DESIGN, ENGINEERING AND EVALUATION OF REFRACTORY LINERS FOR SLAGGING GASIFIERS

AUGUST 1982

FINAL REPORT

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Final Report

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FOREWORD

IIT Research Institute is pleased to submit this final report to the Department of Energy on Contract No. DE-AC05-78ET13410.

We wish to acknowledge the encouragement and advice of Mr. E. E. Hoffman of Oak Ridge Operations, Messrs. R. A. Bradley and D. L. Lennon of Oak Ridge National Laboratory, and Dr. C. R. Kennedy of Argonne National Laboratory.

Respectfully submitted,

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1. INTRODUCTION

The conversion of coal to a suitable and economic gaseous fuel is an emerging new technology with unique materials requirements. Operating temperatures, pressures, and gaseous environments of these processes have little precedent in previous reactor operations. A slagging gasifier* belongs to the type of high-temperature gasifiers that maintain a portion of the gasifier volume at temperatures above the melting point of the coal ash. This type of operation produces a high-efficiency conversion of the coal to a gas that contains no tars or other condensable hydrocarbon. Heating values of the gas produced can range between 100 and 300 Btu/scf, depending on coal type, steam addition, outlet gas temperature, and type of oxidizing medium used--whether oxygen, oxygen-enriched air, or possibly air alone. Slag granules are produced which are refractory and inert; therefore, disposal to landfill creates minimal environmental problems. The interaction of the slag and fuel stock, as well as method of feeding the gas flow through the unit, leads to greater heat and mass transfer rates, which produce an improved coal gasification system compared to other methods.

Temperatures in slagging gasifiers are in the 2500°-3300°F range, which limits the materials that can be used. In combination with high pressure (up to 1500 psi), water vapor, carbon monoxide, and hydrogen, this environment can cause severe corrosion of refractories. Silica in aluminum silicate refractories is chemically attacked by hydrogen and may be removed either by formation of volatile silicon monoxide, or hydrosilicic acid, which is leached out and redeposited in another area of the gasifier. The reaction of carbon monoxide with iron compounds in refractories can cause disruptive carbon deposition. Other potential refractory failure mechanisms in coal gasifier assemblies include:

*Research sponsored by DOE/FE AA 15 10 10 0, AR&TD Fossil Energy Materials Program, Work Breakdown Structure Element IITRI-4.9.

- a) slag corrosion
- b) abrasion and erosion due to high velocity particles in gas streams and
- c) thermomechanical failures (spalling) resulting in hot spots on the shell.

The conditions found in vessels used in coal gasification require the use of dense and insulating refractory shapes and castables. Low iron, high alumina refractories are the presently preferred materials for coal gasification plants. Low SiO_2 and low Fe_2O_3 refractories are necessary to resist steam and CO. Fused cast, fully dense refractories are used to avoid corrosion and erosion by slag running down the walls. However, considerable research is required to establish optimum refractory systems and design methods for slagging gasifiers.

This program was a first attempt at the required research. While there have been a number of programs to test refractories for slagging gasifiers (of which the work of Dr. C. R. Kennedy at Argonne National Laboratory is the most relevant), none have tested more than a few small specimens of each refractory or closely simulated gasifier conditions. On this program, approximately 38 cubic feet (over six hundred 9-in. straight equivalents) of refractory will be tested during each run in the environment of a typical slagging gasifier. By testing this large amount of refractory, material variations are averaged out, a closer approximation to liners for large gasifiers is achieved, and total refractory system performance can be studied.

The objectives of this program under Department of Energy Contract No. DE-AC05-78ET13410, "Design, Engineering and Evaluation of Refractory Liners for Slagging Gasifiers," were:

- a) To determine the rate of wear of refractory liner systems under conditions simulating actual conditions in slagging gasifiers and to develop models for life prediction.
- b) To develop design practices and specifications for refractory liners in large slagging gasifiers which can perform for at least two years with only routine annual maintenance.
- c) To prepare a liner design handbook which will communicate the results of this program to gasifier designers and users.

The program was composed of six tasks which were grouped into three parts. The first part included only Task A, Conceptual Liner Designs, which summarized the state-of-the-art of the design of refractory liners for slagging coal gasifiers. The second part included Task B, Design and Construction of Test System; Task C, Refractory Liner Tests; and Task D, Liner Design Evaluation. The test system constructed in Task B was to be used to test refractories under simulated slagging gasifier operating conditions and to evaluate the results in Tasks C and D. The third part included Task E, Liner Model Development, and Task F, Liner Design Handbook. Here, the results of the first part (Task A) were to be combined and modified with the results of the second part (Tasks B, C, and D) to prepare refractory liner design models and develop recommended design practices, which could then be incorporated into a handbook for gasifier designers and refractory suppliers.

The program organization chart is shown in Figure 1. IIT Research Institute had the overall direction and responsibility for the program. Davy McKee Corporation provided general consultants, and their personnel led Tasks A and F. The remainder of the tasks were led by IITRI Materials Technology Division personnel. The program team was composed of the Program Manager, who was responsible for efficient and timely performance of the program; the Operations Manager, who was responsible for day-to-day operations and for fulfilling the reporting requirements; and the Task Leaders, who were responsible for the individual tasks.

The efforts of the program team were overseen by the DOE Managers, the DOE Technical Monitor, the IITRI President, an internal IITRI Review, and an external Advisory Committee. The Review Committee met with the program team monthly to review progress of the program. The Advisory Committee met semiannually to be informed of the results of the program and to advise on the relevance of the program to their needs.

The tasks, for the most part, were sequential and continued uninterruptedly until completed. The exceptions were Task E, Liner Model Development, which started with a data compilation phase to determine the information available on blast furnace operation in order to plan the calibration run, and Task F, Liner Design Handbook, which was to use some of the material generated during Task A.

Figure 1. Program organization.

Each of the active tasks was divided into activities and events which were the data base for developing a project scheduling and control network. The network was monitored on a Gantt chart, and the program was updated as needed.

The contract for this program was awarded at the end of September 1978. Work was started on 1 October 1978, on Tasks A, B, and E. Task A, Conceptual Liner Designs, and Task B, Test System Design and Construction, were completed. Task C, Liner Tests, and Task D, Liner Design Evaluation, were to begin upon completion of Task B. Task E, Liner Model Development, is inactive after an initial data compilation and theoretical model development effort. It was to be activated as soon as data were available from Task D. Task F, Liner Design Handbook, was active along with Task A since the reports of both tasks were to use the same format. At this time, Tasks C, D, and F are not to be completed since funding of this project was phased out by DOE directive.

2. TASK A - CONCEPTUAL LINER DESIGNS

The objective of this task was to prepare conceptual designs for the liners of slagging commercial gasifiers using information available in the literature and from commercial experience with similar processes. These designs were used in the design of the test unit, Task B, and were to form the basis of the liner design handbook to be prepared in Task F.

Refractory materials used to line slagging coal gasifiers must resist gaseous atmospheric corrosion, solution by molten slag, and erosion by particulate material over the temperature range from 2300° to 3300°F (1260°-1815°C). A ternary diagram of the system C-O-H was used to classify oxidizing and reducing environments in gasifiers. The ratios of various gases and phase diagrams were used to classify coal slags.

