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# Technical Review of Entrained Design Report

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December 14, 1979

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Miamisburg, Ohio 45342
operated by
**MONSANTO RESEARCH CORPORATION**
a subsidiary of Monsanto Company
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**U. S. DEPARTMENT OF ENERGY**
Contract No. DE-AC04-76-DP00053

Monsanto

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# Contents

# 1. Introduction

Morgantown Energy Technology Center (METC) is planning to expand its in-house coal gasification R&D capabilities by installing a research facility that can address a number of concepts including entrained, fluid bed, and catalytic gasification and flash pyrolysis. This Advanced Gasification Concepts (AGC) facility is, in addition, intended to have sufficient flexibility to allow its use beyond the stated objectives that formed the basis for its design. The design, as it currently stands, includes piping and instrumentation diagrams, vessel drawings and specifications, instrumentation lists and specifications, and equipment layout and isometric drawings. Before the design is finalized, a critique is needed to ensure that the intended flexibility and objectives can be met.

This Technical Review of the Entrained Design Report was prepared by Monsanto Research Corp. (MRC) to satisfy the requirements of the U. S. Department of Energy Field Task Proposal/Agreement bearing Contractor Number P79-8-249. The overall objective was to provide Morgantown Energy Technology Center (METC) with a critique of the design report entitled "Engineering and Specification for Entrained Coal Gasification Bench-Scale Pilot Plant," dated August 1979, prepared by Science Applications, Inc. (SAI).

The design approach was evaluated to determine whether the present design will meet the research objectives, including the need for flexibility.

Heat and material balances, critical velocity requirements, vessel arrangements, potential operational problems, and instrumentation were reviewed.

The mechanical design review included a critique of the drawings and specifications, adherence to standards and codes, materials of construction, vessels, piping, valves, heaters, and fittings. In addition, utilities requirements, heat transfer and particulate removal calculations, and pumping and heat exchanger requirements were checked.

An evaluation of the equipment cost includes a critique of the reliability of the equipment cost breakdown, the areas of cost uncertainty, and the areas for potential cost savings.

A safety analysis is provided that identifies highly probable and highly serious potential safety hazards and includes appropriate recommendations.

# 2. Summary of conclusions and recommendations

This section is a concise comprehensive summary of the significant conclusions and recommendations pertaining to the functional capabilities, cost, and safety of the system. It does not include the suggestions regarding minor clarifications. Additional discussions regarding the conclusions and recommendations are presented in the subsequent sections of the report.

2.1. Several statements in the report require updating and clarification before the associated items are procured. Overall project accuracy should be defined. The criteria should be revised to reflect the actual flow rates for both the gas and coal streams and the actual vessel sizes based on the final reactor volume. Comments in the critique are based on a 3 in. i.d. x 4 ft long reactor, rather than the designs in the SAI report.

2.1.1. The coal feed storage and the char pot volumes should be increased.

2.1.2. The range of the coal feeder should be increased to 1.8 to 24 lb/hr.

2.1.3. The gas flow rates should be increased to the levels shown on the revised Table 3.2. in Section 3 of this report.

2.2. Because of expected high temperatures, further investigation into the use of Dowtherm G or a change in the process to lower the temperature at the char cooler inlet is recommended.

2.3. It was concluded that the proposed rotary star feeder, coupled with modifications based on METC's experience is the best approach.

2.4. The specific design for the heater/reactor has been in a state of development during the time this review was made. A recent design has a larger reactor section (3 in. i.d. and 4 ft long) than the designs described in the report. Design improvements have minimized or eliminated many of the concerns regarding the reactor designs in the report. A review will be made of a different reactor whose size is 3 in. i.d. x 30 in. long.

2.5. The heat transfer calculations in SAI's report for the gas heater are numerically incorrect. The proposed heater design can provide sufficient heat transfer area if higher temperatures can be used, but concern exists regarding the temperature limitations of the silicone carbide. It is recommended that the heater be designed with multiple heating zones, that consideration be given to additional preheater capacity, and that the heat transfer calculations be again reviewed when the heater design is more firm and the maximum gas flow rates have been firmly established. Verbal discussions with SAI indicate that their representative concurs with the above conclusions and recommendations: SAI recommends use of silicone carbide in the 3000°F to 3100°F range.

2.6. The flexibility of the instrumentation for this project could be increased by the use of dual thermocouples to eliminate unnecessary loss of data and the use of data loggers to provide programmable capability.

2.7. The hole configuration for entry of the gas into the reactor and the subsequent mixing of the gas and coal should be dealt with experimentally as suggested in the SAI report.

2.8. The product condenser, H-501, will be marginal at best and should be increased in size since the increased cost would be minimal.

2.9. Since quality control is not mentioned in the documentation provided, it is recommended that consideration be given to the implementation of appropriate quality control measures.

2.10. The liquid cooling system cannot be checked until the heater/reactor is designed. It is not expensive to add extra capacity for future flexibility and it is recommended that this be done.

2.11. The cost estimate should be redone since it was primarily based on both a high and a low pressure system.

2.11.1. Items not on the flow sheet should be deleted from the estimate; for example, dual system components, reverse osmosis system, and $N_2$ and $CO_2$ compressors.

2.11.2. Most of the material costs assigned to individual items seemed reasonable.

2.11.3. The estimated cost of the engineering seems low considering the significant amount of effort needed to complete the project.

2.11.4. The allowance for contingency is low for this early in the life of the project.

2.11.5. An escalation factor should have been added to allow for the rise in costs due to inflation.

2.12. The safety requirements of the system and facility and their relationships are not clearly defined in the report. It is recommended that the planned SAR be completed. The following safety recommendations are made:

2.12.1. Use only blow-out walls rather than blow-out walls and a blow-out roof because of the problems associated with snow and ice loading on the roof and the problems of containment of the blow-out portion of the roof.

2.12.2. Use flashback arrestors in pipelines carrying flammable gases and provide pressure sensing and venting devices at all points where pressures may be isolated.

2.12.3. Revise the action and alarm levels for toxic and flammable gases to better ensure personnel safety.

2.12.4. Provide a two-speed ventilation system for the cell. The high speed ventilation should prevent build-up of toxic or flammable gases, and the low speed should maximize the sensitivity of gas detection monitors.

2.12.5. Consider "Human Factors" in the design of the information/alarm systems to ensure proper reaction from operators to system deviations.

2.12.6. Provide fire protection, preferably Halon, for the electronic equipment.

2.12.7. Provide emergency power to all systems necessary to monitor and shut down the process including such things as the air supply to air-operated valves.

2.12.8. Investigate the possible use of the Fenwall explosion suppression system inside the cell area.

# 3. General review of design report

Section 3 includes general discussions of topics applicable to most of SAI's design report, but not specifically applicable to any single page or few pages of the design report. It complements the discussions in Section 4, which address topics page by page.

### 3.1. Valving

Temperature, pressure, and flow conditions are specified for each valve, but no manufacturer is listed. Valve specifications need to match conditions at the point of use, and when material lists are generated, these conditions should be verified.

It is important that relief valves be properly sized for flow and that the valve materials are compatible with the gas compositions. It would also be desirable to have a remote indication to show activation for each relief valve.

### 3.2. Piping Interface

In general, the interfacings do not appear to be a problem. Note, however, that as the final design is generated for the heater/reactor interfacing to the star feeder, gas preheater, steam injector, and char pot will all be important to consider in relation to the temperature gradients at these points.

In general, the vessels appear to have oversized inlet/outlet connections. For example, vessel V-505 calls for a 1-in. Grayloc fitting when 1/2 in. Grayloc could be used for the process connections. Even 1/2 in. Graylocs would require downsizing to fit 1/2 in. tubing.

### 3.3. Process Flow Limits

Changes in reactor volume have a major impact on the gas and coal flow rates through the system. Several of the test cases were reviewed in an attempt to find the flow limits. These calculations were restricted per METC to a pressure range of 200 to 600 psig and a gas residence time of from 5 to 10 sec for the 3-in. i.d. x 4 ft long reactor size. Table 3-1 in this report lists these limiting tests. The final reactor size should be determined to accurately set these flow requirements.

### 3.4. Dowtherm System

The recommended temperature use range for Dowtherm G is listed as up to 650°F. The system as designed should not exceed 650°F bulk temperature but film temperatures between 700 - 800°F at the char cooler should be expected. The maximum recommended film temperature is 725°F.

An article in Chemical Engineering, May 28, 1973, p. 91, states that by "exceeding the maximum recommended fluid temperature by 50°F, a 10% sample loss (attributable to venting of volatile products and carbon deposition) has been shown to result from 2 to 4 weeks of continuous operation."

Further investigation into Dowtherm G and other heat transfer media should be done or the process should be changed to reduce the temperature in the char cooler.

