INDUSTRIAL APPLICATION FLUIDIZED BED COMBUSTION

CATEGORY III

INDIRECT FIRED HEATERS

Quarterly Technical Report No. 16

April 1 - June 30, 1980

Prepared By
Exxon Research and Engineering Company
Engineering Technology Department
P.O. Box 101
Florham Park, NJ 07932

There is no objection from the patent
point of view to the publication or
dissemination of the document(s)
listed in this letter.

BROOKHAVEN PATENT GROUP

8/5 1980 By UAC

For
U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States DOE, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

PRELIMINARY

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>PAGE</u>
List of Figures	
Abstract	1
1. Objectives and Scope of Work	2
2. Summary of Progress to Date	4
3. Discussion of Technical Progress	5
3.1 Two-Dimensional Flow Visualization Studies	5
3.1.1 Background Information	5
3.1.2 Status of Work	5
3.2 Process Stream Coking Studies	7
3.2.1 Background Information	7
3.2.2 Status of Work	7
3.3 Fluidized Bed Heat Transfer Studies	9
3.3.1 Background Information	9
3.3.2 Ambient Temperature Heat Flux Tests	10
3.3.3 High Temperature Heat Flux Tests	10
3.3.4 Status of Work	
3.4 Unit Operability (Coal)	
3.4.1 Background Information	11
3.4.2 Description of Experimental Equipment	11
3.4.3 Summary of Operations	12
3.4.4 Results	15
3.4.4.1 Heat Transfer Results - In-Bed Coil	16
3.4.4.2 Heat Transfer Results Freeboard Coil	18
3.4.4.3 Unit Response Characteristics	18
3.5 Economic and Applications Evaluations	20
3.5.1 Task Objectives	20
3.5.2 Conclusions of the Applications Evaluation	20
3.5.3 Status of Work	21

Figures 1 thru 17

LIST OF FIGURES

- Figure 1. Milestone Plan and Management Report.
- Figure 2. Schematic Two-Dimensional Flow Visualization Unit.
- Figure 3. Process Stream Coking Unit Schematic.
- Figure 4. FBC Heat Flux Unit Flow Plan.
- Figure 5. Coal and Sorbent Handling Facilities.
- Figure 6. Champion Coal Particle Size Distribution.
- Figure 7. Temperature Measurements on the Heat Removal Coils.
- Figure 8. Total Outside Heat Transfer Coefficient Tube 3c.
- Figure 9. Convective Heat Transfer Coefficient Tube 3c.
- Figure 10. Polar Plot of Bed Tube 3c Total Heat Transfer Coefficient.
- Figure 11. Tube 3C Maldistribution Factor.
- Figure 12. Total Outside Heat Transfer Coefficient Coil 1c - Freeboard Coil.
- Figure 13. Freeboard Coil Correlating Heat Transfer Relationship.
- Figure 14. Convective Heat Transfer Coefficient Coil 1c - Freeboard Coil.
- Figure 15. Unit Response to Changes in Coal Rate - Run 8.
- Figure 16. Unit Response to 10% Changes in Air and Coal - Run 9.
- Figure 17. Unit Response to 25% Changes in Air and Coal - Run 8.

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 complementary 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 effect 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 of 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 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. All test runs have been completed. The data analysis shows that in addition to film temperature, mass velocity is an important parameter in controlling coking rate. No coke laydown occurred in any tests run at a mass velocity of 600 lb m/sec ft² at heat fluxes up to 60,000 Btu/hr ft².

The High Temperature Heat Flux Test Unit was put into operation during July 1979. Tests using both propane and coal fuels have been completed. Test results are summarized in this report.

The object of the Economic and Applications Task of the Program is to evaluate the economic and logistic factors that might influence the schedule and circumstances under which coal fired Atmospheric Fluidized Bed Combustion (AFBC) technology might be applied to petroleum and petrochemical plant process heaters. The results of these studies indicate that the potential for near term application of AFBC technology to refinery crude heaters is relatively low. A possible alternative application of FBC heaters in the Exxon Donor Solvent Process for the liquefaction of coal has been identified. In this alternative an FBC heater would be used to burn the heavy vacuum tower bottoms. A preliminary design of such a heater has been completed and released to the Exxon Synfuels Division for further evaluation.

The final task of the program will be to prepare a design specification for a hypothetical commercial sized process heater from which all interested parties can make a definitive evaluation of the technical and commercial prospects of the technology. This design work is now underway.

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 hydrocarbons 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 and applications analysis necessary to evaluate the attractiveness of fluidized bed combustion for indirect fired process heater applications.
- c. To prepare a complete Design Specification and 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 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 oriented 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°F (as required for separation by distillation or other typical processes) some degradation of the oil and resulting 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 are being investigated during the initial laboratory R&D phase of the program. This work is being 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 followed by the commercial unit design study.

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. These results are fully documented in Program Quarterly Report Nos. 5, 6 and 7.

