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INTERIM DEVELOPMENT REPORT FOR SECONDARY BURNING

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ABSTRACT

The HTGR fuel reprocessing flowsheet consists of crushing the spent fuel elements to a size suitable for burning in a fluidized bed to remove excess graphite; separating, crushing, and reburning the fuel particles to remove the remainder of the burnable carbon; dissolution and separation of the particles from insoluble materials; and solvent extraction separation of the dissolved uranium and thorium.

Burning the crushed fuel particles is accomplished in a secondary burner. This is a batch fluidized-bed reactor with in-vessel off-gas filtration. Process heat is provided by an induction heater.

This report documents development work performed to date on the secondary burner. Analysis of the work is provided and recommendations are made for future applications in larger burners.

CONTENTS

FIGURES

FIGURES (continued)

FIGURES (continued)

TABLES

1. INTRODUCTION

The HTGR fuel reprocessing flowsheets for Fort St. Vrain and large reactors are shown in Figs. 1 and 2. They 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. 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 secondary burner is a batch fluidized-bed reactor with a flat perforated inlet gas distributor plate and in-vessel off-gas filters. Process heating is supplied by an induction heater while cooling is accomplished by air flow through annular cooling jackets. Crushed particle feed is supplied by a gravity-pneumatic feeder at the upper end of the vessel. Product is removed through a valve port just above the distributor plate; it is then pneumatically transported to the next process step.

A fluidized-bed reactor is being used because of its good heat transfer properties. It also serves as an excellent containment for the dusty feed material.

The distributor plate allows good fluidization characteristics (as seen from an even bed temperature profile) and interfaces well with the product removal valve and pneumatic product transport system. Sintered metal cylindrical filters separate the off-gas from entrained bed material. They are cleaned by a reverse jet blowback technique.

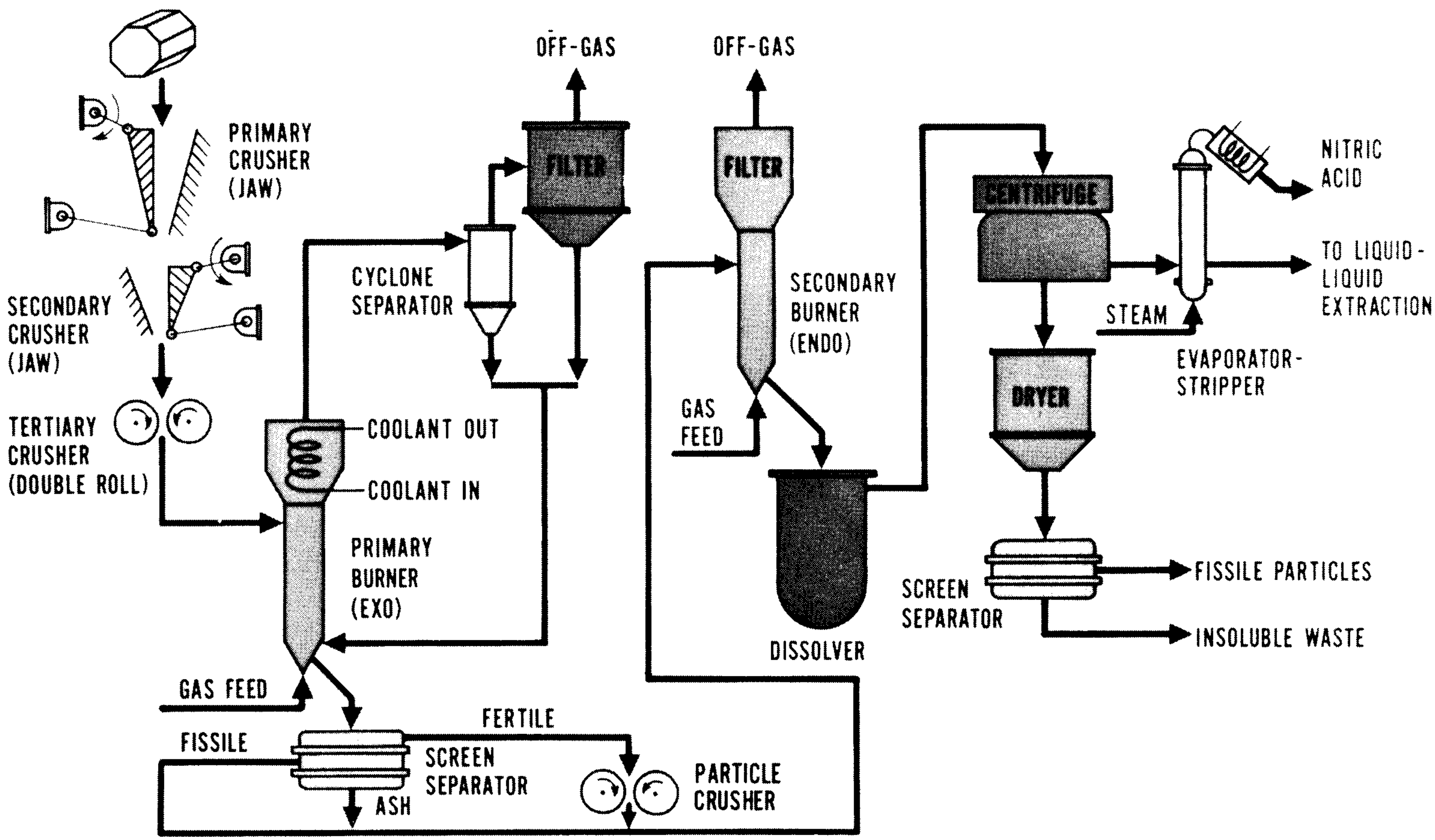


Fig. 1. Simplified HTGR head end flow diagram (TRISO-TRISO fuel)

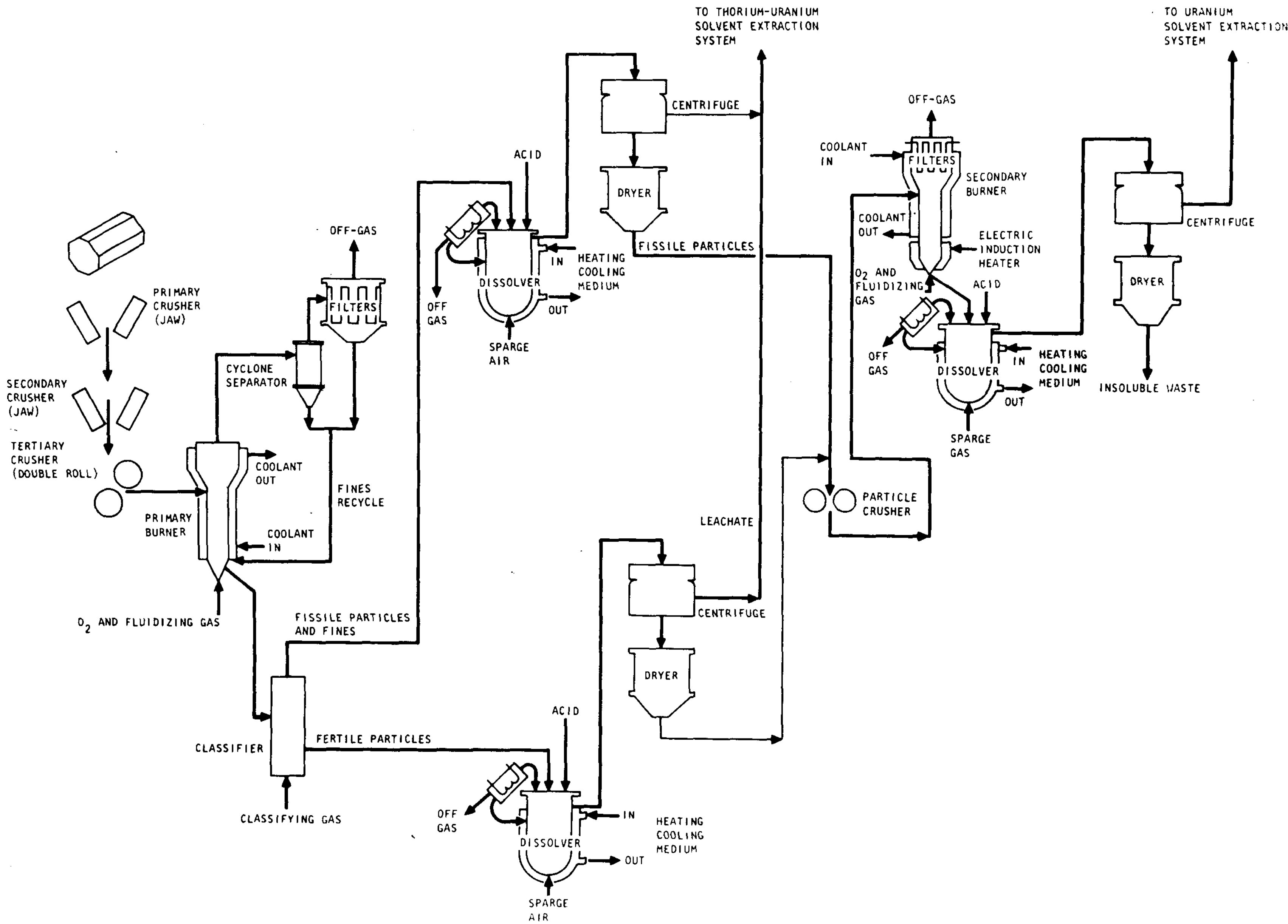
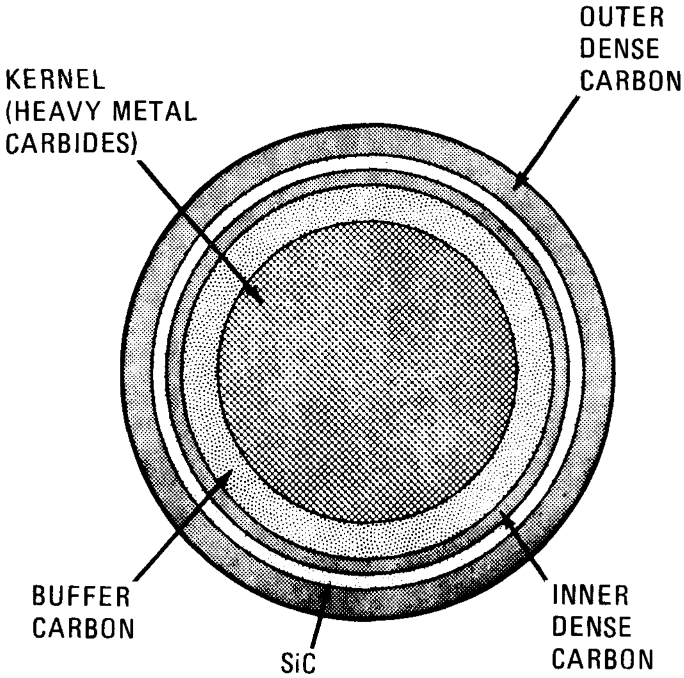


Fig. 2. Simplified TRISO-BISO reprocessing flow diagram



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. 3. Fort St. Vrain TRISO coated fissile and fertile particles

The burning cycle is as follows:

1. Feed crushed particle batch and induction heat to 700°C. Use a 2 ft/sec inert gas flow for fluidization.

2. Ignite by gradually increasing the gas flow to 3.5 ft/sec of pure O_2. External heating and cooling are on demand to keep the bed at 900°C during the run.

3. Low bed carbon is detected by measuring the off-gas CO level; when it falls below 2%, the bed velocity is reduced to 2.5 ft/sec (60% O_2) to allow fine carbon to re-enter the bed for combustion.

4. When the burning rate decreases to a preset value, fluidize the bed with pure CO_2 and cool to 500°C.

5. Pneumatically transport the product to a storage bunker.

Development work on the secondary burner unit operation was performed on a 10-cm diameter burner. An overall view of the burner vessel, illustrating the key features just discussed, is shown in Fig. 4.

A 20-cm-diameter burner is presently being fabricated. It incorporates remote burner disassembly concepts necessary for hot cell operation as well as the process features developed on the 10-cm burner.

This report serves to document the development work performed on the 10-cm secondary burner. It includes detailed summaries of individual systems development as well as a complete description of the present configuration and operating mode. The prototype design is briefly discussed in the form of actual equipment layout and expected operating parameters. A summary of all secondary burner runs performed to date is included in Appendix B.

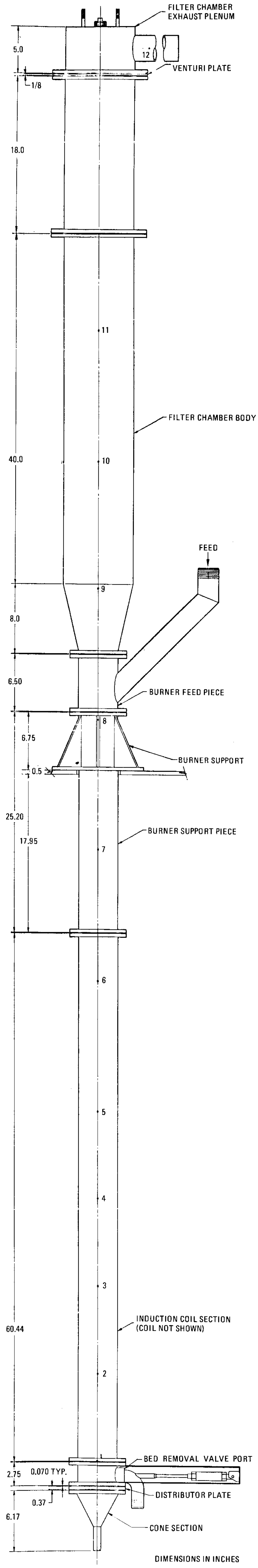


Fig. 4. Overall view of 10-cm secondary burner

2. PROCESS PARAMETER SELECTION

Work on the pertinent burner variables has been varied due to the inherent differences in how they may be most effectively studied. They are therefore discussed below as related to the way in which GA has approached them.

2.1. BED TEMPERATURE

There are several reasons to maximize the bed temperature up to the wall limitation of 900°C. Increased heat transfer, oxygen utilization efficiencies, and a large margin from unstable low temperature operations are attained by running the burner at as high a temperature as the vessel wall coding allows (900°C). In addition, the final burning portion of the cycle must be carried out at a wall temperature of 900°C in order for the residual carbon to be combusted. Operation has been found to be satisfactory at this temperature.

2.2. BED WEIGHT

An 18 kg bed weight was found to submerge the off-gas filter in the slugging bed regime. This caused the filters to operate at a higher temperature than they could tolerate, yielding excessive corrosion and a lowered strength. A 20% reduction in bed size significantly reduced the filter temperature by lowering the slugging bed height. For this reason, 14 kg beds are now being used.

2.3. INLET VELOCITY

Off-gas filter operation determined the maximum inlet gas velocity. Superficial gas velocities greater than 4 ft/sec result in excessive fines entrainment to the filter chamber with subsequently high filter pressure drops. A large portion of these fines will not re-enter the bed for combustion until the gas velocity is lowered. Operation at 4 ft/sec and lower has been satisfactory with a reduction to 2.5 ft/sec to allow fines to re-enter the bed.

2.4. MISCELLANEOUS PARAMETERS

Parametric studies have been carried out to optimize the crushed particle feeder. The product removal device was designed, tested, and modified to optimize cleanout capabilities. It performs the task it was designed for and requires no further development. The minimum temperature (600-700°C) for safe (no off-gas $CO-O_2$ mixture) startup was defined as soon as a suitable induction heater was installed.

Based on these values, which have been determined either by parametric studies or design optimization via testing, an automatic batch cycle control system has been designed. Details of this system are discussed in Section 11 of this report for completely automatic operation of the 10-cm secondary burner.

3. GRAVITY-PNEUMATIC FEEDER SYSTEM

Loading the burner batchwise requires a feeder of high throughput to perform the job quickly while having a reasonably constant solids flow rate. The feeder must be as simple as possible while minimizing the possibility of blockages and must be capable of virtually complete cleanout for accountability purposes.

In February 1972 a feeding system meeting these requirements was developed for use on a 20-cm primary burner. Although it was never used for this original purpose, it found immediate use on the 10-cm secondary burner, where it has since been used in making 49 separate burner runs over a 2-1/2 year period.

This section serves to document, interpret, draw conclusions, and make recommendations concerning this gravity-pneumatic feeder, especially as applied to secondary burners.

3.1. ORIGINAL DEVELOPMENT FOR PRIMARY BURNERS

The gravity-pneumatic feeder was first developed for the addition of fresh feed to the upper portion of the primary fluidized-bed burner. Augers were being used at that time but were in disfavor due to their frequent tendencies to bind and/or lockup. A feeder without mechanically moving parts was seen to be desirable in eliminating these types of problems.

The result of these considerations is depicted in Fig. 5 (shown without dimensions). The bottom of the feed bunker empties into a double-elbow arrangement which leads to the burner. The distance between the elbows is sufficiently long so as to preclude feed material from spilling over into the burner (determined by measuring the feed material angle of

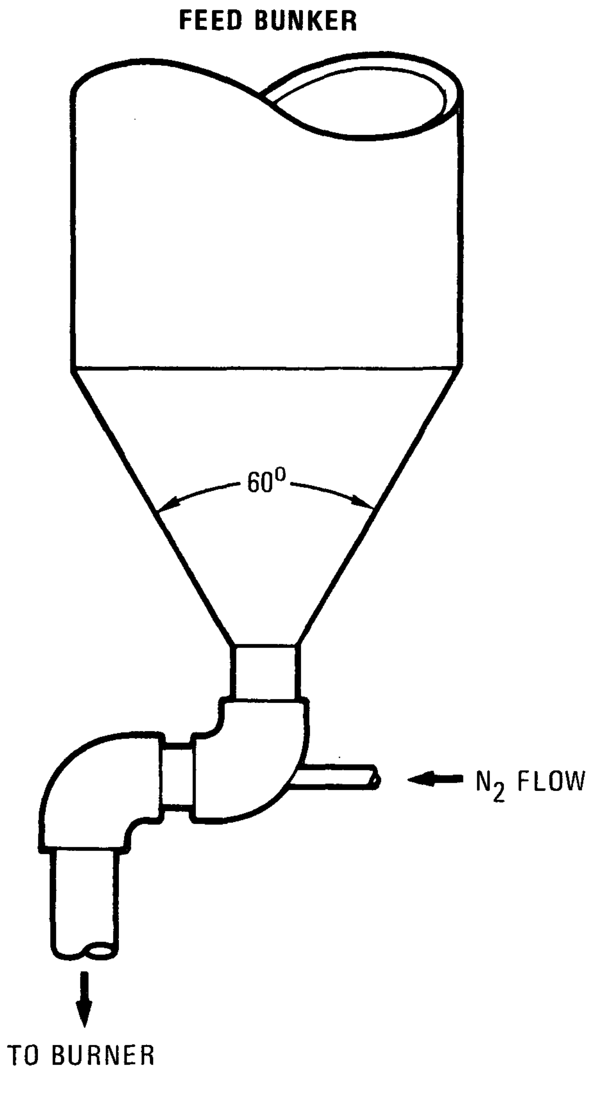


Fig. 5. Gravity-pneumatic feeder

repose). When the N_2 flow is activated, material between the elbows is swept into the burner and is replenished by the gravity flow of feed from the hopper into the elbows.

This concept was tried for the -3/16 in. size primary burner feed using several different sizes of pipe, ranging from 1/2 in. to 4 in. Both 2 in. and 4 in. feeders were found to be erratic in their flow characteristics, with material packing and spurting unevenly. The 1/2-in.-diameter feeder was not usable due to the tendency of the small pipe to clog with the -3/16 in. graphite mixture. One-inch and 3/4 in. diameter feeders were both found to be suitable for use on the primary burner.

3.2. ACTUAL USE ON 10-CM SECONDARY BURNER

A few months after the development work had been completed on the primary burner gravity-pneumatic feeder, the 10-cm secondary burner was relocated and extensively renovated. Up to that time, the secondary burner had been manually loaded via gravity and was in need of an automatic feeder. A 1-in. gravity-pneumatic feeder was then installed to allow top feed of crushed TRISO fertile particles to the secondary burner.

For about a year the feeder was merely used and accepted because it never failed to add the feed material to the burner. Time was then allotted for some tests on larger feeders in order to allow a shorter feed addition period in the burner cycle. This is a minor consideration in the 10-cm secondary burner because of the small bed sizes (about 14 kg) but becomes more important in the 20-cm burner with bed sizes of up to 60 kg planned. The other purpose of the tests was to gain more insight into the mechanism by which the feeder operates and to clearly establish the working range of the feeder.

3.3. TEST PROGRAM

All of the feeders used in the test program were of seamless butt-weld elbow construction with smooth inside surfaces unobstructed by pipe threads or similar rough edges which might cause material holdup. Table 1 gives the dimensions of the elbow spacing as a centerline-to-centerline measurement and of the actual pipe inside diameter.

The elbow spacing was chosen to give 50% more horizontal length than required for the angle of repose (normally about 38°). This was done to prevent solids from trickling over the edge after the N_2 flow was terminated.

As shown in Fig. 6, the feeders were fitted with a cleanout port aimed at the outer corner of the first elbow. This port was designed to remove any heel left by the normal feeder activation gas.

A N_2 gas supply was used for the feeder activation flow and for feeder cleanout. An automatic timer was connected to a solenoid valve for setting the time duration of gas flow to the feeder.

Three kg of crushed TRISO fertile particles were used in the test program. The particle size distributions before and after crushing by a double roll crusher with 3-in. diameter rolls and a 0.016 in. gap are shown in Fig. 7. This is typical of the feed material used in secondary burner experimental runs. Crushed particle angle of repose was 37°; the bulk density was 2.2 g/cc, while the tap density was 2.6 g/cc.

In the initial series of scoping tests, each of the three feeders was tested at 50 cfh and 60 cfh N_2 activation flow for 5 sec in each test. Ten repetitions were made at each point to gain some repeatability data. Results of these tests are listed in Table 2. They indicated that the 1-1/2 in. feeder was well suited for future development, both from throughput and repeatability standpoints.

The next set of tests was to determine heel weights, both with and without use of the cleanout port. The results are shown in Table 3. These indicate superiority of the smaller feeders on heel weights, which is to

TABLE 1
FEEDER GEOMETRIES

Nominal Feeder Size (in.)	Elbow Centerline-to-Centerline Spacing (in.)	Feeder Inside Diameter (in.)
1	5.60	1.05
1.25	6.25	1.38
1.50	7.30	1.61
2	8.50	2.07

TABLE 2
FEEDER THROUGHPUTS (kg/min)
(% Standard Deviations In Parentheses)

Nominal Feeder Size (in.)	Activation Flow	
	50 cfh	60 cfh
1	6.5 (σ=5.5%)	6.0 (σ=7.6%)
1.25	10.6 (σ=4.0%)	10.2 (σ=6.0%)
1.50	12 (σ=8.7%)	13.7 (σ=5.9%)
2	Exhibited erratic flow characteristics at all flows	

TABLE 3
FEEDER HEEL WEIGHTS

Nominal Feeder Size	Heel Without Using Clean-out Port (g)	Heel Using Clean-out Port (g)
1	61	3
1.25	136	4
1.50	214	22

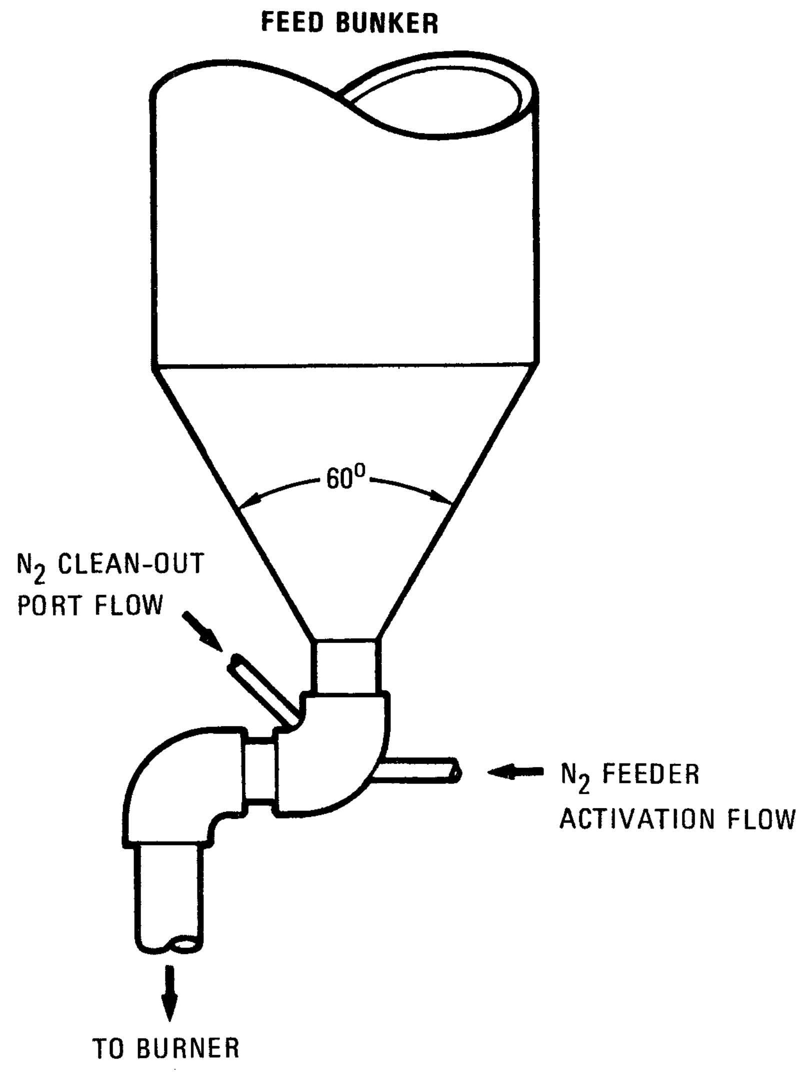


Fig. 6. Gravity-pneumatic feeder with cleanout ~~port~~

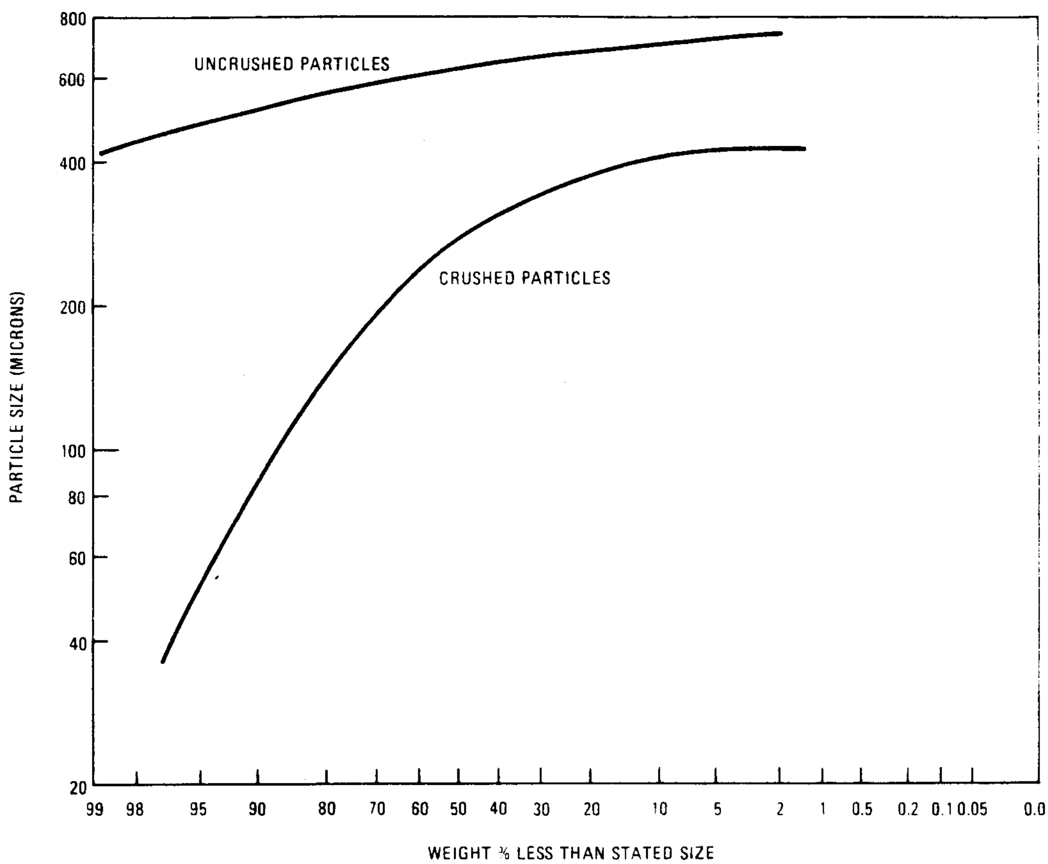


Fig. 7. Feed size distribution

be expected. Also, the cleanout port was seen to work well. It was activated in these cases at 30 psi inlet pressure for 10 sec after the feeder activation port had stopped blowing material out of the feeder. The 22 g heel on the 1-1/2 in. feeder represents only 0.2% of a typical burner batch. The superior flow performance of this configuration outweighs this increase in heel. It was therefore selected for more intensive study.

As shown in Fig. 8, the solids feed rate on the 1-1/2 in. feeder increases slightly with N_2 activation flow rate. Each plotted point represents the average of 10 tests performed under identical conditions.

Feeder cleanout capabilities were markedly improved by repeating the following cycle five times: 40 cfh gas flow through the feeder activation port for 5 sec followed by 70 cfh gas flow through the cleanout port for 5 sec. This procedure was tested 10 times with heel weights averaging 3 g and no heel weights greater than 5 g.

3.4. CONCLUSIONS AND RECOMMENDATIONS

The 1-1/2 in. nominal diameter feeder has demonstrated the highest material throughput while providing excellent cleanout capabilities. It is therefore recommended for use on the 20-cm prototype secondary burner in the same configuration used in the test program. Figures 9 and 10 are of the upper portion of the burner, including the feeder.

Operation of the feeder at 40 cfh activation flow is recommended to minimize the gas requirements while keeping a high throughput of 14 kg/min. The feeder cleanout procedures discussed in Section 3.3 should be followed to ensure a minimum of heel.

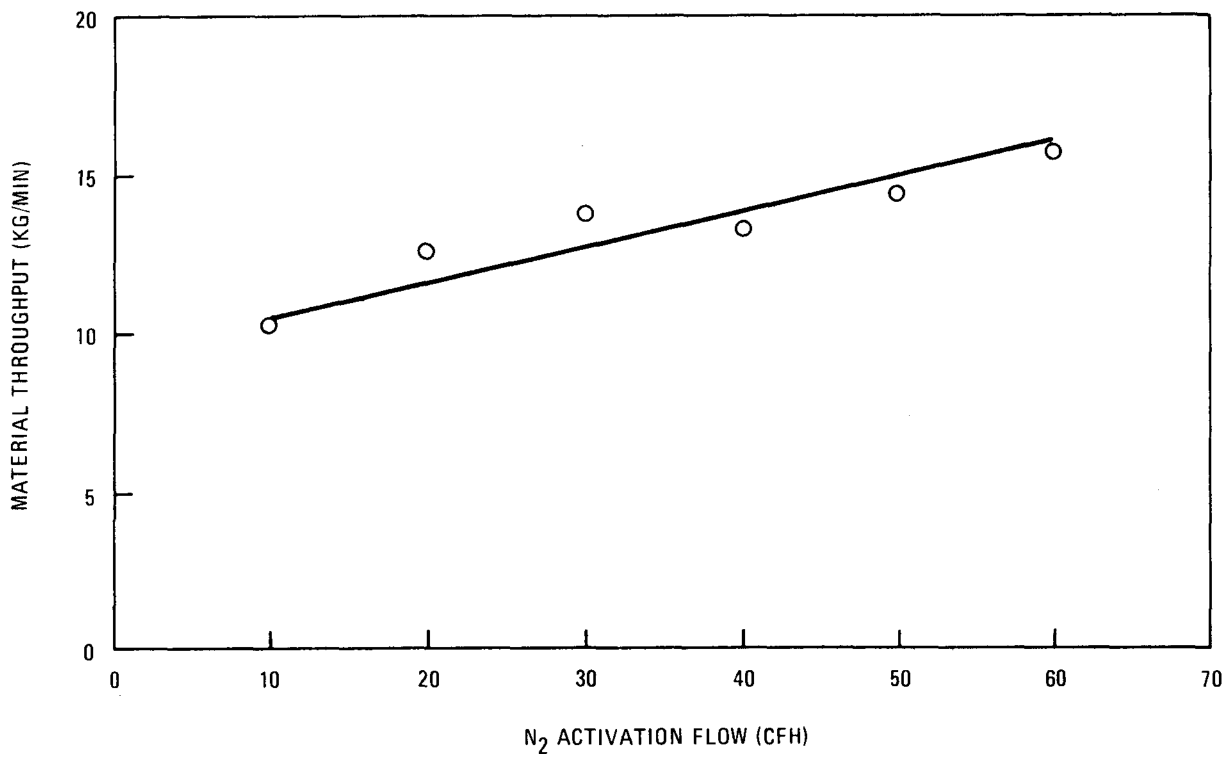


Fig. 8. One and one-half inch feeder throughput rates

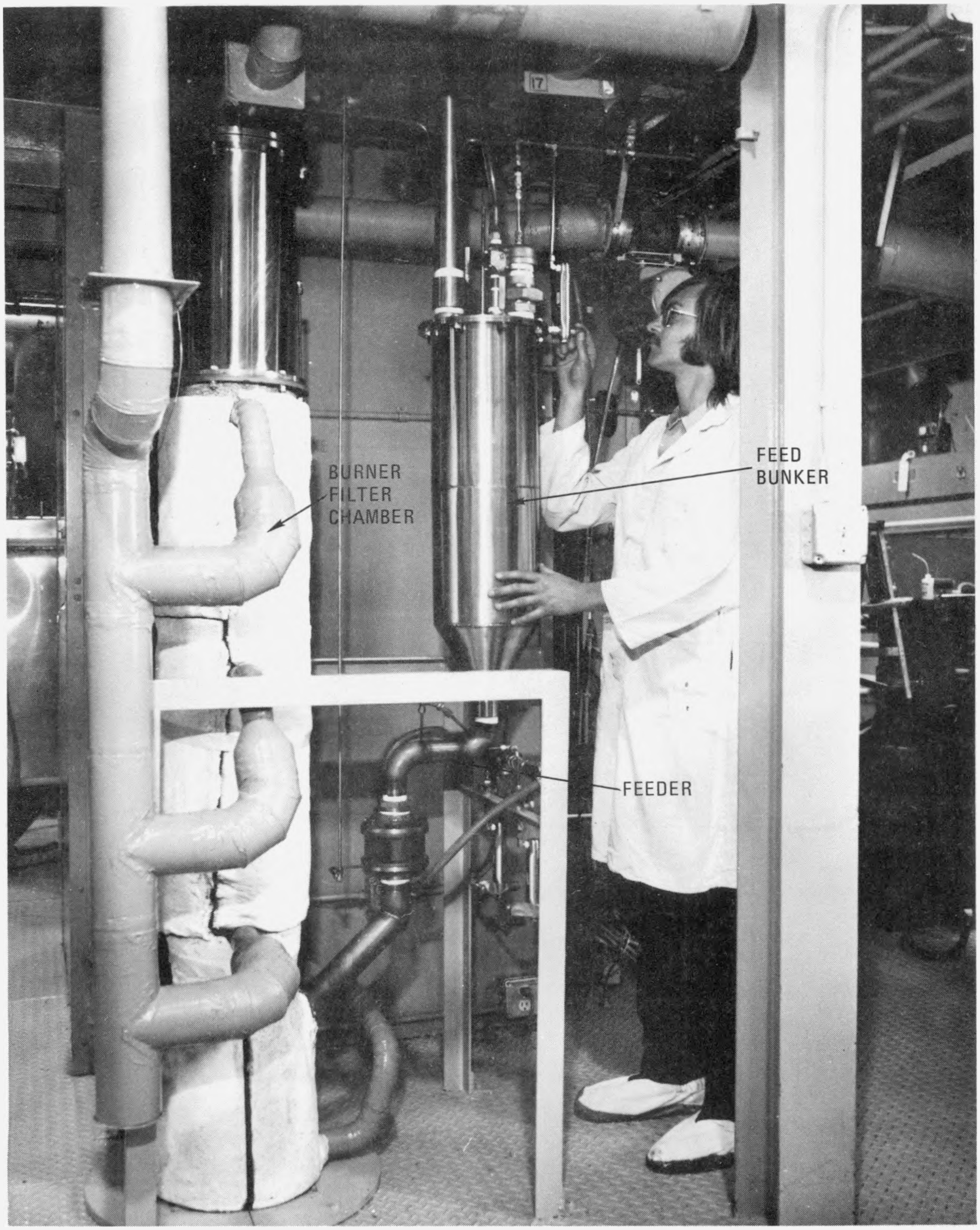


Fig. 9. Upper portion of 10-cm secondary burner including gravity-pneumatic feeder

Fig. 10. Upper portion of 10-cm secondary burner

4. FUEL PARTICLE CRUSHING

4.1. DEVELOPMENT DATA

Double-roll crushers have been used in the GA pilot plant for the preparation of crushed TRISO fertile particles as feed for the secondary burning operation. Fissile particle work is scheduled for FY 1976. The particles to be crushed typically have diameters ranging from 400 to 800 microns. It is desired to achieve the highest possible crushing efficiency in order to fully expose the fuel kernels to combustion in the secondary burner. It is also desired to avoid overcrushing the particles, which yields a dustier burner feed that is more difficult to evenly fluidize, with a tendency for stagnant hot spots to form within the burner.

