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SRC-II SLURRY PREHEATER TECHNICAL UNCERTAINTIES
Report for the Technical Data Analysis Program

Work Performed Under Contract No. AC22-82PC50046

The Pittsburg & Midway Coal Mining Co.
Denver, Colorado

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

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SRC-II SLURRY PREHEATER TECHNICAL UNCERTAINTIES

**Report for the
TECHNICAL DATA ANALYSIS PROGRAM**

**The Pittsburg & Midway Coal Mining Co.
1720 South Bellaire Street
Denver, CO 80222**

Prepared For The

**U.S. Department of Energy
Division of Energy Technology
Coal Conversion Utilization**

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ABSTRACT

This report reviews the performance, and draws conclusions therefrom, the coal slurry preheaters of the Ft. Lewis, Washington, Solvent Refined Coal (SRC) Pilot Plant in the following areas:

Coking

Erosion/Corrison

Heat Transfer & Pressure Drop Effects

Using prudent engineering judgement it postulates how such conclusions should affect the design and operability of large preheaters in future commercial scale plants. Also a recommendation is made for a small scale research and development effort that should result in a much firmer preheater design for any future facility.

This report is not a "stand-alone" document and should be read in conjunction with the Solvent Refined Coal (SRC) Final Report, and volumes 1 and 2 of Slurry Preheater Design, SRC-II Process and also Ft. Lewis Slurry Preheater Data Analysis, 1½ Inch Coil by Gulf Science & Technology Company of Pittsburgh, Pennsylvania.

The Pittsburg & Midway Coal Mining Co.'s background is based primarily on a racetrack shaped up-flow coil and these comments pertain specifically to a commercial heater of that type of design.

Summary

P&M believes there is a sufficient data base on several of the more widespread eastern and midwestern bituminous coals, and also enough engineering expertise, to design, construct, and operate a coal slurry preheater of a size required in a commercial scale coal liquefaction plant processing an appropriate coal feedstock. Furthermore, P&M believes that run lengths of six months or longer could be routinely attained before decoking is required. While technical uncertainties do exist with regard to maximum inside film temperature, maximum slurry velocity in tubes, and maximum heat flux, by taking a conservative design approach it should be possible to "design around" these unknowns. It is recognized that such a design approach will result in a non-optimized heater design and also a more expensive one.

Under present circumstances (i.e., no large coal liquefaction heater operating in the U.S. on which to conduct experiments), P&M believes time and money is better spent consolidating a conservative heater design rather than trying to optimize beyond a certain point the design of the heater itself. Operating experience will eventually determine the true limits of process parameters on coal heaters for a particular coal feedstock.

One area where P&M believes a modest effort now on research and development could result in a firmer design and a much shorter period of unstable operations, i.e. the "debugging" period, is automatic preheater control utilizing a new concept -- nuclear density meters.

There are several important aspects of heater design that, because of time constraints, were not completely investigated when the preheater design for the proposed 6,000 TPD SRC-II Demonstration Plant was developed. For example, P&M believes that a staged heat flux design for the preheater is possible and should result in a smaller heater, thus a less costly one. Also, conditions during startup and shutdown, and decoking, should have been investigated more thoroughly to determine if any operating constraints are violated. However, it is believed enough "fat" was included in the proposed design to permit these essential operations to occur without any danger of jeopardizing the preheater integrity. All these matters fall under optimizing a design

and should be addressed by any competent heater vendor under contract to provide a heater design.

1.0 Introduction

The Ft. Lewis Solvent Refined Coal Pilot Plant was operated by The Pittsburgh & Midway Coal Mining Co. under a contract with the U.S. Department of Energy to develop coal liquefaction technology. Initial operations started in late 1974 and continued until mid-1981. The plant was originally designed to operate at 50 tons per stream day and produce a solid product (SRC-I). The plant was later modified to operate in a slurry recycle mode and produce a liquid product (SRC-II), but remained capable of operations in the SRC-I mode.

Slurry Preheater A was supplied by Foster-Wheeler Corporation. The coil configuration was a cylindrical helix of 3" x 0.41" minimum wall Incoloy 800 tubing. The unit was fired by four vertical natural gas burners in the bottom center of the coil. Preheater A was installed when the Ft. Lewis Pilot Plant was built in 1973/74 and was in service from startup in mid-1974 until November 1979. No program was in effect during this period to systematically evaluate erosion/corrosion, coke laydown rate, etc. Primarily this was because Preheater A was so vastly oversized, and so conservatively designed (low slurry velocity, low heat flux) that on those occasions when it was inspected no indications of erosion/corrosion, or coke laydown were ever detected.

