HCP/T2471-33

Industrial Application Fluidized-Bed Combustion

Category III

Indirect Fired Heaters

Quarterly Technical Report No. 10

October 1—December 31, 1978

Published April 1979

Prepared for

U.S. Department of Energy
Assistant Secretary for Energy Technology
Division of Fossil Fuel Utilization

Under Contract No. EX-76-C-01-2471

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INDUSTRIAL APPLICATION FLUIDIZED BED COMBUSTION

CATEGORY III

INDIRECT FIRED HEATERS

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Prepared By
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For
U.S. Department of Energy
Assistant Secretary for Energy Technology
Division of Fossil Fuel Utilization
Washington, D.C. 20545

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ABSTRACT

A program is underway to evaluate the technical and economic potential for the application of fluidized bed combustion to refinery and petrochemical plant indirect fired process heaters. The strategy of the program is to build on available boiler oriented FBC technology. Areas common to both steam generating boilers and process heaters will not be intentionally advanced by this program. However, the results of complimentary programs in the boiler area will be considered in the assessment of potential heater applications.

Two pertinent areas that are not being addressed in the on-going boiler oriented programs and which are being investigated here concern the effects of larger tube size and hydrocarbon coking. Phase I of the program consists of the design, construction and operation of three laboratory facilities to carry out these studies. Fluidized bed performance studies, including bed mixing and density measurement, have been completed on six alternative tube bundle configurations ranging from 2-inch to 6-inch diameter tubes arranged on nominal 2-diameter, 3-diameter and 4-diameter horizontal spacing. Conductive/convective heat transfer coefficients as a function of tube size, location and surface orientation have also been obtained on these same bundle configurations and on isolated single tubes. Finally, evaluations have been made on the effect of altering the tube-to-grid dimensions and of operating with limestone beds of different particle size distributions.

A Process Stream Coking Test Unit has been commissioned and is being used to study the parameters affecting coke laydown on the internal surfaces of hydrocarbon containing tubes under conditions of high temperature and heat transfer rate. Five test runs have been completed. The preliminary data analysis shows that in addition to film temperature, mass velocity is an important parameter in controlling coking rate. One final test run is planned to complete this series of tests.

Design, procurement and construction activities are underway for the third laboratory facility which will be a "hot" coal fired fluidized bed combustor. The unit design, status of the construction and planned test matrix are described in this report. This facility will be used to study overall heat transfer coefficients in a "hot" fluidized bed in addition to fuel combustion. A late first quarter 1979 startup is anticipated.

1. Objectives and Scope of Work

The purpose of this program is to extend the state-of-the-art of fluidized bed coal combustion, which at present, addresses the generation of steam to applications where oil passing through immersed tubes in the bed will receive heat and be heated to a required condition. This purpose will be achieved by the successful completion of the following program objectives:

a. To conduct an R&D program necessary to provide the engineering data and know-how for designing a fluidized bed process heater.

b. To conduct an economic analysis necessary to evaluate the economic attractiveness of fluidized bed combustion for indirect fired process heater applications.

c. To demonstrate the operation of a coal fired fluidized bed heater in an actual refinery environment for an extended period of time.

d. To prepare a complete Design Specification and Control Cost Estimate for a commercial sized fluidized bed coal fired process heater.

The basic approach to be followed in pursuing the objectives of this program will be to build on the fluidized bed technology that is now available and under development by others in the related areas of fluidized bed boiler applications. Effort in this program will be concentrated on doing the incremental work necessary to extrapolate the boiler oriented technology to refinery and petrochemical plant type indirect fired process heaters. The areas of technology common to both steam generating boilers and process heaters will not intentionally be advanced by this program. However, the state-of-the-art and the results of complimentary programs in the boiler area will be used in the overall technical and economic assessment of potential fluidized bed process heater applications.

The two principal areas of technology that have been identified as being peculiar to process heater applications and which are not being addressed in the on-going boiler orientated programs concern the effects of tube size and hydrocarbon coking. These two areas will be investigated in this program.

Indirect fired process heater tubes are conventionally larger in diameter than boiler tubes. A typical crude oil heater, for example, may have a multitude of 4" to 8" diameter tubes in the heat pick-up zones as contrasted to the 1" to 2" diameter tubes normally used in steam boilers. The effect that these larger tubes have on fluidization characteristics and the definition of the optimum or acceptable configuration for a tube bundle immersed within a fluidized bed must be determined.

Similarly, the parameters affecting hydrocarbon coking must be investigated. When heating a hydrocarbon to 600°+ (as required for separation by distillation or other typical processes) some degradation of the oil and coke laydown on the inside tube wall is unavoidable. The rate of coke laydown is affected primarily by the temperature of the hydrocarbon film on the inside wall of the tubes. This film temperature, in turn, is a function of several parameters relating inside film coefficient and heat transfer rate. Both overall average and localized conditions within the heat transfer zone must be examined.

The effects of tube size and coking described above will be investigated during the initial laboratory R&D phase of the program. This will be accomplished through the design, fabrication and operation of three separate laboratory test units. These units are designated as follows:

a. Two-Dimensional Flow Visualization Unit

b. Process Stream Coking Unit

c. High Temperature Heat Flux Unit

Other portions of the Phase I effort involve economic and operability evaluations of the technology and design of the Phase II Demonstration Unit followed by the Design Specification and Control Cost Estimate for a commercial-sized FBC process heater.

If, at the conclusion of Phase I, the technical and economic assessment of the data indicate favorable commercial potential, the program will be advanced to the demonstration phase. This will involve the installation of a 10-15 MBtu/Hr coal fired fluidized bed process heater in an Exxon refinery and its operation for a sufficient period of time to obtain the engineering data necessary to design a commercial sized facility.

2. Summary of Progress to Date

The Program is structured into 10 tasks or cost centers which are being used to monitor and report the progress of work. The overall schedule and identification of tasks are shown in the revised Milestone Plan and Management Report included here as Figure 1.

The first major laboratory task, the Two-Dimensional Flow Visualization Study, has been completed. This study evaluated the effect on fluidization and heat transfer when an array of relatively large diameter tubes was immersed in a fluidized bed of limestone. Alternative configurations of tubes up to 6 inches in diameter arranged on 2 to 4 tube diameter center-to-center spacing were investigated. The studies defined the range of acceptable tube bundle configurations that might be used in commercial process heater applications. Engineering data on fluidization parameters and conductive/convective heat transfer patterns were obtained.

The Process Stream Coking Test Unit is now in operation and five test runs have been completed. All coking runs to date have been conducted at a nominal coil inlet temperature of 650°F and heat fluxes ranging from 15 to 60 kBtu/hr ft^2. The preliminary data analysis indicates that coking rate is not only a function of process film temperature but is a strong function of process mass velocity. Modifications to the unit to permit operating at higher coil inlet temperatures have now been completed. A final test run at a nominal coil inlet temperature of 750°F is now planned.

The third laboratory facility, the Heat Flux Test Unit, is well into the procurement and construction phase. All major components are on order and field construction is approximately 50% completed. A late first quarter 1979 construction completion is anticipated. The unit design, status of the construction, and planned test matrix is described in this report.

3. Discussion of Technical Progress

3.1 Two-Dimensional Flow Visualization Studies

3.1.1 Background Information

The flow visualization studies were carried out in a two-dimensional atmospheric pressure, transparent fluidized bed chamber. The unit was approximately 1 ft. in depth by 7.5 ft. wide by 12 ft. high (see Figure 2). The facility was designed to accommodate a range of tube bundles assembled from tubes up to 6 inches in diameter and arranged on spacings up to 4 tube diameters on center.

Tube bundles were immersed in the bed and the effect on fluidization of these relatively large tubes was determined through a systematic study of the parameters of tube diameter, tube-to-tube spacing, tube-to-grid spacing and tube orientation. Other variables such as bed particle size, fluidization velocity, grid location and bed pressure drop were also examined although these were of secondary interest since they are being investigated by boiler oriented programs.

3.1.2 Status of Work

All work planned under this Task of the Program has been completed and reported. Briefly summarized, the work successfully defined the configurations of 4" and 6" diameter tubes that would be suitable for use in Process Heaters. It defined several limiting parameters on fluidization velocity, tube spacing and combustor configuration that would have to be adhered to in order to assure satisfactory performance. Useful conductive/convective heat transfer data were obtained which are necessary to initiate full scale design studies. These same data also suggest effective means of operation for load following on commercial units by altering expanded bed depth and exposing more or less tubes to the fully fluidized zone in the bed. Other engineering parameters and general observations on fluidization and heat transfer performance in the presence of 4" and 6" diameter tubes were made which will be used in the later parts of this program.