Conceptual refractory liner designs which minimize spalling were illustrated for the slagging zone of an 18 ft (5.5 m) diameter gasifier for typical eastern and western coals. Variations were shown to adapt these designs to various reducing and oxidizing atmospheres. Cooling systems, injection ports, and a novel approach to slag removal were discussed and illustrated.

The final report on this task was published in the Second Quarterly Technical Progress Report (Report No. IITRI-D6160-2), and forms Appendix A of this report.

3. TASK B - DESIGN AND CONSTRUCTION OF REFRACTORY TEST SYSTEM

The objective of this task was to design and construct a system to test refractory liners for slagging gasifiers. This system simulates not only the atmosphere, pressure, temperature, and fresh, flowing slag, but also the actual refractory configuration including cooling elements of gasifier liners. The system is very versatile and can also be adapted to simulate MHD combustor conditions. Extensive instrumentation is used so that all relevant conditions can be recorded during the test.

3.1 TEST SYSTEM DESIGN

3.1.1 Characteristics and Calculations

(a) Parameters of Test System

Materials tests can be divided into two classes: derivative and simulative. If enough is known about the conditions under which materials are to be used so that the critical parameters can be identified, a derivative test is appropriate. For example, the strength of structural members of a bridge can be derived from the strength of a small, tensile test specimen. Because of past experience and mathematical modeling, it is not necessary to test full-size members. If the applied conditions are poorly defined and the critical parameters are unknown, a simulative test which follows the actual conditions as closely as possible must be used. Clearly, testing refractories as materials for slagging gasifiers falls into the latter class.

The test system is designed to simulate as closely as possible the conditions to which a refractory liner will be exposed in a commercial-size slagging gasifier. The important parameters are: temperature, pressure, gas composition, slag composition, temperature gradient, slag flow and velocity, size, liner configuration, and cooling system.

Temperature in slagging gasifiers range from 2400° to 3400°F and are set by the process conditions and liquidity of the coal slag. In general, a temperature is chosen at which the slag from the particular coal used will have a viscosity of 150 to 250 poises, or about that of honey at room temperature.

The temperature range of the test facility is 2400° to 3400°F, with a nominal design temperature of 3000°F in the test section.

Pressure in slagging gasifiers ranges from slightly negative to about 1000 psig. The pressure used is determined by the process. The test facility pressure is from atmospheric to 100 psig.

Gas composition in slagging gasifiers ranges from reducing to very reducing, depending upon the process. The test facility can produce the entire range of oxygen partial pressures found in gasifiers, as discussed in Section 3.2.

Slag composition is determined by the particular coal involved and can range from acid to basic. In a slagging gasifier, the slag composition is approximately constant since fresh, flowing slag is in contact with the refractory liner. This is a very important parameter to simulate since static slag can quickly become saturated with components from the refractory liner.

Temperature gradient along the refractory liner in a slagging gasifier is very low since the unit is so large. The gradient through the liner thickness depends upon the cooling system, but can be quite high. The test facility has a low longitudinal gradient and an adjustable thickness gradient.

The resistance of the refractory liner to flowing slag is the single most important factor in determining the life of a slagging gasifier. However, there is no universally accepted test for the resistance of refractories to attack by slags.

The simplest method of slag testing is the "crucible test" in which a hole is drilled part way through a rectangular block of refractory to form a crucible. Powdered slag is placed into the hole, and the block is heated to a specified temperature for a given time. After cooling, the block is sliced vertically through the slag hole and the extent of slag attack is determined. The determination is usually visual, sometimes with a microscope, but X-rays and other analytical equipment are also used. The test has the following disadvantages:

- 1) There is a very small quantity of slag and a very large quantity of refractory, so attack by solution of a component of the refractory into the slag is quickly stopped when the slag becomes saturated with the component.
- 2) There is a temperature gradient through the block, or under the best of circumstances, the block is at uniform temperature throughout. Thus, the slag as it attacks the refractory does not move into a colder region as it would in an actual liner but may move into a hotter region which will accelerate the attack.
- 3) The slag is static so the effect of slag flow is not simulated.
- 4) The atmosphere and pressure are usually not simulated.

The "finger dip" test uses long columnar specimens which are dipped into a crucible containing molten slag at a specified temperature for a given time. The specimens may be moved through the slag to simulate the effect of slag flow. The slag resistance is usually assessed by volume loss, which is determined optically. This test has the disadvantages that:

- 1) The entire specimen is not covered with slag so that the principal attack is at the slag/atmosphere interface.
- 2) The specimen is small and at a constant temperature so that the effect of a temperature gradient is not taken into consideration.
- 3) The atmosphere and pressure are usually not simulated.

The most realistic method of slag testing uses a rotary furnace which allows both slag flow and thermal gradient to be simulated. The test refractories form the liner of an inclined cylindrical vessel which is rotated while being heated along the axis. Molten slag is introduced into one end of the cylinder and allowed to flow through. After a certain length of time, the slag flow is stopped and the slag attack is evaluated by the reduction in thickness of the segments from the vessel lining. This test has the disadvantages that:

- 1) The radius of curvature of the liner segments is very small so that the keying effect is large, unlike an actual gasifier.

- 2) The atmosphere and pressure are usually not simulated.
- 3) There is a longitudinal temperature gradient along the cylinder.

The tests discussed previously require little initial investment to set up and are inexpensive to run; however, they are not inexpensive in terms of the results since relevance of the data to actual use conditions is doubtful. An expensive method of refractory testing is to line a pilot plant gasifier with them. This would seem to be the best method of testing refractories short of exposing them in an actual commercial-size coal gasifier. However, even this method has its drawbacks. First, the radius of curvature is small, on the order of only a few feet for most pilot plants, and the keying effect is large so that refractories may last longer in the pilot plant than in a commercial plant. Second, and more important, the pilot plant is not operated by ceramic engineers who are interested in refractories. Thus, the data relevant to refractory testing are usually not collected, and even specimens of the liner may not be obtained during the rush to turn around the plant after the test.

The IITRI test facility has been set up to obviate the disadvantages of the test methods discussed above since it has been designed specifically for refractory liner testing. All conditions in slagging gasifiers are simulated, and it can be adapted to simulate conditions in dry ash gasifiers and MHD combustors.

A large volume of refractory is tested at one time (38 ft³ of monolithic refractory or over six hundred 9-in. straight equivalents of brick), and so the effect of material variation, mortar joint (in brick liners) cracks, and other materials variations can be determined. The test facility is compared with other test methods in Table 1.

(b) Liner Life Prediction

The test facility is operated by ceramic engineers who evaluate the data obtained. Their sole interest is in refractories testing, and the output of the tests is data required to design a reliable, long-lived liner. These data include:

- 1) Refractory selection
- 2) Refractory liner wear rates

TABLE 1. COMPARISON OF SLAG RESISTANCE TEST METHODS

Factor	Commercial Coal Gasifier	Pilot Plant Gasifier	IITRI Test Facility	Rotary Slag Test	Finger Dip Test	Crucible Test ^a
Coal Gasification Atmosphere Simulated	Yes	Yes	Yes	Rarely	Rarely	Rarely
Pressure Controlled	Yes	Yes	Yes	No	Rarely	Rarely
Quantity of Refractory Tested	Large	Large	Large	Moderate	Small	Small
Liner Curvature	Large	Moderate	Large	Small	Small	Small
Temperature Gradient Through Refractory	Negative	Negative	Negative	Negative	None	None or Positive
Slag/Refractory Ratio	High	High	High	High	Moderate	Low
Moving Slag	Yes	Yes	Yes	Yes	Yes	Rarely
Life Prediction	Excellent	Poor	Good	Poor	Poor	Poor
Dollar Cost per Test	Extravagant	Excessive	Moderate	Low	Low	Cheap
Cost of Useful Data	Very high	High	Low	High	High	High

^aThe slag drip test and gradient slag test are essentially variations of the crucible test.

