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Lewis Research Center's Coal-Fired, Pressurized, Fluidized-Bed Reactor Test Facility

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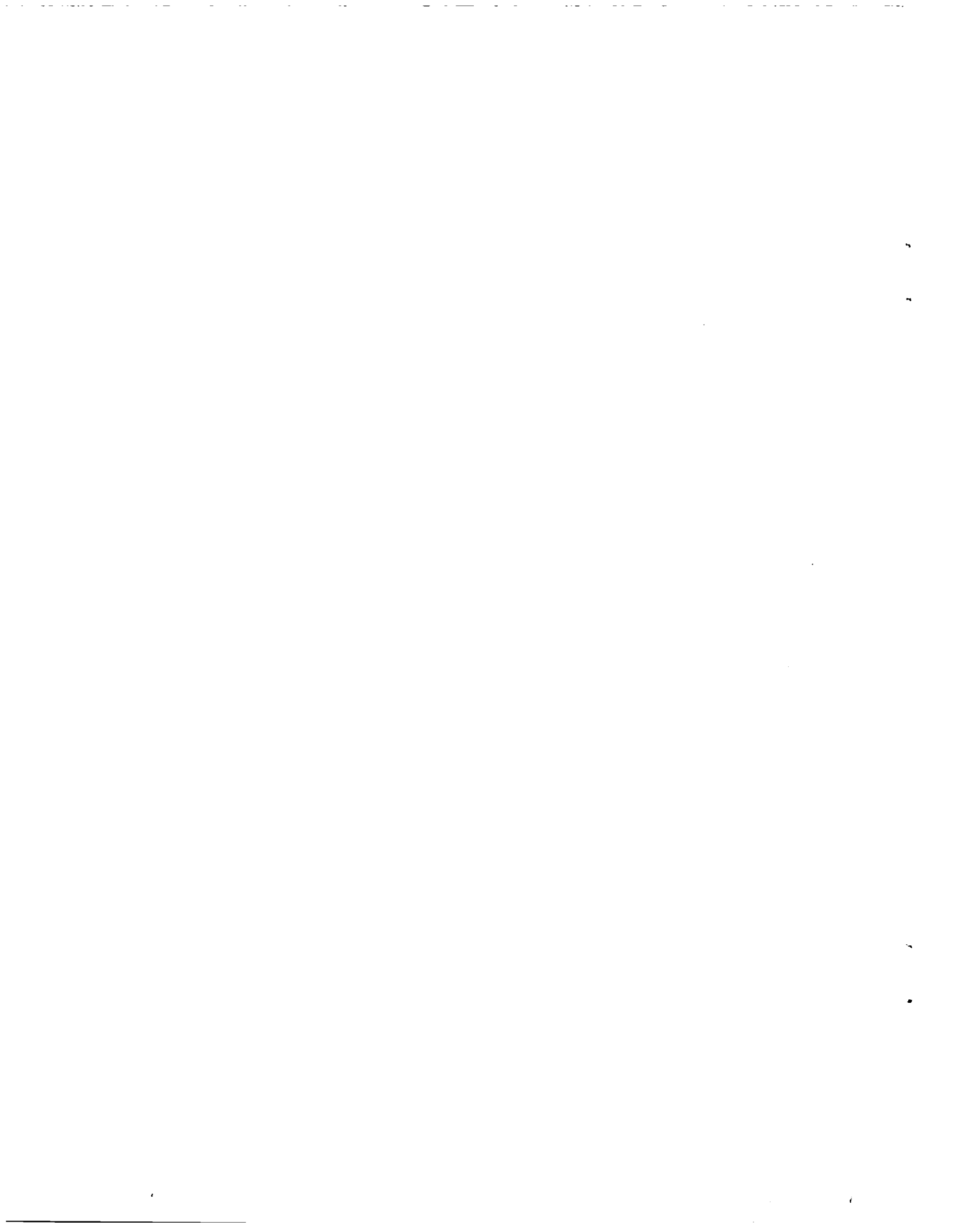*Lewis Research Center*
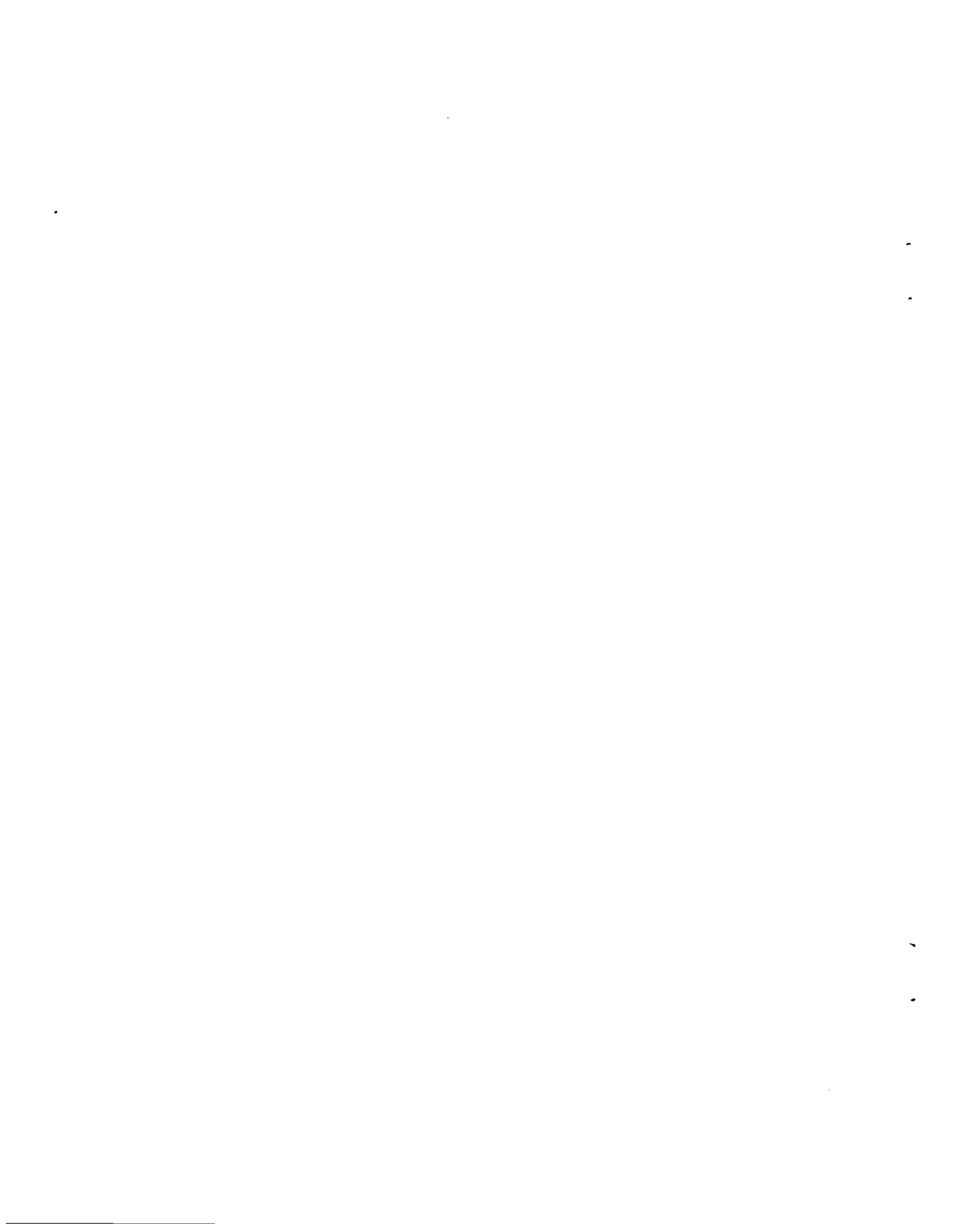*Cleveland, Ohio*

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Summary

A 200-kilowatt-thermal, pressurized, fluidized-bed (PFB) reactor, research test facility was designed, constructed, and operated by the NASA Lewis Research Center. This facility was established as part of a NASA-funded project to assess and evaluate the effect of PFB hot-gas effluent on aircraft turbine-engine materials that might have applications in stationary-power-plant turbogenerators.

The facility was for research and development work and was designed to operate over a wide range of conditions. These conditions included the type and feed rate of the coal and the sulfur sorbent; the ratio of coal to sorbent; the ratio of coal to combustion air; the depth of the fluidized bed; the bed temperature and pressure; and the type of test unit exposed to the combustion exhaust gases.

This report describes some of the unique techniques and components developed for this PFB system in order to carry out the program. One of the more important items was the development of a two-in-one, gas-solids separator that removed 95 + percent of the solids in 1600° to 1900° F gases. Another was a coal and sorbent feed and mixing system for injecting the fuel into the pressurized combustor. Also important were the controls and data-acquisition systems that enabled one person to operate the entire facility. The solids, liquid, and gas subsystems all had problems that were solved over the 2-year operating time of the facility, which culminated in a 400-hour, hot-gas, turbine test.

NASA has terminated its in-house experimental PFB research. The efforts put forth in this program may be of benefit to others who are considering such work for eventual commercial development of a PFB facility. Many of the technical problems solved in this small facility are expected to be scalable to larger R&D or commercial rigs.

Introduction

The Lewis Research Center (LeRC) designed, constructed, and operated a 200-kilowatt-thermal, pressurized, fluidized-bed combustor system. The system was needed to furnish high-temperature, pressurized gases for the evaluation of hot-gas turbine materials. The ultimate goal of this effort was the characterization of these turbine materials for service in coal-burning power-plant turbine blades and stators.

The pressurized, fluidized-bed (PFB) reactor was chosen because of the widespread national interest in the development and demonstration of this type of system for utility central-station power generation. Major features of this system are: in-situ sulfur capture without wet slurry sludge formation and more efficient power generation than by conventional coal plants with scrubbers. This improvement is estimated to be as high as 15 percent (ref. 1).

The use of a PFB reactor system to power a gas turbine is a challenging task in that the system not only must contain hot, high-pressure gases, but the gases must be cleaned of entrained solids and fly ash. Excessive particulates and contaminants in the exhaust can quickly erode and corrode the gas turbine blades and pollute the environment. Because of its proximity and abundance, the coal from Ohio and other Eastern States is a desirable fuel for utility plants in the East and the Midwest. Unfortunately, this coal has a high sulfur content. In order to capture the sulfur, a calcium-based mineral (limestone or dolomite) was mixed with the burning coal, and the calcium in the mineral reacted with the sulfur from the coal to form a solid residue of calcium sulfate. The fly ash in the combustion gases leaving the PFB reactor were removed by a gas-solids separator with a minimum loss in gas temperature and pressure.

A significant amount of R&D, worldwide, has been undertaken on PFB reactor systems over the past 10 years (refs. 2 to 5). Each has contributed something to the overall understanding of how to best operate a PFB reactor. This report is intended to illustrate and clarify the features of the LeRC PFB system, many of which are unique to this area of work. Just as many of the concepts used in the LeRC PFB reactor have been gleaned from the works of others, so some of the ideas evolved in this program might be of use to others working on PFB systems. The LeRC PFB reactor was unique in that the reactor bed had a tapered, conical shape, rather than the usual cylindrical shape. This conical shape, with a larger cross section at the top of the reactor bed, reduces the gas velocity at the bed surface and consequently reduces the amount of particulates being exhausted from the top of the bed. It was found (ref. 6) that the combustion gas fly-ash concentration is a direct function of this gas velocity.

Also, the LeRC system was one of the first PFB systems to flow 1500° + F gas through a gas turbine for long durations. The LeRC PFB will first be described in an overall view; then, details about the various subsystems will be described. The areas that presented the most difficulties and those for which future work is required will be mentioned.

General Description of PFB Reactor Facility

Figure 1 shows an artist's rendering of the facility. The facility was designed to study fluidized-bed combustion of coal with a sorbent used to remove the sulfur products during combustion. The PFB reactor was suspended from the second floor of the high bay area of the facility test cell. The control room, calibration gases for the gas analyzer, and the coal and sorbent feed system were located in the lower bay area. Not shown in the figure, but also located in the area, was the grinding, screening and storage area for the solids. There was also a room where samples of solids from the PFB reactor were screened, weighed, and prepared for chemical analysis. The data system (described in a later section) transmitted the data signals to the computers of the Research Analysis Center for on-line operational calculations. Also, the data parameter signals were recorded every 30 minutes for computations by the Lewis Research Center IBM 360/67 large processing computer. The entire system was designed so that the PFB reactor could be operated by just one person. A thorough safety analysis was made to ensure that all systems would be fail-safe and that redundant methods would be used to initiate critical shutdowns. The facility was designed to be able to run a wide range of independent variables: coal flow, coal-to-sorbent ratio, fuel-to-air ratio, bed pressure, bed temperature, type of reactor solids, reactor bed height, and location of heat exchangers within the bed. The hot exhaust gases from the PFB reactor were used to test turbine-blade materials and coatings. The PFB reactor was also used for testing potential boiler-tube materials.

Facility Subsystems

The eight subsystems comprising the PFB reactor facility, which will be described in more detail, are introduced in figure 2. An artist's rendering of the test cell is shown in figure 3, while figure 4 shows the addition of the turbine material testing and hot-gas cleanup system to the test facility.

PFB Reactor

Design details of the PFB reactor are shown in figure 5. The lower portion of the reactor was the combustion section, which was cylindrical and 34 inches high overall. The inside diameter of this section was 8.9 inches up to a height of 26 inches and then flared out to 11.5 inches at the top, 34 inches above the air-distribution plate. The upper portion of the reactor was conical, with an inside diameter of 11.5 inches at the bottom, where it joined the combustion section, and 18.5 inches at the top, 114 inches above the air-distribution plate.

As originally designed, the entire conical, upper portion of the reactor was insulated with a 3/4-inch layer of Babcock & Wilcox "Kaowool" between the boiler-plate outer shell and the refractory inner lining. This lining was A.P. Green "Lo-Abrade" refractory, varying in thickness from 4¼ inches at the bottom to 4½ inches at the top. The inside diameter at the top of the reactor was originally 21 inches. With this original design, the bed temperature was very uniform, but there was a high loss of heat from the combustion gases at the top of the reactor. Therefore, in this upper section of the reactor, the "Kaowool" insulation was replaced with Johns-Manville "Superex 2000" block insulation. The thickness was varied from ¾ inch at the bottom to 2½ inches at the top and across the top cap. The inner lining was again A.P. Green "Lo-Abrade" refractory, but cast to a thickness of 4 inches. Stainless-steel needles were mixed with the refractory to prevent crack propagation and were quite effective. The changes in the thickness of the insulation and of the lining reduced the inside diameter at the top of the reactor from the original 21 inches to 18.5 inches.

The bed temperature distribution was monitored with 10 type R thermocouples installed in Hastelloy wells at various levels inside the reactor, as shown in figure 6. (The symbols and abbreviations used in the schematics of the various subsystems are defined in figure 7.) Heat-transfer rates through the walls were monitored with type R thermocouples at various depths within the refractory lining at various levels and with type T thermocouples on the outer wall surface at various levels. The entire outer steel shell of the reactor was cooled with copper coolant tubes brazed to the surface to keep the shell surface temperature lower and to increase the allowable stress. When the reactor insulation thickness was increased, the water cooling on the conical section and top cap were eliminated, because the surface ran cooler. The changes in insulation thickness and elimination of external cooling made a significant improvement in reducing the heat loss from the combustion gases. The exhaust-gas temperature

normally ran about 150° F below the temperature at the bottom of the bed.

A viewing port was installed in the top cap of the reactor. The viewing assembly consisted of two quartz windows through which a TV camera surveyed the process. The camera was installed in a pressure vessel which was designed to withstand bed pressure in case of window breakage. The air purge on the inner window kept the inside surface free from contamination. Air pressure between the two windows was regulated so it was always 10 psig above bed pressure. An air purge through the camera containment vessel kept the camera temperature below 100° F. The TV camera had a remote zoom and focus, so that the top of the bed could be observed no matter where the bed level was maintained. The only viewing illumination came from the bed itself after its temperature was greater than 1500° F. The picture quality was excellent, and the exact height of the bed and the degree of fluidization could be visually observed.