All task data have been reported in Quarterly Technical Report Nos. 5, 6 and 7. The Technical Society and Professional Journal Publications resulting from this task are listed in Figure 3. In addition, a film titled "Solids Mixing and Fluidization Characteristics in a Tube Filled Bed" was made as part of this task. The purpose of the film was to illustrate four important observations made during the flow visualization studies; namely, particle mixing and bed expansion, particle activity around a tube surface, solids layering above the tube bundle, and solids bridging on tube and wall surfaces. The film is being loaned to interested organizations upon receipt of written request.

3.2 Process Stream Coking Studies

3.2.1 Background Information

The Process Stream Coking Studies are designed to determine what effect the high heat flux rates available in a fluidized bed combustor will have on the coking rate of of a hydrocarbon stream and if these coking rates can be controlled within an acceptable range of operations. More specifically, they will establish a relative rate of carbon or coke deposition on the inside wall of hydrocarbon containing tubes as a function of bulk temperature, heat flux, mass velocity and inside film temperature.

The test facility that has been built to carry out these studies has been installed at Exxon's Bayway Refinery, Linden, N. J. The unit consists of four heat exchangers, each heated by an electric radiant heater. Each exchanger is a single 0.6 in. I.D. x 9 ft. long (heated length) stainless steel tube. The basic scheme is to pass a stream of virgin crude oil through each of the four exchangers. Total unit throughput is approximately 900 Bbl/Day.

Each exchanger is exposed to a different combination of process conditions (mass flow, bulk temperature and heat flux) and each is carefully monitored for indications of coke deposition on the inside surface of the exchanger tube. In this way, comparative coking rates as a function of the varying process parameters can be determined.

A detailed description of the facility including a discussion of the planned test matrix and basis to be used for analysis of data is given in the Quarterly Technical Report No. 2 dated January 26, 1977. The reader is referred to that report for more detailed background information.

3.2.2 Status of Work

A hot calibration run and five test runs have been completed to date. The hot calibration test was reported in Quarterly No. 7, Test Run Nos. 1 and 2 were reported in Quarterly No. 8, and Test Run Nos. 3, 4, and 5 were reported in Quarterly No. 9. These tests were all conducted with a crude inlet bulk temperature of 650°F. One additional test at higher bulk temperature is now anticipated as necessary to complete this task.

3.2.3 Construction of New By-Pass Line Completed

The range of operating conditions experienced in the tests conducted to date are shown on Figure 4. The results of these tests are shown on Figure 5. Test Run No. 1 is not shown on either display since it was prematurely aborted. Nominally the range of conditions covered in these tests were: crude inlet bulk temperature 650°F, mass velocity 150-600 lbm/sec ft^2, heat flux 15k to 60k Btu/hr ft^2. This combination of test variables resulted in multiple tests in the film temperature range of 700-780°F but only a limited number of tests reaching film temperatures above 800°F. In addition, the highest film temperature tests were achieved only on the lowest mass velocity.

The results of these tests have shown that in addition to the film temperature, the rate of coke deposition on the inside tube wall can be controlled by mass velocity. This effect appears to be above that expected by the effect of mass velocity on film temperature alone. To continue the investigation of the mass velocity effect on coking a full series of tests (mass velocity 150-600 lbm/sec ft^2, heat flux 15k to 60k Btu/hr ft^2) was judged necessary.

Unfortunately as the coking unit was designed it was not possible to produce the high bulk temperatures (approximately 750°F) required to achieve the desired film temperature on the high mass velocity cases. The reason for this, refer to Figure 6, is that as originally designed the total crude flow discharged by the booster pump must pass through the gas fired preheat furnace. At full flow the required 30% increase in crude delta T could not be achieved with this preheat furnace. The only way to achieve the higher bulk temperatures was to reduce flow to the fired heater by limiting crude flow. Therefore, a new by-pass line around the fired heater was necessary.

During the past quarter the new by-pass (shown dotted on Figure 6) was designed and installed. The new by-pass has been successfully operated as a flow control around the fired heater. Unfortunately a seal leak in the booster pump and a one month forced outage caused by the host refinery rerouting powerlines to the coking unit delayed initiation of the final coking test.

During the extended downtime, all temperature sensitive equipment such as the data logger, logic controller, and burner controller were removed from the unit. At the end of this reporting period power had been reestablished at the unit and the removed items were reinstalled. A complete system check-out was deemed necessary and begun. The final test is expected to begin after the system check-out has been completed.

3.3 Fluidized Bed Heat Transfer Studies

3.3.1 Background Information

The objective of the Fluidized Bed Heat Flux Studies is to quantitatively define both the peripheral and the tube-to-tube maldistribution of heat input to tubes immersed in a fluidized bed. The maldistribution patterns will be determined as a function of controllable design parameters including tube size, spacing, orientation and fluidization velocity.

The data to satisfy the requirements of this task are being obtained in two separate series of tests. The principle tests will be carried out in a "hot" fluidized bed facility. These tests will determine the overall level and pattern of heat transfer to tubes in a fluidized bed. Some complimentary ambient temperature studies, which are now completed, have defined the conductive/convective component of the heat transfer mechanism. By comparing results from the high temperature and ambient tests, the radiation component will be determined by difference.

A detailed discussion of the facility design and Task Plan for this part of the Program is given in the Quarterly Technical Report No. 3, dated April 25, 1977. The interested reader is referred to that report for additional information.

3.3.2 Ambient Temperature Heat Flux Tests

The conductive/convective heat transfer measurements on single tubes and tube bundles were completed in conjunction with the Two-Dimensional Flow Visualization tests completed earlier in this program. Results have been reported in Quarterly Technical Report Nos. 5, 6, and 7.

Briefly summarized, the tests defined the peripheral patterns of heat input to horizontal tubes fully immersed in a fluidized bed of limestone as well as to tubes in the splash and freeboard zones above the bed. Three distinct regions of heat transfer were identified around the tubes; namely, the predominately gas shrouded underside of the tube, the dense layer or "cap" on top of the tube and the "surfline" or rapidly oscillating region of solids-to-tube contacting at the 45° and 315° region (0° or 360° region defined as the top of the tube).

It was also determined that for a wide blend particle size bed material, heat transfer performance is predominately determined by the finer particles in the blend and is relatively unaffected by the coarser particles.

3.3.3 High Temperature Heat Flux Test Unit

The High Temperature Heat Flux Test Unit is being constructed at the Exxon Engineering Center, Florham Park, N. J. A schematic flow sheet showing the principal components of the system is shown in Figure 7. A plot plan of the unit area is illustrated in Figure 8. An elevation and plan view of the test facility were previously documented (Quarterly Report No. 8, August 28, 1978).

The heat flux unit is divided into eight identifiable subsystems; these are: (1) air supply and metering system, (2) propane supply system, (3) precombustor and fluidized bed test unit, (4) heat removal system, (5) heat transfer coils, (6) cyclones, (7) flue gas cooler, (8) dust filter. A description of these eight major subsystems follows.

Air Supply and Metering System

The air supply system consists of a 10,000 SCFM Hoffmann Frame 77106 Centrifugal Air Blower and a 700 hp, 4160 volt, 60 cycle WPII Louis Allis electric motor. Nominal discharge pressure of the blower at design air flow is 10 psig. This equipment was designed and installed as part of the Two-Dimensional Flow Visualization Test Unit.

The air metering system consists of one 10-inch diameter schedule 20 carbon steel orifice meter run. The straight run is 25'-0" upstream and 6'-0" downstream of the orifice plate. The capacity of the metering system is 3467 CFM at 60°F and 14.7 psia (dry air basis). The metered air will be at 24.3 psia and 230°F. The differential head of the orifice at rated conditions will be 23.4 inches water gauge for a beta of 0.65.

Propane Supply System

Five-1000 gallon aboveground tanks are used for propane storage. Two Ransome RW-100 water bath vaporizers are connected in parallel to supply propane vapor to the precombustor burner. Each vaporizer is rated for 100 gph liquid, equivalent to 3639 scfh (9.17 M Btu/hr) and is designed for 25 psig discharge pressure and 0°F minimum ambient temperature.

Precombustor and Fluidized Bed Test Unit

The combustor (Process Combustion Corp.) is of the horizontal type and is designed to fire propane at a maximum heat release of 12 M Btu/hr with a 10:1 turndown. The combustor is designed for 3 psig and a maximum combustion gas temperature of 2600°F. The shell is refractory lined based on a maximum outside shell temperature of 250°F at 70°F ambient air and zero wind velocity. The hot flue gases pass up through a six-inch thick refractory (RESCO RS 17 with metal fibers) grid of 0.25 in holes on 1.25 inch square pitch. The test bed cross section is approximately two feet by 4.8 feet for an area of 9.7 ft^2. The bed tempertures will range from 1000°F to 1600°F.

