.9	2.94×10^{-4}	230	4.60	3.20
26.9	4.35×10^{-4}	31.0	2.94×10^{-4}	260	5.41	3.45
26.9	4.35×10^{-4}	31.5	2.94×10^{-4}	280	5.87	3.72
28.8	4.35×10^{-4}	30.9	2.94×10^{-4}	260	5.62	3.72
32.7	4.35×10^{-4}	30.2	2.94×10^{-4}	285	6.58	4.29
32.7	4.35×10^{-4}	31.4	2.94×10^{-4}	275	6.45	3.86
33.6	4.35×10^{-4}	31.7	2.94×10^{-4}	260	6.22	3.51
33.6	4.35×10^{-4}	31.6	2.94×10^{-4}	260	6.22	4.03
33.6	4.35×10^{-4}	31.5	2.94×10^{-4}	275	6.57	5.45
RUN 2						
25.0	4.35×10^{-4}	34.2	2.94×10^{-4}	280	5.86	3.46
15.4	4.35×10^{-4}	33.6	2.94×10^{-4}	315	5.22	3.36
23.1	4.35×10^{-4}	33.2	2.94×10^{-4}	260	5.15	3.29
23.1	4.35×10^{-4}	33.3	2.94×10^{-4}	270	5.36	3.37
23.1	4.35×10^{-4}	33.3	2.94×10^{-4}	280	5.55	3.47
21.1	4.35×10^{-4}	33.7	2.94×10^{-4}	235	4.49	2.53
15.4	4.35×10^{-4}	32.9	2.94×10^{-4}	255	4.17	2.80
30.8	4.35×10^{-4}	33.2	2.94×10^{-4}	220	5.09	3.29
28.8	4.35×10^{-4}	27.2	2.94×10^{-4}	175	3.60	2.94

TABLE 2-5
HEAT GAIN BY COOLING AIR IN CYCLONE

ΔT (°C)	Flow (std m^3/s)	Cρ (kcal/kg-°C)	$\rho \left(\frac{kg}{m^3}\right)$	$Q \left(\frac{kcal}{s}\right)$	ΔT_{1m} (°C)	A (cm^2)	$U \times 10^6 \left(\frac{kcal}{cm^2\text{-}s\text{-}°C}\right)$
RUN 1							
125	0.0337	0.241	1.298	1.48	401	974	3.79
105	0.0590	0.241	1.298	1.94	432	974	4.61
95	0.0660	0.241	1.298	1.96	428	974	4.70
90	0.0500	0.241	1.298	1.39	402	974	3.55
115	0.0425	0.241	1.298	1.53	411	974	3.82
110	0.0590	0.241	1.298	2.03	440	974	4.74
105	0.0684	0.241	1.298	2.25	454	974	5.09
125	0.0377	0.241	1.298	1.48	417	974	3.64
115	0.0377	0.241	1.298	1.36	410	974	3.41
RUN 2							
90	0.0967	0.241	1.298	2.72	433	974	6.45
110	0.0542	0.241	1.298	1.87	353	974	5.44
80	0.0896	0.241	1.298	2.24	419	974	5.49
85	0.0896	0.241	1.298	2.38	421	974	5.80
85	0.0896	0.241	1.298	2.38	436	974	5.60
105	0.0967	0.241	1.298	3.18	486	974	6.72
105	0.0967	0.241	1.298	3.18	372	974	8.78
115	0.0896	0.241	1.298	3.22	518	974	6.38
100	0.0566	0.241	1.298	1.77	400	974	4.54

2.5.3. Estimation of Overall Heat Transfer Coefficients

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

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

where

Q = heat load, kcal/s,

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

and

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

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

Furthermore,

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

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

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

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

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

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

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

2.5.4. Conclusions

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

2.6 FINES ROTARY VALVE TEST

An 11-hour burner run was successfully completed June 22, 1978. The purpose of the run was to test the operability of the fines recycle rotary valve at 600° to 650°C. No problems were encountered with the valve in that temperature range. Burner operation was simplified by the ability to recycle fines at a temperature close to their combustion threshold. Continued operation of the valve in excess of 600°C is planned during future burner runs.

A TRISO/BISO, 20 wt % carbon fluidized bed was added to the burner for startup. It was heated to 700°C and ignited with plenum O_2. The burn rate was quickly brought to 200 g/min.

Fresh feed was initiated at 240 g/min in order to maintain the bed carbon inventory. Fines recycle was then started at a fines rotary valve speed of 3 to 4 rpm. The mid-reactor O_2 flow was increased to 160 slpm as the fines stream heated. Fines bunker and rotary valve temperatures were allowed to increase to 630°C by modulating the fines pipe and cyclone cooling air.

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

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

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

2.7. BURNER RECONSTRUCTION

As part of fiscal year 1978 activities, the 0.20-m primary burner was reconstructed in a gravity fines recycle configuration. The burner was then used to thoroughly explore the operability of this recycle mode, and it was upgraded as follows:

1. The burner tube was repaired by cutting out the failed section and welding in a replacement piece.

2. The susceptor was rebuilt and lowered to allow the entire lower burner tube to be heated. The bellows-sealed susceptor/burner tube interface ensures zero cooling air leakage.

3. The gas distributor was rebuilt to allow plenum drainage into a detachable can.

4. A sealed product can was located directly below the vertex gas line.

5. A high-pressire (83 kPa) cooling air supply system was installed.

6. A cooling air shroud was installed on the pipe between the burner and the cyclone, and on the cyclone itself.

7. A filter chamber containing six filter elements rather than four was fabricated.

8. A fines hopper with large volume (277 liters) and aerated conical bottom was constructed.

9. A sealed fresh feed hopper with aerated conical bottom volume (424 liters) was constructed.

10. A fresh feed rotary valve with sensitive speed control capabilities was added.

11. Extensive use was made of level sensors and flow sensors in the burner tube, feed hopper, fines hopper, and fines recycle lines.

12. Resistance type plenum and vertex gas preheaters were made.

13. A vacuum type fines sampler capable of remote operation was built.

Photographs of this equipment are shown in Figs. 2-22, 2-23, and 2-24. Drawings of the equipment are shown in Figs. 2-25 through 2-31.

2.8. SUBSYSTEM UPGRADES

2.8.1. Plenum Backflow Reduction

Backflow of fuel particles through the plenum gas distributor was reduced over four orders of magnitude by increasing the distributor pressure drop so that it was greater than the maximum slug pressure fluctuation. This prevented any instantaneous reverse gas flow, which would allow material to go back through the distributor holes. Further testing will be done during future burner runs to gather additional backflow data and determine gas distribution effectiveness.

The plenum gas distributor that had been previously used was a 90° cone with a 12 mm lower diameter and a 16.5 cm upper diameter. It had 360 holes, each being 0.9 mm in diameter. During normal operation, with a flow of 450 slpm of CO_2, the pressure drop was 2.5 kPa.

Maximum slugging pressure variations, caused by the up-and-down movement of a 50 kg fuel particle fluidized bed, have been observed to be ±7 to 10 kPa. There was thus a possibility for a significant reverse pressure drop across the distributor, which would yield a reverse gas flow that would allow fuel particles to go backwards through the distributor holes.

During previous burner runs, there had been as much as 850 g/hour of plenum backflow. This material is typically at least 90 wt % burned back BISO fuel particles (ThO_2 microspheres).

The most convenient method of increasing the pressure drop on the existing distributor was to reduce the total number of holes by welding them closed. It was then calculated that half the holes would need to be

Fig. 2-22. Lower section of 0.20-m primary burner system including susceptor, induction coil and capacitors, gas distribution, product can, and plenum drain can

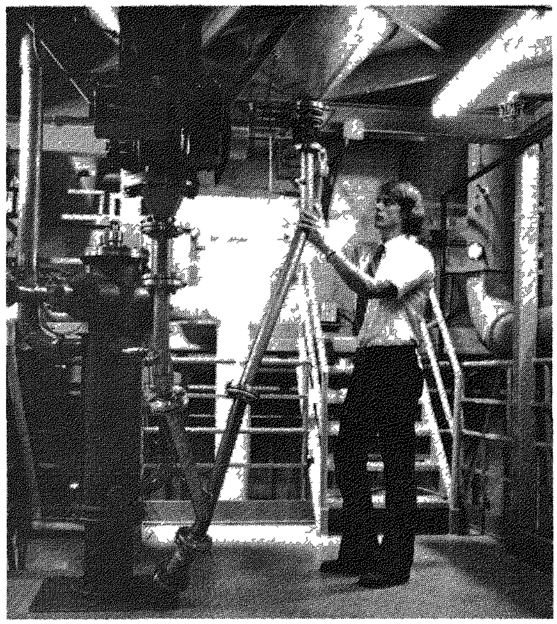


Fig. 2-23. Upper section of 0.20-m primary burner system including burner tube, fines upflow line, fresh feed metering valve, fines metering valve, fines downflow line, and cooling air lines