Table 3-1 - PROCESS FLOW LIMITS FOR 3-in. i.d. x 4 ft REACTOR

| Test Number | Temp. (°F) | Pressure (psig) | Residence Time (sec) | Flow (SCF/lb coal) | Flow (SCFH Specific Gas) | Limit Comment |
|---|---|---|---|---|---|---|
| II $A_{1-3}$[a] | 2800 | 600 | 6 | 65 | 128 | Max. CO Flow |
| II $D_{1-3}$ | 2800 | 500 | 5 | 85 | 145 | Max. $CO_2$ Flow |
| III $B_{1-3}$ | 2200 | 600 | 5 | 100/50 | 1180 | Max. $N_2$ Flow |
| III $C_{1-3}$ | 2200 | 600 | 5 | 100/50 | 1180 | Max. $H_2$ Flow |
| III $D_{1-3}$ | 2200 | 600 | 5 | 100/50 | 1180 | Max. $H_2O$ Flow |
| | | | | | (lb coal/hr) | |
| II $D_{3-1}$[b] | 3000 | 200 | 10 | 86 | 1.8 | Min. Coal Flow (Total 158 SCFH) |
| III $B_{3-1}$[b] | 2800 | 200 | 5 | 100 | 3.4 | Low Coal Flow (Total 335 SCFH) |
| III $B_{1-3}$ | 2200 | 600 | 5 | 50 | 24 | Max. Coal Flow |

[a] Indices - Relate to SAI Table 6.1 and the order in which the temperature and pressures are listed - i.e. II $A_{1-3}$ - first temperature and third pressure in table.

[b] This pressure minimum is different from those listed on page 35 of SAI report.

If it is decided to retain the Dowtherm G system, METC should take advantage of the free analysis service for Dowtherm media from Dow Chemical and periodically (six months to a year) submit a sample.

## 3.5. Quality Control

Quality control is not mentioned in any of the documentation provided. The system involves unique designs, hazardous materials, and considerable complexity. As the end result must be meaningful experimental data, it is recommended that consideration be given to the implementation of appropriate quality control measures that meet the intent of a formal program such as DOE AL Appendix 08XA.

## 3.6. Solids Monitoring

No provision for monitoring solids flow in the system during an experimental run was included in the final report. A further review should be made of this area and consideration given to possible alternatives for verifying solids flow.

# 4. Detailed review of design report

Section 4 includes discussions that are specifically applicable to a single page or a few pages of SAI's design report. Some topics, of a more general nature, were previously discussed in Section 3, which complements Section 4.

Page 3

The report should be clarified to reflect the intent that 200-600 psig is the pressure range of most interest. Operating pressures as low as 14.7 psia and as high as 1000 psig are desired for flexibility; however, instrument accuracy can be sacrificed at the extremes.

Page 5

The SAI report specifies a range of residence times from 5 to 10 sec in SAI Table 3.1, but subsequently calls for residence times of 3 and 12 sec for test IID. The report should make clear the intent that SAI's Table 3.1 should adhere to.

The term "adiabatic" should be clarified to reflect the intent that heat is to be supplied to the reactor vessel walls so the vessel wall temperature will match the reaction mixture temperature in order to prevent heat loss from the reaction mixture. For more flexibility to achieve this condition, a multizone heater and control system is recommended.

The stated method of sampling the solids in batches on completion of the runs seems acceptable; however, it may be found, when the system is operational, that solids samples are desired during the runs. It is recommended that provisions be made for additional remote solid sampling as a potential add-on feature. For example, two valves in series at the bottom of the char pot could be operated remotely to remove samples during runs. The additional cost may not be justified at this time.

The coal throughput rate of 10 lb/hr is too low for the reactor as specified in the report: 15 lb/hr would be more appropriate. Based on the possible new larger reactor size, the throughput would be in the range from 1.8 to 24 lb/hr.

Page 6

The gas supply systems should be revised to reflect the higher gas flow rates if the larger reactor is used (See revised Table 3.2 for maximum flows).

Page 7

The coal feed storage volume (0.8 $ft^3$) is low based on the original design. It should have been about 1.2 $ft^3$, but it should be increased to about 2.0 $ft^3$ to handle the larger reactor size.

Page 8

A more meaningful basis than temperature (2100°F) for determining actual $ft^3$/hr (ACFH) is the volume of the reactor and the gas residence time.

Nitrogen should replace one of the hydrogens in "Gas Composition."

For the new reactor volume, the flow rates should be 160-1200 SCFH and 70-141 ACFH.

REVISED Table 3.2 - DESIGN CRITERIA GAS SUPPLY SYSTEM

| Component | Purity (%) | System Pressure (psig) | Temperature[+] (°F) | Maximum Flow (SCFH) | Capacity[**] (SCF) |
|---|---|---|---|---|---|
| He | 99.995<br>(High Purity)[†] | 1100 | 50 | 950 | 7600 |
| $N_2$ | 99.998<br>(Prepurified)[†] | 1100 | 50 | 1200<br>(800)[***] | 9600<br>(6400)[***] |
| CO | 99.5<br>(C.P.)[†] | 700 | 50 | 130<br>(80)[***] | 1040<br>(640)[***] |
| $CO_2$ | 99.8<br>(Bone Dry)[†] | 700 | 80 | 145<br>(75)[***] | 1160<br>(600)[***] |
| $H_2$ | 99.95<br>(Prepurified)[†] | 1100 | 50 | 1200<br>(800)[***] | 9600<br>(6400)[***] |
| Steam | Demineralized | 1100 | 600 | 1200<br>(800)[***] | 9600<br>(6400)[***] |

[+] Prior to Preheater which raises the nonaqueous gases to 600°F.

[†] Designation of the Matheson Company.

[**] Based upon an 8-hr total run time.

[***] Original in parentheses.

<u>Page 9</u>

The operating temperature of the reactor should be specified over approximate ranges as follows:

Inlet: 2200-3000°F, and

outlet: 1600 to 2300°F.

<u>Page 10</u>

Several ranges of coal analysis were found in the literature: It appears that the solids loading could be 0.3-2 lb/50 SCF of gas. The gas flow rate should be approximately 200-1700 SCFH (25-600 ACFH at 2100°F, 200 to 600 psig) for the new reactor size. The coal feed rate should be 1.8 to 24 lb/hr and the condensate loading should be 55 lb/hr.

<u>Page 11</u>

The pressure criteria should show a design pressure of 1100 psig and an operating pressure of 200-600 psig to be consistent with the rest of the criteria. For the new reactor size, the liquid volume storage size should be around 3.0 $ft^3$ to hold a 3-hr run at 55 lb/hr of $H_2O$. The solids volume should be approximately 6.0 $ft^3$ for 57 lb of char and ash from 3 hr of operation (19 lb/hr and a density allowance of 10 $lb/ft^3$).

Page 15

It would help clarify "operation at 1800°F and 300 psig" by stating that steam injection will be used only when the reactor pressure is less than 300 psig.

Creep could cause the joints and seals to develop leaks after the reactor is used at high temperature over a period of time. (Reference MRC comments on SAI's page B-15). This would be particularly true with use of 304 or 316 stainless steel in the lower reactor section.

The steam supply subsystem as shown in the P&I diagram indicates measurement of the steam pressure and temperature at two different locations. The same location should be used for both in order to determine the mass flow rate of the steam.

Page 16

The proposed rotary star feeder and other potential feed mechanisms were evaluated for this application. Vibrating feeders, fluid bed feeders, and screw feeders were considered. The design may require several interchangeable star wheels to minimize pulse feeding at low feed rates. A vibrating system on the feed hopper and feeder may be helpful. A fluid-bed coal feeder would not have a wide feed-rate range and the carrier gas could interfere with operation of the reactor. A screw type coal feeder may be acceptable; however, pressure fluctuations between the reactor and the pressurized feed hopper may cause problems since the screw feeder does not provide positive pressure isolation. Calibration provisions are unclear. It was concluded that the proposed rotary star feeder, coupled with modifications based on METC's experience, is the best approach.

The P&I diagrams show three temperature sensors for the gas heater (303, 304, and 305), but only one temperature controller. The intent of this arrangement is not clear. As discussed in response to the heat transfer calculations on SAI's page B-12, more flexibility could be obtained by independently controlling multiple heating zones.

Page 19

The dimensions given for the heater tube do not agree with the dimensions used in the calculations on SAI's page B-12 which were based on a 1/2-in. square channel, 20.2 ft long.

The initial gas temperature entering the heater is stated elsewhere in the report as 600°F, not 50°F.

The maximum temperature of the ceramic will exceed 3000°F in order to heat the gas to 3000°F. This is discussed further in response to the heat transfer calculations on SAI's page B-12.

During experiments using the steam injection probe, care must be taken to ensure that the ash will be solidified before passing through the throat of the reactor where it will be cooled by the steam. Otherwise it could accumulate on the throat surface and plug the reactor.

Pages 20 to 24

The specific design has been in a state of development during the time this review is being done. A recent design has a larger reactor section (3 in. i.d. and

4 ft long) than the designs described in the report and has minimized or eliminated many of the concerns regarding the reactor designs in the report.

The purpose of the taper at the bottom of the reactor is unclear. It appears to be an unnecessary restriction of the flow and potentially a place where plugging could occur. It is recommended that its purpose be reviewed.

Since it is important to be able to replace parts easily, such as the ceramic tube, it is recommended that the steps required to do this be reviewed with the manufacturer during the detailed design phase.

Even though the most recent design has minimized the concern about leakage through the slip joints, it is recommended that consideration be given to specifying a minimum acceptable leak rate and appropriate testing procedures for acceptance from the vendor.

The hole configuration for entry of the gas and the subsequent mixing of the gas and coal can best be dealt with experimentally as suggested in the SAI report. A 30° angle from vertical and a slight radial angle to impart a swirl are recommended for testing. It may be necessary to provide different hole configurations for widely varying flow rates.

The heater and reactor tube wall thicknesses are significantly different. At the heater/reactor joint, excessive stresses may develop in the heater tube as a result of joining irregular cross sections. These stresses may reduce the heater tube life.

If the horizontal heater tube is not properly supported, sagging will result after prolonged use.