Heat Removal System

The heat removal system consists of a closed loop through which cooling water is circulated between coils in the fluidized bed and a GEA air cooled heat exchanger. The air cooled heat exchanger will dissipate approximately 5 M Btu/hr absorbed in the bed. Water temperature to the coils will be controlled at 150°F. A centrifugal pump (Peerless Pump) will circulate the cooling water at controlled rates up to 500 gpm (115 feet head). A surge tank located upstream of the pump will contain adequate volume for thermal expansion. It will also provide an air-water interface where compressed air will be used to pressurize the system in order to suppress vaporization in the coils.

Heat Transfer Coils

The heat transfer coil being tested is the arrangement determined in the Two-Dimensional Flow Visualization Studies as an acceptable bundle configuration. It consists of four inch diameter tubes on a two diameter equilateral spacing. The unit is sized to allow for six tubes per row with three rows immersed in the fluidized bed and one row contained in the free board zone. Water is used as the process fluid for heat removal.

The tubes are instrumented to determine the effect of tube position on heat transfer performance. RTD measurements of the process water temperature for various tube passes are made. From the water temperature and flow measurements, overall heat transfer coefficients for each tube will be determined. Three tubes are instrumented with thermocouples to determine local peripheral heat transfer coefficients. These coefficients will be evaluated from measurement of inside tube wall temperature, water flow rate, water temperature and bed temperature measurements. The peripheral variation in inside tube wall temperature will be monitored at eight locations per tube cross section. By comparing the above data, obtained at several bed temperatures, with the ambient temperature unit data, a separation between the radiative and the conductive/convective components of the heat transfer mechanism will be determined.

Vortex shedding meters and manual control valves are located on the inlet side of each pass to provide for flow rate measurement.

Cyclones

Two primary Ducon cyclones are provided to separate the particulate carryover in the bed from the flue gas. These parallel cyclones are made of carbon steel and designed for 1700°F and 3 psig. Normal operating conditions will be at 1600°F and 2 psig and a maximum flow to each unit of 80 ACFS. The maximum inlet dust loading to each cyclone is 0.04 lbs/ACF. At this rate the maximum loss to the downstream dust filter is 200 lbs/hr which is equivalent to an efficiency of 99.2%. The captured solids are recycled via two external diplegs to the fluidized bed.

Due to the elevated temperatures of operation, the cyclones are lined with Resco RS-17E refractory reinforced with one inch long by 0.013 inch diameter 310 stainless steel fibers. Minimum refractory thickness is five inches.

Flue Gas Cooler

A flue gas cooler is provided to cool the nominal 1600°F dusty flue gas before it enters the dust filter unit. The cooler is designed to remove 4.5 M Btu/hr. The shell side flue gas runs co-currently to the tube side (396 ft^2) water whose inlet and outlet design temperatures are 120°F and 150°F, respectively. Water is circulated using a Crane/Deming Model 4121H-3S pump rated at 300 gpm, 200 ft. of head. It should be noted that the outlet water temperature is limited to 150°F because of the design temperature (160°F) of the plastic cooling tower used for cooling the water.

In order to control the temperature of the cooled flue gas for a wide range of hot flue gas temperatures (up to 1600°F), the tube surface area must be variable. Six separate bundles are provided: the first bundle, always in service, provides sufficient surface area for minimum cooling requirements, the other five tube bundles are brought in or out of service depending on the cooled flue gas temperature. The variable surface area is controlled using a Texas Instruments programmable controller. The outlet water temperature is controlled at the surge tank upstream of the cooling tower. A three-way valve proportions flow to the cooling tower or to a drain. Water in the cooling tower is maintained by level control.

Dust Filter

Dust passing through the cyclones will be collected by a Mikro Pulsaire Dust Collector, Model 100S-10-20 and flow by gravity to a disposal unit. The unit is designed for 425°F and 20 inches water gauge.

During normal operating conditions, 32-97 CFS flue gas at 370°F, 0.3 psig will enter the dust filter at a maximum solids loading of 200 lbs/hr (0.00082 lb/ft^3). The flue gas discharged to the atmosphere will contain less than 1 lb/hr particulates, satisfying the requirements of the New Jersey State Department of Environmental Protection.

The unit has been designed for operation above the dewpoint: the water dewpoint for propane firing and the acid dewpoint during coal combustion. It is important that the metal surfaces and bags do not become wet and thus present the possibility of "cement" formation from the dusty flue gas. The 100-10 ft filter bags (1180 ft^2) will be made of Nomex to allow for operation at temperatures up to 425°F, i.e. above the acid dewpoint. Three inches of external insulation will keep the metal temperature of carbon steel body above the dewpoints.

3.3.4 Construction Progress

Procurement and field assembly work on the heat flux unit continued during the reporting period. All major pieces of equipment arrived onsite with the exception of the flue gas cooler whose delivery has been guaranteed for mid-January by the vendor.

In the field, work progressed on several fronts. Installation of piping from the propane vaporizer to the combustor has been completed. The vaporizers have been test fired. Pumps and surge tanks for the flue gas cooling circuit and heat removal loops have been sited. The dust filter has also been sited. The blocking of the cyclones and the combustor-to-cyclone duct work at ground level enabled the welding/piping contractor to complete field welding of the duct work and required flanges. These pieces along with the cyclone-to-cooler pipe sections were lifted into place above the combustor for fitting. The cyclone diplegs and additional pipe sections were sized and the required flanges welded. All pieces were match marked before disassembly and shipment to a vendor for refractory lining. After the pieces are returned refractory lined a final lift into place will be required.

Installation of piping for the flue gas cooling and fluidized bed heat removal loops is now partially complete. Before these loops can be completed, the flue gas cooler and the fluidized bed cooling coils must be installed. Steam, water, and air lines to the unit have been installed.

Other areas in which work is in progress include installation of process control and data acquisition equipment and the required cabling to the unit, installation of the 110V and 480V distribution panels and preparation of the operating manual. A revised coal and limestone handling specification was completed and issued for vendor bids.

3.3.5 Process Control and Data Acquisition/Analysis

In order to illustrate the control and data acquisition features of the unit, the "P&I" (Piping and Instrumentation) flow diagrams are shown in Figures 9a, b and C. The numbering system for these diagrams is consistent with the eight individual subsystems, i.e. (1) air system, (2) propane system, (3) heat flux unit (combustor), (4) heat removal system, (5) heat transfer coils, (6) cyclones, (7) flue gas cooler, and (8) dust filter. The control and data acquisition features of these components are summarized in Figure 10.

As is indicated on Figure 9c, the tubes in the heat transfer coils are instrumented to determine the effect of tube position on heat transfer performance for bed surface tubes, tubes near the grid or wall and tubes "buried" in the center of the bundle. From bed temperature and water temperature/flow rate measurements, the overall heat transfer coefficients for each tube can be calculated from Equation (1), Figure 11. From the overall heat transfer coefficient the tube average outside heat transfer coefficient can be evaluated, Equation 2. This average coefficient will be compared to the ambient temperature heat transfer coefficients previously determined. By conducting a series of experiments at varying bed temperatures, an assessment of the radiation effects on $h_{o\ avg.}$ will be made.

Three tubes are instrumented to determine local peripheral heat transfer coefficients. The peripheral variation in inside tube wall temperature will be monitored at eight locations per tube as illustrated in Figure 9c. The coefficients will be calculated per Equation (3), Figure 11. An integration of these local coefficients should equate to the average valves obtained from a heat balance on the energy picked up by the water, Equation (2).

The effect of the tube wall will be to smooth high or low rates of heat transfer occurring along the outside tube periphery. Mathematical techniques to determine this effect are being investigated. However, primary concern will be focused on the effective inside heat transfer rates that include the effect of the tube wall since it is these heat transfer rates that will ultimately effect the hydrocarbon coking in a commercial FBC heater.

3.3.6 Test Program

A discussion of the proposed test sequence and test matrix for high temperature heat flux tests was originally discussed in Quarterly Report No.3, April 25, 1977. Based on results from the Two-Dimensional Flow Visualization Studies and the Ambient Temperature Heat Flux Tests, the original test matrix has been updated and is presented in Figure 12.