A solids high-level detector (Nuclear Research Co.) was used to indicate when the bed level was too high. A cesium 137 radiation source mounted on the outside of the pressure vessel was detected by a radiation monitor on the opposite wall of the reactor. If the bed level became too high, it absorbed enough of the radiation to trigger an alarm. For radiation safety reasons, the source could be shielded and locked out if anyone wished to work on the inside of the PFB reactor.

Solids Handling Systems

Procurement and preparation of coal and sorbents. – The process coal was purchased from Whitehead Bros. Co., who in turn purchased the raw coal from Consolidation Coal Company's Pittsburgh Seam #8 (Champion) or Ohio Seam #8 (Georgetown) mines. Whitehead ground the coal to a "die piercer grind," $-12/+50$ mesh, and packaged it in 55-gallon drums.

The sorbents used were limestone rock purchased from M. J. Grove, Virginia, and dolomite rock from Davon Inc., Plum Run Stone Division, Ohio; both kinds of stone were sized to $-6/+100$ mesh. Attempts were made to have local companies grind and/or screen the sorbent, but the size variation and quality control were unacceptable; consequently, the sorbent was ground here at Lewis with an American Pulverizer Co. mill and was double screened with a Cleveland Vibrator Co. screen to a $-7/+18$ mesh. The ground and screened stone was stored in 55-gallon drums in a covered storage area.

Coal and sorbent supply. – The coal and sorbent feed system, the storage hoppers, and the fuel feeding and blending system are shown in figure 8. The "Acton" pneumatic-transport feed system was filled with one drum of coal or sorbent, the hopper valve was closed, the hopper was pressurized, and the solids were air-injected through the 2-inch transfer line, which contained a perforated hose designed to keep the solids aerated and moving. The transport gas was vented from the storage hoppers to a small bag-house filter which automatically back-flushed itself after each drum was transferred. Transfer time was 15 to 20 minutes per drum. The system was very susceptible to plugging from ice in the winter. If the drums were left uncovered outdoors, they tended to accumulate moisture which agglomerated the solids and completely plugged the system. Moisture also was able to enter the system through the supply hopper.

Coal and sorbent feed and blending. – The supply hoppers were suspended from load cells so that the contents could be continuously weighed. The solids then fell into the "Acrison" volumetric screw feeders. Both feed screws had variable-speed motors, but the coal feed was always run at 100-percent speed (105 lb/hr), so that the hoppers could be refilled as rapidly as possible. The sorbent feed rate was varied from 1 to 40 lb/hr. The nominal sorbent-to-coal ratio was 0.13 but was varied in different tests from 0.06 to 0.30. The coal and sorbent were fed into a blender and then into the bed feed system. All three feeders used hollow helices welded to a solid drive shaft. Several times the feeders clogged with oversize particles which caused a deformation of the feed-screw helix. The feed screws were strengthened by a solid rod welded into the inside of the feed-screw helices.

Reactor-bed feed. – The reactor-bed feed system and the manner in which the fuel from the blender was fed into the pressurized, fluidized bed are shown in figure 9. The fuel dropped through a shutoff valve (RKL Controls) into the lock hopper until an ultrasonic level switch (Automation Products) indicated the hopper had been filled with approximately 25 pounds of fuel (coal and sorbent). The coal, sorbent, and blender feed screws then turned off, and the top valve of the lock hopper closed. The lock hopper was then pressurized to within $+2$ psi of the feed-hopper pressure. The valve between the two hoppers opened, and the lock-hopper vibrator turned on for 60 seconds. After 60 seconds, the valve between the hoppers closed; the lock hopper depressurized; the top valve of the lock hopper reopened; the coal, sorbent, and blender feed screws turned back on; and the filling cycle was repeated. Once the fuel feed hopper was filled to its operating level (approx. 100 lb) the valve between the hoppers was prevented from reopening until the fuel

level again dropped below a given point. The feed hopper was pressurized to 1 psi above the PFB combustion pressure before the fuel shutoff valve below the hopper opened. The shutoff valve was prevented from opening until the bed had been preheated to more than 1400° F. It was found that if coal was introduced to a bed which was less than 1400° F, the coal agglomerated with the sorbent and could completely clog the bed.

The rotational speed of the fuel feed screw downstream of the feed hopper could be varied to change the fuel injection rate from 1 to 120 lb/hr. The screw could not run unless the fuel shutoff valve was opened. The valve could not open unless the screw hopper pressure was at least 0.5 psi greater than the reactor bed pressure, and it would close if the bed pressure increased too rapidly. (Before this interlock feature was adopted, the pressure balance occasionally reversed, and hot solids from the reactor bed were pushed back into the feed line and into the feed hopper.) The fuel was injected into the center of the bed along with a fixed injection air flow of 60 lb/hr. The fuel injection line was made from Hastelloy pipe which was externally coated with a ceramic for corrosion protection. If the injection air flow decreased or reversed in the feed line, the fuel shutoff valve closed. Any oversize particles in the feed solids system usually ended up plugging the injection line at the point where the injection pipe diameter decreased from 1.0 inch to 0.37 inch. If plugging occurred, the fuel feed system would shut off. It was found that if the fluidizing air to the bed were quickly shut off and the bed was depressurized, the injection line could be disassembled, cleaned out, and reassembled with minimum bed cool down (i.e., reactor bed temperature dropping no lower than 1400° F). The bed could then be refluidized, and the fuel could be restarted without having to preheat the bed. The reactor bed temperature was controlled by the fuel injection rate, which was set by manual adustment of the feed screw rate. Once the system reached steady state (6 to 8 hr), the screw speed was not varied, and the bed temperature usually stayed within ±25° F of its desired value.

Solids-Removal and Exhaust-Cleanup Systems

Reactor solids removal. – The solids-removal system shown in figure 10 was used to control the solids level in the PFB reactor. The accumulating solids were removed from the top of the bed by the solids-removal screw, were cooled, and then fell through the top valve (Kaymr Valve Co.) into the dump hopper. The top valve of the dump hopper remained open for 15 minutes and then closed, and the hopper depressurized. Then, the bottom valve of

the hopper opened, the hopper vibrator was energized, and the solids dropped out of the hopper. After 1 minute, the bottom valve of the hopper closed, and the hopper repressurized to within 1 psi of the bed pressure. The top valve then reopened for another 15 minutes, and the cycle was repeated.

Initially, the solids from the hopper simply dropped into a drum on a weight scale. But each time the bottom valve of the hopper opened, dust escaped to the test cell. So, a cloth filter bag (Cleveland Canvas Goods) was installed on the outlet of the dump hopper to contain the solids. This eliminated the dust problem. But if the solids did not cool enough in the hopper, they would burn through the bag. The bed height could be maintained at six different levels between 28 and 99 inches above the air-distribution plate by installing the solids-removal screw in one of six available discharge ports. Originally, both the removal screw and its housing were water-cooled.

The solids-removal screw was made from copper with a coating of nickel for corrosion protection. It was found that too much heat was being lost from the top of the bed and the copper was eroding, so the screw was redesigned. The portion of the screw which protruded into the bed was fabricated from uncooled Hastelloy, and the rest was left water-cooled. This screw material stood up well, and the bed heat loss was greatly reduced. The screw would occasionally jam from oversized particles in the bed. It was found that if the rotation was reversed, the screw would clean itself and it could then resume its forward direction. This reversing feature was put on an automated cycle, which was activated whenever the screw speed dropped too low. No further problems with jamming occurred. Initially, some problems with moisture in the cooled solids from this screw caused the hopper system to plug. To overcome this, the following changes were made: (a) A slight nitrogen purge was put on the solids-screw discharge dump line; (b) the water cooling was not turned on until the bed reached 500° F; and (c) the differential pressure across the hopper shutoff valves was increased to 5 psid so the solids would be blown through the valve. No further problems with plugging occurred.

Exhaust-gas cleanup. – The details of the exhaust-gas cleanup system are shown in figure 11. The exhaust gas from the PFB reactor test section was cooled and then cleaned with single-stage, cyclone separators (Anderson-Ibec Co.) before flowing to the back-pressure control valve. The system used one to four separators operating in parallel, so that for various combustion-gas flow rates and PFB-system bed pressures, optimum gas cleanup could be obtained. The reactor-gas solids removal hopper

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system for the cyclone separators is similar to the reactor-level discharge-hopper system described previously.

For most of the testing, all four cyclone separators were used. Since the separator solids were dumped into a common hopper system, without shutoff valves, the separators could not be individually purged while they were in operation, and if one plugged, it could not be reopened. It was found to be best not to cool any portion of the exhaust system until the reactor vent gas temperature went above 300° F. If cooling was introduced too soon, condensation of moisture in the exhaust gases caused the solids to collect in the condensate and plug the cyclones or the connecting piping. Almost all problems with plugging occurred at startup. The damp fly ash also caused problems with the Kaymr ball valves. The valves had Stellite seats and hard chrome plating on the balls. The flyash would cling to the ball and force itself between the seat and the ball until the valve actuator could no longer force the valve ball open or closed. The valve seats were remachined so that only a sharp knife-edge was in contact with the ball. The valves became self cleaning and functioned quite well thereafter.

Particulate sampling. – The most critical aspect of the hot-gas turbine material testing was the amount of particulates in the bed exhaust. In order to determine if the exhaust gas was being cleaned sufficiently, 25 percent of the bed combustion gas flow was passed through a solids-collection unit. The unit consisted of a cyclone separator similar to the fly-ash cyclone separators and a 10-micron (nominal) filter or a cloth filter bag on the exit of the line. The gas flow into the unit was kept relatively constant by a manual valve adjustment as the unit became filled. Samples were taken for 1 to 3 hours. The solids content from this solids-collection unit was weighed and analyzed to determine the net quantity and size of solids collected from the combustion gases that had flowed through the unit.

Combustion-Air Systems

Reactor-bed pressure and flow control. – The combustion-air supply system to the bed is shown in figure 12. The reactor bed and its systems were designed to operate at pressures up to 150 psia. The reactor combustion air was supplied from the Lewis 125-psig service air system. This service-air pressure limited the reactor-bed maximum pressure to about 100 psia. The bed pressure was regulated by a back-pressure control valve (Annin Co.) in the combustion-gas exhaust line, and the valve was controlled by a closed-loop controller that sensed bed pressure.

This back-pressure control valve required frequent periodic maintenance, because the gas/solids separators did not always work efficiently. The fly ash would erode and clog the valve and its seat. Better cleanup of the combustion gas reduced the required maintenance, and the erosion was slowed by use of a ceramic-coated seat and plug. The combustion air flow rate to the reactor was held constant with the use of a closed-loop flow-control valve. Flow rates could be varied from 200 to 1100 lb/hr.

Combustion-air inlet temperature control. – The reactor inlet air to the bed could be preheated by heat exchangers in the combustion-gas exhaust system. The inlet air temperature was controlled by an automatic system that mixed the hot air from the heat exchanger with ambient-temperature air. The system was designed to operate from ambient temperature to 400° F, but most of the tests were made with an inlet air temperature of 100° F.

Reactor vent gas bypass. – At the start of a test series, the exhaust gases bypassed the materials test section or the hot-gas turbine until the bed was preheated and brought up to operating conditions. The bypass loop consisted of a gas cooler and a gas/solids separator to cool and clean the exhaust gas before it was vented to atmosphere. When gas flow was ready to be initiated into the test section, the gas shutoff valve in the main combustion gas system was opened, and the throttle in the bypass loop was slowly closed.

Air-distribution plate. – The combustion air entered the reactor bed at the bottom through an air-distribution plate. The original distribution plate was made from Hastelloy, with eighty-four 0.078-inch-diameter injection holes. There was no problem with the distribution plate getting hot, but the sorbent and ash kept plugging the holes, even when attempts were made to keep a constant air purge flowing through the holes whenever the bed was filled. The plate was redesigned with a bubble-cap design (9 caps). The new plate had the same air flow area as the first plate. The injector had larger holes which did not plug, but the sorbent still tended to migrate through the air-distribution plate and accumulate in the bottom cavity of the combustor. This area could be drained while the reactor was in operation, but some reinjection of the sorbent through the distribution plate occured, causing errosion of the plate and injection holes. The final (9-cap) air-distribution plate was made from AISI type 304 stainless steel, the only cooling of the plate being from the air going through the injection caps. Some development is still required in this area.

Reactor-bed nitrogen quench. – An emergency shutdown was programmed to occur whenever the

reactor pressure exceeded 100 psig, when any coolant water outlet temperature (in systems which are internal to the bed) exceeded 180° F, or when there was a loss of service air pressure to the facility.

The shutdown sequence turned off the fuel, the air to the distribution plate, and the air to the fuel injection line. It depressurized the bed by opening the back-pressure control valve and the vent-gas bypass valve. A nitrogen purge was then automatically turned on to the reactor through the distribution plate and the fuel injection line. This nitrogen purge quickly cooled the bed and quenched any further reaction.

Reactor Preheater Burner

Before the coal-and-sorbent (fuel) mixture could be injected into the reactor bed, the material in the bed had to be preheated above 1400° F. In order to preheat the bed, the high-pressure natural-gas burner shown in figure 13 was used. The LeRC-designed, two-stage burner utilized a swirl-cup burner for the first stage in an uncooled 4-inch-diameter pipe. The bed was first preheated at 40 psia up to 500° F. The natural gas flow rate was controlled by a closed-loop controller which kept the burner combustion temperature at 1400° F. In order to get enough heat into the bed to overcome the heat losses to the walls and to the heat exchangers, the burner second stage had to be used. Before the second stage could be turned on, the bed had to be fluidized or else local overheating would occur. The second-stage burner consisted of a natural-gas injection port upstream of an air-cooled sleeve. It was designed to operate close to stoichiometric conditions and could not be turned on unless the main burner was above 1300° F. Natural gas flow to the burner was limited by a controller which prevented the total fuel/air ratio of the burner from exceeding stoichiometric conditions while the air flow rate could be varied from 200 to 1000 lbs/hr. The air-cooled sleeve was damaged a few times when the burner was operated at too high a temperature or when back-flowing reactor solids plugged the cooling passages and then caused local overheating.

After the material in the bed was heated above 1400° F, the fuel was injected into the bed at a low rate. When the bed temperature started to increase rapidly, the second-stage burner was turned off, and the fuel (coal-and-sorbent) flow rate was increased. When the bed reached 1600° F, the air to the main burner was slowly throttled back, while the main air to the reactor air-distribution plate was slowly increased. When the air to the burner was being throttled back, the controller automatically decreased the fuel flow to maintain the fuel-air ratio until a minimum fuel flow was reached. When the

burner temperature started to increase with further air throttling, the fuel and air were shut off; the main combustion air flow was then set to its desired value. The bed pressure was slowly increased from 40 psia to the desired operating pressure (nominally, 80 psia).

Water Cooling System

Flow system. – The reactor water-cooling system shown in figure 14 utilized an existing cooling-tower water system. A filter and boost pump were located in the PFB facility. If the cooling-tower water pressure dropped below 40 psig, the pump automatically turned on; if the pressure downstream of the pump dropped below 35 psig, the domestic-water backup system turned on. The domestic water system was protected from cooling-tower water contamination by a back-flow preventer.

Reactor heat exchangers. – The reactor bed operates nominally from 1600° to 1900° F. The temperature could be obtained by using excess combustion air and varying the fuel/air ratio to vary the temperature in the bed. In order to change the fuel/air ratio independently of the bed temperature, provisions were made to vary the heat-exchanger area. The original reactor design provided 26 ports, each of which could accomodate a heat-exchanger assembly, an uncooled material specimen, or a blank-off flange, in any combination desired. Installation of any configuration required no disassembly other than draining the bed material below the desired installation port. Sixteen of the heat exchangers and/or specimens could be mounted in the bottom 30 inches of the bed, and 10 in groups of two could be distributed across the upper portion of the combustor. The heat exchangers each had seven 1/2-inch o.d. tubes with 3/8-inch o.d. concentric tubes inside the 1/2-inch tubes. Initially, the water flow through each of the seven tubes was in parallel (fig. 15(a)). This caused a problem, since the flow and temperature alarms measured the total water flow and temperature rise through any one heat exchanger. If one of the annular passages plugged or started to overheat, the flow would shut off to that tube, and the other six tubes would average the flow and temperature so that an alarm would not occur. The heat exchanger was redesigned (fig. 15(b)) so that the cooling water flowed in two parallel paths—one path having three tubes in series, and the other having four tubes in series. Each water outlet had its own alarms. The flow through the three-tube leg was orificed to give the same flow per unit of tube area as the four-tube path. At the same time, the bottom of the reactor combustor was redesigned to eliminate 8 of the 16 possible heat exchangers. This was done so that a cast-ceramic-

lined bottom bed wall could be used. If 16 rows of exchangers or material test specimens were used, the holes would be too close to each other, and the ceramic liner would break apart. There were no failures with the new heat-exchanger design. If none of the heat exchangers were desired, the reactor ports could be plugged, leaving no blockage in the bed. The heat-exchanger locations shown in figure 14 retained the numbering system from the original 26-port design.