All testing on the Process Stream Coking Test Unit has been completed. All coking tests were conducted at a nominal coil inlet temperature of 650°F and heat fluxes ranging from 15 to 60 kBtu/hr ft². The conclusions reached from these tests are documented in Quarterly Report No. 12. The results show that coke laydown in fluidized bed heaters can be controlled by designing for all liquid flow and tube side mass velocity in the range of 450 to 600 lb/sec ft².

A total of nine runs have been completed on the Heat Flux Test Unit. The first five runs were made with propane fuel only being fired in the precombustor. The results and analysis of these tests were reported in Technical Quarterly Report No. 14. Runs six through nine included the firing of coal. The analysis of the coal fired tests is included in this report.

The Economic and Application Evaluation Task (Program Task 1.6) is well underway. The first effort in this Task concentrated on the Applications portion which has been completed and reported in Quarterly Report No. 11. The conclusions drawn from the Applications Evaluations suggest that the potential for near term application of fluidized bed technology to refinery crude oil process heaters is relatively low. In many cases the siting and logistics problems associated with on-site replacement of gas or liquid fired heaters with coal fueled units preclude their practical consideration. A potential alternative application for FBC process heater technology has been identified. This involves the combustion of heavy vacuum bottoms from a synthetic-fuel-from-coal process now under development. A screening study is underway to evaluate the economic and operational advantages/disadvantages such a system might have compared to alternative options. The preliminary design of an FBC heater to burn these vacuum bottoms has been completed and is described in Technical Quarterly Report No. 15. The final design task of the program is now underway. This task includes the preparation of design specifications for hypothetical 400 M and 135 M Btu/hr coal fired process heaters. These designs will be compared to assess the impacts of size and service on heater design and costs.

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 foot deep by 7.5 feet wide by 12 feet high (see Figure 2). The facility was designed to accommodate a range of tube bundles assembled from tubes up to six inches in diameter and arranged on spacings up to four 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 later parts of this program.

All task data have been reported in Quarterly Technical Report Nos. 5, 6, and 7. 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

e4724

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 were designed to determine what effect the high heat flux rates measured in fluidized bed combustors will have on the coking rate of a hydrocarbon stream and to determine if the coking rate can be controlled within an acceptable range of operation. The specific objective of the coking tests was to establish the relative rate of coke deposition on the inside wall of hydrocarbon carrying tubes as a function of the process variables: bulk temperature, heat flux, mass velocity, and inside film temperature. Conventional fired heater operating conditions were used as the norm for comparison.

The test facility built to carry out these studies was installed at Exxon's Bayway Refinery located in Linden, New Jersey. The prime elements of the coking unit (Figure 3) were the four electrically heated heat exchanger tubes. The basic scheme was to pass a stream of virgin crude oil through each heat exchanger tube, impose a known heat flux, and carefully monitor each tube for indications of coking. In this way, comparative coking rates as a function of the varying process parameters were determined.

3.2.2 Status of Work

All work planned under this Task of the Program has been completed and reported in Quarterly Report No. 12. This portion of the program had two objectives:

- o Determine what design or operating conditions are required to limit coking to acceptable levels.
- o Determine what effect the high heat fluxes expected in an FBC heater have on coking rates.

Both of these objectives have been met. The first generation FBC process heater would use horizontal tubes to assure that all tubes are fully immersed in the fluidized bed and have all liquid flow within the tubes to prevent gas-liquid flow stratification from occurring. Under these general guidelines, the coking rate of the process stream can be controlled to acceptable levels if tube side mass velocities of the order of 450-600 lb/sec ft² are used. Several general conclusions/observations were made from the coking tests:

- o A family of coking curves exists, one for each mass velocity. At a constant film temperature, coke laydown increases with reduced mass velocity.
- o No coke laydown occurred in any test run at $G = 600$ lb/sec ft² and very little occurred at 450 lb/sec ft².
- o Coke laydown rate increased at higher film temperatures. At $G=150$ lb/sec ft² approximately 70°F increase in film temperature is required to double the coking rate. This temperature sensitivity is relatively weak compared to thermal cracking data in which the reaction rate doubles with every 25°F increase in temperature.

It should be noted, however, that no study was made to determine if coking material formed under any of the above conditions was being carried downstream.

3.3 Fluidized Bed Heat Transfer Studies

3.3.1 Background Information

The objective of the Fluidized Bed Heat Transfer Studies is to quantitatively define the heat transfer coefficients and the peripheral and tube-to-tube maldistributions of heat input to tubes immersed in a fluidized bed. The heat transfer rates are 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 have been obtained in two separate tests. The first was a series of ambient temperature tests in which conductive/convective heat transfer patterns were defined. These were followed by additional tests in a "hot" fluidized bed where overall coefficients including the contribution of the radiant heat transfer component could be measured.