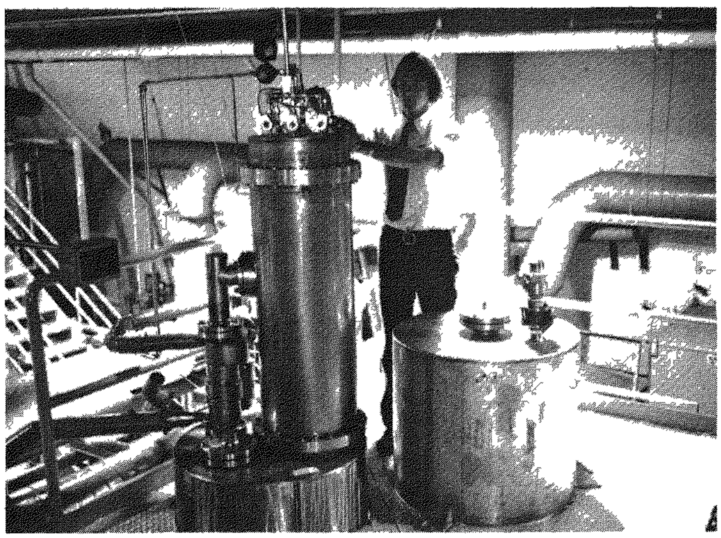
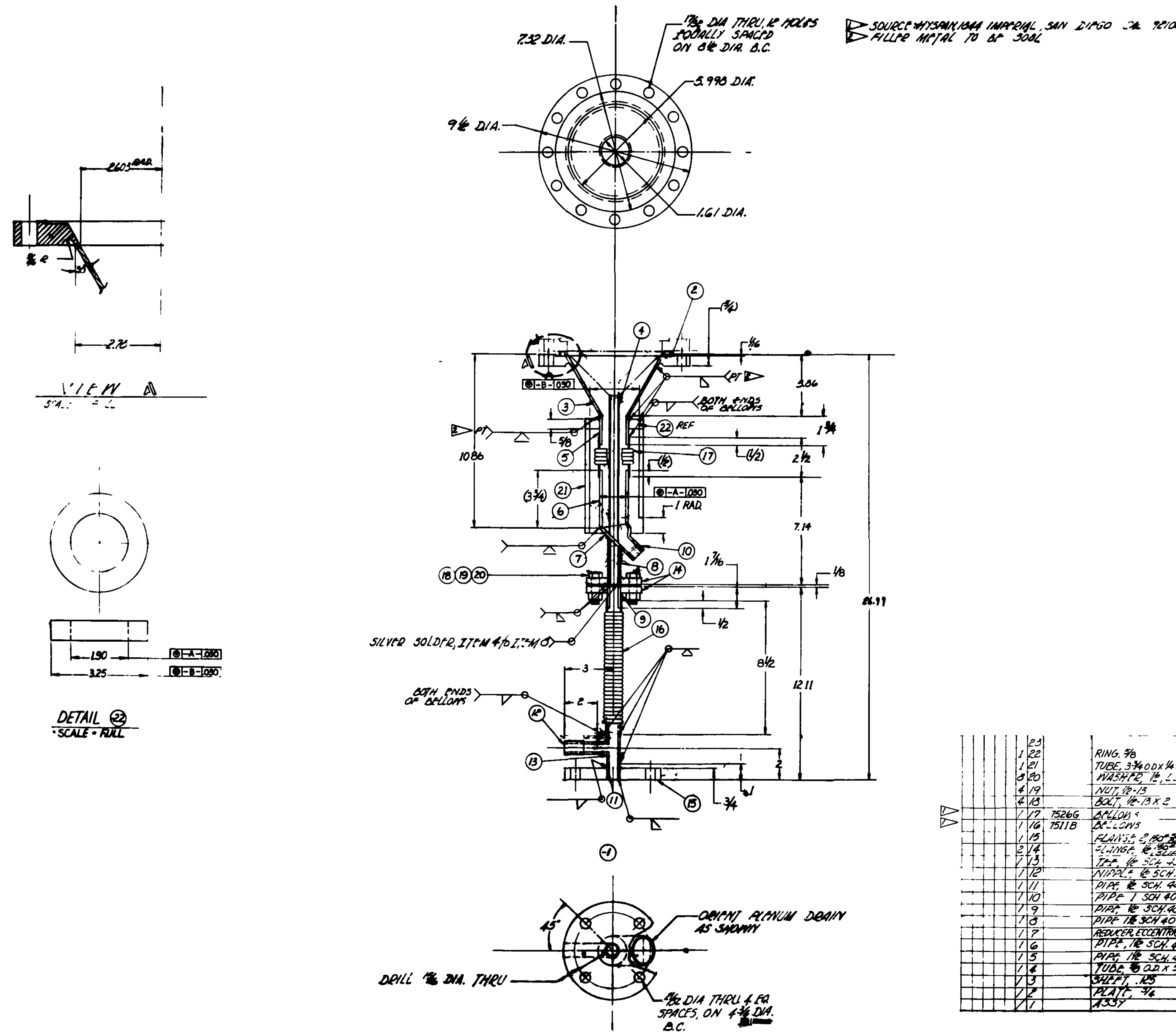


Fig. 2-24. Top section of 0.20-m primary burner system including fresh feed hopper, fines recycle hopper, offgas cyclone, offgas filter chamber, and cooling air lines



Qty	Item	Part No.	Description	Material	Spec.
	23				
1	22		RING, 5/8	304 SS	ASTM-A-240
1	21		TUBE, 3¾ OD X ¼ WALL		ASTM-A-269
8	20		WASHER, ½, LOCK		COM'L
4	19		NUT, ½-13		COM'L
4	18		BOLT, ½-13 X 2		COM'L
1	17	7526G	BELLOWS		
1	16	7511B	BELLOWS		
1	15		FLANGE, 2, 150# BLIND		COM'L
2	14		FLANGE, ½, 150# SLIP-ON		COM'L
1	13		TEE, ½ SCH 40		COM'L
1	12		NIPPLE, ½ SCH. 40		COM'L
1	11		PIPE, ½ SCH. 40		ASTM-A-312
1	10		PIPE 1 SCH 40		
1	9		PIPE, ½ SCH. 40		
1	8		PIPE 1½ SCH 40		
1	7		REDUCER, ECCENTRIC 1½x1		COM'L
1	6		PIPE, 1½ SCH. 40		ASTM-A-312
1	5		PIPE, 1½ SCH. 40	304 SS	ASTM-A-312
1	4		TUBE, ⅝ O.D. X .50 I.D.	HASTELLOY-X	
1	3		SHEET, .125	HASTELLOY-X	
1	2		PLATE, ¾	HASTELLOY-X	
	1		ASSY		