TRISO fertile particles processed through the present GA double-roll crushers contain approximately 0.0002 weight fraction uncrushed particles. These uncrushed particles are generally slablike in configuration and probably slip through the roll gap sideways.

A typical size distribution before and after crushing is shown in Fig. 7. Crushed material of this same approximate size distribution has been successfully burned in over 20 separate burner experimental runs. Material with smaller average diameter has been burned with extreme hot spots (>1100°C) evident in the burner (10-cm secondary burner runs 16 and 17. See Appendix B for run summaries.)

Particle crushers are therefore seen to produce acceptable feed material for the burner from the standpoint of both crushing efficiency and stable fluidization characteristics.

The crusher configuration, shown in Fig. 11, includes two rolls (3 in. o.d. x 1 in. wide) keyed to 1 in. shafts, one of which is driven by a 1/2 hp, 29 rpm motor gearbox; the other is turned in the opposite direction by a gear arrangement. The frame is constructed of 0.40 in. thick plates. Plates and rolls are made of hardened (Rockwell C-60) 1040 steel. The crusher contains precision bearings which are locked in place by set screws.

The nominal gap between rolls is 0.017 in., as measured with solid solder ribbons run through the rolls. A wiper arrangement keeps material from bouncing around to the back of the rolls. Fuel particles are choke fed in batches of up to 20 kg with no apparent effect on the crusher.

Wear of the 1040 steel crusher rolls is significant with the gap increasing about 0.002 in. after processing 70 kg of particles. The crushing section is currently examining alloys that are more wear resistant and will be testing them in the next year.

Crusher throughput at the conditions given above is about 10 kg/hr. Doubling the roll width should approximately double the capacity, making the crusher more suitable for the preparation of 60 kg batches, as required by the 20-cm secondary burner.

4.2. PROCESS GUIDELINES FOR FUEL PARTICLE CRUSHING AS APPLIED TO THE 20-CM SECONDARY BURNER

Reference 1 establishes a maximum of 1% unbroken fuel particles in the secondary burner ash. Since the burner is not effective in breaking particles, this specification can be applied directly to the fuel particle crusher.

Applying the preceding criteria to fertile particles, the maximum roll gap is 0.017 in. (as determined experimentally). The minimum gap for fertile particles is dictated by the ability to handle the finer material

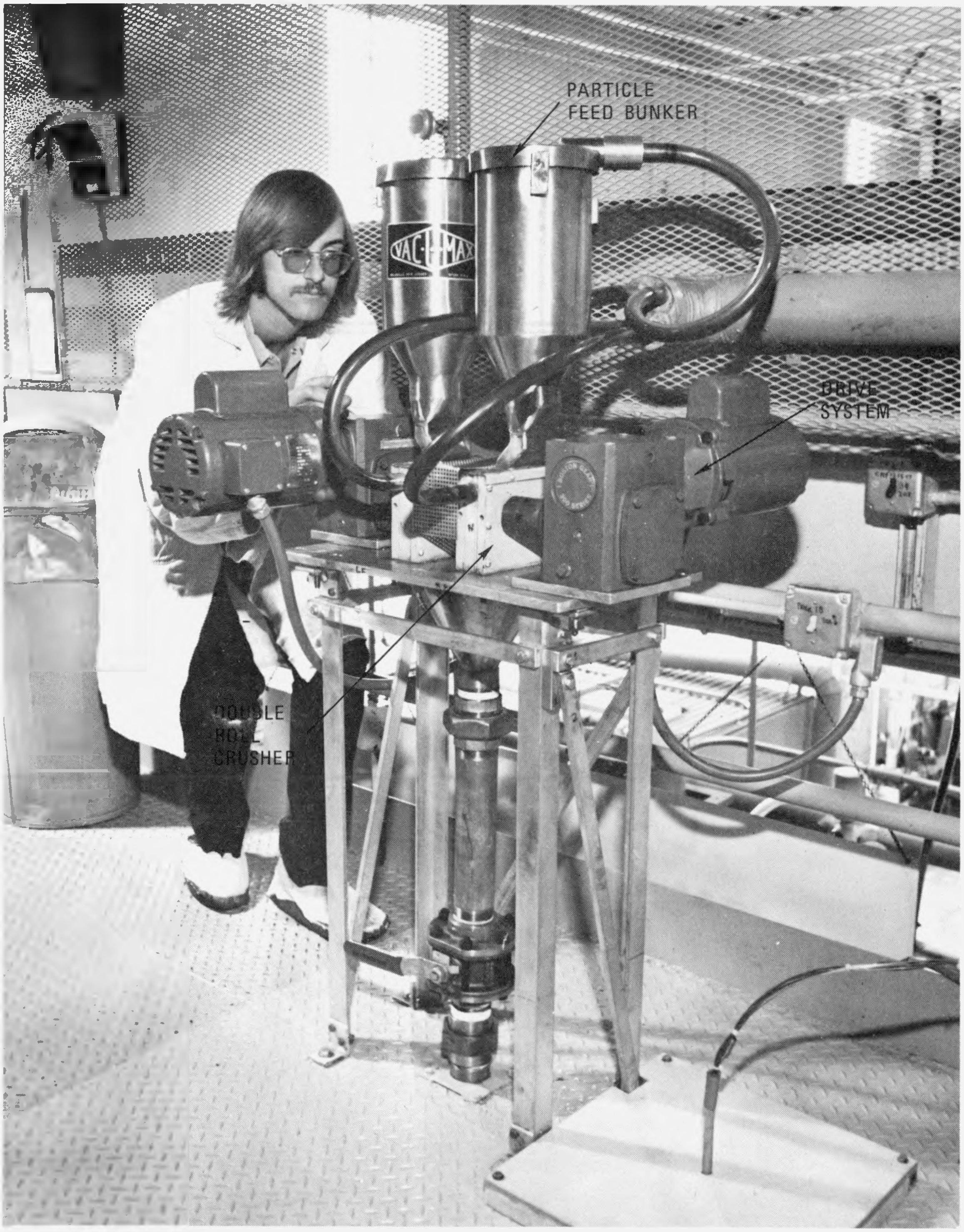


Fig. 11. Fuel particle double roll crushing system

in the secondary burner. Early experiments indicated that the minimum gap should be 0.012 in. At this gap, the fineness is beginning to increase filter chamber loadings excessively as well as causing materials handling problems. The crusher would thus have an initial gap of about 0.012 in. and would be used until the gap is 0.017 in. This agrees with data from Allied Chemical Corporation in Ref. 2.

Crusher system throughput should be 30 kg/hr. A 1 in. x 3 in. (roll size) crusher will process 10 kg/hr at 29 rpm. Higher speeds may be beneficial for throughput and should be checked on the new crusher system. Reference 2 notes that the crushed product was slightly smaller in size with increased roll speeds, but does not give data on choke fed crusher throughputs as a function of roll speed.

Fissile particles have not been processed yet. However, available size distribution data for such particles indicate that a maximum roll gap of about 0.012 in. is allowed. Minimum limits have not been determined, of course, but the leeway will probably be less than on the fertile particles. A first guess would be a crusher with an initial gap of 0.010 in. that would be allowed to wear to 0.012 in. Throughput requirements are the same as for fertile particles.

No ventilation is required on the crusher since the product hopper below it is vented. Accountability is obviously maximized by minimizing internal cavities. It is suggested that the spaces behind the rolls be solid (part of the frame). The frame could be extended to form the particle feed funnel, eliminating the need for wipers. A 0.005 in. gap around the rolls would be sufficient to prevent particles (>0.017 in. diameter) from entering this area and yet would be adequate clearance for crusher operation. It is suggested that the lower portion of the crusher be fitted in a similar manner.

5. BURNER TUBE MATERIAL

Austenitic stainless steel tubes were used in the early development stages. Hastelloy X was later introduced to yield better oxidation resistance, lower creep, and higher strength at the conditions in the burner and has been used satisfactorily for the last 15 runs.

Hastelloy X is planned for use in larger scale burners. It is coded for 900°C operating conditions and has the useful physical characteristics mentioned in the preceding paragraph.

6. BURNER ALIGNMENT MECHANISMS

Operation of the secondary burner at 900°C develops substantial thermal stresses in the vessel. These stresses with attendant thermal growth give rise to substantial deflections of the vessel's free end. If not otherwise restrained, this deflection will hamper alignment of the induction heating coils and attachment of the pneumatic transport system. An ability to constrain thermal expansion of the vessel to its centerline has been successfully demonstrated using two straight-line mechanisms at right angles. These mechanisms, called Peaucellier cells, have been used to maintain burner tube alignment during 30 separate runs.

As shown in Fig. 12, the straight line mechanism of Peaucellier consists of eight bars and six turning joints. The four bars in the "kite" (BE, BC, CD and DE) all have the same length(a). AF and EF are each equal to twice the length[(c)] of a kite member. Another constraint is that AB and AD must be the same length[(b)], which is greater than twice that of a kite member.

A cell constructed in this manner will lead to point C moving in a straight line, perpendicular to AF, which is fixed. Further properties are that

$$|\overline{AE}| \cdot |\overline{AC}| = \pm (b^2 - a^2) = \text{constant} \quad ,$$

and the distance from point A to the intersection of liners AF and the perpendicular path of C is equal to $\pm 1/2C\ (b^2 - a^2)$.

The two cells are attached to the burner tube at right angles such that side deflection of each cell is compensated by the axial holding power of the other cell.

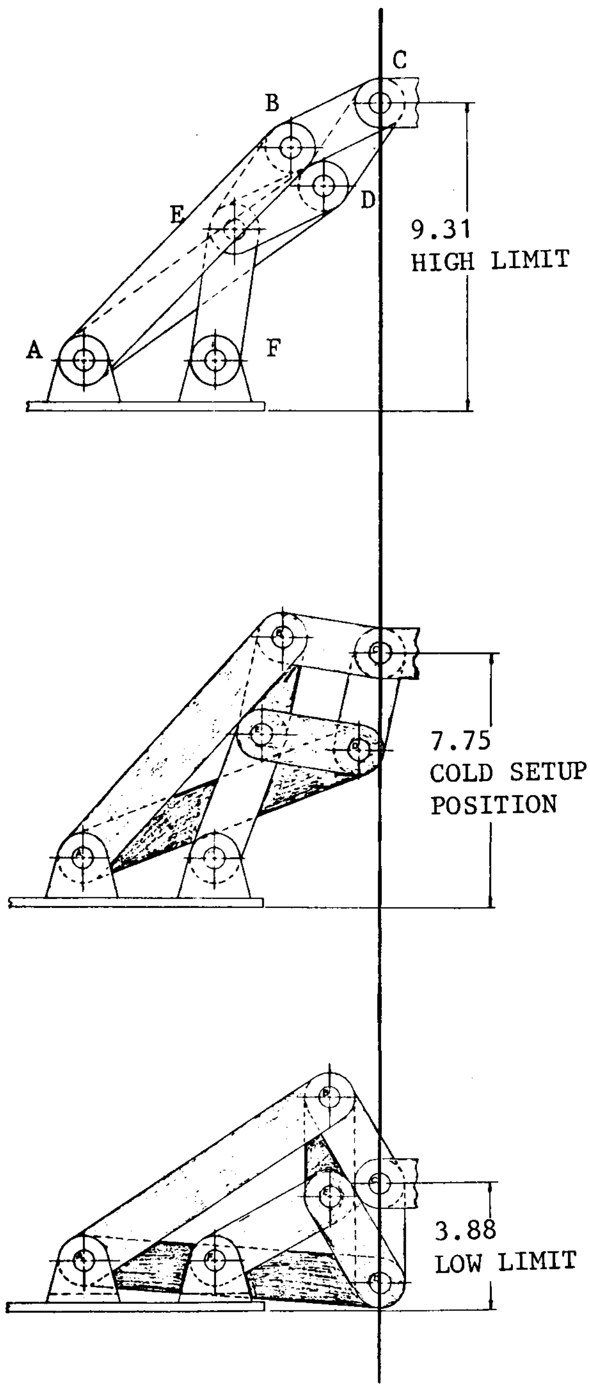


Fig. 12. Peaucellier mechanism

7. PROCESS GAS FLOW

7.1. MAXIMUM O_2 CONCENTRATION FOR FLUIDIZING GAS

The prior use of a resistance heater instead of an induction heater meant that combustion heat generated in the lower portion of the burner had to be removed about 2 ft above the heater elements. This is due to the fact that air cooling in this zone would severely deteriorate the ceramic heater by cracking it. This cracking breaks the nichrome heating wire and then the element must be replaced. For this reason, the specific heat generation rate was lowered by using a maximum of about 75% O_2 in the inlet gas. This was sufficient to preclude overtemperatures in the lower burner section (just above the distributor plate). The addition of an induction heater meant that the burner could be cooled along the entire length, which eliminated the axial heat transport problem.

The use of induction heating, therefore, permits the inlet O_2 concentration to be 100% during much of the main burning portion. No overtemperatures or local hot spots are detected and burner operation is smooth. An added advantage is that with no inert gas flow to raise the superficial velocity, much lower filter pressure drops are possible at the same burn rate, reducing stresses on the in-vessel filter.

During the burnout portion, the gas velocity is significantly decreased to help fines return to the bed for oxidation. The reduced heat removal capabilities at this point make it necessary to lower the O_2 concentration to reduce specific burn rate.

7.2. SAFE FLUIDIZING VELOCITY RANGE

The minimum velocity is determined by the onset of bed stagnation accompanied by localized hot spots. In burner run 30 (see Appendix B for run summaries), a velocity of 0.3 ft/sec during startup yielded a hot spot sufficient to burn through the distributor plate. In burner run 36, a velocity of 1.6 ft/sec in the burnout portion of the run resulted in stagnation and a subsequent hole in the burner just above the distributor plate.

The only time in the run that gas flow should be minimized is during the tail burn in order to allow fines to re-enter the bed.

Fourteen runs have been made since run 36 using a 2.5 ft/sec velocity in the tail burn portion. This has yielded no observable temperature excursions and has allowed satisfactory fines return to this portion.

During the main burn portion, the gas velocity should be maximized to decrease the overall burn time per batch. Upper limits include heat removal capability and fines blowback characteristics. A filter failure in run 43 occurred when using a 4.9 ft/sec superficial velocity in the main burn portion. This high velocity was thought to have contributed significantly to the failure by loading excessive fines into the filter chamber and carrying sufficient heat and O_2 to ignite them on the filter surface. The maximum in the six runs following has been 3.7 ft/sec with no problems at that level.

8. IN-VESSEL OFF-GAS FILTER SYSTEM

The burner incorporates in-vessel filters to separate the off-gas flow from the particulate fines elutriated from the fluid bed.

Sixty-five batches of crushed particles have been processed through the 10-cm secondary burner, with a significant amount of performance data collected to aid in larger burner design. In this section the data covering such areas as the filter pressure drop dependence on process variables, the high temperature metallurgy of the filters, and controls required to avoid excessive filter temperatures are analyzed.

8.1. FILTER SYSTEM COMPONENTS

Figure 13 shows a cross section of the 10-cm secondary burner filter chamber. The filters are 2-3/4 in. o.d. x 1/8 in. wall x 36 in. long. They are made of 316 L stainless steel in porosity grade H, which designates a largest pore size of 12 microns and a mean pore size of 5 microns. For gas filtration, they remove 100% of 1-micron particles and 98% of 0.4-micron particles. Two filters in the chamber have a total surface area of 4.6 ft^2.

The grade H filters have the finest pore size available, and are thus quite attractive for use on fine powders as in the secondary burner. (Up to 5% of the product is less than 44 μm by screen analysis.)

Filter blowback is effected through two 1/8 in. orifices located an inch above the venturi plate. These venturis (see Fig. 14) are based on a design recommended in Refs. 3 and 4. The blowback gas pulse causes a reverse pumping action as it passes through the venturi, drawing filtered off-gas back through the filters. This increases the effectiveness of the

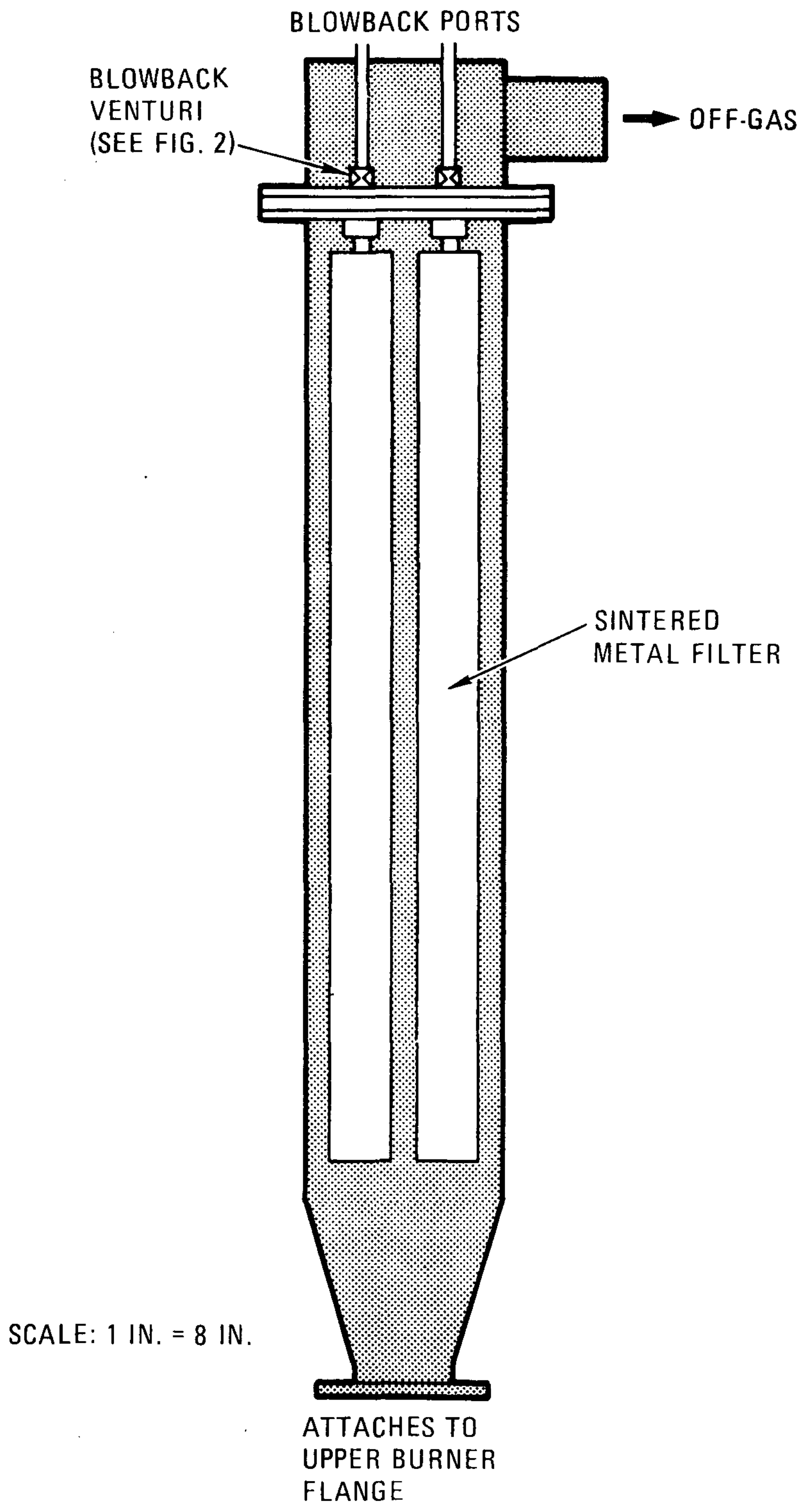


Fig. 13. Ten-centimeter secondary burner filter chamber

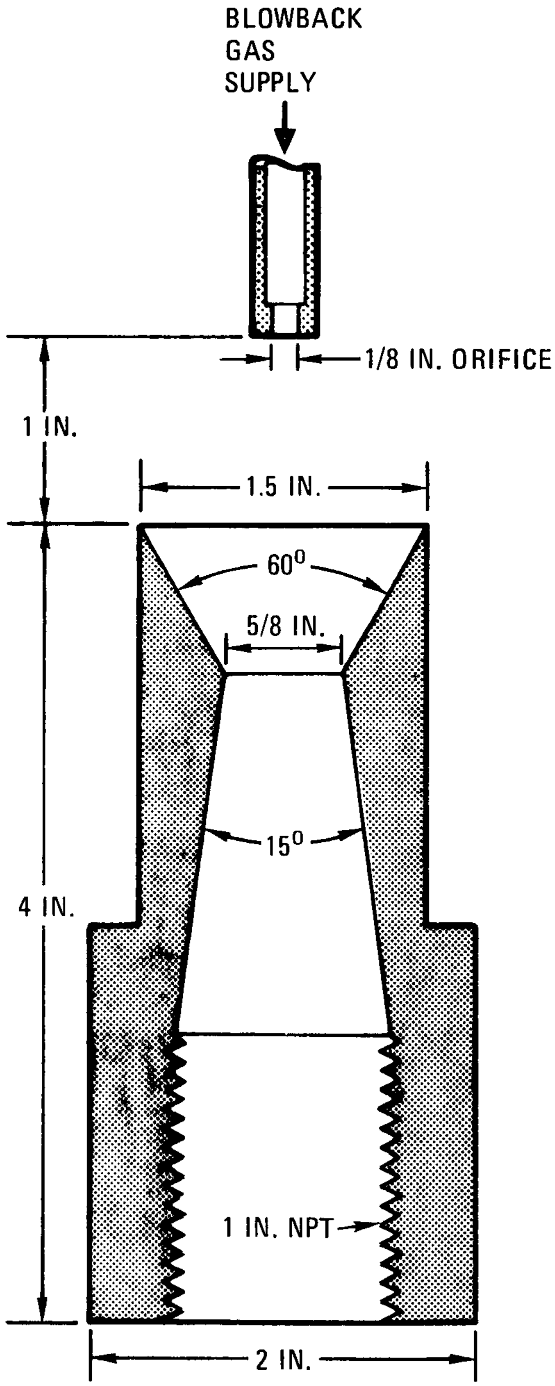


Fig. 14. Filter venturi

blowback while keeping the volume of gas added to the system at a minimum. In this way, the quantity of burner off-gas is reduced, yielding a decreased load on the off-gas cleanup system. Reducing blowback gas is also desirable to minimize dilution of the off-gas, which is sampled throughout each run to provide an indication of combustion efficiencies.

During approximately one-third of the 10-cm secondary burner runs, the main blowback gas supply consisted of recycled burner off-gas. A diaphragm pump was coupled with a surge tank to yield a 45 psig blowback gas supply with essentially the same composition as the gas exiting the burner. This eliminated gas sampling errors associated with the previous practice of using N_2 for the blowback gas, allowing a more accurate study of burning characteristics. A compressed CO_2 blowback supply is now available and will probably be used in later applications since it will not obscure the data as markedly as did the N_2 supply (burner off-gas is very nearly 100% CO_2 in many cases).

Blowback at 50 psi through the 1/8 in. orifices yields about 5 liters of gas per each 1-sec pulse. This yields 15 liters per minute in the most recent runs, which is about 10% of the process flow. Keeping the blowback rate this low prevents pressurization of the burner vessel during blowback; the filter chamber pressure rise at present is about 10 in. of H_2O during each pulse.

8.2. OPERATING EXPERIENCE

The first 40 secondary burner runs were made without filter pressure drop instrumentation. In the next 25 runs the pressure drop was continuously recorded, as were temperatures between the two filters. Table 4 contains parameters from 18 runs.

Filter blowback is used throughout each run at the frequency noted in Table 4. The filter pressure drop increases in the early portion of the run to a maximum, where it remains during the main burning portion. In this

TABLE 4
BURNER OPERATING PARAMETERS

Run	Bed Weight (kg)	Max. ΔP (in. H_2O)	Max. Filter Temp. (°C)	Max. Process Flow (slpm)	Blowback Frequency (cycles/min)	$\overline{Dp}$ Feed (D_{sv})
27	12	4	700	100	1	227
29	13	9	800	100	1	222
30	14	6	700	100	1	258
31	15	6	725	120	1	258
32	15	11	900	140	1	291
33	17	23	900	140	1	291
34	18.5	>50	900	120	1	111
35	20	31	900	140	1	160
36	20	45	800	140	2	145
37	20	25	800	140	2	150
38	18	21	800	160	2	155
39	18	35	800	160	2	167
41	18	45	800	160	2	167
42	18	-	-	160	2	156
43	18	-	-	160	2	120
44	14	15	750	140	3	167
45	14	20	800	140	3	165
46	14	16	800	140	3	165
47	14	18	820	140	3	160
48	14	17	820	140	3	160

constant ΔP period, fines are removed via blowback at the same rate they are being re-elutriated into the filter chamber. When the off-gas analysis indicates that the bed is about to burn out (carbon content is becoming low), the process gas flow is lowered both to conserve heat in the bed and to allow carbonaceous fines to re-enter the bed more easily.

The filter pressure drop is slowly reduced throughout this burnout period as fines re-enter the bed. An air-actuated vibrator mounted on the filter chamber upper flange is actuated at intervals during this final burning portion to help dislodge fines from the filter chamber. It is definitely effective in this function as seen by increases in O_2 utilization following vibrator actuation.

Failure of the in-bed filter system on two occasions defined the necessary operating conditions to allow successful operation. In one instance one of the blowback pumps quit working about halfway through run 42, yielding essentially no blowback. The result of this was a quick building of fines in the filter chamber as evidenced by high filter pressure drops. Just before the run was terminated, high temperatures (925°C) were noted in the filter chamber, while the bed was only at 700°C. This was the reason for shutdown at that time. The high temperatures are believed to have been caused by the carbon depletion of the fluidized bed allowing O_2 to enter the filter chamber and oxidize the large amount of fines contained therein. Local temperatures may have been much higher than 925°C because the carbon fines were essentially a cake surrounding the filters, resulting in poor heat transfer capabilities.

At the same time that the high temperatures were noted, the filter pressure drop decreased to about 10 in. H_2O, which is somewhat less than normal when fines are in the filter chamber. The burner was shut down, emptied, and dismantled later. One of the filters was deformed in its upper portion as if flattened by a hammer. The longitudinal weld seam formed one of the flattened edges and was cracked open as shown in Fig. 15. This opening explains the sudden reduction in filter pressure drop.

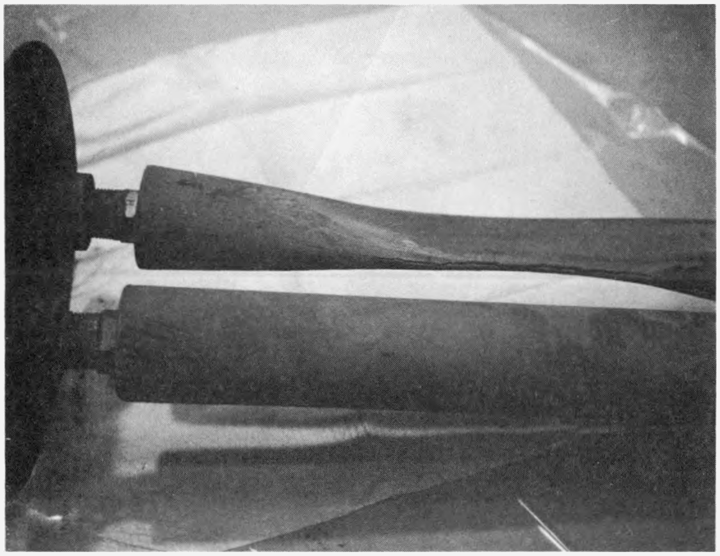


Fig. 15. Ten-centimeter secondary burner off-gas filter following run 42

The most probable cause of the filter failure was:

1. The blowback system became inoperative, allowing large amounts of fines to build up around the filter, causing high (4-5 psig) filter pressure drops.

2. When the fluidized bed burned down to a low carbon content, oxygen was allowed to pass through unreacted and enter the filter chamber.

3. The fines packed around the filters began reacting with the oxygen and generating significant amounts of heat, thus causing localized hot spots due to the static nature of the fines.

4. One of the filters developed a local hot spot that sufficiently reduced the filter strength to allow it to collapse due to the pressure drop across the filter. When it collapsed, the weld seam was put in a severe stress and cracked, yielding an opening in the filter that reduced the pressure drop quickly to a low value.

In a second instance, a feed was introduced with a significantly larger fraction of fine material. The feed was 18 kg of finely crushed TRISO fertile particles. The <100 μm fraction was 25 wt % and the <50 μm fraction was 10 wt % as compared to values of 11 wt % and 4 wt %, respectively, in previous feeds.

This feed was generated using a close gap crusher in order to test the feasibility of using such finely divided material. Previous runs with finer material had been unsuccessful (runs 16 and 17 - see Appendix B for run summaries), but there was no data in the intermediate region.

The run proceeded uneventfully with a 20 in. H_2O filter ΔP (using 60 psi N_2 for blowback). When the bed began to burn out, as evidenced by the presence of O_2 in the off-gas, the filter ΔP dropped suddenly to a very low value, indicating an opening in a filter. At this point the run was terminated.

Subsequent disassembly of the burner revealed that the lower end of one filter had been burned off. Using the finely crushed feed resulted in a higher portion of unburned material on hot filter surfaces throughout the run. When the O_2 front reached the filters, in situ combustion occurred, melting the filter.

To prevent further filter failures, it is desirable to eliminate both the large fines buildup and the presence of O_2 in the filter chamber when filter temperatures are high. The first problem is handled by reducing bed size to 14 kg and reducing total flow 15%. This will reduce the fines loading in the filter area. The second problem is handled by reducing flow to bring fines down from the filter chamber when the off-gas CO gets below 5% (indicating the O_2 front is nearing the filter chamber). This lowers the filter temperature caused by the expanded hot bed before the O_2 enters the chamber.

Using feed as fine as has been described must be avoided in the future. Correct roll crusher gap size (0.012-0.017 in. gap) is essential to provide feed that can be successfully burned. Five runs have been made since these two filter failures and no further filter problems were encountered.

The long term buildup of fines in the filters is of concern as it raises the pressure drop across the filters which can lead to filter collapse. Figure 16 illustrates the filter pressure drop measured between runs (no fluidized bed - only gas flow) as a function of the number of runs made. It appears that the first run added a precoat that approximately doubled the ΔP observed with a new filter. Modest increases that followed after 6 runs can be attributed either to a larger precoat or migration of material into the filter voids.

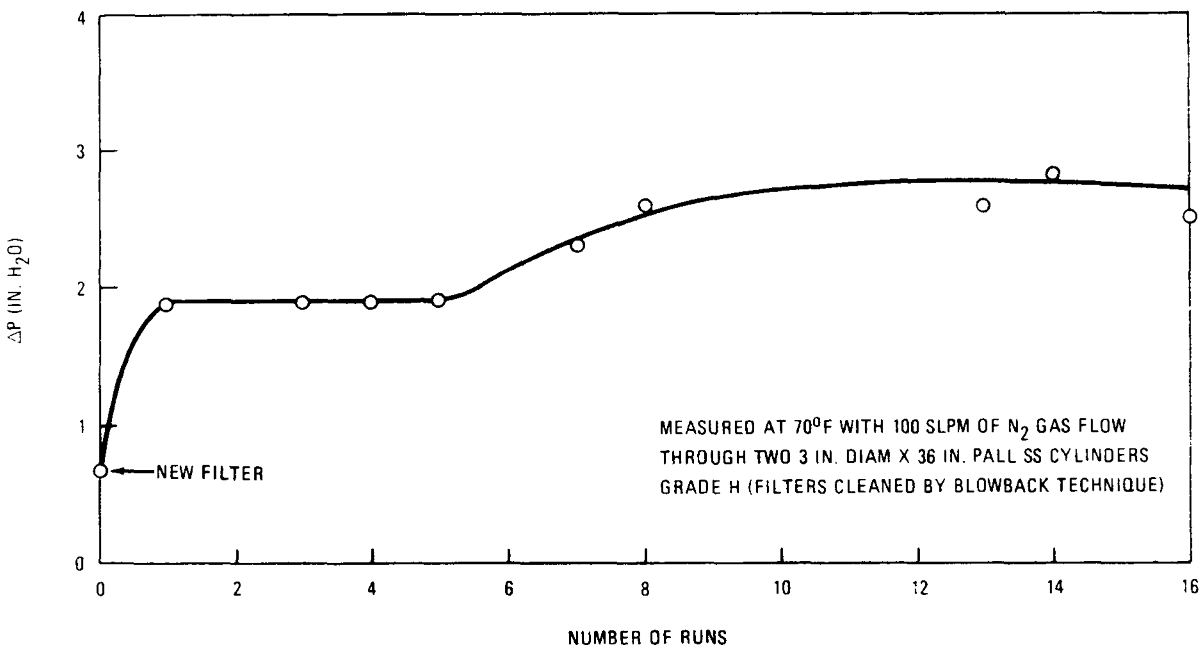


Fig. 16. Filter pressure drop prior to 10-cm secondary burner runs

The precoat is composed of colonies of fine particles that congregate at the filter pore opening, yielding much finer filtration than the porous material. This minimizes filter clogging by keeping small particles out of the filter internal pores.