As noted, the velocity test points have been changed to reflect the previous work. The maximum velocity of 20 ft/sec has been eliminated since at these velocities it is known that our limestone bed particles would be carried out of the tube bundle region and drastically reduce the bed density and heat transfer potential. As previously reported, a practical upper limit of fluidization velocity is reached when the absolute velocity of gas exiting the bundle region prevents the draining of material back into the tube region and a layer of bed material is formed above the bundle. Although 15 ft/sec is higher than this critical velocity for our system (~ 12 ft/sec), that velocity test point has been left in our matrix for comparison with data from the Ambient Temperature Heat Flux Tests. Test points at 6 ft/sec and 8 ft/sec have been changed/added to obtain direct data comparisons with the "ambient" tests.

It should be noted that extending the range of the test matrix to include the lowest velocity and the highest bed temperature is dependent on (1) actual heat transfer coefficients obtained in the fluidized bed and (2) the maximum flue gas temperature passing through the grid (design limits approximately 2600°F).

The test sequence is planned to begin with all velocity test points at the lowest bed temperature (1000°F). Test cycles will be repeated at progessively higher temperatures until all proposed tests have been run.

FORM ERDA 535
(2/1/77)

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

MILESTONE PLAN AND MANAGEMENT REPORT

PAGE OF

1. Contract Identification: Industrial Application of Fluidized Bed Combustion - Category III Indirect Fired Heaters

2. Reporting Period: through 12/31/79

3. Contract Number: EX-76-C-01-2471

4. Contractor (name, address): Exxon Research and Engineering Company
P. O. Box 101
Florham Park, New Jersey 07932

5. Contract Start Date: June 30, 1976

6. Contract Completion Date: March 31, 1981

9. Fiscal Years and Months: FY'78, FY'79, FY'80, FY'81 — CY'78, CY'79, CY'80, CY'81

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7. Identification Number	8. Reporting Category (e.g., contract line item or work breakdown structure element)	9. Fiscal Years and Months	10. Percent Complete
1.1	Project Management	Start 7/76	
1.2	2-Dimensional Flow	8/76	100
1.3	Process Stream Coking Studies	8/76	
1.4	Fluidized Bed Flux Studies	1/77	
1.5	Unit Operability Studies		
1.6	Econ. & Applications Eval.		
1.7	Demo. Unit Design		
1.8	Commercial Unit Design		
2.1	Demo. Unit Fab. & S/U		
2.2	Demo. Unit Operation		

11. Remarks

12. Signature of Contractor's Project Manager and Date: D. C. Cherrington 1/18/79

13. Signature of Government Technical Representative and Date

Figure 1

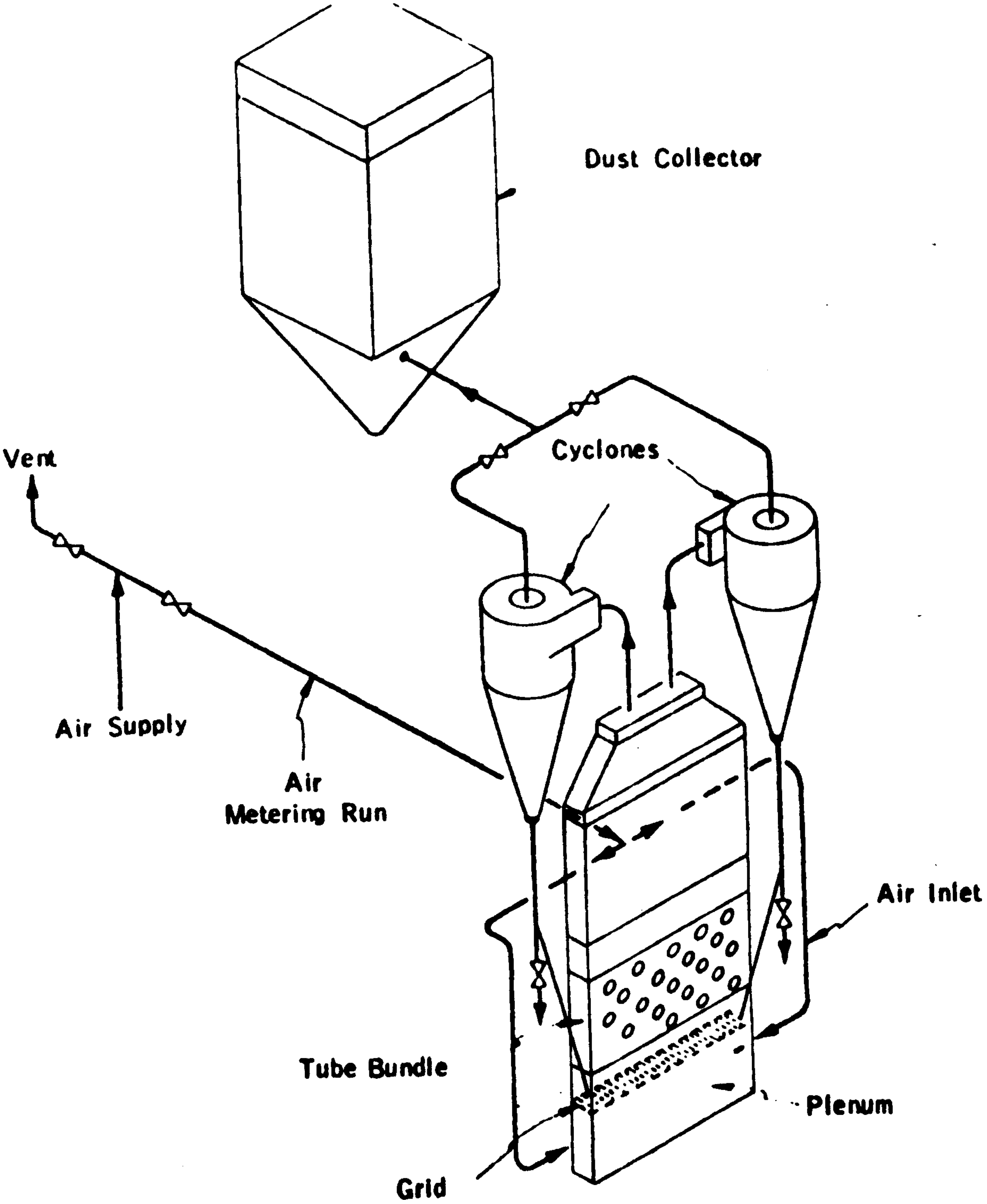


Figure 2

SCHEMATIC-TWO DIMENSIONAL FLOW VISUALIZATION UNIT

Papers and Presentations

1. Cherrington, D. C., Golan, L. P., "Fluidized Bed Combustion for Industrial Applications - Process Heaters", AIChE Paper No. 1, 17th National Heat Transfer Conference, Salt Lake City, Utah, Aug. 1977.

2. Cherrington, D. C., Golan, L. P., Hammitt, F. G., "Industrial Application of Fluidized Bed Combustion - Single Tube Heat Transfer Studies", Proceedings of the Fifth International Conference on Fluidized Bed Combustion, Washington, DC, Dec. 1977.

3. The Oil and Gas Journal, pp. 96-97, January 9, 1978.

4. Cherrington, D. C., Golan, L. P., "Coal Fired Fluidized Bed Process Heater Design Studies" Proceedings of 43yd mid year API Refining Meeting, Toronto, Canada, May 1978.

5. Hydrocarbon Processing, pp. 145-150, May 1978.

6. Weiner, S. C., Golan, L. P., Cherrington, D. C., "Solids Mixing and Fluidization Characteristics in a Tube Filled Bed", Thirteenth Intersociety Energy Conversion Engineering Conference, Aug. 20-25, 1978 San Diego, California.