All work planned under this task of the program has been completed. The ambient temperature test results and analysis have been reported in Quarterly Technical Report Nos. 5, 6 and 7. The high temperature results are covered in Report No. 14. A brief summation of each test series is given in the following paragraphs.

3.3.2 Ambient Temperature Heat Flux Tests.

The Ambient Temperature Heat Flux Tests were completed in conjunction with the Two-Dimensional Flow Visualization studies earlier in this program. These tests defined the patterns of heat transfer from horizontal tubes fully immersed in a fluidized bed of limestone as well as from tubes in the splash zone and freeboard zones above the bed. Three distinct regions of heat transfer were identified around the tubes; namely, the predominantly gas shrouded underside of the tube, the dense layer or "cap" on top of the tube, and the "surflines" or rapidly oscillating region of solids-to-tube contact at the 45° and 315° regions (0° or 360° region defined as the top of the tube). The conductive/convective variations in heat transfer patterns around the periphery of the tubes were clearly identified with these three zones. The peripherally measured coefficients were used to develop maldistribution plots, row by row heat transfer values and bundle average heat transfer coefficients.

It was also observed from these tests that for a blend of particles covering a wide size range, the heat transfer performance was predominantly determined by the finer particles in the blend and was relatively unaffected by the coarser particles.

3.3.3 High Temperature Fluidized Bed Heat Flux Tests

The data developed in the Ambient Temperature studies were used in the design of the facilities for the second part of this task. This was the 12 M Btu/hr Fluidized Bed Heat Flux Test Unit (Figure 4). While this facility was designed with the ultimate capability of firing coal, the early tests described here were conducted without the direct combustion of fuel in the fluidized bed. Rather, heat to the bed was provided via an integral upstream combustor where propane was burned and the hot gases were used as the fluidization medium. In this way, heat transfer data could be developed over a wide temperature range without being compromised by the uncertainties of fuel distribution and combustion characteristics in the bed.

Five periods of operation have been completed and the data analyzed and reported. Briefly summarized, the results define the overall heat transfer coefficients and patterns, including radiation, for fully immersed and freeboard tubes. The tube diameter used was four inches, bed temperatures ranged up to 1200°F and fluidization velocity up to five times minimum fluidization were tested. The test results in the freeboard tubes followed the traditional single phase correlation except that coefficients were augmented by a factor of fifteen by the entrained particles in the gas stream. The in-bed tubes again displayed little dependence on velocity but varied significantly with bed temperature. General patterns of peripheral maldistribution of heat input around the tubes were very consistent with those defined by the earlier ambient temperature test.

3.3.4 Status of Work

All planned tests dedicated to propane firing have been completed. In a continuation of the program, subsequent test runs fired coal directly in the fluidized bed. These tests are reported under the program task on Unit Operability (Coal).

3.4 Unit Operability (Coal)

3.4.1 Background Information

As part of the previously reported task on the design, construction and operation of the Fluidized Bed Heat Flux Studies, continuous coal and limestone feed facilities were added to the test unit. Operation of these facilities is now completed. A series of four test periods (Runs 6, 7, 8 and 9) were made from March to June 1980.

For all four runs, the unit was started up using the normal procedure of firing propane in the precombustor to bring the fluidized limestone bed to about 1200°F. A small quantity of coal was then added. As soon as ignition of the coal had been verified by increasing bed temperature, propane fuel was reduced and coal feed rate increased in corresponding increments until 100% coal firing was achieved.

3.4.2 Description of Experimental Equipment

Coal and sorbent handling facilities, shown in Figure 5 have been added to the high temperature heat flux test unit. These facilities enable the unit to operate as a functional coal fired fluidized bed test facility. The unit was run to obtain data under actual coal firing conditions including unit response characteristics, load following, start-up and shutdown procedures.

The coal storage hopper had a volume of 600 ft³ and a capacity of 10 tons of coal. The sorbent storage hopper had a volume of 60 ft³ and a capacity of 2.5 tons of sorbent. Both hoppers were fitted with Vibra Screw Bin Activators to insure good solids flow and prevent bridging and ratholing. The hoppers were monitored by high and low level alarms in addition to a Monitor level indicator. Solids were charged to their respective storage hoppers via a Vac-U-Max system. Solids were drawn above the storage hoppers to a disengaging hopper where the solids fell into the storage hopper. A Semco gravity flow diverter valve was used to direct the solids to the correct storage hopper.

Solids were metered from the storage hopper through two Acrison Model 105Z Volumetric Feeders. The coal metering auger had a maximum output of 2840 lb/hr. The sorbent metering auger had a maximum output of 800 lb/hr. The feeders had a variable speed drive which could be adjusted to feed the desired Ca/S ratio to the bed from a common ratio proportioning control panel. From the feeders, the solids fell into a small surge hopper which was also equipped with a Monitor high level alarm. A Semco rotary airlock valve located at the outlet of the surge hopper metered the solids into a conveying line adaptor where a

flow of air pneumatically transported the solids to the combustor fluidized bed. A Scarpa Laboratories Ultrasonic device sensed the solids flow in the line.