It is important to note that the filter plus cake pressure drop during the run is approximately 10 times the drop across the filter alone. Thus a large amount of interstitial pore clogging is allowed before the pressure drop during the run is significantly affected.

8.3. METALLURGICAL EVALUATION OF RUN DATA

To determine the expected useful life of the filters, a set of filters was subjected to 30 typical burner cycles. These filters are described in Section 8.1. A sample was cut from each end of the filters, representing the extremes in temperature to which the filters were subjected. During each cycle (1-1/2 hr duration), one sample was at 800°C and the other was at 300°C. The total filter operating life was 45 hours.

The gas composition to which the filters were exposed had been 20% CO, 70% CO_2, and 10% N_2. The normal gas flow through the filters was 0.85 $ft^3/min/ft^2$.

The filters were used to remove fine carbon and ThO_2 (-40 μm) from the gas stream. To prevent carbon buildup on the filter surfaces, a backflow of gas was effected every 2 min for a short duration (1 to 2 sec).

Both samples were submitted to metallographic examination. The hardness of the sample exposed at 800°C was measured at DPH 250, while the 300°C sample measured DPH 140.

The following observations were made from photomicrographs (see Figs. 17 through 20):

1. The section exposed at 300°C revealed no signs of oxidation and carburization, and no signs of significant microstructural changes.

2. The section exposed at 800°C revealed significant oxidation attack (>0.5 mil on each side). Considering that the porous structure is held together by a metal network on the order of 1 to 2 mils thick, approximately half of the "useful" life of the filter is used up. The only significant microstructural change observed in the photomicrographs was precipitation of $M_{23}C_6$ carbides, predominantly at grain boundaries (sensitization).

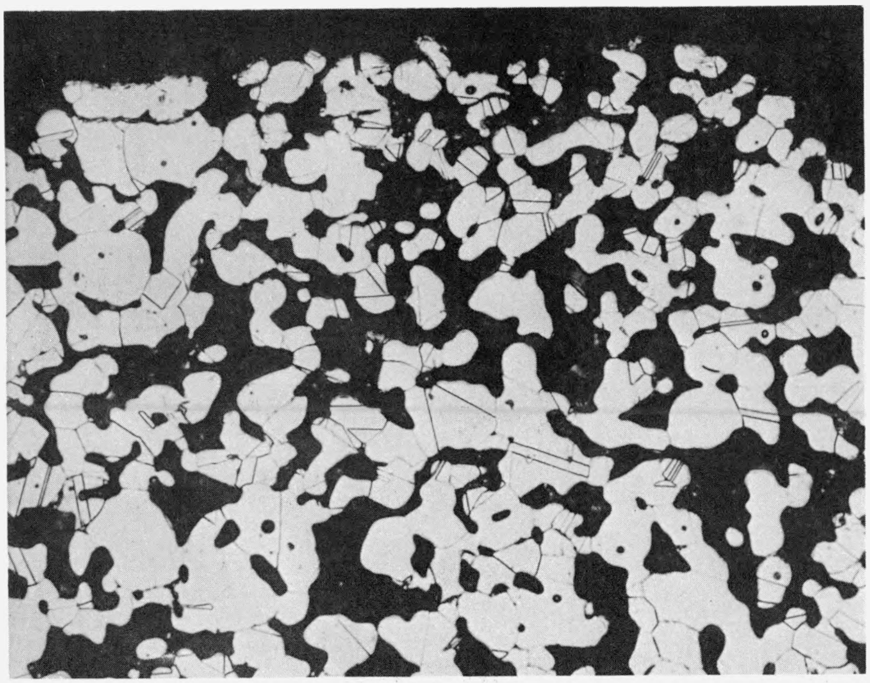
The above observations are considered normal for this material. It is not believed that the sensitization phenomenon played any role in the high rate of oxidation at 800°C.

In view of these results, the use of materials such as Hastelloy X, which is more resistant to oxidation and carburization (in that order), is recommended. Hastelloy X filters have been ordered and will be tested in the 10-cm secondary burner to determine oxidation rates. Filter manufacturers have indicated that experimental data are the only guide to the actual operating life of these Hastelloy X filters.

8.4. STATISTICAL EVALUATION OF RUN DATA

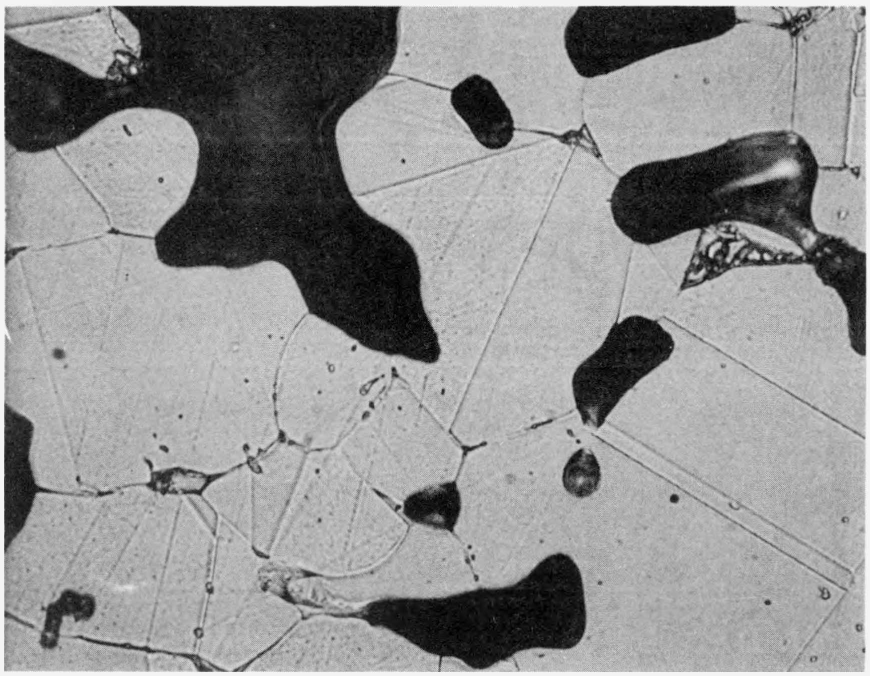
The data from 18 recent runs were examined to determine which process variable affects the filter pressure drop most significantly. Minimizing this pressure drop accomplishes two tasks:

1. Reduces the absolute pressure of the burner (which is 30 psia maximum).



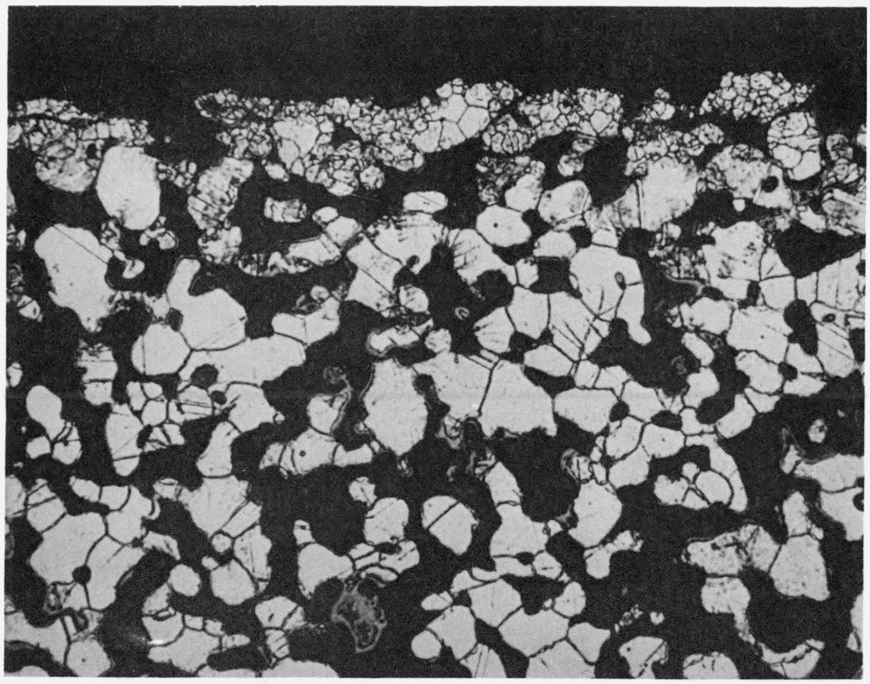
M40628-1

Fig. 17. Filter cross section, 300°C sample (250X)



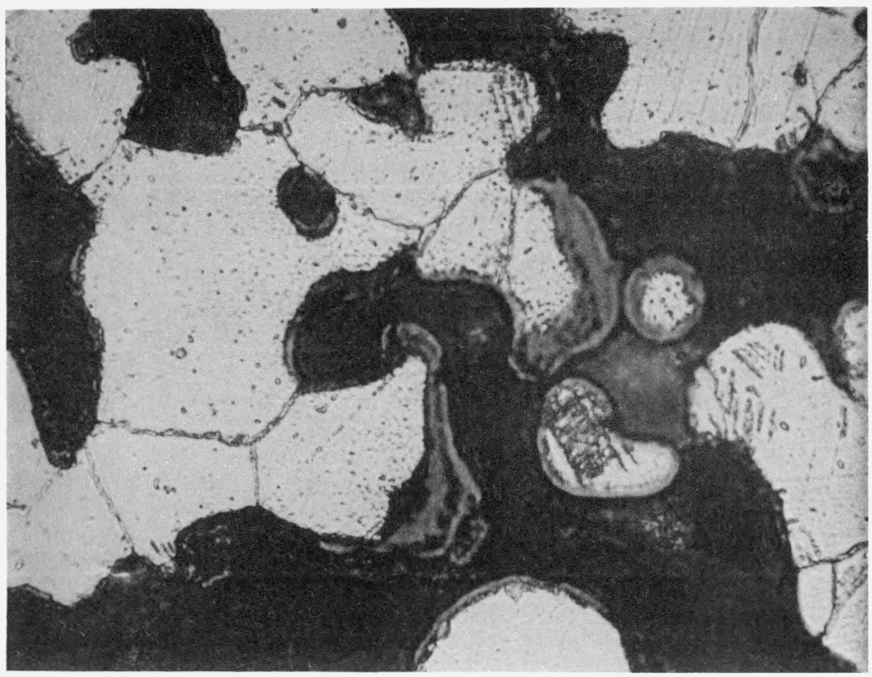
M40628-2

Fig. 18. Filter cross section, 300°C sample (1000X)



M40627-3

Fig. 19. Filter cross section, 800°C (250X)



M40627-4

Fig. 20. Filter cross section, 800°C sample (1000X)

2. Reduces the pressure induced stress on the filter to help prevent collapse during high temperature operation as in run 43.

The data were analyzed using a multiple linear regression analysis. The filter pressure drop in these 18 runs was approximated by the following equation:

$$\Delta P = -5.9 + 0.16V + 2.4W - 0.13\,\bar{d}_{sv} - 3.8\,\nu \quad ,$$

where ΔP = filter pressure drop, in. H_2O,

V = fluidizing gas flow rate, slpm,

W = fluidized bed weight, kg,

$\bar{d}_{sv}$ = fluidized bed average particle size, microns,

ν = filter blowback frequency, minutes^{-1}.

It was also determined that there is less than 0.1% chance that the variables examined are not significant with respect to the dependent variable, filter pressure drop. A further calculation provided the information shown below. For each independent variable, a percent chance is listed for the hypothesis that the given variable is responsible for deviation of actual data from the multiple linear regression equation.

Flow	- 50%
Weight	- 85%
Size	- 92%
Frequency	- 50%

A larger number percentage indicates a more positive correlation with the dependent variable; thus weight and size are more certain to affect the pressure drop than are flow and frequency.

Extrapolation of this curve outside the defined range is not strictly allowed, but may be done in a modest step without undue risk. Thus, reducing the pressure drop further from the last few runs (where it is 17 in. H_2O) can be accomplished by increasing particle size or blowback frequency or by decreasing bed weight or fluidizing velocity. Particle size cannot be increased without yielding >1% unbroken particles; thus this variable cannot be modified to lower ΔP. It should be noted that this gives a definite impetus for maximizing particle size in the crushing operation. Blowback frequency can be increased; doubling the frequency should give a reduction of 11 in. H_2O. This is probably too far outside the range of the previous work to be valid, but it does indicate significant reductions. The burner is presently operated with 100 slpm O_2 and 40 slpm N_2 (or CO_2) in the main burning portion. This can be changed to 100 slpm of O_2 (without sacrificing burn rate) to lower superficial velocities with a predicted filter ΔP decrease of 6 in. H_2O. It is desirable to maximize bed weight with respect to increasing burner throughput, so bed weight should not be changed. From these arguments, to reduce the maximum filter pressure drop during the run, further burner experimental runs will include reduced flow rate in the main burning portion and increased blowback frequency.

The maximum operating temperature of the filters in the burner runs has been in the 700-900°C range. This is excessive and should be reduced both to minimize the metal oxidation rate and to increase the margin of safety from filter collapse due to reduced strength at higher temperatures.

The prototype secondary burner filter chamber has been designed with an 18 in. long expanded space between the main burner tube and the bottom of the filters. This should help reduce filter operating temperature and will thus be incorporated into the 10-cm secondary configuration to give an indication of what reduction is actually attained. Baffles are located in the prototype between each set of two filters (there are six total). This is to prevent the dislodged fines from simply traveling from one set of filters to another, without reaching the fluidized bed.

Subsequent to this evaluation, a burner run was made incorporating the suggested improvements (18 in. longer filter chamber, lower process flow (100 slpm) and higher blowback frequency (6 min^{-1}). The result was a maximum filter pressure drop of 4 in. H_2O. These modified operating conditions will be used routinely in all future runs.

9. INDUCTION HEATING SYSTEM

Induction heating has been chosen for the heating system on the secondary burner. Induction heating is defined as the heating of an electrically conducting material in a varying magnetic field due to its internal losses. In the case of Hastelloy X, internal losses are due to eddy currents induced in the metal by transformer coupling action.

Three different induction coil designs (Figs. 21, 22, and 23) have been used on the 10-cm secondary burner during a total of 13 burner runs. A summary of the work and the reasoning involved are presented below.

9.1. GENERAL INFORMATION

The induction heating system was identical in all runs except for changes in coil design. The system has a general layout as shown in Fig. 24. The motor generator area is shown in Fig. 25. The burner area is shown in Figs. 26 and 27.

Basic operation of the system is as follows:

1. The motor generator produces 10,000 Hz current at 0-440 V with a maximum power level of 30,000 watts at 440 V (68.2 A). It is water cooled to remove mechanically and electrically produced heat, and it is actuated by a magnetic starter. Regulation of motor generator output is accomplished by varying the field from approximately 0 to 55 V. The voltage required for the field is supplied by a magnetic amplifier to allow use of an automatic controller in adjusting the generator field. The field voltage required to yield maximum generator current output increases as the load (in this case the burner) changes temperature.

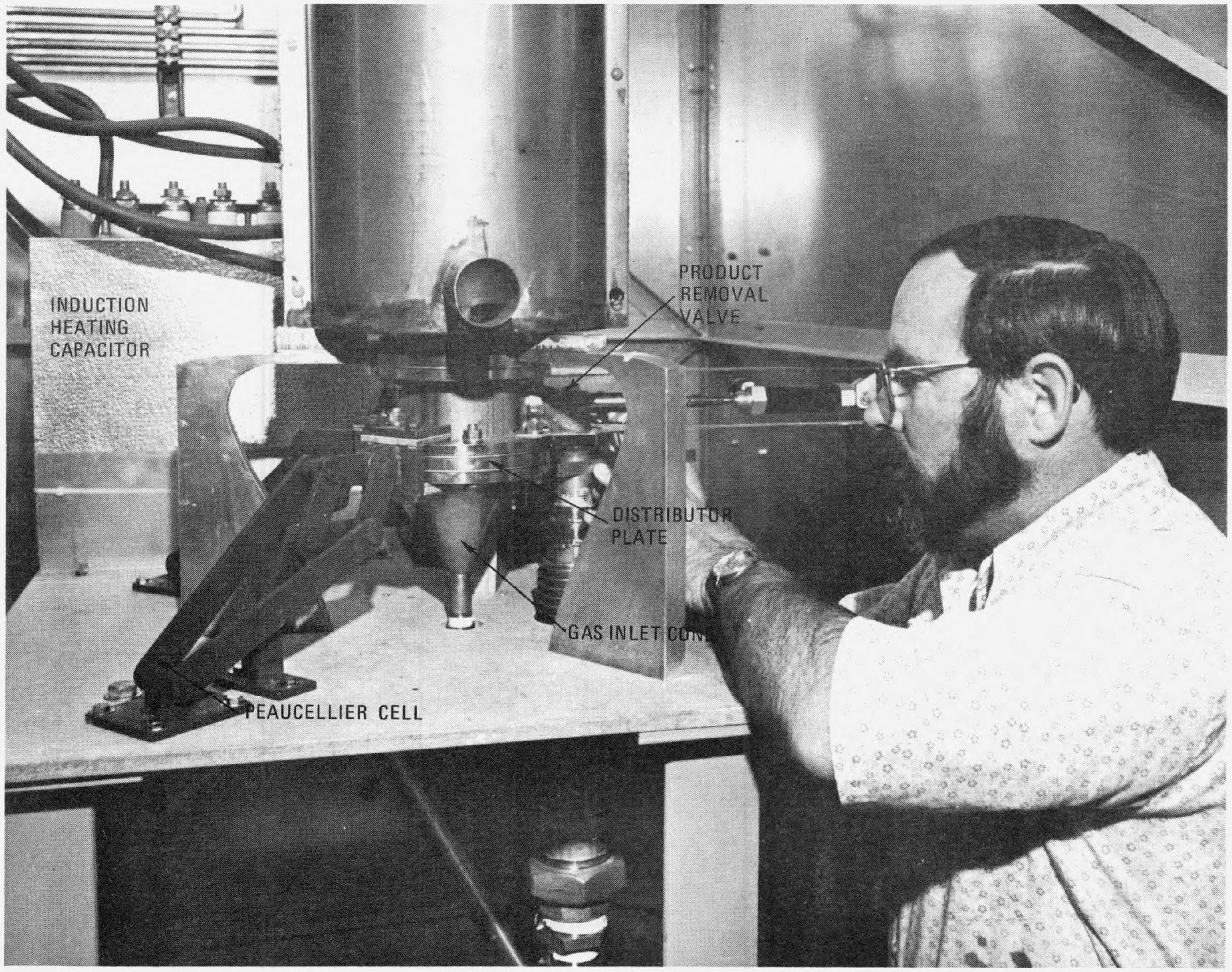


Fig. 21. Lower portion of secondary burner showing product removal valve, distributor plate, gas inlet cone, Peaucillier cells, and induction heating capacitors (coil design 1)

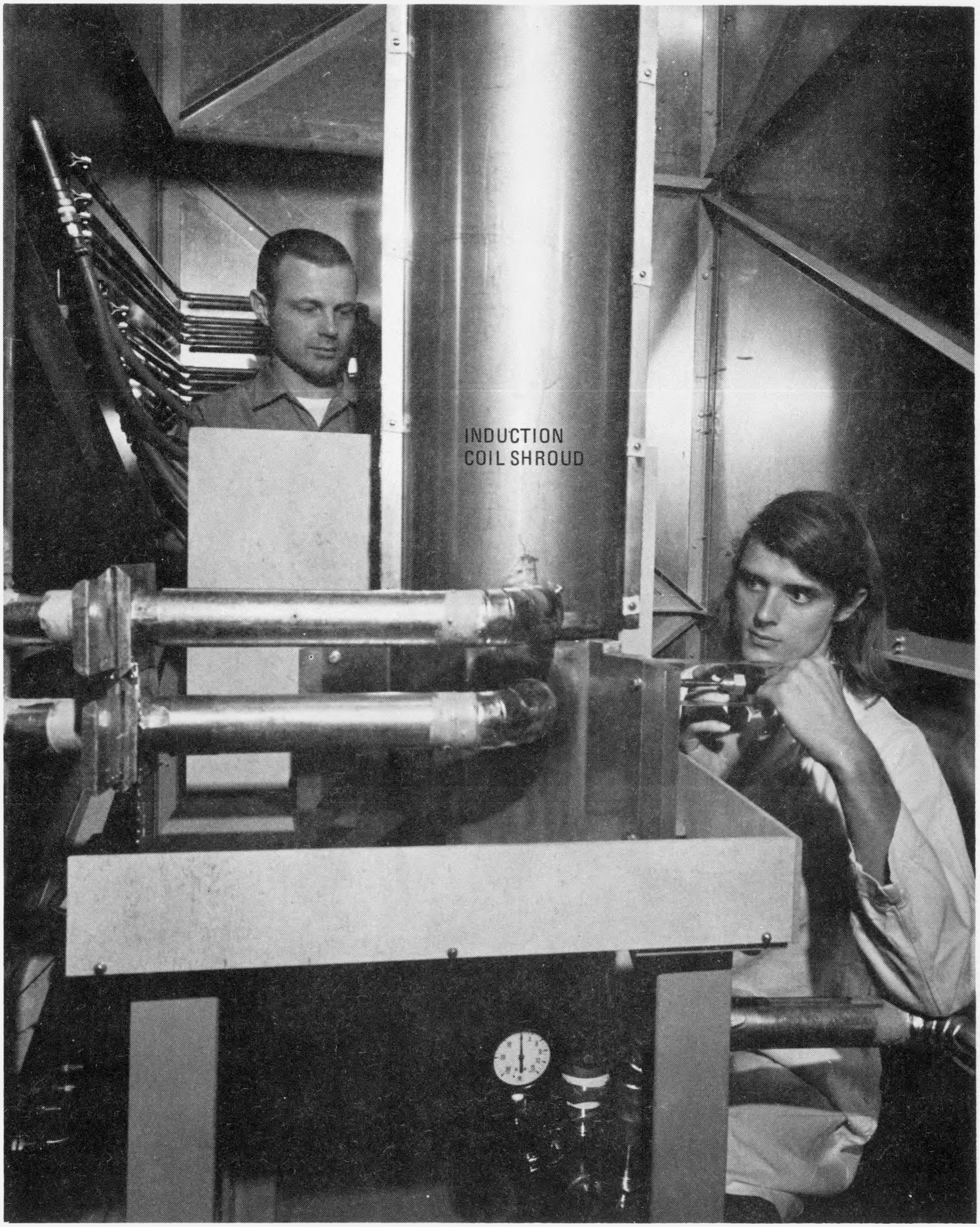


Fig. 22. Lower portion of secondary burner with induction coil outer shroud in place (coil design 2)

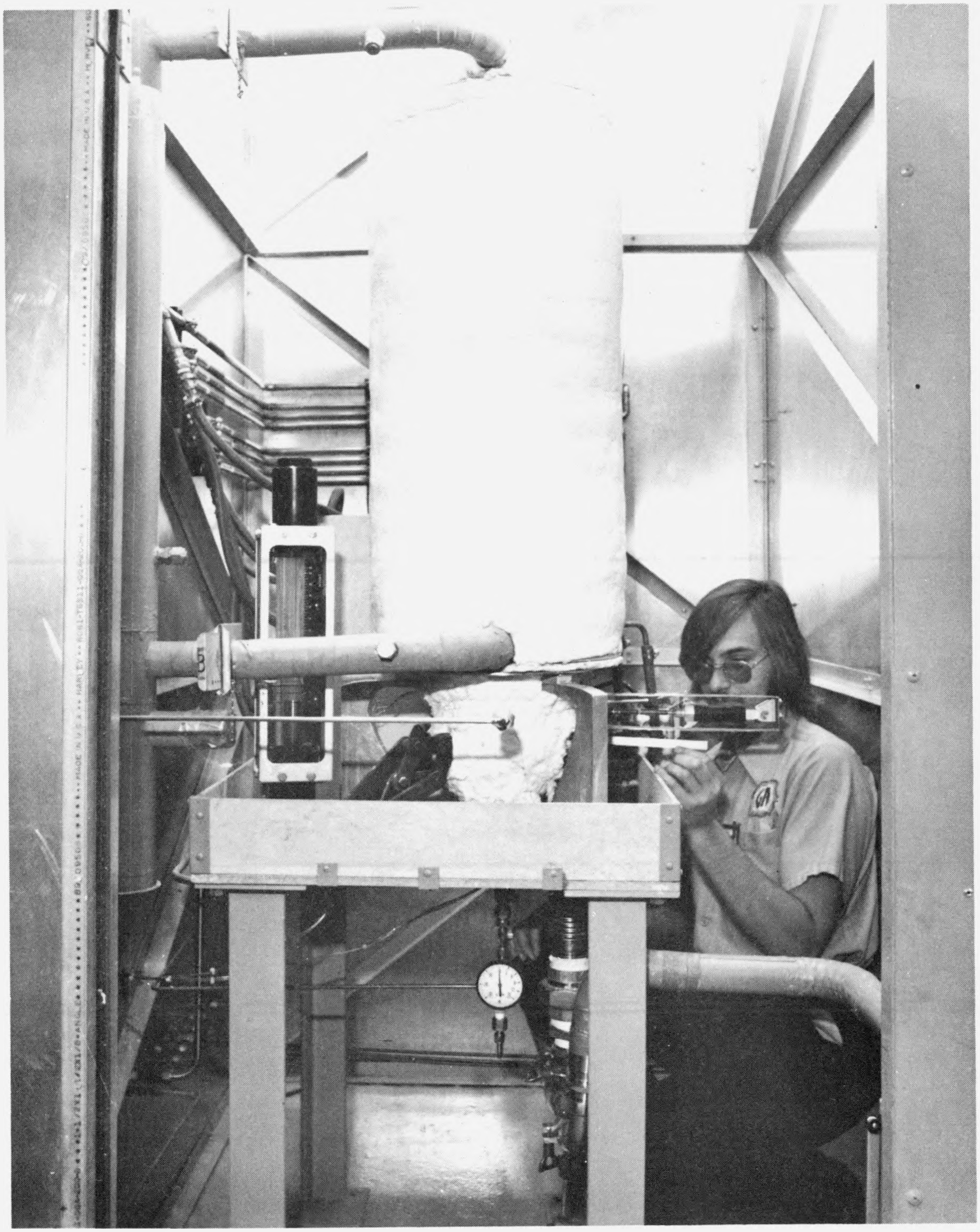


Fig. 23. Lower portion of 10-cm secondary burner (coil design 3)

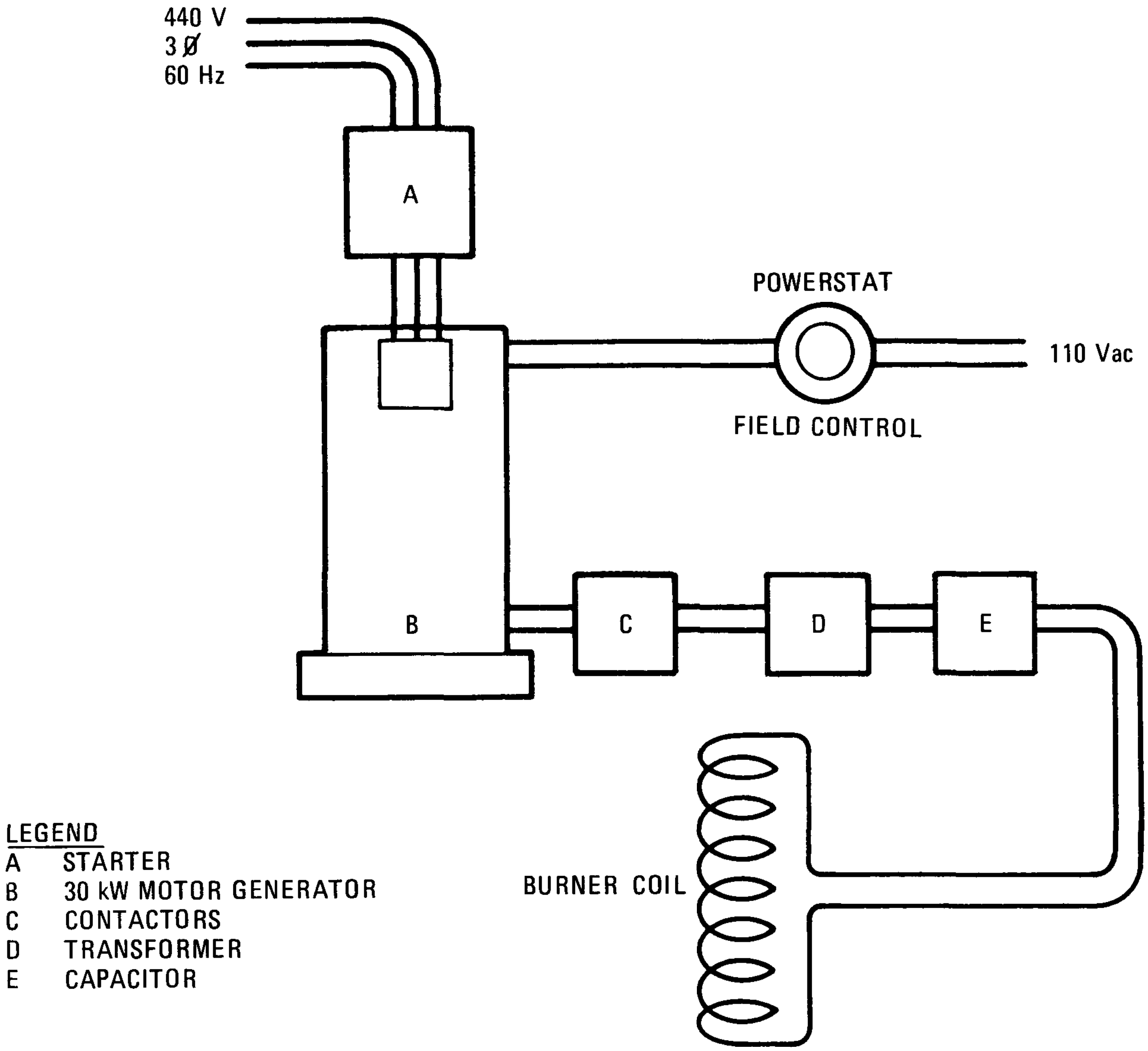


Fig. 24. General system layout

Fig. 25. Motor generator system

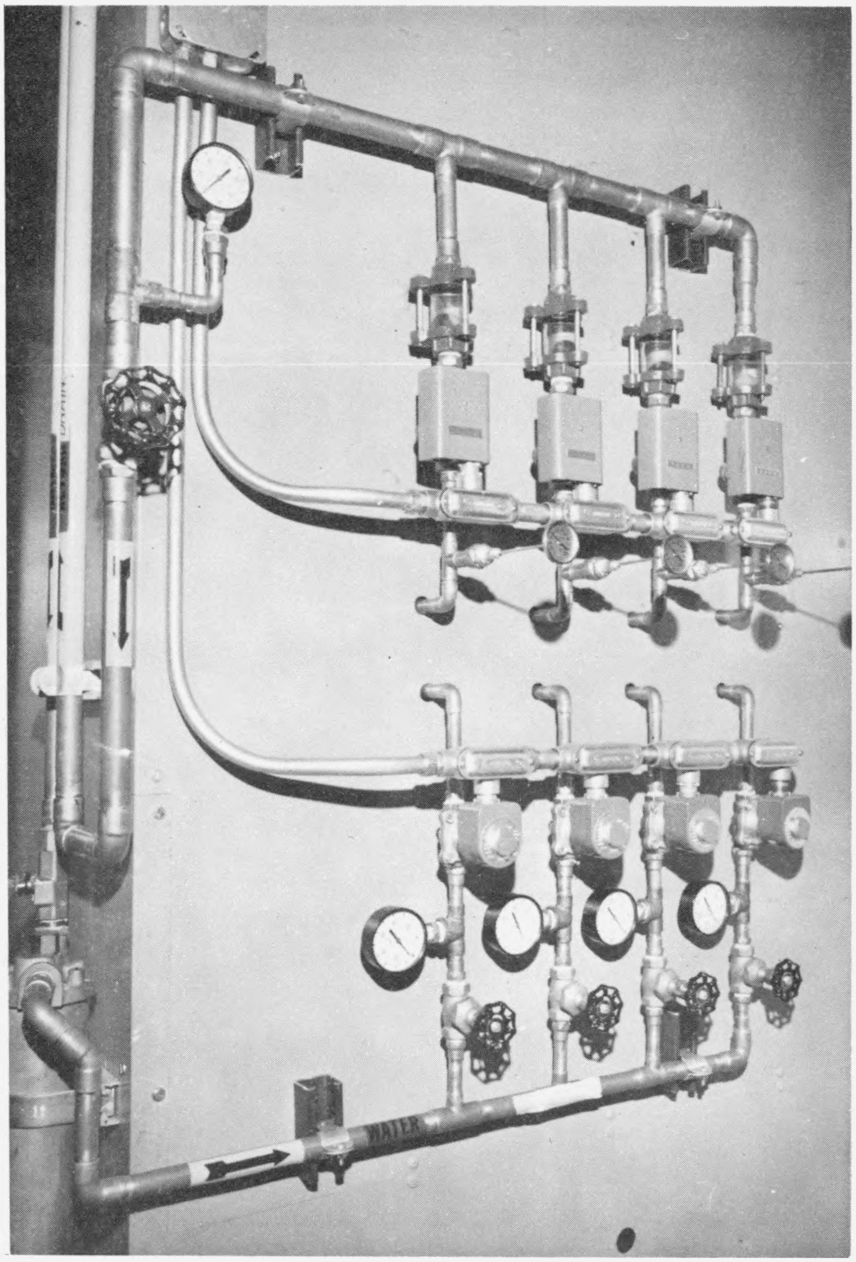


Fig. 26. Water supply manifold

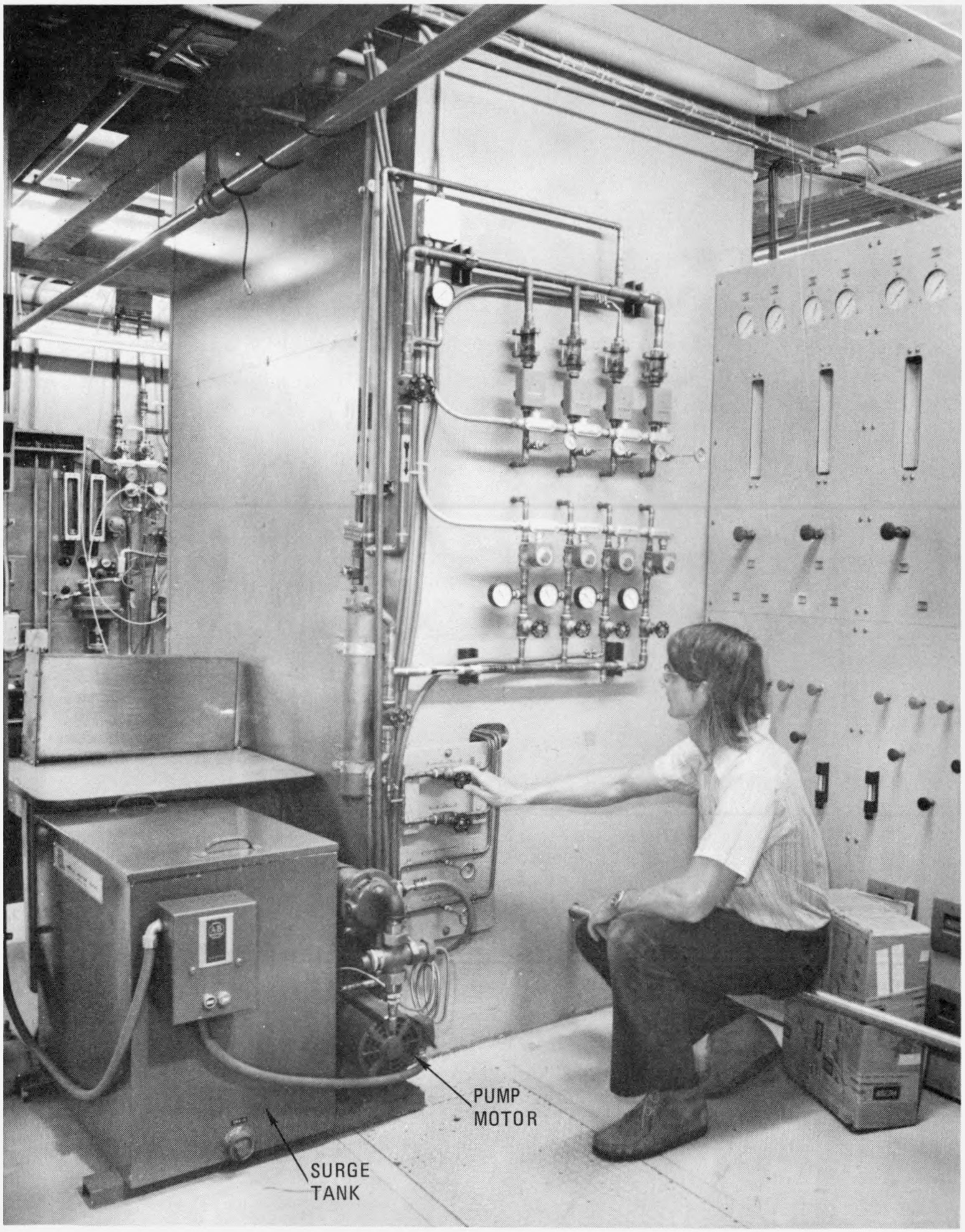


Fig. 27. Induction heater water recirculation system

2. High frequency contactors are used for absolute shutoff of high frequency current to the coil.

3. The autotransformer reduces the high frequency supply voltage to match the coil with the motor generator. It is water cooled.