- 3) Refractory liner life prediction
- 4) Information on liner radius and thickness effects
- 5) Heat flux through the liner
- 6) Heat flux to cooling elements
- 7) Liner construction and installation practice
- 8) Design and construction of cooling elements
- 9) Design and construction of slag and injection ports
- 10) Design and installation of gas sampling probes, temperature probes, and other instrumentation for slagging conditions.

Since the test facility is a model of a commercial gasifier, mathematical models have been developed for refractory liner wear rates, liner life prediction, and heat flux through the liner including heat flow to cooling elements. These models have been programmed on a computer, and are available for use by design engineers of commercial gasifiers.

The refractory liner data obtained in refractory tests will provide comparative data initially. The data will be used as the basis for a mathematical model to predict liner service life in a commercial gasifier. A major problem with prediction is that the operating parameters for a commercial unit are, as yet, unknown. Parameters such as gas flow rates, slag deposition rates, operating temperatures, and steady-state gas composition have not been established. Furthermore, the coal composition, including ash content and A/B ratio of the coal ash, has not been defined. All of these variables will influence refractory behavior in commercial units. This will complicate the ability to predict the performance of refractories in the commercial unit based on data from any test facility.

Fortunately, the prediction can be refined by studying the blast furnace, which is a good model for a commercial slagging coal gasifier. Extensive information in the form of operating histories and a mathematical life expectancy model (Figure 2) is available on the expected service life of iron blast furnace linings using several systems of cooling and different qualities of refractories.

In order to use this information to predict the probable service life of various refractories and cooling systems for slagging gasifiers, a calibration run was to be the first run. For this calibration run, we were to duplicate

Figure 2. General refractory liner life curve.

the refractories and cooling system used in a substantial number of blast furnaces (about 60) whose service life is known. At the same time, the temperatures, slag chemistry, and reducing conditions of the blast furnace were to be duplicated. The results of this test, and comparison with refractory lining data under gasifier operating conditions, would yield the necessary data to refine the predictions of refractory service life in commercial slagging coal gasifiers. These data would produce a scale factor for the test facility which would allow life data from the facility to be scaled to commercial-size gasifiers. This approach was discussed in detail in Section 6 and Appendix B of the First Annual Technical Progress Report (IITRI-M06043-4).

In order to simulate a section of the liner from a commercial gasifier in a test section 4-1/2 ft high with a 4 ft OD, it is necessary to heat the section with hot gas from a separate combustor so the temperature difference between the top and bottom is small, less than 100°F, and there is no direct flame impingement. Gas flow is primarily laminar, and the gas velocity is less than 10 fps.

The test section hot face has a 16 x 36 in. elliptical cross section. The refractories parallel to the major axis have a large radius of curvature which simulates an 18 ft diameter circular liner of a commercial gasifier (Figure 3). The refractories parallel to the minor axis have a very small radius of curvature such as might be found at injection ports of a commercial gasifier.

The test section refractories are cooled by a cylindrical stave cooler, and the refractory liner thickness varies between 3-1/2 and 13-1/2 in. so that the heat fluxes and temperature gradient through the liner vary (Figure 4). There are eight water circuits so that the heat fluxes may be measured.

The different wall thicknesses of the liner simulate conditions of gasifiers with thick and thin liners or the conditions of a thick liner gasifier at the beginning and end of a campaign.

A general refractory liner life curve is shown in Figure 2. If the liner in the test section were of constant thickness (say, 13-1/2 in.) and if the wear during the 1000 hr test run were small (say, 2 in.), then only a small region of the curve (which appears as a thick line on the figure) would be defined. Since a great many curves could pass through this region, the liner

Figure 3. Comparison of radius of test section with radius of refractory liner in full-size commercial gasifier.

Zone A1 and B1 for investigating lining thickness in the $3\frac{1}{2}$ -6 in. thickness range. (Measure total heat flux through circuits (1).)

Zone A2 and B2 for investigating lining thickness in the 6-12 in. thickness range. (Measure total heat flux through circuits (2).)

Zone A3 and B3 for investigating lining thickness in the 12-13 $\frac{1}{2}$ in. range. (Measure total heat flux through circuits (3).)

(No data to be collected in transition zones 4.)

Figure 4. Test region cross section and cooling circuits.

wear rate is poorly defined. The variation in liner thickness in the test section from 13-1/2 in. to 3-1/2 in. allows the liner wear curve to be more exactly defined and a more confident prediction to be made of liner life.

For the initial test, the refractories will be cooled by circular stove coolers with eight water circuits to allow measurement of heat flow through different wall thicknesses. For later tests, plate coolers may be used. The test section will normally be bricked with two types of refractory for simultaneous testing.

(c) Computer Simulation

A computer model simulation was developed to determine the effect of various cooling loads on the isothermic profile of the refractory materials within the test vessel. The model employed a matrix displacement method of solution based on a finite element idealization of the refractory/cooling system being simulated. The refractory/cooling system was simulated using an axisymmetric model of revolution, illustrated in Figure 5.

The model was developed around the two major heat transfer mechanisms determined by first-order hand calculations using the classical heat transfer equations for planes of revolution. The heat transfer mechanisms were radiation heat transfer from the combustion gases to the slag layer surface, and conduction heat transfer from the slag/refractory interface to the cooling elements. The radiation links are shown in Figure 5 as a set of arrows emanating from the axis of symmetry and terminating at the slag layer. The conduction elements are shown as an array of rectangles and triangles assembled as a geometric representation of the refractory/cooling system.

The model was developed into three zones: burner, transition, and test sections. The zones define changes in material and/or cooling element type. The burner section elements were defined using the temperature-dependent physical properties of thermal conductivity, density, and specific heat for each material: graphite, castable, and 90% alumina refractories. The transition section elements were defined by the physical properties for 84% alumina refractory, and the test section elements were defined for super-duty firebrick refractory.

Figure 5. Computer heat flow model.

The results of one model solution is shown in Figure 6, which is an enlargement of the interface of the transition and test zones. The figure shows the temperature gradient surrounding the three uppermost copper coolers and the bottom of the test zone. The surface temperature of the copper coolers was maintained at 100°F, and each isotherm represents an increase of approximately 200°F. The isotherms are represented by adjoining line segments instead of smooth curves because of the point interpolation scheme used by the computer plotter processing routine.

The model is flexible enough to handle changes in materials and cooling rates, and can be easily expanded as the need for a more complex or more complete simulation arises.