Movie Distribution

1. Department of Energy

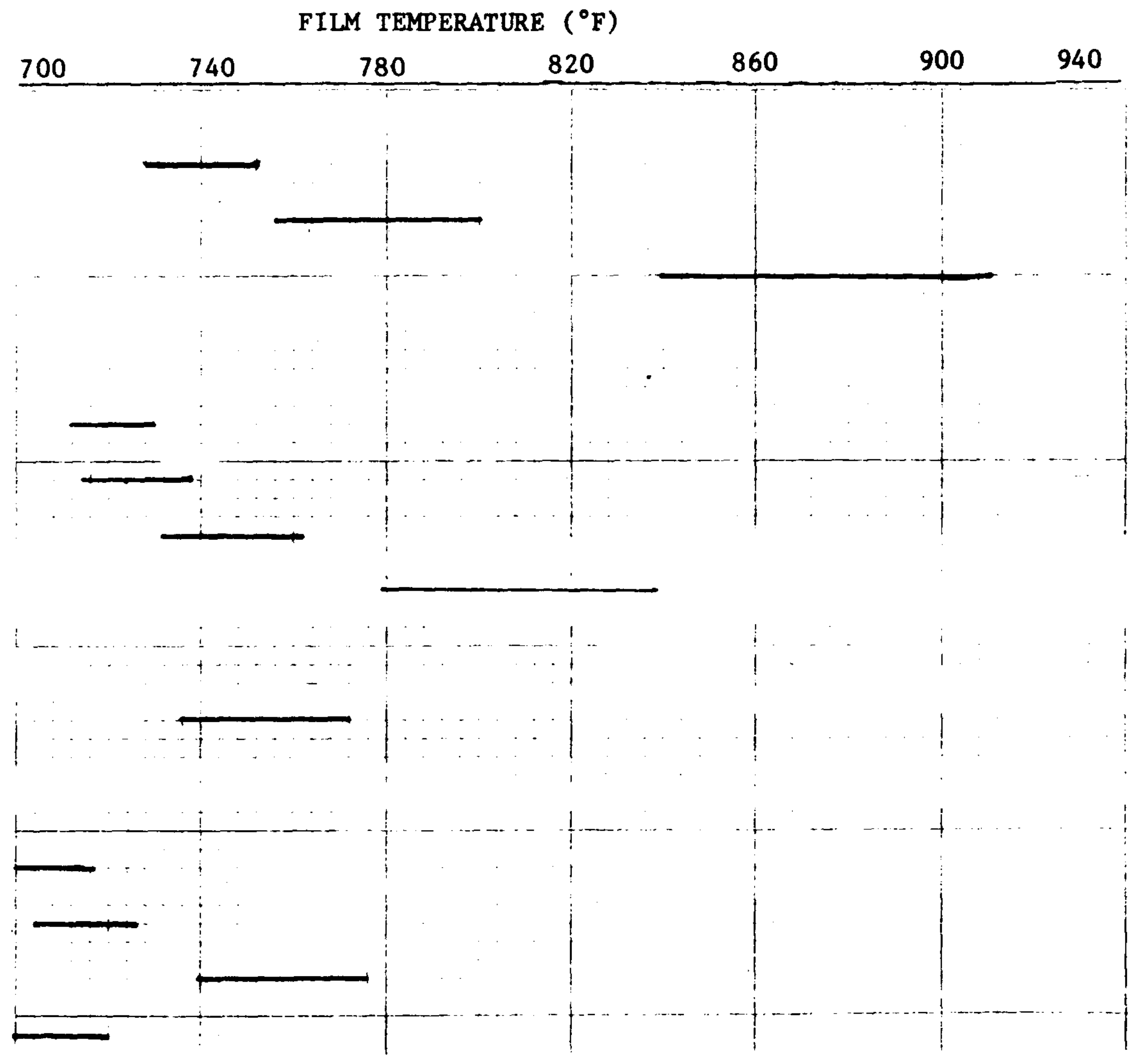
2. Fluidyne Engineering Corporation

3. Morgantown Energy Research Center

Flow Visualization Study Technical Society/Journal Publications

Figure 3

HTR	MASS VELOCITY LBM/SEC FT^2	HEAT FLUX BTU/HR FT^2	HOURS ON TEST
TEST 2			
A	595	61,000	93
C	285	59,000	132
D	143	59,000	40
TEST 3			
A	595	49,000	400
B	430	44,000	314
C	288	45,000	400
D	145	45,000	142
TEST 4			
D	145	30,000	190
TEST 5			
A	148	17,000	406
B	440	53,000-38,000	406
C	290	57,000	392
D	290	31,000	406



COKING TEST SUMMARY SHEET - OPERATING VARIABLES

FIGURE 4

	TEST NO. 2			TEST NO. 3				NO. 4	TEST NO. 5			
Heater Identification	A	C	D	A	B	C	D	D	A	B	C	D
Hours on test	93	132	40	402	314	402	142	191	406	406	392	406
Nominal test conditions:												
Oil in - °F	665	660	650	655	650	645	640	640	637	643	644	640
Oil out - °F	690	710	750	676	677	684	720	693	667	669	689	666
Heat flux - kBtu/hr ft^2	61	59	58	49	44	44	45	29	17	53-38	57	31
Mass velocity - lb m/ft^2 sec	595	285	143	600	430	285	143	143	148	441	290	290
Film temperature - °F	731-753	756-798	837-909	713-726	715-737	732-762	782-838	736-773	695-717	705-726	741-776	699-720
Increase in tube temp. over test period - °F	NIL	170	250	NIL	NIL	300	400	300	190	NIL[1]	480	120
Increase in thermal resistance over test period - °F/Btu/hr x 10^{-3}	NIL	NIL-1.9	2.5-3.2	NIL	NIL	3.1-5.2	4.5-7.7	4.3-6.3	6.5-10.0	.7-1.9	5.1-6.6	1.4-2.9
Avg. increase in thermal resistance per hr - $\frac{°F/Btu/hr}{hr}$ x 10^{-5}	NIL	1.3*	7.8	NIL	NIL	1.1	4.5	3.1	2.2-3.8	.4-.7	1.6-2.2	.5-1.6
Coke thickness at end of run - in. x 10^{-2}	NIL	.12-.33	.22-1.18	NIL	NIL	0.2-1.8	1.7-2.7	0.5-1.6	1.0-1.6	NIL	2.2-3.5	NIL