A thorough analysis should be made of the deformations resulting from thermal expansion of the reactor. For example, the varying expansion rates of the outer jacket, because of its attachment to the hot char cooler, may cause deformation at the mounts and connections.

It is recommended that dual thermocouples be specified, particularly for the critical temperatures inside the reactor. The cost is small compared to the additional reliability.

Vessel wall thicknesses are discussed in our review of SAI's calculations on SAI pages B-15 through B-18.

Alternative designs for the joints which were reviewed and discussed with METC included flanges, slip joints, threaded joints, and ceramic cemented joints. The new reactor design reflects the use of several of these alternatives.

## Page 24

There is some concern regarding the ability of the char cooler to cool the char and gases adequately for worst condition cases. Thus, the following preliminary analysis was considered:

Note Figure 4-1 for the cooler conditions and sizes.

The following assumptions were made in the analysis:

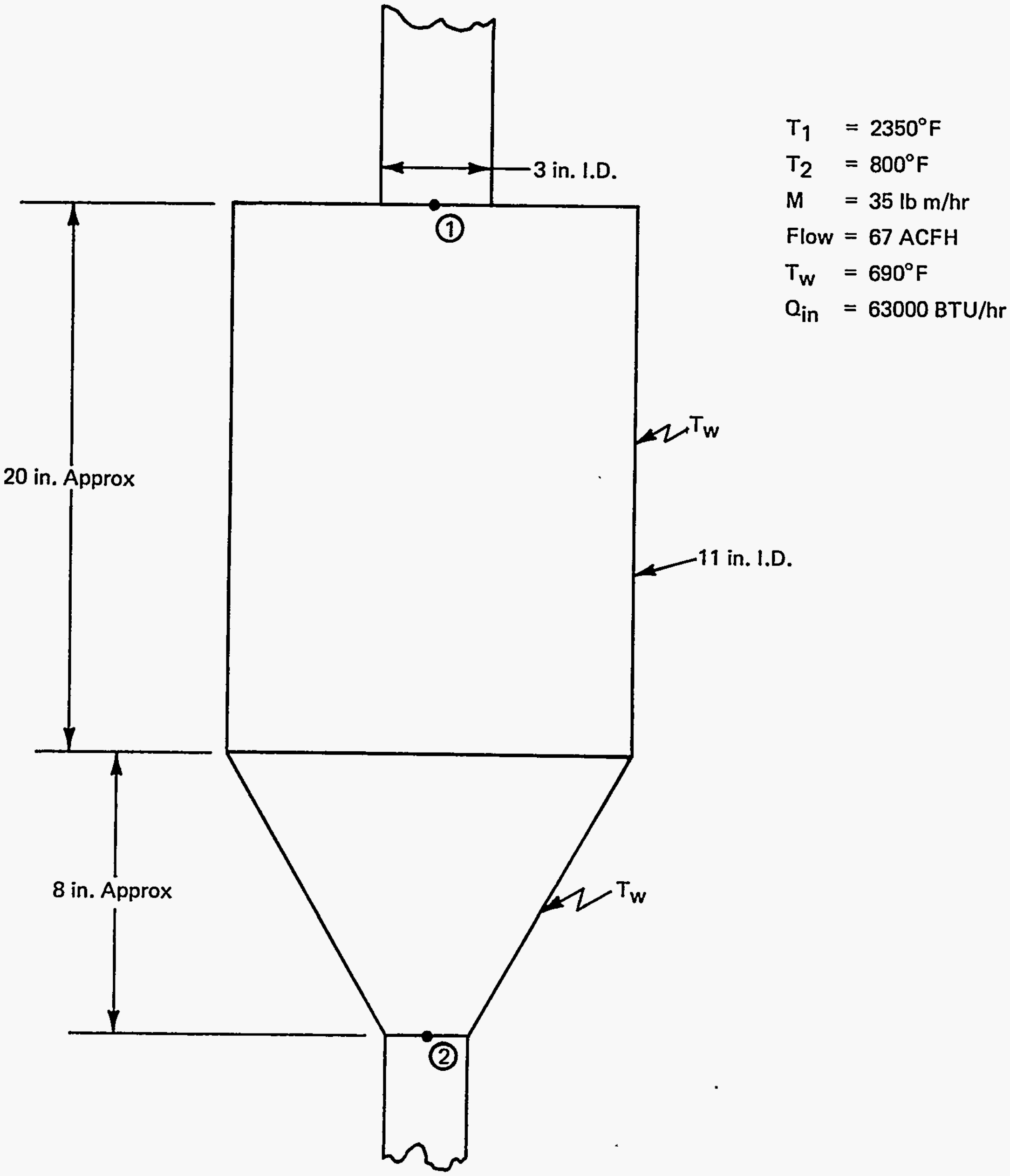

FIGURE 4-1 - Basis for char cooler heat transfer calculations.

1. Total surfaces and volumes are approximate.

2. The char cooler can be adequately modeled as a "fired heater."

3. The inner wall temperature is a constant 690°F.

4. All properties are evaluated at a mean temperature based on the outlet and inlet conditions ($T_1$ and $T_2$).

5. Gases such as He and $H_2$ are transparent and, thus, have no significant contribution to the overall radiative transfer.

6. The only gases that significantly contribute to the radiative transfer are $CO_2$ and $H_2O$ (steam). The sum of their expected molal percents equals their additive partial pressures.

The following analysis follows closely a paper written by Norman Wimpress of C. F. Braun and Company which appeared in Chemical Engineering magazine (May 22, 1978).

For the total radiation and convective transfer inside a firebox or, in this case, the char cooler, the governing equation is,

$$q_T = AF\left[\sigma\left(T_g^{\,4} - T_t^{\,4}\right) + 35\left(T_g - T_t\right)\right]$$

where

$q_T$ = Total energy transfer including both convection and radiation, BTU/hr.

A = Plane area of tube heat exchanger. For the char cooler this will be the total internal surface area or Total Surface Area (Approximate) = Cylinder + Cone + End = 945 in.$^2$ or 6.56 ft$^2$

F = Radiant exchange factor, dimensionless.

$\sigma$ = Stefan-Boltzmann constant,

$$0.173(10^{-8})\ \frac{\text{BTU}}{\text{hr ft}^2\ {}^{\circ}\text{R}^4}$$

$T_g$ = Mean gas temperature, $T_g = \frac{T_1 + T_2}{2} + 460°$, °R

$T_t = T_w + 460°$, °R

Evaluating these terms for the char cooler gives

<u>A</u>

A = 6.56 ft$^2$

<u>F</u>

"F" is determined graphically from Wimpress's paper. Briefly, an effective length, "L", is determined by,

L = 3.6 V/A

where A is the char cooler enclosed area, and V is the enclosed volume or Total Volume = Cylinder + Cone = 2192 in.$^3$ or 1.27 ft$^3$. "L" is multiplied by the partial pressure of the $CO_2$ and $H_2O$ summations ($\sim$0.05 x 69 atm). An emissivity, $\varepsilon$, is determined from a graph using the mean gas temperature.

With $\varepsilon$ known, a second graph involving the area of the char cooler is consulted and the exchange factor, "F", is determined.

In this particular case, F equals 0.4.

<u>$\sigma$</u>

As noted.

### $T_g$

According to energy balance calculations, the worst case reactor outlet condition is

$$T_1 = 2350°F.$$

The char cooler outlet temperature was specified as

$$T_2 = 800°F.$$

Thus,

$$T_g = \frac{T_1 + T_2}{2} + 460° = 2035°R.$$

### $T_t$

$$T_t = T_w + 460 = 690 + 460 = 1150°R$$

All terms in equation (1) have been specified; thus, $q_T$ can be evaluated.

$$q_T = 6.56(.4)\left[.173(10^{-8})\ (2035^4 - 1150^4) + 35(2035 - 1150)\right]$$

$$\boxed{q_T = 150{,}000 \text{ BTU/hr}}$$

Compared to a maximum amount of energy to be removed of 63,000 BTU/hr, the heat exchanger calculations indicate an oversizing by a factor of approximately 2. With the aforementioned assumptions, particularly the constant wall temperature, this sizing would be appropriate. Finally, these calculations are preliminary and further analysis is advisable.

### Page 27

There is some concern regarding potential plugging of the sintered metal filter. METC's intent to clean the filter between runs will alleviate this concern.

The symbol $\triangle$P on the char pot outlet is unclear.

### Page 28

There is some concern regarding potential plugging of the sample filter.

### Pages 30 through 32

The assumptions that the gaseous products would be similar to the devolatilized gases given in SAI Tables 5.1 and 5.2 and that the tars and oils would gasify according to the equation on page 32 are inconsistent with experimental data listed in SAI's reference 2 and the equilibrium constants for the higher temperatures. The amount of $CH_4$ is much too high. Also, the assumption that 10% of the fixed carbon reacted with water seems low for some of the experiments.

### Pages 35 through 37

Tables 6.1 and 6.2 in SAI's report should be revised to reflect METC guidance to limit the calculations to the pressure range of 200 - 600 psig, to gas residence time of 5 to 10 sec, and the actual reactor size.

### Page 38

The location of stream #11 is not shown on Figure 6-1 of SAI's report.

### Page 39

The system heat and material balance in general appears consistent based on the assumptions on pages 30, 31, and 32 of SAI's report and the smaller reactor size as listed on page 19. The only stream that appears inconsistent is #14, but the basis could not be checked since SAI did not include any calculations for this stream.