3.1.2 Process Description

The heat and gas composition needed in the test section are provided by a 10 million Btu/hr natural gas/O₂ burner and two auxiliary lances in the combustion chamber (see Figure 7). The burner is angled downwards such that flame impinges on the molten slag layer at the bottom of the vessel in front of the slag tap, minimizing the chances of plugging at the slag tap hole. The burner will fire at between 55% and 80% FSA* with a flame temperature greater than 4500°F, providing enough heat to keep the slag molten in the test section. The two water-cooled lances, one with a capacity of 0-200 scfm natural gas and one 0-800 scfm air, are positioned above the burner and 120° away from it. These lances will be used as needed to modify the gas composition to obtain the appropriate conditions in the test section (see Section 3.2.1).

As the hot gases rise from the channel-cooled combustion chamber, they pass through the copper plate cooled transition section. This section channels the gases from the 30 in. diameter circular combustion chamber into the 16 x 36 in. elliptical test section.

The hot gases continue to flow through the stove-cooled test section and into the elliptical incinerator. At the bottom of the incinerator, excess air is injected to burn off all combustibles. It is expected that, under certain

*FSA = Full Stoichiometric Air. 100% FSA indicates complete combustion.

Figure 6. Computer model of transition section.

Figure 7. Refractory test unit.

operating conditions, the temperature of the gas after this combustion could be as high as 3500°F.

The completely combusted gas then passes out of the refractory test vessel through water-cooled piping, and into a pressurized flooded venturi scrubber. Pressure is then dropped across two parallel 3 in. pressure control valves, and the gas passes up a stack to the atmosphere.

Slag is injected at the top of the incinerator in the form of a slag/water slurry.* The heat from combustion in the incinerator melts the slag as it is sprayed on the walls. The molten slag then runs down the walls of the vessel to the inclined floor of the combustion chamber. Here, the main burner keeps the slag and any spalled refractory hot enough to flow out of the slag tap hole towards the slag tap vessel. A 400,000 Btu/hr natural gas/O₂ torch is used to track the slag tap notch and keep the slag flowing. In the slag tap vessel, the molten slag pours into a large mass of cold (<100°F) water and is granulated by thermal shock. A slag and water mixture is continuously drawn out of the slag tap vessel under system pressure and sent to a cyclone for dewatering and slag disposal into a hopper. Any large pieces of slag or refractory are manually removed from the slag tap vessel during scheduled shutdowns.

3.1.3 Ancillary Equipment

In order to retain flexibility with the test unit, the subsystems are designed, as much as possible, as independent units. This also provides the following advantages:

- 1) The subsystems can be under running conditions before the test unit is heated and pressurized.
- 2) Additional nozzles or feeds can be provided from each system in case modifications are required.
- 3) Minor problems with ancillary equipment will be less likely to cause a shutdown of the unit.

An assortment of ancillary equipment is needed to run the test unit (see Figure 8 and Table 2). Since the operating pressure of the unit is 100 psig, a pressurized supply of natural gas, oxygen, air, water, and nitrogen is

*The slag/water slurry is 12% slag by weight.

Figure 8. Block diagram of refractory liner test system.

TABLE 2. SUMMARY OF MAJOR EQUIPMENT FOR REFRACTORY LINER TEST SYSTEM

Item	Size, ft	Number of Units	Rated Pressure, psi	Remarks/Flow/Capacity
Test Vessel	5 ID x 30 long	1	300	48 in. high test section
Slag Tap Vessel	6 ID x 16 long	1	155	Water filled
Slag Storage Vessel	8 ID x 36 long	1	155	75 tons slag
Slag Feed System	4 dia x 7 long	1	150	150 lb/hr slag feed as slurry
Slag Removal	---	1	150	Pressure letdown + dewatering
Scrubber	1 dia x 7 long	1	150	Fixed flooded venturi
Demister	3 dia x 12 long	1	150	Air Pol design
Main Burner	10 in. dia x 4 long	1	150	10×10^6 Btu/hr oxygen/gas
Oxygen Tank	8 dia x 38 long	1	240	9600 gal liquid O ₂
Ambient Vaporizers	2 x 2 x 10 long	12	300	300 scfm
Electric Vaporizer	75 amp/440 V	1	300	200 scfm
O ₂ Pipeline	1-1/2 in. dia	1	250	Totally enclosed copper
Nitrogen System	10 dia x 400 ft	1	200	9000 gal liquid N ₂
Gas Supply	4 in. dia x 30 long	1	15/1.5	Special line installed
Gas Compressor	9 x 3 x 4	1	125	300 scfm; 125 hp
Gas Filter	10 in. dia x 4 long	1	150	Replaceable element
Air Receiver	4 dia x 12 long	1	135	
Air Compressors	I.R. 2 stage recip.	2	125	250 hp total; after-cooled
Water Storage Tank	7 dia x 18 long	1	---	5500 gal
Cooling Tower	9 x 18 x 9	1	---	400 ton
Water Pump	500 gpm centrifugal	5	125	2500 gpm at 300 hp total
Water Pump	100 gpm centrifugal	1	150	100 gpm at 25 hp
Water Pump	3 stage centrifugal	1	150	25 gpm at 8 hp
Gas Engine-Generator	10 x 3 x 7	1	---	220 hp for 175 kW O/P
Main Power Supply	1200 amp/480 Volt	1	---	~750 kW
Gantry Crane	40 x 12	1	---	13 tons

needed as well as a back-up power supply and equipment to inject the slag/water slurry. Following is a brief description of the ancillary equipment.

- 1) Gas Compressor. A specially installed 4 in. gas main and a 100 hp gas compressor supply 300 scfm of natural gas at 125 psig to a 2 in. gas line, which feeds the main burner, the natural gas lance, and the slag tap torch.
- 2) Oxygen System. A 9300 gal liquid oxygen tank with 12 ambient vaporizers (300 scfm) and one electric vaporizer (200 scfm) supply oxygen at 125 psig to the main burner and the slag tap torch through a 1.5 in. diameter line.
- 3) Air Compressors. Two 125 hp air compressors supply approximately 1000 scfm of air at 125 psig. A 4 in. air line feeds from the air lance. An electrical terminal box has been provided for a third 125 hp compressor, should this need to be rented for a particular low Btu run requiring additional air.
- 4) Slag Injection System. Consisting of a vibratory feeder, a conveyor, slurry tank with agitator, and a six-stage slurry pump, this system meters, mixes, and pumps a slag/water slurry into the refractory test unit at the top of the incinerator. The system feeds 150 lb/hr of slag with 120 gal/hr of water.
- 5) Water Pumps. Water is divided into two categories:
 - (a) Low pressure recirculated water is supplied at 95 psig to the refractory cooling circuits and is returned to a storage tank through a cooling tower (when necessary). This water is supplied by five 60 hp pumps, each of which outputs 500 gpm at 125 psig. Two of these pumps are powered by a generator, and three are powered by normal city power, one being an emergency pump.
 - (b) High pressure consumed water is injected into the scrubber venturi and the slag tap vessel. This water is supplied by one 25 hp power and one 8 hp pump. The former outputs 100 gpm, and the latter outputs 25 gpm, both at 150 psig. The 25 hp pump is powered by city power, and the 8 hp pump is powered by the generator.
- 6) Generator. A 175 kW natural gas fired generator is run continuously to provide power for the two 60 hp and one 8 hp pumps. This system ensures adequate water to the test unit in the event of a city power failure. The generator is also sized to power all control circuits in addition to the pumps.