Slurry Preheater B was supplied by Heat Research Corporation (HRC), a subsidiary of Pullman-Kellogg. The design¹ consisted of a 2" Schedule 160, Type 321 stainless steel "oblong helical" coil which was a series of straight tubes with long sweep (approximately 18" radius) 90° bends at each corner configured similar to a radius cornered rectangle. Six natural gas fired burners were located two each in the center of the helix and two on either of the longer straight sections of the coil. This design provided double firing over most of the exposed tubes, and the long sweep bends minimized the erosion in the tubes. The double-fired design tends to more nearly equalize the temperature gradient around the tubes, thus minimizing the problem of tube bowing in the direction of the heat, and maximizes heat flux per unit length. Preheater B was installed in November 1979 to gather data that would be more appropriate for use in designing the commercial scale preheater that was to be included in the planned SRC-II Demonstration Plant. In December, 1980, a 1½ inch coil was installed. This smaller coil was used for a series of preheater tests and was in service

from January 1981 until the plant was shut down in July 1981. The coil was fabricated of Type 321 stainless steel Schedule 160 pipe. The design configuration was identical with the original 2 inch coil.

Two constraints² had to be observed in defining the Preheater B test programs: 1) a maximum slurry flow of 7500 lbs/hr in order to stay close to the design slurry residence time in the dissolver, and 2) a maximum preheater pressure drop of 400 PSI (dictated by maximum discharge pressure of slurry charge pumps, and desired dissolver pressure). With the first constraint the maximum slurry velocity in the 2 inch coil was about 2.0 ft/sec--considerably lower than the slurry velocity of 6.0 ft/sec expected for the Demonstration Plant Preheater. One of the reasons for testing the 1½ inch coil was to extend this range of slurry velocities closer to the design value of the Demonstration Plant.

2.0 Recommendations

1. DOE should conduct small scale tests on relative simple and inexpensive equipment, such as shown in Figure 11, to confirm that the concept of using a nuclear densitometer or other non-invasive densitometer to control flow regime in the preheater is valid.
2. If the tests mentioned in item 1, and described elsewhere in this report, are successful then live tests on a large operating coal slurry heater should be undertaken.

3.0 Discussion

3.1 Coking

Preheater B, with the 2 inch coil, was first put on stream in November 1979. In December 1980 it was shut down and a new 1½ inch coil installed. Within this 13-month time period the preheater was down a number of times for both scheduled and unscheduled outages. Normally, during any extended shutdown period, if time permitted, the heater coil was stream/air decoked. Decoking took place during each of the following months: January, May, July, August, September, October, and December.

The longest run time for preheater B (with the 2 inch coil) between decoking operations was approximately 1,132 hours or 47 days. This period occurred between February and May of 1980. A check of the Ft. Lewis monthly reports shows that Preheater B was put in service on February 15 but various problems delayed testing until February 22. Several short runs were undertaken during the remainder of the month, but they were of questionable value because of plant outages for various reasons. The total on-stream time in February for Preheater B was thus estimated to be three days. In March the plant was on-stream 416 hours and in April it was on-stream 572 hours. On May 4 the plant shut down to switch over to SRC-I operations. All the time during this period was spent processing Powhattan #6 coal in the SRC-II mode at high heat flux ($12,000 \text{ BTU/hr-Ft}^2$) in the preheater. Except for the period during baseline runs, exit temperature was at or near 800°F . This exit temperature is considerably higher than that envisioned for the commercial heater, which would be about 730°F . A summary of the runs times is as follows:

February (estimated 3 days) -	72 hours
March (from monthly report) -	416 hours
April (from monthly report) -	572 hours
May (from monthly report) -	<u>72 hours</u>

Total	1,132 hours
-------	-------------

$$1,132/24 = 47 \text{ days}$$

In May, when the plant shut down, a half inch layer of coke laydown was found in the last three sections of the coil. First indications of coking were detected during raw solvent conditioning (for SRC-I operations mode) which occurred sometime during the first three days of May. Thus, it is not certain if the coke laydown occurred gradually over the entire operating period, or if it occurred during the solvent conditioning. The first attempt at decoking proved to be inadequate. The coil was decoked once again, and this time all coke deposits were removed.

One important aspect of the baseline runs² was to provide a means of determining if any coking or fouling occurred during periods of operations with coal. The baseline runs -- conducted after steam/air decoking, and before coal slurry runs -- served as reference runs for similar runs made at the end of the appropriate slurry run test program. Any significant increase in tube skin temperatures or significant decrease in the calculated heat transfer coefficients would indicate the possibility of fouling or coking having taken place during the run.

Although baseline runs were made before each series of slurry runs inaccurate skin thermocouple readings negated much of the value of these earlier runs. Primarily, the earlier runs are good for comparative indications only. It was only after the 5th generation thermocouples were installed in July of 1980 that accurate skin temperature readings were obtained. (Immersion type thermocouple readings were always good.) Because of SRC-I mode operations in July, August, and September ---and a month long shutdown from September 26 to October 28--it was not until the end of October that SRC-II baseline runs (solvent and gas only -- no coal) utilizing the new thermocouples could be completed. These tests, R-8 and R-9, were repeats of previous tests conducted before the 5th generation thermocouples were developed. In early December 1980, just before Preheater B was shut down to remove the 2 inch coil and install the 1½ inch coil but before steam/air decoking, two more runs (R-14 and R-15) similar to R-8 and R-9 were made.