Pages 40 through 44

These heat and material balances were not checked in detail since they were based on the smaller reactor size which results in smaller gas and coal flows, and higher pressures than are now anticipated. Also the methane content seems higher than possible.

Page 101

The cooling water total requirement cannot be evaluated until the final design is made of the heater/reactor. See the revised SAI Table 3.2 in this report for the new maximum gas flow rates based on the new larger reactor size.

Page 201

The amount of heat to be exchanged in the high pressure gas preheater, H-101, has increased from 9400 to 12,600 BTU/hr because of the larger gas flow in the larger reactor. To match the heat transfer, the Dowtherm 'G' flow rate should have a corresponding increase from 655 to 1600 lb/hr. The heat exchanger still appears to be adequate to handle the additional load.

Page 202

The heat load for this exchanger condenser H-501, would increase from 49,800 to about 57,400 BTU/hr because of the larger reactor. The large load occurs with $H_2O$ but the overall transfer should be divided into three sections, super heated steam to water, condensing steam to water, and water to water. The heat exchanger, as sized, is marginal without any allowance for fouling by organic films. A larger transfer area should be specified or two exchangers should be used.

Page 203

The heat load for the condenser H-602 should be around 3100 rather than 625 BTU/hr. The specified heat exchanger should be able to handle the load.

Page 206

A check cannot be made of this cooling water heat exchanger, H-805, until the heater/reactor design is completed.

Page 300

At this time it is difficult to predict what the exact pressure drops, pipe lengths, and tubing configurations will be in order to predict total dynamic head for pump sizing. SAI's parameters predicted for the various pumps in Appendix B, page B-14, look reasonable for the system shown. The required horsepower equations appear mathematically correct and should be adequate for the system. The capacity for the P-101 steam generator water pump should be increased from 0.1 to 0.11 gpm. The capacity for the Dowtherm pump should be increased to minimize the high film temperature problem in the char cooler.

Pages 500 through 538

The flexibility of the instrumentation for this project could be increased by the use of dual thermocouples eliminating unnecessary shutdowns and by the use of data loggers. A digital data logger which can be programmed for increased flexibility has the capacity to easily monitor one hundred temperature points and could replace many three-pen recorders for a cost savings. Since the system is heavily instrumented with top-of-the-line equipment, cost saving potentials also exist by reducing the quantity of instruments and possibly the quality of the instruments after the accuracy requirements on the process have been defined.

Conceptually, the P&I diagrams provide sufficient information as to what kinds of instrumentation are being proposed, but METC is making major changes which have not been evaluated. The two major areas of concern on instrumentation are the need to further define the safety interlocking system and the need to define what valves require remote operation to eliminate the need to enter the pressure cell during operation.

In some cases the instrumentation specifications are too specific: They appear to be rigid specifications from a particular manufacturer, e.g., multipoint recorders. In other cases the specifications are too general. The instrumentation specifications should be reviewed in greater detail after the process accuracy requirements are defined and completion of the P&I diagram.

Page 602

The coal feeder should be sized to handle the flow rate required by the actual reactor size (range of from 1.8 to 24 lb/hr for the 3 in. i.d. x 4 ft long reactor). METC may want to consider a non-electrical drive rather than E.P. electrical.

Pages 604 and 605

The coal hopper should be increased in size to about 2.0 $ft^3$ to handle the maximum flow rate for 3 hr if the larger reactor is used. A cone shaped bottom would probably feed better.

Page 607

The use of Hastelloy X for the transition tube from the reactor to the char cooler will cause a problem. The design temperatures are in the range of 2200 to 2300°F and Hastelloy X will not take that high a temperature (melting point 2300-2470°F).

Pages 608 and 609

The char pot should be increased in size to handle the additional volume if the larger reactor is used. Estimates indicate a worst condition of about 5.3 $ft^3$ based on a density of 10 $lb/ft^3$ for the char and ash.

Page 611

The process line between condenser H-501 and vessel V-505 is 1/2 in. o.d. tube but V-505 has a 1 in. pipe nozzle. Such a large reduction in size requires more fittings than necessary.

Page 701

The steam generator B-101 should be sized to generate at least 55 lb/hr of steam. It would be much cheaper and safer to locate the generator outside the cell rather than use E.P. electrical per code.

Pages 702 through 704

The specifications for the low pressure superheater for the steam could not be checked since steam injection requirements were not established.

Pages 906 through 911

These specifications for the gas heater/ reactor assembly, M301/401, should be revised to agree with capacity and sizes associated with the actual reactor size.

Pages 1100 through 1104

There are no specific comments on the P&I diagrams since MRC plans to provide feedback to METC as a follow-up to this report after the revised P&I diagrams are received from METC.

Page B-1

SAI used a different gas composition for the feed gas than that listed on page 11 of the project proposal (SAI Reference 2). The comparison follows:

| | SAI | Reference 2 |
|---|---|---|
| $N_2$ | 57.7 | 56 |
| $H_2$ | 4.8 | 7 |
| $H_2O$ | 14.7 | 13 |
| CO | 12.2 | 16 |
| $CO_2$ | 10.6 | 8 |

The major impact is the 16% requirement of CO to feed the system, the other changes have no significant impact. The gas flow rate in SCFH is essentially correct for the 2 3/4 in. i.d. x 3 ft reactor size in SAI's report. This needs to be corrected for the actual reactor size as mentioned earlier in the comments.

Page B-2

The friction factor, f, used in the friction pressure drop equation is too high (0.031 vs. 0.008). The pressure drop for the tube listed should be 0.05 psi instead of 0.071 psi. The 3/8 in. i.d. tube size does not agree with the heat exchange surface calculation for the size on SAI's B-13.

Page B-3

There appear to be several errors in the calculations of the heat and energy balances. The amount of coal (carbon and ash) in stream #12 should be 3.935 lb and the amount of gas should be 35 lb (see SAI's page B-5). The specific heat equation for coal is wrong. Handbooks indicate a range of 0.26 to 0.37 BTU/lb °F for coal. If this method is used, the approximate temperature for stream #12 would be around 2250°F.

Pages B-4, 5, and 6

These calculations of the heat and material balance appear to be correct based on the assumptions listed on SAI's pages 30, 31, and 32. As stated earlier in Section 4 the basis for these assumptions is questionable.

Page B-7

It is not clear what pressure drop ($\Delta P$) is being calculated.

Page B-9

The equation used to calculate terminal velocity from Stokes's Law is not valid for Re >0.1 per Reference 3 page 60. This is not a major problem since the friction factor equation gives only a 30% higher number (0.17 vs. 0.13 ft/sec).

Page B-10

SAI's calculations were checked based on the physical property data and the equations presented. The Nusselt number, coal heat capacity, and dimensionless temperature calculations are in need of clarification; however, the overall conclusion resulting from the calculations may not change.

It is not clear why the Nusselt number calculation is based on the entrained particle being at the terminal velocity of a falling particle: It is doubtful that the terminal velocity assumption applies during the brief time involved. SAI calculated Nu = 2.24 on this basis, whereas a value of Nu = 2.0 would be obtained if the gas and the particle were assumed to be at the same velocity.

The heat capacity of coal, C, listed by SAI to be 1.05 BTU/lb°F could not be calculated from the equation given on Page B-10. Perry's Chemical Engineer's Handbook (Page 3-136) gives the range of C for coal as 0.26 to 0.37 BTU/lb °F.

It is not clear how SAI obtained a value of $(T-T_\infty)/T_O-T_\infty)$ = 0.05 or why the symbol $T_1$ was used rather than $T_O$ as given in SAI's Reference 7. If values of T = 2030°F, $T_\infty$ = 3000°F, and $T_O$ = 50°F are substituted into the equation, the result is (2030-3000)/(50-3000) = 0.329.

The above concerns do not seem to alter the apparent conclusion drawn by SAI that the coal particles can be heated quickly enough. If the calculations are modified using the above value of $(T-T_\infty)/(T_O-T_\infty)$ = 0.329, the resulting value of $\theta$ = 0.013 sec, which is less than the $\theta$ = 0.035 sec obtained by SAI. It is recommended that these calculations be again reviewed for the larger particle sizes based on the final reactor size and residence time.

Page B-12

The equations and numerical results presented on pages B-12 and B-13 for heat transfer from the ceramic spiral channel to the steam were reviewed, and it was found that some of the numerical results could not be reproduced. An independent calculation was also performed.

Apparently two of the equations were miscopied: The sixth equation should be

$$h_i^* = \frac{Nu^* k_f}{4d^*}$$

and the seventh equation should be

$$\frac{1}{U^*} = \frac{1}{h_i^*} + \frac{D_i \ln\left(\frac{D_o}{D_i}\right)}{2k_s}$$

It was assumed that the steam properties given were at 3000°F and 1000 psig and a value for the density was determined at these conditions since none was given. The results compare as follows:

| | SAI | Review |
|---|---|---|
| q, $\frac{BTU}{hr}$ | 57,500 | 57,500 |
| U*, $\frac{BTU}{hr\ ft^2\ °F}$ | 590 | 60 |
| $\Delta T_{ln}$, °F | 45 | 45 |
| Area, $ft^2$ | 2.16 | 21 |
| $L_{Helix}$, ft | 20.2 | 127 |
| ℓ , ft | 1.1 | 17 |

Also, the calculations were repeated using property values from THERMAL (a commercially available heat transfer computer code) at 1500°F: A value of U* = 53 resulted.

Thus, SAI calculations are numerically incorrect, although it is difficult to determine exactly where since the detailed sample calculations were not provided.