- 7) Nitrogen System. A suitable liquid nitrogen system is leased to supply N_2 to the burner system for purging on start-up and shutdown, to the slag tap vessel for purging the gas space above the water, and to the refractory test vessel for maintaining a nitrogen jacket between the refractories and the pressure vessel wall.

3.2 OPERATING CONDITIONS

3.2.1 Gas Composition

From the start of the project there has been animated discussion on what gas composition should be used to most closely simulate slagging gasifier conditions. It is not really possible to measure the actual gas composition in the slagging zone of slagging gasifiers; consequently, the discussions were always based on back-calculations from off-gas conditions or on experience with the oxidation or reduction of different types of slag. A visual representation of oxidizing/reducing conditions for most slagging gasification processes is presented in Figure 9. Additional points have been plotted by Dr. Christopher Kennedy of Argonne National Laboratory. For purposes of discussion, the simulated gas atmospheres produced by various amounts of various CH_4/O_2 ratios have been plotted on the same diagram. The points for varying amounts of methane, air, and oxygen (as originally proposed) are also shown in Figure 9. From this, it will be seen that the proposed gas atmosphere was too oxidizing and too rich in hydrogen, compared with most gasifier atmospheres. However, there were two further points brought out in the discussions:

- 1) In two-stage gasifiers, the slagging usually takes place in the combustion chamber, which is operated close to stoichiometric conditions and is, therefore, more oxidizing than in other sections of the gasifier.
- 2) The principal reason for these refractory tests is to investigate the reaction between the slag and the refractories, rather than the gas and refractories. It is recognized that the gas composition affects the slag composition, and that the gas will penetrate the refractories. However, it is possible to obtain the correct slag composition for various gas compositions, as long as the partial pressure of oxygen is kept within the correct range.

KEY:

- - Points plotted for various gasification processes by Dr. Melvin Greaves, Arthur G. McKee Company, in quarterly report (IITRI-D6160-2). Additional points submitted by Dr. Christopher Kennedy, Argonne National Laboratory.

○ - DOE standard atmosphere.

▼ - Bigas (upper stage with supplemental CH_4 firing).

◻ - Texaco coal gasification (exit gas).

▼ - Argonne National Laboratory experiments.

■ - Combustion Engineering (in slagging zone - from input)

▲ - IITRI-proposed atmosphere with input gas ratio of:

Dotted line indicates change in atmosphere with addition of excess methane.

Figure 9. Oxidizing, reducing, and transition zones for coal gasification processes.

The decision reached on the gas composition, and confirmed by letter from DOE to IITRI, was as follows:

That although it would be preferable to decrease the H/C ratio of the proposed composition by using a fuel other than the proposed methane, the additional costs and difficulties incurred are not warranted, provided that the ferritic content of the slag lies between 5% and 35%. While precise correlation of atmosphere and ferritic content is not possible, it would appear--based on data from pilot plants and Argonne National Laboratory experiments--that 40-80% FSA (fraction of stoichiometric air) will produce the desired ferritic content.

It is advisable that a small amount of carbon (coke) be added to the slag before injection (about 1%).

The predicted approximate low-Btu gas composition used for design purposes was:*

51% N₂, 26% H₂O, 6.0% H₂, 7.3% CO, 8.9% CO₂,
0.8% miscellaneous (O₂, H₂S, SO₂, etc.)

Calculations show that this composition will be obtained in the test section at 2800°F if fuel is passed through the burner in the ratio of:

This fuel ratio represents 80% FSA and, by addition of methane, may be adjusted as required to obtain the desired ferritic content in the slag.

For high-Btu runs, the approximate gas composition used for design purposes was:

35% H₂O, 33% H₂, 23% CO, 8.6% CO₂,
0.4 % miscellaneous (O₂, H₂S, SO₂, etc.)

Calculations show that this composition will be obtained in the test section at 2800°F if fuel is passed through the burner in the ratio of:

This fuel ratio represents 55% FSA.

*Percentages given are mole percents.

3.2.2 Test Unit Flexibility

It should be noted that the arrangement of the burner and lance system gives the test unit great flexibility. The natural gas lance can, for instance, be replaced by a lance to inject fuel oil, coal, or carbon black in order to increase the C/H ratio of the gas composition. Different fuels have been investigated as to their effectiveness in changing this ratio and the associated costs. While it was decided to use natural gas, the flexibility existed to add higher C/H fuels without drastic modifications to the test unit.

3.3 SITE PREPARATION

Major building modifications and foundation work were necessary for installation of the refractory test system, and many difficulties were encountered during the work. Space for the project was limited, existing facilities had to be used, and as IITRI is located on a nonindustrial site, within the City of Chicago, much persuasive discussion was required in order for the work to be carried out successfully.

Figure 10 shows a plan view of the complete system and, with reference to this drawing, the following building work was required before all the equipment could be installed:

- Excavation of 6 ft deep pit for the refractory test unit, and concrete foundation poured
- A 10 ft square hole cut in the south wall of the building for vessel access, and balcony floor removed
- Placement of concrete pads for the oxygen system, water tank, pumps, compressors, slag storage tank gas compressor, and tap house (enclosing burner piperack)
- Construction of control room on extended balcony
- Construction and insulation of tap house
- Construction of steel frame to carry water-cooling tower above the water pump location
- Numerous modifications of room to allow piping to enter or exit
- Construction of steel shielding around test unit
- Upgrading crane runways and installing a new 13 ton x 40 ft gantry crane above the test unit.

Figure 10. Refractory test unit system layout.

In addition to these major items, a myriad of smaller changes were made: fans and lights were installed, existing conduits and piping rerouted, and other equipment relocated.

3.4 DETAILED DESIGN

3.4.1 Pressure Vessels

Although a total of 9 pressure vessels are incorporated into the refractory test system, 6 of these are of conventional design and require no further description. The other 3 vessels are: refractory test vessel, slag tap vessel, and slag storage vessel.

(a) Refractory Test Vessel

When the original concept evolved into a final design, it appeared that a vessel of 5 ft ID and about 30 ft high would be required for the test unit. An almost completed carbon steel vessel from a cancelled contract was purchased from Superior Welding Company in Decatur, and this was extensively modified to the project requirements by the addition of over 50 nozzles, two sets of body flanges, and a shorter skirt.

This not only gave a time and cost advantage to the project, but also resulted in a vessel rated at 300 psi, even though the operating pressure is 100 psi. The vessel shell had originally been designed for 625 psi, but was derated to 300 psi when the body flanges were added. These points are of great importance when it comes to operation of the unit:

- a) The vessel wall is thick enough to allow cold wall design without risk of failure through corrosion.
- b) Should any explosions occur within the vessel, the walls can withstand instantaneous pressure excursions without exceeding code stress levels.