Comparison of tube skin temperatures² of Runs R-8 with R-14 and R-9 with R-15 definitely indicated fouling towards the coil outlet. These runs are shown in Figures 1-4. Also, the overall heat transfer coefficients for these two pairs of runs are

compared in Figures 5-6. There is some scatter in the data plotted but this is to be expected since no two runs can be made exactly identical in gas and liquid flow rates or gas and liquid characterization. The significant observation from these plots is that the heat transfer coefficients in the last two or three coils are definitely lower at the end of the program than at the start of the test run program. The equivalent fouling factors that approximate this reduction in overall heat transfer coefficients was calculated to be about 0.0015 for both cases. However, the cause of this observed fouling could not be determined. During normal operation of slurry runs the temperature to which tube metal was exposed in this section of the coil where foulings occurred ranged from 900°F to 950°F. It is known, however, that during this particular set of slurry runs there were a number of upsets when tube metal was exposed to abnormally high temperatures for relatively short time periods. Whether the observed fouling was caused by long exposure to temperatures in the 900°-950°F range or by short exposure to temperatures above 1000°F is not known.

While none of the above information proves or disproves conclusively that run lengths of commercial duration ($\sim$ six months) will be possible in a commercial scale preheater, several facts indicate that runs of such length could be expected. For example, consider the following:

1. In the 79 calendar days period from February 15, 1980 to May 4, 1980, preheater B was on-stream 47 equivalent days. Many of the slurry runs that took place during this period were interspersed with numerous periods of scheduled and unscheduled heater downtime caused by various factors. Such "bouncy" operation is not typical of commercial service and is considerably more severe on a heater than steady state operation normally experienced in commercial service.
2. Bulk temperature of the slurry exiting the coil was maintained at approximately 800°F during the vast majority of run time during the 47 days period. The preheaters envisioned in the commercial SRC-II Plant Design were to have an outlet slurry bulk temperature range of from 735-750°F.
3. The 2 inch coil in preheater B during the high heat flux runs was subjected to an average flux of 12,000 BTU/HR-Ft². This is 20% greater than

average flux of 10,000 BTU/HR-Ft² specified for the large commercial size heater in the SRC-II Demonstration Plant Design.

4. Coking was rarely a significant problem with preheater B, with either the 2 inch or 1½ inch coil, but decoking was performed at nearly every opportunity to assure that preheater tests would be conducted on reasonably clean coils. There was never sufficient coke in the coil to detect a burn front moving through the coil during decoking. The relative ease experienced in decoking both the 2 inch and the 1½ inch coils, on those occasions when it was undertaken, does indicate decoking in a commercial heater would be a routine operation.

Based on the above information prudent judgement would dictate longer heater runs than 47 days could be expected and that decoking, when necessary, would be relatively easy and routine.

3.2 Erosion/Corrosion

The Solvent Refined Coal (SRC) Process Final Report¹ of May, 1982 contains a good description of the erosion monitoring program carried out on Preheater B. Appropriate paragraphs from that report are duplicated below:

Preheater B was in service for 2 years and it was continually monitored for metal loss. The preheater had two different size coils; a 2 inch and a 1½ inch nominal, Schedule 160, 321 SS pipe. The 2 inch coil was in service for over one year while the 1½ inch coil was in service less than 6 months. Baseline on-the-wall ultrasonic measurements were taken on the coil at various sites identified as potentially high metal loss areas. Not only were the gas and liquid velocities being changed during the tests but the flow regime was also changing. For example, models indicate that slug, bubble, and elongated bubble flow regimes sometimes exist at the same time within different sections of the coil. During preheater testing liquid and gas phase velocities were extremely variable as may be seen from the data given in later sections describing that program.

The areas of the coils which were monitored were: Straight coil runs, coil bends, hydrogen purge tap zones, fluid thermowell insertion zones and coil tube welds (downstream coil wall).

2-Inch Coil. The erosion rates indicated that the 2 inch Schedule 160 (0.344" wall thickness) 321 stainless steel coil had very little metal loss. As expected, the greater loss occurred in the bends of the coil. With each successive turn, metal loss became greater, especially in the bends. The other areas examined remained very low in metal loss, with rates of 5 mpy and less for these zones. Data profile for metal losses (mpy) on the length of the coil per coil turn is as follows:

<u>Erosion Rate-MPY (2" Coil Only)</u>					
<u>Coil</u>	<u>Bend</u>	<u>Straight</u>	<u>Thermowell</u>	<u>Pressure Tap</u>	<u>Welds</u>
1	5		3	1	1
3	6				
5	4	1	2		
7	4				
9	5	2			
11	6				
12	5	2			
13			5	3	2
14	11	3			

An alternate method of measuring wall thickness of the 2 inch preheater coil was used, the Argonne National Laboratory High Temperature Erosion Monitoring System. Four wave guide monitoring sites were used to gather the data. The sites were evenly spaced from the bottom coil to the top coil on the bends (see Figure III-C-7). * Results were very similar to the on-the-wall measurements. Continuous measurements of 4 to 12 mpy metal losses were recorded for the operating time of one year on the 2 inch coil (Table III-C(10)). *

*Contained in reference 1.

The 2 inch coil was decoked on numerous occasions. The decoking procedure had very little effect on the metal wear rates. Readings taken on several occasions before and after decoking showed virtually no wall thickness change.