Combustion-Gas Analysis System

The gas-analysis system shown in figure 16 was used to obtain combustion gas samples from various parts of the PFB reactor system. Gas samples were obtained from the top of the combustor (A), one of six side ports (B), and downstream of the turbine exhaust (C). The sample line was a 1/4-inch-diameter, stainless-steel tube with an 80 psig steam jacket around the line. The steam heat maintained the gas sample at 325° F, so that any hydrocarbons in the exhaust would not condense inside the line. The gas-analysis system was a LeRC assembled system using commercial, laboratory-type instruments for each gas constituent. The O_2, CO, CO_2, and HC analyzers were from Beckman Co., the SO_2 analyzer from Thermo Electron Corp., and the NO_2 analyzer from Air Monitoring Inc. Figure 17 is a photograph of the gas analyzers. The gas-analysis system was calibrated daily with calibration-grade gas mixtures. The system had fair repeatability and had an overall accuracy of ±5 percent of the reading.

The gas sample line had an inside diameter of only 0.18 inch; consequently, solid particles entrained in the sample gas would sometimes plug the line. A large-capacity, 10-micron filter was used to protect the system. The sample line up to the filter was purged continuously whenever a gas sample was not being taken to prevent the line from plugging. This system worked satisfactorily. The technique of gas and/or solids sampling from the side of the bed was marginally successful. The system was designed with 0.30-inch i.d. sampling tubes. Attempts to obtain a solids sample by blowing the solids through the line to a collection device caused the line to plug. No further attempts were made to redesign the probe as a solids sampler. It was then decided that combustion gases could be sampled with the same tubes if filtering were done in the bed so that the line would not plug with particulates. A spring-loaded ceramic filter was installed in the solids-removal port holes, and gas samples were taken. After a short time, the ceramic filter fractured. If gas analysis from within the bed is desired, further work must be done. The steam-jacketed line worked well in maintaining the temperature of the sample. But if the steam system had not already existed in the area, an electrically heated line would have been chosen, as it is a much simpler system. The sample line failed from corrosion at the section where the steam jacket ended. A major portion of the sample line was replaced with an electrically heated, flexible, stainless-steel sample line with a 7/16-inch i.d. (Heat/Line Products). The line worked just as well as the steam-jacketed line, but it had only been in operation for a short time prior to the end of the program.

Materials Testing Systems

The major reason for running the PFB reactor was to investigate various materials both in the bed and as turbine blades or stators. The materials were investigated for corrosion, erosion, and deposition (refs. 7 to 9).

In-bed samples. – The water-cooled heat exchangers shown in figure 15 could be installed in 18 different locations at various heights, as shown in figure 7. Instrumented, uncooled test specimens were installed at various locations in the bed in the same access ports. Only preliminary tests were performed, since the wall temperature at which the samples ran was not representative of temperatures which would be experienced in boiler tubes. Further work in this area could be performed.

Carousel wedge tester. – Initial turbine materials tests were performed in the reactor combustion gas stream at the reactor exit with no gas cleanup. The combustion exhaust gases were accelerated through a nozzle and impacted on six different test specimens which were rotated in front of the nozzle. Severe erosion of all materials occurred, and it was obvious that hot-gas cleanup would be required to get long life from turbine blades (ref. 7).

Hot-gas cleanup. – A two-stage, gas/solids separator (Aerodyne Development Corp.) was installed downstream of the reactor exhaust gas exit, as shown in figure 18. In addition, a large ceramic filter (Aerodyne Development Corp.) was installed to remove the smaller fly-ash particles. Initial testing without the ceramic filter elements installed showed that the heat loss through the ceramic filter housing was excessive; so the filter was bypassed.

Figure 19 shows the details of the separator design. The first stage of cleanup is a simple cyclone separator. It is ceramic lined and insulated to decrease the heat loss from the exhaust gases. The first-stage inlet flow was split, with two-thirds of the flow going up to the second-stage downswirl inlet, and one-third of the flow going down to the second-stage upswirl inlet. The two swirling gas streams met inside the second stage and then exited out the top of

the separator. The first separator tested had a large gas leak from the first- to the second-stage drain legs and also out the top of the first stage to the exhaust. The efficiency would vary from 25 to 90 percent. After the unit was repaired to seal it properly, the efficiency did not show a great improvement. When the separator was not efficient, high erosion rates were apparent on the test turbine stators and rotor blades. The separator was then modified by elimination of the second-stage gas upswirl and installation of a 6-inch-long gas oulet tube down into the second stage. This modified separator worked quite well, although it had a higher gas pressure drop. At low solids loading, the efficiency was better than 95 percent (ref. 6).

The solids collected by the cyclone separator dropped down into the two legs, which then drained into a dump hopper by alternate opening of the valves in each leg in a timed cycle similar to that of the reactor solids removal system described earlier.

Turbine-blade cascade tester. – When it was found that the efficiency of the cyclone separator was extremely important to the life of turbine blades, turbine testing was temporarily stopped, and effort was diverted to improving separator performance. In an attempt to get some material erosion data while separator modifications were being evaluated, it was decided to test non-rotating specimens in the exhaust gas downstream of the two-stage separator. A tapered, rectangular exhaust duct was installed at the same location as the test turbine. Various material samples were installed at different locations in the duct to get velocity-geometry effects. When the cyclone separator was finally operating properly, a full-scale automotive turbine was installed.

Gas-turbine test section. – The test unit was a 6-inch-diameter, 50 000-rpm, gas turbine which was subjected to the hot gases from the PFB reactor. All tests were run at approximately the same conditions: 1500° F inlet gas temperature; 80-psia inlet pressure; and 670 ±50 lb/hr gas flow rate.

A constant pressure ratio was maintained across the turbine. The turbine output energy was absorbed by an air brake which controlled the turbine speed to 40 000 rpm. Because of the low bed flow rate, the existing turbine could not be run as a full-emission, axial-flow turbine. The inlet stator flow area was reduced by 90 percent by reduction of the annular passage from 360° to 30°. The same turbine which was used as an air brake was also used as an air starter. When little or no flow was passing through the power turbine, the braking turbine was used to rotate the power turbine to prevent uneven particulate coating or erosion. The turbine was heavily instrumented and quite complicated to install and maintain. With high solids loading (0.3 to 1.5 grains/SCF), the turbine blades eroded significantly

in 13 hours. When the cyclone separator was working well, solids loadings were below 0.1 grain/SCF, and a 400-hour test left the turbine wheel still in good condition. A more detailed description of the test turbine and results are contained in reference 10.

Instrumentation and Controls

A block diagram of the instrumentation and controls is shown in figure 20. The two main components were the programmable controller (Gould Corp., Modicon Div.) and the data and alarm system (ESCORT). The switches and controllers were located on four panoramic control panels, shown in figure 21. Each control panel operated one of the major systems (i.e., gas, solids, water, and turbine) of the PFB reactor.

Programmable controller. – The programmable controller (PC) is a solid-state device which can operate in an industrial environment. It was simple to program by use of relay ladder logic. It was reliable, easy to maintain, and used less space than the equivalent number of relays and timers which it replaced. The system basically consisted of inputs, outputs, and a central processing unit (CPU). The 160 input modules received 110-volt input signals from the flow, pressure, level, limit, temperature, and control-panel switches and the alarm relays. The 96 output modules supplied 110-volt (3-A) power to the solid feed screws, solenoid valves, vibrators, motors, panel lights, and annunciators. The CPU contained all the logic necessary to provide the switching, controlling, and timing functions, and was programmed by the use of a cathode ray tube (CRT) programmer. In addition to the 110-volt input and outputs, the system had four (0 to 10 V) analog inputs and outputs and two binary coded decimal (BCD) inputs and outputs. All permissives, interlocks, and timing were accomplished by programming ladder diagrams into the CPU. The CRT programmer also had provision for a hard-copy printout of the program for a permanent record. Changes to the program could be accomplished on line with the PFB reactor in operation. Besides the standard relay and timer logic networks, the PC could do calculations. It could add, subtract, multiply, and divide and store the results in storage registers. In one phase of the program, the feed hopper weight was used as an analog input. The PC calculated the weight flow from the hopper by use of a least-squares fit of the change in hopper weight versus time. The resultant flow calculation was displayed on a digital display and stored in a first-in, first-out register stack, so the present rate could be compared with previous calculated rates. The rate was also outputed to the data system by use of one of the analog outputs of the PC. The PC had a

magnetic-core memory and would retain its program even with loss of power.

Data and alarm system. – A multichannel data and alarm system, "ESCORT" (ref. 11), was used for all data acquisition and most of the alarms and shutdowns. The system is flexible, with selectable features to fit the needs of the facility and has the capability to acquire 300 channels of data, convert the data to engineering units, and do simple calculations. A relay interface was provided which could be triggered by any data word or calculation. As many as two low and two high limits per channel were available for use as alarms or shutdowns. There were 15 digital displays, updated every 4 seconds, to continuously display data or calculations. In addition, a CRT display was used to view up to 17 different display formats. Each CRT display could contain 40 data words with labeled descriptions and units. There was also a provision to make a hard copy of any CRT display whenever desired. The Digital Equipment Corp. PDP 11 minicomputer also interfaced with the central LeRC data-collector system. The data collector recorded all raw data signals on magnetic tape which was then processed by an IBM 360 computer. The 360 computer can do elaborate batch calculations and output to a high-speed line printer. As configured for these tests, the data-collector system automatically recorded one scan of data every 30 minutes. A 16-channel voltage sensor (continuous abort monitor) was utilized to monitor critical parameters in order to provide instantaneous facility shutdown. The monitor provided both low and high alarms and was redundant to the ESCORT system.

Concluding Remarks

The design of the LeRC PFB reactor facility was begun in January 1975. By June 1976, the support systems had been installed at the test site. The PFB reactor unit was constructed and instrumented, and initial "shake-down" operations started with the burning of coal in the bed in January 1977. By August 1977, the PFB reactor had been operating for 650 hours.

From September 1977 to February 1978 the PFB reactor was extensively remodeled, especially the combustor portion of the reactor, in which the internal heat exchangers were reduced in number, and the entire reactor was reinsulated. An exhaust gas particulate clean-up system was installed in preparation for hot-gas turbine testing. Testing was restarted in March of 1978. The PFB reactor was in an operational state until June of 1979. During this time, numerous parametric combustion tests were made with different coals and sorbents, different bed heights, various bed operating temperatures and pressures, and different degrees of internal bed cooling. This amounted to over 1200 hours of testing at various conditions, 630 hours of which were carried out at relatively constant operating conditions with a hot-gas turbine using the PFB reactor exhaust gases. The turbine test results are presented in references 8 and 10. An additional 200 hours of testing were also accumulated testing materials in a cascade test section.

The LeRC PFB reactor facility has now been deactivated. If the unit were to be placed in operation again, the experimental program would benefit from additional work in the following areas:

1. Development of a hot-gas cleanup system which is 95+ percent effective in removing the 5- to 10-micron particles from the gases and yet has a minimum effect on the gas pressure and temperature drop.

2. Testing at bed pressures as high as 190 psia; the present reactor was tested only to 90 psia. The present system and reactor were designed for 190 psia conditions. Additional air compressors would have to be used to increase the air-supply pressure to the PFB reactor.

3. Testing turbine blade materials in a replaceable-blade, hot-gas turbine. Such a turbine was designed for PFB reactor testing but was never used. It could be used to screen many turbine-blade materials in a shorter time span.

4. Redesign or modification of the solids dump valves. The PFB reactor system ball valves used in the exhaust-gas solids lines became inoperable intermittently because of a buildup of damp solids.

5. Redesign of the PFB-reactor air-distribution plate to eliminate any plugging with solids or erosion of the plate.

6. Redesign of the PFB reactor, second-stage, preheater-burner, air-cooled sleeve to prevent its occasional failure.

7. Provision of alternate means of controlling the PFB reactor pressure to eliminate occasional maintenance required on the back-pressure control valve.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 1981

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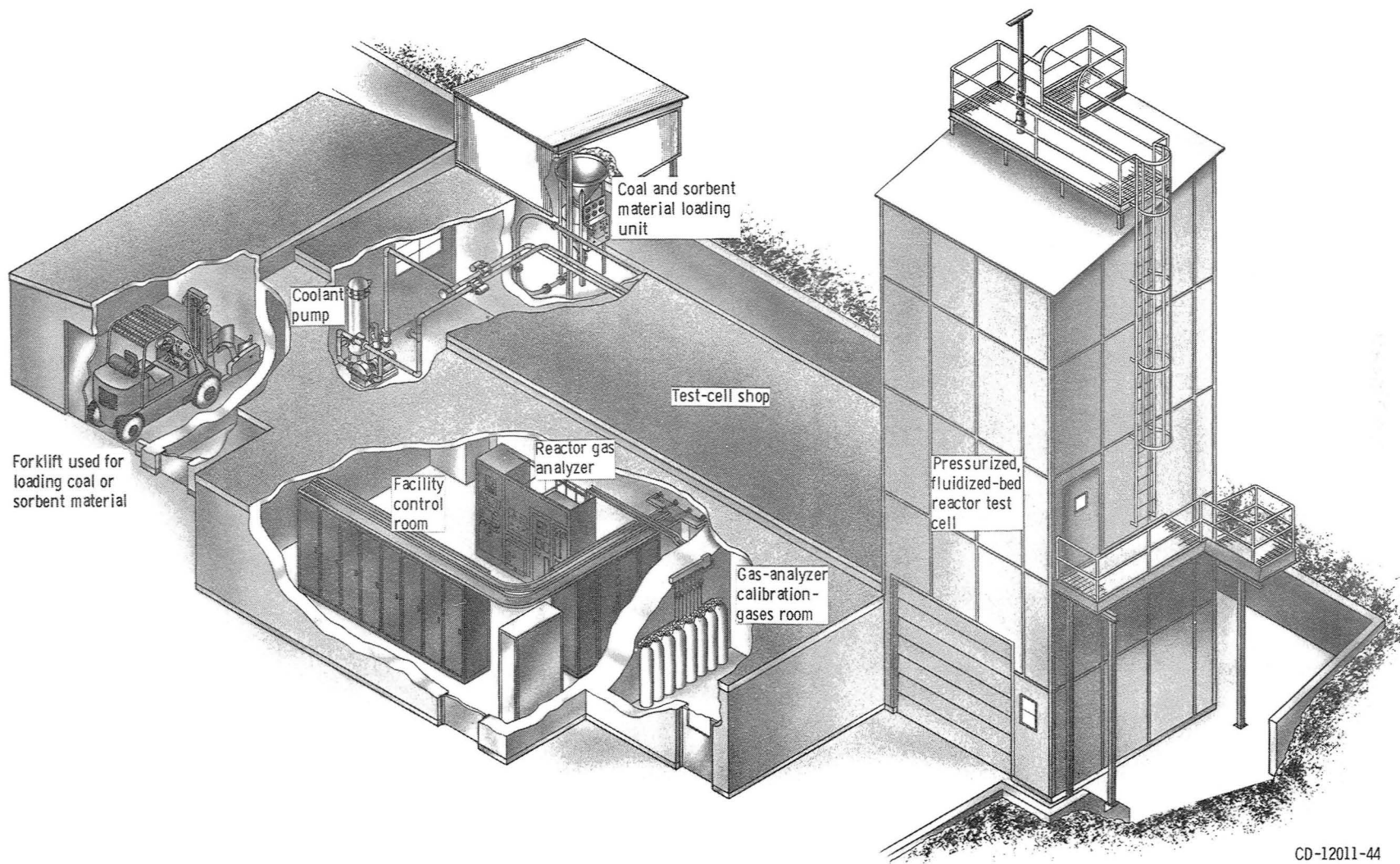
Figure 1. - Lewis Research Center's pressurized, fluidized-bed reactor facility.