The solids transport line consisted of a 2 inch diameter schedule 80 carbon steel pipe upstream of the solids convey point and a 2-inch stainless steel pipe from the convey point to the combustor. Air flow was controlled by a manual valve and measured across an orifice plate upstream of the convey point.

Downstream of the convey point, the transport line made two 90° turns. Stainless steel flanged cross tees rather than 90° elbows were used to prevent excessive erosion and facilitate clearing the lines of solids blockage if required.

For safety, the coal system was equipped with an automatic shutdown system similar to the propane shutdown system. Originally, it was planned to use a minus 1/4 inch pulverized coal, but due to an available supply, minus 6 U. S. mesh Champion Coal (Consolidation Coal Co.) was used. Figure 6 gives the particle size distribution of the coal.

3.4.3 Summary of Operations

The initial operation on coal, Run 6, was successful and all test objectives were achieved. Namely, the startup and transition from propane to coal fuel went smoothly, a 100% coal operation was demonstrated, some heat transfer data for propane and propane/coal firing were obtained and some unit limitations were identified.

The only potentially serious equipment limitation observed during the run was an inability to adequately cool the flue gas at high bed temperature. Target bed temperature for the run was 1550°F. As the temperature approached 1450°F the flue gas temperature exiting the flue gas cooler reached 410°F and the alarm circuit protecting the down stream bag filter (max design limit of 425°F) was activated. It was clear that we could not have reached a 1550°F bed temperature without overheating the bag filter. A possible undersizing of the flue gas cooler was suspected.

A post run analysis of the data indicated that the necessary additional cooling could be accomplished by injecting a very small amount (< 1 gal/min) of quench water into the flue gas downstream of the flue gas cooler. Facilities were, therefore, installed to do this on subsequent runs if needed.

The second test in the series, Run 7, was started April 14th. The major objective of this run was to obtain heat transfer data with 100% coal firing at a bed temperature of 1550° and a range of fluidization velocities. Startup proceeded normally but around the time the switch from propane to coal firing was completed, a number of problems occurred that resulted in an unavoidable shutdown. These included an overheated precombustor shell, plugging of the bag house rotary airlock valve, coal afterburning in the combustion freeboard zone and an excessively high temperature flue gas discharge into the bag filter. Each of these problems will be discussed briefly.

During normal startup propane is fired in the precombustor until the fluid bed temperature reaches 1150°F permitting the transition to coal firing. To achieve this bed temperature, it is necessary to heat the precombustor to about 2500°F. During Run 7, as the precombustor approached 2400°F it was noted the carbon steel shell in the vicinity of the access manway was glowing cherry red indicating a probable shell temperature in excess of 1200°F. To quickly reduce the temperature in the precombustor the transition to all coal firing was hastened. The precombustor cooled, allowing the run to continue.

After Run 7 was terminated the precombustor was opened for inspection. The refractory lining consists of a 3 inch hot face layer of 2600°F high density castable refractory backed by 9 inches of insulating castable. The dense layer is reinforced with 5 lb/ft³ of type 310, 0.13" diam x 1" long s.s. needles.

The general condition of the refractory lining was good considering the more than 25 full temperature cycles it has been subjected to during its 10 month operation. Numerous cracks and separations of the dense layer were visible but none that were considered to require immediate repair. The apparent cause of shell overheating was attributed to cracks in the immediate vicinity of the access door. This doorway is normally filled with loose layed bricks (not mortared in place) before the access door is bolted in place. If not layed up tightly it may be possible for some hot flue gas to bypass the refractory lining and contact the precombustor shell just above the doorway.

As a correction to this problem, the refractory was repointed in the area of the doorway, all visible cracks were sealed and the bricks were replaced as tightly as possible. The repairs were supervised by a refractory specialist and the judgment was that the repairs would permit restart of the unit.

When the hurried transition from propane to coal fuel firing was made in Run 7, the flue gas temperature out of the cooler immediately began to increase. The water injection system

installed after Run 6 was commissioned and it did drop the flue gas temperature about 100°F as designed. However, the gas temperature out of the cooler continued to increase and it became clear that the combination of the cooler plus water injection was not going to be adequate to maintain temperature into the bag house below the 425°F limit.

At this point it was necessary to shut down the system. After cool down, the flue gas cooler was opened and inspection revealed a substantial amount of fouling on all the coils. Deposits of elutriated limestone and fly ash were up to 1/4 inch thick in places and apparently had been forming for some time. The deposits probably formed during startup when water vapor can condense on the outside of the cold tubes, capturing the elutriated fines. The fines are then solidified as the unit heats up, making it very difficult to remove. This gradual buildup of foulant on the tube surfaces explained in large part the apparent "under sizing" or low performance of the flue gas cooler.