Another important factor in the design of the vessel was the ASME classification. The vessel does not come under Section I (Power Boilers), or Section IV (Heating Boilers) of the ASME code, and could thus fall into the Section VIII (Pressure Vessel) category, which broadly embraces vessels not classified under other sections. However, it is a fired pressure vessel (not unfired), and thus becomes a special case. The case which comes closest to this would be a gasifier vessel, for which a special report on design criteria

has been issued.* This report, called "Basic Requirements for the Design and Construction of Gasifier Vessels," was produced for the DOE/GRI as a guide to the design of this type of vessel. The report is geared towards large-scale gasifier vessels, and addresses the problems which make gasifier vessels a special case. The general recommendation is that Section VIII, Division 2 rules should be used in the design and construction of large gasifier vessels, together with supplementary requirements laid out in the report.

It was decided that the guidelines from this report should be adopted for this refractory test vessel, but only insofar as they apply to this laboratory situation.

One major deviation was that Division 1 rules were used instead of Division 2. With large vessels, it is almost essential to use the 'design and analysis' Division 2 rules, rather than the more empirical (and conservative) Division 1 rules, in order to minimize material and fabrication costs, and to ensure that adequate stress analysis has been performed on complicated configurations. Instead of specifying allowable stress levels, to ensure an adequate margin of safety even at points of unknown stress, higher stress intensities are allowed with Division 2 rules, but the points of unknown stress must be analyzed more thoroughly to prove that an adequate margin of safety exists. This requires more engineering design time, but generally will allow thinner sections to be used on the vessel, saving material. While this can be justified with large vessels or with production runs of smaller vessels, it cannot be justified with a relatively small but complicated experimental vessel such as this test vessel. In fact, for experimental purposes, it is better to have an overdesigned vessel so as to avoid as many vessel problems as possible, and to allow future modifications without great additional expense. It was clear that for this vessel, where speed in design and fabrication coupled with a guarantee of safety under all kinds of possible experimental conditions was essential, the best approach would be to design to Division 1 rules, but using a design pressure far in excess of the required operating

*F. W. Clemence (C. F. Braun & Co.) "Basic Requirements for the Design and Construction of Gasifier Vessels," Final Report FE-2240-46 on Contract No. EX-76-C-01-2240 prepared for the United States Department of Energy and the Gas Research Institute, April 1978.

pressure to cover any unforeseen circumstances. Compliance with the DOE report would then also be made easier, as stress levels in the vessel would be low.

Since the vessel is installed within a building, wind calculations were not required, and seismic calculations were not considered necessary. The vessel operates on the 'cold wall' principle so that thermal stresses are insignificant and the thermal cycles during the life of the vessel will not cause any degradation. Pressure cycling and even possible external loadings on the vessel will not cause problems as the pressure rating is triple the actual operating pressure. Even for this rating, the shell has excessive thickness which is available as additional corrosion allowance.

Shell design temperature is 650°F as required by the report; the vessel is registered with the National Board of Inspectors, and has been nameplated in accordance with ASME rules.

Generally, the philosophy was to comply with the report where it was felt necessary for safety, and also where the vessel cost was not substantially increased. For instance, it was decided that the additional great expense of full double radiography on all welds rather than spot X-ray checks called for by Division 1 rules could not be justified, as the shell stresses would be so low in any case.

(b) Slag Tap Vessel

The slag tap vessel, which connects with the test vessel at a specially shaped nozzle, is mounted on four legs, and hangs below floor level in a concrete pit. Slag flows continuously through this nozzle into the water-filled slag tap vessel, which, therefore, had to be mounted lower than the test vessel. The pit was required in order to maintain headroom for crane operations without major building modifications.

This vessel was mounted on legs with a ring support at the same height as the tangent line on the test vessel. There are three major reasons why this was done:

- a) To minimize vertical differential expansion between the two vessels,
- b) To minimize the pit floor thickness by using the massive walls to support the vessel, and

- c) To allow the vessel lateral freedom of movement relative to the rigidly mounted test vessel, by using Teflon sheets between the legs and support lugs.

From an operational point of view, it was an advantage to keep the slag tap vessel below the balcony since balcony floor space will be critical as a work area.

This vessel is primarily a hot water storage vessel, and no special design requirements apply. It was designed to ASME Section VIII, Division 1 for 155 psig at 500°F maximum. Again, an almost completed vessel was used as raw material, and although extensive modifications were required to convert it to the project specifications, a significant cost saving was made.

(c) Slag Storage Vessel

Early in the design work it was decided that a tank should be installed to hold enough slag for a full 1,000-hr run (75 tons). At that time, no details on feeding had been considered, and it was felt that it could be an advantage to have a system where the entire slag storage tank was pressurized to the test vessel operating pressure of 100 psig. Quotations were obtained, and it was found that another almost completed pressure vessel of suitable size was available at a cost no greater than that of a new atmospheric pressure tank. As this gave greater flexibility to the system, this 8 ft dia x 40 ft high vessel was purchased, and modified to the project specifications, including a platform mounted on top for access from the Materials Technology Building roof. Suitable nozzles were fitted to allow installation of mechanical agitators and aerator systems along with a feeder system at the bottom. The pressure rating on the vessel is 155 psig, which meant that a pressure differential of 50 psig could be produced for slag feeding, if necessary.

3.4.2 Refractory Test Unit

(a) Vessel Cooling

The type of refractory lining under investigation in this project is characterized as a cold wall design. Cooling water on the outside of the lining causes a layer of frozen slag to form on the inside hot face. This "viscous-solid" layer helps to protect the refractory from interaction with the gasifier environment. This type of design is generally preferred over a hot wall design which employs a thicker lining. Although the cold wall

requires greater cooling and allows more heat loss, its advantages for refractory lining design are threefold:

- a) Formation of a protective frozen slag layer retards corrosion and erosion of the refractory.
- b) Lower average operating temperature of the refractory increases liner life.
- c) Thinner wall thickness requires lower capital cost for refractory and associated components.

Several different cooling methods are used in the refractory test vessel. Figure 11 illustrates the locations in the test vessel of each type of cooling method. The following is a brief description of the major cooling elements:

- a) Channel Cooler located around the combustion section of the lining. It consists of two concentric cylindrical steel shells with the internal spacer bars arranged to form cooling water passages.
- b) Copper Plates inserted into the transition section of the lining. These are cast copper plates with internal cooling water passages. They are placed horizontally in the lining interspersed with the bricks and extend from the hot face to the cold face of the lining.
- c) Stave Coolers around the test section of the lining. Steel plates are rolled to fit the outside of the lining, and vertical holes for cooling water are gun-drilled through the plates. The plates are held firmly against the bricks by spring-loaded cables wrapped around them.
- d) Incinerator and Hood located above the refractory bricks. These components are studded membrane walls with rammed refractory linings.

These cooling methods are based on blast furnace and boiler practice. Channel cooling was chosen for the combustion section because this design is most easily adaptable to large and varied openings in the lining. The main burner, two lances, and the slag tap notch penetrate the lining in this section. Uniform cooling of the transition section is complicated by its constantly changing thickness in both the axial and circumferential direction. Copper plates are used here because they can be designed in several different patterns to fit the lining thickness. Stave coolers are well suited to the test section with its elliptical inside contour. They provide uniform cooling over the cold face of the lining. The separate circuits provide a means for determining the distribution of heat transfer through the different

Figure 11. Refractory test unit elevation.

brick thicknesses. Access to the test section for inspection and replacement involves removal of the top section of the test vessel, and the internal components above the test section. This consists primarily of the incinerator, hood, jacketed gas pipes, and associated cooling water interconnections. The incinerator and hood, being of membrane wall construction, are much lighter and easier to move than a comparable stack of bricks.