Hot-gas turbine
materials testing

Instrumentation
and controls

Combustion
gas analyzer

Pressurized
fluidized-bed
reactor

Water cooling
system

Preheater
burner system

Solids handling
system

Combustion-
air system
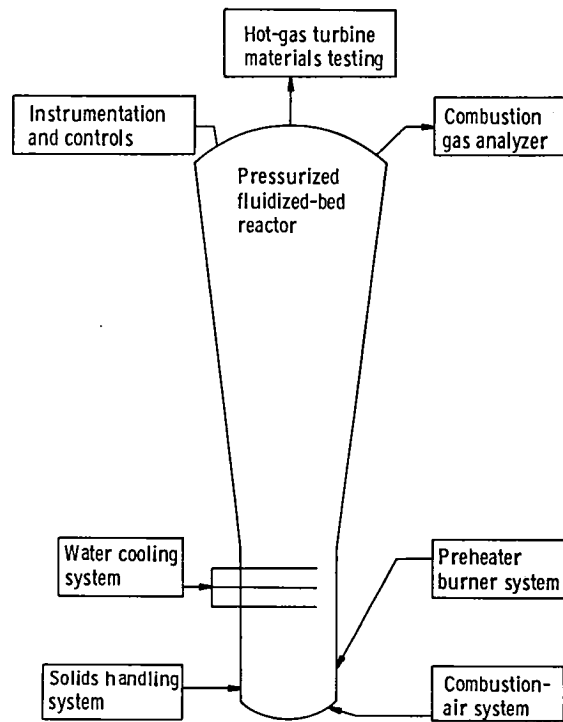
Figure 2. - Pressurized, fluidized-bed reactor facility subsystems.

Vent stack

Bag filter

Preheater/cooler

Coal hopper

Limestone hopper

Limestone/coal blender

TV camera

Feed hopper

Particle separators

Turbine blade tester (CWT)

Fluidized bed

Solids removal screw

Screw hopper

Sample filter

Vent particulate hopper

Screw feeder

Solids removal hopper

Ash hopper
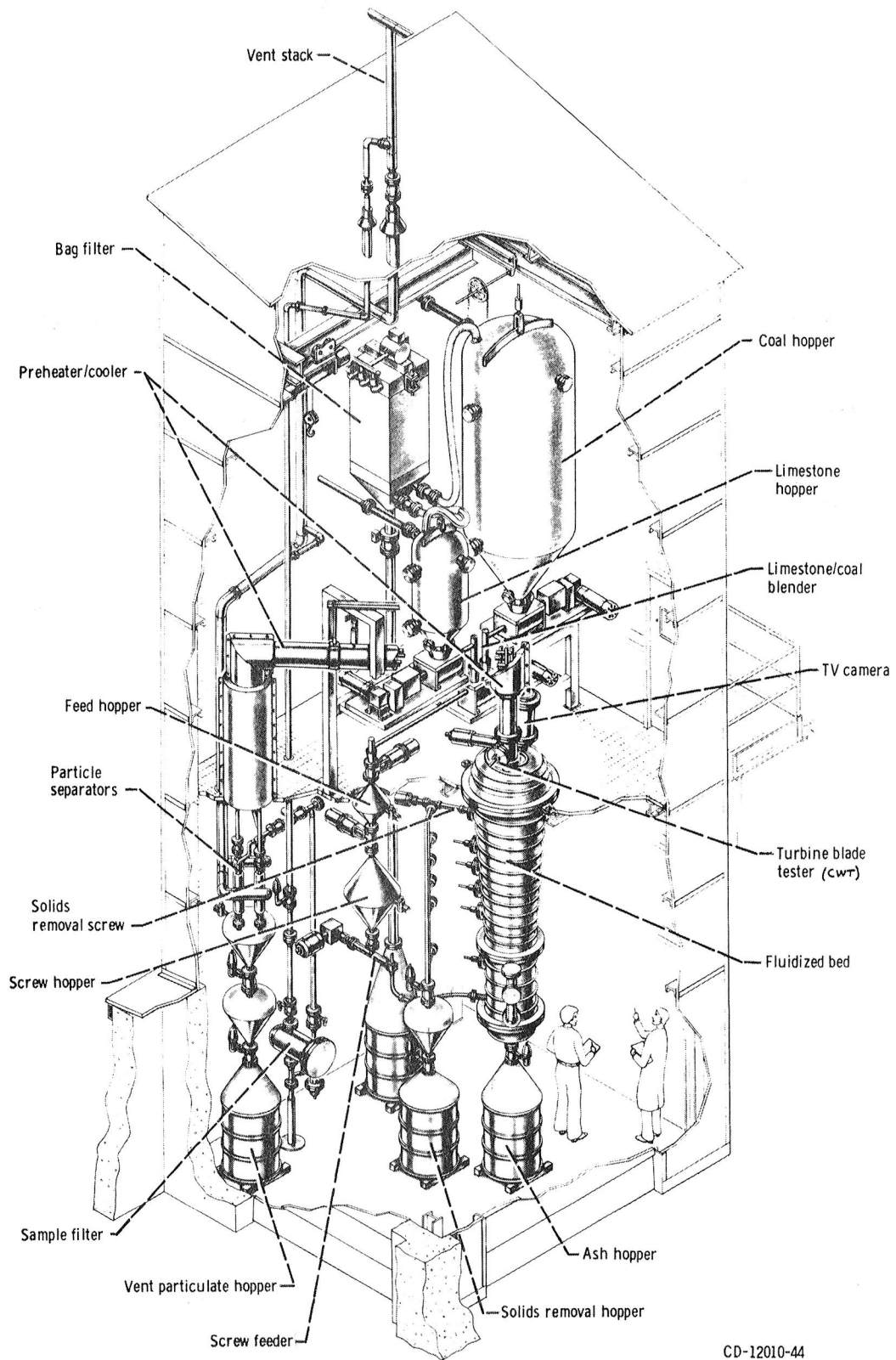
CD-12010-44

Figure 3. - Pressurized, fluidized-bed reactor test cell.
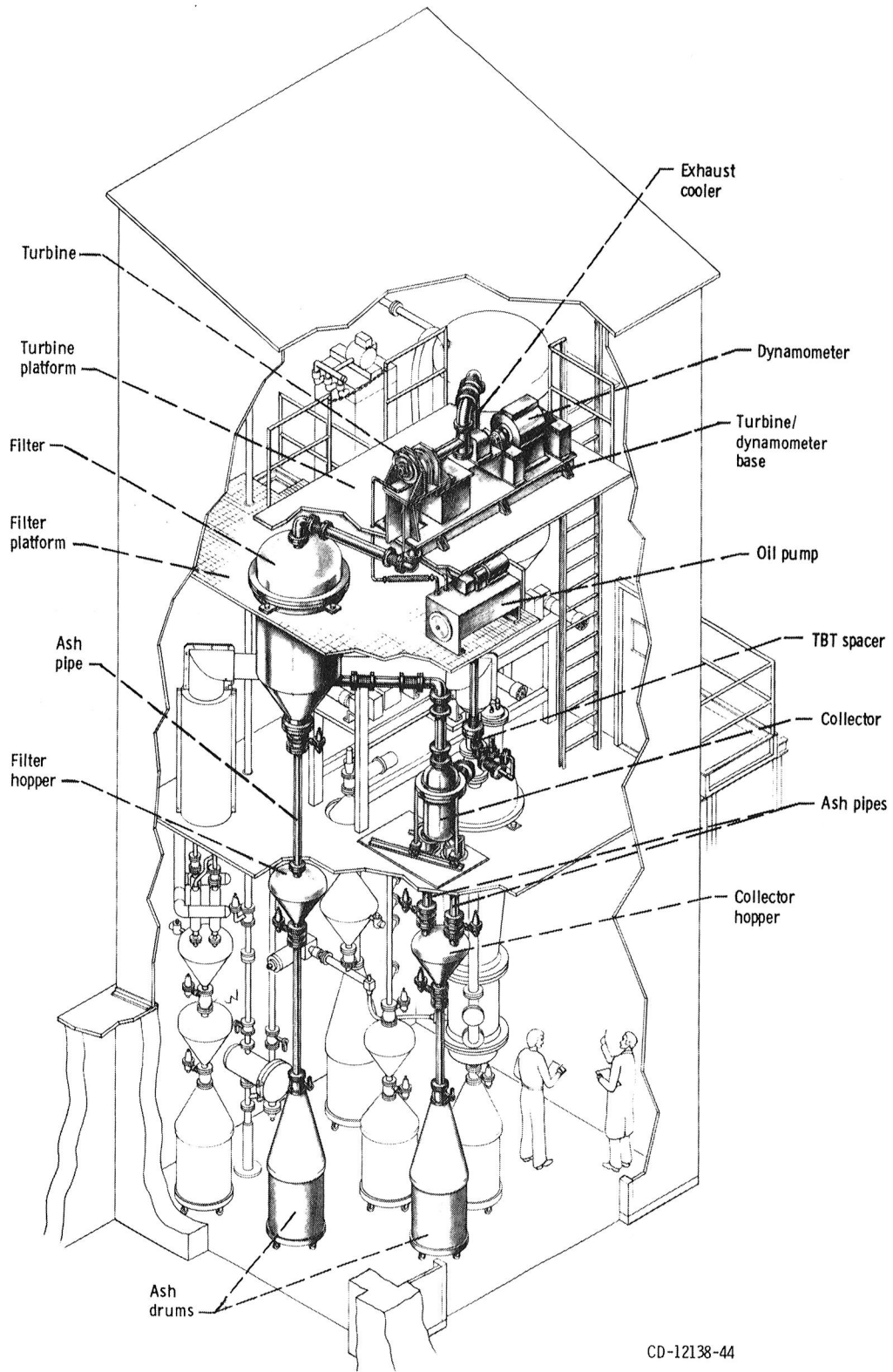
Figure 4. - Turbine-test, hot-gas cleanup system.

CD-12138-44
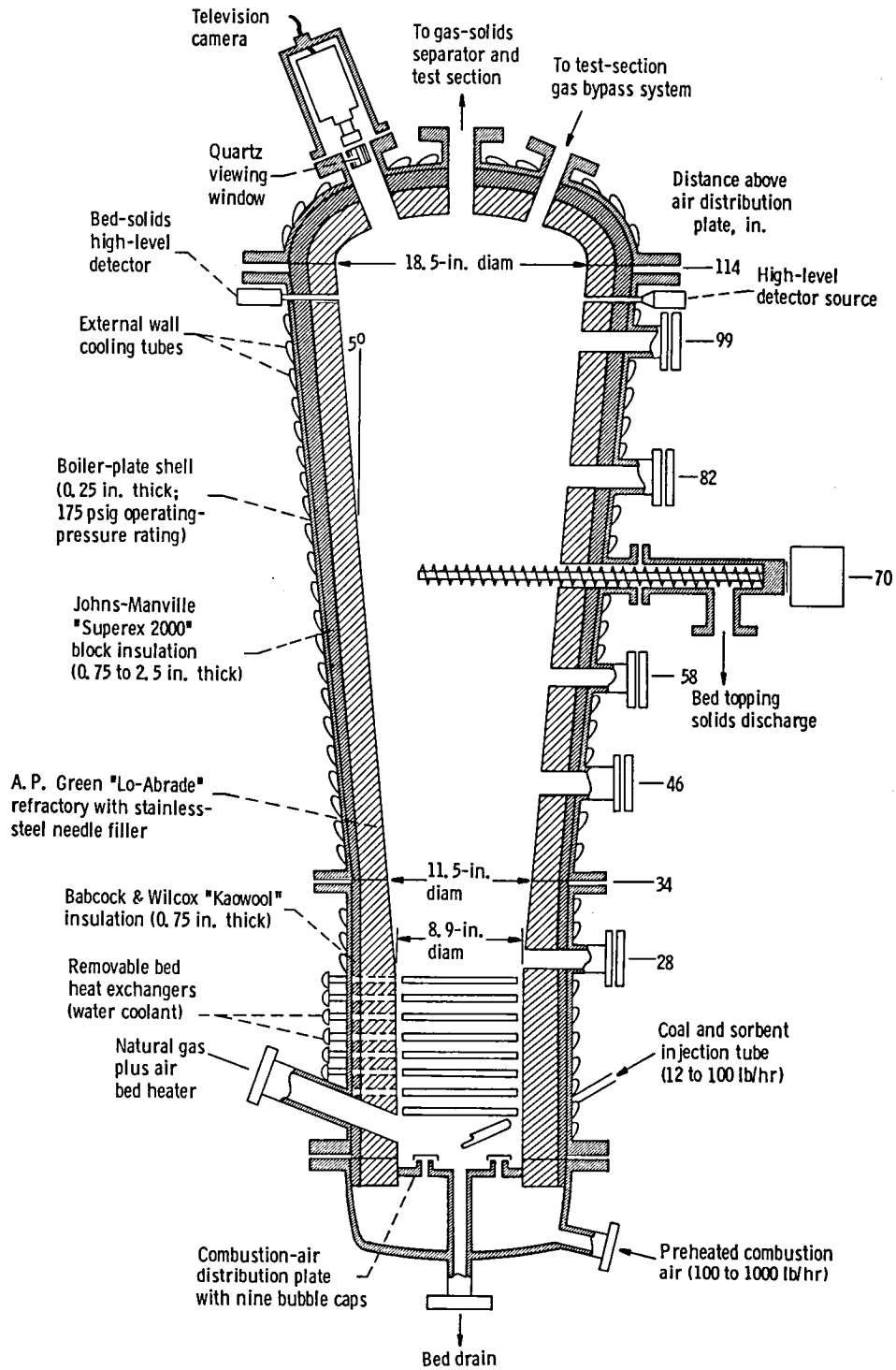
Figure 5. – Cross-sectional view of Lewis PFB reactor. (Drawing not to scale.)
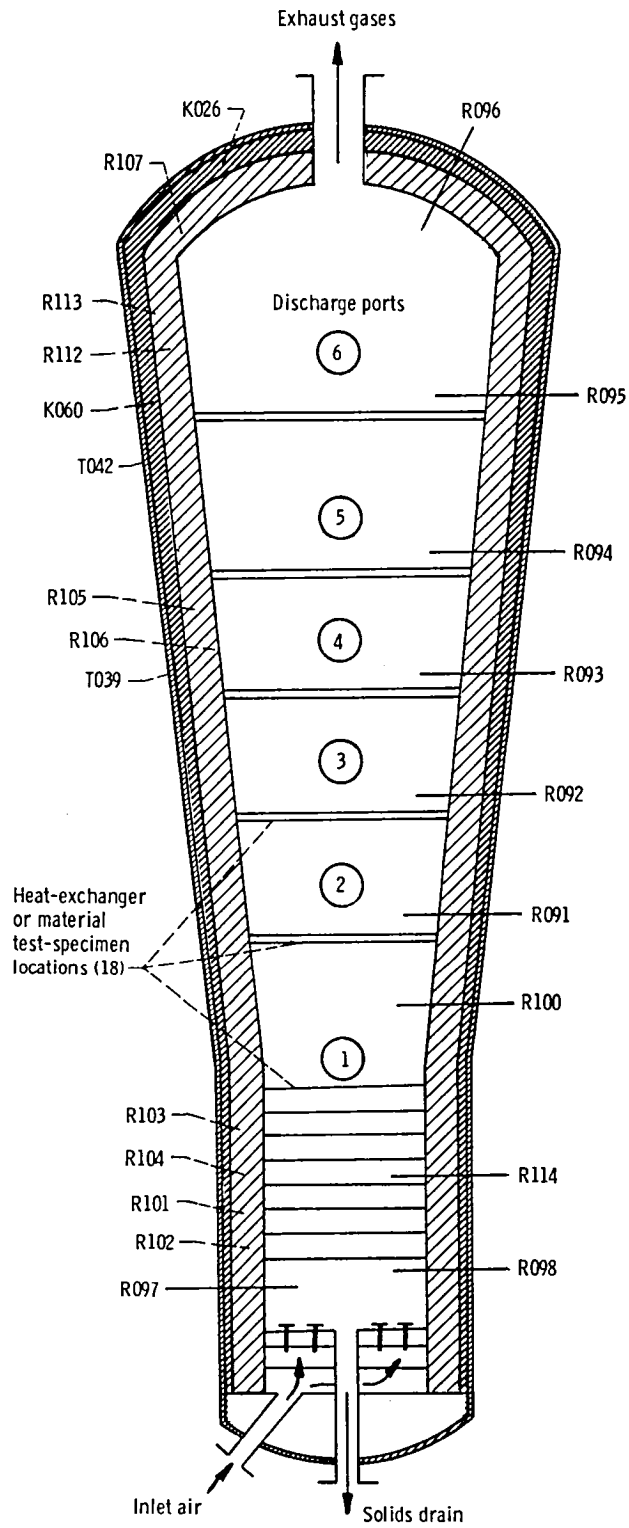
Figure 6. - P. F. B. reactor temperature instrumentation.
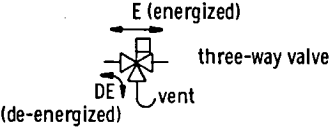
⋈	pneumatic "on-off" valve	PS	pressure switch
	three-way valve	ΔPS	differential pressure switch
	pressure regulator	SLS	solids level switch
⋈	manual valve	□	vibrator
⋈	pneumatic control valve	ASxxx	component part number
⋈	check valve	DCxxx	data word number
⋈	venturi flowmeter	Fxxx	flowmeter number
⊕	turbine flowmeter	FNxxx	component part number
Ⓕ	filter	Kxxx	type-K thermocouple number
C	controller	Rxxx	type-R thermocouple number
M	motor	Txxx	type-T thermocouple number
P	pressure transducer	TPxxx	component part number
ΔP	differential transducer	WPxxx	Component part number
		WSxxx	component part number