The cooler was mechanically cleaned. A revised start up and operating plan was designed to minimize the period of time when cool air or flue gas will be circulated over cold cooler tubes since this appears to be the conditions most susceptible to fouling.

Immediately after introduction of coal feed the temperature increased rather rapidly in the freeboard and cyclones indicating that unburned coal was being carried out of the bed and burned in the downstream zones. Analysis of available data following the shutdown indicated the most probable cause was the very high (100 ft/sec plus) solids transport air velocity that was being used during the short time that coal was being fired. The coal feed line entered the fluidized bed horizontally about 6 inches above the distribution grid. Calculations indicate that the high inlet velocity probably formed a jet which penetrated through the 2 foot dimension of the bed, impacted on the opposite wall of the combustor and then carried out the bed without really distributing or mixing within the bed. The relatively high fluidization velocity being used at the time may also have contributed.

The fourth and final malfunction that precipitated the termination of Run No. 7 came about when it was observed that no fines were being discharged from the bag filter. Normally about 20-60 lb/hr of limestone fines and fly ash are discharged at this point.

Subsequent inspection indicated a plug of solidified limestone in the throat of the rotary air lock. Several hundred pounds of solids had backed up into the lower cone of the air filter. It is probable that this plug at least partially formed during the down time period between Run Nos. 6 and 7 and was not detected immediately on restart.

The filter and air lock were cleaned and an air line installed in the throat of the air lock. This will permit air blasting the air lock if future plugs begin to form.

Run No. 8 was successfully completed in May and verified the adequacy of the corrective actions described previously. During Run No. 8, two primary objectives were achieved. Heat transfer data were obtained at bed temperatures near 1550°F and some data on unit response to changes in fuel rate were developed.

The final portion of the coal firing test, Run No. 9, was successfully completed in June. Additional heat transfer data at a bed temperature of 1550°F over a range of fluidizing velocities was taken. A large part of the run was dedicated to unit response testing. Changes in coal only, air only, and proportional changes in both coal and air were made. The effect on bed temperature was recorded as a function of time from the change. Once data collection was completed, operations were continued until the remaining inventory of coal in the hopper was depleted. The unit was then shutdown. Results of all coal firing runs are presented in the next section.

3.4.4 Results

Figure 7 shows the locations where the temperature measurements were made on the four heat transfer coils. Coils 1 and 3 were instrumented so that local heat transfer coefficients could be calculated at Section A-A on tubes C. The local coefficients were calculated from measured tube metal temperatures and water temperature at the peripheral thermocouple location. The overall coil coefficients were calculated from the measured water flow rates and the measured temperature increase of the water through each per coil. The results include:

In-bed tube 3c

- + average outside heat transfer coefficient
- + radiation effect on the heat transfer coefficient
- + maldistribution

Freeboard tube 1c

- + average outside heat transfer coefficient
- + radiation effect

The outside heat transfer coefficients were calculated from measurement of the inside tube wall temperature and bed temperature. It was assumed that all heat transfer occurred in a one dimensional manner across the tube wall. The effect of circumferential conduction in the tube wall was not considered in the calculations. In addition, the Dittus Boelter equation was used to predict the water side heat transfer coefficient.

A detailed discussion of the method of data reduction and analysis used in the interpretation of these test results is given in Program Quarterly Technical Report No. 14, dated April 23, 1980. In that report, all of the data obtained on the earlier propane fired runs were documented. Four completeness and ease of reference, the heat transfer data from Run Nos. 6 through 9 with coal firing have been added to the previously published propane derived plots and republished here.

In addition to the heat transfer data taken during the coal firing operations, unit response to perturbations in air and fuel inputs were studied.

3.4.4.1 Heat Transfer Results - In-bed tube 3c

The total outside heat transfer coefficient for tube c coil 3 is shown in Figure 8. These heat transfer coefficients were evaluated by numerically averaging the eight local heat transfer coefficients calculated for this tube. The results are plotted against superficial velocity as a function of nominal bed temperature. Figure 8 contains both the previously reported results on propane firing and the additional data collected during Runs 6, 8 and 9.

Four data points are reported for Run 6. The data at superficial bed velocities of 5.2, 5.7, and 7.6 were made during 100% propane firing. Bed temperatures at these points were 898, 992 and 1088°F respectively. The last Run 6 data point was taken during operations on mixed propane and coal firing at a bed temperature of 1247°F. As seen in Figure 8, the new data are consistent with the previously reported work.

One data point taken during the propane firing portion of Run 8 is reported. The bed temperature for this point was 1124°F. Two additional data points for Run 8 are also reported in Figure 8. These points were obtained on 100% coal firing and will be discussed later.