Fig. 2-25. Distributor assembly

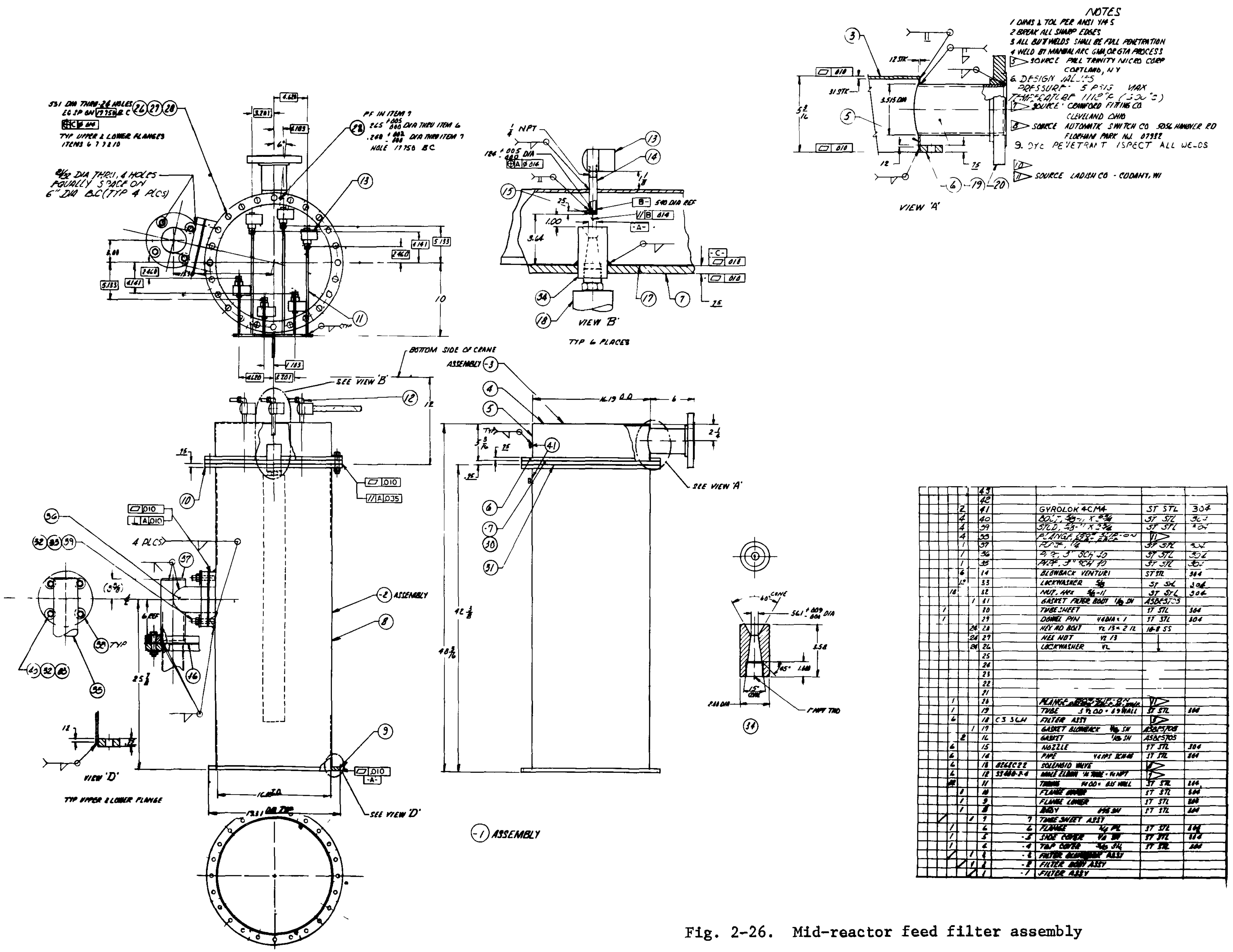


Fig. 2-26. Mid-reactor feed filter assembly

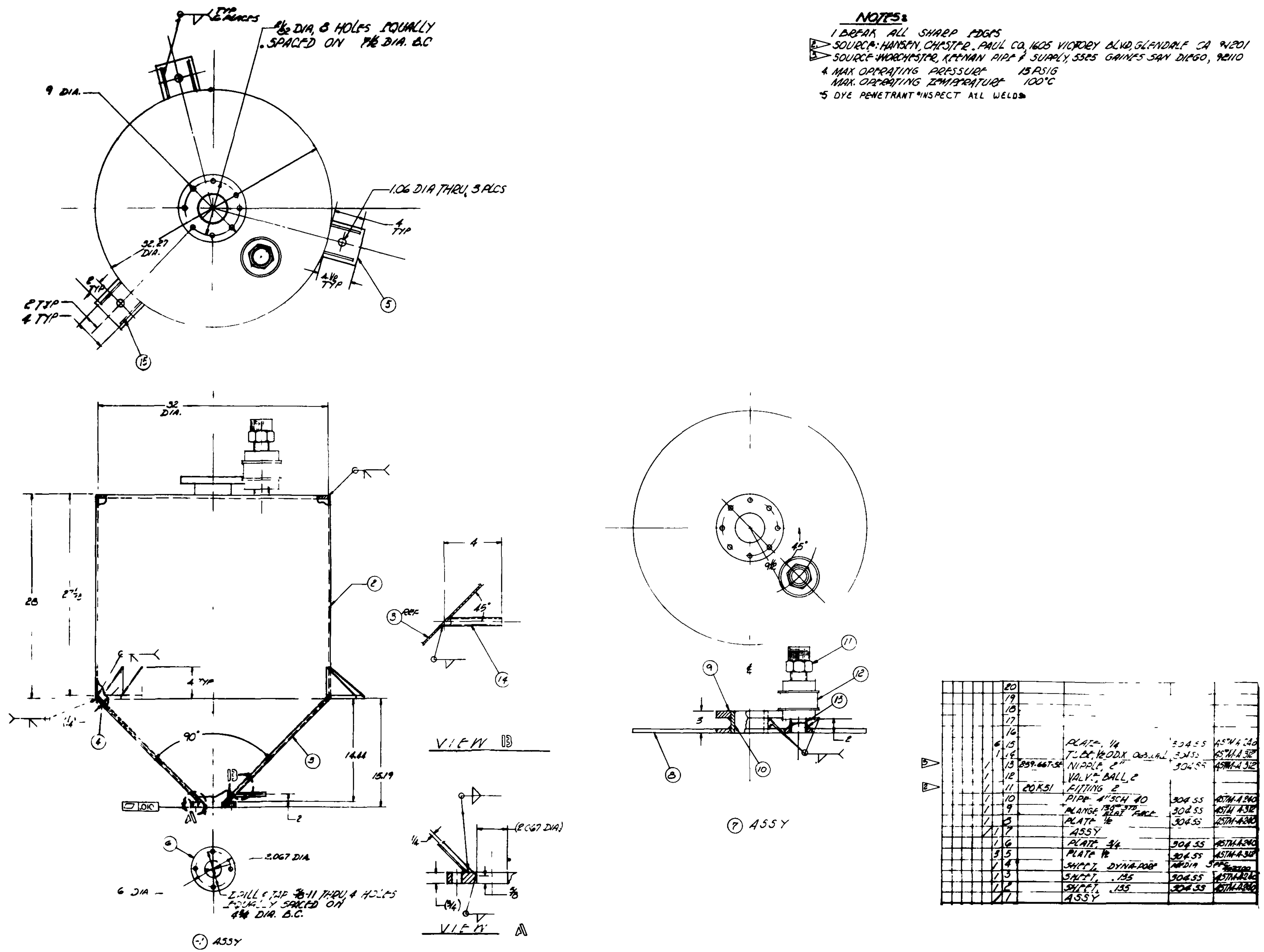


Fig. 2-27. Mid-reactor fresh feed bunker

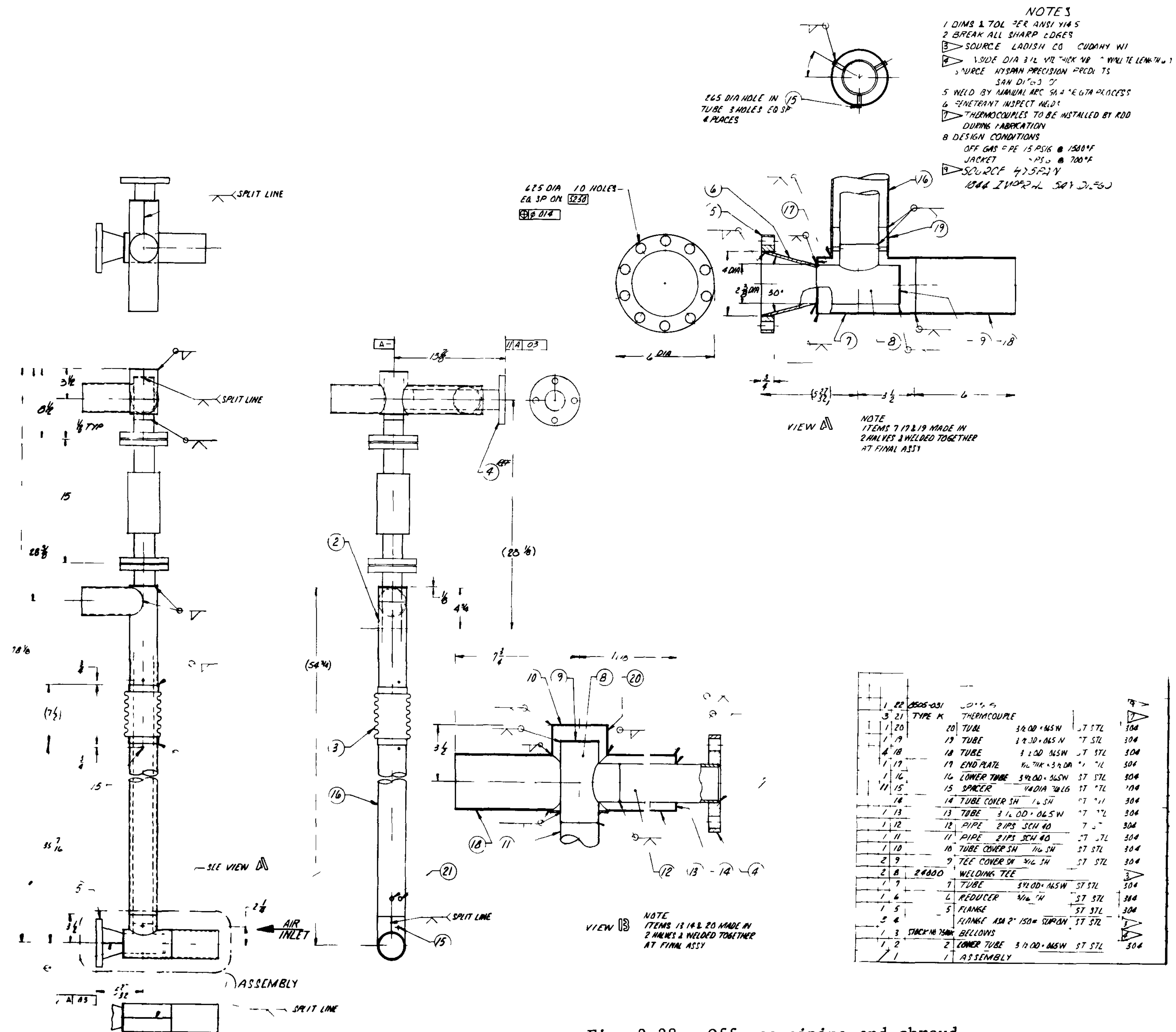


Fig. 2-28. Off-gas piping and shroud

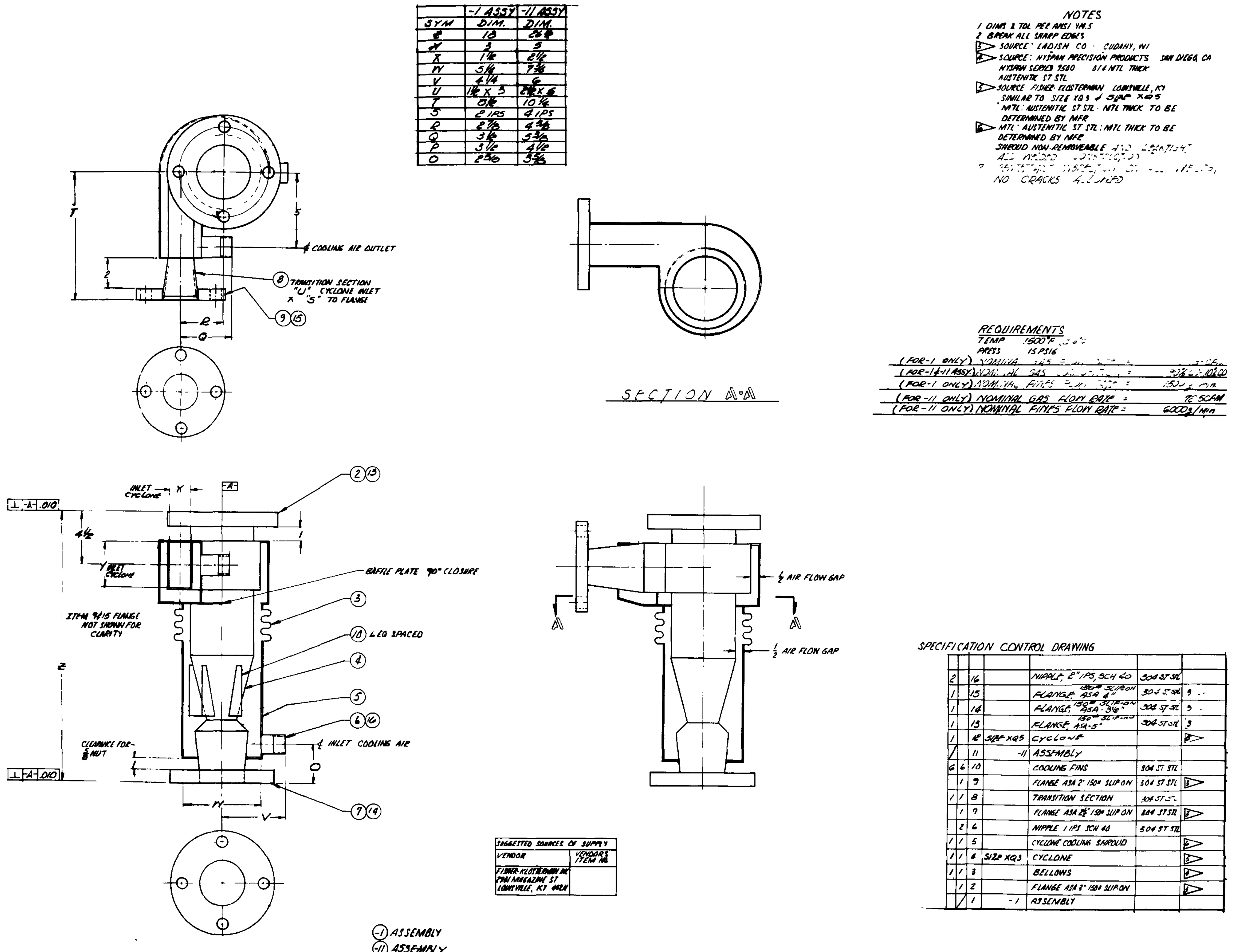


Fig. 2-29. Cyclone collector with cooling shroud

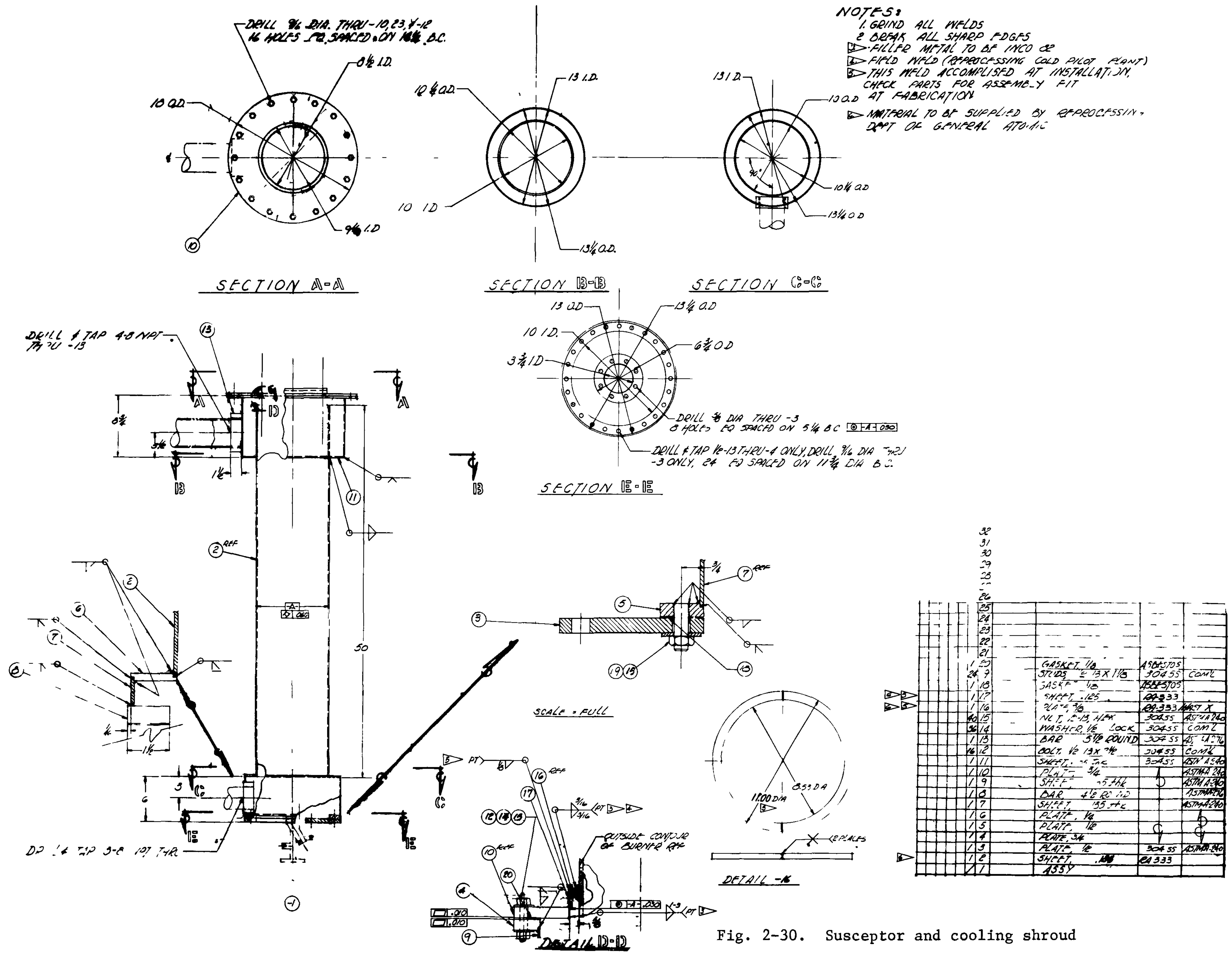


Fig. 2-30. Susceptor and cooling shroud

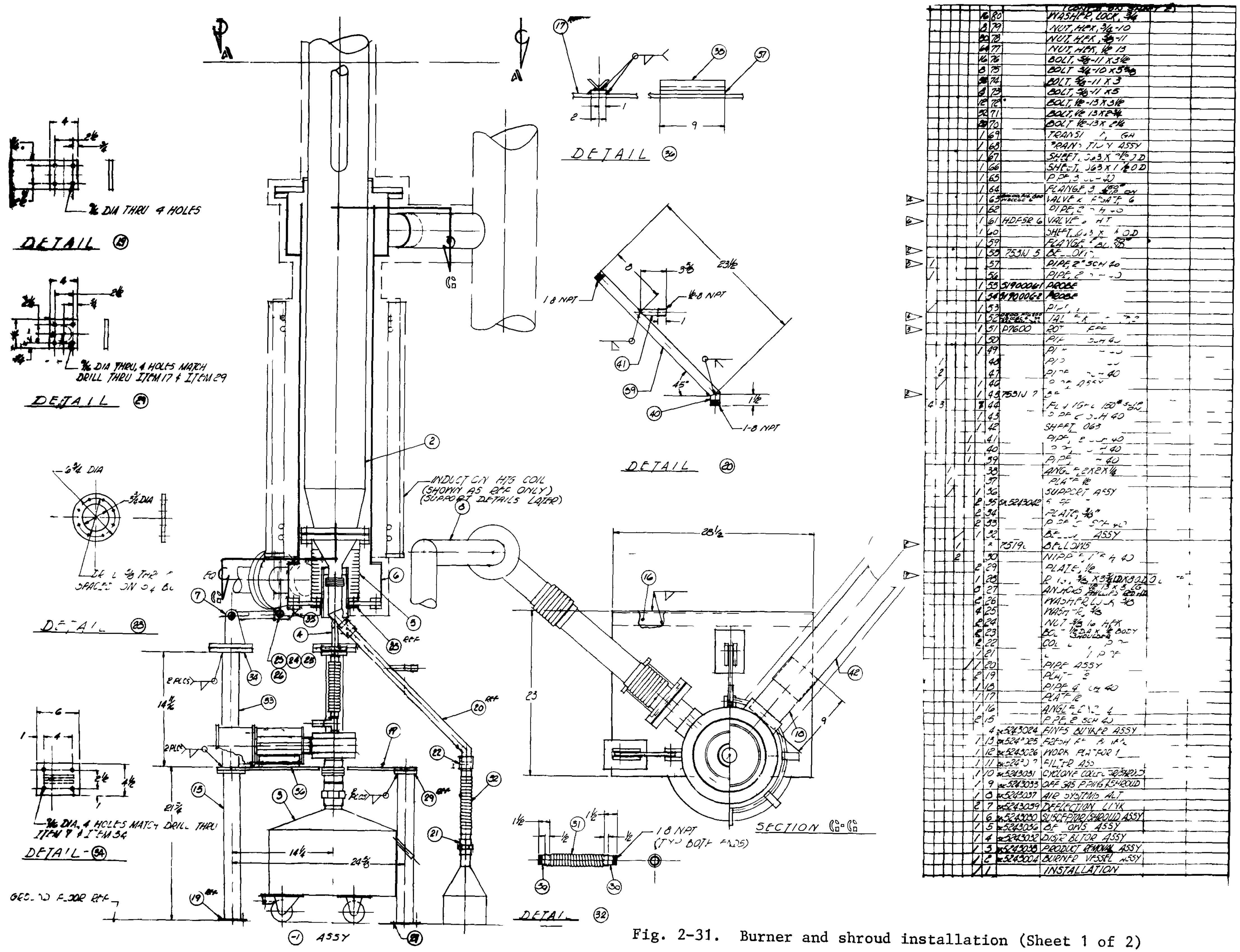


Fig. 2-31. Burner and shroud installation (Sheet 1 of 2)

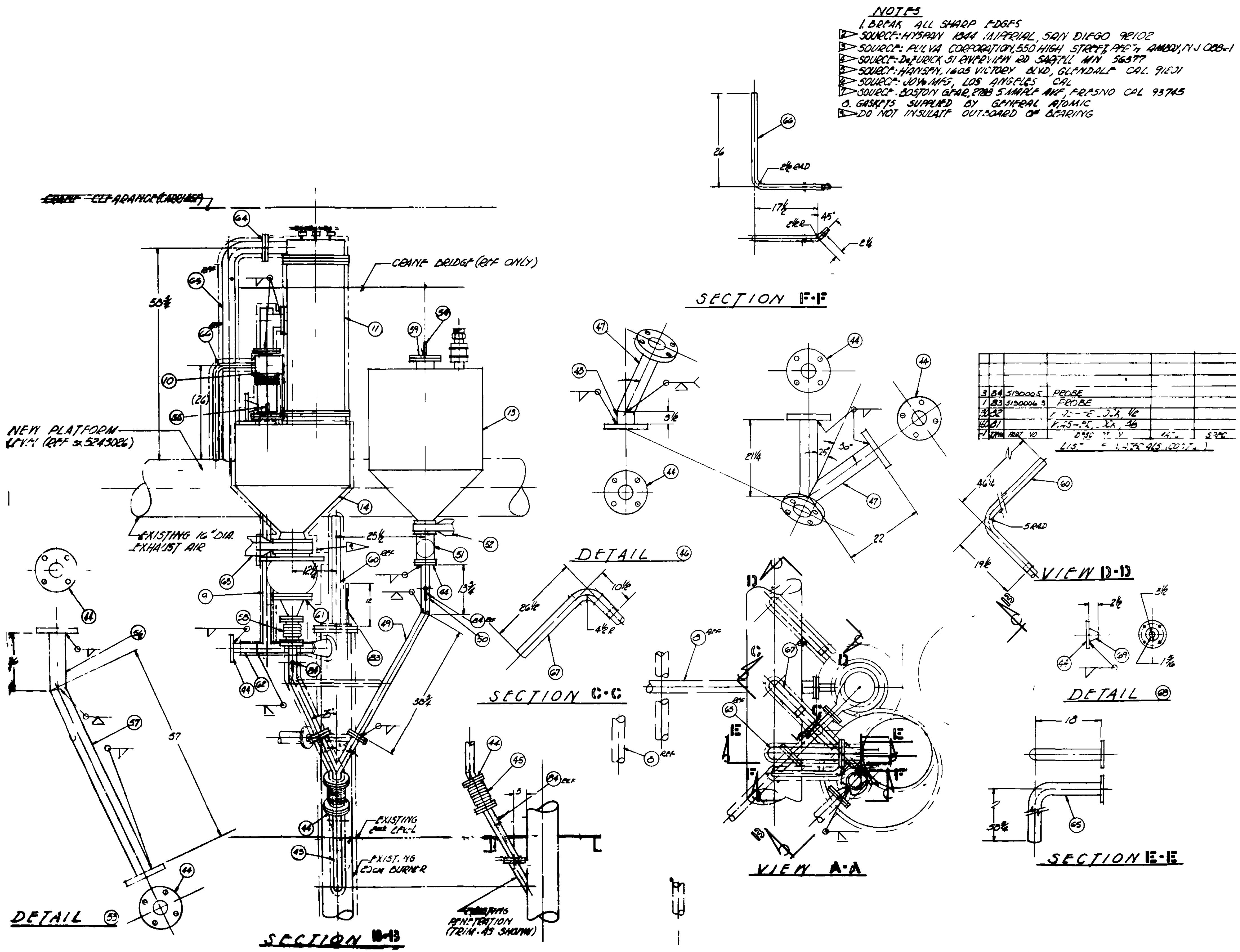


Fig. 2-31. Burner and shroud installation (Sheet 2 of 2)

closed to yield a pressure drop of 11 kPa, or enough to at least equal the greatest slugging pressure fluctuations Half of the holes were welded closed and the distributor was reassembled. The pressure drop at 450 slpm of CO_2 was found to be 13 kPa, somewhat higher than predicted.

An 8-hour test was then run to determine material backflow rates A 50-kg bed of burned back TRISO/BISO fuel particles was heated to 800°C for the 8-hour period. Slugging characteristics were the same as during actual burning operations. Material backflow amounted to 0.6 g of fuel particles after the 8 hours. This is a reduction in backflow rate of 16,000:1 over the final shakedown burner run.

This dramatic reduction in material backflow was due to having sufficient distributor pressure drop to preclude reverse gas flow due to fluidized-bed slugging.

During fiscal year 1977 sequential operations, almost 2 kg/hour of BISO fuel particles were observed to flow backward through the 0.40-m primary burner distributor. This was enough to almost fill the plenum cavity after 48 hours; the planned 96-hour run during this year's sequential operation would overflow the plenum cavity before the run could be completed. It is therefore necessary to alleviate this situation prior to fiscal year 1978 sequential operations.

2.8.2. Fines Sampler

A fines sampler capable of adaptation to a fully remote sampling mode was installed and successfully tested on the 0.20-m primary burner gravity fines recycle system.

Sampling of the fines recycle stream is necessary to determine non-combustible broken particle content of the fines, which increases during the course of a burner cycle or campaign. Operator action may be required, especially during extended (more than 100 hours) operation.

In order to provide that capability, a sample vacuum technique for discrete withdrawal of fines samples was installed. A schematic of the equipment is shown in Fig. 2-32.

Testing was accomplished by manually loading some carbon fines into the gravity fines recycle bunker and running through the operating cycle. A 2-second sample was found to yield 300 g of fines. The sample was conveniently removed from the filter's lower removable housing.