* Thermocouples 2-4

:mac

[1] Due to flux decrease

COKING TEST SUMMARY SHEET - RESULTS

Figure 5

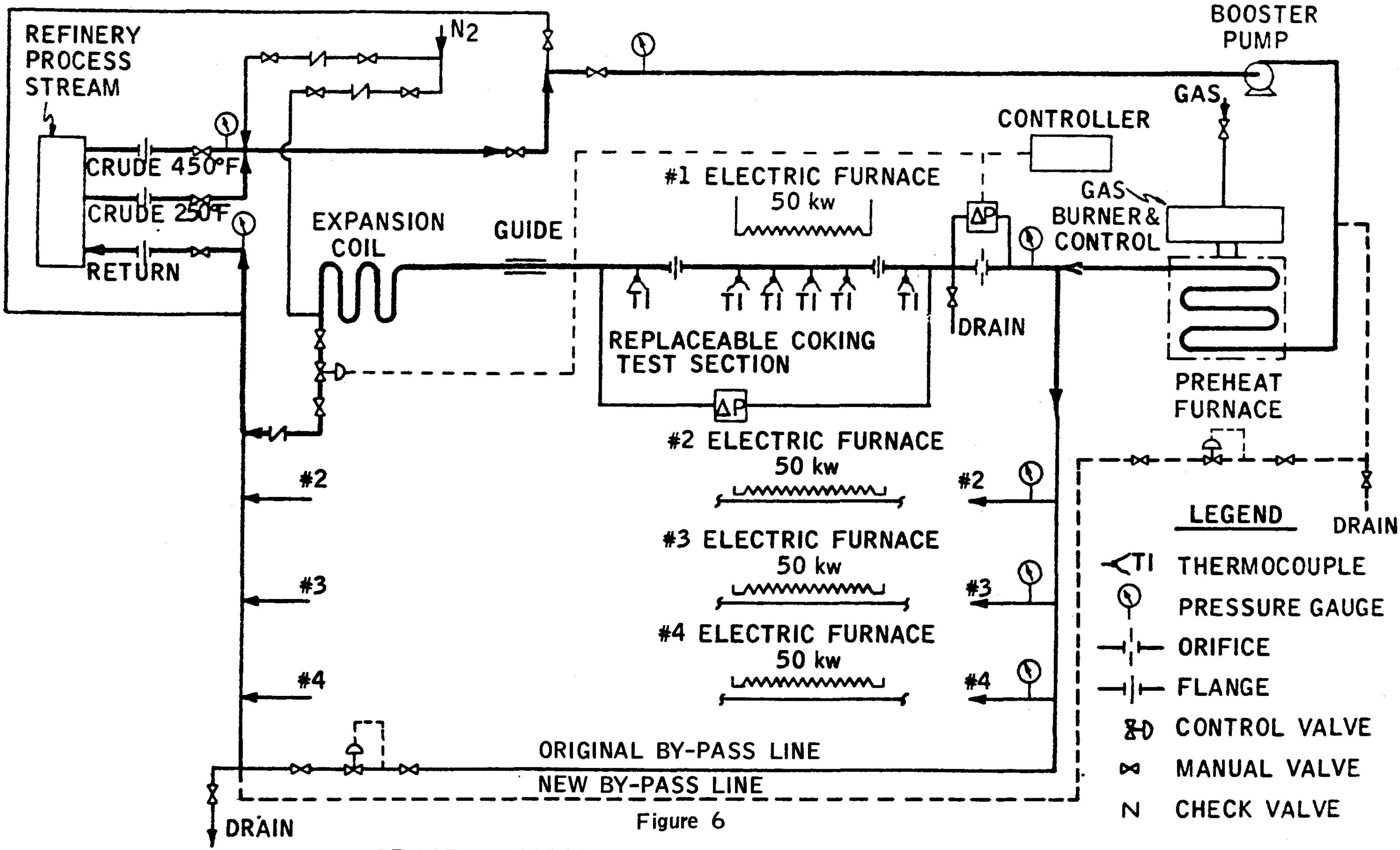


Figure 6

REVISED PROCESS STREAM COKING UNIT SCHEMATIC

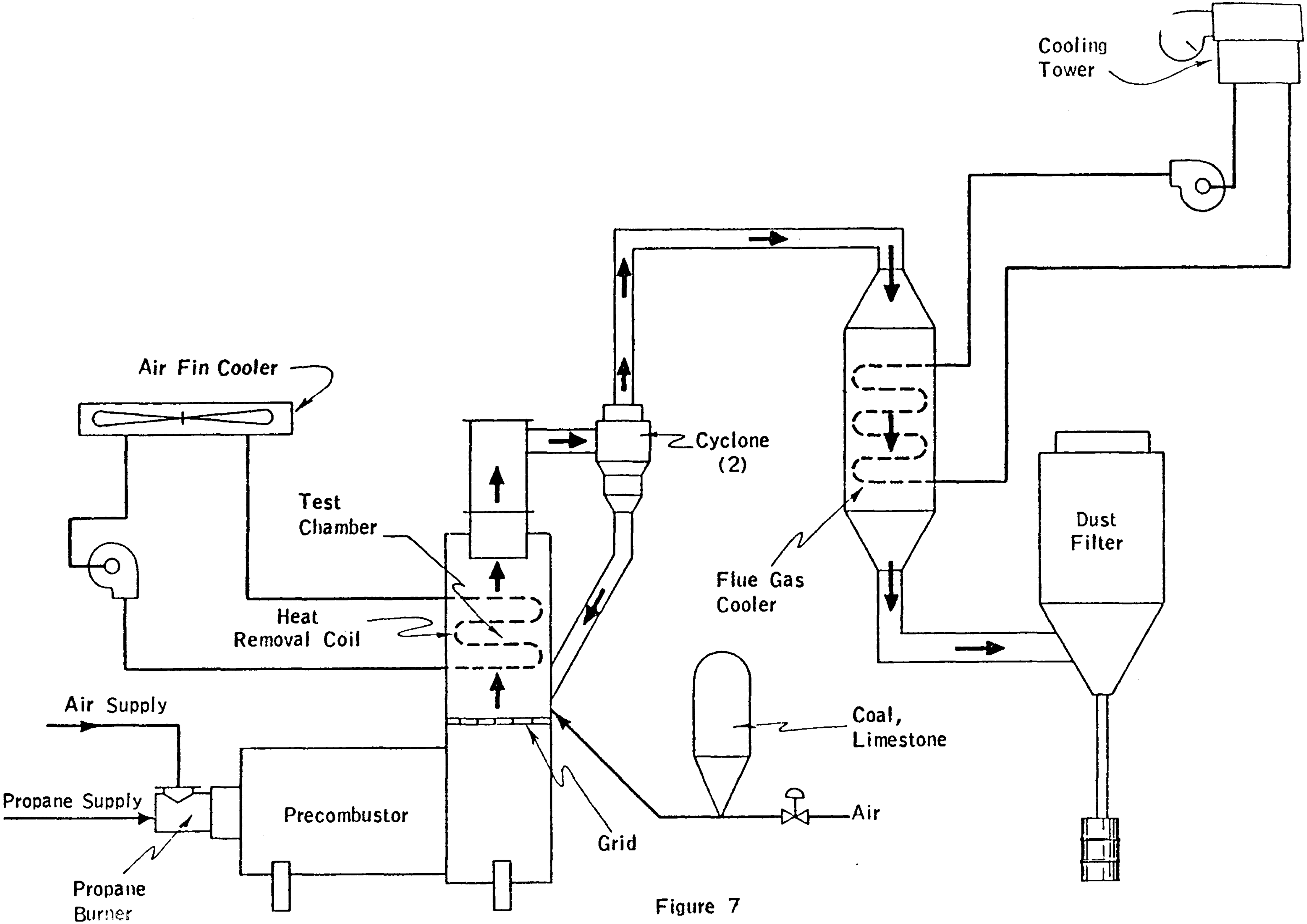
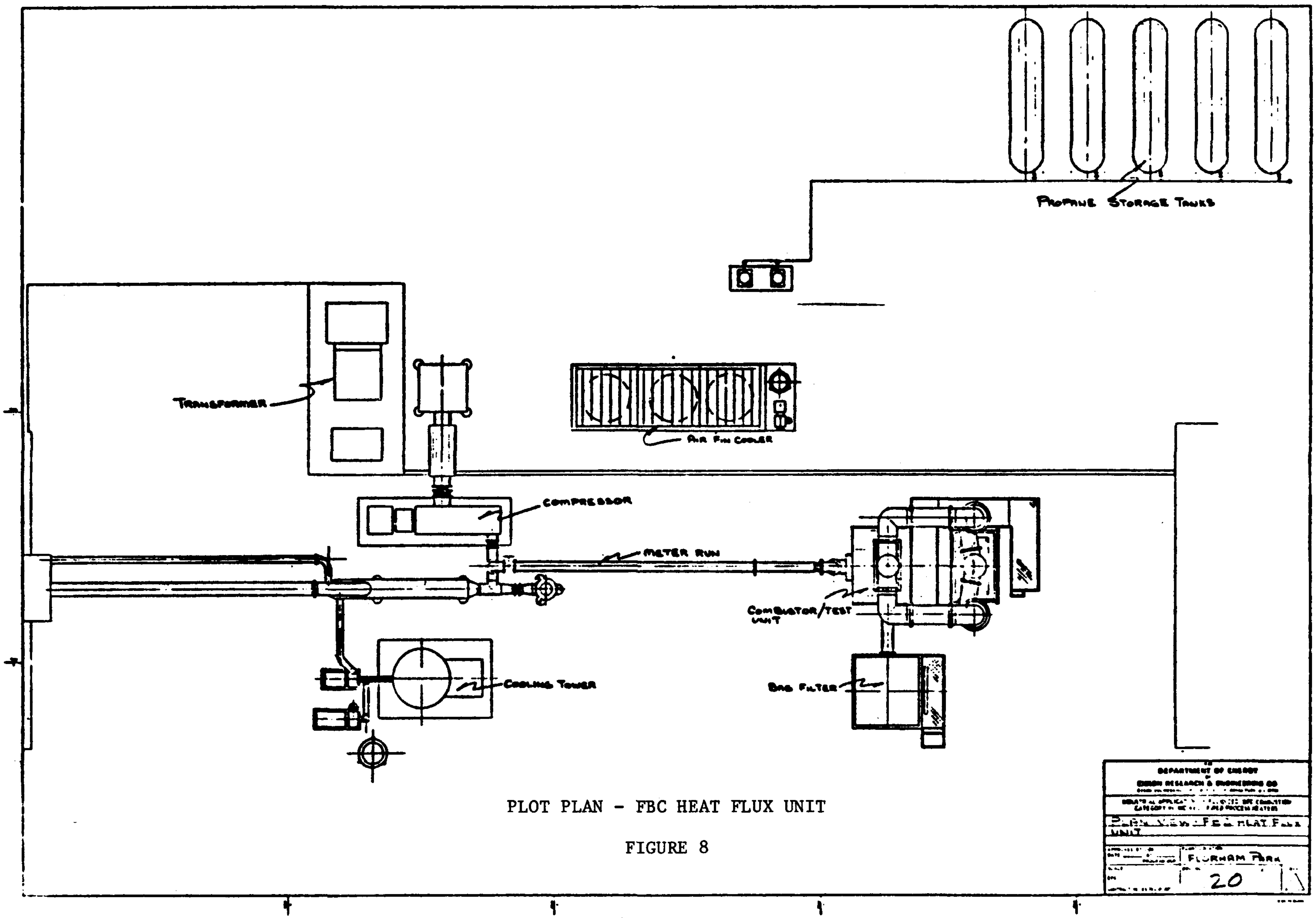