three-way valve labels: E (energized), DE (de-energized), vent

Figure 7. – Schematic symbols.
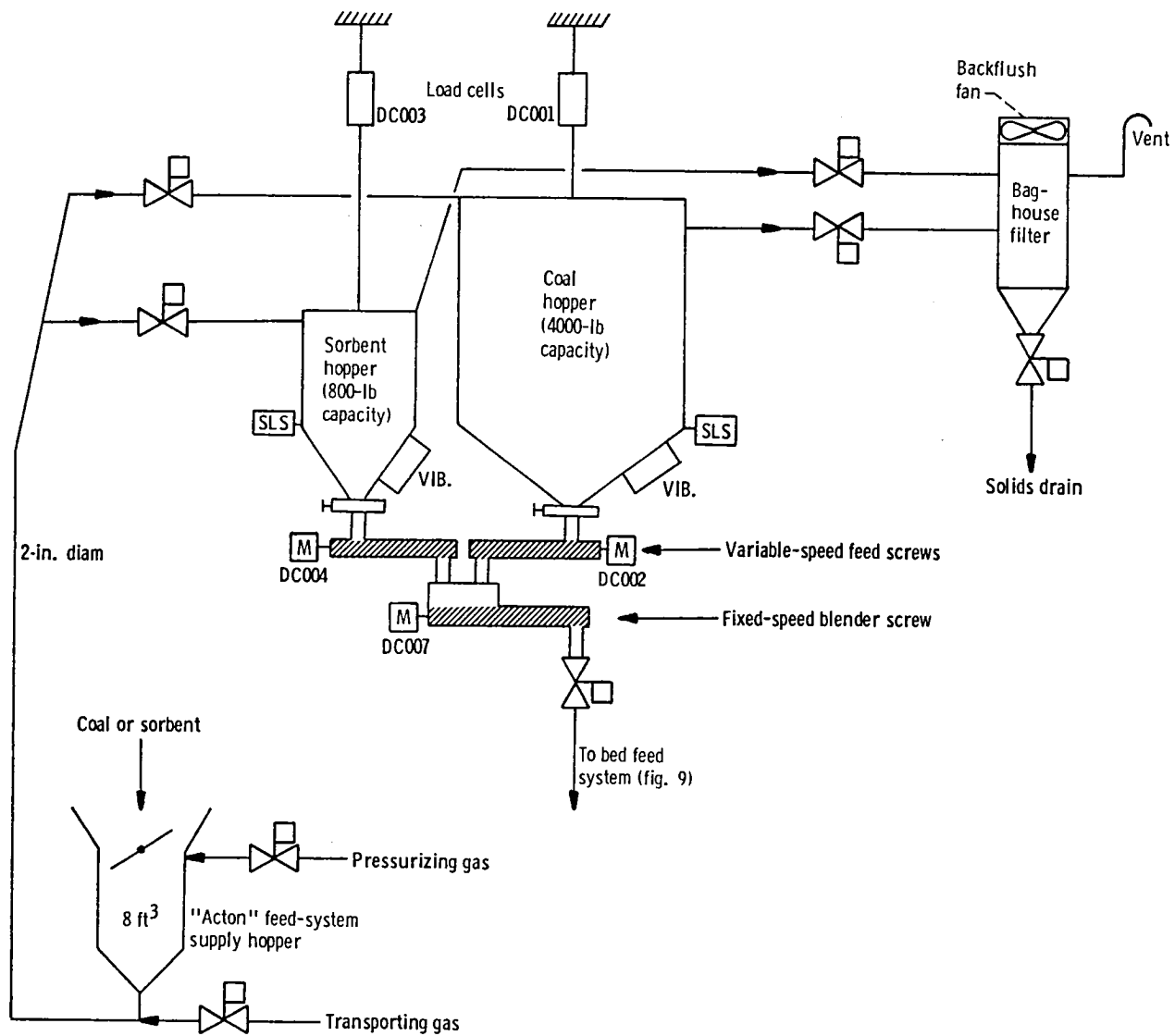
Figure 8. - Fuel supply system.
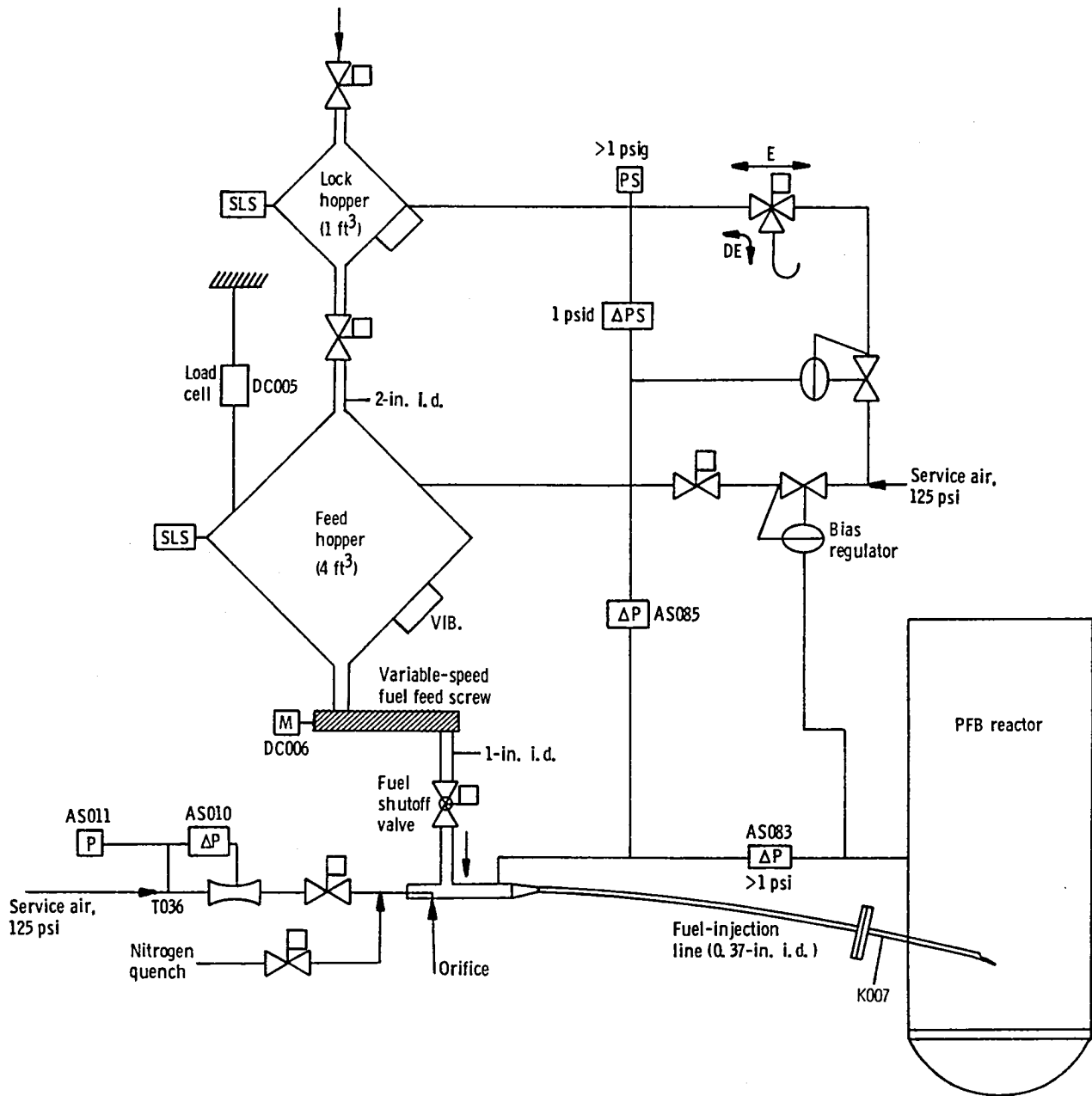
Figure 9. - Bed feed system.
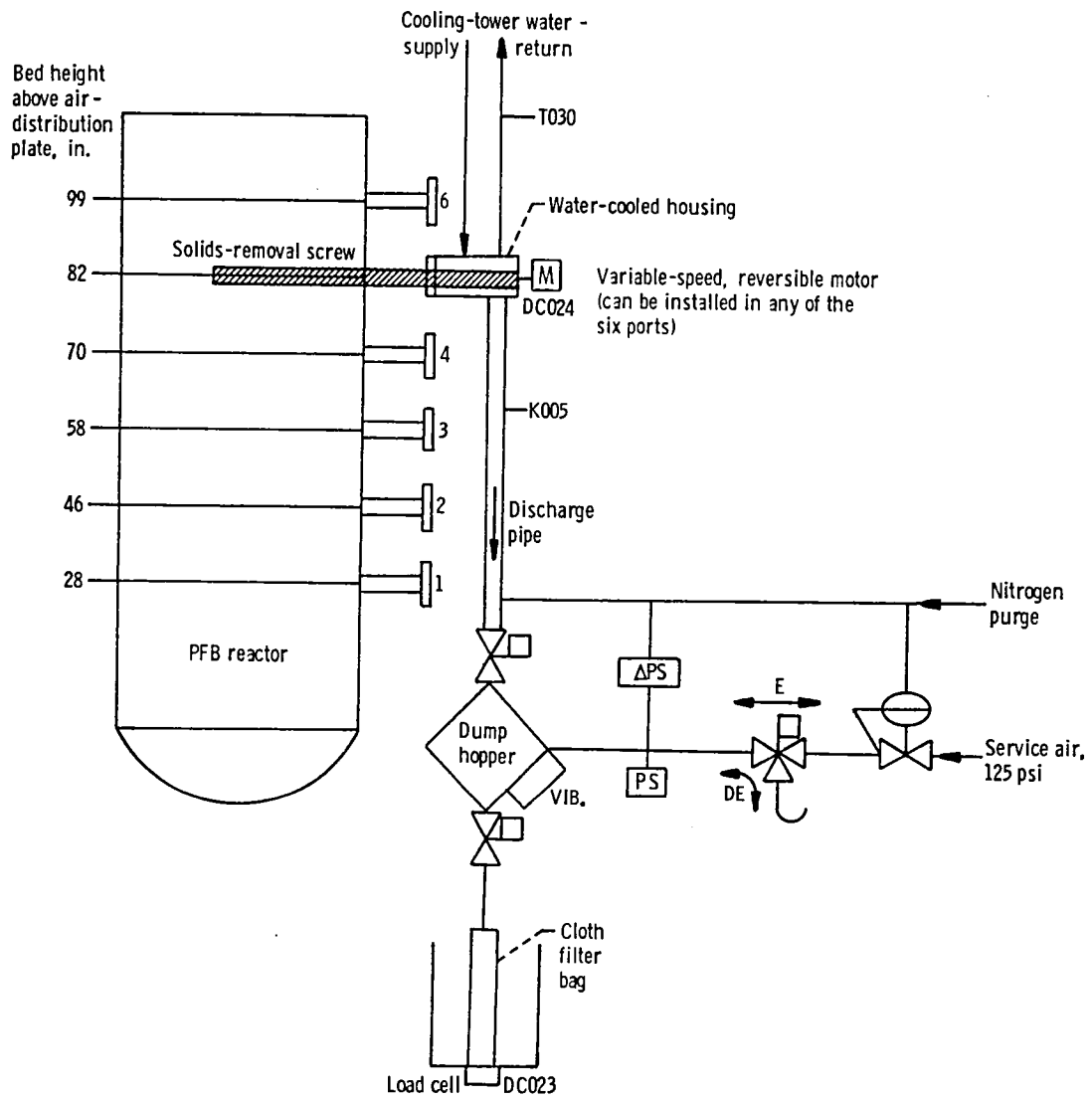
Figure 10. – Solids removal system.
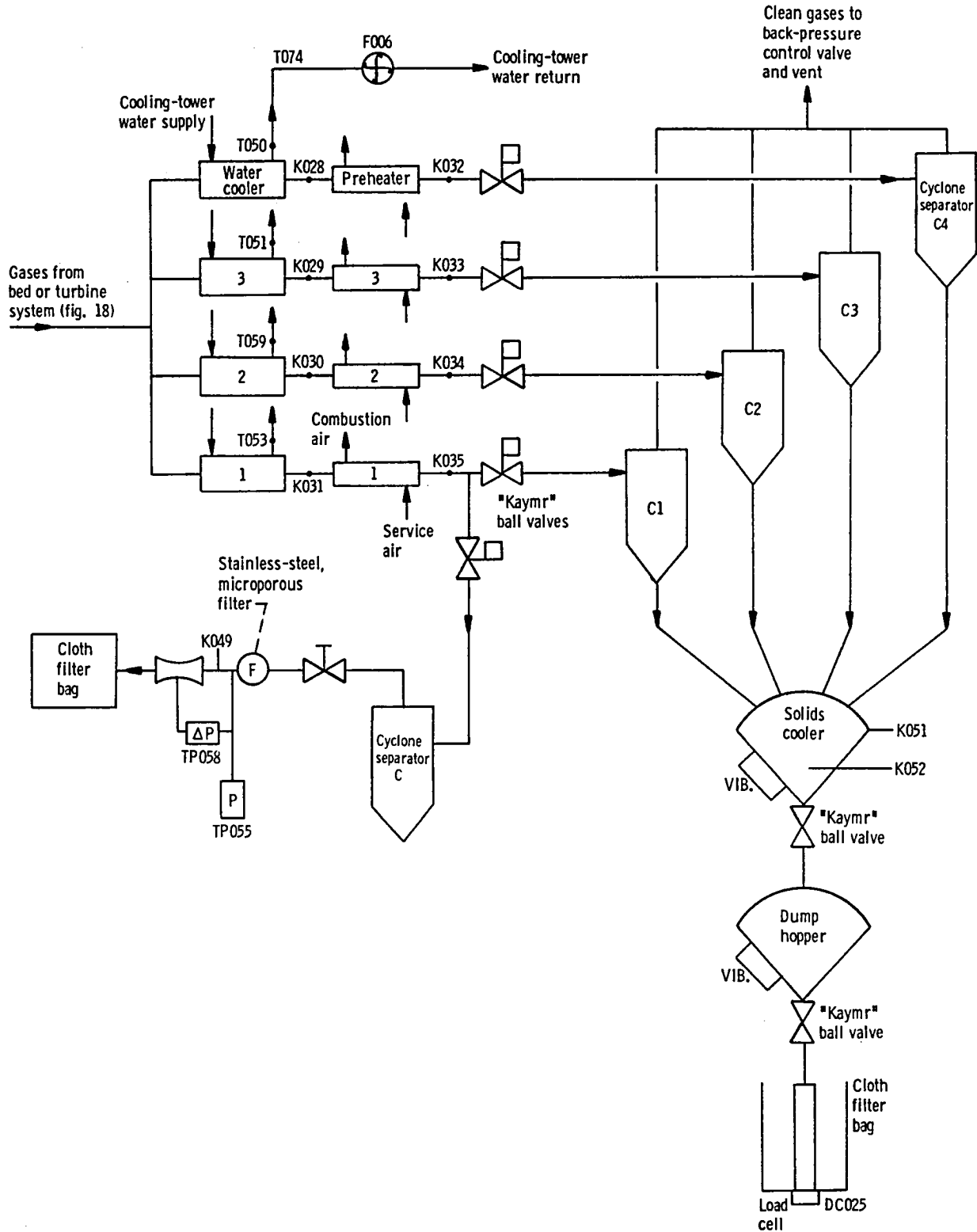
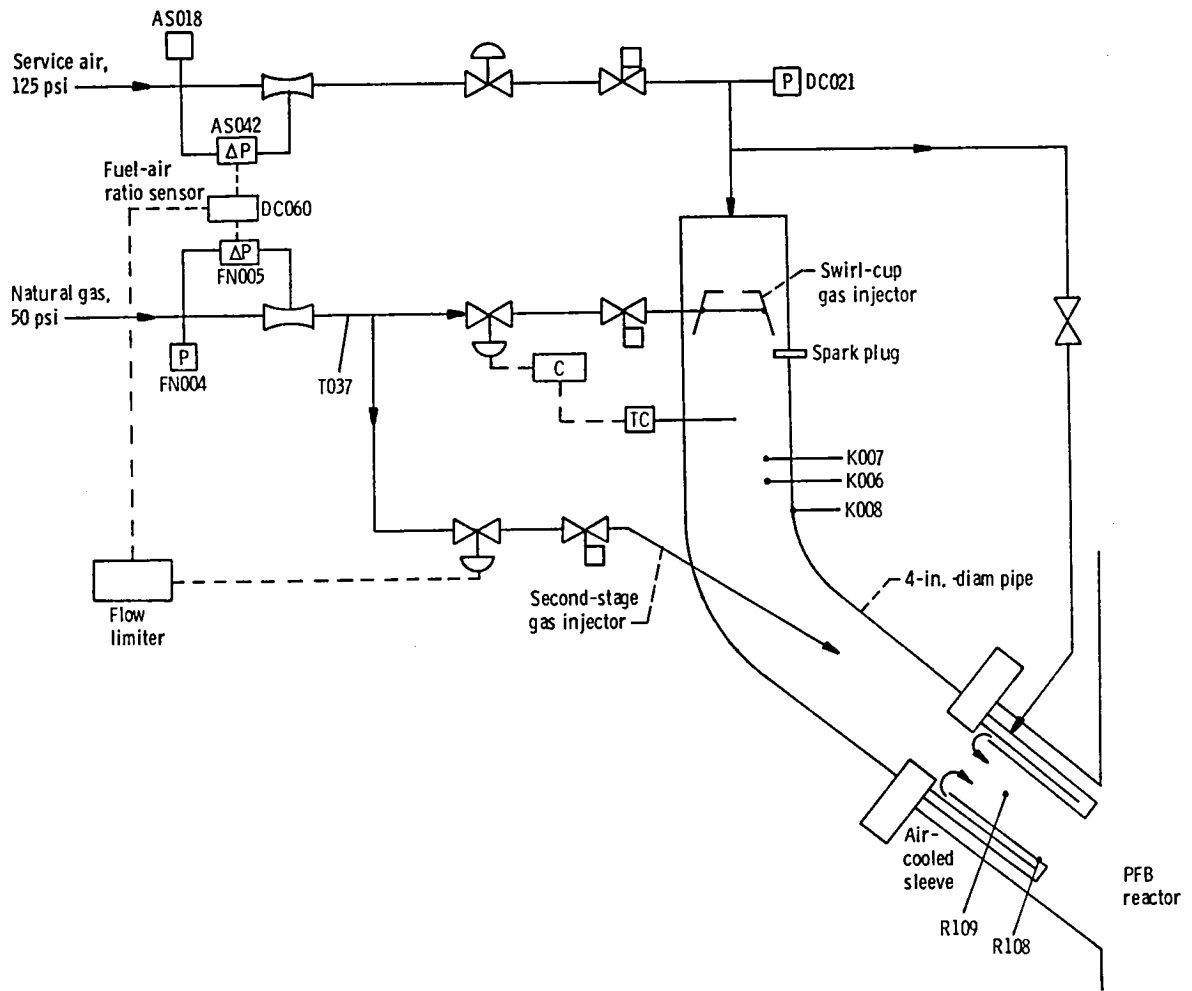Figure 11. – Exhaust system.
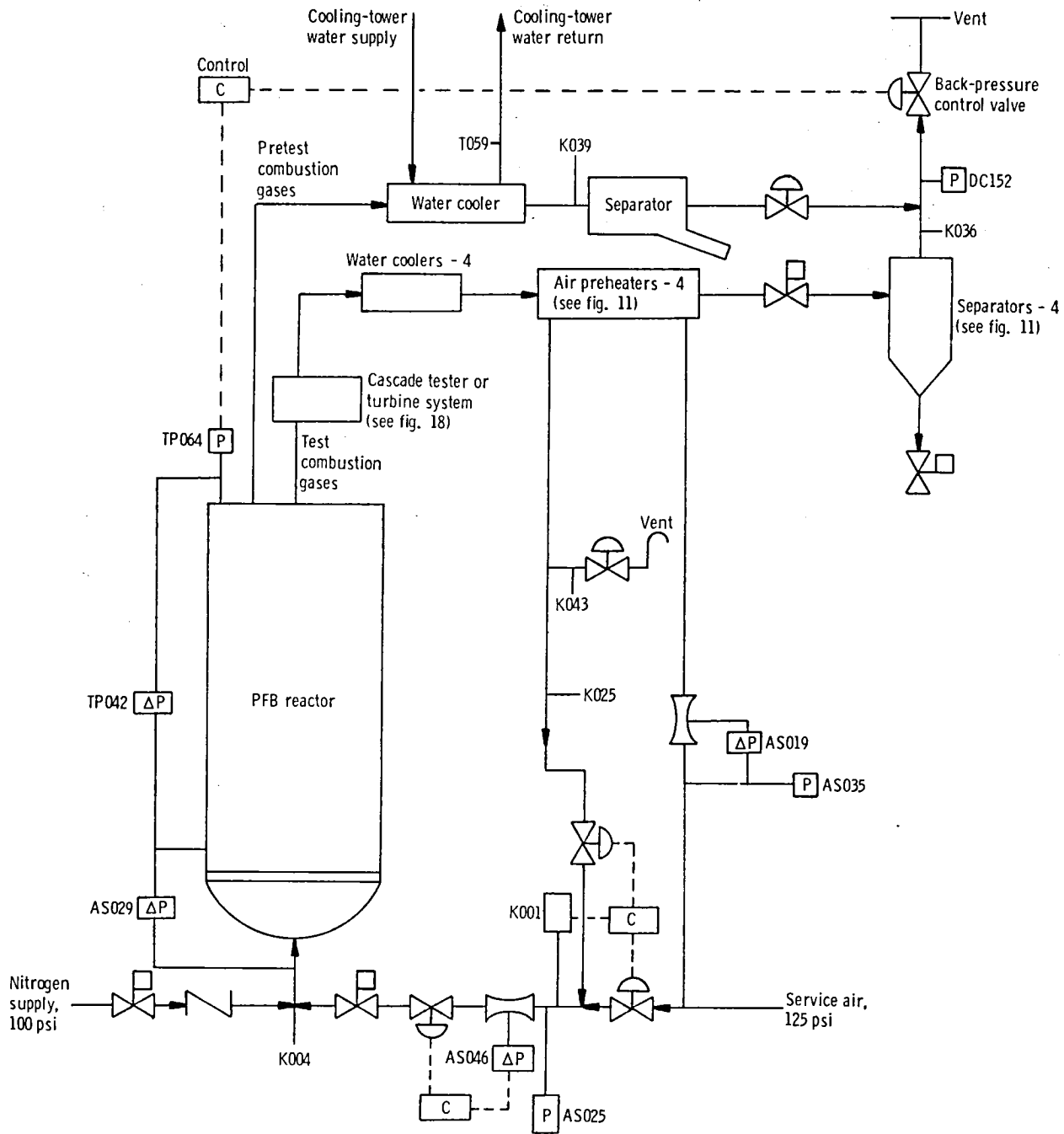
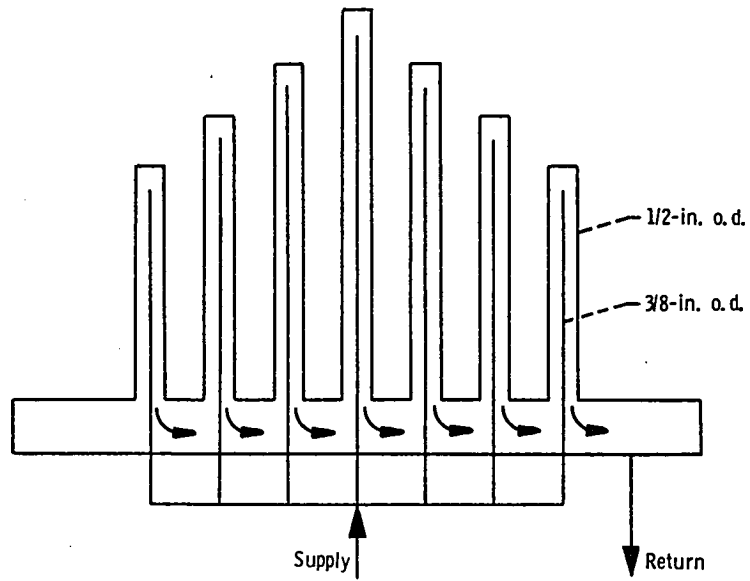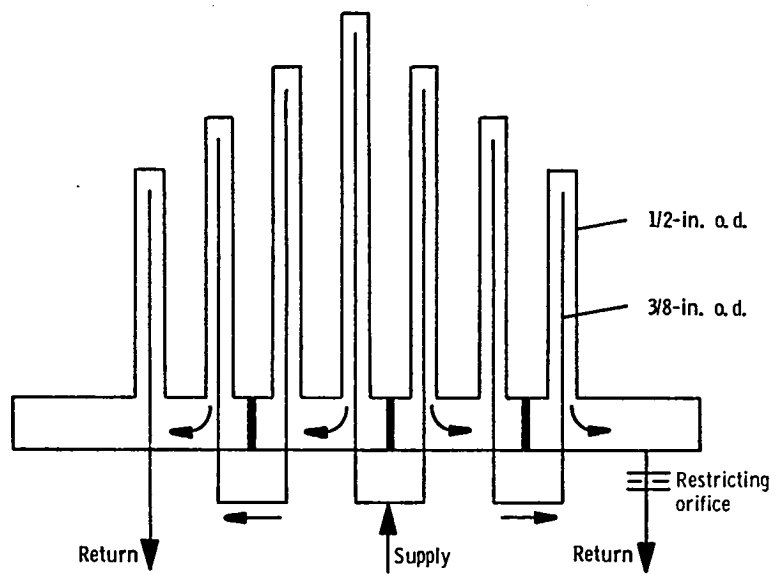Figure 12. – Combustion air system.