The bricks in the combustion section are cooled by a channel cooler. Water is introduced at the bottom of the hollow cylindrical cooler and flows upward through four separate serpentine channels. The cooler consists of a 5/8 in. thick steel plate formed into a cylinder with holes cut for the burner, lances, and slag tap. Steel strips (3/8 x 3/4 in.) are welded to the outside of this shell to form the channel boundaries. Cover plates are welded to the strips through matching slots cut in the plates. All joints are seal welded to prevent bypass leakage, which could lead to localized hot spots. The channel pattern is designed to completely cover the outside surface of the bricks. Routing around penetrations carefully avoids pockets of stagnation. The average velocity of the cooling water is 10 fps.

Components which must penetrate the combustion section in order to admit gases or withdraw slag have additional cooling. The main burner has a water-cooling jacket as an integral part of its barrel. The hole in the bricks through which the burner is inserted consists of a coiled copper tube (1 in. OD) embedded in rammed refractory. Each lance also has integral cooling in its barrel and is mounted in a cast copper monkey. The monkeys were designed for blast furnace use and have been adapted to fit this system. Water circulates through its hollow interior to provide cooling for the lance and surrounding bricks. Molten slag runs out of the combustion section through a cast copper double-nose tuyere which is lined with refractory. This piece was also designed for blast furnace service. Its hollow walls consist of two separate chambers. One passageway brings cooling water directly to the nose of the tuyere where it is needed most. The other circuit cools the rest of the body of the tuyere.

The floor of the combustion section averages about 13 in. thick and is sloped toward the slag tap tuyere. Below this brick floor is an 18 in. thick block of graphite surrounded by the bottom of the channel cooler. Thermal protection for the bottom head of the vessel is provided by filling it with a

castable refractory. A coil of copper tubing is embedded in this refractory to provide additional cooling, if needed. Since the thermal conductivity of the graphite is much higher than that of the bricks and the castable, nearly all of the heat escaping through the bottom of the combustion section will be drawn into and removed by the channel cooler rather than heating up the bottom head of the vessel.

Cast copper plate coolers are used to cool the bricks in the transition section of the vessel. This section consists of 16 layers of 3 in. bricks. Four coolers are placed in every other layer so as to replace approximately half of the bricks in that layer. The outside diameter of the transition section is 48 in. The inside dimensions change continuously from a 30 in. diameter circle at the bottom to a 16 x 36 in. ellipse at the top. To precisely account for the changing geometry would require coolers of many different shapes. This requirement has been approximated by using three different patterns.

The internal baffles are arranged so that the flow of cooling water is directed along the nose of the cooler first and then back toward the outlet. The velocity at the nose is greater than 10 fps. Since these coolers are exposed directly to the slag, it is important that they have a high thermal conductivity in order to cool the slag sufficiently to maintain a frozen protective layer on the nose of the cooler. The chemical composition of the material used in the cooler casting was carefully controlled to obtain a minimum of 99.5% copper. All finished castings were subjected to a hydrostatic test at 1.5 times operating pressure. In addition, they were heated and subjected to mechanical shock while under pressure. All leaks were repaired by welding.

The 32 plate coolers are interconnected into four parallel circuits. For each circuit, cooling water is introduced at the bottom of the transition section and flows in an upward spiral through eight coolers connected in series. After flowing through the last cooler at the top of the circuit, the water is piped back down near its inlet so that both penetrations can be made through the same section of the pressure vessel. Any gas that might collect at the top of a circuit can be drawn off through a small copper tube located inside each return line. The coolers are connected in spiral-shaped circuits to minimize the effect of losing any one circuit. Incapacitated coolers from one circuit would be distributed evenly through the transition section so that

their load could be effectively absorbed by the remaining coolers without creating a localized hot region which could lead to refractory failure.

The hoses which connect the plate coolers (as well as all other hose connections inside the test vessel) have been carefully selected, tested, and installed to meet severe requirements. The cut ends were sealed before the fittings were installed to prevent gas from seeping in between the inner tube and the reinforcement, which would cause the former to collapse. Protection against hot gases which might leak through the refractory lining is afforded by wrapping each hose with asbestos and covering with a heat reflective tape. Refer to Section 3.4.2.(b) for more details on these hoses.

As a final protection for both the hoses and the vessel shell, the entire annular space between the vessel and the internals, from the bottom of the channel cooler to the top of the transition section, is filled with bubble alumina. This acts as both an insulator and as a block for small gas leaks.

The stave coolers are a set of eight identical panels which fit around the outside of the cylindrical test section of bricks. Each panel is a 1-1/2 in. thick steel plate rolled to the proper curvature. Axial holes, 1/2 in. diameter on 1 in. centers, are gun-drilled through the length of the plate to provide vertical cooling water passages. Manifolds, constructed from 3/8 in. plate, are provided at either end of the cooler. Water is admitted at the bottom and drawn off at the top with a separate line for each cooler. This allows individual instrumentation for each cooler so that a radial distribution of the heat flux may be determined. Designing the size and spacing of the vertical holes involved a compromise between large surface area for high heat transfer, and small volume for minimum water usage while maintaining a reasonable velocity. In an effort to maximize the surface area to volume ratio, a 5/16 in. diameter rod was inserted into each hole forming an annular flow channel. The stave coolers are assembled around the test section bricks with an intervening layer of carbon paste to fill the gaps between bricks and steel. The staves are held in place with four spring-loaded cable straps. The springs provide a preload of approximately 300 lb/ft² and allow for about 1/2 in. radial expansion of the bricks.

Gas leaving the test section is directed up through the incinerator, where excess combustibles are oxidized, into the hood, and out of the vessel through two horizontal pipes. Both the hood and incinerator are membrane wall

construction with an elliptical cross section which matches the inside of the test section. The incinerator rests on top of the test section and surrounds the central elliptical opening. Crescent coolers cover the remaining uncooled area on top of the test section. The crescent coolers (so called because of their half-moon shape) fit between the circular stave coolers and the elliptical incinerator. They consist of a pair of flat steel plates with copper tubing brazed to them in a serpentine pattern. The plates are joined to the test section bricks with heat-conducting carbon paste, and cooling water is circulated through the tubing.

The membrane wall construction of the incinerator consists of 3/4 in. schedule 80 carbon steel pipes forming the vertical elements of a right elliptical cylinder. They are located on approximately 2 in. centers, and are connected by 3/8 in. thick strips in the intervening spaces. Pipes and strips are joined by full-penetration welds forming a gastight enclosure. The entire inside surface is lined with short pin studs closely spaced to increase heat transfer surface. These studs also serve to hold a 1-1/2 in. thick lining of rammed refractory. Water flows from bottom to top through manifolds (3 in. diameter) at either end. Combustion air is introduced near the bottom of the incinerator from a rectangular manifold around the outside of the membrane wall. Air flows through high temperature stainless steel nozzles located in the webs between pipes. The nozzles are designed to inject air at close to half the speed of sound in order to promote mixing and to reduce the possibility of clogging a nozzle with slag. The 310 stainless steel nozzles extend through the refractory lining, protecting it from erosion by the high-velocity air.