1½ Inch Coil. The 1½ inch coil was in service for less than six months. Actual service was very short because of one major shutdown and is estimated to be actually less than 3 months in coal slurry service. The small amount of data which was gathered from the 1½ inch coil is, at best, a marginal data base to establish metal wear rates. However, initial trends did indicate some metal loss in the bends of the coil as indicated in the table as follows (loss calculated in mpy) and Table III-C(11):*

Preheater B 1½ inch coil
Wear Rates MPY (assuming ½ year service)

<u>Coil</u>	<u>Bend</u>	<u>Straight</u>	<u>Thermowell</u>	<u>Pressure Tap</u>	<u>Welds</u>
1	0	0	No Data	0	No Data
5	1	0	No Data	0	No Data
7	2			0	No Data
9	5	0	No Data		No Data
11	3		No Data		No Data
12	9		No Data		No Data
13	13	4	No Data	0	No Data
14	11		No Data		No Data

*Contained in reference 1.

Erosion/Corrosion Loop SL-183. To study the metal wear rates on the material exiting Preheater B, an erosion/corrosion loop was installed to gather the information. A 1½ inch, Schedule XX pipe made from 321 stainless steel was used for the loop. Baseline measurements were made by on-the-wall ultrasonic techniques and recorded. After each shutdown an additional set was then compared with the baseline measurements.

The erosion/corrosion loop on Preheater B was in service for approximately 6 months. During this time the loop was examined only once and erosion was minimal. The process stream entered the first diameter 180° bend following a 10 foot long straight section, immediately downstream of the preheater outlet. Metal loss on the straight run of pipe was fairly low, about 4 to 5 mils per year. The most extreme metal loss was found in the bends as expected. Most metal loss occurred on the inner surface of the outside of the pipe bend. Wear was found to be more extreme in specific areas of the bends. Usually the 30° locations had greater erosion rates than did the 90° location. The measurements indicated the following erosion rates (mpy):

<u>Location, Degree in Bend</u>	<u>Loss Rates (mpy)</u>
0°	5
15°	10
30°	20
45°	18
60°	12
75°	16
90°	8

This data indicated specific zones in the bend where the severity of erosion was worse. The zone from 15° to 75° was the major impact zone of the slurry as it moved through the bend.

Additional erosion data was gathered by use of the High Temperature Erosion Monitoring System designed by Argonne National Laboratory (refer to Section III-B-9 for system details).^{*} The preheater loop had three ultrasonic monitoring sites. All three were located on the outside of the pipe wall, one on a straight run and the other two located on the 30° and 90° bend sites. Each site was scanned continuously and logged in the plant computer with recorded data available daily on computer print-out sheets. Information gathered by the system on the erosion loop was brief due to the limited operating time, which was approximately six months. Erosion was fairly low throughout, and measurements taken through the system closely matched the direct on-the-wall measurements. Metal loss detection was from 2 mils on the straight run to 2-6 mils on the bend sites. The metal loss calculated on a yearly loss would be 4 mpy on straight pipe and 4-12 mpy on the bends.

The above data indicates that at a slurry velocity of about 2 ft/sec the highest erosion rate expected on coil straight runs would be 5 mpy and on coil bends would be about 10 mpy. If slurry velocity is raised to 6 ft/sec -- the design velocity in the preheater of the proposed SRC-II Demonstration Plant--erosion rate would certainly increase but it would not be expected to double. The main reason for believing this centers on the number of times (seven total) the 2 inch coil was decoked during its 13 months service life. While, as previously reported, coil wall thickness showed no change as a result of decoking, the decoking process does contribute to wear rate on the coil. When a clean coil is first put in service the erosion/corrosion rate is probably high initially and then decreases after the coherent scale forms on the metal wall. Unfortunately, the decoking of the coil removes part of this protective scale, and consequently each time the coil is decoked, a small amount of exposed metal loss can be expected when slurry service is resumed. If commercial runs approaching six months duration are realized, and it is believed this will be the norm, then erosion/corrosion should be less than projected above since decoking would only take place twice a year rather than the seven times that was done on the 2 inch coil in the 13 month time frame.

^{*}Contained in Reference 1.

As a general rule fired heater tubes are designed for about 100,000 hours of operation. Assuming an on-stream factor of 0.9, this equates to 12 years life. If a $\frac{1}{8}$ inch, or 250 mils, erosion/corrosion allowance is assumed then maximum allowable erosion/corrosion would be 250 mils/12 years, or 20.8 mpy. Based on experience at the SRC-II Pilot Plant at Ft. Lewis it is P&M's judgement that the normal tube life in a commercial scale coal slurry preheater processing an appropriate coal would be ten years or longer. Shorter lives for coils, or sections of coils, however would not necessarily be intolerable. For example, in ethylene unit cracking furnances it is quite common to replace the last section of tubes every 18-24 months.