An independent approach was taken to evaluate the maximum temperature of the ceramic wall. SAI's approach involved assuming the maximum temperature to be 3001°F. This provides conservatism in evaluating the length, but does not provide an assessment of the maximum temperature.

THERMAL was used to make the calculations for pure helium, nitrogen, hydrogen, steam, carbon monoxide, and carbon dioxide at the following conditions:

Volumetric Flow = 800 SCFH
Pressure = 1000 psig
Inlet gas temperature = 600°F
Outlet gas temperature = 3000°F
Channel dimensions = 0.0147 ft x 0.0147 ft x 20.2 ft long

The results obtained are as follows:

| | Q (BTU/hr) | Inside Surface Temperature of Ceramic Channel At Inlet (°F) | Inside Surface Temperature of Ceramic Channel At Outlet (°F) |
|---|---|---|---|
| Helium | 25,000 | 830 | 3190 |
| Nitrogen | 40,000 | 1000 | 3280 |
| Hydrogen | 36,000 | 700 | 3080 |
| Steam | 53,000 | 900 | 3330 |
| Carbon Monoxide | 40,000 | 1000 | 3410 |
| Carbon Dioxide | 66,000 | 1070 | 3350 |

The statement of the problem, analysis, and results for the steam case are as shown in the computer printout on the following pages.

The gas stream compositions summarized in Table 6.2, page 37 of the SAI report were then used to estimate the ceramic surface temperature at the outlet for the mixtures. It was assumed that the ceramic temperature increase above the bulk fluid temperature necessitated by each gas was proportional to the concentration of the gas and that the total volumetric flow in all cases was 800 SCFH. The results are as follows:

| Case | Ceramic Inside Surface Temperature at Outlet (°F) |
|---|---|
| II A | 3300 |
| II D | 3290 |
| III B | 3080 |
| III D | 3330 (pure steam) |
| III F | 3210 |
| IV B | 3080 |

The hottest temperature calculated was for Case III D which is pure steam. The temperature increase across a 1/4-in. ceramic wall was estimated to be 30°F so that the maximum calculated ceramic temperature is 3360°F.

Mark's Handbook (7th Edition, page 6-171) states that silicone carbide decomposes above 4060°F. Manufacturers' recommended maximum temperatures are substantially less than this.

Uncertainties regarding the heat transfer calculations exist as follows:

## STATEMENT OF PROBLEM
********************

CALCULATE THE FORCED CONVECTION HEAT FLOW Q FROM THE LENGTH OF RECTANGULAR DUCT BETWEEN SECTIONS 1 AND 2. THE FLOW AND THERMAL CONDITIONS ARE:

- TURBULENT FLOW
- UNIFORM HEAT FLUX
- FULLY DEVELOPED VELOCITY PROFILE AT SECTION 1
- FULLY DEVELOPED TEMPERATURE PROFILE AT SECTION 1

THE GIVEN CONDITIONS ARE:

| | | |
|---|---|---|
| DUCT LENGTH L, FT | = | .2020E+02 |
| DUCT WIDTH W, FT | = | .4170E-01 |
| DUCT HEIGHT B, FT | = | .4170E-01 |
| FLUID TEMPERATURE TB1, F | = | .6000E+03 |
| MASS FLOW RATE M, LBM/HR | = | .3720E+02 |
| HEAT FLUX Q/A, BTU/HR-SQ FT | = | .1563E+05 TO .1564E+05 |

## ANALYSIS
********

HEAT FLOW Q FROM A DUCT OF LENGTH L TO THE FLUID FLOWING IN THE DUCT MAY BE EXPRESSED BY

$$Q = H\ A(TS - TB) \quad , A = 2(W + B)L \qquad (1)$$

HOWEVER, EQN. (1) IS OF LIMITED VALUE FOR THE FOLLOWING REASONS:

- THE SURFACE TEMPERATURE TS VARIES ALONG THE DUCT
- THE FLUID BULK TEMPERATURE TB VARIES ALONG THE DUCT DUE TO HEATING OR COOLING
- THE HEAT TRANSFER COEFFICIENT H WILL VARY DUE TO ITS DEPENDENCE ON FLUID PROPERTY VALUES WHICH DEPEND ON TB
- H WILL VARY IN REGIONS OF DEVELOPING VELOCITY AND/OR TEMPERATURE PROFILES

IT IS NECESSARY, THEREFORE, TO USE THE DIFFERENTIAL FORM OF EQN. (1)

$$DQ = H(TS - TB)DA \qquad (2)$$

IN THIS ANALYSIS THE HEAT FLUX DQ/DA IS SPECIFIED. SINCE H MAY DEPEND ON TB THROUGH TEMPERATURE DEPENDENT PROPERTY VALUES, THE VARIATION OF TB ALONG THE DUCT IS NEEDED. THIS IS OBTAINED BY NOTING THAT THE HEAT TRANSFERRED TO THE FLUID RESULTS IN A RISE IN THE BULK TEMPERATURE,

$$DQ = M \ SPH \ DTB \quad , \ M = \text{MASS FLOW RATE} \qquad (3)$$

EQNS. (2) AND (3) ARE INTEGRATED NUMERICALLY TO OBTAIN THE SURFACE AND BULK TEMPERATURES.

THE FORCED CONVECTION HEAT TRANSFER COEFFICIENT IS OBTAINED FROM THE FOLLOWING CORRELATION.

REF: W. M. ROHSENOW AND J. P. HARTNETT, HANDBOOK OF HEAT TRANSFER, SECT. 7, P. 33, MC GRAW-HILL(1973)

$10,000<RE$
$0.7<PR$
REFT = TB AT LOCATION X

$$NU = 0.022 \ RE^{0.8} \ PR^{0.6}$$

THE DIMENSIONLESS PARAMETERS ARE DEFINED AS FOLLOWS,

$$PR = VIS \ SPH/CON$$

$$RE = (M/AC)(4 \ W \ B/2(W + B))/VIS$$

$$NU = H(4 \ W \ B/2(W + B))/CON$$

```
                              RESULTS
                              *******


   IN THE CALCULATIONS FOR THE FOLLOWING BLOCK OF RESULTS THE
REFERENCE TEMPERATURE FOR THE INDICATED MATERIAL WAS ABOVE OR
BELOW THE TEMPERATURE RANGE FOR THE INDICATED PROPERTY. THE
PROPERTY VALUE AT THE UPPER OR LOWER LIMIT WAS USED IN THE
CALCULATIONS.

 OUTPUT  MATERIAL  PROPERTY  TEMPERATURE LIMITS, F
 COLUMN   NUMBER               LOWER      UPPER
   1        1      DENSITY   .5463E+03   .1500E+04
   1        1      SP HEAT   .5463E+03   .1500E+04
   1        1      TH COND   .5463E+03   .1500E+04
   1        1      DYN VISC  .5463E+03   .1500E+04
   2        1      DENSITY   .5463E+03   .1500E+04
   2        1      SP HEAT   .5463E+03   .1500E+04
   2        1      TH COND   .5463E+03   .1500E+04
   2        1      DYN VISC  .5463E+03   .1500E+04
   3        1      DENSITY   .5463E+03   .1500E+04
   3        1      SP HEAT   .5463E+03   .1500E+04
   3        1      TH COND   .5463E+03   .1500E+04
   3        1      DYN VISC  .5463E+03   .1500E+04
   4        1      DENSITY   .5463E+03   .1500E+04
   4        1      SP HEAT   .5463E+03   .1500E+04
   4        1      TH COND   .5463E+03   .1500E+04
   4        1      DYN VISC  .5463E+03   .1500E+04


MATERIAL PROPERTIES          Case 1     Case 2     Case 3     Case 4*

PRESSURE, ATM              .6900E+02  .6900E+02  .6900E+02  .6900E+02
DENSITY, LBM/CU FT         .8797E+00  .8797E+00  .8797E+00  .8797E+00
SP HEAT, BTU/LBM-F         .5805E+00  .5805E+00  .5805E+00  .5805E+00
TH COND, BTU/HR-FT-F       .6720E-01  .6720E-01  .6720E-01  .6720E-01
DYN VISC, LBM/FT-HR        .1010E+00  .1010E+00  .1010E+00  .1010E+00


RANGED INPUT PARAMETERS

Q/A, BTU/HR-SQ FT          .1563E+05  .1563E+05  .1564E+05  .1564E+05


OUTPUT PARAMETERS

D, FT                      .4170E-01  .4170E-01  .4170E-01  .4170E-01
PR1                        .1324E+01  .1324E+01  .1324E+01  .1324E+01
RE1                        .1765E+05  .1765E+05  .1765E+05  .1765E+05
NU1                        .6501E+02  .6501E+02  .6501E+02  .6501E+02
H1, BTU/HR-SQ FT-F         .5352E+02  .5352E+02  .5352E+02  .5352E+02
TS1, F                     .8920E+03  .8920E+03  .8921E+03  .8922E+03
PR2                        .8724E+00  .8724E+00  .8724E+00  .8724E+00
RE2                        .8834E+04  .8834E+04  .8834E+04  .8834E+04
NU2                        .2909E+02  .2909E+02  .2909E+02  .2909E+02
H2, BTU/HR-SQ FT-F         .4688E+02  .4688E+02  .4688E+02  .4688E+02
TS2, F                     .3331E+04  .3332E+04  .3333E+04  .3334E+04
TB2, F                     .2998E+04  .2998E+04  .2999E+04  .3000E+04
H, BTU/HR-SQ FT-F          .4603E+02  .4603E+02  .4603E+02  .4603E+02
Q, BTU/HR                  .5265E+05  .5266E+05  .5268E+05  .5270E+05
```

*Case 4 results in a final gas temperature of 3000°F.