4. A water-cooled capacitor is used parallel to the burner coil to electrically balance the system such that the phase angle is at a minimum and realized power is thus maximized. Water cooled copper bus bars connect it to the coil, which is also water cooled.

9.2. OPERATING EXPERIENCE

The first coil used was a 53 turn, 30 in. long solenoid coil made of 3/8 in. copper tubing. It was made by TOCCO and tuned prior to shipping to GA. The air gap between the 4 in. schedule 40 Hastelloy X tube and the coil was 0.30 in. The coil was insulated only on the outside so that the copper tubing was bare on the side towards the burner tube. The outside insulation consisted of 2 in. of Fiberfax with a stainless steel outer jacket (10 in. diameter). The end plates of the stainless jacket were 2 in. from the end coil turn. No appreciable heating of these plates was noted due to induction, only by convection and radiation from the burner tube. The coil was balanced by setting the autotransformer at a 0.8/1 turndown ratio and setting the capacitor at 154 kVA. The coil cooling water flow was 2.3 gpm.

The initial heatup rate using this coil indicated that 18 kW were being dissipated in the burner tube as heat. The remaining 12 kW were taken up by resistive losses in the coil, autotransformer, capacitor, and lead line from the motor generator set. Since these readings were taken essentially at ambient temperatures, heat losses to the surroundings were negligible. The tube could be heated to 900°C, at which time the heat losses to the coil via radiation would rise to 18 kW, thus bringing the tube temperature to a steady state.

This coil was used in burner runs 37 and 38. After combustion was stabilized with the tube at 900°C, the 18 kW of power loss to the coil with the motor generator set off was enough to remove sufficient heat even at peak burn rates to keep the tube at 900°C. Because of this ample cooling capacity, no cooling air was required in the vicinity of the coil.

The second coil was built to enable 1/8 in. of asbestos insulation to be placed between the coil and the burner tube to cut down on radiant losses. It was built with a 6.5 in. i.d. such that it could be slipped around the burner tube over the existing flanged ends. It was 28 in. long with 12 turns (the number of turns was determined by shunting to get the correct impedance) and was made of 3/8 in. copper tubing. There was a 1 in. air gap between the coil and the burner tube. The coil cooling water flow was 2.3 gpm. There was 3 in. of Fiberfax insulation outside of the coil and a 13 in. diameter stainless steel jacket holding it in place. The jacket was initially 10 in. in diameter but was suscepting too much power from the coil; therefore, it was enlarged to reduce induced power. The jacket end plates were originally stainless steel (located 2 in. from the coil end turns) which was getting very hot due to induced current from the coil. They were changed to transite, which performs well with no heating due to induction effects. The end plates are not required to be mechanically strong, only to seal the cooling air flow, so transite was acceptable.

This coil was balanced at a 0.8/1 transformer turndown and 539 kVA of capacitance. The initial heating rate with this coil indicates 12 kW being dissipated in the tube with the remainder as coil and peripheral electrical equipment resistive losses. Steady state tube temperature with this coil configuration was about 850°C, without a fluidized bed.

To check induced power in support rods required for the prototype burner design, a test was made by imbedding a thermocouple in a 1/2 in. stainless steel rod positioned 1/2 in. from the present coil. No appreciable induction heating of the rod was noted; only convective heatup was seen.

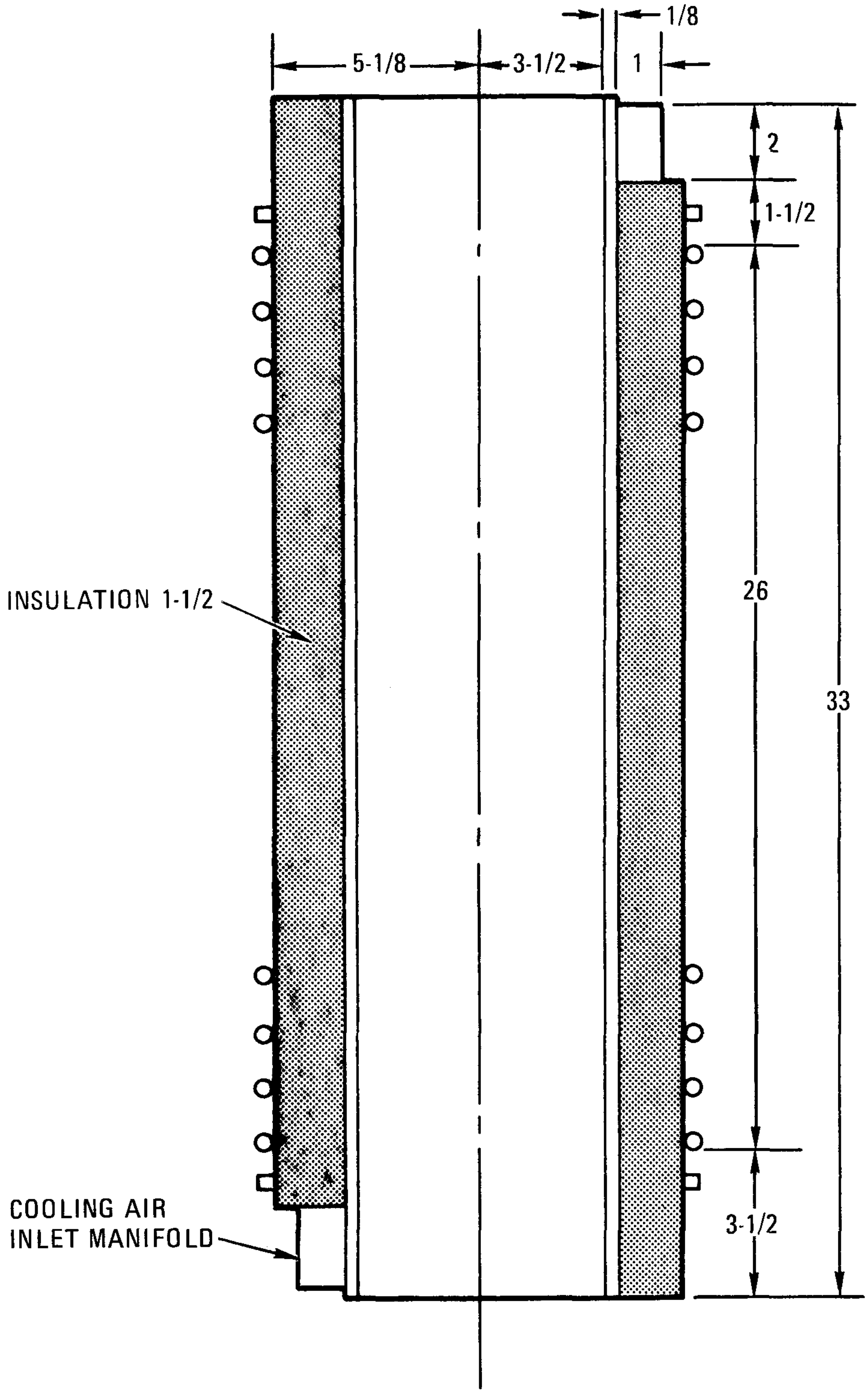
Burner runs 39 through 46 used this second coil design. It was capable of holding the bed temperature during tail burning to 800°C, yielding acceptable product carbon contents.

The present coil design is a basic departure from earlier work in that the coil now suscepts onto a cylinder that is placed concentrically around the burner tube. The old coils suscepted directly on the burner tube. This new coil was installed for the purpose of prototype design verification (both primary and secondary). The larger burner heating systems will be more efficient with an intermediate susceptor.

As shown in Fig. 28, the susceptor is a 7 in. i.d. cylinder, 34 in. long, made from 1/8 in. thick RA-333, a trade designation, with removable end plates to seal cooling air flow as well as allow removal of the susceptor over the 6-1/2 in. burner flanges. The susceptor outer surface is insulated with 1-1/2 in. of WRP-X moldable insulation (a silica type insulation); a 26 in. long, 10-turn helical induction heating coil made from 3/4 in. copper tubing surrounds the insulation. One field cutting copper coil is located at each end of the induction coil, adjacent to the end plates. These cutting coils serve to block the induction field from coupling to the end plates and dissipating heat therein.

Heating tests were made using the empty burner tube. Figure 29 shows the time-temperature plot of the susceptor and the tube.

The present heating system has been used to make three secondary burner runs (47, 48, and 49). It is capable of holding the bed at 775°C during tail burning (a period of low combustion just prior to the end of the run). This is slightly less than the second coil design, but still yields acceptable product carbon contents. The most important result of using this susceptor plate system is the data gathered to verify the prototype burner design. This data has been in the form of heatup transients and steady-state idling of the fluidized bed. It is being analyzed as applied to the



DIMENSIONS IN INCHES
○ INDUCTION COIL
□ MAGNETIC FIELD CUTTING COIL

Fig. 28. Susceptor coil assembly

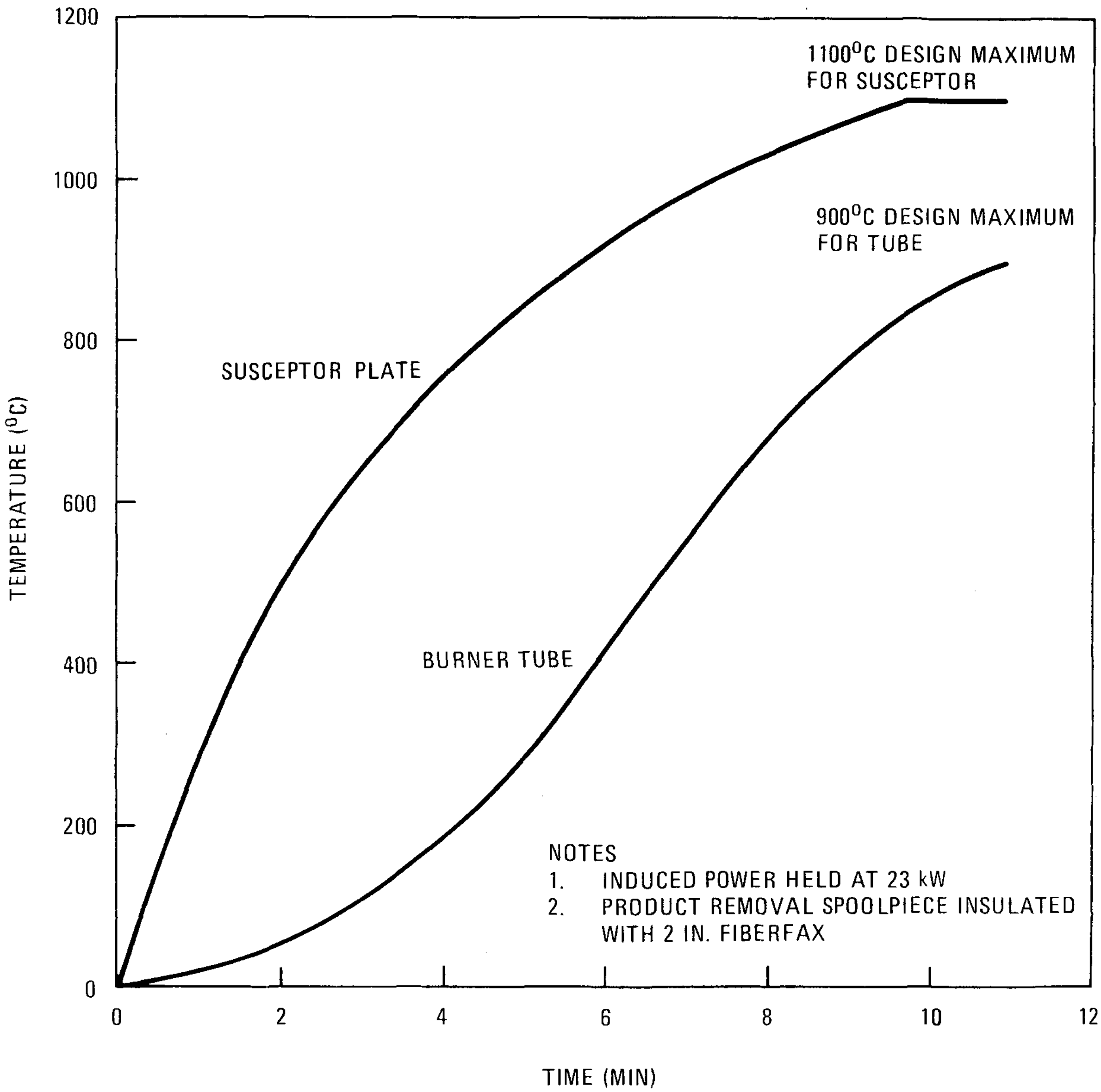


Fig. 29. Empty tube heating transient

prototype burners. Heat-transfer coefficients, burner end-losses (fines heat transport to filter areas), and induction coil design parameters (coil spacing, coil tube size, etc.) are being determined.

9.3. CONCLUSIONS AND FUTURE WORK

Induction heating has proved to be a versatile, trouble-free operation as used on the 10-cm secondary burner. Three different coil designs have all yielded workable heating rates. Support was given to the prototype design effort by the installation of a susceptor plate heating system. All indications are that there will be no problems in the use of an induction heater on larger burners.

10. HIGH TEMPERATURE BED REMOVAL SYSTEM INTEGRATED WITH A DISTRIBUTOR PLATE AND THE PNEUMATIC TRANSPORT SYSTEM

The product removal device was designed in mid-1973. It consists basically of a circular valve that seats flush with the burner wall just above the inlet gas distributor. Product flows through the valve into a pneumatic solids conveyor, which transports it to the next step in the flowsheet, the leachers.

This system has been used in 26 secondary burner runs, and several improvements have been incorporated into the design.

10.1. DESIGN

The product removal system was designed with the following features in mind:

1. Use of a distributor plate.
2. Ability to empty the burner quickly.
3. Ease of interfacing with a pneumatic transport system.
4. Minimum internal burner ledges, etc., which could create holdup.
5. Remote operability.
6. Simplicity.

The system is illustrated in Figs. 30, 31, and 32. It consists of a 1-in. exhaust valve and a mating valve seat (welded into the burner wall) from an air-cooled, spark ignition engine. The valve is opened and closed by a double acting pneumatic cylinder. The valve stem is supported by a standard valve guide equipped with a nitrogen purged seal.

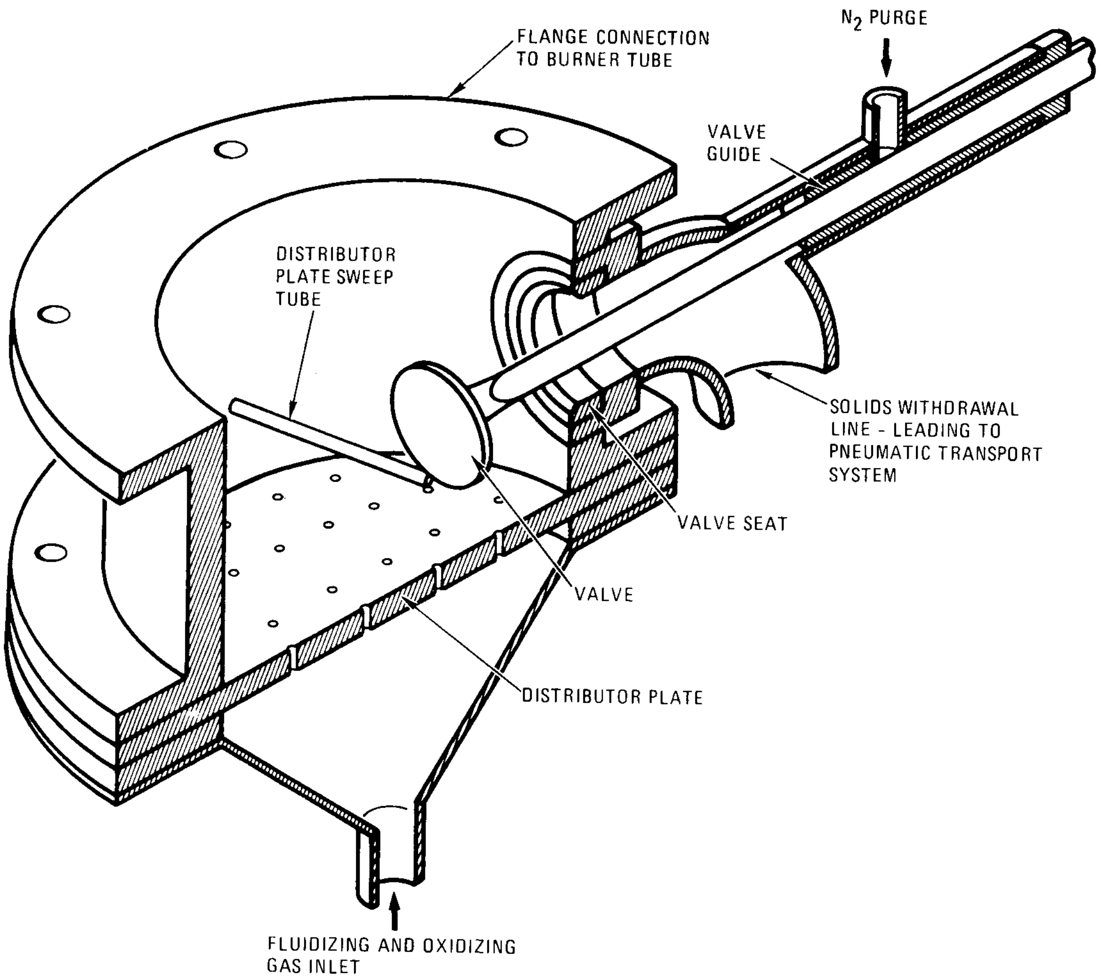
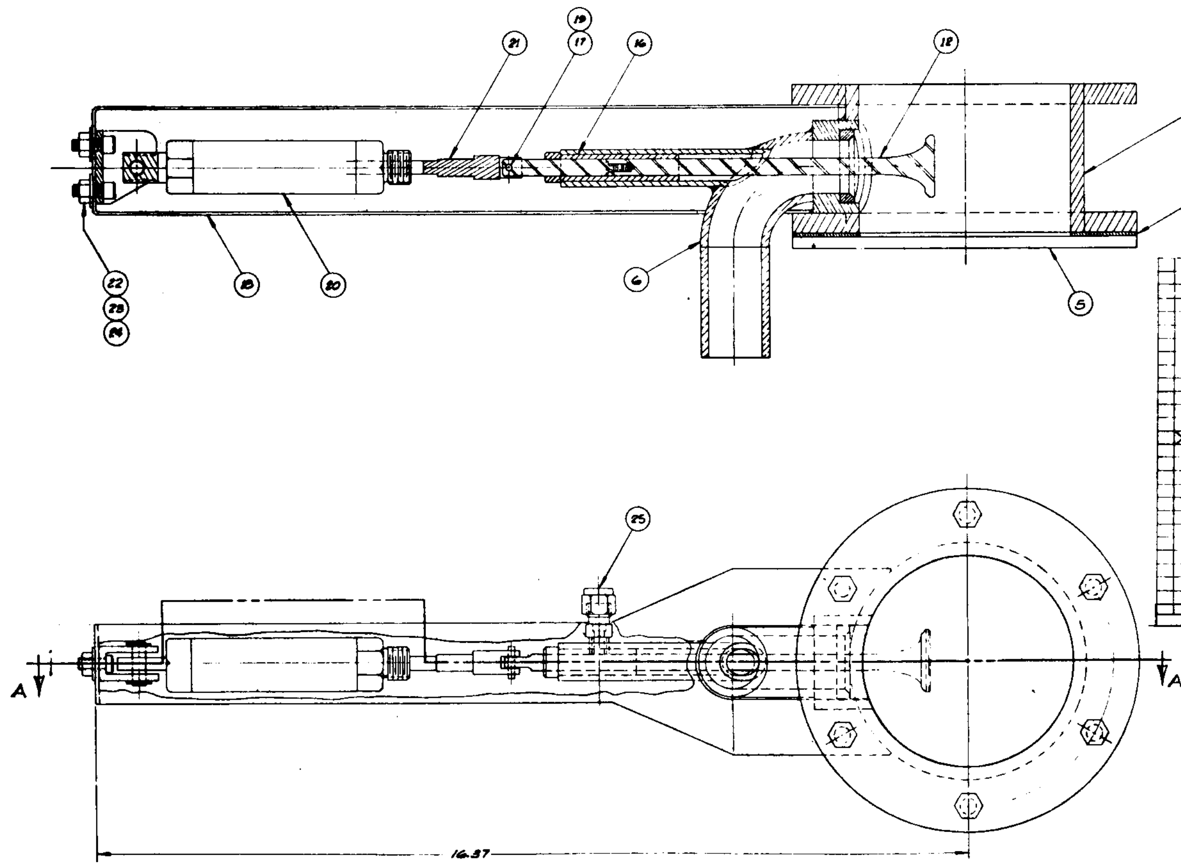


Fig. 30. High temperature bed removal system for 10-cm secondary fluidized bed burner



Required	Item	Part No.	Description	Mat'l	Mat'l Spec
1	-25	220002-25	SWAGELOK FITTING 1/4 TUBE TO 1/8 NPT		316 SST
2	-24	-24	HEX NUT 1/4-20		
2	-23	-23	WASHER, 1/4" PLAIN		
2	-22	-22	BOLT 1/4-20 × 1/2 LG		
1	-21	-21	VALVE ACTUATOR EXTENSION 1/2 DIA × 1 5/16		DRILL ROD
1	-20	-20	VALVE ACTUATOR (DIGIT AIR CYL. FTM 3/4-2)		
2	-19	-19	RETAINER RING		
1	-18	-18	SUPPORT BRACKET 1/16 PLATE		304L SST
1	-17	-17	PIN 5/16 DIA × 5/8 LG		DRILL ROD
1	-16	-16	VALVE GUIDE (MODIFY), REPCO		115-109-4016
1	-15	-15	VALVE EXTENSION, 5/16 DIA × 2 1/2 LG		DRILL ROD
1	-14	-14	VALVE EXTENSION, 5/16 DIA × 2 3/8 LG		DRILL ROD
1	-13	-13	VALVE, REPCO (MODIFY)		118-109-612
X, 1	-12	-12	VALVE ASSY		
1	-11	-11	GUIDE LOCATOR, 3/4 DIA × 2 7/8 LG		304L SST
1	-10	-10	PIPE, 1 IPS × 2 1/4 LG SCH 40S		
1	-9	-9	ELBOW, 1 IPS × 90° SCH 40S		
1	-8	-8	VALVE SEAT, 1.380 DIA × 11/32 LG		WELLTITE W1701
1	-7	-7	PIPE BOSS, 1.150 DIA × 1 1/4 LG		304L SST
X, 1	-6	220002-6	DUMP VALVE WELDMENT		
1	-5	220003-1	DISTRIBUTOR PLATE		
1	-4	220002-4	GASKET		
2	-3	-3	FLANGE, 6.50 DIA × 3/8 THK HASTELLOY X		AMS-5536
1	-2	-2	TUBE, 4 IPS SCH 40S × 2 3/4 LG		
X, 1	-1	220002-1	BODY WELDMENT		
X	-1	220002	BURNER DUMP VALVE ASSY		

LIST OF MATERIAL

Fig. 31. Secondary burner dump valve assembly

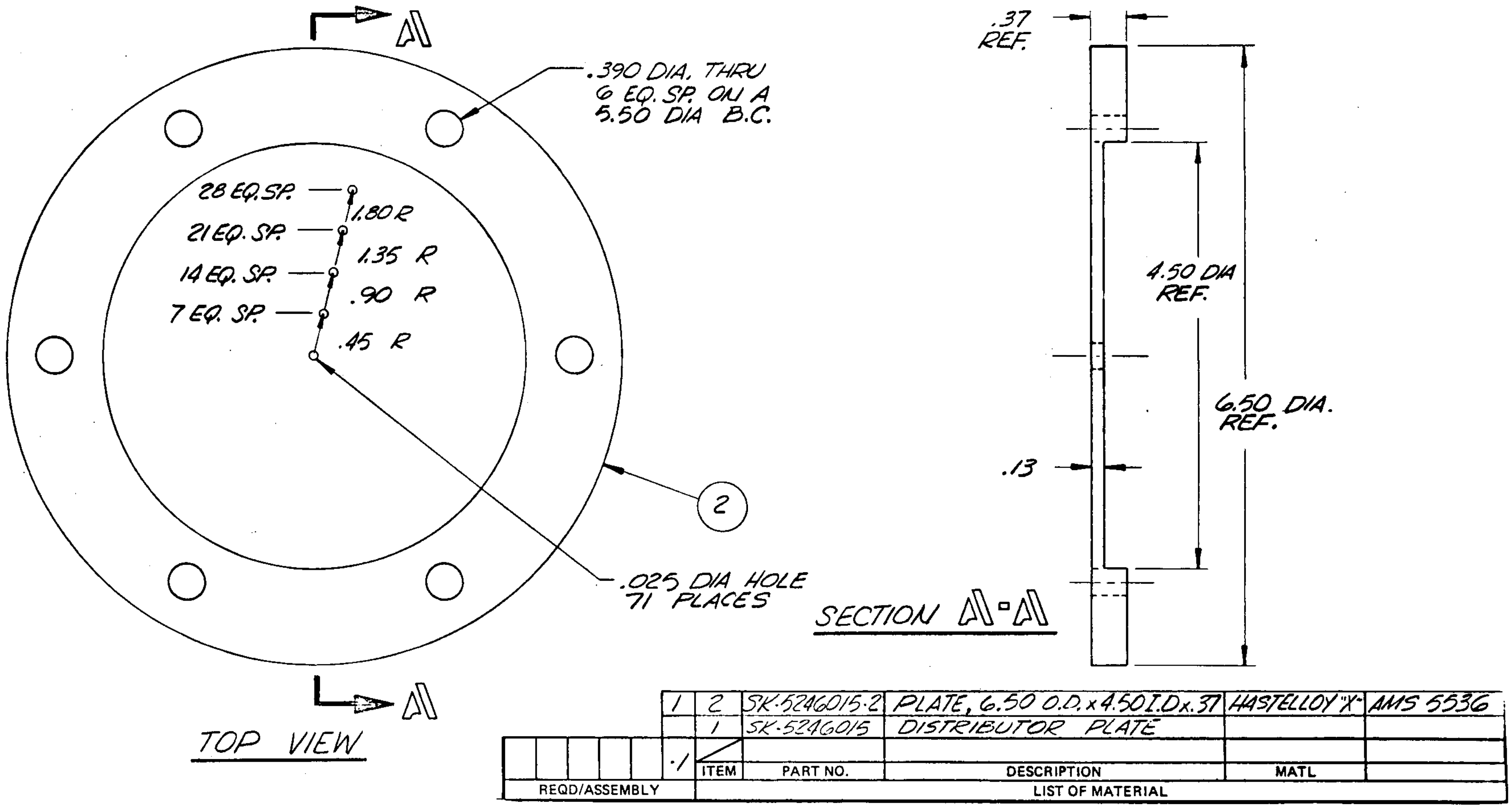


Fig. 32. Secondary burner distributor plate

All materials exposed to high temperatures are Hastelloy X with the exception of the product valve and seat, which are forged Stellite.

The distributor plate is shown in Fig. 32. Its design is based on the methods presented in Ref. 5. The general criterion is for the pressure drop across the plate to be the maximum of (1) 10% of the bed pressure drop, 35 cm H_2O, or (2) 100 times the pressure drop encountered in gas expansion into the distributor plenum. The maximum is calculated to be 35 cm H_2O. Evolution of the distributor plate design is discussed in the next section. A flow versus pressure drop curve for the distributor plate is shown in Fig. 33.

The product removal transporter is a vacuum type for two reasons:

1. Vacuum transport is inherently cleaner than pressure transport because leaks will not cause material to be sprayed about as a pressure transporter would.

2. Burner cleanout through the product removal valve will be aided by the slightly negative pressure at the valve outlet.

Operation of the system includes letting the product flow essentially by gravity through the partially opened product valve into a moving air stream as shown in Fig. 34. When about 90% of the product has been removed, the product valve is opened fully (2 in.), the distributor plate sweep (discussed in the following section) is actuated, and the air supply valve is closed. This causes the transport air to be drawn through the burner product valve, effecting a positive air sweep through the burner tube and valve.

The transport line is horizontal for 13 ft then runs vertically 17 ft followed by a 10-ft horizontal run into the filter receiver. Tube turns are short radius (6 in.) in all cases. The transport pump is a 150 scfm positive displacement type with a maximum suction vacuum of 15 in. Hg

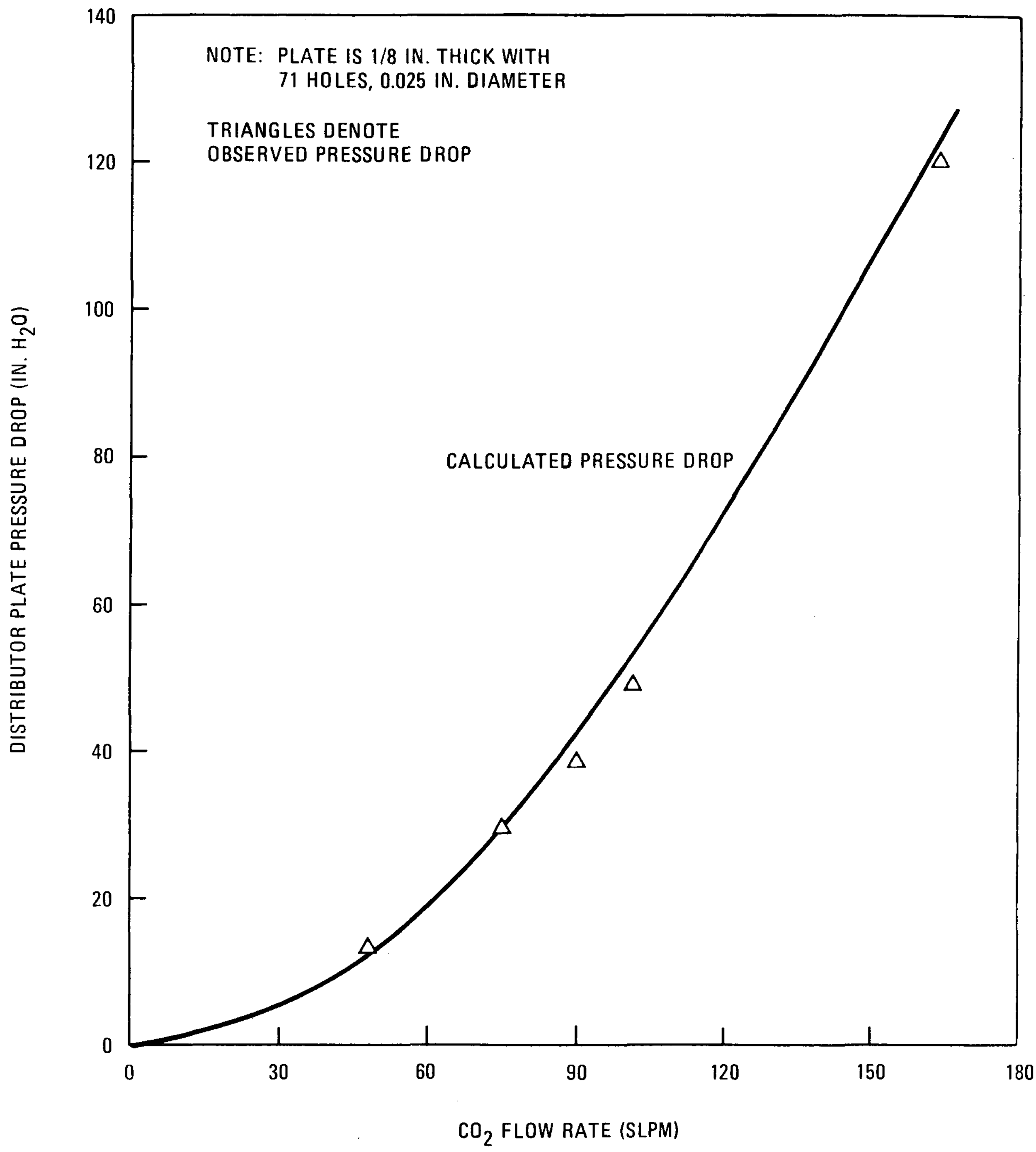
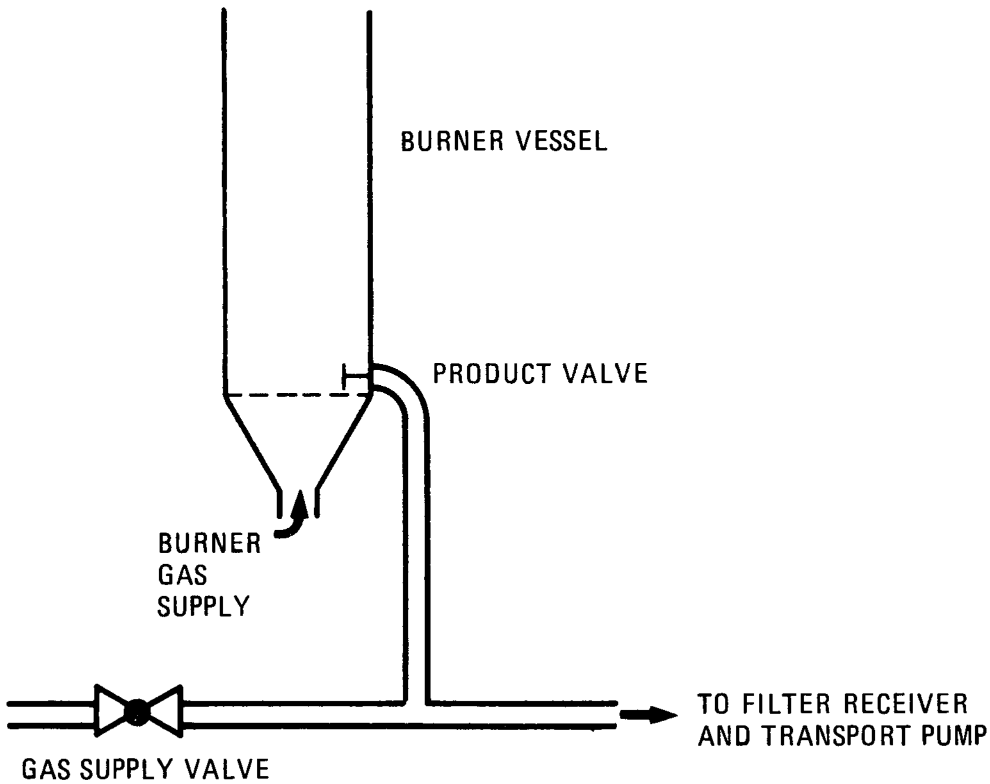


Fig. 33. Ten-centimeter secondary burner distributor plate flow-pressure drop characteristics



THE GAS SUPPLY VALVE IS OPEN DURING REMOVAL OF INITIAL ∿90% OF PRODUCT TO GIVE SUFFICIENT AIR FLOW, AND IS CLOSED DURING CLEAN OUT OPERATION TO GIVE A POSITIVE AIR SWEEP THROUGH THE BURNER TUBE AND PRODUCT VALVE.