3.3 Heat Transfer and Pressure Drop Effects

A number of observations made during the early phases of the Preheater B test program were in conflict with some of the commonly held theories about the behavior of coal-oil slurry as it is heated. Several of the more important of these observations² are listed below:

1. The coil pressure drop observed was higher than expected. Also, the pressure drop per unit length of the coil was high throughout most of the coil indicating high slurry viscosities over a wide temperature range.
2. Heater operation underwent a drastic change when the inlet gas rate was lowered below a certain (critical) level while holding feed slurry rate constant.
3. In general the temperature differences between skin and fluid were found to be lower than expected.
4. The temperature difference between the tube skin and fluid was minimum in the temperature range where gellation of feed slurry is expected to occur, indicating high heat transfer in the gel phase. This observation was in total disagreement with the commonly held view that heat transfer is poor in the gel region.
5. When brief coal outages occurred and the coal concentration in the feed slurry dropped, the pressure drop through the coil decreased and the temperature differences between tube skin and fluid suddenly increased two or three-fold.

6. The differential pressure traces obtained on continuous strip chart recorders were typical of dispersed or elongated bubble flow regime (i.e., stable flow) through most of the coil. Exceptions occurred, however, at high gas flow rates and/or when the limiting gas velocities were reached. During these periods the coil experienced slug flow, hence the differential pressure traces fluctuated wildly.

An explanation of these observations is contained in Volume 1 of the Slurry Preheater Design SRC-II Process² and is reproduced as follows:

In the initial phase of the program at Ft. Lewis the variable targeted for study was the effect of gas to liquid ratio on heater performance at different levels of slurry flow rates. As discussed before, one of the most important observations made during this phase was that the heater operation appeared to undergo a drastic change--nearly becoming unstable--when the inlet gas rate was lowered below a certain critical level. At this critical gas rate corresponding to an established slurry flow rate through the coil, the coil behavior exhibited the following three distinctive characteristics:

- (a) pressure drop through the coil suddenly drops to almost a third of the original pressure drop, (b) the tube skin temperatures very abruptly increase, and (c) the temperature control on the preheater becomes difficult as some of the skin and fluid temperatures show wild oscillations.

Before the critical gas rate is reached, however, the pressure drop through the coil increases as the gas rate is lowered before falling off abruptly at the minimum gas rate. This limiting (critical) gas rate has been found to be higher for higher slurry flow rates, higher total solids in feed slurry and for high coal concentrations, but lower for lower coal concentrations. These observations are depicted in Figures 7 and 8. In case of lower coal concentrations (25 weight per cent and under), larger mesh coal and with low total solids (under 38 weight per cent) in feed slurry, it was observed that the transition

into the unstable flow region is not as sharp as in case of 30% coal and with feed slurry total solids in the range of 42-45 weight percent.

In attempting to characterize this somewhat anomalous behavior two distinct observations are to be noted. First, the pressure drop through the coil increases as the transition is approached, indicating the persistence of high viscosity gel over a wider temperature range in the coil. This is apparent from the measured pressure drop across the different segments of the coil, and also from the viscosity calculated from the data, as shown in Figure 9. Curve B represents these viscosities as the transition to instability is approached, whereas curves A and C represent normal operation--away from the transition region and right at transition respectively. It is also to be noted that both curves B and C deviate from A at about a fluid temperature of 490°F , which is also the temperature at which the tube skin temperatures deviate from normal profile (see Figure 8). The second observation worth noting is that the tube skin temperatures increase as the transition to instability is approached.

Any mechanism proposed to model the transition obviously has to explain these two major observations. First attempt made was to see if any of the present flow regime maps explain the observed phenomena. As this approach failed, it became apparent that the observed flow instability is peculiar to the reacting three phase mixture flowing in the coil rather than a common occurrence applicable to all flow systems. Analysis using this approach led to the conclusion that inadequate mixing, resulting in inefficient heat and mass transfer at low gas to liquid ratio, is responsible for the unusual behavior of the heater.

At low gas rates (below the critical gas to liquid ratio), it appears that the available gas cannot provide adequate mixing energy required for efficient heat transfer from wall to the expanding gel.

As a result, first as the coal solvation reactions slow down, viscosity remains high and so the pressure drop increases. Secondly, the skin temperatures increase to compensate for (or as a consequence of) the poor heat transfer and a distinct liquid boundary layer develops at the wall. The heat has now to pass through the less conductive liquid layer as opposed to highly conductive gas saturated gel at the wall. Consequently, the skin temperatures further increase resulting in decreased viscosity of the fluid at the wall, and the gel is now riding on a smooth liquid boundary layer without excessive frictional losses. Since gel still has high viscosity, mass transfer between gel and any available free gas is still poor resulting perhaps in a distinctly separate gas phase moving in between plugs of gel. Temperature instability and low pressure drop result from such a flow pattern. For a 30 weight per cent coal of standard size, it is possible to deduce from the pilot plant data that large amounts of heat are needed to sustain coal solvation from a starting temperature of about 480-500°F. From the foregoing, it is apparent that to avoid operational instability of the SRC-II preheater, it is necessary to have adequate amount of gas present in the feed. In order to assure the availability of sufficient gas in the slurry phase, a certain minimum gas hold-up is required. The value of hold-up which successfully correlated all the available Ft. Lewis data defining the flow regime transition was determined to be 0.38. This criterion can be stated as follows:

$$\frac{K_B u_{oG}}{u_{oL} + u_{oG}} > 0.38$$

where K_B = Bankoff's "K" factor - a function of mixture Reynolds and Froude numbers.