Figure 13. – PFB preheater burner.
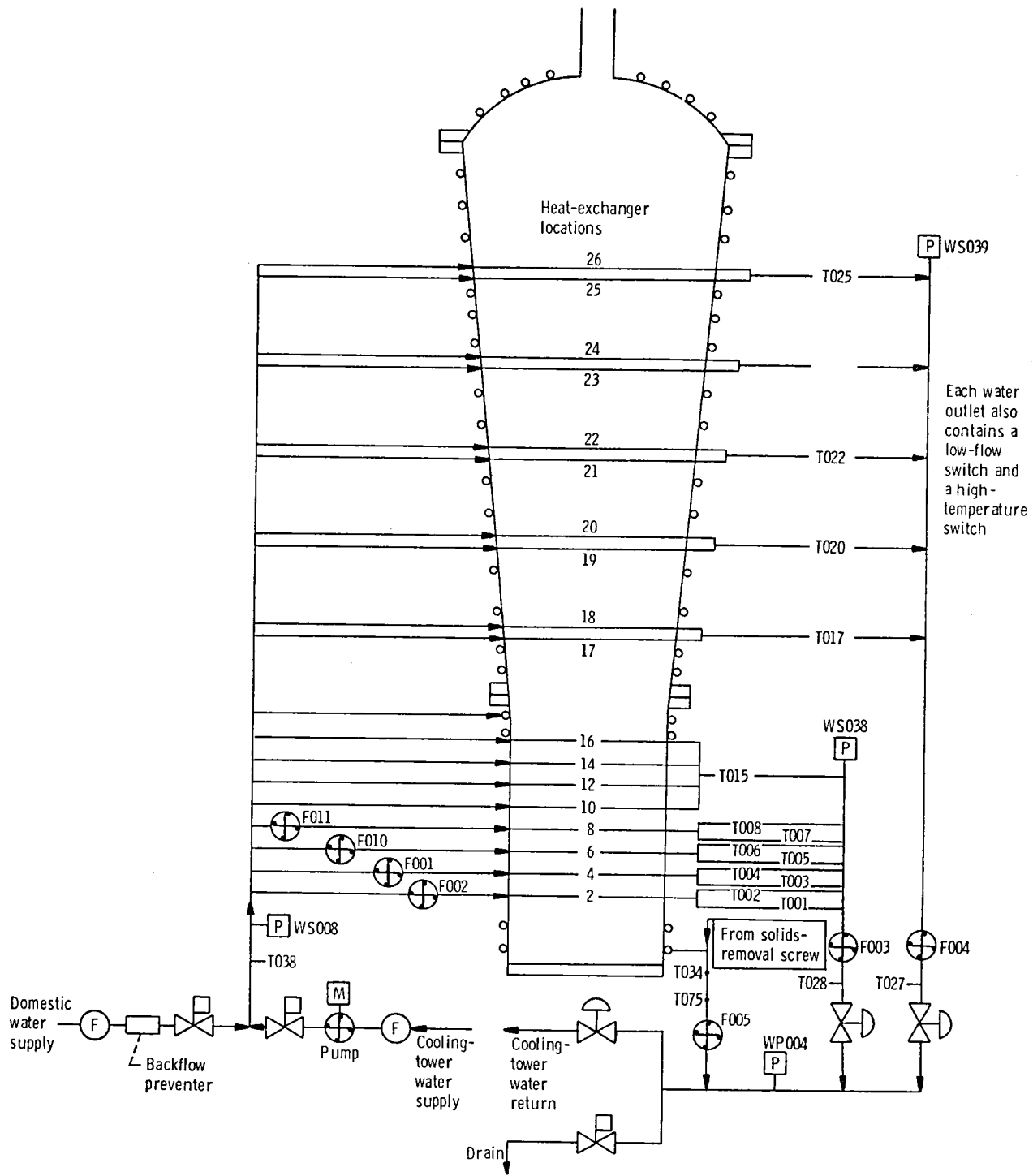
Figure 14. – Water-cooling system of PFB reactor.

1/2-in. o. d.

3/8-in. o. d.

Supply

Return

(a) Initial design.

1/2-in. o. d.

3/8-in. o. d.