Fig. 34. Product removal operational modes

(limited due to pump cooling requirements). Line size is 1-1/2 in. giving a superficial line velocity of 150 ft/sec when the pump suction is at 8 in. Hg and 100 ft/sec when the pump section is at 14 in. Hg. The system is shown in Figs. 35 and 36.

10.2. BURNER RUN OPERATING EXPERIENCE

The first 13 burner runs, made using the high temperature bed removal valve, took place before the pneumatic transport system was installed. Data from these runs is therefore related only to distributor plate performance as the bed removal valve is designed for use with a pneumatic transporter.

In the first two runs, a plate with 21 holes (1/16 in. diameter) was used. This gave good burning characteristics with no hot spots noted. When the bed was removed by gravity through the product valve, a heel of about 2500 g remained that was pierced by jetting holes from the distributor plate and therefore defluidized. A wire mesh laminate was then tried as a distributor, but thermal stresses buckled it during the burner run. Returning to a drilled distributor plate, the jetting behavior was reduced by increasing the number of holes (to 71) and decreasing the diameter (to 0.025 in.) to reduce the jet strength of each hole. The heel with this plate averaged 830 g in six runs (high of 1589 g, low of 403 g).

A distributor plate burnthrough occurred during one startup. The burner at that time had a resistance heater which necessitated low burner gas flow (0.6 ft/sec) at startup to achieve the minimum ignition temperature. This low flow led to stagnation and a hot spot burned through the plate. The induction heater was then installed with reasonable startup flows allowed (2 ft/sec). There have been no further startup problems due to poor heat removal capabilities.

This distributor plate failure did not damage the product removal valve section at all. Replacement of the plate served to repair the burner. Also,

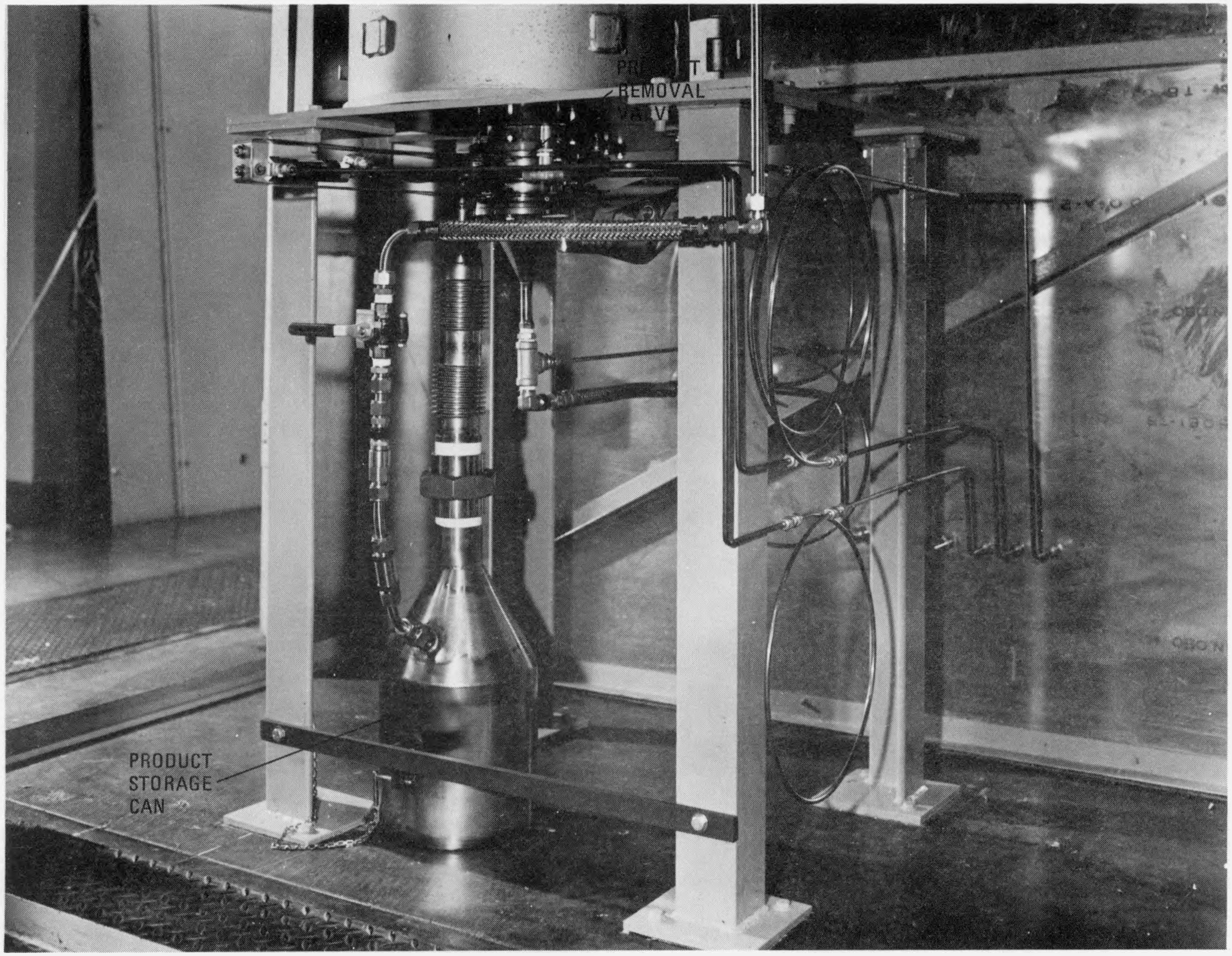


Fig. 35. Secondary burner product removal valve prior to pneumatic transporter installation

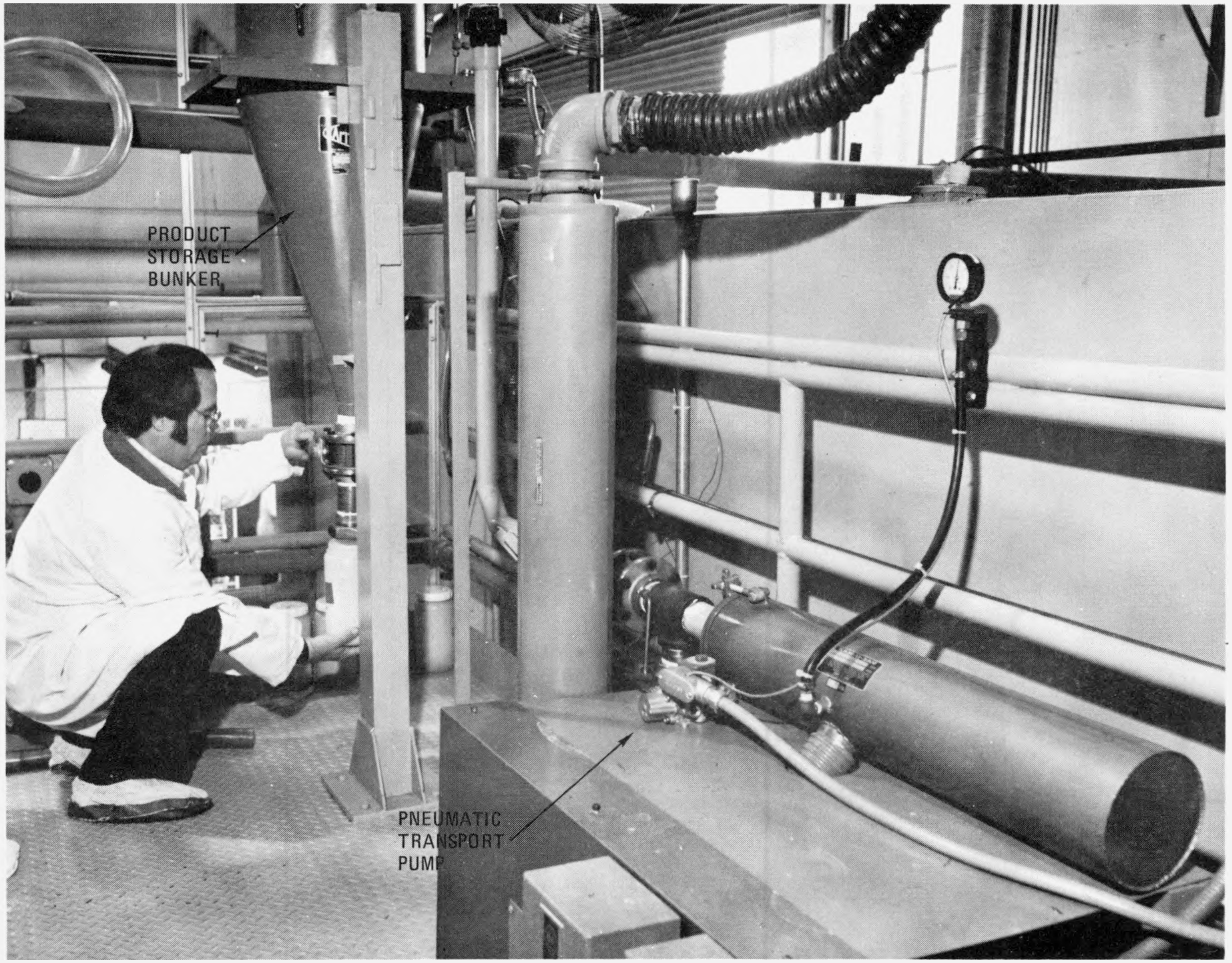


Fig. 36. Pneumatic transport system components

while making a batch primary burner run, a burnthrough of the product removal spoolpiece occurred due to bed stagnation. In spite of extensive damage to the burner wall adjacent to the product valve, it was still operable and seated smoothly. From this it can be seen that the burner valve assembly will withstand the temperature extremes encountered during burner upset conditions.

The pneumatic transporter was then installed and has been used in all subsequent runs. It was found that opening the product valve fully resulted in an excessive solids-to-air ratio, and choking occurred in the vertical sections of the transport tube.

The valve was then tried at a variety of initial openings (1/8 in. to 3/8 in.) for the bulk of product removal, followed by opening the valve fully in each case for burner heel cleanout. Openings of 3/16 in. and smaller were found to be subject to bridging of the product as it tried to exit through the valve. Openings of 3/8 in. and larger were found to cause too high of a solids-to-air ratio, resulting in choking flow in the vertical transport tube. Initial openings of 1/4 in. were found to be satisfactory throughout seven separate runs. The bulk of the bed is removed in the first several minutes through the 1/4 in. opening.

Burner heel cleanout is accomplished using a gas sweep nozzle arrangement penetrating the burner tube above the plate (see Fig. 30). A 1/4 in. o.d. x 1/8 in. i.d. tube is welded closed on one end and swaged into place perpendicular to and at the same elevation as the valve stem, parallel to the distributor plate and crossing the burner tube centerline. High-pressure (80 psig) gas is routed through 15 holes (1/32 in. diameter) in the sweep tube yielding a total flow of 400 slpm. They are arranged such that five holes point straight down and the other 10 point at 45° either way from straight down; they are equally spaced across the burner diameter.

This distributor plate sweep is actuated in discrete 2-sec pulses when the product valve is opened fully (2 in.). The heel (averaging 800 g as noted earlier) is blown up into the burner and flows through the product valve to the transporter in dilute phase transport. In the eight runs using the sweep, the distributor plate was completely cleaned off. The only heel remaining in the burner is a dust precoat on the filters and the dust clinging to the vessel walls.

In four of the last runs, the product was transported through the 1/4 in. valve opening for varying time durations prior to full opening for cleanout. In all cases 5 minutes of heel cleanout time was used (with the valve opened fully and the sweep used).

In the first run, 93% of the product (about 11 kg total) was removed in 5 minutes, but 84% was removed in the second run in 5 minutes. During the third run, 90% was removed in 2 minutes, with 74% removed in 1 minute on the fourth run. It appears that 2 minutes gives sufficient time for the bulk of the product to be removed, and 5 minutes is adequate for heel removal. This 7 minutes is small compared to 2 to 3 hour batch cycle times.

These numbers indicate that the product is removed at about 5-6 kg/min during the initial product removal stages with a 1/4 in. valve opening.

The vacuum-pneumatic transport system operates with a total pressure drop of about 14 in. Hg during the initial dump operations (with loadings of about 2 lb solid/lb air). The pressure drop during the initial stage is broken down as follows:

Air flow in transport tube	2 in. Hg
Solids transport in transport tube	5 in. Hg
Main filters	4 in. Hg
Pump prefilter	3 in. Hg
	14 in. Hg

When the system is transporting the final heel, with a negligible loading, the total pressure drop is about 8 in. Hg as follows:

Air flow in transport tube	2 in. Hg
Main filters	3 in. Hg
Pump prefilter	3 in. Hg
	8 in. Hg

Plans are to test secondary burner product pneumatic transport on a test rig. Saltation velocities, choking loadings, pressure drops, wear rates, etc. will be determined for this material. Product removal with larger transport lines will be tried to lower the solids/air ratio, enabling larger initial product valve openings. Product receivers representative of prototype design will be used on this system.

10.3. CONCLUSIONS AND RECOMMENDATIONS

The high-temperature bed removal system incorporating a valve and seat arrangement in the burner tube, a flat multiorifice distributor plate with a sweep provision, and a vacuum pneumatic transport system is capable of rapid and complete batch bed removal at high temperature. It does not interfere with normal burner operation and does not permit any ledges or pockets of static material since it is flush with the internal diameter of the tube. It is well suited to remote operations and has only one moving part, yielding high mechanical reliability. It is therefore recommended for future use on larger scale burners by direct scaleup.

11. AUTOMATIC CONTROL SYSTEM

The 10-cm secondary burner was operated manually during many runs. When the operating mode became sufficiently well known, automation of the batch cycle was begun in steps. The first steps were to test individual control loops, leaving other systems in a manual mode. At present, all the control loops are used in each burner run. They are operated from the central control room shown in Fig. 37. This report documents the hardware these systems require, their performance during burner runs, and an alternative that has been considered.

11.1. OPERATING CYCLE

The secondary burner operates as a batch combustor, burning an initial bed of crushed fuel particles to a low carbon ash of ThO_2 and SiC.

The basic operating steps are:

1. Preheat. Preheat the burner tube to 900°C with a 40 slpm CO_2 purge. Actuate filter blowback.

2. Feed. Add the crushed feed using the gravity pneumatic feeder.

3. Startup. When the bed heats to 700°C, introduce O_2 as a ramp from 40 to 100 slpm in a 6-min period. Decrease CO_2 flow to 0.

4. Main Burn. Control the bed temperature at 900°C using cooling air flow modulation. Filter chamber cooling air is on demand (when filter temperature is >400°C).

5. Tail Burn. Change inlet flows to 60 slpm O_2 and 40 slpm CO_2 when the bed begins to burn out as evidenced by a drop in off-gas

Fig. 37. Control room - secondary burner panel is in the center

CO concentration below 2%. Hold bed temperature as close to 900°C as possible.

6. Shutdown. When the bed is sufficiently low in carbon (as seen by the balance of O_2 in = O_2 out), switch to pure CO_2 inlet flow and cool the bed to 500°C.

7. Cleanout. Pneumatically transport the product through the high temperature bed removal system. Include burner cleanout procedures to remove heel from distributor plate surface.

11.2. TEMPERATURE CONTROLS

The heating and cooling instrumentation is illustrated in Fig. 38. The heater is actuated to bring the burner tube to 900°C without raising the susceptor temperature over 1100°C or the bed temperature above 900°C. There are 15°C deadbands on the temperature setpoints. Thus, the bed is held as close to 900°C as possible using induction power whenever it is required throughout the run.

Burner cooling is on demand when the bed temperature exceeds 900°C. This cooling system holds the bed to a 20°C overshoot when it is actuated in a run.

Filter cooling is actuated when the filter temperature is above 400°C, which is generally during the entire main burning portion of the run.

11.3. GAS FLOW CONTROLS

The gas inlet flow is controlled at preset values and is changed as discussed in the operating cycle. For example, when the bed is heated to 700°C, the flow changes to allow an O_2 ramping procedure for startup. The flow control system is shown schematically in Fig. 39. In practice, this system keeps the flows at the preset levels ±2 slpm, which is more than sufficient accuracy. Typical gas flows are shown in Fig. 40.

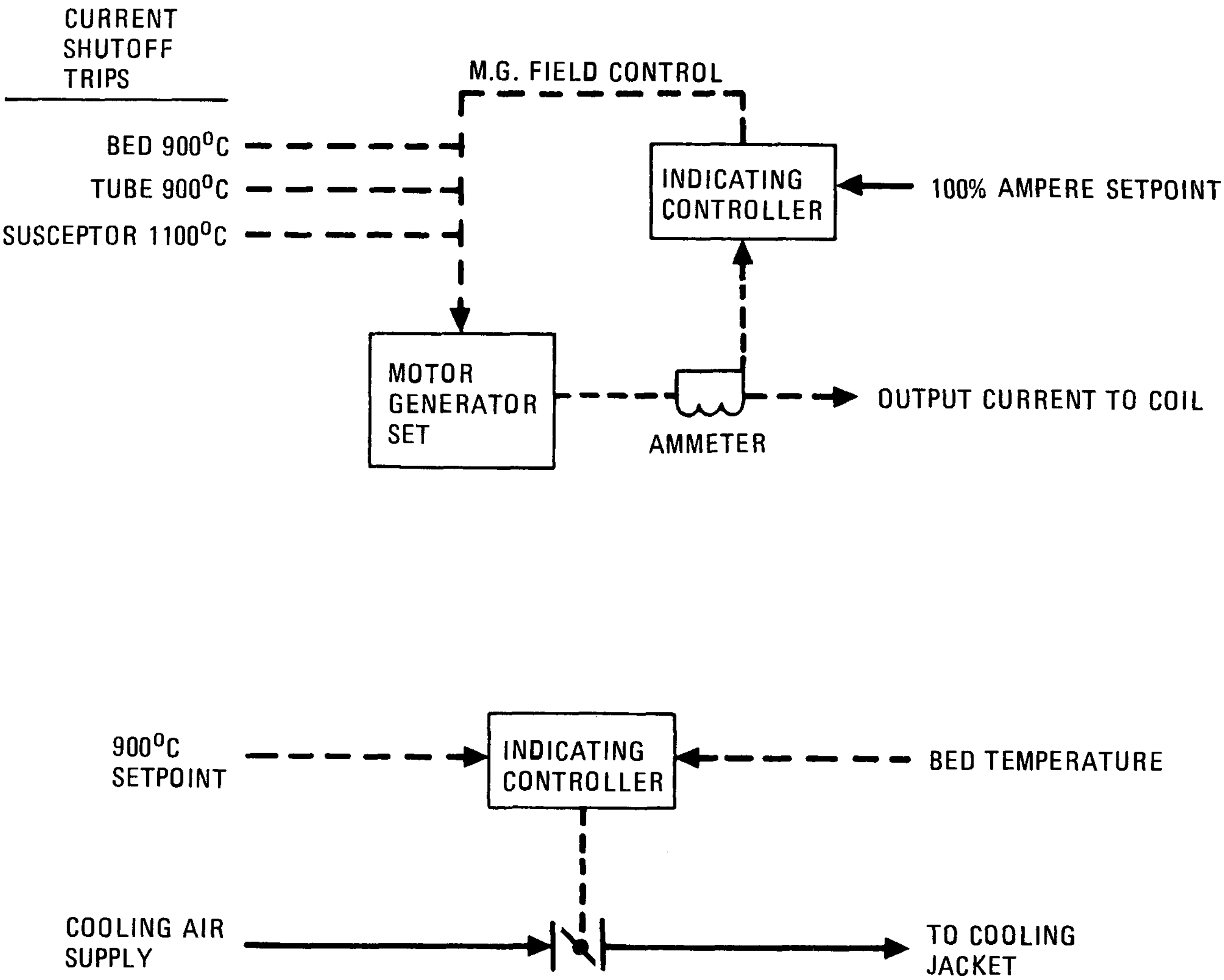
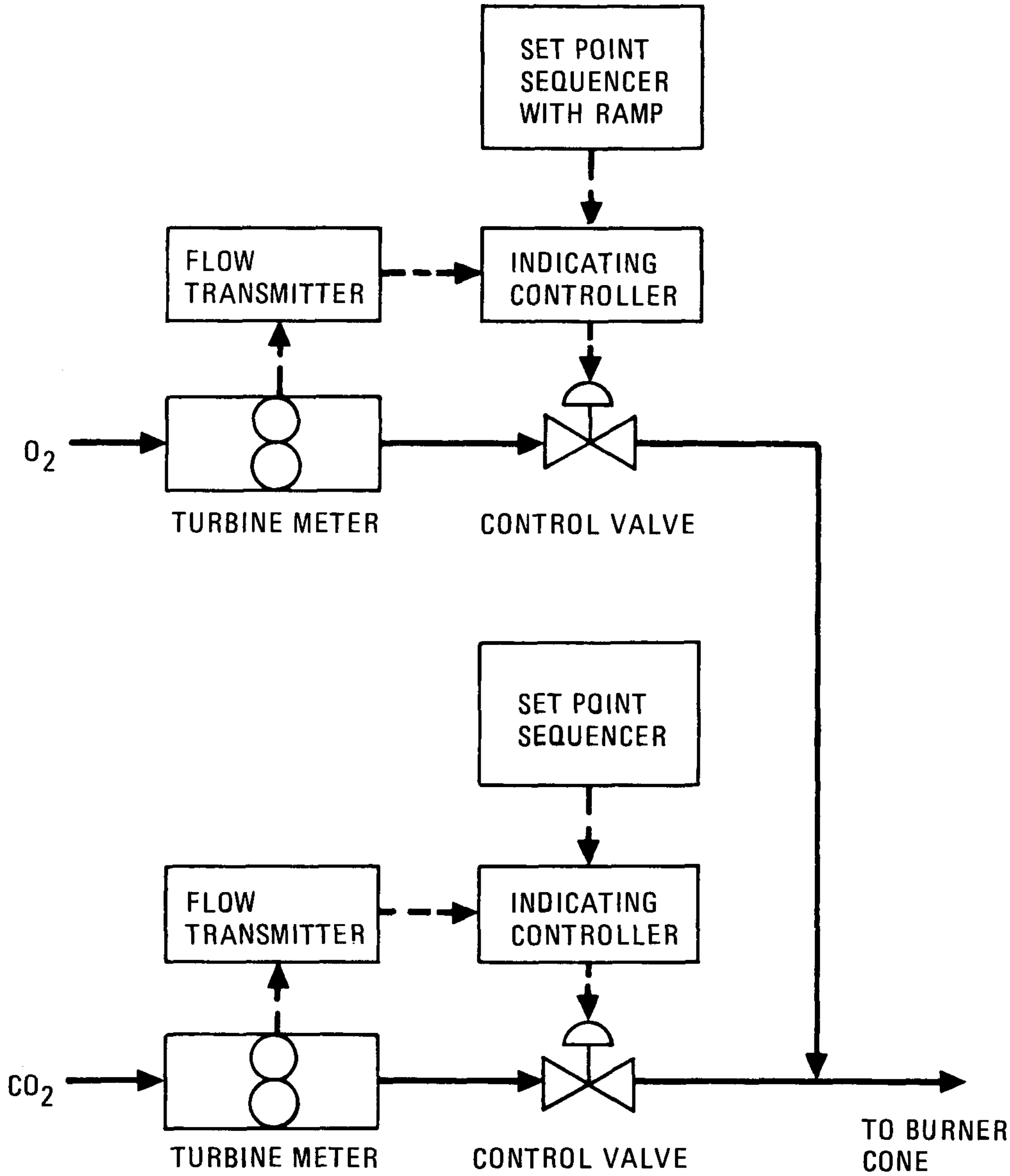


Fig. 38. Heating and cooling controls



NOTE: SET POINT SEQUENCERS ARE ACTUATED BY TRIPS INDICATING IGNITION, MAIN BURN, TAIL BURN, SHUTDOWN, ETC. – THIS YIELDS PRESET FLOWS OF EACH GAS TO THE BURNER.

Fig. 39. Gas flow controls

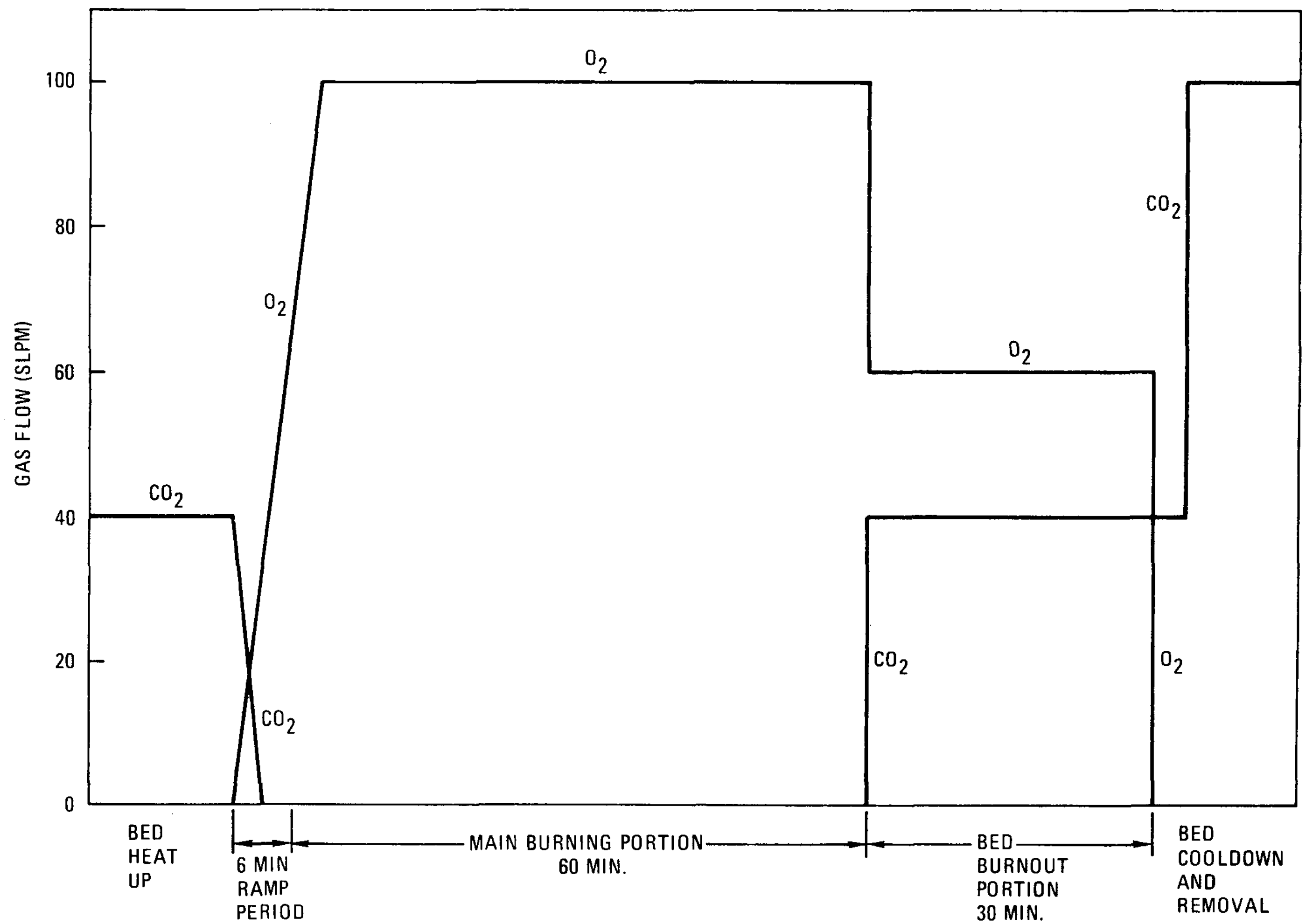


Fig. 40. Typical inlet gas flows

11.4. AUXILIARY SYSTEMS

The filter blowback system consists of two timers; one sets the blowback pulse duration (1 sec) while the other sets the frequency of blowback (6 cycles per min).

Feeding the burner requires actuating the gas flows required for feeder operation for preset times (2 min). It also requires opening and closing the appropriate ball valves for feed hopper isolation.

Removal of product requires a cycle of actuating the pneumatic transport pump, opening the product valve, and performing steps for burner cleanout.

Although these three systems are presently actuated manually, they can be adapted to use automatic cycle timers.

11.5. ACTUAL OPERATING EXPERIENCE

Burner run 49 was made using automatic gas flow systems as well as the automatic heating and cooling systems. Auxiliary systems were manually actuated as discussed earlier.

The gas flows in the run deviated a maximum of ±1 slpm. This type of system is expected to work well as it is a simple feedback situation.

The heating control system kept the output amperage from the induction heater power supply at 100% during all demand periods. The temperature of the susceptor will normally affect this amperage as much as 20-30% if not controlled suitably. The susceptor temperature controlled the heating demand during the tube preheat portion of the run. The burner wall controlled the demand during bed heating and ignition. Cooling was called for intermittently through the main burn portion. The bed temperature kept the induction heater deenergized during that period. In tail burning, the susceptor was the limiting temperature.

There were no problems encountered throughout the run, indicating the suitability of the system during normal operation. Should a problem develop, adequate means are available for correction. If a bed temperature were to rise above 900°C, the cooling air would keep increasing until the bed temperature decreased. An output of 30% cooling air is capable of cooling the bed 50°C per minute. Full cooling should result in bed cooling rates of at least 100°C per minute. Bed temperatures over 950°C actuate an alarm so that appropriate operator action may be taken.

11.6. ALTERNATIVE CONTROL MODES

The only other control mode considered was the oxygen flow-bed temperature feedback loop, as used on the primary burner. It has the advantage of a faster response to temperature upsets and it may even be faster than is actually necessary.

The startup must still be coordinated via an O_2 ramping mode, in this case followed by switching to temperature feedback control of O_2 after ignition. During the tail burning portion, the temperature feedback would have to be terminated to avoid driving O_2 flow to maximum when the temperature falls off. This feedback O_2 control would thus be operable only during the main burning portion.

Burner cooling would have to be fixed with incremental adjustments possible if the temperature could not be held at 900°C by O_2 flow alone.

The induction heating system would be identical to the present system. Inlet CO_2 flow would be controlled in a similar manner to that presently used. The only real difference is that during the main burn portion, bed temperature would be controlled by O_2 flow instead of by cooling air flow. Because this has not been shown to be required (upsets should be self correcting at a workable speed with the present system) and because changing control modes in the middle of the run is a complication, that method is not used or recommended.

11.7. CONCLUSIONS

The 10-cm secondary burner automatic control system has been selected as the most desirable of two options. It has worked well whenever used in making burner runs and will be used in future experimental plans. It is being incorporated, in principle, in the prototype secondary design with no problem areas anticipated.

12. REPRESENTATIVE BURNER RUN

Based on the development work to date, secondary burner run 49 accurately represents the recommended operating mode. The operating procedure used for the run is included in Appendix A.

The run was made to test several improvements as follows:

1. CO_2 inert gas was used instead of N_2.

2. A prototype sized feeder was used.

3. An 18 in. filter chamber extension was installed, and more frequent blowback pulses were used; these two changes significantly reduced filter pressure drop.

4. Completely automatic heating and cooling systems were used throughout the run.

5. Pure O_2 fluidizing gas was used during the main burning portion.

All of these improvements lived up to expectations, yielding a very smooth stable run with final product containing <0.1% burnable carbon.

12.1. FEED

A 14 kg batch of TRISO fertile particles was crushed through a double roll particle crusher system yielding product with a size distribution as shown in Fig. 41. Other physical properties of the material are also listed in Fig. 41.