This functionality is shown in Figure 10.

u_{oL} , u_{oG} = slurry and gas superficial velocities

The possible mass/heat transfer limitations in preheater reactions was speculated by Traeger⁴. Normally chemical reaction control is assumed in the preheater reactions. The experience with the preheater at Ft. Lewis clearly demonstrated that this need not be the case in all situations.

As stated in the quoted material, to avoid the type of instability experienced it was necessary to raise the gas rate so that a minimum gas volume in the coil of 38% was achieved. It should be noted, however, that at high gas-to-liquid ratio, the possibility existed that the flow pattern would shift into the slugging region. Therefore, the amount of gas added to the slurry feed at the inlet to the preheater is bounded by two constraints. If the gas rate is too low, flow instability will result because of inadequate mixing in the slurry phase. If the gas rate is too high, however, unstable flow may also result because of slug flow. For efficient and smooth operation of the heater the gas rate so chosen should provide homogeneous flow.

The desired flow regime throughout the entire length of the preheater coil ideally is bubble/froth flow. This means that the critical gas to liquid ratio should be maintained throughout the length of the coil. In an improperly designed preheater, or one operated in an improper manner, apparently, even though throughout most of the coil length a minimum gas volume of 38% is maintained, in that section of the coil where rapid coal swelling occurs the gas volume could be less than the desired 38% and unstable flow would occur with resultant high skin temperatures and extremely poor heat transfer into the fluid. This point is illustrated by examining the computer program summary printout³ for run R-20 (an unstable run) on the 1½ inch coil reproduced as Table I on page 24 of this report. Under the heading Gas Holdup, you can see that apparent gas volume in coil No. 1 (or coil section No. 1) at 381°F is 40% - - greater than the 38% required for stable operations. However, in coils No. 4 & 5 the apparent gas volume has decreased to 34% --well below the 38% required for stable heater operations. In coil No. 7 the gas volume has again increased, this time to 39%. From that point on in the coil the gas volume gradually increases.

The phenomenon taking place in the swelling zone is not well understood. The preheater computer model calculates gas volume from flow rates and physical properties of gas and slurry phases using the VLE and physical properties models of Gulf's proprietary computer program (CHAMP), which employs a modified version of the Grayson-Streed correlation for phase equilibrium calculations. Since bulk temperature increases along the length of the coil in the swelling zone, and pressure is decreasing, you would expect gas volume to increase gradually along the coil length. Apparently, as the data from run R-20 illustrates, this is not so. More basic research is needed to fully understand what takes place in the swelling zone.

While it is possible with present instrumentation to measure gas and slurry flows and use ratio controllers to adjust gas flow to slurry flow at the preheater inlet this may not be the optimum method of control. For example, when the plant is on automatic control, process upsets that cause changes in slurry or hydrogen gas flow rates or composition, or firing rate to the heater, would also cause changes in the quantity of vapor generated within the coil, and also vapor density. These changes in slurry composition or vapor quantity or vapor density would have an immediate impact on void space within the coil. A ratio controller, without being recalibrated for the new vapor density, could not automatically maintain the desired gas/slurry ratio for these new conditions. A much better method of control would appear to be measuring void fraction (gas phase) of the slurry at the preheater exit and comparing that value with a predetermined range (maybe 40-45 vol%) that is known to give the desired flow regime/regimes throughout the coil and especially in the coil section where coal swelling occurs. If the actual void measurement showed less than the target range then gas to the preheater would be increased to increase gas holdup; if measured void were greater than the target range the gas would be cut to decrease gas holdup. A possible method of controlling a preheater in such a manner as described above might be by using a nuclear densitometer. These devices are used in many applications to measure average density of flowing fluids over certain times spans. P&M is not aware of densitometers in any service controlling heaters comparable to what is being proposed. However, we believe such a system could work, and in fact, The Pittsburg & Midway Coal Mining Co. has just recently been issued such a patent.⁵

The concept of using nuclear densitometers to control flow regime/regimes in the preheater tubes could be tested in small scale and relatively inexpensive equipment. For example, Figure No. 11 shows a scheme that could be used to determine if the concept is viable. A mixture of water, sand, and air (or crushed coal, light oil and an appropriate gas) could be pumped around the system at various rates and concentrations while the K-RAY device monitored slurry density, and using appropriate algorithms in a micro processor, controlled air input to maintain air volume within a preset range in the coil. If this method of controlling void space in such a simple system works, then the next logical step, would be to pilot the control system on an actual coal slurry heater. A schematic of such a system is shown in Figure 12. At the present time the SRC-I facility at Wilsonville, Alabama is the only coal liquefaction pilot plant in the United States with a heater which might be suitable for such testing. In Germany there is a large coal liquefaction pilot plant at Bottrup that probably would be suitable if such a test could be scheduled.