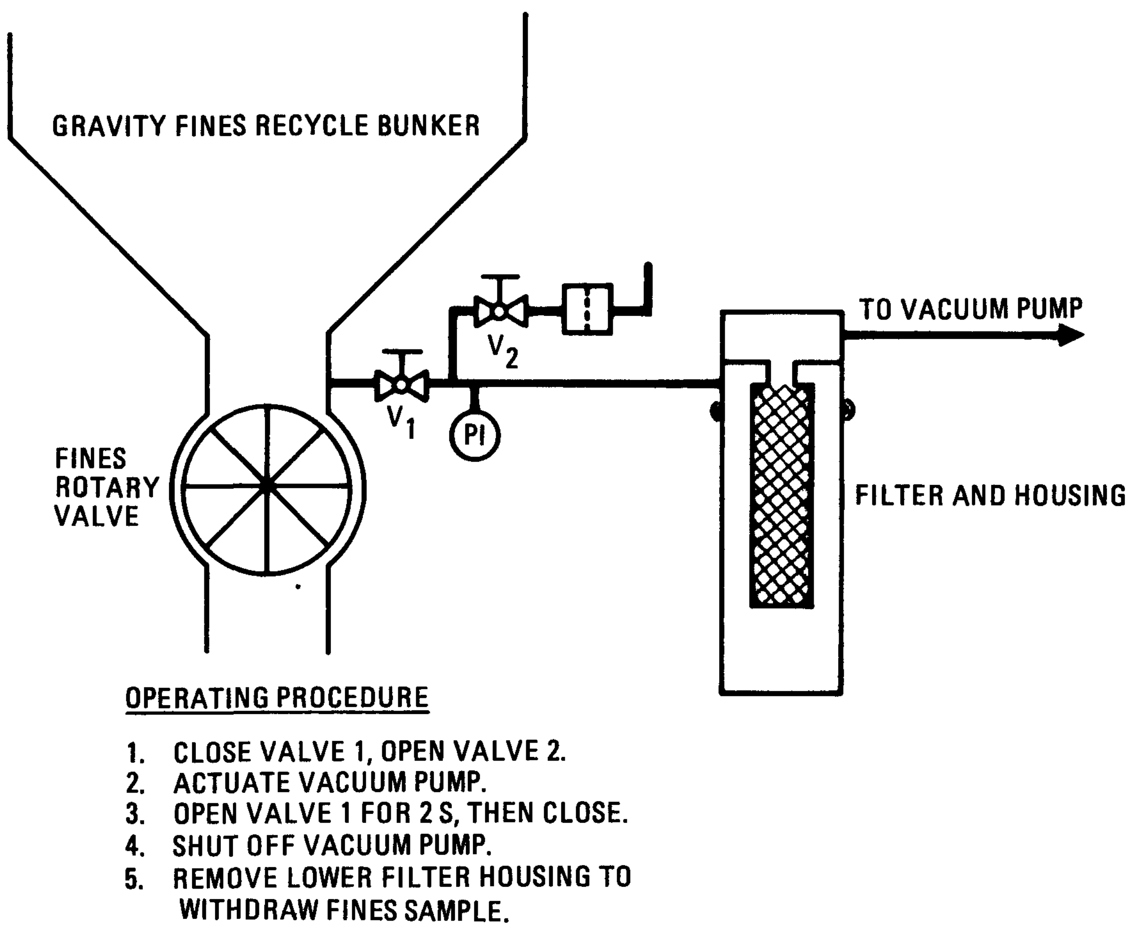


Fig. 2-32. Fines sample system

3. SUMMARY

Successful operation of the 0.20-m primary burner during two separate 48-hour runs has proved the operability of the gravity fines recycle system. Other advances included:

1. Reduction of material backflow through the inlet gas distributor.

2. Use of level sensors and flow sensors throughout the burner.

3. Sampling of recycling fines using a method adaptable to remote operation.

4. Using a bellows-sealed cooling air jacket to minimize gas leakage.

5. Accomplishment of fines heat transfer characteristics analysis.

4. RECOMMENDATIONS

Future work should include the following:

1. Long-term operation of the fines rotary valve at normal operating conditions to determine its service life.

2. Fabrication of an inlet gas distributor suitable for remote removal and replacement.

3. Provide for pneumatic product transport and discrete removal of any plenum material accumulation.

4. Conduct tests to evolve more durable level sensors, or make some provisions for their protection.

5. ACKNOWLEDGMENTS

The author wishes to extend appreciation to the following individuals who have contributed to this year's work on the 0.20-m primary burner:

- Design support - Bob Huston and Niles Johanson
- Burner operating team - Carol Kergis, Dale Fields, and Jim McNair
- Technician support - Tom Wright and his crew of Marshall Zacavich, Roy Nelson, Bob Earle, John McLean, and Gil Cox
- Electrical support - Dale Fields, Pat Knoll, Ernie Simmons, Sam Modica, and Carl Hays

Early researchers in this field were instrumental in the evolution of burner design and operation. They include Bob Zimmerman, Derrell Young, Mike Spaeth, Brent Palmer (Allied Chemical), and Lionel Brooks.

APPENDIX A
ACTIVITY PLAN

GENERAL ATOMIC COMPANY

GA 777 (Rev 6/76)

ACTIVITY PLAN - 20-cm & 40-cm PRIMARY BURNER

	Doc. No. AP 524401	Issue E	Date 10/20/77

Issue Summary — Approval Level 2

Issue	Date	Prepared by	Approval			Purpose of Issue/ Sections Changed
			Engineering	QA	Project	
RDD RELEASED A	8/2/76	W.S.Rickman				Initial Issue - ECO 00314 incorporated.
RDD RELEASED B	1/19/77	D.T.Young				General Revision/ ECOs 00348, 00401, 00402, 00414.
RDD RELEASED C	3/29/77	D.T.Young				Incorporates ECOs 00422, 00429, 00430, and 00431.
RDD RELEASED D	6/16/77	D.T.Young				General Revision/ ECO 00466
RDD RELEASED 11/15/77 E	10/20/77	W.S.Rickman (signed: WS Rickman)	R.D. Zimmerman Nov 10, 1977			General Revision for FY-78

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Notations in this column indicate where changes have been made

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1.0 SCOPE

Activities planned for both the 40-cm and 20-cm primary burners during fiscal year 1978 are described in this document. Included are rebuilding of both burners along with their checkout and testing. Acceptable performance levels are identified as being contained in DC 524401. Documentation of the work is provided for in the form of design and development reports and monthly and quarterly reports.

Equipment to be tested in each burner includes feed and product removal equipment, burner vessel, cyclone and filter chambers, cooling air systems, induction heating system, fines recycle systems and control and instrumentation equipment.

2.0 OBJECTIVES

2.1 General Comments

During FY-77, primary burner activities included the following items:

1. An extensive series of burner runs were completed to establish operating parameters and techniques. This was done on the 20-cm primary burner using TRISO/TRISO fuel and adding a particle bed shortly after ignition to keep the total run times at less than 8 hours each. As a result of these tests, gravity fines recycle was selected as the most promising of the fines recycle methods.

2. Five attempts were made at completing a 48-hour burner run using TRISO/BISO fuel particles on the 20-cm primary burner. They were all hampered by excessive fines inventory buildups during the period of high carbon bed operation. In the last attempt, the fluid bed segregated and yielded locally severe hot spots that resulted in a burner wall burnthrough.

3. A series of 40-cm primary burner checkouts including heatup transients and low carbon startup. These indicated that use of the lower induction coil was sufficient and that the upper coil was not necessary for efficient bed heatups.

4. Two burner runs were made on the 40-cm primary burner to determine the relative merits of vertex or above-bed pressurized fines recycle. These used a TRISO/BISO fresh feed mixture with buildup of the bed over an ∿18-hour period. Fuel particle breakage was higher and bed expansion was excessive with vertex fines recycle, so above-bed recycle was chosen for the 20 fuel block TRISO/BISO sequential operations. There was no gravity fines recycle capabilities in the burner system, so the fines recycle mode recommended as per 20-cm burner experience could not be utilized.

5. During sequential operation, pressurized fines recycle eroded several metal parts. A fines recycle bellows failed first; it was replaced and the run proceeded uneventfully. The thermowell then eroded and later burned off completely, just after final addition of all feed material. A "Y" connection in a fines line eroded through shortly before the thermowell finally fell off. In terms of process consideration, the sequential operation run was successful but the process imposed too severe of a condition to the components in the fines recycle system, leading to repeated failures. Bringing the mid-reactor gas supply into the burner independent from the fines recycle flow may decrease this problem markedly, but gravity fines recycle will first be given a full opportunity for success.

2.2 Test Objectives

Plans for the current fiscal year (1978) include work on both the 20-cm and 40-cm primary burners. These are aimed toward having a reliable method for burning crushed fuel elements to yield a low carbon content product stream. Present specifications for product carbon content and fuel particle breakage will be confirmed or redefined.

3.0 TEST DESCRIPTION

Actual test plans are as follows:

A. Complete reconstruction and checkout of the 20-cm primary burner system. This includes a gravity fines recycle system, fully jacketed off-gas lines to allow for air cooling, a lower susceptor to increase heating capabilities of shallow fluid beds, gas preheaters to shorten bed heatup times, a gas inlet distributor that allows for drainage of bed material into a removable can, a series of level sensors and flow sensors to allow better knowledge of solid buildups and/or blockages, a vacuum fines sampler to take discrete grab samples from the fines bunker, a bellows sealed burner tube cooling air jacket to minimize leakage, a sealed product can to eliminate burner area contamination and a more sensitive speed indicating meter on the fresh feed rotary valve.

B. A series of burner runs on the 20-cm primary burner comprising shakedown of the components mentioned in (A). A minimum of two tests will be required. The first will include heatup, fines recycle and fines sampling, but no combustion. The second will use a TRISO/BISO fresh feed for ignition followed by a low carbon (∿10-15 wt %) feed of TRISO/BISO fuel particles to quickly buildup a fluid bed containing sufficient fuel particles to allow a final bed burnout to low carbon content. If all systems are fully operable, then section (C) may proceed. If it is not possible to make the gravity fines recycle mode function properly, even after modifications, then pressurized above-bed recycle will be installed with separate mid-reactor gas flow to minimize erosion problems, and the balance of the ΔP will be completed using this fines recycle mode.

Notations in this column indicate where changes have been made

C. Completion of 48-hour burner run on the 20-cm primary burner using a representative TRISO/BISO fresh feed throughout the run. During this run, extensive automation will be brought on line such as cooling air control loops, inlet gas flow control loops, induction heater control loops and automatic data logging and a running material balance calculation to allow close projections of fluid bed composition during the burner run. Off-gas piping heat transfer calculations will be made using data generated in this burner run.

D. Completion of 48-hour burner run on the 20-cm primary burner using a representative TRISO/TRISO fresh feed. Continue optimization of control loops used in (C).

E. Completion of an 8-hour burner run on the 20-cm primary burner fuel system in which the BISO coating incorporates a silicon dopant. Determine where the fine silica goes in the system and whether it complicates fines recycle.

F. Completion of fluidization tests on advanced HET-type inlet gas distributor. Determine operability of plenum drainage provisions.

G. Complete a 40-cm primary burner heatup using a graphite bed for the purpose of testing the concept of supporting the entire burner on load cells and for overall system checkout.