Figure 7

FLOW PLAN
FBC HEAT FLUX UNIT



PLOT PLAN - FBC HEAT FLUX UNIT

FIGURE 8

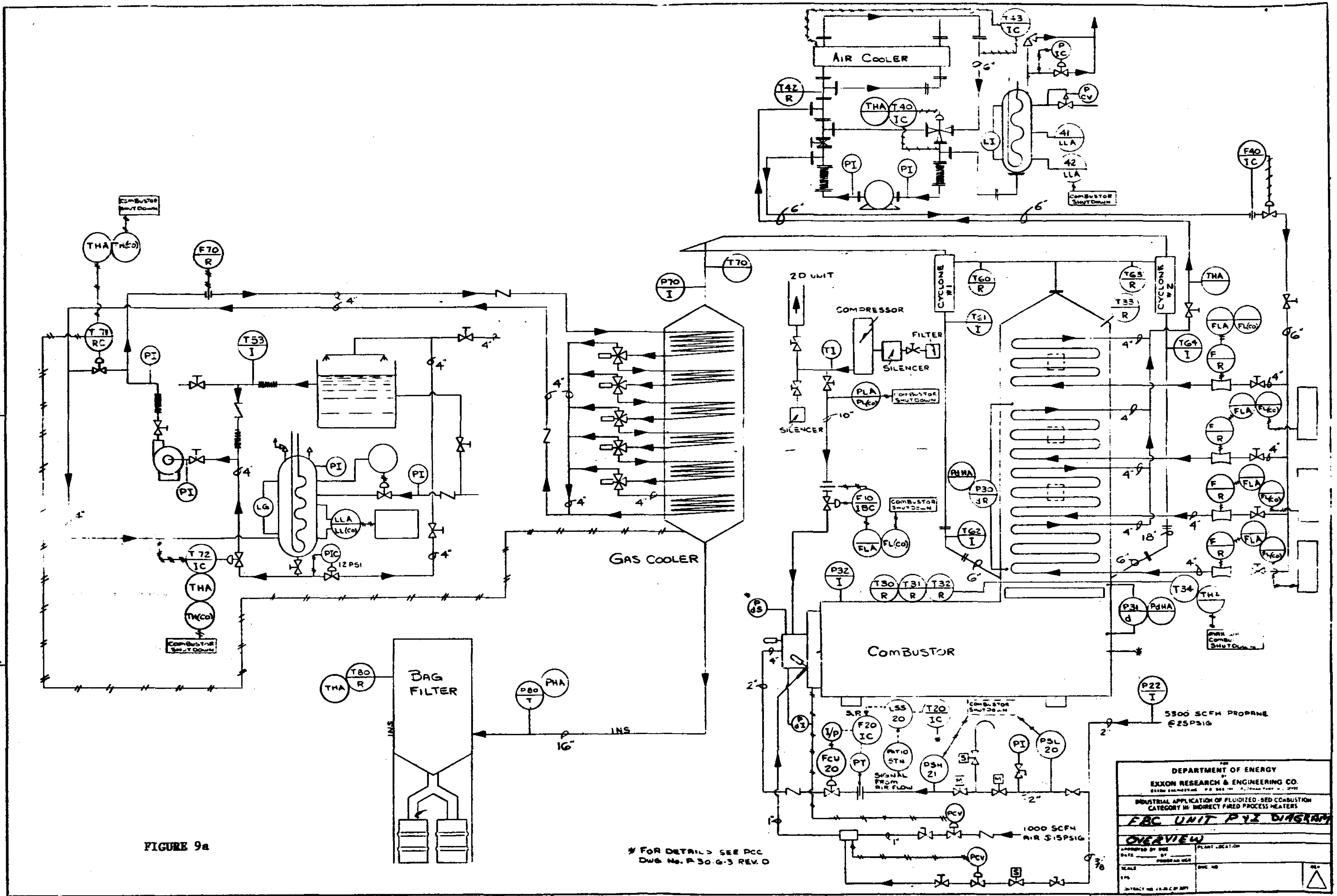
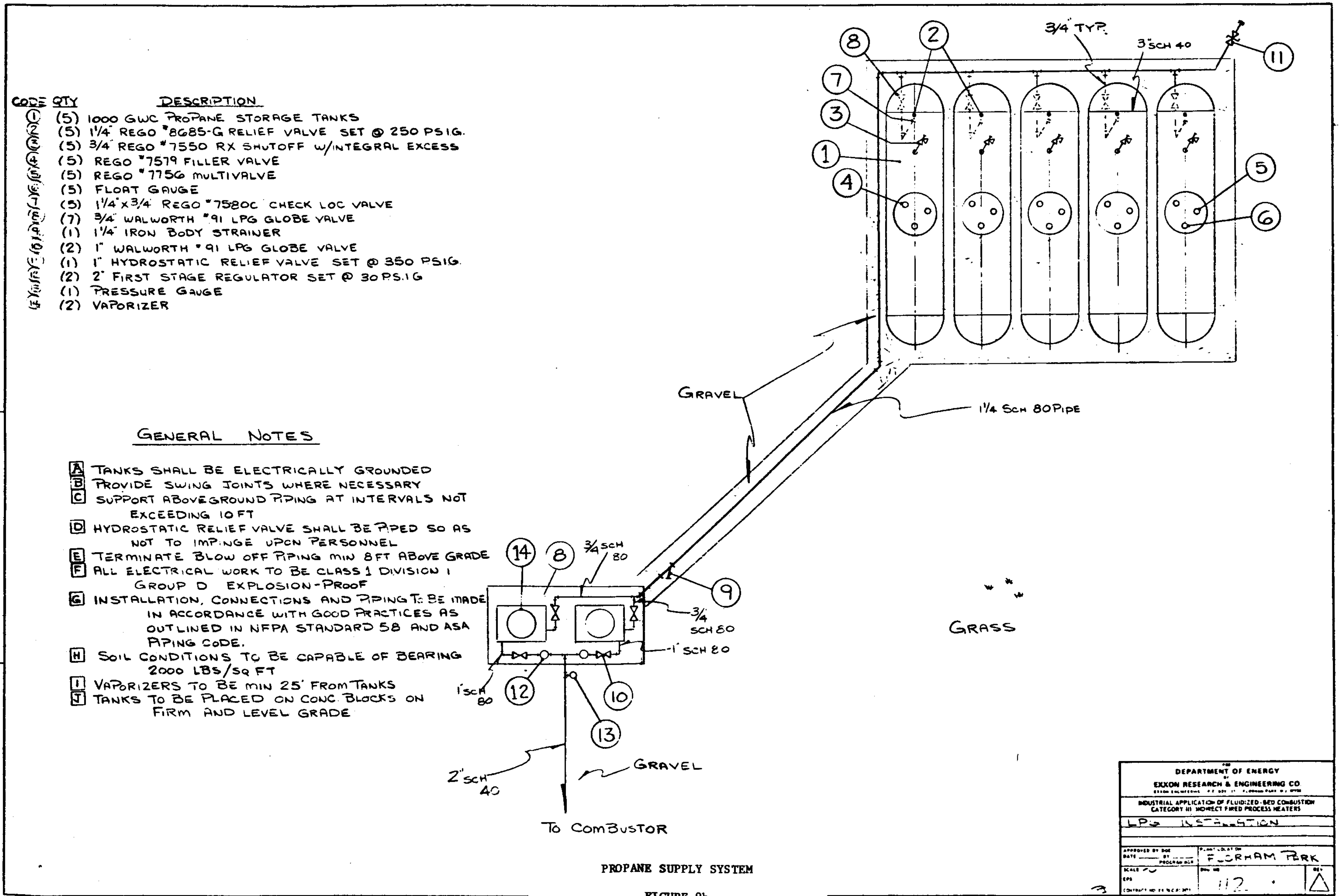

AIR COOLER
COMPRESSOR
FILTER
SILENCER
20 UNIT
CYCLONE #1
CYCLONE #2
GAS COOLER
BAG FILTER
COMBUSTOR
COMBUSTOR SHUTDOWN
5300 SCFH PROPANE @25PSIG
1000 SCFH AIR @15PSIG
SIGNAL FROM AIR FLOW
RATIO STN
12 PSI
INS
16"
* FOR DETAILS SEE PCC DWG No. P30-G-3 REV. D
DEPARTMENT OF ENERGY
EXXON RESEARCH & ENGINEERING CO.
INDUSTRIAL APPLICATION OF FLUIDIZED-BED COMBUSTION
CATEGORY III: INDIRECT FIRED PROCESS HEATERS
FBC UNIT P&I DIAGRAM
OVERVIEW