3.4 Multipass Design

In fired heater design the number of passes will have a major impact on preheater cost. However, cost alone should not determine heater design. In optimizing a design those practical features that promote high on-stream time should be incorporated. In early preheater designs for the SRC-II Demonstration Plant, SRC International specified a dedicated reciprocating high pressure charge pump for each preheater pass. Experience at the Ft. Lewis pilot plant indicates that, with a properly designed system, this type of charge pump can provide an acceptable on-stream time. This dedicated pump-per-pass design was later changed and a manifold design adopted. Although not finalized, preheater design at the time of project termination specified six reciprocating high pressure pumps for each reactor train, and that each train share a common discharge manifold for providing feed to each of the four preheater passes. The pumps were sized so, at design capacity, five pumps would be running with one spare.

Several factors contributed to the decision to change to a manifold design. The major factors include the following:

1. Sudden loss of a charge pump would not create an emergency condition in the reactor preheater. That is, the total flow would be reduced, but not stopped.

2. The capital cost and spacing requirements for the manifold configuration will be considerably less than the dedicated pump per pass design.
3. The piping layout is greatly simplified, improving operations, maintenance, and reducing the number of dead end piping legs. Slurry flow from the coal slurry mixing system circulates through a common suction manifold for the charge pumps with approximately one-half of the flow recycled to the mix tank to provide adequate circulation to the pump suction.
4. With five pumps operating and one spare, the pump speed would be lower than for a dedicated pump per pass design. Lower plunger speeds would likely prolong the plunger, packing and valve life. If a high head centrifugal pump, which can handle coal slurries, is ever developed, it should be more suitable and also less costly than reciprocating pumps for this type of service.

While it is felt that, with regard to bulk heater throughput, a manifold feed system will be safer and more reliable than a system in which a single reciprocating charge pump is dedicated to a single heater pass, there still exists a problem of control and balancing of slurry flowrates through the preheater passes. Instrumentation for this charge pump configuration is unproven with respect to flow measurement, flow control through each preheater pass, and backpressure control on the discharge manifold. Ft. Lewis experience with flow control measurement utilizing a quadrant edged orifice plate indicates that if the sensing lines are properly purged, these elements have an accuracy of about 5% in this type of slurry. The H-coal pilot plant used the segmental wedge flow element for slurry flow measurement and reported similar accuracy. Both of these types of measuring elements, in conjunction with ratio controllers, would be adequate for preheater pass control if, having once set the hydrogen gas/slurry ratio, the system remained relatively static. However, any change in flow rate or composition that occurs in the slurry, process gas, or fuel to the preheater would change the gas volume in the preheater coil. This in turn would affect the flow regime throughout the preheater coil and could shift the heater into unstable operations.

The most promising slurry flowmeter tested at Fort Lewis was the acoustic doppler flow meter being developed by Argonne National Laboratory. However, testing

of this device was cut short due to project expiration. Further testing of the doppler meter was planned at the EDS pilot plant. The current status of Argonne's development work on this flowmeter should be reviewed. A reliable, accurate, non-intrusive device for measuring slurry flows would eliminate certain problems associated with the quadrant edged orifice and segmental wedge flow elements.

Unless reliable instrumentation systems are available, control may be difficult because of the temperature and pressure variations between the preheater passes. Inadequate heater control could severely curtail the operability of the plant and lead to reduced rate operations.

As previously described under Heat Transfer and Pressure Drop Effects, maintaining at least a minimum gas volume of 38% throughout the entire coil length -- and especially in that portion of the coil where coal swelling occurs -- is critical to good preheater control. If the nuclear densitometer controlled instrumentation system proposed in the above referenced section (See page 21) works as postulated, P&M believes such a system will adequately balance and control slurry flow emanating from the pump discharge manifold and going to the various heater passes.

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2. Slurry Preheater Design, SRC-II Process, Report No.: 560RM149, Gulf Science & Technology Company, Pittsburgh, Pennsylvania, April 1981. File B 5.2-02.02, SRC-II Project Documentation File System.
3. Ft. Lewis Slurry Preheater Data Analysis 1½ Inch Coil, Report: 560RM158, Gulf Science & Technology Company, Pittsburgh, Pennsylvania, September 1981. File B 5.2-02.02, SRC-II Project Documentation File System.
4. Traegar, T.K., Bickel, T.C., and Curlee, R.M., "Preheater Studies in Coal Liquefaction, "Annual Report, October 1977 - September 1978, Sand-79-0150, Sandia Laboratories, Albuquerque, N.M. , May 1979.
5. U.S. Patent No. 4424108, issued to The Pittsburg & Midway Coal Mining Co., January 3, 1984.

TABLE 1.