H. Following installation of a gravity fines recycle system, a plenum drain provision, a lock hopper feed system, and a cooling-air jacketed off-gas cyclone and filter chamber on the 40-cm primary burner, complete 2 shakedown runs as described in (B).

I. Participate in sequential operation by burning 45 crushed fuel elements in the 40-cm primary burner to yield a low carbon content product.

4.0 ACCEPTANCE CRITERIA

The design criteria DC 524401 will be used as a guide to the acceptability of each test item.

Some specific criteria for acceptability of the long-term cycles (>20 hrs.) are as follows:

1. No feed line blockage
2. Product removal with heel < 0.5 wt %
3. Burner heating to ignition in < 2 hrs.
4. Off-gas filter pressure drop < 5 psig
5. Main burn rate of 800 g/min in 40-cm burner, 200 g/min in 20-cm burner
6. Fines heel at end of burner cycle to be < 0.5 wt % of graphite throughput
7. Product broken particle fractions < 5 wt %
8. Product bed carbon content < 1 wt %

Notations in this column indicate where changes have been made

5.0 DOCUMENTATION

In addition to the specific burner tests, three reports will be completed. They are:

1. 40-cm Primary Burner Interim Development Report--a summary of FY-77 burner tests.

2. 40-cm Primary Burner Interim Design Report--a summary of actual burner design philosophy and detail.

3. 20-cm Primary Burner Interim Development Report--a summary of FY-78 burner tests.

Test data and records shall be maintained in accordance with DP-143-11, "Experimental Data Recording, Identification and Retrieval," including the use of QA lab notebooks. Monthly and quarterly reports will also be used to present results.

6.0 SAFETY REQUIREMENTS

The operation of the 40-cm primary burner system will be conducted in a manner which ensures that the following safety requirements are met:

5.1 Nuclear criticality control is accomplished by administrative inventory control.

5.2 Radiological protection of the burner system operating personnel shall be afforded by the burner vessel and by the use of ventilation and controlled access to hazardous materials. Provisions shall also be made to reduce the spread of contaminants during maintenance and repair operations in the event of equipment failures.

5.3 Safety inspections are periodically made by the plant safety coordinator.

5.4 The ambient air at operating points near the feed, discharge, and fines recycle system shall be monitored for airborne radioactive contaminants.

5.5 Access to high temperature materials within the burner system shall be limited by physical barriers whenever practicable.

5.6 Equipment shall be operated by qualified operators in accordance with the operating procedures.

7.0 QUALITY ASSURANCE REQUIREMENTS

Quality Assurance activities shall be in accordance with the Quality Assurance Program Document QAPD-3225.

Notations in this column indicate where changes have been made

8.0 SCHEDULE

Test	Completion Date
A. Complete reconstruction of 20-cm primary.	12/15/77
B. Complete checkout of 20-cm primary.	12/31/77
C. Complete shakedown and short-term burner runs on 20-cm primary.	2/28/78
D. Complete 48-hr run using TRISO/BISO feed on 20-cm primary.	6/30/78
E. Complete 48-hr run using TRISO/TRISO feed on 20-cm primary.	7/30/78
F. Complete 8-hr run using TRISO-SiBISO feed on 20-cm primary.	9/30/78
G. Complete fluidization tests on HET-type distributor on 20-cm primary.	9/30/78
H. Complete graphite heatup test on 40-cm primary with burner tube load cells.	11/30/77
I. Complete shakedown and short-term runs on rebuilt 40-cm primary burner.	7/30/78
J. Complete burning of 45 crushed fuel elements as part of sequential operations on 40-cm primary burner.	9/30/78
K. Complete drafts of development and design reports:	
40-cm development	1/01/78
40-cm design	4/01/78
20-cm development	7/30/78

APPENDIX B

OPERATING PROCEDURE

GENERAL ATOMIC COMPANY

GA 777 (Rev 6/76)

OPERATING PROCEDURE: 0.20M PRIMARY BURNER

	Doc. No. OP 524301	Issue A	Date 2/13/78

Issue Summary APPROVAL LEVEL: 2

Issue	Date	Prepared by	Approval			Purpose of Issue/ Sections Changed
			Engineering	QA	Project	
A	2/13/78	W.S.Rickman				Initial Issue

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I. SCOPE

This procedure describes the operation of the 0.20m prototype fluidized bed crushed fuel element (primary) burner system, including both normal and abnormal modes of operation. This equipment includes the primary burner, the burner feed bunker, burner feed and discharge mechanisms, primary off-gas filtering, sampling systems, fines recycle system, burner external heating and cooling systems, and the controls and instrumentation necessary to monitor system variables and to maintain them within operating ranges.

II. REFERENCES

1) PI 524301 Piping and Instrumentation Diagram - 0.20m Fluidized Bed Crushed Fuel Element Burner
2) - Diogenes Process Control System User's Manual

III. NORMAL OPERATION

Included in this section are the steps taken in preparation for every run and for the actual operation of every run. They define how the burner is designed to operate. Deviations to this are included in the next section.

An operating log book shall be kept for this burner in a signed out GAC lab notebook. This is to be kept by the cognizant engineer and will contain operating commentary. It will be separate from the operating sheets and strip chart outputs - which will be assembled into a file after each run.

A calibration notebook is kept for pertinent up-to-date process equipment calibrations.

A. Pre-Operational Preparation

1. Induction Heater

a. Lockout access to the burner cabinet. Ensure that the MG power controls are set at zero in the control room.

b. Open water supply valves to yield the following minimum water supply pressures:

MG set	30 psig	located at MG
Auto transformer	20 psig	
Coils	30 psig	located at burner
Capacitors	10 psig	

c. Select 0.20m primary on 3 position switch; this and the remaining steps are done at the MG location.

d. Close 600A circuit breaker.

e. Push MG protect reset switch.

f. Start motor with key switch.

g. Switch field on - wait for time delay to close relay.

h. Push start button - this allows the system to be operated from the control room.

2. Feed Preparation

a. Ensure that an adequate quantity of fresh feed is in the primary feed hopper.

b. This feed must be sampled for carbon content, size distribution and particle breakage. This data shall be included in the operating log book and the run summary on a form attached. Samples will be saved back for future reference or rechecking.

Carbon content is determined by burning a weighed 150 g sample in the muffle oven at 800°C for $\geq$ 24 hours. The ash is weighted to yield non-carbon content.

Size distribution will be run using standard series screens as follows: Mesh - 3-1/2, 4, 5, 7, 9, 12, 16, 24, 32, 42, 60, 80, 115, 170.

Notations in this column indicate where changes have been made

0.20M PRIMARY BURNER MATERIAL DATA

(Fill out one for each feed, product and fines samples)

Weight ____________

% Carbon ____________

Wt. Carbon ____________

Wt. Particles ____________

% Broken Particles ____________

Bulk Density ____________

Tap Density ____________

Angle of Repose ____________

Size Distributions

Screen Size, μ	% Retained on Screen	Cumulative %
5613		
4699		
3962		
2794		
1981		
1397		
991		
701		
495		
351		
246		
175		
124		
88		

Particle breakage is determined by burning the carbon out of a sample and sending it to analytical chemistry for a % particle breakage analysis.

Bulk density is measured by loosely filling a tared 100 ml graduated cylinder and weighing. Density = net wt/volume. Tap density is determined by shaking and tapping the cylinder to yield minimum volume.

Angle of repose is measured by pouring material onto paper marked with 1" squares.

$$\text{Angle of repose} = \arctan\left[\frac{2 \times \text{height of pile}}{\text{width of pile}}\right]$$

3. Gas Analyzer Calibration

The gas analyzer pumps a continuous sample of burner off-gas through O_2, CO, and CO_2 analyzers at set pressure and flow rates. Calibration requires running known gases through the analyzers to set zero and span. A complete calibration procedure is posted on the analyzer system cabinet.

4. Instrumentation Description

Strip chart pen recorders are used to continuously record variables of interest. They are:

Plenum O_2 Flow	0-500 SLPM
Plenum CO_2 Flow	0-500 SLPM
Vertex O_2 Flow	0-170 SLPM
Vertex CO_2 Flow	0-190 SLPM
Mid-reactor O_2 Flow	0-190 SLPM
Mid-reactor CO_2 Flow	0-235 SLPM
Upper Cooling Air Flow	0-375 SCFM
Lower Cooling Air Flow	0-660 SCFM

Notations in this column indicate where changes have been made

Fines Pipe Cooling Air Flow	0-375 SCFM
Cyclone Cooling Air Flow	0-375 SCFM
Highest Susceptor Temperature	100-1100°C
Highest Vessel Temperature	100-1100°C
Highest Bed Temperature	100-1100°C
Lower Bed Temperature	100-1100°C
Above Bed Temperature	100-1100°C
Vessel ΔP	0-200" H_2O
Filter ΔP	0-150" H_2O
Cyclone ΔP	0-50" H_2O
Off-Gas O_2 Concentration	0-100%
Off-Gas CO_2 Concentration	0-100%
Off-Gas CO Concentration	0-100%

Three twenty-four point temperature recorders are used to record burner temperatures. A thermocouple chart is maintained by the cognizant burner engineer(s).

There are some meter readouts also as follows:

Percent Rated Volts	
Percent Rated Amps	
Percent Rated KW	
Percent Rated KVAR	
Fresh Feed Motor RPM	0-5 RPM
Vessel Pressure	0-15 PSI
Blower RPM	0-3000 RPM

Alarms are provided as follows:

High Above Bed Temperature	950°C
Low Upper Bed Temperature	825°C
High Upper Bed Temperature	950°C
Low Middle Bed Temperature	875°C
High Middle Bed Temperature	950°C
Low Lower Bed Temperature	875°C
High Lower Bed Temperature	950°C

High Vessel Temperature	905°C
High Susceptor Temperature	1100°C
High Cyclone	850°C
High Bed Differential Pressure	170" H_2O
Low Bed Differential Pressure	40" H_2O
High Filter Differential Pressure	100" H_2O
High Flow Plenum/Low Flow Plenum	450 SLPM/350 SLPM
High Flow Vertex/Low Flow Vertex	150 SLPM/100 SLPM
Low CO_2 Supply Pressure	100 psi
Low O_2 Supply Pressure	100 psi
High O_2 Off-Gas	5%
High CO Off-Gas	25%
High Blower Discharge Temperature	150°C
High Exhaust Temperature	100°C
High Off-Gas Temperature	400°C

Control loops are contained in the Diogenes process computer. Use of this machine is described in an operator manual. For our use, it has been set up in loop drawings and scaling data tables maintained by the burner cognizant engineer(s).

A set of level sensor lights are provided for the burner, feed hopper, and fines bunker.

Induction heating is controlled by monitoring bed, wall and susceptor temperatures. Set points for these temperature controls are 850°C, 900°C, and 1080°C respectively. Each controller gives an independent output corresponding to its demand for heat. The lowest demand is selected for power control (this will be that controller closest to or above set point).

When the burner is heated to 700°C, a temperature switch initiates a ramp for plenum O_2 flow rate. Total flow to the plenum is held constant by varying CO_2 flow. Vertex and mid-reactor total flow are kept constant also, with vertex and mid-reactor O_2 flow rate entered manually when desired.