1. The amount of gas which will leak past the spiral channel was not estimated.

2. The additional heat transfer from the ceramic channel to the gas by radiation was not estimated.

3. The calculation model assumed a 1/2-in. square channel with a 1/4-in. thick wall. The proposed design, a spiral groove in a solid cylinder, is physically different.

4. The extent of hot spots is unknown.

5. The computer code did not contain fluid property data up to 3000°F in several cases. The steam fluid properties did not exceed 1500°F.

In conclusion, it appears that the SAI proposed design will provide sufficient heat transfer area to heat the gases to 3000°F, but concern exists regarding the temperature limitations for silicone carbide. A more conservative approach is available. It is recommended that additional preheater capacity be provided and that the heater section of the reactor be used only for high temperatures that would exceed the capabilities of the preheater. This would enable the reactor heater to operate with lower ceramic temperatures and/or provide some extra capacity. Detailed specifications for manufacture of the square channel should specify an ample radius to avoid stress concentration problems. The heat transfer calculations should again be reviewed when the heater design is firmer and the maximum gas flow rates have been firmly established for the actual reactor design.

Page B-13

SAI's approach and numerical values were used to check the calculation of $T_4$, the heating element temperature. The calculated value of $T_4$ was found to be 2940°F compared to SAI's value of 3518°F: Apparently, there is a numerical error in SAI's calculation. Also, SAI's assumption that

$$T_{ceramic} = \left[(T_2{}^4 + T_3{}^4)/2\right]^{1/4} = 2452°F,$$

leads to the erroneous conclusion that $T_4$ = 2940°F is adequate, but the gas cannot be heated to 3000°F if the heater temperature is only 2940°F.

In addition, THERMAL, a commercially available heat transfer computer code, was used to provide a second approach. For this approach, a value of 2.73 ft (rather than 1.1 ft stated in the report) was used for the heater length since this is the length corresponding to a 20.2 ft long spiral according to the last equation on page B-12. Also to be conservative, it was assumed that the entire outside surface temperature of the ceramic tube was at 3360°F, the maximum calculated temperature for 800 SCFH of pure steam (Case III D). The resulting value of $T_4$ was calculated to be 3440°F.

Since both values of $T_4$ calculated in this report were less than the value of 3518°F reported by SAI, any conclusions drawn by SAI regarding the acceptability of the heating element materials would still appear to be valid. It is recommended that the heater be designed with multiple independently monitored and controlled heating zones. This would allow the flexibility in providing a greater heat flux near the cooler inlet and a lesser heat flux near the hotter outlet to minimize the ceramic temperature at the outlet.

The statement of the problem, analysis, and results are as shown in the computer printout on the following pages.

Page B-14

At this time it is difficult to predict what the exact pressure drops, pipe lengths, and tubing configurations will be in order to predict total dynamic head for pump sizing. SAI's parameters predicted for the various pumps look reasonable for the system shown. The required horsepower equations appear mathematically correct and should be adequate for the system. The capacity for the P-101 steam generator water pump should be increased from 0.1 to 0.11 gpm. The capacity for the Dowtherm pump should be increased to minimize the high film temperature problem in the char cooler.

Page B-15

Maximum allowable stress values used to calculate wall thicknesses are too high resulting in the calculation of thinner walls than are acceptable according to ASME code. The equations should all be reviewed.

Though this is a very minor error, the head stress equation should be,

$$t = \frac{PD}{2SE - 0.2P} \qquad (1)$$

rather than

$$t = \frac{PD}{2(SE - 0.2P)}$$

Example:

For V202 coal hopper, the original values are

| | |
|---|---|
| design temperature | 400°F |
| design pressure | 1100 psig |
| material | 304L |
| allowable stress | 15800 psi |
| E | 0.9 |

Thus, the resulting vessel thicknesses calculated by SAI are

wall t = 0.405 in.
head t = 0.390 in.

Using Equation 1 and an allowable stress of 14700 psi for 304L seamless pipe gives

wall t = 0.426 in.
head t = 0.409 in.

Thus, in either case, 10 in. Sch 80 (0.500 in. thick) 304L stainless steel is acceptable. However, erroneous stress values and equations give a feeling of incompleteness and uneasiness.

The sample receiver and Dowtherm surge tank should be made out of 304L rather than 304 stainless steel. Since welding is required during fabrication, 304L would be a much better choice.

Tubing materials appear adequate at all locations. Tubing wall thicknesses are adequate, though for safety, appropriate relief valves made of compatible material should be employed. Note that 304L tubing and pipe should be used rather than 304 because its corrosion resistance is better after welding.

The remaining stress calculations in Appendix B were checked and are acceptable,

## STATEMENT OF PROBLEM

CALCULATE THE THERMAL RADIATION EXCHANGE BETWEEN TWO FINITE LENGTH CONCENTRIC CYLINDERS. THE THERMAL CONDITIONS ARE:

- . UNIFORM SURFACE TEMPERATURES
- . ABSORPTANCE EQUAL TO EMITTANCE
- . DIFFUSE EMITTANCE AND REFLECTANCE

THE GIVEN CONDITIONS ARE:

SURFACE LENGTH L, FT = .2730E+01
DIAMETER OF SURFACE ONE D1, FT = .2384E+00
SURFACE SPACING R, FT = .4750E-01
SURFACE TEMPERATURE TS1, F = .3360E+04
SURFACE TEMPERATURE TS2, F = .3430E+04 TO .3445E+04
EMITTANCE EM1 = .9500E+00
EMITTANCE EM2 = .9500E+00

## ANALYSIS

THE NET RADIATION EXCHANGE BETWEEN TWO SURFACES IN THE ABSENCE OF ANY OTHER PARTICIPATING(REFLECTING)SURFACES IS DEFINED TO BE:

> THE ENERGY ABSORBED BY SURFACE 2 WHICH WAS ORIGINALLY EMITTED BY SURFACE 1 MINUS THE ENERGY ABSORBED BY SURFACE 1 WHICH WAS ORIGINALLY EMITTED BY SURFACE 2, TAKING INTO CONSIDERATION ALL INTERREFLECTIONS BETWEEN THE TWO SURFACES.

UNDER THE ASSUMPTIONS THAT

- . THE SURFACES ARE ISOTHERMAL
- . THE ABSORPTANCE OF EACH SURFACE IS EQUAL TO ITS EMITTANCE, I.E., THE SURFACES ARE GRAY
- . THE SURFACES EMIT AND REFLECT DIFFUSELY

IT CAN BE SHOWN THAT THE NET RADIATION EXCHANGE IS GIVEN BY

$$Q = (EM1\ EM2\ F12/((1 - (1 - EM1)F11)(1 - (1 - EM2)F22) - (1 - EM1)(1 - EM2)F12\ F21))\ A1\ SIG(TS1^{4} - TS2^{4})$$

FOR THE CASE OF TWO CONCENTRIC CYLINDERS OF EQUAL LENGTH, THE INNER CYLINDER BEING SURFACE 1, THE ANGLE FACTOR F11 IS ZERO AND F21 = (D1/D2)F12 GIVING

$$Q = (EM1\ EM2\ F12/(1 - (1 - EM2)F22 - (1 - EM1)(1 - EM2)(D1/D2)F12^{2}))A1\ SIG(TS1^{4} - TS2^{4})$$

THE ANGLE FACTORS F12 AND F22 ARE GIVEN BY

```
    F12 = 1 - (1/PI)(ARCCOS C/B
                                        2     2 1/2
                      - (1/2 Y)(((B + 2) - 4 X )   ARCCOS (C/X B)

                      + C ARCSIN 1/X - PI B/2))
                                      2    1/2
    F22 = 1 - 1/X + (2/PI X)ARCTAN(2(X - 1)   /Y) - (Y/2 PI X)
               2   2 1/2                  2         2  2   2
         (((4 X + Y )   /Y)ARCSIN((4(X - 1) + (Y /X )(X - 2))/
                                   2     2
                                 (Y + 4(X - 1)))
                     2      2                  2   2 1/2
          - ARCSIN((X - 2)/X ) + (PI/2)((4 X + Y )   /Y - 1))
                                           2   2          2   2
 WHERE X = (D1 + 2 R)/D1, Y = 2 L/D1, B = Y + X - 1, C = Y - X + 1



                              RESULTS
                              *******



RANGED INPUT PARAMETERS

TS2, F                  .3430E+04  .3435E+04  .3440E+04  .3445E+04

OUTPUT PARAMETERS         Case 1     Case 2     Case 3*    Case 4

F12                     .9866E+00  .9866E+00  .9866E+00  .9866E+00
F22                     .2743E+00  .2743E+00  .2743E+00  .2743E+00
F21                     .7055E+00  .7055E+00  .7055E+00  .7055E+00
Q/A1, BTU/HR-SQ FT     -.2485E+05 -.2668E+05 -.2851E+05 -.3035E+05
Q/A2, BTU/HR-SQ FT     -.1777E+05 -.1908E+05 -.2039E+05 -.2170E+05
Q, BTU/HR              -.5081E+05 -.5454E+05 -.5830E+05 -.6206E+05
```

*Case 3 results in a heating element temperature of 3440°F.

with the exception of allowable stress values and the head equation noted above. Neither of these errors will change the calculated vessel thicknesses enough to require drawing changes.