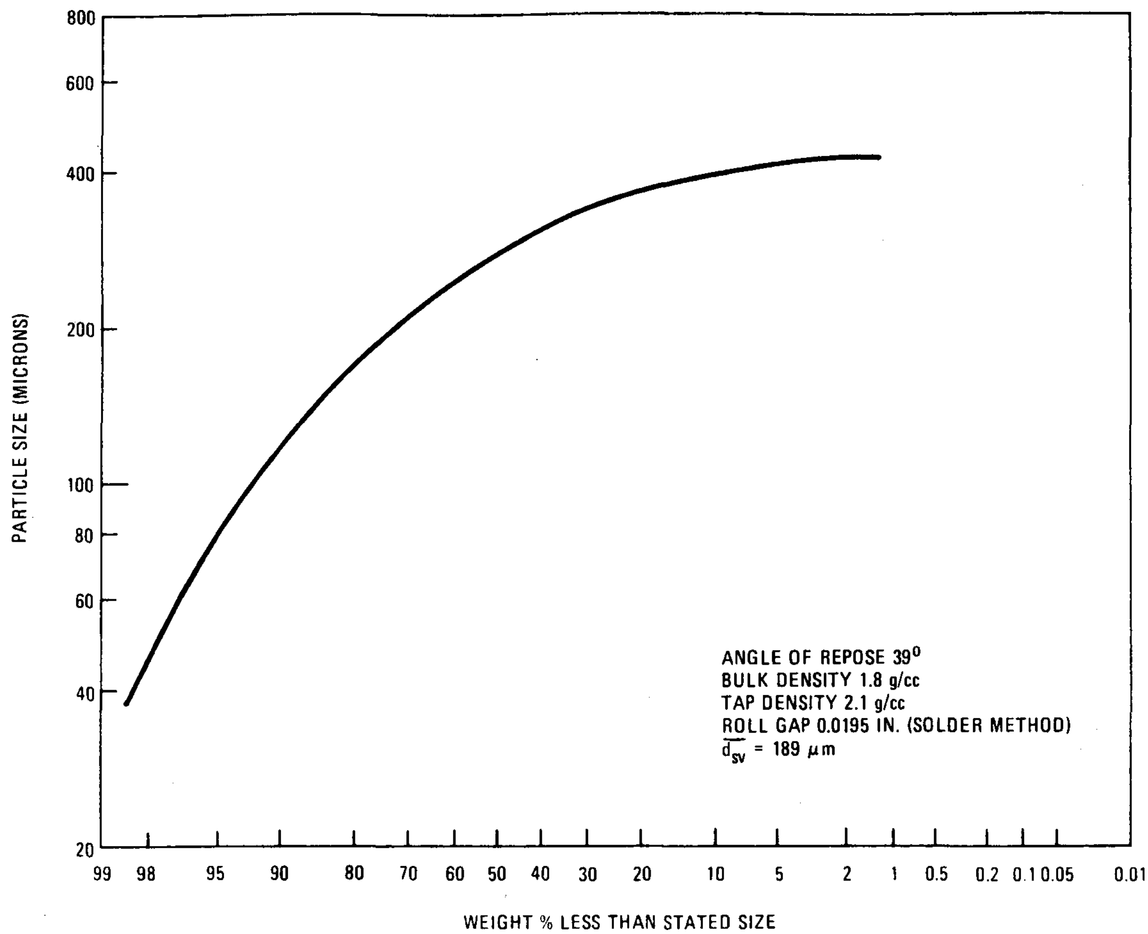


Fig. 41. Size distribution for run 49 feed

12.2. COMBUSTION

Figures 42 through 46 contain time plots of burn rate, gas flow, temperature, L/D, and off-gas composition.

The burner tube was preheated to 900°C using a completely automatic temperature control system. This system modulates the induction coil power output to control the susceptor temperature, the burner wall temperature, and the fluidized bed temperature within preset limits (in this case 1100°C, 900°C, and 900°C, respectively, with 15°C deadbands).

With a 40 slpm purge of CO_2 passing through the burner tube, the feeder was actuated to introduce the crushed particle bed to the burner. The feeder is identical in both type and size to the one specified for the prototype secondary burner. This feeder performed well and will be used in all future runs.

The bed was then heated to 700°C followed by ignition. Oxygen flow was automatically ramped to 100 slpm over a 6 min period. The burner cooling air rate was automatically controlled to keep the bed temperature at 900°C. Twenty minutes after ignition, the CO_2 flow through the burner was terminated, leaving only a pure O_2 flow at the inlet. This mode of operation was continued throughout the main burning portion of the run.

No significant change was noticed when changing to pure O_2 flow. The filter cooled slightly due to the decreased superficial velocity. The filter pressure drop also decreased for the same reason. These are normal indications of lower velocity. There was no O_2 in the off-gas and no bed temperature transients. All of these findings indicate no problem with the use of a pure O_2 inlet gas during the main burning portion of the run.

The filters were blown back every 10 sec with a 1 sec pulse of 50 psig CO_2. To reduce filter pressure drop the filter chamber length was increased 18 in., the blowback frequency was increased, and the superficial velocity was decreased.

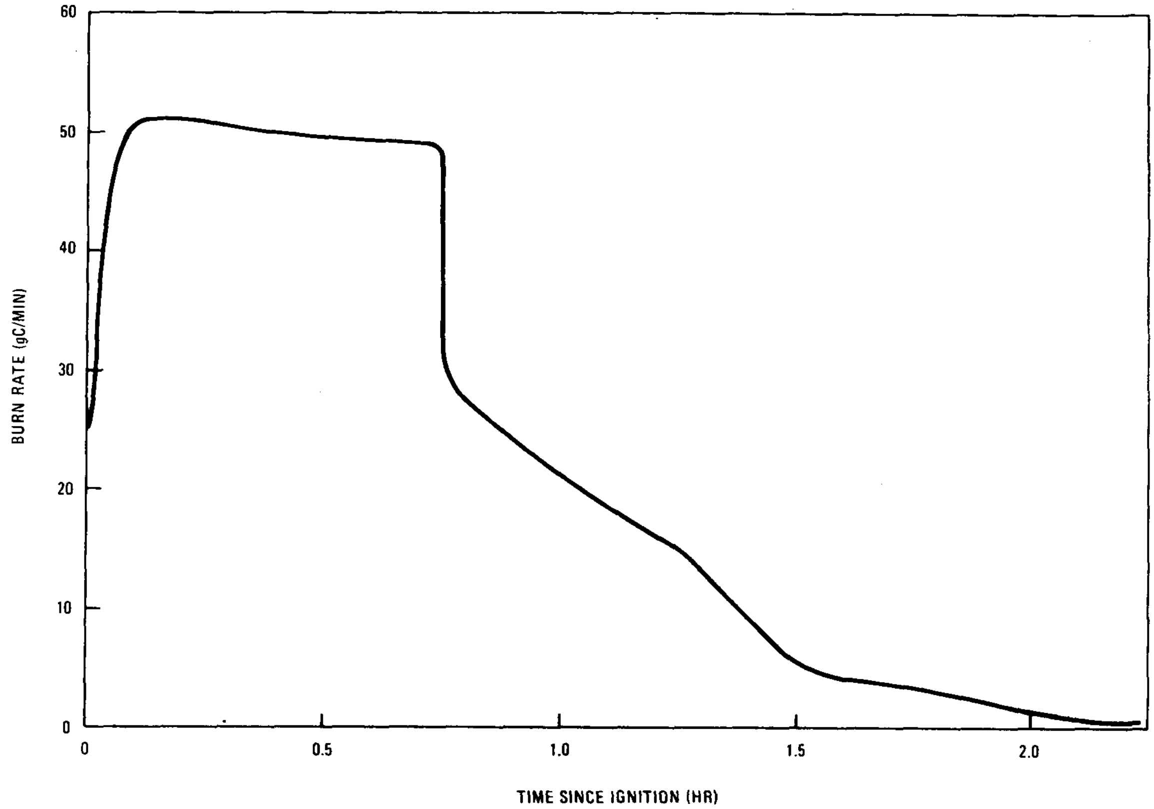


Fig. 42. Carbon burn rate - run 49

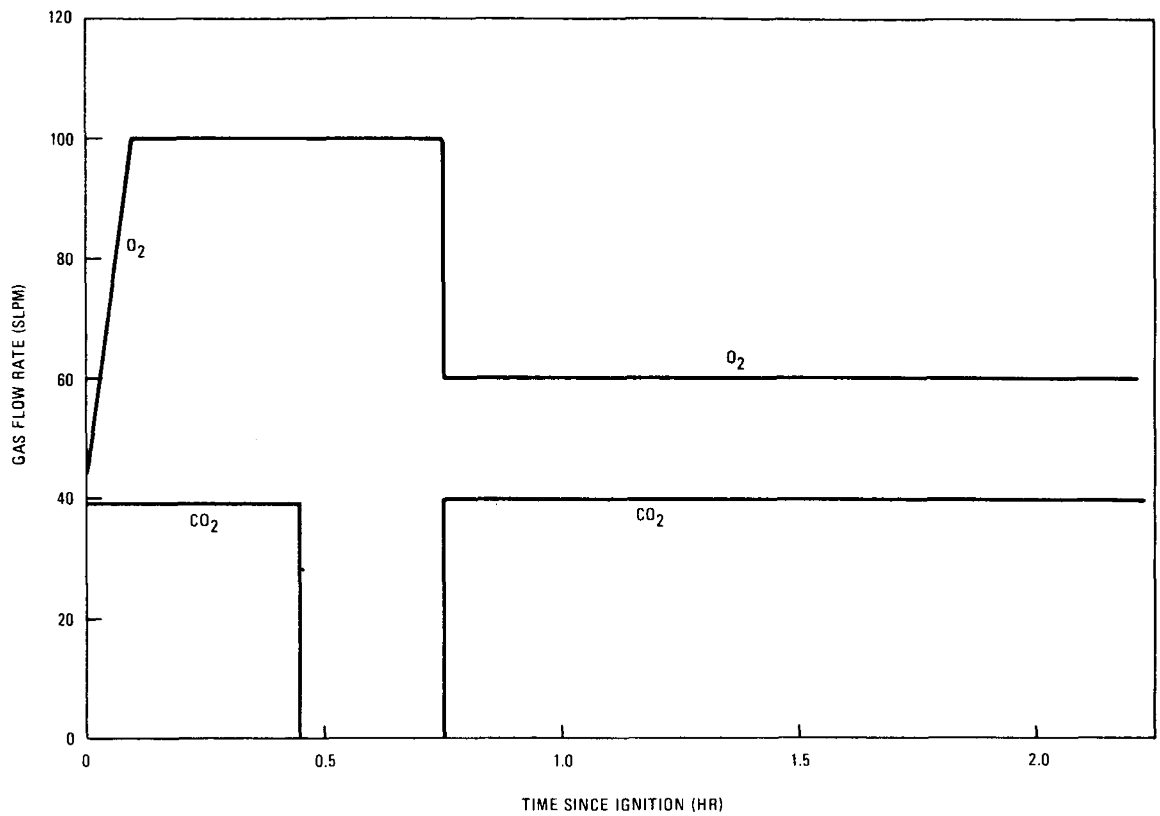


Fig. 43. Inlet gas flow - run 49

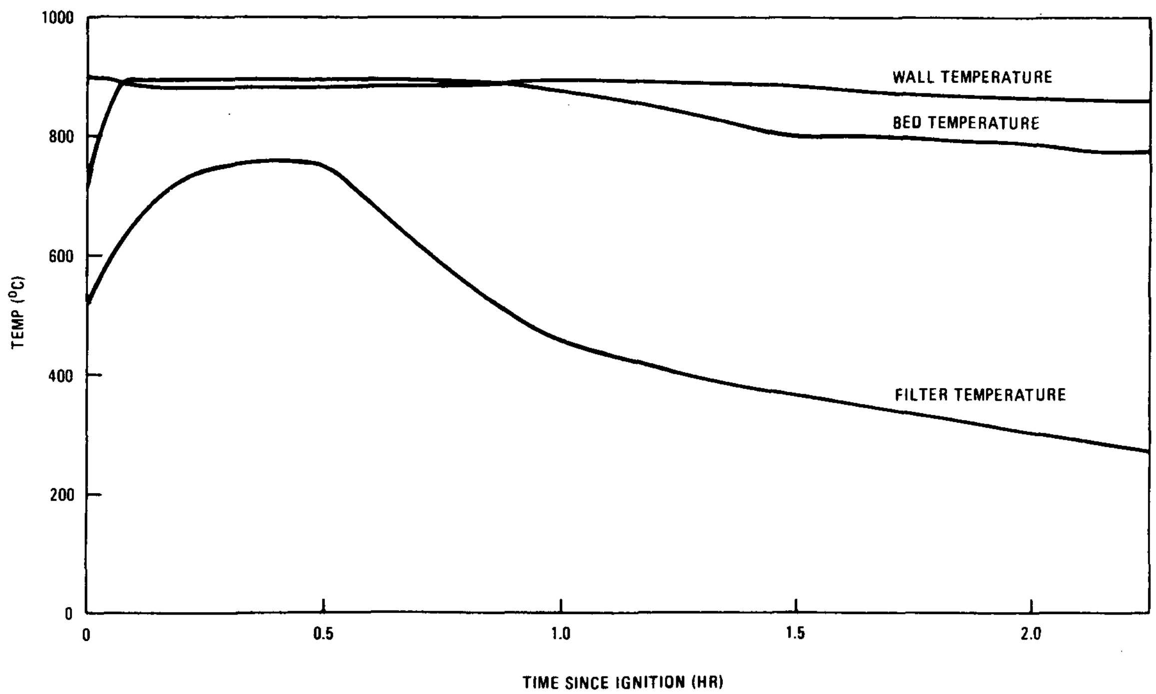


Fig. 44. Burner temperatures - run 49

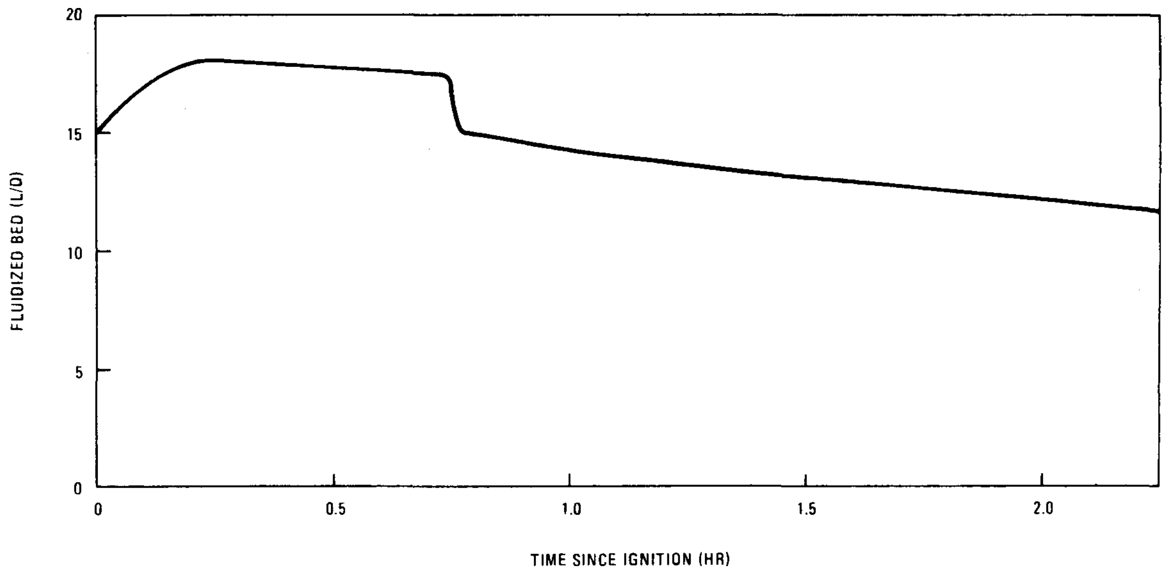


Fig. 45. **Fluidized bed L/D - run 49**

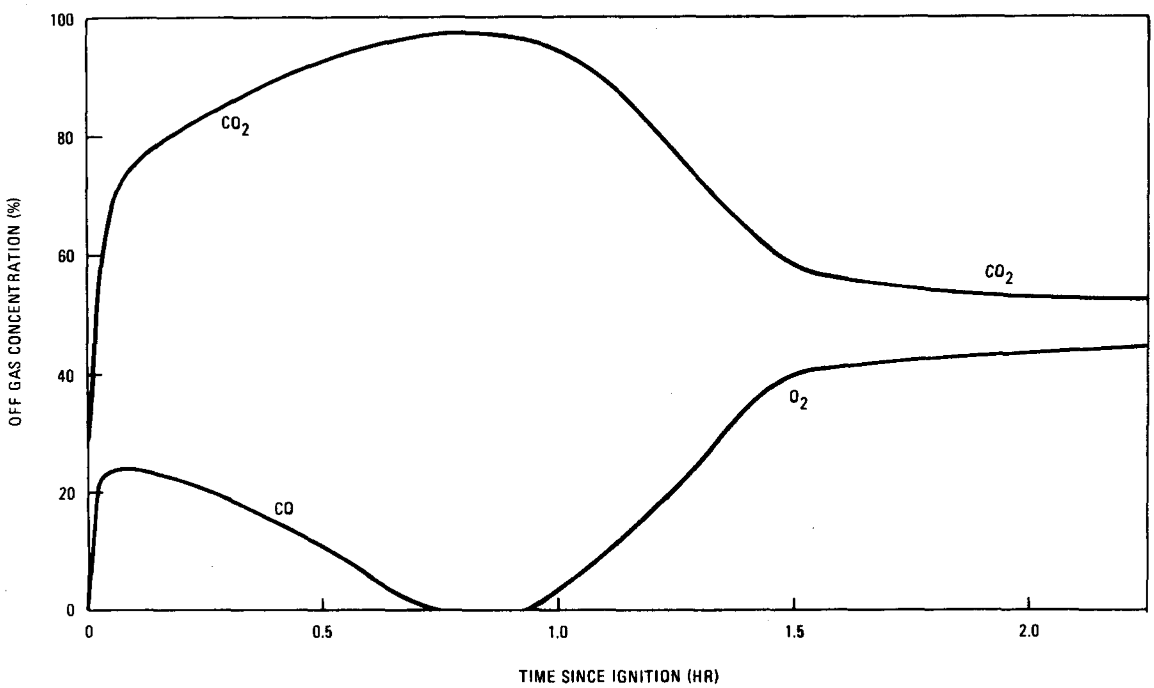


Fig. 46. Off-gas composition - run 49

The observed filter pressure drop during the main burning portion was 10 in. H_2O when the total flow was 140 slpm and 4 in. H_2O when the total flow was 100 slpm. This is about one-half the pressure drop encountered in previous runs at these same flows. This procedure will therefore be used in the future to keep filter pressure drop down to these low levels.

The tail burning portion of the run was begun when the off-gas CO content fell to 2%. Inlet gas flows were then changed to 60 slpm O_2 and 40 slpm CO_2. Filter chamber vibrators were actuated every minute to help return fines to the bed. The heating system again automatically controlled temperature. Just before shutdown, with the burner wall controlled at 900°C, the fluidized bed was at 775°C.

The bed was transported after cooling to 500°C. Bed removal and burner cleanout was accomplished in 5 min.

12.3. PRODUCT

The product had a size distribution as shown in Fig. 47. Other physical properties are also listed in Fig. 47. No burnable carbon could be detected by a tray burning technique. This indicates the carbon level is less than 0.1%.

12.4. FUTURE WORK

As indicated above, all of the changes made in this run have yielded favorable results. Future runs will concentrate on gathering Hastelloy X off-gas filter operating data, running heat transients to support the prototype design effort, and finalizing the overall control system.

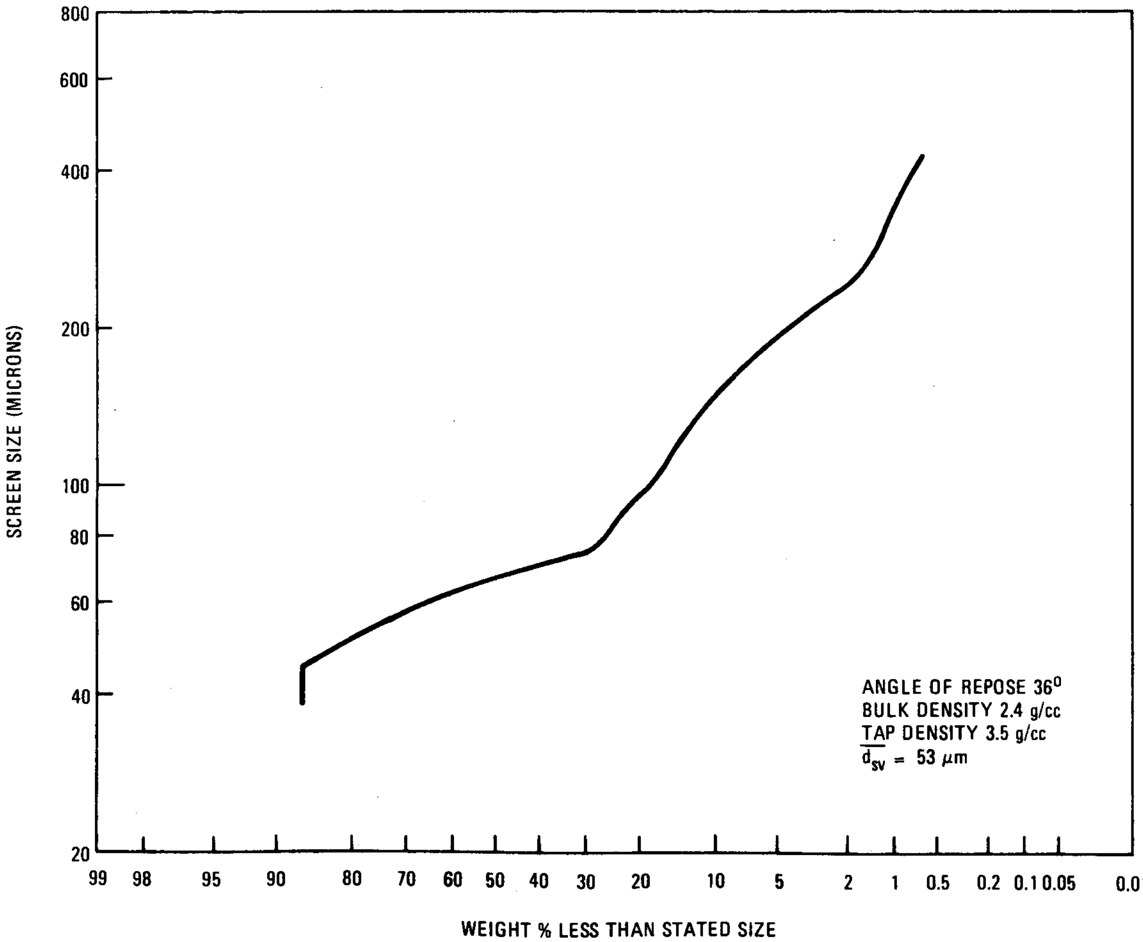


Fig. 47. Size distribution for run 49 product

13. PROTOTYPE BURNER DESIGN

The prototype design effort is summarized in Tables 5 and 6 and Figs. 48 through 50.

The burner vessel is divided into five sections: the gas plenum, the burning section, the disengaging section, the in-vessel filter chamber, and the plenum to accommodate the filter blowback nozzles and off-gas exit. The disengaging section and the filter chamber are constructed as one piece; the other sections can be separated by the semi-remotely operated flange assemblies, shown as clamps 1, 2, and 3 in Fig. 48.

Peaucellier cells will be utilized for burner alignment. They are to be attached to the inlet gas plenum.

The feeder is a nominal 1-1/2 in. gravity pneumatic type, as described in Section 3. Crushed feed is provided by a double-roll crusher now being designed.

The heater is an induction type with an intermediate susceptor that radiates energy to the burner wall. Details of such a system are described in Section 9.

Control of the prototype secondary is accomplished by administrative manipulation of inlet gas flow based on run progress indicator trips. Temperature control is accomplished by automatic induction heating and annular cooling air supplies. They are regulated by bed temperature and serve to keep that temperature at 900°C throughout the burning cycle. In addition, the control system limits the susceptor to 1100°C and the bed and wall to 900°C.

Six Hastelloy X sintered metal filters are divided into three groups, each group having two filters. Each group is separated from the other groups by baffles. The three groups of filters will be backblown sequentially. The physical dimensions of the filter are given in Table 5.

The product removal system consists of a 1 in. valve flush with the burner wall located just above the distributor plate. It is coupled with a flat perforated distributor plate, a distributor plate sweep tube, and a vacuum-pneumatic transport system. They are all identical in concept to the system used on the 10 cm secondary. Performance characteristics are discussed in the product removal development section.

TABLE 5
SINTERED METAL FILTERS

Material	Hastelloy X
Total surface area	13.8 ft^2
Diameter	3 in.
Length	36 in.
Thickness	1/8 in.
Mean pore size	5 μm (Grade H)
Nominal removal ratings (98%)	0.4 μm
Absolute removal ratings (100%)	1.0 μm

TABLE 6
PROTOTYPE SECONDARY BURNER DESIGN CONDITIONS

Burner main vessel	
Average burn rate	Minimum 1 FE/hr (50 g C/min)
Design temperature	900°C
Design pressure	Maximum 20 psia
Startup	By induction heating
Cooling	Wall cooling by forced air
Operational mode	Batch
Charge/cycle	60 kg
Solid transport	Pneumatic
Fluidizing gas	Oxygen
Diluent gas	CO_2
Burner components	
Feed hopper, maximum 24 psia	<450°C
Cooling shroud, -10 in. WG[a] to 5 psig	900°C
Off-gas filter	700°C

[a] Water gauge.

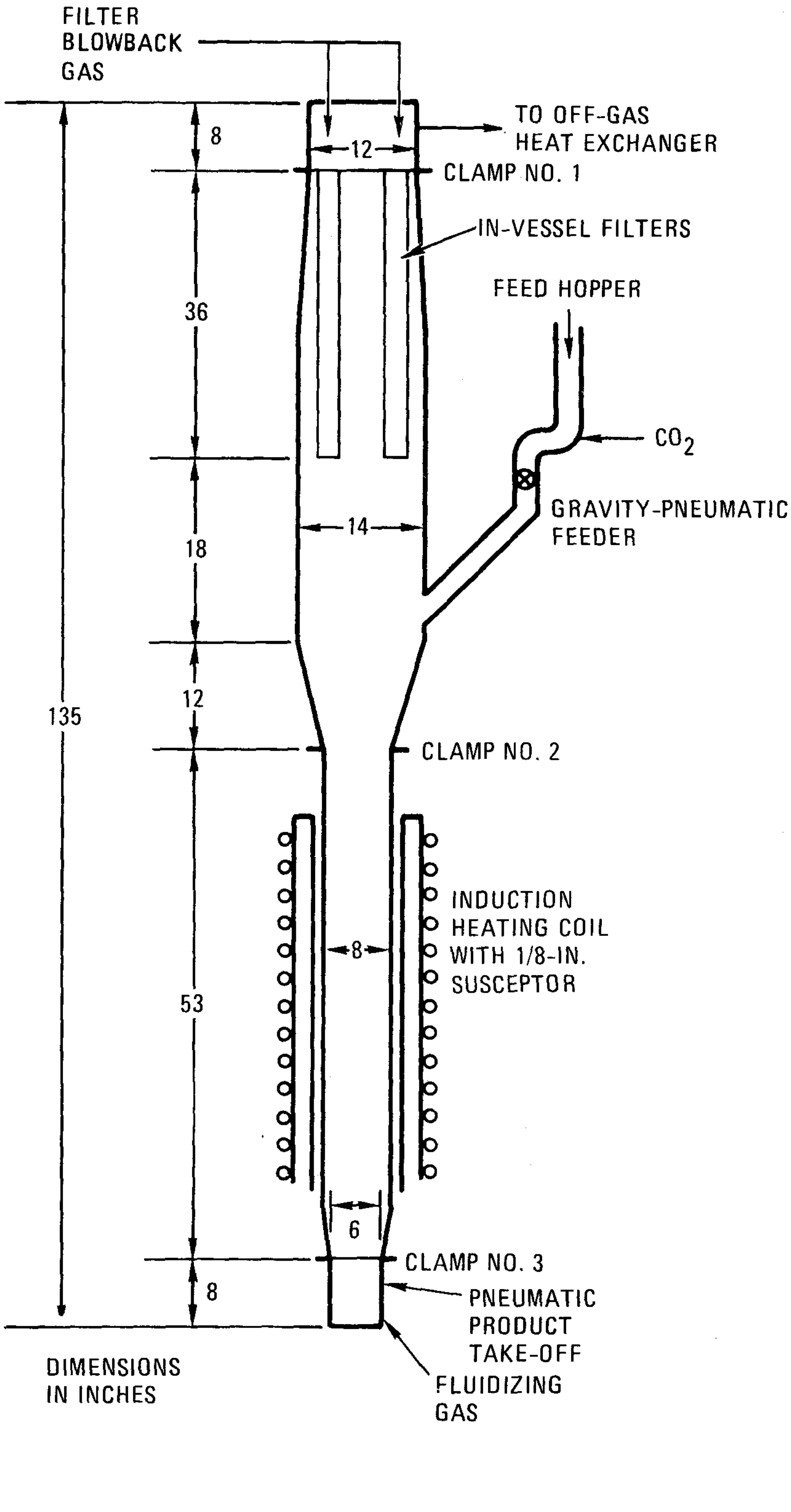


Fig. 48. Twenty-centimeter secondary burner prototype

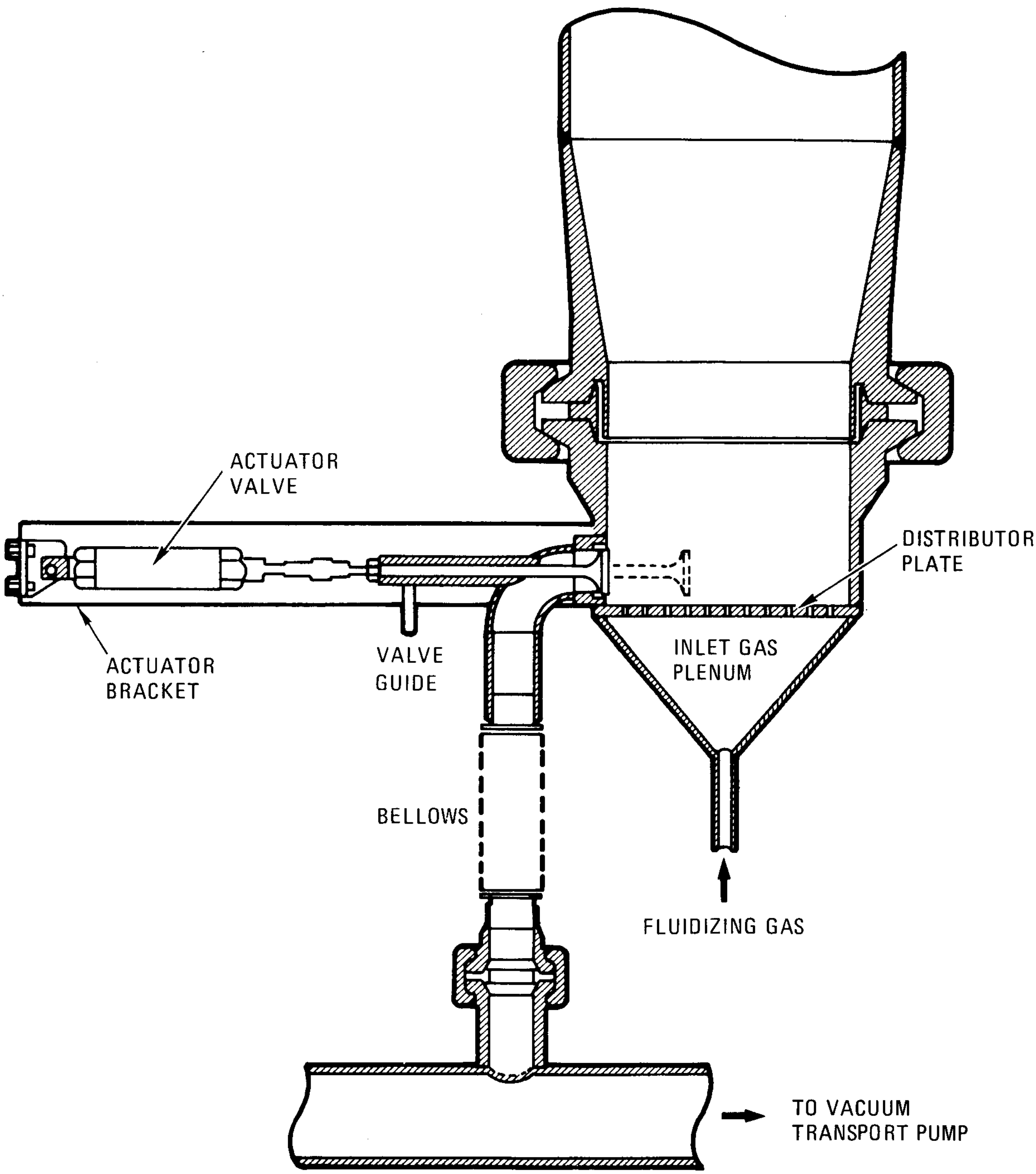


Fig. 49. Secondary burner product removal valve

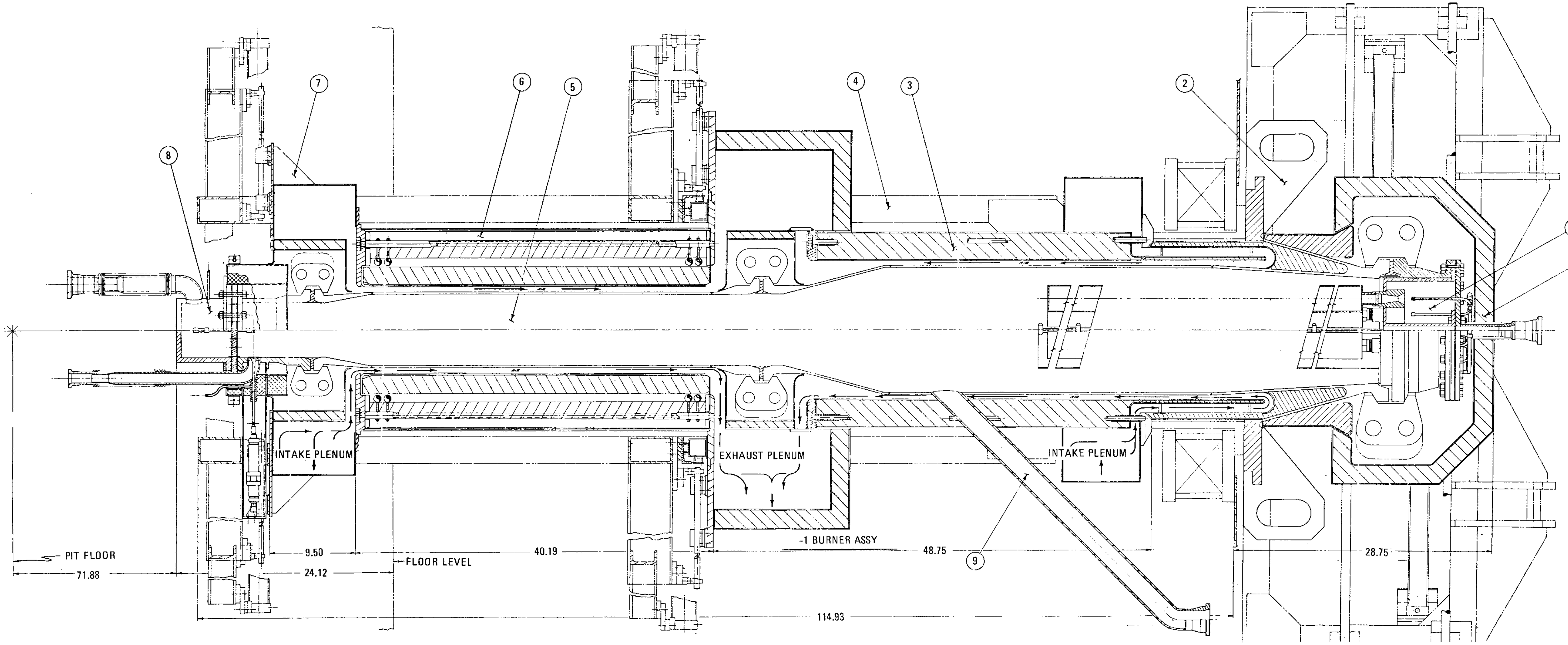


Fig. 50. Overall view of prototype secondary burner

14. SUMMARY AND RECOMMENDATIONS

Development work on the 10-cm secondary burner has led to a number of concepts that are recommended for use in future burner designs. They include:

1. A gravity pneumatic feeder for rapid bed addition without moving parts.

2. A flat perforated distributor plate for effective inlet gas deployment leading to proper fluidization conditions.

3. Feed should consist of crushed fuel particles without any added inerts. The crushing operation should yield the largest average size possible while breaking the desired percentage of particles.