RUN NUMBER R-20

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 FEED SLURRY, LB./HR= 6864. FEED GAS, LB./HR= 130.
 TOTAL SOLIDS, WT.PCT.= 45.90 COAL CONC., WT.PCT.= 30.20
 PI IN RECYCLE SLURRY, WT.PCT.= 22.49
 TOTAL DELTAP, PSI= 299. HEAT ABSORBED, MMBTU/HR= 1.8437

COIL NUMBER	AVE TEMP DEG F	HEAT FLUX BTU/HR/F ²	HEAT TRANSFER COEFFICIENT	THERM.COND.	VISCOSITY	FLOW PATTERN	SHEAR RATE	HIS	HIL	BS	VISC	W3
1	381.5	0.6849E 04	19.38	0.044	235.62	DISPERSED BUBBLE	305.9	28.85	9.06	1.60	1.88	1.00
2	414.0	0.6621E 04	19.30	0.045	579.31	DISPERSED BUBBLE	292.6	28.74	9.25	1.54	2.01	1.00
3	446.0	0.7205E 04	22.09	0.044	781.72	DISPERSED BUBBLE	288.6	33.12	9.08	1.52	2.40	1.00
4	478.0	0.8349E 04	27.92	0.056	1074.37	DISPERSED BUBBLE	287.9	42.49	10.73	1.52	2.61	1.00
5	509.5	0.9262E 04	31.72	0.073	837.34	DISPERSED BUBBLE	292.4	48.74	12.75	1.52	2.51	1.00
6	541.0	0.9608E 04	31.45	0.114	622.53	DISPERSED BUBBLE	303.3	48.30	17.22	1.57	1.79	1.00
7	573.0	0.8513E 04	25.92	0.031	291.11	DISPERSED BUBBLE	318.9	39.23	7.30	1.73	3.10	1.00
8	605.0	0.7542E 04	21.67	0.027	120.64	DISPERSED BUBBLE	341.5	32.46	6.59	2.01	2.45	1.00
9	637.0	0.7186E 04	21.13	0.024	74.21	DISPERSED BUBBLE	362.1	31.61	6.05	2.28	2.29	1.00
10	668.5	0.7191E 04	23.33	0.026	73.05	DISPERSED BUBBLE	374.1	35.09	6.55	2.35	2.28	1.00
11	700.0	0.7562E 04	28.12	0.000	3.92	ELONGATED BUBBLE	391.9	42.82	5.84	4.84	1.52	1.00
12	732.0	0.7656E 04	32.54	0.000	3.02	ELONGATED BUBBLE	425.0	50.12	6.80	5.04	1.46	1.00
13	764.0	0.7857E 04	37.10	0.000	0.06	ELONGATED BUBBLE	441.0	57.82	8.45	5.84	1.17	1.00

COIL NUMBER	AVE TEMP FLUID	AVE. TEMP FILM	GAS REY.NO.	LIQUID REY.NO.	MIX.REY.NO.	GAS HOLDUP	X	PHILS	SRTM MIN.	SEV.FCT. MIN.
1	381.5	718.6	42405.48	137.54	238.40	0.40	27.00	1.45	0.0	0.0
2	414.0	741.1	42253.87	55.91	92.59	0.36	41.30	1.29	0.0	0.0
3	446.0	755.2	42579.82	41.41	67.39	0.35	46.69	1.26	0.0	0.0
4	478.0	757.0	43497.09	30.10	48.70	0.34	53.08	1.23	0.14	0.21
5	509.5	779.3	44914.04	38.58	63.04	0.34	45.27	1.27	0.28	0.51
6	541.0	823.4	46885.57	51.81	87.02	0.36	37.53	1.32	0.42	0.94
7	573.0	881.1	49710.72	110.59	193.25	0.39	24.54	1.49	0.54	1.53
8	605.0	934.9	53575.77	266.20	491.94	0.42	15.03	1.80	0.66	2.29
9	637.0	959.8	58541.79	431.39	937.37	0.45	11.18	2.08	0.78	3.28
10	668.5	959.7	64533.27	436.63	871.45	0.46	10.48	2.15	0.88	4.57
11	700.0	951.3	71868.81	8092.78	16668.55	0.48	4.49	5.51	0.99	6.20
12	732.0	949.1	81108.25	10461.87	22977.43	0.51	4.10	5.93	1.08	8.16
13	764.0	957.1	92386.44	483597.38	713413.56	0.52	2.62	8.79	1.18	10.60

FIGURE 1.(3)

FIGURE 2.⁽³⁾

FIGURE 3.⁽³⁾

FIGURE 4.(2)

FIGURE 5.⁽²⁾

COMPARISON OF OVERALL HEAT TRANSFER COEFFICIENTS
AT THE BEGINNING AND END OF EXTENDED SLURRY RUN PROGRAM ON THE PREHEATER

FIGURE 6⁽²⁾

COMPARISON OF OVERALL HEAT TRANSFER COEFFICIENTS
AT THE BEGINNING AND END OF EXTENDED SLURRY RUN PROGRAM ON THE PREHEATER

FIGURE 7⁽²⁾

EFFECT OF CHANGING GAS RATE ON PREHEATER-PRESSURE DROP

Typical

Pressure Drop per Unit Length

Gas Rate

34
Temperature, °F

FIGURE 8(2)
EFFECT OF CHANGING GAS RATES
ON TUBE SKIN TEMPERATURES

FIGURE 9⁽²⁾

EFFECT OF TEMPERATURE ON SLURRY VISCOSITY
AT DIFFERENT LIQUID TO GAS RATIOS

Figure 10⁽²⁾

CORRELATION FOR BANKOFF'S FLOW PARAMETER, K_B

SMALL SCALE TEST FACILITY

FIGURE 11

CONCEPTUAL COMMERCIAL CONTROL SYSTEM

FIGURE 12