Restricting orifice

Return

Supply

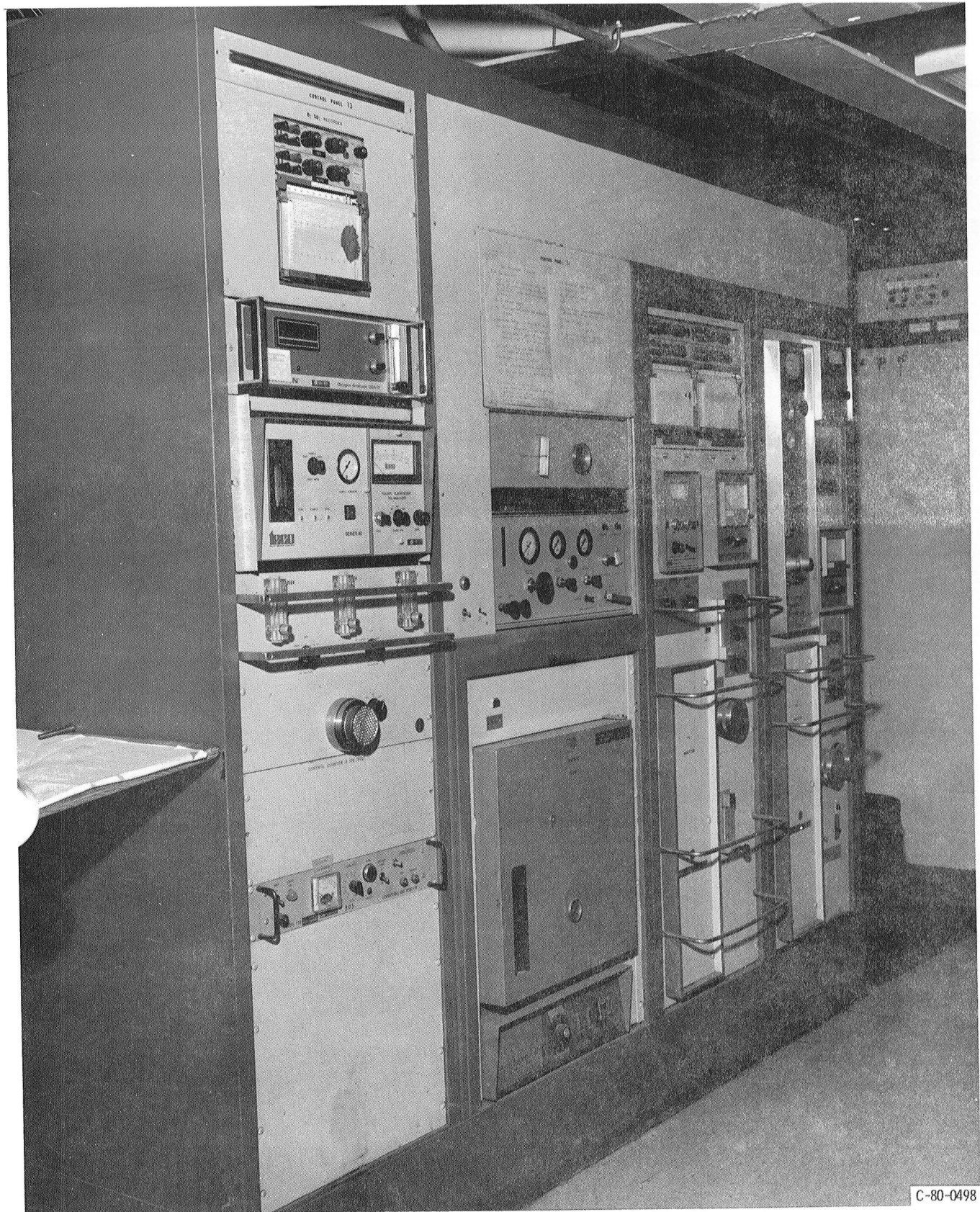Return

(b) Final design.

Figure 15. - Water-cooled heat exchangers.
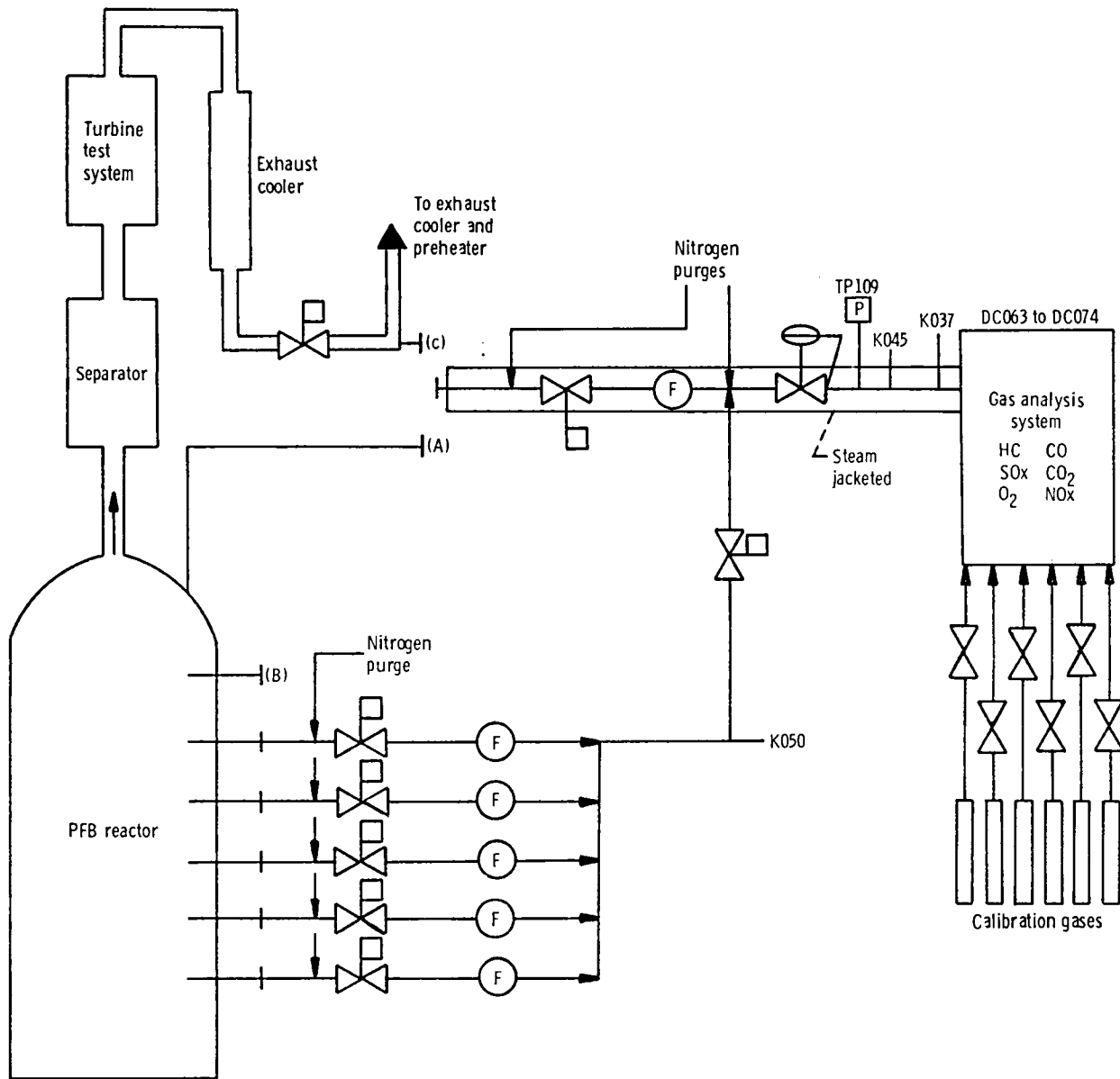
Figure 16. – Gas analysis system.

Figure 17. - Combustion gas analyzer.

C-80-0498

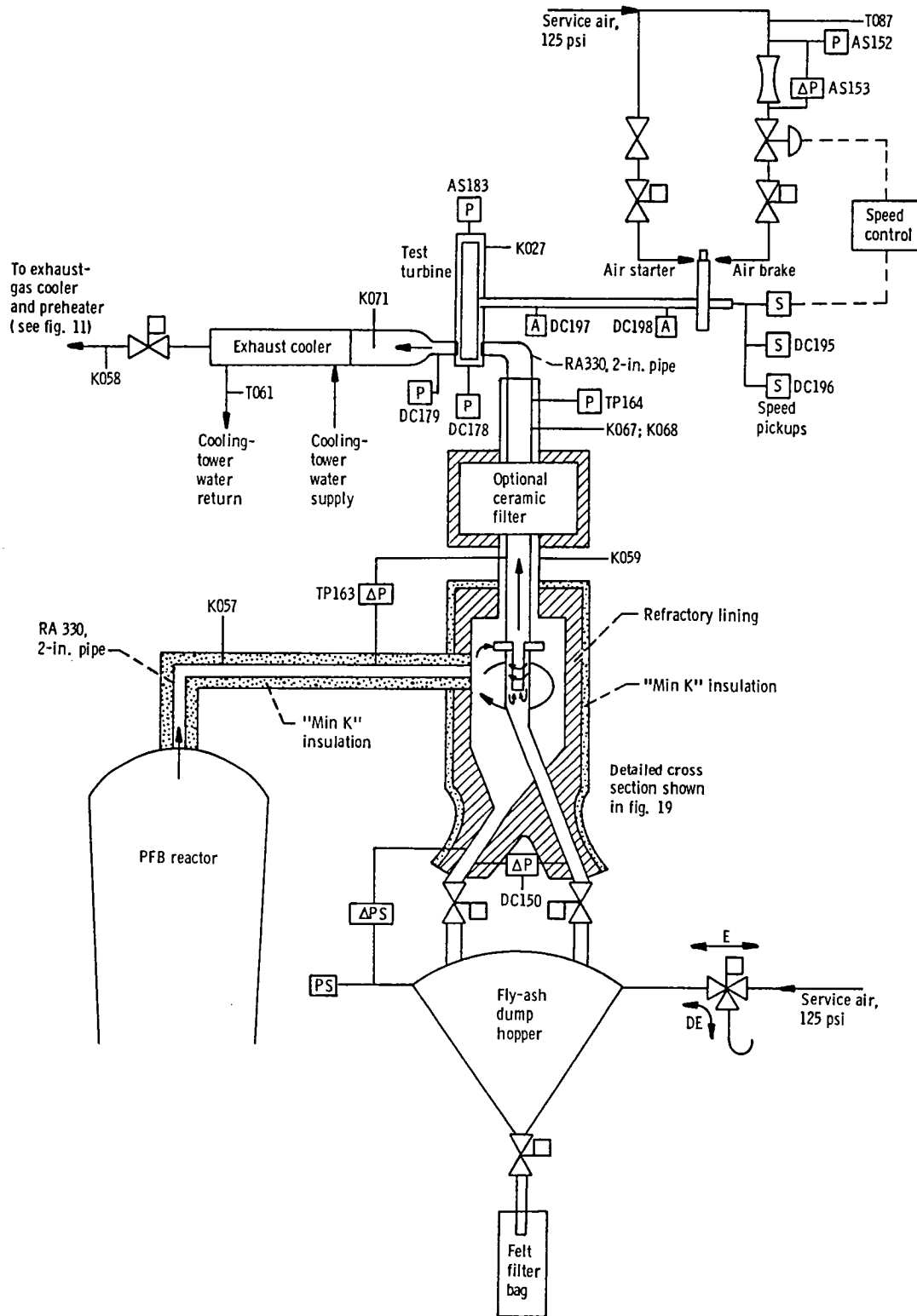Figure 18. – Turbine test section and hot-gas cleanup system.

Combustion-
gas discharge

Retractory
lining

Downward
swirler
inlet

Combustion-
gas inlet

Upward
swirler
inlet

Johns-Manville
"Min-K" insulation

First-stage
solids discharge

Second-stage
solids discharge

(a) Separator as received.
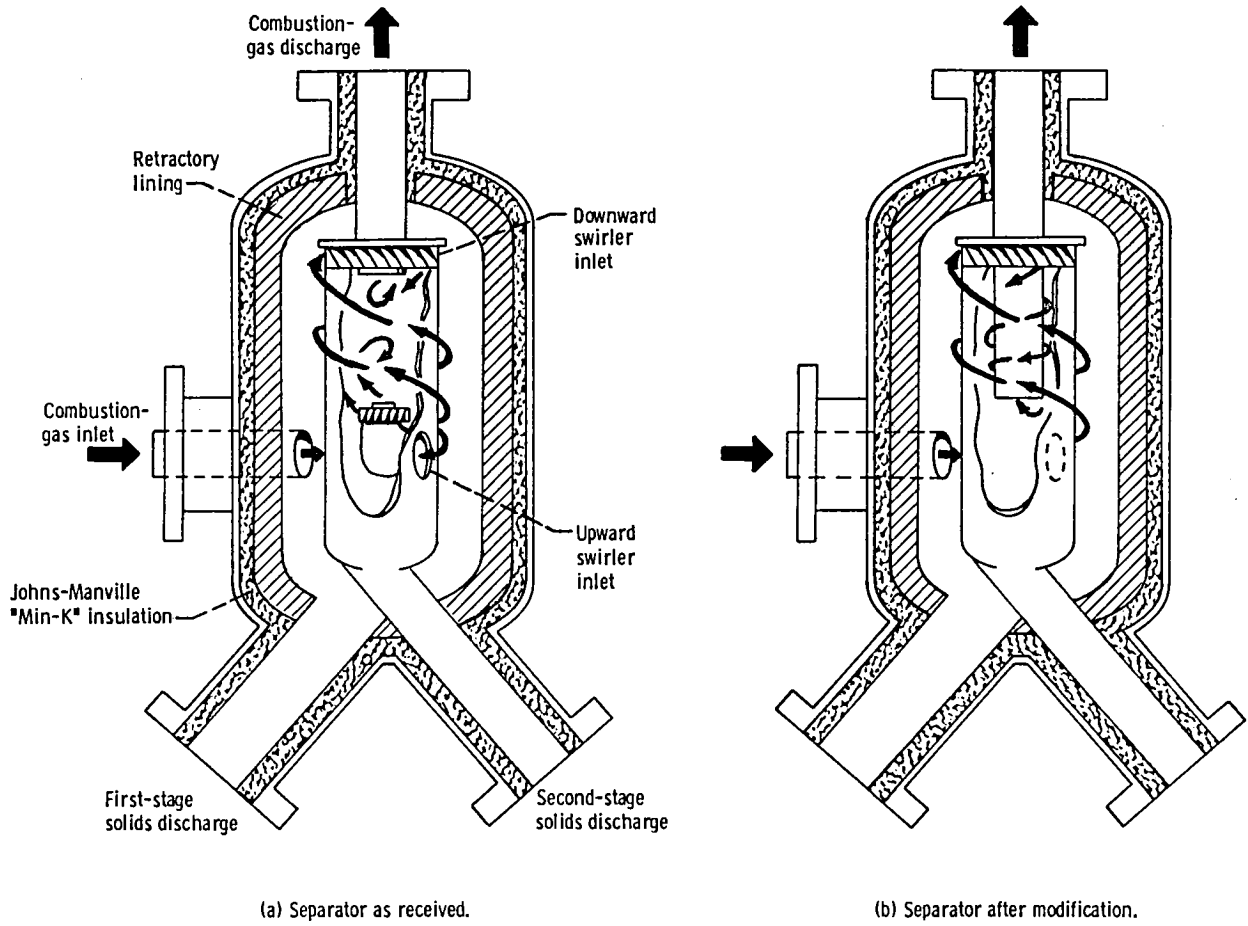
(b) Separator after modification.