Tubing thicknesses were checked via ANSI B31.1 and found to be adequate; however, one exception to this is the tube from the steam superheater to the injector. This tube is called out as Hastelloy X and would not meet code at 1800°F. This could be enclosed and shortened to minimize potential dangers.

Note that the steam superheater is to be enclosed in a purged enclosure because of electrical concerns; however it should also be mandatory from pressure considerations. The stress analysis for tubing and pipe was as follows:

$P = 1100$ psig
Allowable stress, $SE = 9000$ psi at 800°F (ANSI B31.1, 304L SST seamless tubing and pipe)

From B31.1, the governing equation for calculation of the wall thickness, t, based on the diameter, $D_O$, is

$$t = \frac{PD_O}{2(SE + Py)} \quad \text{where } y = 0.5$$

for

<u>1/4 in. tubing</u>

$$t = \frac{1100\ (0.250)}{2[9000 + 1100\ (0.5)]} = 0.014 \text{ in.}$$

<u>3/8 in. tubing</u>

$$t = \frac{1100\ (0.375)}{2[9000 + 1100\ (0.5)]} = 0.022 \text{ in.}$$

<u>1/2 in. tubing</u>

$$t = \frac{1100\ (0.5)}{2[9000 + 1100\ (0.5)]} = 0.029 \text{ in.}$$

<u>1/2 in. pipe</u>

$$t = \frac{1100\ (0.840)}{2[9000 + 1100\ (0.5)]} = 0.048 \text{ in.}$$

# 5. Review of cost estimate

Section 5 contains a review of SAI's cost estimate that was provided as an informal supplement to the design report. It was reviewed for reliability of the equipment cost breakdown, the areas of cost uncertainty, and the areas for potential cost savings.

## Section No. 1 - Utilities and Chemicals

This section cannot be evaluated without a layout of the facility and knowledge of the utility source locations and conditions. Several items are listed, such as R/O water pump, $N_2$ and $CO_2$ compressors, which are not on the flow sheet.

## Section No. 2 - Heat Exchangers

The estimate lists two heat exchangers each (both a high and low pressure unit) for H-101, H-501, and H-602 but only one is shown on the flow sheet.

## Section No. 3 - Pumps

There are two P-702 Dowtherm pumps in the estimate, but only one is shown on the flowsheet.

## Section No. 4 - Compressors

This section should be deleted since neither of the two compressors are shown on the flow sheet.

## Section No. 5 - Instruments and Control Valves

In general, unit pricing looks reasonable, but the total list should not be used since a major revision is being made on the instrument flow sheets.

## Section No. 6 - Process Vessels

Vessels V-101, 102, and 103 are costed in the estimate but do not show on the flow sheet. Two each of vessels V-202, 503, 504, 505, 606, and 707 are in the estimate, but only one each is shown on the flow sheet. The estimate of $1700 equipment cost on the coal hopper/feeder, V-202, does not agree with the quote of $12,000 from PEMCO in the final report document.

## Section No. 7 - Burners and Fired Heaters

Two each of heaters B-102 and B-704 are costed, but only one is shown on the flow sheet.

## Section No. 9 - Miscellaneous

Two each of items X-101, M-301, M-401, F-502, X-604, and F-603 are listed in the estimate, but only one is shown on the flow sheet. A reverse osmosis permeator unit, X-104, is in the estimate but is not shown on the flow sheet. Since the heater/reactor is still not well established, no additional investigation into their costs was made. It seems strange that such major items of costs are listed under miscellaneous.

## Sections X2 and X3 - Valves, Fitting, Tubing, and Miscellaneous Building Support

No comments could be made on these sections since a major revision is under way on the flow sheet, and no information on the building is available to MRC.

## Contingency

A contingency of 15% on the overall project seems very low with such key uncertainties as the gas heater design, the reactor design, and other incomplete designs. In addition, no allowance was made to coordinate costs to a construction schedule and include an escalation factor to account for inflation.

# 6. MRC safety analysis

The purpose of this safety assessment is to provide a third party review to assist in maximizing the safety and property protection features. This analysis identifies the highly probable and highly serious potential safety hazards and includes appropriate recommendations.

This safety review is concerned with the process concept and generic safety features of the conceptual facility design. Specific design features are considered when identified in the Operation and Safety Manual, indicated on process flow sheets, or verbally communicated to MRC personnel; however, a comprehensive safety analysis of the design was not possible because of a lack of a definitive design. We have attempted to identify potential hazards in the process, facility, monitoring systems, and procedures from information available and to suggest corrective or mitigating changes.

The general method of analysis used was based upon the ERDA developed "Occupancy-Use Readiness Manual - Safety Considerations" ERDA-76-45-1. This method provides an overall review of the safety concerns of the project but does not provide a systems analysis on the component and component interaction level as does fault-tree analysis. This technique involves the DOE's management oversight and risk tree (MORT) concepts.

The major areas considered in the analysis were: the structures, services, process and hardware design, management control systems, monitoring systems, and personnel readiness. Each of these areas is discussed in greater detail and suggestions to improve or ensure safety and property protection in each area are offered.

## 6.1. Building and Grounds

It is important to be assured that no one is in the cell, or endangered by the relief mechanisms, while the process equipment is energized. This involves:

- Assurance by the operator that the cell is unoccupied prior to system activation.
- Methods of preventing entry into the cell - possibly system interlocks.
- Methods of locking and assuring that the perimeter fence around the test cells is secured. The fenced area should allow for safe "blow-out" of the cell without endangering personnel.

If the blow-out design of the roof is considered, the effect of snow loading on the degree of blow-out protection needs to be evaluated. A preferred cell relief mechanism may be to blow the rear walls into bunkers. The blown-out panels should be designed not to shear any utilities.

Employe evacuation routes into the proposed fenced enclosure or near any endangering utilities (high pressure lines, etc.) must be avoided. Thus, to meet Life Safety Codes, two or more exits in the direction opposite the cell are recommended.

The layout of the total system (control room, cells, gas supplies, etc.) should consider all energy sources with the potential for causing accidents. Ground space permitting, all such energy sources should be separated so that they will not impinge on each other. This will probably exclude all gas storage, etc. from the proposed fenced area. Also, supply lines should not be endangered by the cell relief mechanism, see Figure 6-1.

It is recommended that the Control Room and test cells be physically isolated from each other as far as practical. This is recommended because:

- Design analysis of the cells cannot anticipate consequences of all possible system failures.
- Noise created by an explosion may be harmful to control room occupants and it will be difficult to analyze these effects as part of the cell safety analysis.
- Minimize cross-ventilation problems.

## 6.2. Ventilation

To enable the monitoring system to be used to detect leaks, the cell ventilation should be set at the minimum level required to prevent heat buildup. To

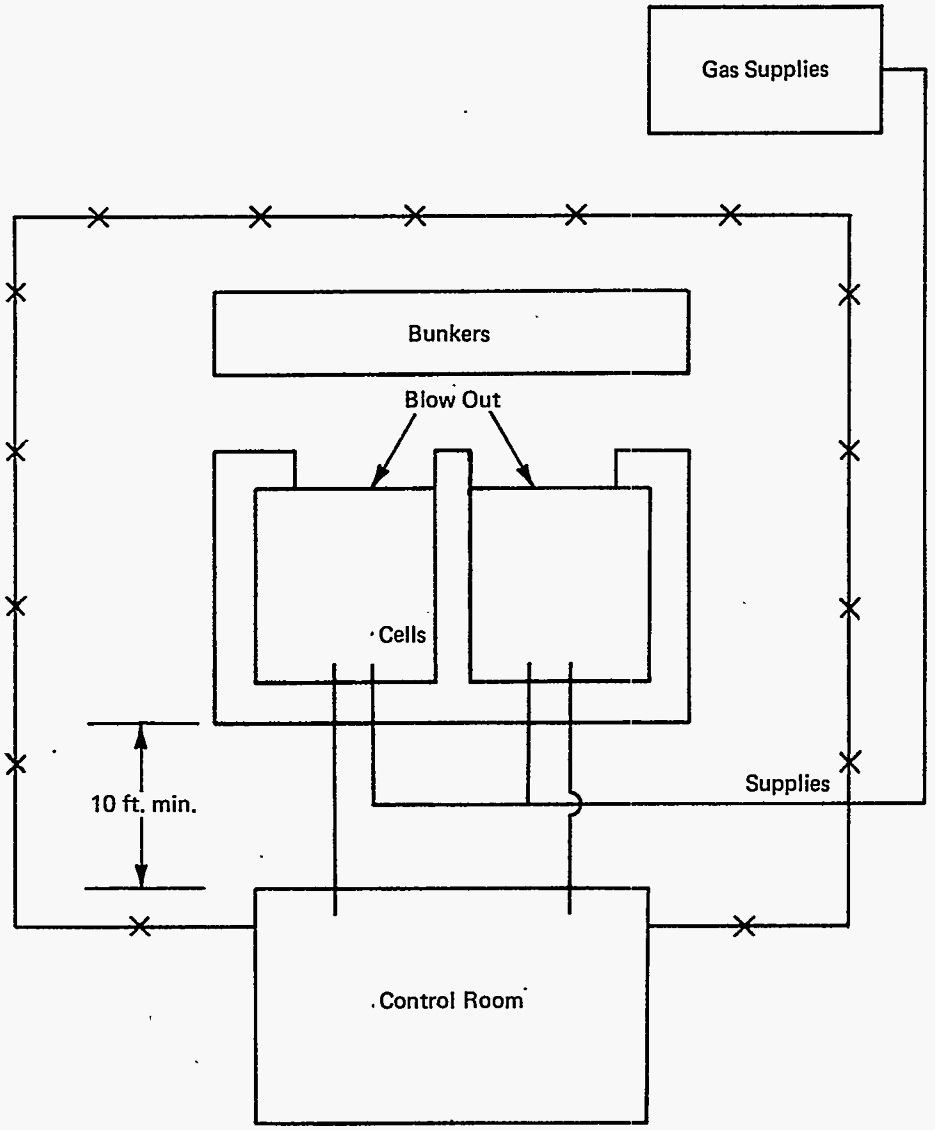

FIGURE 6-1 - Suggested facility and exclusion layout.

further reduce required ventilation, all heat generating equipment that is not an explosion hazard can be placed outside the cell. This will also reduce exposure of maintenance personnel to hazards presented by the process equipment in the cell.