Five data points for Run 9 are reported. All measurements were made at a nominal bed temperature of 1550°F once the system was lined out on 100% coal feed. As Figure 8 shows, the coal fueled heat transfer data is consistent with the trends developed in the earlier propane data. The heat transfer coefficient displayed little dependence on the superficial velocity. This nondependence of the average heat transfer coefficient on velocity for totally immersed tubes was also observed in both the ambient and propane-fired heat transfer studies. However, the heat transfer coefficients measured here did display a significant increase in numerical value with increased bed temperatures.

Several outside heat transfer coefficients measured during Run 8 fell below those measured in Run 9 although the bed temperatures and superficial velocities were comparable. Examination of the data revealed that some of the tube wall temperatures in coil 3 tube c exceeded the saturation temperature of the water at the operating system pressure during Run 8. It is theorized that subcooled boiling was at times occurring on the upper portion of the tube wall, making the actual heat flux higher than that calculated by the Ditters-Boelter equation, and therefore giving a calculated h that was too low. Correcting for the subcooled boiling by using Ditters-Boelter for most of the tube wall and a subcooled boiling correlation for the "hot" part of the tube yielded the two additional data points reported for Run 8 at a nominal bed temperature of 1550°F. This problem of subcooled boiling was avoided during Run 9 by back-pressuring the coil to 120 psi (vs 40 PSI for Run 8).

From Figure 8 it can be seen that at identical superficial velocities the heat transfer coefficient increased as the bed temperature increased. The only difference between these tests was the flue gas temperature. This in turn resulted in a variation of the thermal properties of the flue gas, hotter dolomite particles and possibly a different radiation interaction between the bed and tube surface. As was done with the previous propane data, the probable radiation effect was assessed by assuming that the sum of the convective heat transfer coefficient (h_c) and the radiative heat transfer coefficient (h_r) equalled the measured total heat transfer coefficient. Therefore:

$$h_o = h_c + h_r$$

where

$$h_r = \frac{\delta \sigma (T_{\text{Bed}}^4 - T_{\text{Wall}}^4)}{T_{\text{Bed}} - T_{\text{Wall}}}$$

and

$$\begin{aligned} \sigma &= \text{Stefan Boltzman constant} \\ T_{\text{Bed}} &= \text{Fluidized bed bulk temperature} \\ T_{\text{Wall}} &= \text{Temperature of the tube surface} \\ \delta &= \text{Emissivity of the 304 SS tubes} = 0.4 \end{aligned}$$

The radiative heat transfer coefficient was evaluated at each peripheral tube wall position and subtracted from the total outside heat transfer coefficient, h_o , to arrive at the convective heat transfer value. The radiative heat transfer coefficient calculated in this manner was approximately $h_r = 9.7$ Btu/hr ft² °F at 1550°F bed temperature. The corresponding values reported earlier from the propane firing tests were; 1.50 Btu/hr ft² °F at 525°F, 2.3 at 725°F, 4.0 at 975°F and 6.0 at 1200°F.

The convective heat transfer coefficient evaluated by subtracting h_r from h_o are shown in Figure 9. As can be seen the difference between the heat transfer coefficients at the various temperature levels has been reduced but the radiation effect did not account for the entire difference. This suggests that the thermal effects of the fluidization media and fluidized solids are also important contributors to the heat transfer coefficient.

Figure 10 is a polar plot of typical local heat transfer coefficients measured on coil 3c during 100% coal firing. The plot exhibits the same general characteristic shape as previously obtained during the propane and ambient temperature tests.

Similar polar plots were generated for all data sets and this reduced to a maldistribution plot, Figure 11. The maldistribution is defined as the peak coefficient divided by the tube average coefficient. As before, the maldistribution of heat transfer displayed relatively little dependence on either temperature or fluidization velocity.

3.4.4.2 Heat Transfer Results - Freeboard Tube 1c

The average outside heat transfer coefficients for coil 1c, the freeboard coil, are shown in Figure 12 along with the previously reported data from the earlier propane runs. These data show a distinct difference between Run 8 and Run 9. The Run 8 data are very consistent with previous runs while Run 9 data show significantly higher values than previously observed. This is an interesting observation in that Run 9 was made with approximately 25% more bed material than any previous runs. Presumably, this increase in bed inventory increased the amount of solids carried into the freeboard which in turn increased the heat transfer coefficient. These data points replotted on Figure 13 as $h_c D_o / k_g$ vs. VD_o / v_g consistently fall above the previously reported curve (See Quarterly Report No. 14 for full discussion) indicating that the heat transfer coefficient for the freeboard tube shows the same Reynolds number dependence as a tube in an air stream but is also affected by the solids void fraction in the freeboard.

The convective coefficient ($h_c = h_o - h_r$) for coil one is shown in Figure 14. Neglecting the 1550°F data from run 9, it appears that the convective heat transfer coefficient drops with increased bed temperature. If the Stefan Bottzman calculation of the radiative heat transfer coefficient is assumed valid, it can be concluded that radiative heat transfer becomes more significant (contributes a larger portion to the total outside coefficient) at higher bed temperatures.