Notations in this column indicate where changes have been made

Cooling air is adjusted via temperature feedback loops, one from the fluid bed and the other from the fines recycle temperature.

Before each run, the operator should check the CFM board to ensure that it corresponds to the drawing and should also punch in each channel to ensure that scaling data is properly entered.

5. System Operability Checks

At least a day or two prior to operating the burner, the following list of checks must be made to identify any problem areas. On the day of the run, these checks must be re-made prior to beginning operation.

a. Turn on all purges-set to levels noted on purge meters.
b. Turn on all cooling water supplies (induction heater and off-gas cooler).
c. Test cooling air system flow response.
d. Calibrate off-gas analyzer.
e. Check three knifegate positions (feed, fines and product).
f. Test flow response of all inlet gas flow system.
g. Operate filter blowback and verify cycling.
h. Operate fines rotary valve and, if possible, fresh feed rotary valve.
i. Note distributor and filter pressure drop at 450 SLPM plenum CO_2 flow.
j. Actuate induction heater and "spike" susceptor temperature to 150°C to note response.
k. Check CO_2 and O_2 supply tanks, if below 30% full, arrange for filling.
l. Check pen recorders for paper and ink supplies.
m. A leak test is to be made on the burner prior to each run; this includes both bubble checks at 3 psig and a burner pressure decay curve.

B. Start-Up

During the entire burner run, a process technician will be responsible for physical inspection of the burner system as follows:

Every 10 Minutes:

- Observe entire burner for evidence of overtemperature, leaks, loss of flow, warpage, excessive vibration, noises or other abnormal conditions.

Every Hour:

- Observe gas supply tanks, MG set, cooling air blower and cooling tower for proper operation and supply.

Every 4 Hours:

- Add feed material to feed hopper; this will be approximately 60 kg of material.

1. Open the vertex, plenum, and mid-reactor gas supply solenoids and bring CO_2 flows to 450, 125, and 100 SLPM respectively. These are the total flows to use on each for the entire run.
2. Switch all Diogenes induction heating loops to automatic except for the MG heater controller - leave it on manual with zero output.
3. Actuate the filter blowback cycle.
4. Open the Fresh Feed knifegate valve.
5. Start the Fresh Feed Rotary Valve and run it until the startup bed has been added (determine by observing the fluid bed differential pressure).
6. Switch the MG control loop on Diogenes to automatic and depress time mark to mark the charts every 10 minutes. When the highest bed temperature gradient is less than 100°C. Then return to normal flow rate.

Notations in this column indicate where changes have been made

7. The temperature of the bed will increase to 700°C, at which time an O_2 ramp to the plenum will begin. This ramp goes from an initial 80 SLPM to 290 SLPM over a 30 minute period. The induction heater will shut off as the temperature increases above 850°C.

8. Initiate fines recycle at 2 RPM when the fluid bed reaches 820°C.

9. Fresh feed must be established at somewhat less than the burn rate, in order that a particle bed be built up while carbon level decreases. This requires setting the bed addition rotary valve speed to yield the desired built up rate. Start fresh feed when the fluid bed reaches 860°C. Cooling air to the lower bed is brought up on manual by actuating the cooling air blower and opening the control valve such that bed temperature is maintained at 900°C. The cooling air blower outlet pressure control loop may then be switched to automatic to ensure constant cooling air supply pressure.

C. Steady State

1. Vertex O_2 flow should be raised to 60 SLPM when the bed temperature reaches a stable 900°C. Mid-reactor O_2 flow should be raised slowly to 70 SLPM when the fines recycle temperature reaches 200°C. Above bed cooling air will be required if the process temperature surpasses 900°C or if the fines bunker temperature goes higher than 400°C (due to rotary valve temperature limitations).

2. Mid-reactor O_2 flow should be kept at a maximum such that off-gas O_2 concentration is less than 1-2 volume percent. Keeping the mid-reactor O_2 flow as high as possible ensures a minimal fines inventory.

3. When the bed has been converted to a low carbon particle bed, the fresh feed rate must be increased to match the burn rate, such that further particle bed weight increases may be attained.

4. When the desired particle bed weight is reached, fresh feed is stopped manually to allow the bed to burn to low carbon.

Notations in this column indicate where changes have been made

5. As soon as O_2 breaks through the bed at greater than 5%, begin turning down O_2 flow, first to the mid-reactor then to the vertex and finally to the plenum. This may be gradual or abrupt depending on the particular burner run, such that discretion must be used in how fast to turn down inlet O_2 flows in order to keep the off-gas at a maximum of 10 volume percent. Cooling will have to be carefully modulated during this time period.

6. When the burn rate is calculated to be less than 10 g/min, stop combustion by shutting off all O_2 flow. As always, the CO_2 flows must compensate to keep total flow constant. Stop fines recycle. Override the induction heater by switching loop H1 to manual with zero output.

7. Remove the desired weight of interim product to the product hopper by opening the product knifegate and shutting off vertex gas flow. Observe material removal by the bed DP cell readout. To stop material removal, turn vertex flow back on and close the knifegate valve.

8. Reheat the bed to 700°C with the induction heater by resetting loop H1 to automatic. Add fresh feed to yield 15% bed carbon, manually increase inlet O_2 flow and cooling air to yield the design burn rate in a similar manner to initiate startup.

9. Repeat 4 → 8 until fresh feed supply is exhausted.

D. <u>Shutdown</u>

1. When all the feed has been added, run until O_2 breakthrough occurs. Then manually reduce mid-reactor vertex and then plenum O_2 flow such that off-gas O_2 concentration is kept below 10%. CO_2 flows will automatically adjust to compensate. Manually adjust cooling air at this time to keep bed temperatures at 900°C. When the bed is very low in carbon, combustion generated heat will no longer be sufficient to maintain 900°C bed temperatures. The induction heat will automatically prevent the bed from cooling below 850°C.

Notations in this column indicate where changes have been made

2. When the burn rate has dropped to < 10 g/min, terminate the run by changing the inlet gas to pure CO_2, shutting off the induction heater, cooling the bed to 700°C and removing it as previously described.

3. Transfer all PIMs to manual and decrease outputs to zero.

4. Shut off the cooling air blower, the gas solenoids, and the fresh feed valve and then open the induction heater contactors.

5. Turn off the induction field switch, the MG set and then inlet breaker.

6. After all equipment is cooled, shut off the cooling water (coil, capacitors, autotransformers, MG set off-gas exchanger and cooling air heat exchanger) and the off-gas analyzer.

E. Post - Operation

1. Analyze all product samples as described in section IIIA2.

2. Remove the burner cone and inspect for particle agglomerates, erosion patterns, etc.

IV. ABNORMAL OPERATION

There are many abnormal conditions which may exist, they are described here with specific action to be taken for each. Undoubtedly, there will be combinations of these conditions that are not covered. The main point to remember is that it is easy to make another run if something appears to be wrong, but it is extremely difficult to rebuild a damaged burner. Therefore, always operate very conservatively and always take corrective actions immediately.

A. Upsets and Transients (Ref. 10)

1. Temperatures

There are alarms (visual and audio) for key burner temperatures as described in section IIIA. In addition, all other thermocouple temperatures are recorded on multipoint recorders. These allow observation of gradual trends while the alarms yield immediate data on over or under temperatures.

The susceptor temperature is controlled @ 1060°C and alarms at 1080°C. Burner wall and in-bed temperatures are controlled at 900°C and alarm at 905°C and 950°C respectively. In-bed temperatures will also alarm if below 850°C.

Action should be taken when any of these alarms activate, or when trends indicate that an alarm condition is imminent. The probable conditions and corrective actions are listed below in order of most probable to least probable occurrence.

HIGH IN-BED TEMPERATURE

CONDITION	CORRECTIVE ACTION
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 flowrate 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 wt.% carbon bed and larger graphite segregation to the distributor area, or if the bed height gets too low for good heat transfer - 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 happens.
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	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%.

Notations in this column indicate where changes have been made

HIGH IN-BED TEMPERATURE (Cont.)

distributor area and burning semi-statically.	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 BED TEMPERATURE

CONDITION	CORRECTIVE ACTION
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 % carbon conditions.	a) Decrease cooling air.
b) Local reduction of temperature with remainder of bed stable - usually due to local cooling effects of ambient fresh feed or fines entering the bed.	b) No correction necessary unless general cooling occurs. If so, lower cooling air rate and/or reduce fresh feed rate and stabilize temperatures.

HIGH ABOVE-BED TEMPERATURES

Burner above-bed temperature elevation to $\gtrsim$ 930°C (alarm at 950°C) may occur especially if fines recycle is in operation and lowered wt. % bed carbon allows excess O_2 to reach the above-bed fines burning zone. This applies to the off-gas cyclone also.

Notations in this column indicate where changes have been made

HIGH ABOVE-BED TEMPERATURES (Cont.)

CONDITION	CORRECTIVE ACTION
a) O_2 breakthrough from a low carbon bed elevating temperature in the fines burning zone below the MID-REACTOR GAS INLET.	a) Increase above-bed cooling air flow. Reduce the vertex, then plenum O_2/CO_2 ratio for 900°C stable above-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) Increase above-bed cooling air flow. 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.

2. Loss of the induction heater motor generator is evidenced by reading voltage but not amperage on the induction supply meters. This may be caused by:

a. overtemperature of bed, wall, or susceptor
b. low MG cooling water pressure
c. low cooling water flow to the induction coil
d. open electrical relay enclosure

Restart may be accomplished only after correcting these problems.

3. An increase in the off-gas O_2 concentration is evidence of either:

a. bed temperature too low for combustion (reheat bed to > 750°C).
b. bed carbon concentration too low (add fresh feed at a higher rate).

Do not let off-gas O_2 increase above 10 volume percent for any reason.

4. High pressure drop across the cyclone (30" H_2O) or filter chamber (140" H_2O) indicates that either an excessive fines loading has blocked the main process flow path or that a DP cell tap has plugged. The former requires a reduction in fines loading by reducing fines recycle rate while the latter may be fixed by increasing the purge meter flow rate. Low filter pressure drop (< 5" H_2O) is an indication of a leak to the atmosphere or a hole in a filter. A leak may be checked for directly during the run while a filter failure may only be determined by inference. Should it occur, shutdown of the burner system is required to avoid large amounts of fines buildup in the vent piping.

5. Should O_2 and CO both increase such that an explosive mixture (see Appendix for explosion envelope) is formed, decrease O_2 flow manually (CO_2 will automatically compensate) to eliminate this condition.

B. Emergencies

1. Loss of Diogenes Computer

Diogenes goes on "back up" on all process interface loops with valves held where last set by the computer. Operation is then fully manual from the process interface modules. Shutdown is required in this event if the computer can not be brought back on-line.

2. Loss of Cooling Air Blower

This will be seen by the cooling air flow recorder falling off to zero, or by the blower RPM meter falling to zero. Immediate shutdown should be taken (increase total CO_2 flow to 600 SLPM and shut off O_2 flow).

3. Loss of all Electrical Power

CO_2 flow goes fully open while O_2 flow is shut off. Cooling air is lost as is vent suction.