4. An in-vessel off-gas filter located directly above the fluidized bed, with a sufficiently long disengaging section to reduce filter fines loadings.

5. An induction heating system for quick startup capability coupled with the ability to hold the bed at temperature during the final burning portion.

6. A side penetration product removal valve coupled with a distributor plate sweep and vacuum pneumatic product transporter for complete removal of burner ash at the end of each batch cycle.

7. Automatic burner control with administrative setting of inlet gas flow. Bed temperature should be modulated by demand control of induction heating and air jacket cooling.

APPENDIX A

OPERATING PROCEDURES

10 CM SECONDARY BURNER OPERATING PROCEDURE

I. General

A. Procedures for feed preparation, induction heater operation, gas analyzer calibration, and product analysis are referred to in the following summary. These procedures may be found in this binder for easy reference.

(1) Familiarity with these procedures and a good working knowledge of the burner are required to operate the burner. W. S. Rickman, T. D. Wright and R. C. Proppe are presently qualified to operate the burner.

(2) A run outline will be prepared before each run that lists objectives, parameters, etc.

B. A piping diagram is maintained in the drafting room.

C. A wiring diagram is maintained by the electrician.

II. Emergency Shutdown

A. Shut off the oxygen flow.

B. Switch gas flow to 100 lpm CO_2.

C. Shut off the induction heater.

(1) Shut off high frequency contactors.

D. Actuate the cooling air system at full flow.

E. Immediately contact a qualified burner operator.

F. Reasons for Shutdown:

(1) A bed temperature above 1050°C or any rapidly climbing high temperature trend.

(2) A radical change in bed or filter DP that gives evidence of a blockage or a burnthrough.

(3) An explosive mixture in the off-gas (O_2 and CO both present at greater than 6%).

(4) Any other abnormal occurrence which may be capable of causing material damage to the burner.

10 CM SECONDARY BURNER OPERATING PROCEDURE (continued)

III. Pre-run Preparations

A. Prepare 14kg of feed as described in the Secondary Burner Feed Preparation Procedure.

B. Calibrate the off-gas analyzers the morning of the run as described in the Off-gas Analyzer Operation Procedure.

C. The blast gates are numbered and should be positioned as follows:

OPEN: 3, 4, 5, 6, 7, 8

D. The differential pressure cells, the pen recorders and the controllers are calibrated by our instrument technician. Malfunctions should be reported to him.

E. Set the CO_2 and O_2 regulators to: CO_2, 60psi and the O_2, 62psi.

F. Actuate each switch on the secondary burner control panel and ascertain that each is functioning.

G. Actuate the induction heater as described in the Induction Heater Operating Procedure and bring the field up manually just long enough to detect a temperature rise on the temperature recorder (a thermocouple chart is shown in Figure 1).

H. Set the filter blowback interval timer at 10 seconds and the pulse timer at one second.

I. Set the pneumatic feeder at two minutes.

J. Screw a product can onto the bottom of the filter-receiver and open the ball valve.

K. Actuate the Valve Guide Purge to 12psi.

L. Set the valve actuator regulator at 40psi.

M. Set the sweep purge rotameter to 20 CFH.

N. Adjust the DP cell purge rotameters to 8 on their scale of 10.

O. Record the data on run sheet.

P. Check cryogenic gas supplies (outside, north of E-183) to ensure enough is available to complete the run.

Q. Turn CO_2 up to high flow and check DP cells.

10 CM SECONDARY BURNER OPERATING PROCEDURE (continued)

IV. Crushing Operation

A. Close the feeder ball valve located between the burner and the feeder.

B. Purge the burner feed hopper with 100 CFH of CO_2 for two minutes with the hopper vent open. Shut off the CO_2 and close the hopper vent.

C. Fill the crusher feed hopper with the feed and turn the crusher motor on. It will take about 45 minutes to crush the hopper load (14kgs of fertile particles).

D. Start heating up the burner by actuating the automatic heater control system.

E. Purge the burner with 40 LPM of CO_2.

F. When crushing is completed, close the ball valve located between the crusher and the burner feed hopper and open the feeder valve.

V. Burning Operation

A. Actuate the pneumatic feeder switch (@ 40 CFH, preset to a two minute pulse) to batch in the feed: 14kgs of crushed particles.

B. Perform five of the following cycles: five second feeder pulse, then a five second cleanout port pulse (@ 70 CFH) with the feed hopper vibrator on continuously, then close the ball valve between the feeder and the burner and open the feed hopper vent.

C. When the bed temperature reaches 700°C, actuate the O_2 ramp function switch (this will bring the O_2 to 100 LPM automatically over a six minute interval) while leaving the CO_2 at 40 LPM. When the O_2 reaches 100 SLPM, decrease CO_2 to zero flow.

D. When combustion starts, turn on the filter blowback switch and activate the cooling jacket air supply blower. Butterfly valves will open when the automatic cooling air controller gives demand.

E. When the off-gas CO concentration drops to 1.5%, reduce the O_2 flow to 60 SLPM and increase CO_2 flow to 40 SLPM. Activate the filter chamber vibrator for a minute every other minute during this stage.

F. Burn until the O_2 concentration in equals O_2 out, then fluidize the bed with 100 LPM CO_2. Deactivate the induction heater and cool down the burner with the cooling air on full.

10 CM SECONDARY BURNER OPERATING PROCEDURE (continued)

G. Turn the Transport System on to warm up. When bed temperature reaches 500°C, open up the Product Removal Valve (1/4 in. stop pin opening).

H. After two minutes with product removal valve at 1/4-in. opening, pull the pin for full valve opening. Cycle the distributor plate sweep (2 seconds every 10 seconds).

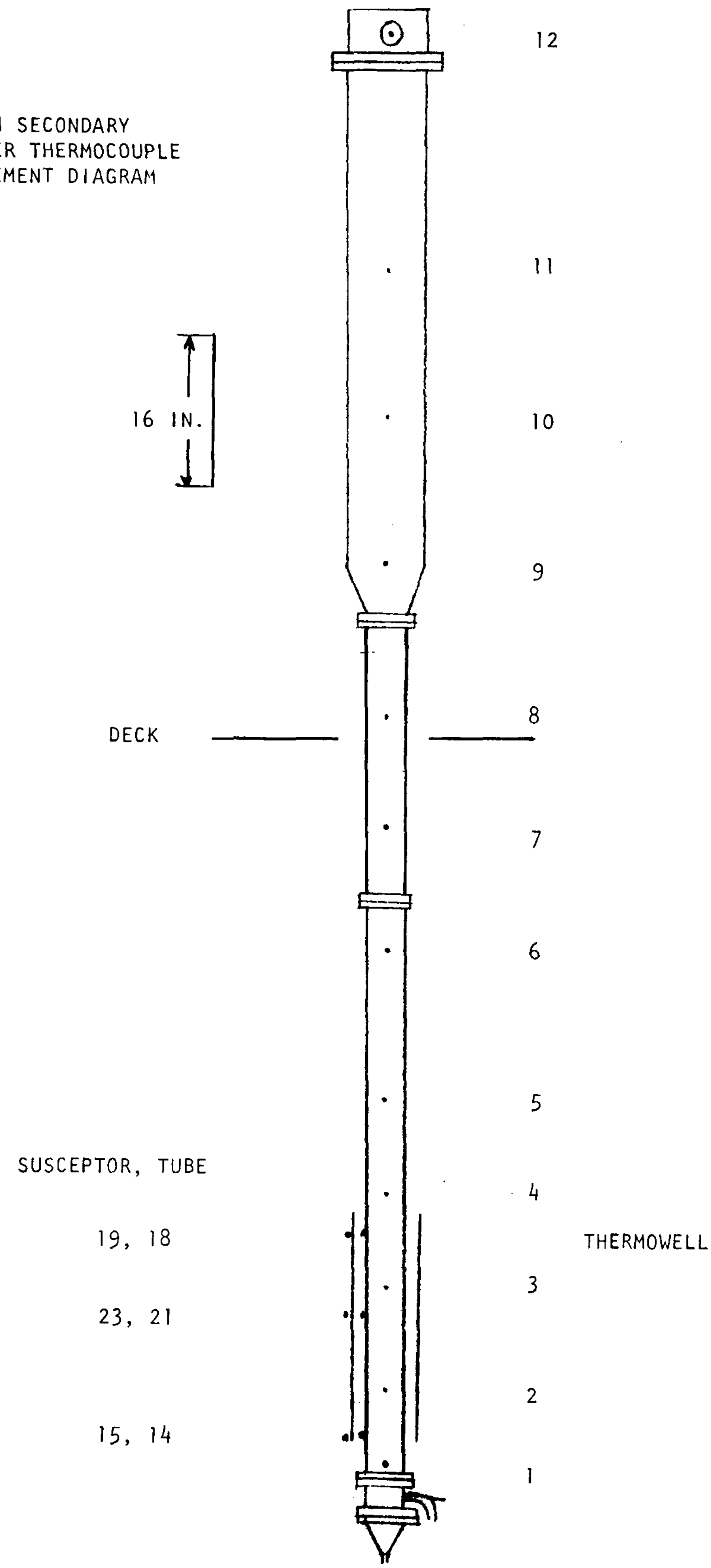
I. After one more minute close blast gate #8 and activate the vibrators on the cone, feed hopper and filter hopper. Continue activating the distributor plate sweep. Continue for one minute. Then open the blast gate to clean out the transport tube.

J. Shut down burner system.

K. Activate the hopper bag shaker before removing the last product removal container.

L. Analyze the product according to the Secondary Burner Product Analysis Procedure.

10 CM SECONDARY
BURNER THERMOCOUPLE
PLACEMENT DIAGRAM



SECONDARY BURNER FEED PREPARATION PROCEDURE

I. GENERAL

A. Enough feed for several runs is prepared at once to reduce analysis time. The total feed that can be made up is 50kg (enough for 3-14kg runs), which is the capacity of the blender.

B. Screens are used for secondary burner material only and are expected to be clean at all times. Sample splitters, funnels, hoods, etc. are used by all groups and must, therefore, be cleaned prior to using for feed preparation.

II. WHOLE PARTICLE OPERATIONS

A. Obtain 60kg of TRISO fertile 5A particles (coated to SiC coat only) from our supply room or order it through Tom Stafford at the vault. Ask him to send up only bottles of "clean looking" particles (shiny surfaces with minimal dust).

B. Sieve the -850μ to 350μ fraction of particles on the Rotap using the intermediate bottom pan to fit two screen sets on at once. Run the Rotap 10 minutes per load.

C. Weigh out 50kg of the cleaned particles and pour them into the V-shell blender. Spin the blender @ about 15 rpm for 10 minutes. Weigh three 14kg batches out of the blender and store them as prepared feed. The remaining 8 kg are for sampling.

D. Screen 500g of whole particles through the sieves as follows: 710, 650, 600, 500 and 425μ. Use the Rotap for ten minutes. Record the cut weights.

III. CRUSHED PARTICLE OPERATIONS

A. Use solid solder and a micrometer to check the crusher gap while cold. Warm up the crusher by crushing 2kg of unblended particles, then check the gap again. Crush 2kg of blended particles followed by rechecking the gap. Note the ambient temperature.

B. Split the crushed particles. Screen one half of the material through the following screens: 500, 425, 350, 300, 250, 212, 180, 150, 125, 106, 90, 75, 63, 53, 45 and 38μ. Rotap the material 10 minutes per screen set (5 screens per set). Record the cut weights.

C. Split out approximately 100g of crushed material, weigh it in a burn tray, put it in a muffle furnace overnight @900°C (with the furnace door cracked open) and reweigh it. Record the before and after material weights. Split the ash down to two 1-2g samples to be sent for Th analysis in cardboard pill boxes. A typical request for analysis form is shown on the following page.

D. Determine the bulk density in a 100ml graduated cylinder by gently pouring crushed material in. Check tap density by impacting the cylinder on a solid object for ~30 seconds to settle the solids. Record the weights of material and volumes.

Gulf General Atomic

REQUEST FOR CHEMICAL ANALYSIS

Date 1/5/74 Sample No. M-35A, M35B

Chg. No. 115762 Send To B. Rickman

Room No. E-227 Ext. 1438 MT No. —

Material Description TRISO FERTILE ASH LEACH ENTIRE SAMPLE, CRUSH ONE SAMPLE, DO NOT CRUSH THE OTHER. % Enr. —

Chemistry Lab Sample No. 34789

Analysis Requested TH by LEACH ~70% TH

Spec. ☐ Radio Chem ☐
X-Ray ☐ Microprobe ☐
Wet ☒ Gas ☐

LABORATORY REPORT

M35A Not crushed Product = 62.24% Thorium

M35B Crushed Product = 62.03% Thorium

2-25-74 R.W.

GEES-FORM-146 REV. (12-71)

GAS ANALYZER OPERATING PROCEDURE

I. General

A. Off-gas from fluid bed burners is continuously analyzed for O_2, CO and CO_2 by pumping a bleed stream through a particulate filter into the electronic analyzers. The flow patterns of gas are shown in Figure 1 as are valve numbers and equipment items.

B. The system should be calibrated prior to each day of use due to drift of the analyzers. Calibration is performed using gases of known concentration.

C. The filter should be replaced at least every six months, depending on usage.

II. Calibration

A. Switch selector valve to burner desired.

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

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

C. Close valves 8 and 9.
Open zero bottle.
Switch valve 3 to calibrate.
Open valve 5.
repeat until stable { Adjust valves 6 and 7 to give .3 and 3 on rotameters.
Adjust valve 10 to give P on pressure gauge. }

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

D. Switch valve 3 to sample.
Switch valve 11 to O_2 line.
repeat until stable { Adjust valve 6 to give .3 on rotameter.
Adjust valve 10 to give P on pressure gauge. }

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

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

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

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

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

OFF-GAS ANALYZER FLOW DIAGRAM

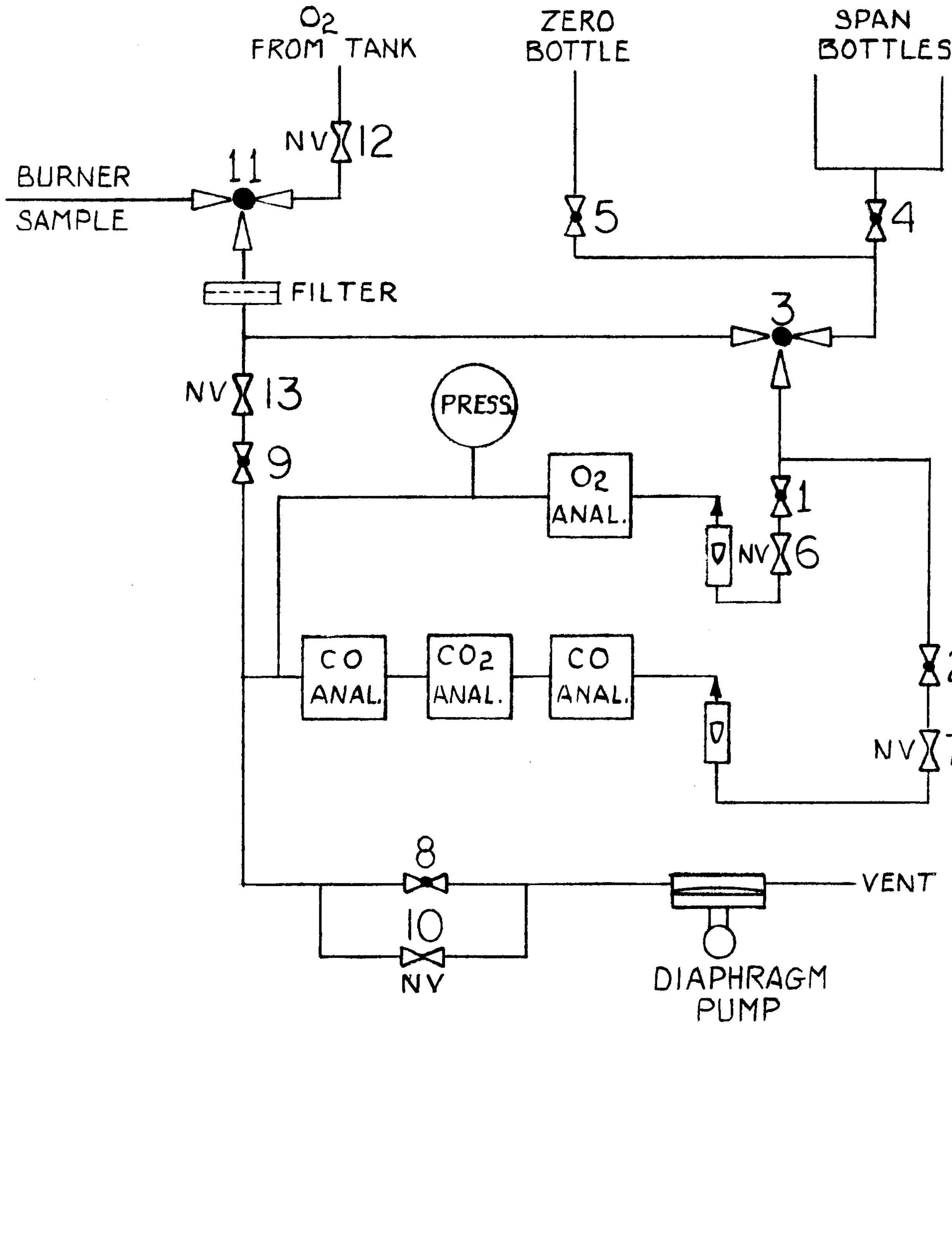


FIGURE 1

INDUCTION HEATER OPERATING PROCEDURE

I. General

A. The system has a general layout as shown in Figure 1. The control room panel is shown in Figure 2. The motor generator area is shown in Figure 3. The burner area is shown in Figure 4.

B. Basic Operation of the system is as follows:

1. The motor generator produces 10,000 cycle/sec. AC current @ 0-440V with a maximum power level of 30,000 watts @ 440V(68.2 amps). It is water cooled to remove mechanically and electrically produced heat. It is actuated by a magnetic starter. Regulation of motor generator output is accomplished by varying the field from approximately 0 to 55V. The voltage required for the field is supplied by magnetic amplifier. An automatic controller is used to modulate the magnetic amplifier output to yield M.G. output at the setpoint level. The field voltage required to yield maximum generator current output increases as the load (in this case the burner) changes temperature.

2. High frequency contactors are used for absolute shutoff of high frequency current to the coil.

3. The autotransformer reduces the high frequency supply voltage before it reaches the coil. It is water cooled.

4. A water cooled capacitor is used parallel to the burner coil to electrically balance the system such that the phase angle is at a minimum and realized power is thus maximized. Water cooled copper bus bars connect it to the coil, which is also water cooled.

5. Two end coils are installed for field shaping; they are water cooled.

II. Operation

A. Start up proceeds as follows:

1. Open water supply ball valves at motor generator and burner cabinet. Include the field end coils supply valves.

2. Actuate <u>Control Circuit</u> switch.

3. Check all five water flows by adjusting control valves to yield pressures indicated on supply valves and visually checking all five sight glasses.

4. Turn field Powerstat to zero.

5. Actuate Field-On/Off selector.

6. Actuate M.G. Protect-Reset switch.

7. Actuate M.G. Start switch.

8. Actuate Field Supply switch.

9. Actuate Start switch.

10. Actuate High Frequency Contactors switch.

11. Bring up the manual controller knob to give desired percent rated amperes (not over 100%). Automatic operation is also available.

B. Shutdown as follows:

1. Turn controller output to zero.

2. Turn off High Frequency Contactor switch.

3. Turn off Field Supply switch.

4. Turn off Control Circuit switch, then reactivate until maximum burner temperatures are below 50°C, and then turn off again.

III. Interlocks

A. Water flow out of the coil and the motor generator must stay above 1-3/4 GPM or an automatic shutdown will occur.

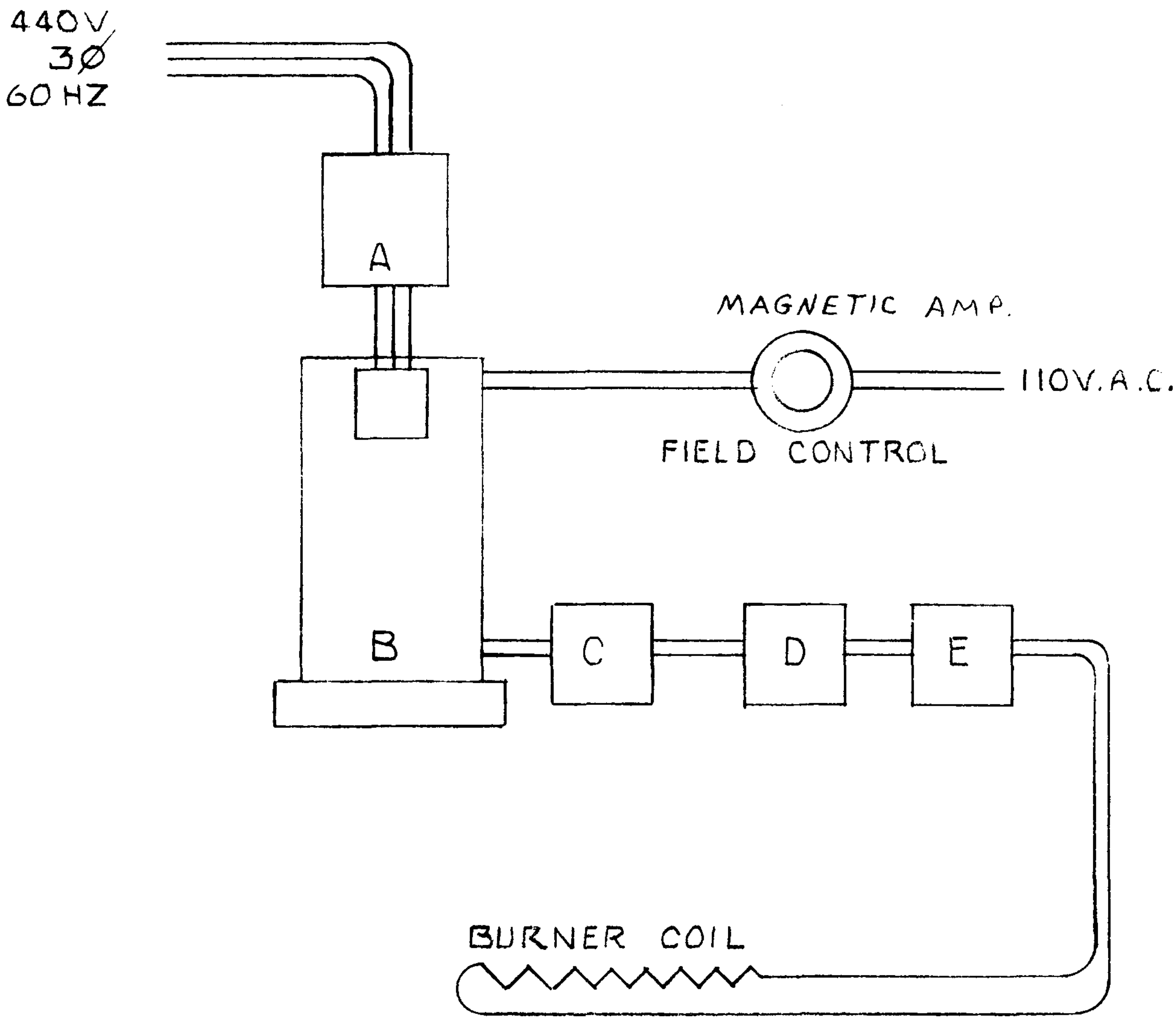
B. Turning off the Control Circuit switch shuts the motor generator off and allows the water flows to continue for approximately 30 minutes on a delay timer.

IV. Maintenance

A. The Cuno water filters should be replaced when the fully open coil supply pressure is more than 20 psi below static pressure.

B. The water supply system should be visually inspected for leaks during each day of operation.

GENERAL SYSTEM LAYOUT



LEGEND

A STARTER
B 30KW MOTOR GENERATOR
C CONTACTORS
D TRANSFORMER
E CAPACITOR

FIGURE 1

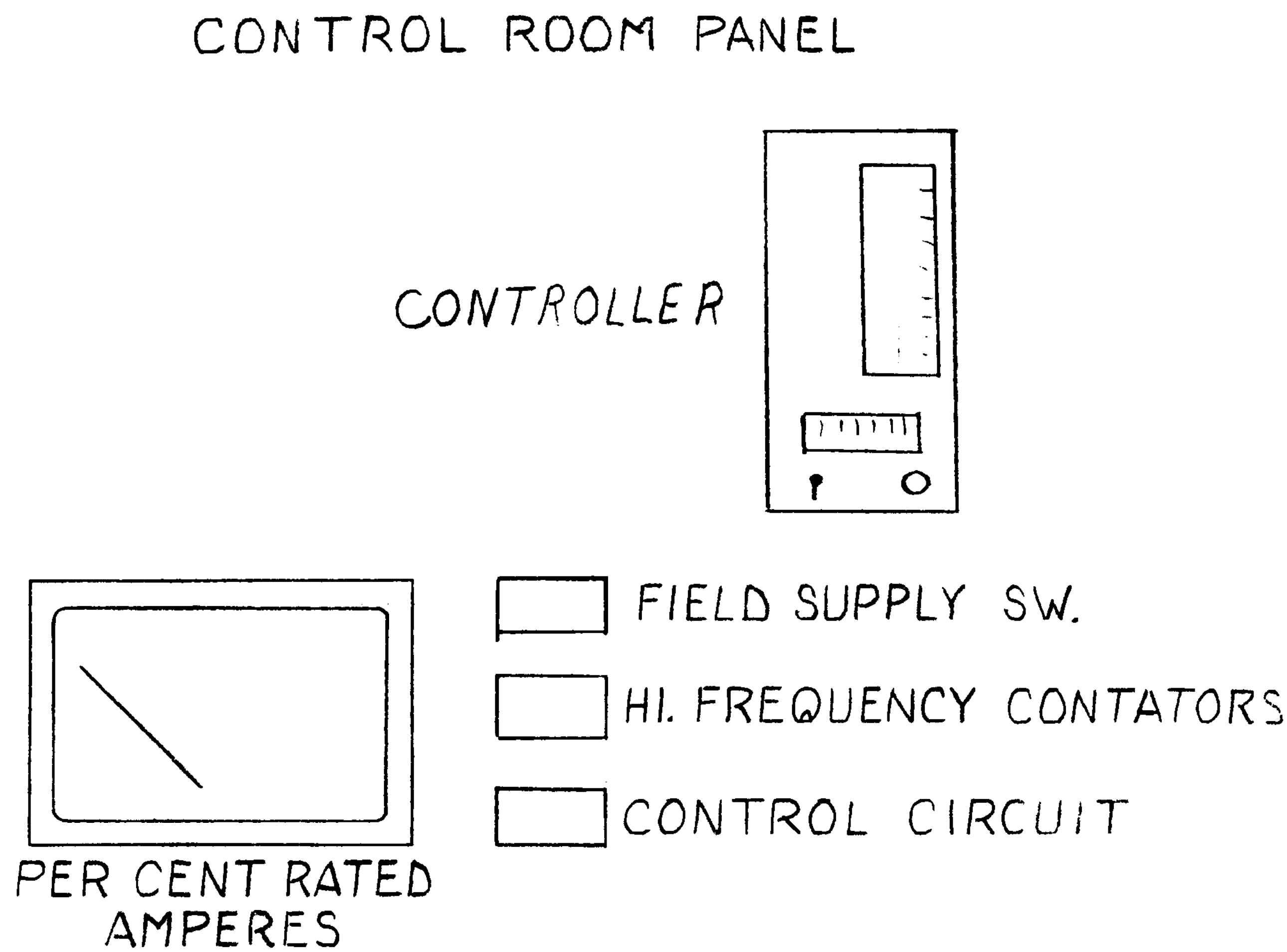

CONTROL ROOM PANEL
CONTROLLER
FIELD SUPPLY SW.
HI. FREQUENCY CONTATORS
CONTROL CIRCUIT
PER CENT RATED
AMPERES

FIGURE 2

MOTOR GENERATOR AREA

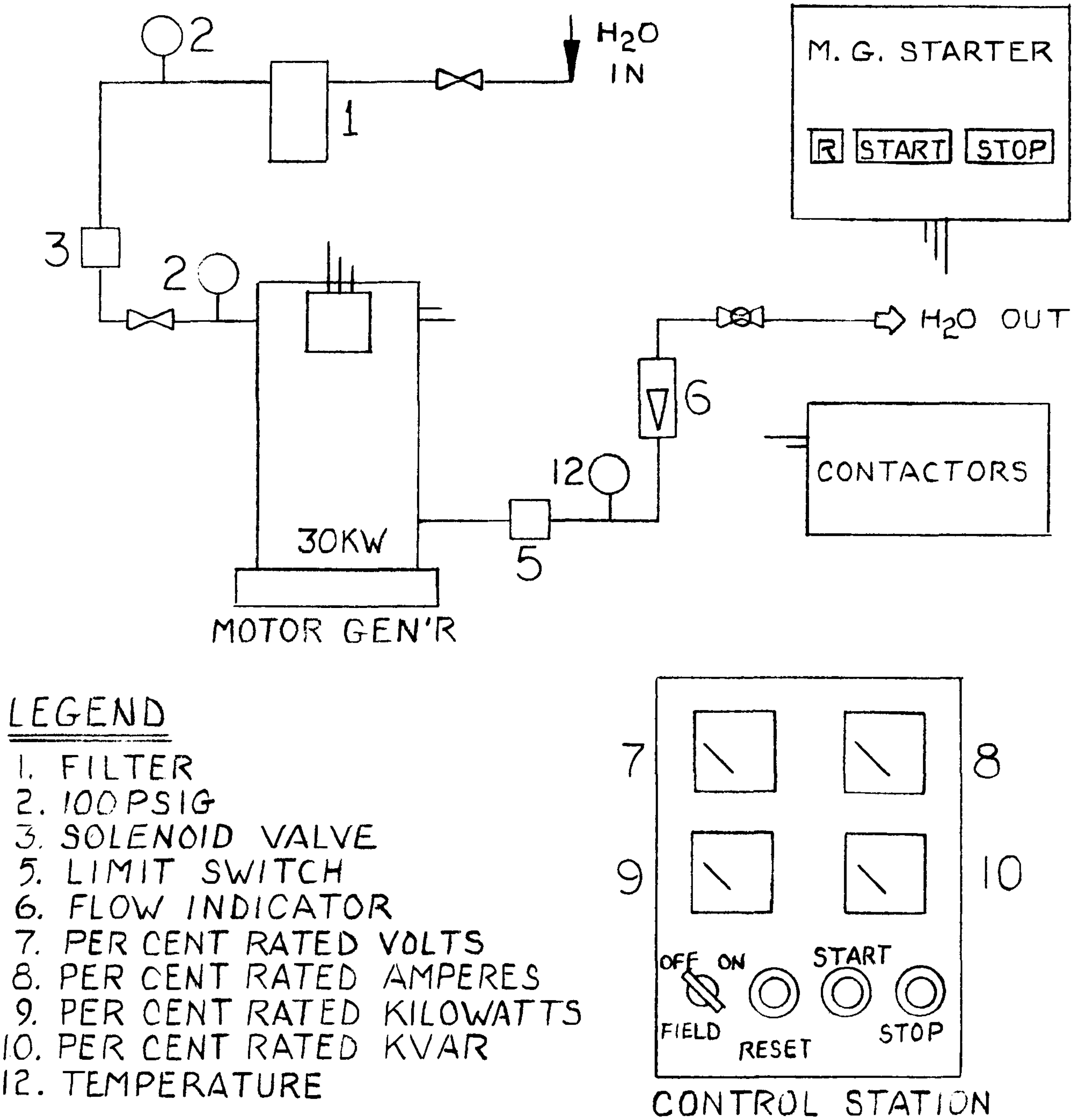
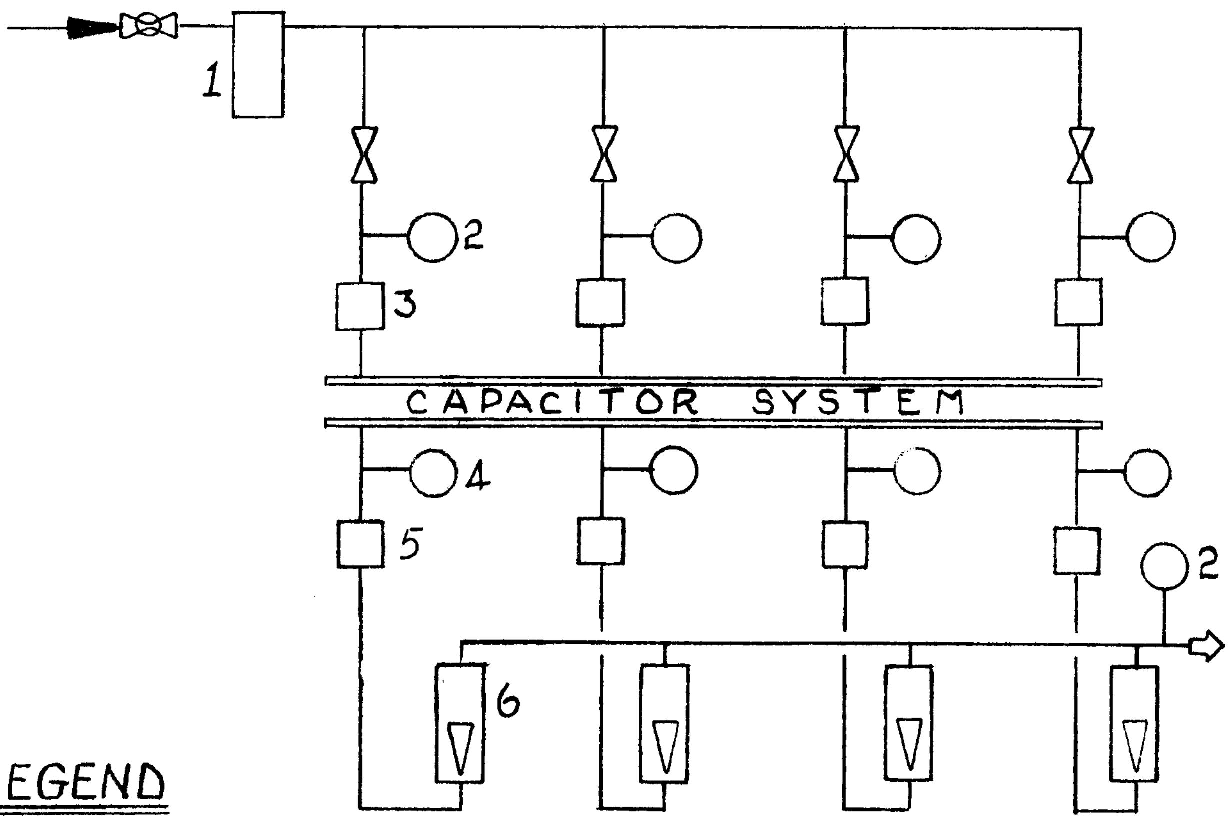


FIGURE 3

BURNER AREA



LEGEND

1. FILTER
2. 100PSIG
3. SOLENOID VALVE
4. TEMPERATURE
5. LIMIT SWITCH
6. FLOW INDICATOR

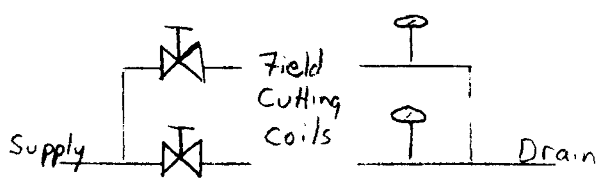


FIGURE 4

SECONDARY BURNER PRODUCT ANALYSIS PROCEDURE

I. GENERAL

A. Analyzing secondary burner product includes determining % burnable carbon in a very low carbon ash (generally less than one percent carbon content). Because of this, extreme care must be taken to be both clean and precise in all operations.