FIGURE 9a



PROPANE SUPPLY SYSTEM

FIGURE 9b

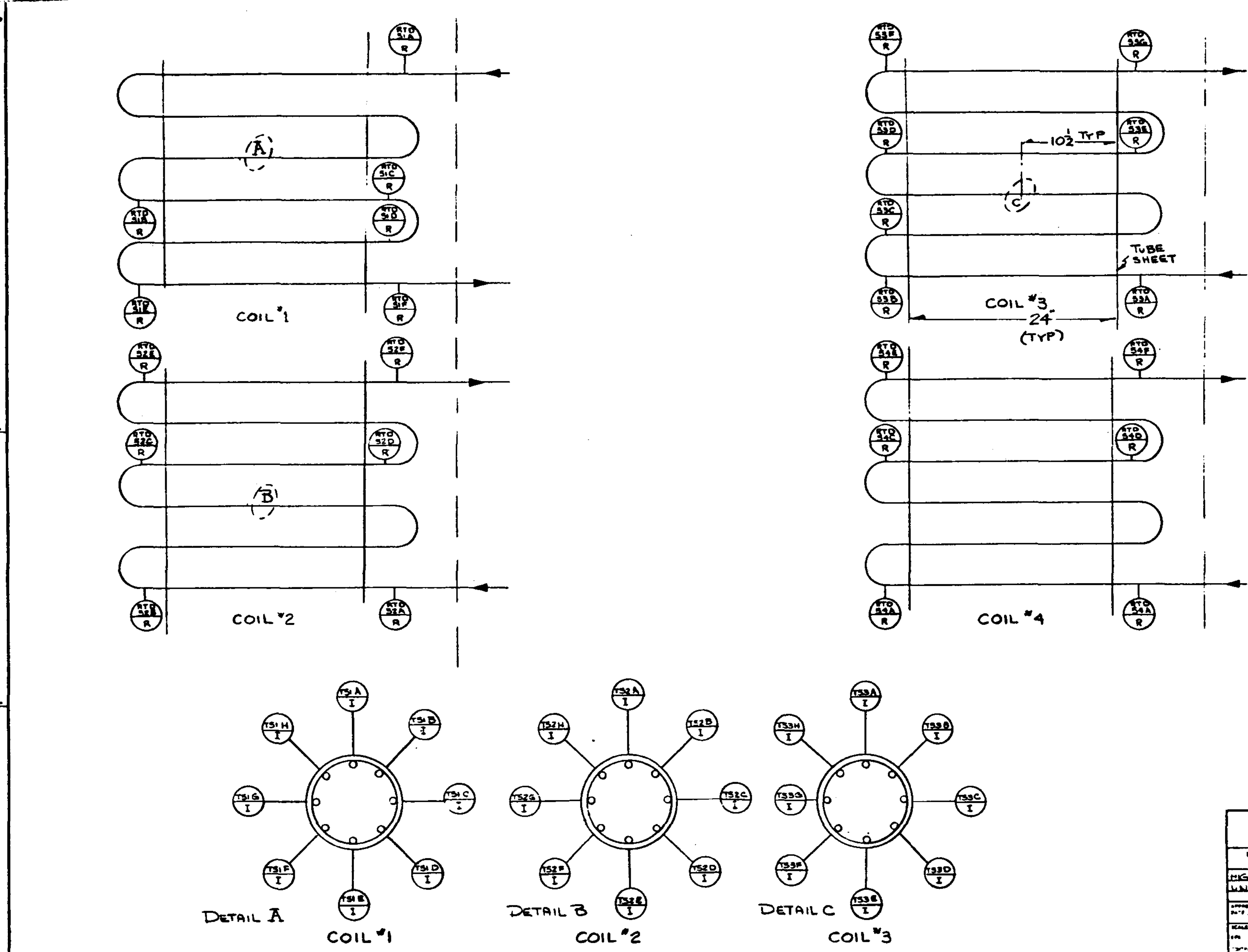


FIGURE 9c

DEPARTMENT OF ENERGY
EXXON RESEARCH & ENGINEERING CO.
INDUSTRIAL APPLICATION OF FLUIDIZED-BED COMBUSTION
CATEGORY III: INDIRECT FIRED PROCESS HEATERS
HIGH TEMPERATURE HEAT FLUX
UNIT HEAT TRANSFER COILS
PLANT LOCATION: FLORHAM PARK
DWG NO 124

FIGURE 10

FBC HEAT FLUX UNIT
PROCESS CONTROL AND DATA ACQUISITION

MEASUREMENT VARIABLE	CONTROL	MONITOR	RECORD	ALARM	SHUTDOWN
Air System					
Combustor air flow rate	X	R	DL	L	X
Blower discharge temperature			DL		
Blower discharge pressure			DL	L	X
Propane System					
Tank level (5)		L			
Vaporizer water bath temp. (2)		L			
Propane pressure		R		L/H	X
Propane flow rate	X	R	DL/T		
Heat Flux Unit					
Combustor pressure		R	DL		
Combustor temperature	X	R	DL/T	H	X
Grid pressure drop			DL	H	
Bed pressure drop			DL/T	H	
Bed temperature (6)			DL/T	H	X
Freeboard temperature			DL/T		
UV flame detection		R		L	X
Heat Removal System					
Total water flow rate	X	R	DL		
Coil water flow rate (4)			DL/T	L	X
Pump suction temperature	X	R	DL	H	
Pump suction pressure		L			
Pump dishcarge pressure		L			
Surge tank level		L		L	X
Surge tank pressure		L			
Coil return water temperature			DL	H	
Cooler inlet temperature					
Cooler outlet temperature	X	R	DL		
Heat Transfer Coil					
Coil periphery temperature (24)		R			
Coil inlet water temp. (4)			DL		
Coil outlet water temp. (4)			DL		
Coil u-bend water temp. (17)			DL		
Cyclones					
Cyclone temperatures (2)			DL/T		
Cyclone dipleg temp. (4)		R			
Flue Gas Cooler					
Gas inlet pressure		R			
Gas inlet temperature			DL		
Gas outlet temperature	X	R	DL/T	L/H	X
Water flow rate (to cooler)			DL		
Water temp. (to cooling tower)	X	R		H	X
Water temp. (from tower)		R			
Pump suction pressure		L			
Pump discharge pressure		L			
Surge vessel pressure		L			
Surge vessel level		L		L	X
Dust Filter					
Dust filter pressure		R		H	
Dust filter temperature			DL/T	L	
Solids discharge weight		L			

Legend

1. Measurement variable - number in parentheses indicates the number of variables.
2. Monitor - R = remote indication, L = local indication.
3. Record - DL = recorded on data logger tape, T = recorded on pen trend recorders.
4. Alarm - L = low alarm, H = high alarm.
5. Shutdown - check marks indicate shutdown of the propane firing system.

FIGURE 11

HIGH TEMPERATURE HEAT FLUX TESTS
PRELIMINARY DATA ANALYSIS EQUATIONS

Calculation of overall heat transfer coefficient, U and average outside heat transfer coefficient, $h_{o\ avg.}$

$$q = M\,C_p(Two - Twi) = UA\,\frac{Two - Twi}{\ln \dfrac{T_b - Twi}{T_b - Two}} \qquad (1)$$

$$UA = \frac{1}{\dfrac{1}{Di\ hi} + \dfrac{\ln(D_o/D_i)}{2k} + \dfrac{1}{D_o h_{o\ avg.}}} \qquad (2)$$

Calculation of Local Peripheral Heat Transfer Coefficient, h_o

$$q = \frac{Twall - Tw}{\dfrac{1}{D_i h_i}} = \frac{T_b - Twall}{\dfrac{\ln(D_o/D_i)}{2k} + \dfrac{1}{D_o h_o}} \qquad (3)$$

A = tube surface area

C_p = heat capacity of water

D_i = inside tube diameter

D_o = outside tube diameter

h_i = inside heat transfer coefficient, Dittus Boelter Equation

h_o = outside heat transfer coefficient

k = thermal conductivity of tube

m = mass flow rate of water through tube

q = heat transfer rate

T_b = bed temperature

T_w = average water temperature

Twall = inside tube wall temperature

Twi = inlet water temperature

Two = outlet water temperature

FIGURE 12

HIGH TEMPERATURE HEAT FLUX TESTS
TEST MATRIX

Fluidized Temperature, °F	Superficial Bed Velocity, Ft/sec: Original Matrix	Updated Matrix
1000	5, 10, 15, 20	6, 8, 10, 12, 15
1300	7.5, 10, 15, 20	8, 10, 12, 15
1600	10, 15, 20	10, 12, 15

*U.S. GOVERNMENT PRINTING OFFICE : 1979 0-281-704/9