4. Overtemperature, which cannot be corrected as described in Upsets and Transients, necessitates an emergency shutdown by increasing total CO_2 flow to 600 SLPM, shutting off O_2 flow, and opening cooling rate fully.

5. An inability to feed material into the burner is evidenced by the feed motor not turning or by the feed flow sensor not indicating. An inability to fix the feeder will result in burner shutdown.

C. Faults

The most probable mode of a fault condition is failure of the tube wall allowing bed material to exit the burner. This may be detected by a rapid lowering of bed pressure drop or physical observation of the rupture. The remedial action is to shutdown O_2 flow and cooling air flow and to adjust CO_2 to plenum flow only $\sim$ 250 SLPM (enough to cool but not fluidize the bed).

V. SAFETY REQUIREMENTS

There are several areas which present hazards to operating personnel. They include radioactive material handling, high voltage electrical equipment and hot burner exterior surfaces. They are dealt with in the following ways:

A. Radioactive Material Handling

Principles of safety around radioactive substances are taught in the GAC on-site "Radiological Safety Course." This is a prerequisite to working on the burners. The GAC Radiological Safety Manual and the health physicists are sources of help in specific operations. In general, gloves, shoecovers, and red-collared lab coats are required. All radioactive material transfers will be made either in a vent hood or in closed containers via airlocks.

B. High Voltage Electrical Equipment

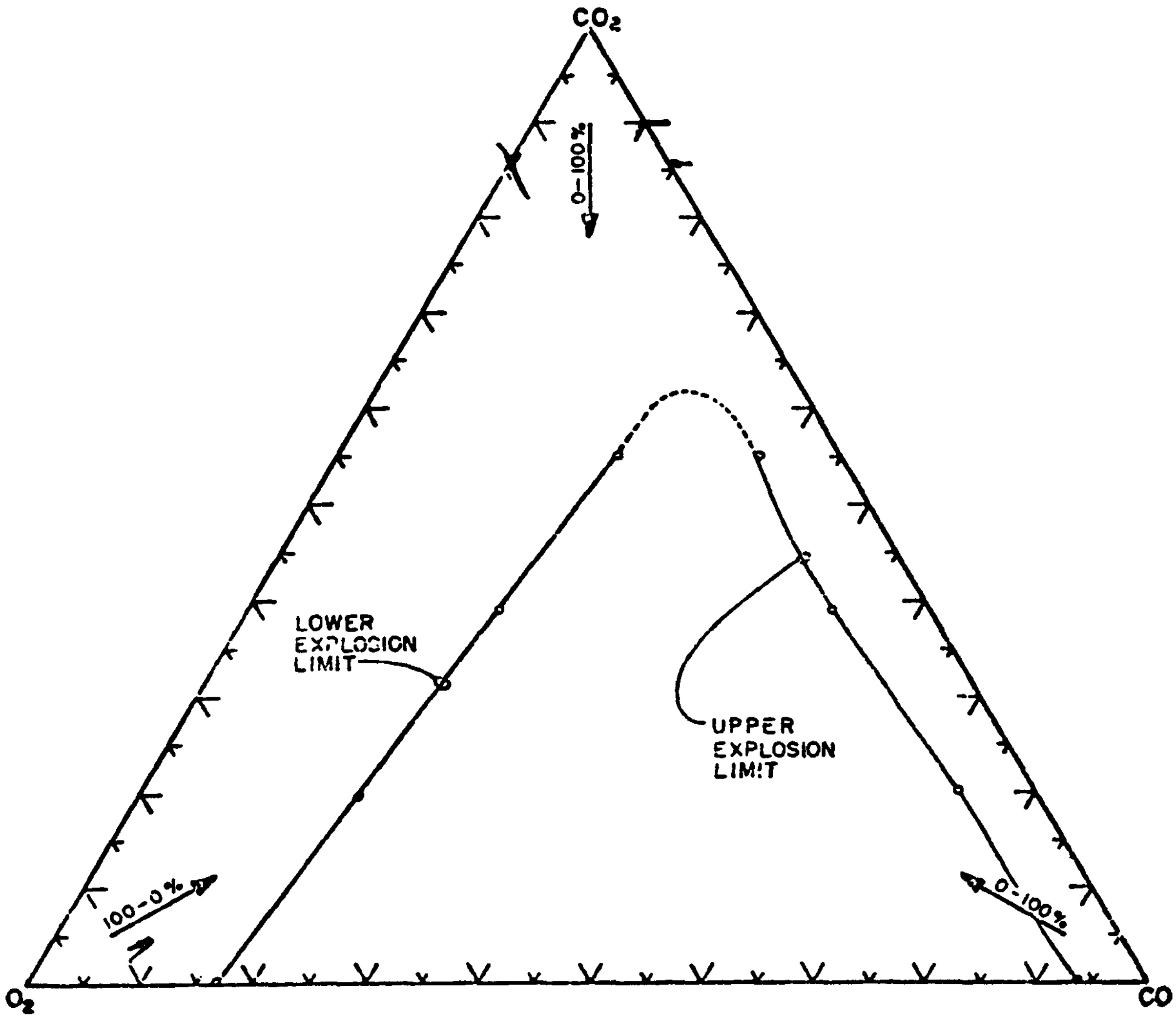
All cables are installed in code-approved conduit. The bus bars and the capacitors in the cabinet are exposed. Because of this, access to the cabinet will be restricted while the motor generator is actuated. This will be done with a flashing red warning light and warning signs.

C. Hot Burner Exterior Surface

The hot burner exterior surface will exist during runs and for at least four hours thereafter. If access to the cabinet is desired during this time, asbestos gloves must be used for equipment contact. Warning signs will be displayed.

Notations in this column indicate where changes have been made

Notations in this column indicate where changes have been made



Explosive limits of carbon monoxide in mixtures of oxygen and carbon dioxide.

(from ORNL TM-4520, Figure B2)

APPENDIX C

TRAINING PROGRAM FOR OPERATORS

A program has been set up to ensure that 0.20-m primary burner operators have a thorough knowledge of the equipment, operating techniques, and process rationale. Essential features of the program are:

1. An up-to-date operating procedure.

2. A class on burner operating theory and hardware, including hands-on equipment operating sessions.

3. A formal testing procedure consisting of a wide range of essay-type questions. The test used is presented on the following pages.

It is recognized that operating fluidized-bed burners is an exacting job that does not leave margin for error. This is especially true during developmental work, when personnel with only a limited amount of burner operating experience are being asked to run burners during shift operations.

The first step has been to thoroughly update the burner operating procedure. That document has been expanded, edited, and clarified to reflect the current operating philosophy.

After completing the operating procedure, a very thorough essay-type test was composed. The purpose of this test is to ensure that each operator is completely checked out on what the equipment is, where it is, how it operates, why it operates that way, and what to do in a wide spectrum of operating upsets.

In order to convey the knowledge required to satisfactorily complete this test, a training class was set up. The operating procedure formed the core of the training material, with calibration notebooks, Diogenes operating manuals, and piping and instrumentation drawings used as reference materials. Hands-on equipment operation was an integral part of the training. Every portion of the operator qualification tests was discussed in depth during the training classes.

Three operators were qualified on the 0.20-m primary burner. Requalification will normally be a yearly process or whenever major revisions are made to the operator procedure. A similar program will be set up for the 0.40-m primary burner.

Operator Qualification Test

1. Describe the steps involved in starting the motor generator system.
2. Where are the gas purge rotometers located on the burner system.
3. What are the pressure gauges located in the 1st floor burner cabinet window?
4. How do you increase above bed cooling air flow without affecting cyclone cooling air flow?
5. Where is the water supply valve for the off-gas heat exchanger?
6. How do you set the filter blowback pressure and time sequence?
7. What is the purge rotometer on the top deck for?
8. How can you tell the feed hopper internal pressure?
9. Where do you set the fines bunker aeration gas flow?
10. Where do you look for O_2 and CO_2 supply inventory indication?
11. Where is the cooling air blower?
12. Where do the fines purges enter the burner system?
13. Why are the DP cell lines purged?
14. Where do you set the O_2 and CO_2 supply pressures?
15. If an inlet gas flowmeter becomes inoperable, how do you control the flowrate?
16. If a Diogenes loop goes on backup, how do you handle the situation?
17. Why is 125 SLPM chosen for total vertex gas flow rate?
18. Why is 450 SLPM chosen for total plenum gas flow rate?
19. Why is 100 SLPM chosen for total mid-reactor gas flow rate?
20. How do we allocate the O_2 flow and why?
21. How do you know if the burner is slugging?
22. How do you determine and set the fresh feed valve rotation speed?
23. How do you determine and set the fines valve rotation speed?
24. How do you add more feed to the feed bunker during operation?
25. How do you know when the fresh feed supply is getting low?
26. How do you know if the fresh feed is flowing and not bridging? What about the fines?
27. During heatup, how do you mix the bed if it is not all heating?
28. How do you initiate cooling air flow to the lower burner jacket? How do ensure constant supply pressure?

29. When do you initiate cooling air flow to the upper cooling air zones?
30. How do you vary the mid-reactor O_2 flow rate during the main burning portion of the run?
31. How do you know if you have a net buildup of fines in the fines bunker?
32. Where are the three knifegate valves located in the burner.
33. How is the bottom of the burner constrained from thermal warpage?
34. How does the induction heater get the fluid bed hot?
35. Why is the induction coil water cooled?
36. How do you know if you are inputting power to the induction coil?
37. How do you know if the coil is potentially electrically "hot"?
38. Where do recycled fines re-enter the burner? What about the feed?
39. Why do we have a fines rotary valve?
40. Why is there a bellows between the product removal valve and the vertex gas connection?
41. How do we figure the initial bed weight? What is its composition?
42. Why does the fresh feed rate change during the burner cycle?
43. How do we know the fluid bed weight during operation?
44. How do we dump a portion of the bed out into the product can?
45. What do you do if O_2 starts showing up in the off-gas during the run? What is the maximum allowable off-gas % oxygen?
46. How do you know if you have an explosive mixture in the off-gas?
47. If the bed temperature goes above 950 C, what action do you take?
48. If the vessel temperature goes above 905 C, what action do you take?
49. If the above bed temperature goes above 950 C, what action do you take?
50. If the fines bunker temperature goes above 400 C, what action do you take?
51. If you suddenly lose all CO_2 flow, what action do you take?
52. If you suddenly lose all panel power, what happens?
53. If you suddenly lose all cooling air supply, what action do you take?
54. If an induction coil water leak occurs, what action do you take?
55. How do you know if the burner wall has burned through, and what action do you take?
56. How do you know if you have melted or ruptured an off-gas filter, and what action do you take?
57. What do you do if a fines leak starts blowing fines all over?
58. What do you do if a process bellows ruptures?
59. What do you do if you get a high exhaust temperature?

60. What do you do if you get a high blower discharge temperature?

61. What does a sudden very low bed differential pressure indicate?

62. Describe the MG control scheme in Diogenes.

63. How are the gas flows to plenum, vertex and mid-reactor held at a constant total while the ratio of O_2 and CO_2 varies?

64. Describe steps required for a normal interim product removal.

65. Describe the steps required for a normal end of burner run including tail burning?