3.4.4.3 Unit Response Characteristics

Understanding the unit response characteristics to variations in fuel and air inputs is essential for

the design of control and load following systems for a commercial process heater. Since an AFBC can operate in only a narrow range of temperatures due to coal ignition temperature and the desulfurization reaction, load following requirements are critical. Variations can be made in fuel or air separately or a combination of both. Compensating changes in both fuel and air would maintain a constant excess air level. This type of change is consistent with normal operating practice and would be desirable for load following. Independent variations in air or coal would most likely be related to an upset condition, i.e. loss of one feed point in a multi-feed point system.

All three types of disturbances were demonstrated on the unit in a step change manner. Once a new equilibrium temperature was reached, the step change was reversed to return to initial conditions. Response characteristics were measured as bed temperature vs. time. Coal feed disturbances of 10, 25, 50, and 75% were made. Air flow rate was changed by 10%. Coal and air rates were perturbed 10 and 25%.

Figure 15 shows the unit response to the decrease and subsequent increase in coal feed rate. The response to the loss of coal feed is rapid. With losses of 10 and 25% coal feed rate, the unit stabilized at a new equilibrium temperature above the ignition temperature of coal. However, with reductions of 50% and 75% (not shown) of coal feed rate, the bed temperature dropped very rapidly toward the ignition temperature of coal and the automatic safety shutdown sequence would have been activated if coal feed had not been restored within minutes. This exercise dramatically illustrates the rapid bed response to changes in coal feed rate and suggests that a quick response backup fuel feed system would be necessary to assure continuous operations on a commercial unit.

Figure 16 compares the effects of a 10% change in coal and air, coal only and air only. Making compensating changes in coal and air simultaneously to maintain constant excess air level tends to dampen both the magnitude and the rate of response as compared to changing coal only. This would probably be the preferred basis of control for any commercial unit. The response to changes in air rate only is rapid; the bed temperature lined out within 15 minutes.

Figure 17 is similar to Figure 16 except that the magnitude of changes is 25% rather than 10%. The same general observations are valid.

From these unit response demonstrations, it can be concluded that the more severe the perturbation, the more severe and rapid will be the unit response. Changing air and coal feed rate simultaneously tends to maintain more stable operations. Automatic response to losses of coal feed on commercial units

will have to be rapid if operations are to be continued without complete shutdown of the unit. Actual response and line out times will depend on the physical characteristics of the process heater and the magnitude of the change. Mathematical modeling and functioning can probably be used to achieve the level of control and load following necessary in process heater applications.

3.5 Economic and Applications Evaluations

3.5.1 Task Objectives

The object of this task is to evaluate the economic and logistic factors that might influence the schedule and circumstances under which coal fired Atmospheric Fluidized Bed Combustion (AFBC) technology might be applied to petroleum and petrochemical plant process heaters. The task has been divided into two phases. The first phase, now completed and reported in Quarterly Report No. 11, concentrated on the logistics considerations that would favor or hinder the application of FBC over competitive alternatives. In this work some considerations were identified which will have significant impact on the future development program and commercialization strategies of AFBC process heaters.

It is very unlikely that significant grass roots refineries will be constructed in the foreseeable future. Refinery expansion will most likely occur as incremental growth at existing sites. Therefore, to achieve significant penetration of coal into the refinery fuel picture, the retrofit situation offers the greatest potential and it is to this application that this study was directed.

3.5.2 Conclusion of the Applications Evaluation

The objective of the Applications Task was to evaluate the practical and logistics circumstances under which fluidized bed coal fired process heaters might be utilized in a petroleum refinery. Based on the findings of this study, it seems apparent that the following general considerations will have significant impact on the ultimate strategy and methodology that might be followed to successfully bring coal into the existing refinery fuel picture.

- o Conversion of existing gas/oil fired heaters to coal firing is generally not practical because of both site and equipment limitation.
- o One-for-one onsite replacement of existing heaters with coal fired units whether they are stoker, pulverized coal, or fluidized beds, would permit some substitutions of coal for gas and oil fuels. However, in many cases siting and fuel distribution restraints would limit replacements to a few of the larger heaters in a typical refinery. This

would significantly reduce the potential penetration of coal and lessen the economics of size.

- o A centralized thermal system, using steam or hot oil as a circulating heat transfer medium would overcome some of the disadvantages inherent in the other alternatives. Such a system would be less complex, more reliable, replace more furnaces, be easier to fit into existing locations and require less time to develop than would use of onsite coal fired heaters.
- o The basic concept of a centralized heat generating station with thermal energy distributed via steam or hot oil would be equally amenable to any of the direct coal utilization options, i.e., stoker, pulverized coal or fluidized bed combustion. Final selection among these options will be based primarily on economic considerations.
- o Any system would most likely have to be combined with an existing or concurrent coal fired steam raising or power cogeneration project to make it commercially viable.