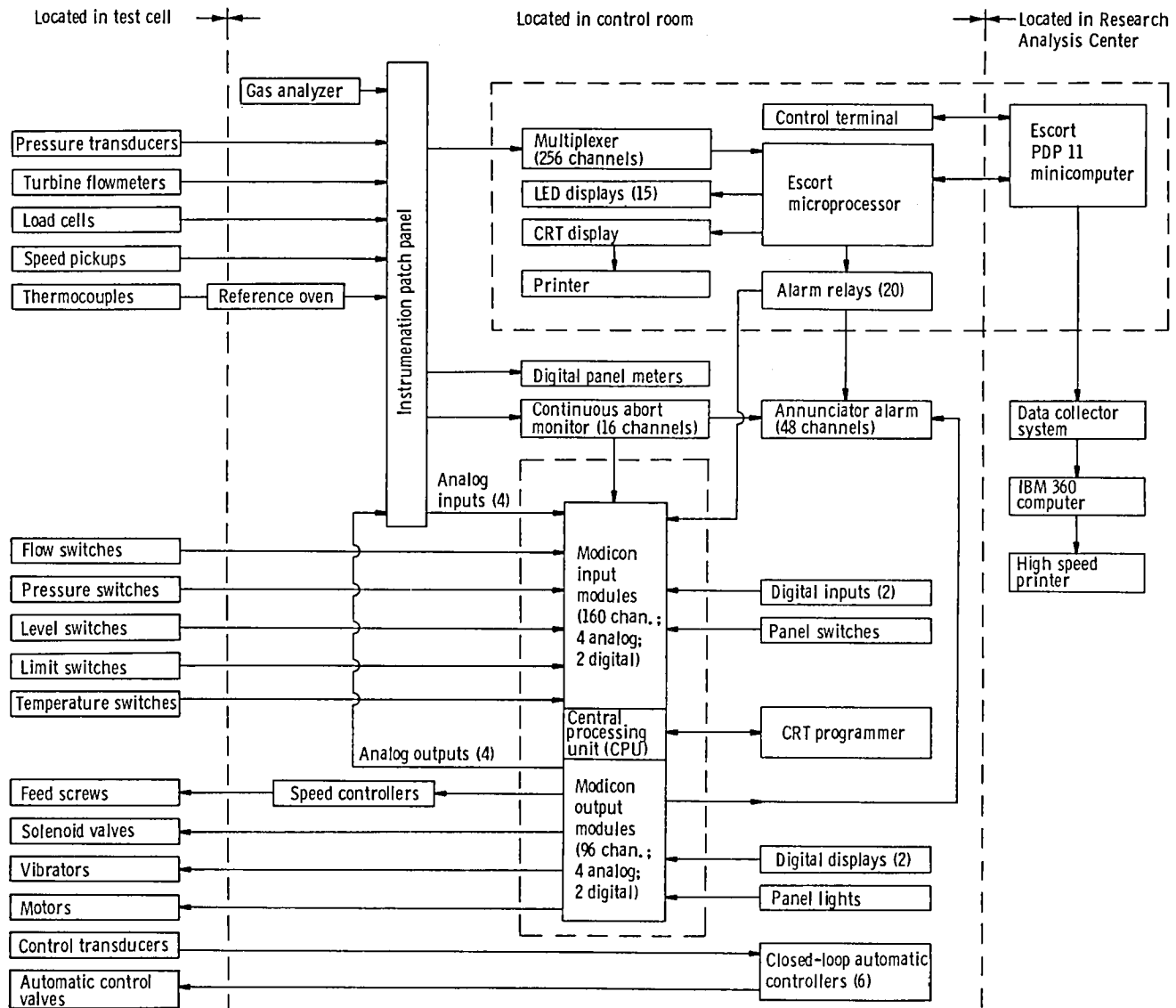Figure 19. - Cross-sectional view of gas-solids separator for Lewis PFB reactor system.
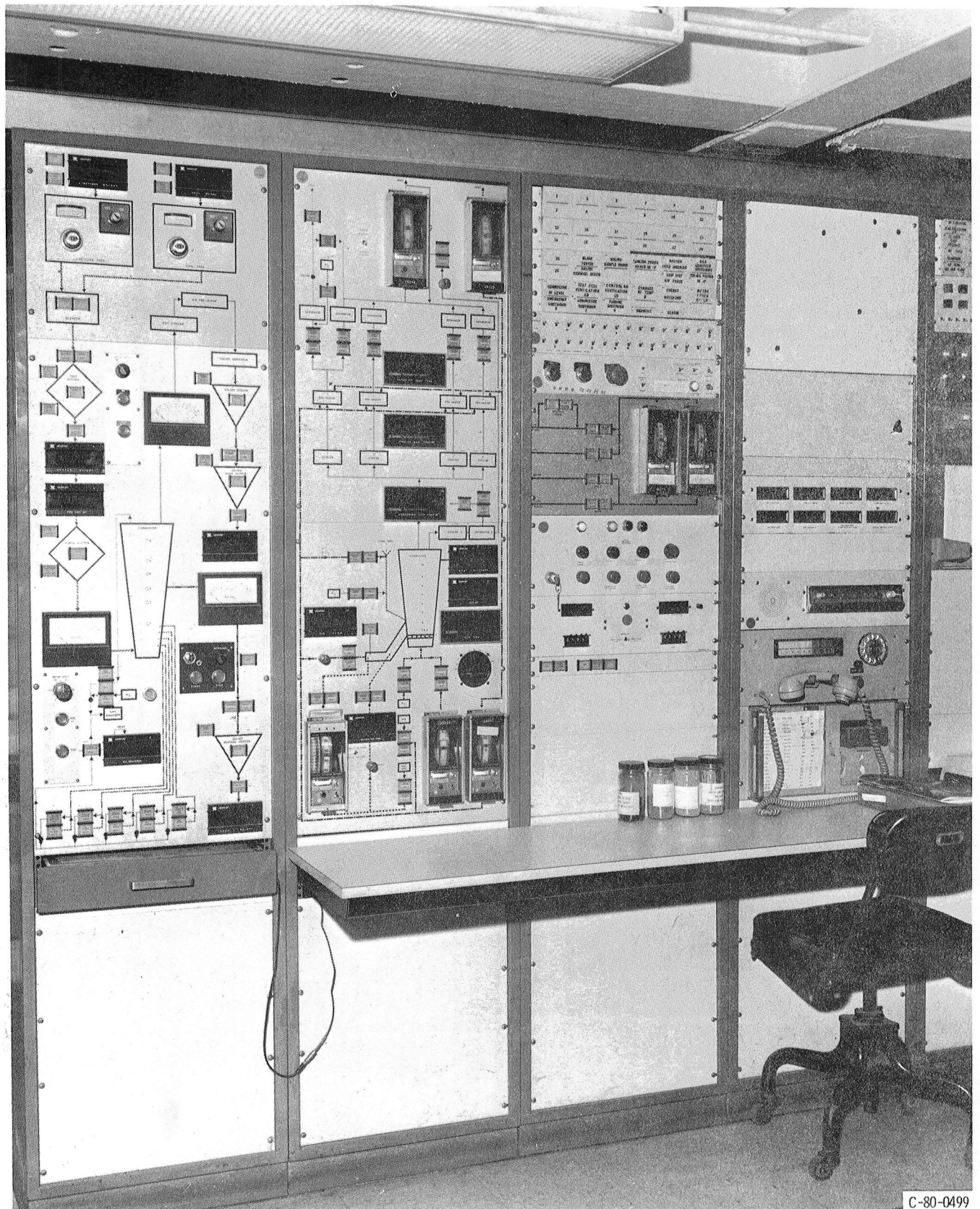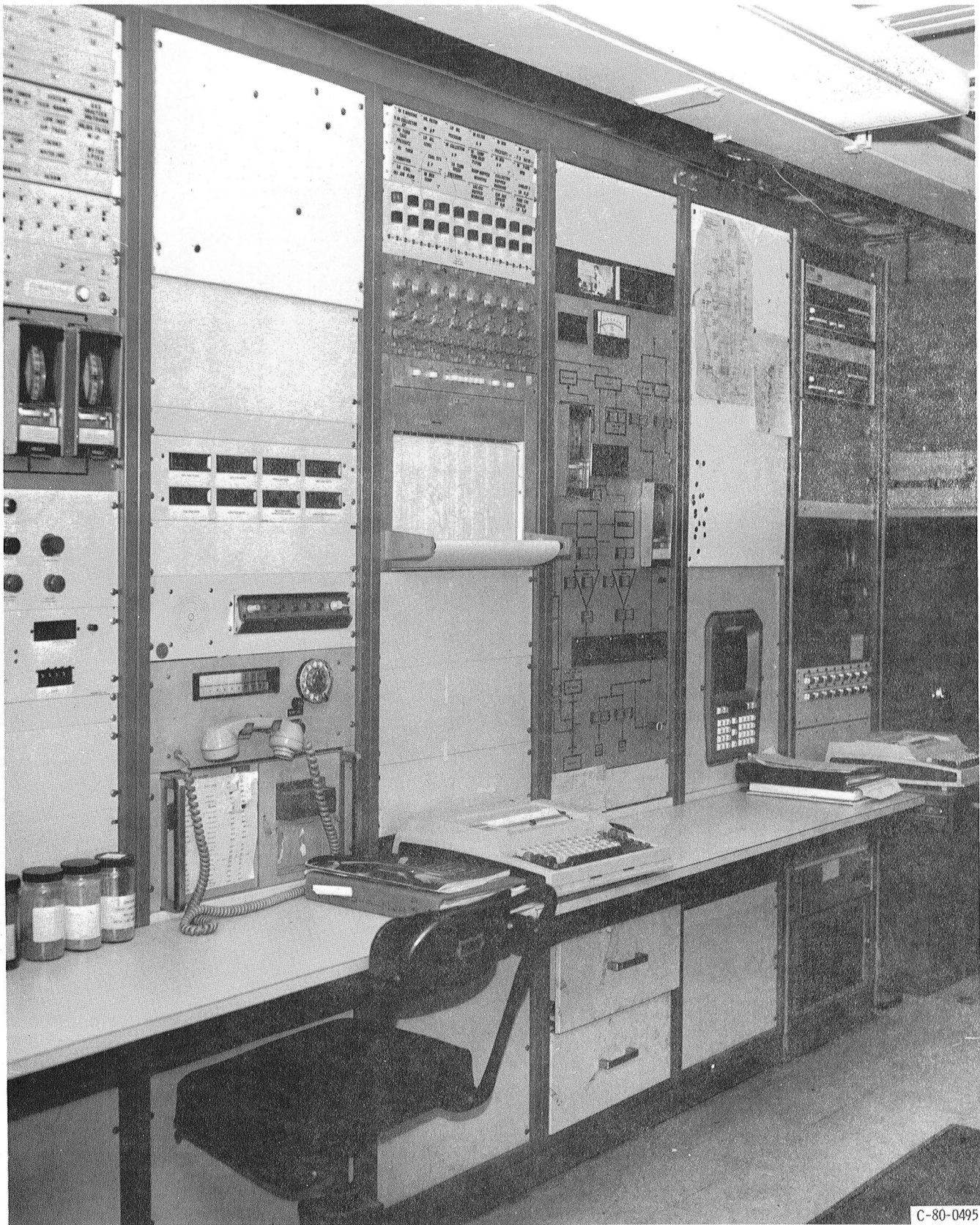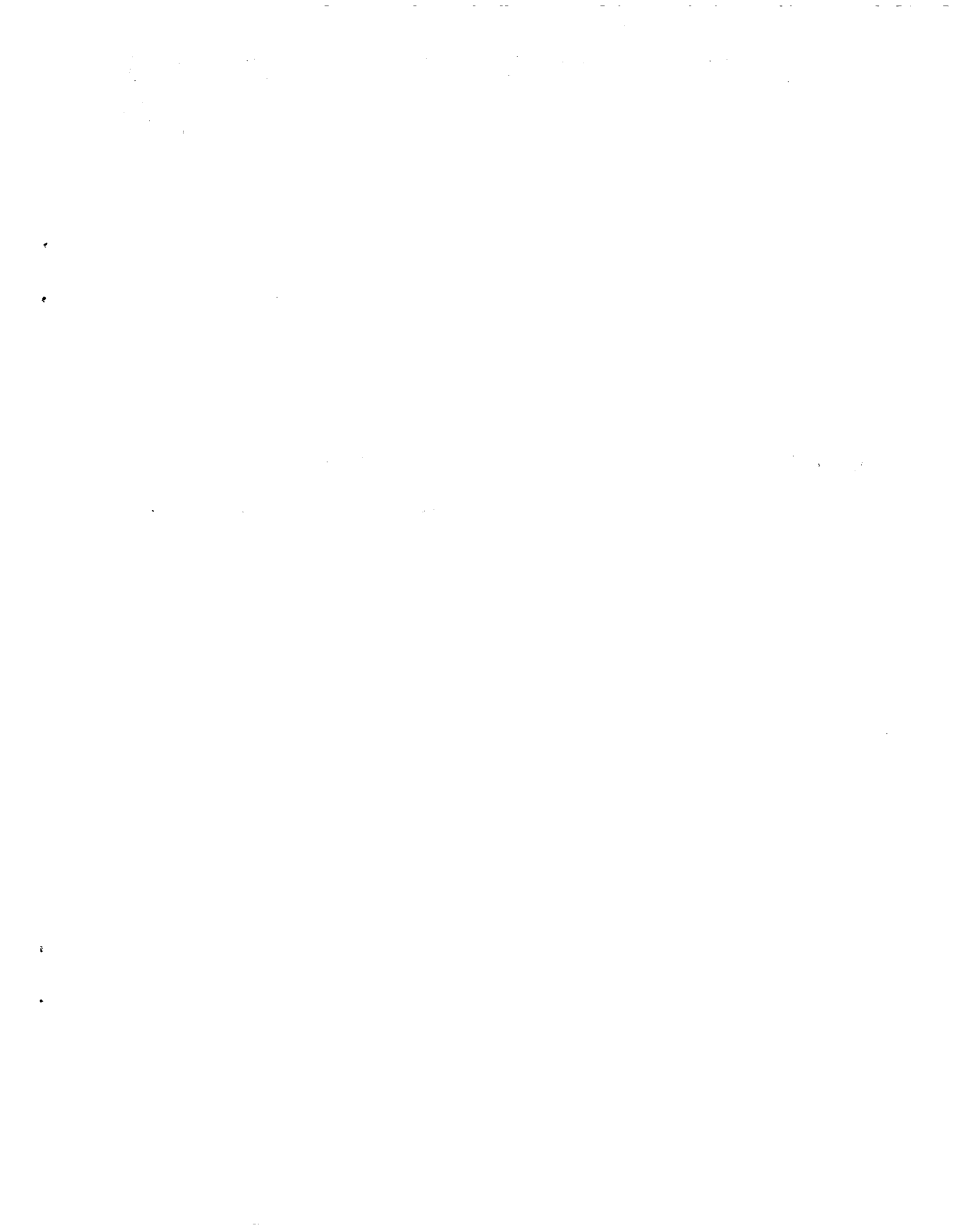
Figure 20. – Instrumentation and control system.

Figure 21. - Panoramic control panels.

C-80-0499

C-80-0495

Figure 21. - Concluded.

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15. Supplementary Notes

16. Abstract

A 200-kilowatt-thermal, pressurized, fluidized-bed (PFB) reactor, research test facility was designed, constructed, and operated by the NASA Lewis Research Center. This facility was established as part of a NASA-funded project to assess and evaluate the effect of PFB hot-gas effluent on aircraft turbine-engine materials that might have applications in stationary-power-plant turbogenerators. The facility was for research and development work and was designed to operate over a wide range of conditions. These conditions included the type and feed rate of the coal and the sulfur sorbent; the ratio of coal to sorbent; the ratio of coal to combustion air; the depth of the fluidized bed; the bed temperature and pressure; and the type of test unit exposed to the combustion exhaust gases. This report describes some of the unique techniques and components developed for this PFB system in order to carry out the program. One of the more important items was the development of a two-in-one, gas-solids separator that removed 95+ percent of the solids in 1600° to 1900° F gases. Another was a coal and sorbent feed and mixing system for injecting the fuel into the pressurized combustor. Also important were the controls and data-acquisition systems that enabled one person to operate the entire facility. The solid, liquid, and gas sub-systems all had problems that were solved over the 2-year operating time of the facility, which culminated in a 400-hour, hot-gas, turbine test. NASA has terminated its in-house experimental PFB research. The efforts put forth in this program may be of benefit to others who are considering such work for eventual commercial development of a PFB facility. Many of the technical problems solved in this small facility are expected to be scalable to larger R&D or commercial rigs.

17. Key Words (Suggested by Author(s)) Pressurized fluidized bed; Test facility; Exhaust-gas cleanup; Materials testing; Sulfur removal from coal; Coal combustion; Gas turbine; Programmable controller	18. Distribution Statement Unclassified - unlimited STAR Category 34

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