II. ANALYSIS

A. The product should be weighed out of the separate container it was withdrawn from the burner in. Record these separate weights.

B. Split the product to ~1000g. for screen analysis. Screen through the following screens: 425, 350, 300, 250, 212, 180, 150, 125, 106, 90, 75, 63, 53, 45, and 38μ. Record the cut weights.

C. Split out ~200g for carbon analysis. Weigh the sample on a furnace tray and heat it to 900°C in a muffle oven (crack the door to admit air) overnight. Split out 2 samples (~1.5g each) of the ash and send them to analytical chemistry in a cardboard pill box for Th analysis. A typical request for analysis is shown on the following page.

D. Use a 100ml graduated cylinder to determine bulk and tap densities of the product. Get tap density by impacting the cylinder repeatedly to settle the material.

E. Determine the angle of repose by pouring material through a funnel onto a flat surface until a pile about 1-2" high is formed. The angle of repose is the arctangent of height divided by half the width of the pile formed.

General Atomic Company

PUM

REQUEST FOR CHEMICAL ANALYSIS

Date 6-21-74 Sample No. M 37-A M37-B

Chg. No. 115762 Send To B. Rickman

Room No. E-227 Ext. 1381 MT No. —

Material Description TRISO Fertile ASH

Leach entire Sample, crush one

Sample, do not crush the other % Enr. —

Chemistry Lab Sample No. 36334

Analysis Requested Th by Leach

~70% Th

Spec.	☐	Radio Chem	☐
X-Ray	☐	Microprobe	☐
Wet	☒	Gas	☐

LABORATORY REPORT

M 37-A (Crushed) 65.20% Th

FR 6-27-74

M 37-B (Uncrushed) 66.26% Th

FR 6-27-74

GA-FORM-146 REV. 1/74

APPENDIX B

HISTORICAL RUN SUMMARY TABULATION

Run:	6	7	8	9	10	11	12	13
Feed type	ZrO_2 + 1% C	Whole TRISO Particles + 5% C	Al. inerts + 11% C	Whole TRISO Particles + Alumina + 1.6% C	Crushed TRISO + Inerts	Crushed TRISO + Inerts	Whole TRISO fertile + 4% C	Whole TRISO fertile + 20% C
Feed weight, kg	4.7	4.1	4.5	6.9	6.2	7.5	4.4	12.4
Feed avg. size, μm			60 mesh					~600
Feeder method	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual
Heating method	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance
Ignition temperature, °C			630		500	600		720
Ignition O_2 flow, SLPM		16				30		40
Ignition inert flow, SLPM		0				10		45
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max. O_2 flow, SLPM		45				50		100
Max. total flow, SLPM		45				50		100
Gas distributor type	Cone	Cone	Cone	Cone	Cone	Cone	Cone	Cone
Blowback duration, sec								2
Blowback frequency, min^{-1}								1
Maximum filter ΔP, in. H_2O								5
Maximum filter temperature, °C	30	50	50					400
Maximum bed temperature, °C	630	>1100	900	700	900	920		1020
Offgas CO_2 concentration at shutdown, %								1
Bed temperature at shutdown, °C			735	650	700			650
Product carbon content, %			0.5	0.5	0.2	0.5	0.3	0.4

Run:	14	15	16	17	18	19	20	21
Feed type	Crushed TRISO Fertile + Alumina Inerts	Crushed Resin Fuel Rods	TRISO-BISO EXO Product	TRISO-BISO EXO Product	Whole TRISO Particles + 18% C	Whole TRISO Particles + 19% C	Crushed Fertile + Inerts	Whole TRISO Particles
Feed weight, kg	11.0	10.0	8.0	9.6	8.2	10.5	11.0	17.3
Feed avg. size, μm		-3/16 in.	-3/16 in.	-3/16 in.	650	650		
Feed tap density, g/cm^3		1.6						
Feeder method	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual
Heating method	20 in. Resistance	20 in. Resistance	20 in. Resistance plus Torch	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance
Ignition temperature, °C	500	720	700	650	750	650	500	600
Ignition O_2 flow, SLPM							30	
Ignition inert flow, SLPM							10	
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max. O_2 flow, SLPM			80				90	
Max. total flow, SLPM			80				90	
Gas distributor type	Cone	Cone	Cone	Cone	Cone	Cone	Cone	Cone
Blowback duration, sec	2	2	2	2	2	2	2	2
Blowback frequency, min^{-1}	1	1	1	1	1	1	1	1
Maximum filter temperature, °C	450	250	500	300	200	250	700	150
Maximum bed temperature, °C	960	950	1000	1020	1050	1050	1020	1000
Offgas CO_2 concentration at shutdown, %	1						1	
Bed temperature at shutdown, °C	700	800	650	600	700	730	600	750
Product carbon content, %	0.1		2.3	1.8	0.1	0.1	2.7	0.1

Run:	22	23 - 32	33	34	35	1	2	3
Feed type	Crushed Fuel Rods	Whole TRISO particles	Whole rods + inert bed	TRISO-BISO primary burner product	Crushed Fuel Rods	Inert bed + 20% C	Whole & Crushed TRISO fertile	Whole & Crushed TRISO fertile
Feed weight, kg	9.0	8 to 20	10.9	14.5	8.4	9	10.5	9
Feed avg. size, μm	-3/16 in.	650						
Feeder method	Manual	Manual	Manual	Manual	Manual	3/4 in. pneumatic	Same	Same
Heating method	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	20 in. Resistance	48 in. Resistance	Same	Same
Ignition temperature, °C	700	∿800	650	720	600	700	650	500
Ignition O_2 flow, SLPM						30	40	30
Ignition inert flow, SLPM						40	80	120
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max. O_2 flow, SLPM						50	100	60
Max. total flow, SLPM						80	120	150
Gas distributor type	Cone	Cone	Cone	Cone	Cone	Cone	Cone	Cone
Blowback duration, sec	2	2	2	2	2	1	1	1
Blowback frequency, min^{-1}	1	1	1	1	1	1	1	1
Maximum filter temperature, °C	600	300	150	550	600	500	750	600
Maximum bed temperature, °C	1000	∿1000	1020	970	1030	1080	960	1020
Offgas CO_2 concentration at shut-down, %						1	5	3
Offgas O_2 concentration at shut-down, %						36	40	65
Bed temperature at shutdown, °C	500	650	750	700	700	550	550	720
Product carbon content, %	0.6	0 to 0.2	0.8	2.7	2.2	1.1	6.4	0.1

Run:	4 & 5	6	7	8	9	10	11	12
Feed Type	Crushed fissile plus whole fertile	Crushed Fertile	Crushed Fertile	Same	Same	Same	Same	Same
Feed weight, kg	13	10	10	10	10	10	10	10
Feed tap density, g/cm^3		2.2						
Feed angle of repose, °		35						
Feeder method	Same	Same	Same	Same	Same	Same	Same	Same
Heating method	Same	Same	Same	Same	Same	Same	Same	Same
Ignition temperature, °C	550	520	550	720	700	700	560	650
Ignition O_2 flow, SLPM	30	40	40	30	30	30	30	30
Ignition inert flow, SLPM	50	40	80	80	80	80	80	80
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max. O_2 flow, SLPM	90	80	80	60	70	70	70	70
Max. total flow, SLPM	100	100	120	110	120	120	110	110
Gas distributor type	Cone	Cone	Cone	Cone	Cone	Cone	Cone	Cone
Blowback duration, sec	1	1	1	1	1	1	1	1
Blowback frequency, min^{-1}	1	1	1	1	1	1	1	1
Maximum filter temperature, °C	700	750	820	850	900	870	860	860
Maximum bed temperature, °C	950	970	1020	1020	1020	1020	1030	1050
Offgas CO_2 concentration at shutdown, %	0	0	0	4	1	44	56	33
Offgas O_2 concentration at shutdown, %	65	62	65	56	60	35	10	61
Bed temperature at shutdown, °C	710	700	700	800	800	850	820	750
Product carbon content, %	0.4	0	1.1	0.4	0.2	1.6	3.7	1.8
Product tap density, g/cm^3		3.3						
Product angle of repose, °		40						

Run:	13	14	15	16	17	18	19	20
Feed Type	Same	Crushed Fertile + 20% Uncrushed	Crushed Fertile	Crushed Fertile	Crushed Fertile + inerts	Crushed Fertile	Crushed Fertile	Crushed Fertile
Feed weight, kg	10	10	10	10	8.1	10	10	10
Feed avg size, μm		130	113	54				
Feed bulk density, g/cm^3				1.8				
Feed tap density, g/cm^3				2.7				
Feed angle of repose, °				37				
Feeder method	Same	Same	Same	Same	Same	Same	Same	3/4 in. pneumatic
Heating method	Same	Same	Same	Same	Same	Same	Same	18 in. Resistance
Ignition temperature, °C	600	620	550	500	500	500	520	500
Ignition O_2 flow, SLPM	40	40	10	20	15	30	30	50
Ignition inert flow, SLPM	70	80	40	40	35	80	70	40
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max. O_2 flow, SLPM	140	130	35	90	50	100	60	110
Max total flow, SLPM	140	130	50	90	50	100	100	120
Gas distributor type	Cone	Cone	Cone	Cone	Cone	Cone	Dist. plate	Cone
Blowback duration, sec	1	1	1	1	1	1	1	1
Blowback frequency, min^{-1}	1	1	1	1	1	1	1	1
Maximum filter temperature, °C	820	700	450	560	200	700	750	820
Maximum bed temperature, °C	1000	950	1050	850	1100	950	1000	980
Offgas CO_2 concentration at shutdown, %	8	4	8	25		50	6	25
Offgas O_2 concentration at shutdown, %	62	65	64	35		50	36	75
Bed temperature at shutdown, °C	400	500	650	800		500	750	750
Product carbon content, %	0.2	1.0	0.3	16.7		0.3	0.1	4.1

Run:	21	22	23	24	25	26	27	28
Feed Type	Crushed & Uncrushed Fertile	Crushed Fertile	Crushed Fertile	Same	Whole fissile particles	Crushed Fertile	Crushed Fertile	Whole Fissile
Feed weight, kg	10	10	10	5	5.9	10	12	
Feed avg size, μm	235	134	140		450	227	227	$\sim$400
Feed bulk density, g/cm^3						2.0	2.0	
Feed tap density, g/cm^3						2.4	2.4	
Feed angle of repose, °						31	31	
Feeder method	Same	Same	Same	Same	Same	Same	Same	Same
Heating method	Same	Same	Same	Same	Same	Same	Same	Same
Ignition temperature, °C	500	550	550	550	600	650	575	600
Ignition O_2 flow, SLPM	20	26	5	30	20	10	30	30
Ignition inert flow, SLPM	60	20	25	40	40	30	20	20
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max O_2 flow, SLPM	90	120	100	80	80	80	60	80
Max total flow, SLPM	120	140	100	150	140	130	100	120
Gas distributor type	Cone	Cone	Cone	Dist. Plate	Dist. Plate	Dist. Plate	Mesh. Dist.	Dist. Plate
Blowback duration, sec	1	1	1	1	1	1	1	1
Blowback frequency, min^{-1}	1	1	1	1	1	1	1	1
Maximum filter ΔP, in. H_2O				11	6	9	4	5
Maximum filter temperature, °C	800	850	750	730	300	730	700	450
Maximum bed temperature, °C	1050	1020	1020	1000	960	950	925	930
Offgas CO_2 concentration at shutdown, %	1	2	1	1	2	1	1	3
Offgas O_2 concentration at shutdown, %	28	21	21	99	98	32	42	70
Bed temperature at shutdown, °C	700	750	620	650	750	750	670	720
Product carbon content, %	3	0.5	1.1	0.1	<0.1	0.7	0.7	
Product bulk density, g/cm^3						2.9	2.8	
Product tap density, g/cm^3						3.2	3.2	
Product angle of repose, °						40	40	

Run:	29	30	31	32	33	34	35	36
Feed Type	Crushed Fertile	Same	Same	Same	Same	Same	Same	Same
Feed weight, kg	13	14	15	15	17	18.5	20	20
Feed avg size, μm	222	258	258	291	291	111	160	145
Feed bulk density, g/cm^3	2.0	2.5	2.5	1.9	1.9			
Feed tap density, g/cm^3	2.3	3.0	3.0	2.2	2.2			
Feeder method	Same	Same	Same	Same	Same	Same	Same	Same
Heating method	Same	Same	Same	Same	Same	Same	Same	Same
Ignition temperature, °C	550	400	550	500	600	500	550	480
Ignition O_2 flow, SLPM	30	20	20	20	20	20	20	20
Ignition inert flow, SLPM	20	0	20	20	20	20	20	20
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max O_2 flow, SLPM	100	80	120	100	110	100	110	110
Max total flow, SLPM	100	100	120	140	140	120	140	140
Gas distributor type	Dist Plate	Same	Same	Same	Same	Same	Same	Same
Blowback duration, sec	1	1	1	1	1	1	1	1
Blowback frequency, min^{-1}	1	1	1	1	1	1	1	2
Maximum filter ΔP, in. H_2O	9	6	6	11	23	>50	31	45
Maximum filter temperature, °C	800	700	725	900	900	900	900	800
Maximum bed temperature, °C	950	880	880	970	970	970	950	1070
Offgas CO_2 concentration at shut-down, %	1	1	1	1	1	1	1	
Offgas, O_2 concentration at shut-down, %	32	50	40	45	75	50	65	
Bed temperature at shutdown, °C	700	600	700	800	750	650	650	
Product carbon content, %	0.8	0.5	0.3	0.4	0.3	0.1	0.7	
Product bulk density, g/cm^3				2.4		2.5		
Product tap density, g/cm^3				2.8		2.9		
Product angle of repose, °						4.0		

Run:	37	38	39	40	41	42	43	44
Feed Type	Crushed Fertile	Same	Same	Same	Same	Same	Same	Same
Feed weight, kg	20	18	18	18	18	18	18	14
Feed avg. size, μm	150	155	167	167	167	156	120	167
Feed bulk density, g/cm^3			1.8	1.8	1.8	1.7	1.8	1.8
Feed tap density, g/cm^3			2.2	2.2	2.2	2.0	2.2	2.2
Feed angle of respose, °			2.7	2.7	2.7	2.4		2.7
Feeder method	3/4 in. Pneumatic	Same	Same	Same	Same	Same	Same	Same
Heating method	Induction Tube	Same	Same	Same	Same	Same	Same	Same
Ignition temperature, °C	600	650	550	600	700	700		650
Ignition O_2 flow, SLPM	40	40	40	40	40	40	40	40
Ignition inert flow, SLPM	40	40	40	40	40	40	40	40
Type inert gas	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
Max O_2 flow, SLPM	130	140	140	140	140	140	140	100
Max total flow, SLPM	140	160	160	160	160	160	160	140
Gas distributor type	Dist Plate	Same	Same	Same	Same	Same	Same	Same
Blowback duration, sec	1	1	1	1	1	1	1	1
Blowback frequency, min^{-1}	2	2	2	2	2	2	2	3
Maximum filter ΔP, in. H_2O	25	21	35	50	45	--	--	15
Maximum filter temperature, °C	800	800	800	800	800	--	--	750
Maximum bed temperature, °C	900	900	900	900	900	900		860
Offgas CO_2 concentration at shutdown, %	1	1	1	1	1	50		3
Offgas O_2 concentration at shutdown, %	40	60	58	50	52	20		50
Bed temperature at shutdown, °C	700	760	650	650	675	650		620
Product carbon content, %	0.8	1.0	0.6	0.7	0.6	4.6		1.1
Product bulk density, g/cm^3		2.4	2.4	2.5	2.4	2.2		2.3
Product tap density, g/cm^3		3.0	3.0	3,1	3.2	2.7		3.0
Product angle of repose, °			33	37	38	38		32

Run:	45	46	47	48	49
Feed Type	Crushed Fertile	Same	Same	Same	Same
Feed weight, kg	14	14	14	14	14
Feed avg size, μm	165	165	160	160	189
Feed bulk density, g/cm^3					1.8
Feed tap density, g/cm^3					2.1
Feed angle of repose, °					39
Feeder method	3/4 in. Pneumatic	Same	Same	Same	1/2 in. Pneumatic
Heating method	Induction Tube	Same	Induction-Susceptor Plate	Same	Same
Ignition Temperature, °C	700	650	670	730	700
Ignition O_2 flow, SLPM	40	40	40	40	40
Ignition inert flow, SLPM	40	40	40	40	40
Type Inert Gas	N_2	N_2	N_2	N_2	CO_2
Max O_2 flow, SLPM	100	100	100	100	100
Max total flow, SLPM	140	140	140	140	100
Gas distributor type	Dist Plate	Same	Same	Same	Same
Blowback duration, sec	1	1	1	1	1
Blowback frequency, min^{-1}	3	3	3	3	6
Maximum filter ΔP, in. H_2O	20	16	18	17	6
Maximum filter temperature, °C	800	800	820	820	780
Maximum bed temperature, °C	910	950	920	930	900
Offgas CO_2 concentration at shutdown, %	4	2	3	1	1
Offgas O_2 concentration at shutdown, %	48	50	45	48	52
Bed temperature at shutdown, °C	700	800	760	800	790
Product carbon content, %	2.8	0.5	0.9	0.2	0.1
Product bulk density, g/cm^3	2.5		2.4	2.4	2.4
Product tap density, g/cm^3	3.3		3.4	3.4	3.5
Product angle of repose, °	39		36	36	36

Runs 1 → 5 (10/23/70 → 11/4/70)	Test resistance heater transients, using a 20 in. long ceramic furnace with nichrome elements.
Run 6 (11/5/70)	Test heatup with an inert bed of ZrO_2.
Run 7 (11/10/70)	Burning whole TRISO particles with 5% carbon resulted in a burnthrough due to lack of fluidization (low flow).
Run 8 (11/18/70)	An alumina bed with 11% carbon was successfully combusted to yield about 0.5% carbon product.
Run 9 (11/19/70)	An alumina-TRISO particle carbon bed was burned for a short time due to low carbon content in feed.
Run 10 (11/25/70)	One kg of crushed TRISO fertile particles was burned with a 5 kg inert bed. Product was low in carbon.
Run 11 (12/1/70)	Three kg of crushed TRISO fertile particles were burned in a 4.5 kg inert bed to 0.5% carbon content.
Run 12 (12/2/70)	Four kg of whole TRISO fertile particles could not be ignited due to insufficient bed height and low carbon in feed.
Run 13 (1/21/71)	A 12 kg bed of whole particle with 20% carbon was burned to low carbon content. Total flow of 75 slpm required for fluidization. Bed temperature allowed to reach >1000°C.
Run 14 (1/27/71)	Eleven kg of mixed alumina and crushed TRISO fertile particles were combusted to yield a low carbon product.

Run 15 (2/9/71)	Crushed resin-type fuel rods were burned with attendant particle agglomeration. Numerous hot spots over the length of the burner. Difficult temperature control.
Run 16 (3/2/71)	A TRISO-BISO primary burner product was cleaned up to 2% carbon content. A $CO-O_2$ torch was used to facilitate ignition.
Run 17 (3/10/71)	Repeat of run 16 with slightly lower carbon product. $CO-O_2$ torch not used for ignition.
Run 18 (3/17/71)	A batch of TRISO fertile particles burned as a service to Fuel Manufacturing.
Run 19 (3/24/71)	Identical to run 18.
Run 20 (3/29/71)	A bed of crushed TRISO fertile particles plus inerts were burned to 3% carbon content. This was for the Fuel Manufacturing scrap recovery effort.
Run 21 (3/31/71)	Defective SiC coated fertile particles were burned to oxidize the kernels that were exposed (∿1%) and other surface carbon. Performed as a service for Fuel Manufacturing.
Run 22 (4/7/71)	Crushed fuel rod demonstration burn for Fuel Manufacturing.
Run 23 → 32 (4/14/71)	Same as run 18.
Run 33 (5/3/71)	Whole fuel rods were burned in a TRISO particle inert bed to yield a clean particle product.

Run 34 (5/20/71) Similar to run 16 but no torch for ignition.

Run 35 (5/24/71) Similar to run 22.

Burner relocated with larger furnace - run sequence starts over at 1.

Run 1 (6/16/72) The new furnace system was checked out with a ZrO_2 - 20% C bed. A long heating time was encountered due to high gas rates required for fluidizing the bed. Acceptable product was obtained (1.1% carbon). There was a temperature excursion just before shutdown in the upper bed (near the middle of the furnace); no obvious explanation.

Run 2 (6/21/72) A 4:1 mixture of crushed and uncrushed fertile particles was burned. Hot spots in the cone area caused an early shutdown. They were caused by stagnant products of material in some cone penetrations. These were then removed for the next run.

Run 3 (7/31/72) A feed similar to run 2 was burned without hot spots following the core modification. Clean product was obtained.

Runs 4 & 5 (8/10/72) A 1:1 mix of crushed fissile and whole fertile particles were burned as a service to Fuel Manufacturing. About 0.2% of the final beds were 1 mm agglomerates due to excess dust on particle surfaces.

Run 6 (9/8/72) Crushed fertile particles without an inert bed were successfully burned. One percent bed agglomeration due to local hot spots during low flow periods.

Run 7 (9/14/72) A repeat of run 6 with total flow held constant to prevent hot spots. This was effective, with no chunks in the product.

Runs 8 → 13 (10/72) These were all performed quite similar to run 7, with shutdown conditions varied in each run to help correlate product carbon content with shutdown conditions. The conclusion was that burning until combustion can no longer be sustained (0% CO_2 in off-gas) is the most reliable method of producing low carbon product. There is not a large increment of time between product with >2% carbon and <0.5% carbon (about 10 min with these 10 kg beds). Thus complete burnout was recommended for future work.

Run 14 (11/1/72) Twenty percent uncrushed fertile particles were added to the crushed particle bed and burned successfully. No other changes.

Run 15 (11/4/72) This run had a total gas flow of only 50 slpm throughout. The main result was a lower filter temperature (due to decreased hot fines elutriation) and, of course, a much longer burn cycle.

Run 16 (11/14/72) Very finely ground (in a Vortec mill) fertile particles were burned to a high carbon product. The average feed size was 1/3 of normal feed, such that a good portion of carbon fines was trapped in the filter area at shutdown, causing the high product carbon. A burner tube cooling jacket was installed above the resisting furnace to reduce the filter heat load.

Run 17 (11/20/72) Ground particles similar to run 16 were mixed with ∿30 wt % whole particles as an inert fluidizing medium. The fluidizing gas flow was lowered to help reduce filter chamber packing. Midway through the run, the central thermowell burned off and several large agglomerates formed (∿3 in. diameter) due to hot spots caused by low gas flow and poor fluidization. No further work on this fine material is planned as the roll crushed material is much more amenable to this operation.

Run 18 (1/8/73) This run was very similar to run 13 and was an operator training run.

Run 19 (1/25/73) In this run, a gas distributor plate was used to make a run similar to run 18. The distributor yielded no noticeable effect with a comparable temperature profile. The plate had 21 holes, 1/16 in. in diameter in a radial pattern.

Run 20 (3/13/73) A short (18 in.) resistance furnace was fitted to allow more cooling jacket heat transfer area. Just after shutdown, fines fell back into the burner, indicating the need for a reduced flow fines burnout period before shutdown.

Run 21 (3/29/73) A mixed crushed and uncrushed fertile particle bed was burned. The suggested burnout period at 70 slpm was successful in reducing the carbon content but will have to be optimized further.

Run 22 (4/6/73) The burnout flow rate was further reduced to 40 slpm with a low carbon product resulting.

Run 23 (4/10/73) This run tested the use of a ball valve on a static leg for high temperature bed removal. High stresses pinched the outlet such that burner disassembly was required for product rmeoval.

Run 24 (9/24/73) The particle roll crusher motor burned out when half done crushing the bed. The 5 kg crushed bed was then burned. A major modification had been completed prior to this run in the way of a bed removal port integral with the burner wall. This was used successfully for product removal, but a heel remained.

Run 25 (9/25/73) A small bed of whole fissile particles was cleaned up as a service to the air classifier project. The product was removed again through the dumping port.

Run 26 (11/7/73) The new roll crusher motor prepared a 10 kg bed of crushed fertile particles. A larger gap between rolls yielded coarser feed (less dusty). Final bed burnout was accomplished at 30 slpm inlet gas flow. Product removal was incomplete, partially due to jetting through the shallow heel left in the burner. Different distributors will be tried.

Run 27 (11/21/73) A wire mesh laminate gas distributor was tried in this burner run in an effort to reduce jetting through the heel. It buckled during the run, so a solid plate with many holes will be tried. A larger initial bed (12 kg) was used without difficulties. The bed size will be slowly increased to detect a maximum constraint (filter loading, etc.).

Run 28 (11/27/73) Fissile particles were again cleaned up in a run similar to run 25.

Run 29 (12/11/73) This run made use of a solid distributor with 80 holes (1/32 in. diameter) drilled through it. This reduced the jetting characteristics, thus reducing the heel weight. Pneumatic transport system installation should reduce the heel. The initial bed was 13 kg with smooth operation still in effect.

Run 30 (1/3/74) A larger bed (14 kg) was burned with some difficulty. Insufficient insulation around the cone area prevented heating the bed to over 400°C for ignition. To conserve heat, a startup attempt was made using 20 slpm O_2; this resulted in a distributor plate failure due to stagnant burning. A second attempt was made with a sufficient cone insulation and the bed was ignited at 500°C with 40 slpm O_2. This time the run went smoothly. Future runs will use plenty of insulation to ensure heat retention during startup.

Run 31 (1/9/74) Fifteen kilograms were ignited at 550°C, with the entire burner well insulated. There are still no real problems with these larger batch sizes. The particle crusher rolls have worn enough to pass 2% unbroken particles.

Run 32 (1/16/74) Fifteen kilograms were again burned at a higher superficial velocity to boost burn rate. This resulted in higher filter pressure drop and temperature, which indicates a possible constraint in runs with larger beds. The roll crusher is now passing 9% uncrushed.

Run 33 (1/18/74) A 17 kg batch showed a definite trend in filter pressure drop, which is nearly double that of a 15 kg bed at the same flow. This means that the expanded bed is getting close to the filter chamber. The particle crusher is now allowing 12 wt % of the particles to pass through unscathed, so it is being renewed with fresh rolls.

Run 34 (1/23/74) The new roll crusher produced excessively fine and dusty feed due to the gap being too small ($\sim$0.011 in.). Thus the data for a larger bed (18.5 kg) was obscured. Very high filter ΔP was noted but was most probably due to the dusty nature of the feed, not the weight.

Run 35 (1/30/74) Twenty kilograms of crushed feed were burned satisfactorily. Reduction in filter pressure drop from the previous run indicates that the fineness of the feed was the most important variable affecting filter ΔP.

Run 36 (3/28/74) Twenty kilograms were again burned with a lower burner wall failure just before shutdown. The run proceeded normally but with high filter pressure drops that cycled occasionally, indicating fall back of "clumps" of fines. After the reduced flow tail burning period was started, a clump again fell back into the bed, followed shortly thereafter by the burnthrough. Low flow at this time caused reduced heat transfer capabilities which, when coupled with a pocket of carbon containing fines, caused very high specific burn rates.

With the resistance heater set-up, there is no heat removal capability in the lower 20 in. of the burner. This mode of heating depends on good axial mixing to remove heat from the bed. Evidently, at the low flows used, there was poor axial mixing and thus, high temperature gradients in the vicinity of the combustion zone.

Normally, at the low flow portion of a run, there is only a small concentration of carbon in the bed and so the specific heat generation rate is low and temperature excursions are not expected (or observed). This clump or pocket of fines was an unusual situation, but one that will be anticipated in the future.

Recommendations for remedying this situation are as:

1. Install the induction heating system such that cooling of the entire burner length is possible.

2. Increase the filter blowback capacity to prevent large buildups of fines in the filter chamber.

3. During low flow portions of the run, limit the inlet O_2 concentration to 50% to reduce the specific burn rate, with total flow rates of no less than 80 lpm in the new tube.

Run 37 (6/17/74) Using an induction heating system, a 20 kg bed was burned to low carbon content. The filter ΔP was decreased by increasing blowback capacity. High filter temperature indicate that a reduction of bed weight is in order. An 18 kg bed will be used in the future. To facilitate bed ignition, a partial bed will be added until burning is established. In this way, the heater can preheat the bed better since it is smaller. The pneumatic transport system was rendered inoperable due to plugging of the transport line. This was attributed to too high of a solids-to-air loading ratio. A reduced initial product valve opening will be used in future runs for the bulk of product removal, followed by full opening for cleanout.

Run 38 (7/17/74) Use of an 18 kg bed yielded lower filter pressure drop in this run. Product removal was successful using a 1/8 in. initial product valve opening. Startup was improved somewhat by the addition of a partial bed initially, but improved heating capability is required.

Run 39 (9/11/74) The induction coil was modified to include a thin (1/8 in.) layer of insulation around the copper coil. This was of some help in increasing heating capabilities. The bed was again 18 kg, with a much higher filter pressure drop than the previous run. A distribution plate sweep nozzle yielded complete cleanoff of the plate when coupled with the product valve and transport system.

Run 40 (9/17/74) This run was very similar to run 39 except for the product removal. The product valve was opened 3/8 in. initially; this resulted in too high a solids exit rate such that the pneumatic transporter overloaded and plugged. This bracketed the useful initial opening of the valve to 3/8 in. > opening ≥ 1/8 in. for the particular transport system in use.

Run 41 (9/19/74) Pneumatic transport tests were continued in this run. A 3/16 in. valve opening resulted in product not being able to flow through the valve (bridging). It was then opened more to allow product to flow and successful transport followed. Future product removal will be with a 1/4 in. opening. Automatic cooling air control was tested in this run. It was quite successful with cooling air being supplied only on demand (based on deviation of bed temperature from the setpoint). This allows a constant fluidizing velocity along with temperature control, a feature to be desired.

Run 42 (9/24/74) This run was made to further test the pneumatic transport system at a 1/4 in. initial valve opening. It worked well with no product removal problems. During the run, the blowback pump failed, allowing fines to build up in the filter chamber. Near the end of the run, O_2 in the off-gas reacted with the unusually high carbon loading in the filter chamber. This generated a lot of heat on the filter surface, which, when combined with the high filter-pressure drop, caused one of the filters to collapse inward and rupture.

Run 43 (10/2/74) Automatic startup operations were simulated in this run. An O_2 automatic ranging sequence was used to ramp O_2 from 40 to 140 slpm for a smooth startup. Crushed feed was much finer than normal due to a close gap pair of replacement rolls in the crusher. During bed burnout, one of the filters melted and opened. The run was then shutdown. This fine feed was judged to have a similar effect to loss of blowback in run 42, as the fines built up inordinately in the filter chamber. To prevent further occurrances, the fines buildup will be reduced by reducing bed size and decreasing total gas flow rate; in addition, the final burn portion of the run will begin a bit earlier to allow the filters to cool prior to the O_2 front penetration of the bed. Finely crushed material will also be avoided.

Run 44 (10/25/74) The new operating guides were employed with resultant smooth operations. Manual O_2 ramping procedures were again used successfully. An automatic ramp device will be used in the next run.

Run 45 (1/29/75) An automatic O_2 ramping device was used for startup. The cooling air automatic supply system was also operable during the run. Actuation of the induction heater was delayed during the final burn period, with a quick loss in temperature. Because of this, the product was high in carbon content (2.8%). Data was taken concerning product transport rates in this run.

Run 46 (2/5/75) — This run again gathered data on automatic control system operation and product removal rates. Actuation of the induction heater earlier in the final burn period allowed the bed to be held at 800°C for burnout, yielding a low carbon product.

Run 47 (2/26/75) — An induction-susceptor plate heating system was installed to verify larger burner design calculations and to hopefully yield better heating characteristics on the small burner. In this first shakedown run, heat losses due to insufficient insulation were determined. Because of these losses, the final burning period proceeded at a reduced temperature, with a resultant increase in the product carbon content.

Run 48 (2/28/75) — Increased insulation yielded better heating performance with a final bed burnout at 800°C. Product carbon content was 0.2% which is quite low. Product transport rate tests were concluded with final data indicating that the bulk (∿75%) of the product is removed within 1 min of valve opening.

Run 49 — The feeder was changed to a 1-1/2 in. nominal size, developed for the prototype burner and now in service here for actual in-place testing.

Based on an off-gas filter evaluation, reduction of filter ΔP was effected by adding an 18 in. long by 8 in. diameter disengaging section, lowering total flow to 100 slpm, and increasing blowback frequency to six pulses per minute. The result was a 6 in. H_2O maximum filter ΔP as compared to previous average of ∿17 in. H_2O.

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