Sensing monitors should be strategically located (including monitoring the exhaust ventilation duct). If toxic gases are monitored, a "leak" alarm can be activated. If gas concentrations begin approaching "Lower Explosive Limits (LEL), the cell ventilation should automatically switch to high-speed. High-speed ventilation should occur at no less than 50% LEL.

Manual switching to high-speed ventilation should be available to sweep the cell of toxic gases prior to personnel entry into the cell.

A similar two-speed ventilation system may be considered for the Control Room. Pipe lines entering the Control Room carrying flammable and toxic gases should be minimized. If some dangerous gases are required for analytical purposes, monitors should be near these pipes and in the exhaust ducts. The manned Control Room should be ventilated when levels of toxic gases reach the "action level."

## 6.3. Services

Emergency power should be supplied to all system components and sub-systems necessary to control or shut down the process and ensure personnel safety when commercial power is lost. Such components or sub-systems should include:

- Instrumentation - both process indicators as well as gas detectors for personnel safety.

- Lighting for the control room.

- Ventilation for the cells (if this method is to be used as a protective feature).

- Air compressor and control system for the air operated valves.

## 6.4. Fire Protection

In addition to standard sprinkler systems in the Control Room, special dedicated automatic fire suppression may be considered for remote and expensive systems. Dedicated "dry" or antifreeze sprinkler systems for the Dowtherm System (which is external to the cell) and other isolated process support systems may be advisable. The need of these sprinklers should be determined by a cost/benefit trade-off.

A dedicated automatic Halon system for the electronic console is recommended, based on the cost of the electronic equipment (several hundred thousand dollars, plus time lost to replace). If dedicated Halon protection for the electronics is not feasible, smoke detectors should be considered in the equipment areas. Smoke detectors will allow fire control action prior to sprinkler ignition. Water may damage the electronics. If the electronics are water sprinklered and become wet during an incident, the electronic instruments should be dried as quickly as possible to minimize losses or damage caused by water.

It is suggested that the Morgantown representative of Fenwall Explosion Suppression

Systems be contacted to evaluate the practicality of protecting the cells from explosions. The equipment contents of the cells are valuable enough to warrant a cost/benefit, feasibility analysis of this type of protection. The Fenwall explosion suppression system would serve to reduce loss of or damage to equipment, rather than serve as a personnel protection device because the cell should be unoccupied at any time the process system is in operation.

All the automatic fire suppression systems recommended above should automatically notify the Fire Department or some 24 hr/day manned, emergency response office. Hand extinguishers of the proper type (i.e. Halon in the electronics areas) are recommended.

## 6.5. Communications

Intercom systems are suggested for use in the cell area to enable continuous and reliable communications with the Control Room.

Emergency procedures should be revised to provide for immediate notification of the Fire Department and/or Safety Department upon occurrence of a fire, before control actions are initiated by operators. Delays in notifying fire departments too often result in catastrophic losses.

## 6.6. Gas Supply

Appropriate relief devices throughout the gas supply systems are always the first line of defense against overpressurization. Venting of relieved toxic and flammable gases requires attention to ensure no additional hazards are created. An overview of the design indicates relief devices were considered. Further design evaluation, however, raises the possibility that flash-back arrestors need to be considered. Wherever burning gases may reach large energy sources, flash-back arrestors should be considered. Also, in long pipe runs that contain flammables, the possibility of detonations resulting from sonic deflagrations should be evaluated. Detonations are prevented by avoiding long straight pipe runs where deflagrations can accelerate to sonic levels. Consultations with Dr. Grelecki of Hazards Research Corp. (Ph. 201/627-4560) concerning system explosion characteristics are strongly recommended.

All piping containing high pressure gases should be heavily anchored (at frequent intervals) to prevent pipe - whip upon failure. This is particularly true of small diameter thin walled pipes. High flow check valves (inertial shut-off valves) should be considered at cell wall penetrations in lines carrying combustible gases. This would prevent flooding the cell if a major leak or rupture occurs.

## 6.7. Process/Hardware Design

Gages containing process fluids that are flammable or toxic should not be located in manned areas (Control Room, etc.). Transducers and digital/remote read-outs are recommended. Backup gages in the remote cells are recommended as a means of observing pressure trapping points in the systems, when cell entry is required.

The capability to remotely vent the char and liquid pots, before the cell is entered to remove them, is recommended in order to prevent personnel from sustaining injury while opening the pressurized containers.

A method of unmanned leak testing of the cell system is recommended. Elevating helium pressures in the system, with no cell ventilation, and observing strategically placed monitors, or monitoring pressure losses from the system may be acceptable techniques.

If carbon steel relief valves are used, they should be located away from the hot equipment. Also, it would be safer to have some system to alert personnel when relief valves are activated. Pressure sensing and venting devices should be incorporated at all points where pressures may be isolated.

All system components (such as the Dowtherm System and the steam generating system) that are not significantly hazardous should be located outside the cell. This will allow maintenance activities without endangering maintenance personnel.

In system designs and operations, such as this one, it is generally observed that operating personnel and system components are usually well protected. Deaths, injuries, and other catastrophies are then usually related to improper maintenance or incomplete identification of all possible unusual failure modes. Thus, special precautions should be taken so that maintenance personnel are not endangered.

## 6.8. Information Systems

The wide range of temperatures and pressures used necessitates the use of a system to positively indicate to the operator what temperatures and pressures exist at various locations within the process system. Use of multiple gages or readouts, however, is a common source of operator error. Also potential errors can occur if the operator has to isolate or valve out high or low pressure sensors from the system. If this potential problem cannot be designed out of the system, then operating procedures should be designed to ensure that the isolating procedures are followed correctly and that the operator obtains information from the active sensor readout.

Notification of out-of-limit parameters such as excessive temperature or pressure or the presence of gases in excess of predetermined concentrations should be made to operators in a positive, active, method rather than rely upon the operator obtaining this information from a passive readout. This is particularly important where the out-of-limit parameter may indicate some hazard to operators. It is also important that such alarms or notification devices be placed where the operator who must react will be notified immediately.

A review of SAI Safety Report Table 4.1, LIMITS FOR HAZARDOUS GAS MONITORING, indicates that some of the Control Room concentration values may be above acceptable levels. The values listed in Table 4.1 reflect single occurrence Threshold Level Values but fail to recognize possible synergistic effects. The synergistic effects of $H_2S$, HCN, and CO are such that the acceptable concentration levels should be lowered. For further reference, the NIOSH criteria document, Coal Gasification Plants, lists suggested concentration levels for various contaminants.

Additionally, the limits for hydrogen gas appear to be too high from an explosion prevention viewpoint. A concentration of 25% of the Lower Explosive Limit (LEL) should trigger an alarm or notification to the operators that a leak has occurred. A concentration of 50% LEL should trigger an automatic shutdown and high-speed ventilation as discussed previously. These action levels should be applied to all flammable gases unless health concerns require lower action levels.

Because gas supply and pressures are essential to the process, it is suggested that the supply of gases be verified prior to starting an operation.

Visual monitoring of the cell from the Control Room could be accomplished by a closed circuit video system. Such a system could also allow for remote damage and risk assessment before personnel enter the cell after a problem occurs.

The design of the controls and instrumentation readouts should consider human factors such as physical man-machine interfaces and visual displays/information transfers. This is particularly important when the operator must react promptly to information he receives. This system has at least 47 alarms associated with it, with several alarms possibly indicating different process deviations. The design of the controls and readouts could have a significant impact on the operator's ability to control the system.

The Automatic Data Acquisition System may be usable for controlling the process or advising operators of the proper response to take to alarm signals.

## 6.9. Written Procedures

Written operating and maintenance procedures should be prepared and used for all operations where risk to personnel is significant. An example of a procedural step which should be documented and followed is verification that high pressures do not exist in the char pot or liquid receiver before initiation of steps to remove these components.

In the area of emergency procedures, actions should be prioritized when they cannot be performed simultaneously. Specifically, the Fire Department should be notified immediately before other actions are taken to control a fire.

Emergency Shutdown Procedures should be prepared both for situations originating within the system/facility and for situations external to the facility (i.e., a fire in an adjacent building).

## 6.10. Personnel Readiness

Emergency equipment such as supplied breathing air and protective clothing and equipment should be readily available and personnel should be adequately trained in their usage.

Training of personnel in standard operating procedures will apparently be done quite well. Additional emphasis on emergency procedures and in training others such as fire/rescue and maintenance personnel may need to be considered.

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