In view of the limited near term potential for application of this technology to coal fired refinery facilities, several alternative applications have been identified. One of the more interesting alternatives involves the combustion of heavy vacuum tower bottoms from a synthetic-fuel-from-coal process now under development. As part of a screening study to evaluate this alternative, a preliminary design has been prepared for an FBC process heater to meet this requirement. The details of this design were documented in Quarterly Technical Report No. 15.

3.5.3 Status of Work

The design of the AFBC Slurry Preheater has been released to the Exxon Synfuels Division for further study and economic evaluation. Design effort is now centered on the design of two coal fired Atmospheric Fluidized Bed Pipestill Heaters. The service for these heaters will be more conventional than the slurry heater in that they will be design for a normal crude oil refinery operation. These heaters are sized at 400 MBtu/hr and 133 MBtu/hr. Design work is now in progress.

MILESTONE SCHEDULE AND STATUS REPORT

1. Contract Identification										2. Reporting Period										3. Contract Number																		
Industrial Application of Fluidized Bed Combustion Indirect Fired Heaters										through June 30, 1980										ED-AC21-76ET10379 (formerly No. EX-76-C-01-2471)																		
4. Contractor Name, address										5. Contract Start Date										6. Contract Completion Date																		
Exxon Research and Engineering Company Engineering Technology Department P. O. Box 101 Florham Park, New Jersey 07932										June 30, 1976										Sept. 30, 1980																		
7. Identification Number	8. Reporting Category (e.g., contract line item or work breakdown structure element)	9. Fiscal Years and Months																								10. Percent Complete												
		1979												1980												1981												
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A														
	Program Management																																					
	2-Dimensional Studies	Completed																								100												
	Coking Studies	Completed																								100												
	Flux Unit Studies	Completed																								100												
	Unit Operability (Coal)																																					
	Econ. & Applic. Eval.																																					
	Commercial Unit Design																																					
	Demo Unit Design																																					
DEFER	Demo Unit Fabrication																																					
	Demo Unit Operation																																					
11. Remarks																																						
12. Signature of Contractor's Project Manager and Date													13. Signature of Government Technical Representative and Date																									
July 21, 1980

Figure 2

SCHEMATIC-TWO DIMENSIONAL FLOW VISUALIZATION UNIT

Figure 3
PROCESS STREAM COKING UNIT SCHEMATIC

Figure 4
 FLOW PLAN
 FBC HEAT FLUX UNIT

FIGURE 5

COAL AND SORBENT HANDLING FACILITIES

CHAMPION COAL
PARTICLE SIZE DISTRIBUTION
FIGURE 6

Section A-A

TC Indicates Thermocouple Location

TEMPERATURE MEASUREMENTS ON THE HEAT REMOVAL COILS

Figure 7

TOTAL OUTSIDE HEAT TRANSFER COEFFICIENT, h_o , (BTU/HR-FT²-°F)

DATA TEST 1-5

RUN	T _{BED}	V _{BED}	FIRING
6	898	5.2	PROPANE
	991	5.7	PROPANE
	1088	7.6	PROPANE
	1247	9.3	COAL/PROPANE
8	1124	5.7	PROPANE
	1550	9.8	COAL
	1550	10.1	COAL
9	1550	ALL DATA	COAL

Total Outside Heat Transfer Coefficient - In-Bed Tube 3C

Figure 8

0007 previously reported

	RUN	T_{BED}	V_{BED}	FIRING
●	6	898	5.2	PROPANE
		991	5.7	PROPANE
		1088	7.6	PROPANE
		1247	9.3	COAL/PROPANE
▲	8	1124	5.7	PROPANE
		1550	9.8	COAL
		1550	10.1	COAL
◆	9	1550	ALL DATA	COAL

Convective Heat Transfer
Coefficient - In-Bed Tube 3C

Figure 9

Polar Plot of Local Heat Transfer
Coefficient for In-Bed Tube 3C

Figure 10

100% Coal Firing
 $T_{\text{Bed}} = 1533^{\circ}\text{F}$
 $\text{Vel.} = 8.1 \text{ Ft/sec}$
 $h_{\text{o avg}} = 65.59 \text{ Btu/hr ft}^2 \text{ }^{\circ}\text{F}$

Tube 3C Maldistribution Factor
Composite of All Program Data

Figure 11

FIGURE 11

TOTAL OUTSIDE HEAT TRANSFER COEFFICIENT, h_o , BTU/hr-ft²-°F

FREEBOARD COIL CORRELATING HEAT TRANSFER RELATIONSHIP

Figure 13

Connective Heat Transfer Coefficient
Freeboard Coil 1C

Figure 14

BED TEMPERATURE - °F

Unit Response to 10%
Changes in Air and Coal - Run 9

Figure 16

Unit Response to 25%
Changes in Coal & Air - Run 8

Figure 17