The hood is essentially a closed-end extension of the incinerator. It too is comprised of 3/4 in. pipes on 2 in. centers. These pipes, however, are each in the shape of an inverted "U." They are connected with flat strips (1/4 in. thick in this case) bent and twisted to accommodate the successive changes of diameter from one pipe to the next. The resulting shape is that of an elliptical cylinder with a hemiellipsoidal head. The 3 in. diameter manifold joining the ends of all the pipes has two internal partitions dividing it into two separate compartments. Water is admitted to one compartment, flows through each pipe in parallel up, around, and down into the second compartment from which it exits the hood. A small fitting at the crown of each pipe is

used to release air from the component and allow complete filling with water. There are three penetrations in the hood: one at the top for introducing slag, and two in the cylindrical portion for withdrawing the burned gas. Membrane wall pipes that are interrupted by these penetrations are connected to ring manifolds which circle the opening and allow the cooling water to flow around. The main purpose of the hood is to contain and direct the gas out of the test vessel. Whereas the incinerator is meant to draw heat out of the gas, the hood is meant to act as an insulating cap. For this reason, many fewer studs are used on the inside surface, their only purpose being to anchor the refractory. The lining thickness is approximately 3 in.

Hot gas is transferred from the test vessel to the scrubber through water-cooled jacketed piping. This piping consists of 8 in. extra strong pipe inside 10 in. standard wall pipe. The two pipes are held concentric by spacers. Gas flows inside the 8 in. pipe, while water flows in the annular space to cool the inner pipe wall. Carbon steel pipe is used in preference to stainless because of its higher thermal conductivity and lower cost. Calculations indicate that the maximum temperature of the inner pipe wall in contact with the gas would be 400°F. This piping was made in five separate, prefabricated sections which were bolted together on site. The manufacturer, Doows Engineering Ltd. of England, deals exclusively with jacketed pipe and fittings and is experienced in applications involving heating and cooling. (Refer to subsequent Section 3.4.2.(d) and Figure 12 for pipe routing.)

Cooling water enters the jacket space near the flange connecting to the venturi, and flows in the opposite direction to the gas, back toward the test vessel. Cooling water for the incinerator is brought in through the vessel shell and introduced to the bottom manifold of the incinerator. From the top manifold of the incinerator, half the water goes to the inlet of the hood while the other half goes to the inlet on one of the jacketed pipes. The outlet from the hood is directed to the inlet on the other jacketed pipe. The jacketed pipe inlets are located just outside the hood. Baffles inside the jacket space direct the cooling water to the nose of the pipe which protrudes inside the hood. The water then turns and flows in the same direction as the gas. Once outside the test vessel, the water leaves the jacket and returns, along with the water coming from the other direction, to the water system return manifold.

(b) Internal Flexible Hoses

In order to distribute the cooling water to the various cooling elements within the refractory test unit pressure vessel, certain circuits require the use of flexible hose. Since some of the interconnected internal cooling elements shift their location with respect to each other and to the pressure vessel shell, hard piping is not possible. The selection of an adequate hose design for this unique application required that several criteria be met:

1) Operating Conditions:

- Internal - City water circulating at 2 to 25 fps; 90°-150°F; 20-100 psig.
- External - Nitrogen gas; 150°-200°F; 0-100 psig.
- External - Hot spots, where small gaps in the refractory wall may develop, require that the hose be wrapped with insulation or covered with a fire sleeve in order to inhibit local burn-through and distribute the heat load over a larger area.

2) Service:

Since the unit operates continuously for up to 500 hr intervals, the hose life should be at least 10,000 hr. Flexing of the hoses is minimal and occurs very gradually after initial installation. Minimum bend radius of hose is about 10 to 12 in. Working pressure of the hose is 150 psi.

3) Size:

Two sizes of hose are required--1-1/2 in. ID and 1 in. ID--in lengths varying from 1 to 16 ft. The total quantity of hose required is about 250 ft of 1-1/2 in. ID and 50 ft of 1 in. ID. The wall thickness of the hose has been kept to a minimum since the space through which the hose passes is only 4 in. wide.

4) Hose Structure:

- Since the pressure drop on certain cooling-circuits which use hose is as much as 80 psi and since the external pressure acting on the hose remains at 100 psi in the nitrogen jacket space through which the hoses are routed, the hose wall is sufficiently reinforced to carry this 80 psi maximum differential pressure (higher on the outside) for extended periods without deforming or constricting to the point where the flow of cooling water would be reduced.

- The possibility of the nitrogen pressure wicking down through the reinforcing layers of the hose by entering through the cut ends has also been eliminated by using a paint-on sealant which bonds firmly to both the casing and tube of the hose prior to assembly of the end fittings.
- A third problem related to the condition of having a higher pressure of nitrogen outside the hose than the water pressure inside involves permeability through the outer casing. The permeability of nitrogen must be low enough to prevent a buildup of pressure between the layers of the hose, leading to possible delamination and pinch-off of the inner tube.
- To keep pressure losses through the hose at a minimum, it must be smooth bore.

After extensive testing of various standard and special hose assemblies, Goodyear "Diversipipe," with a butyl casing, fabric reinforcing, and 1/16 in. diameter helical reinforcing wire molded into the hose wall, was selected as the best hose for the application. This hose is fabricated in 50 ft lengths, but is not obtainable with external insulation wrapping. Consequently, a 1/16 in. thick by 3 in. wide bonded asbestos tape material was used to wrap all hose assemblies using a 50% overlap spiral pattern to give a 1/8 in. total insulation thickness. In addition, the asbestos wrap was then covered with highly reflective 3 mil aluminum tape to reduce absorption of any radiant heat escaping through gaps in the refractory wall.

As a consequence of the heavy wall thickness and wire reinforcing of the Diversipipe hose, the range of fittings compatible with this hose was limited. Since field assembly was essential, only clamp-on and band-on fittings were considered. All clamp-on fittings but one failed at too low a pressure (less than 200 psi), and the one which held was too large to fit the space available. The fittings finally selected were of two types, and held pressures greater than 200 psi--up to a maximum of 700 psi without leaking. They are both serrated end, band-on style fittings, using 5/8 in. wide stainless steel bands (two per fitting). A compact banding tool allowed quick assembly of these fittings, even when access to the hose ends was limited. Using these the most fittings, the most difficult internal cooler connections, the copper plates, were successfully piped and pressure tested.

(c) Support of Internal Vessel Components

The weight of the bricks and coolers inside the test vessel is distributed over several places on the vessel shell. The bricks in the combustion and transition sections are supported by the bottom head of the vessel. The castable refractory spreads the load evenly over the entire dished head. The channel cooler is supported from a ledge running around the inside of the vessel at the tangent point between shell and head. The test section bricks are supported by the stave coolers. This load is supported by 16 springs, located around the outside of the test section, which rest on a ring welded around the inside of the shell near the vessel midpoint. Figure 11 shows the support ring for the test section with brackets indicating the approximate spring location. The springs are adjusted at assembly so that virtually no load is transmitted to the transition section bricks. As the bricks expand during operation, part of the load will be taken by the bottom head through the brickwork, while most of the load will still be transferred through the springs to the vessel shell. The hood is fixed to the top head of the vessel by rigid struts. The jacketed pipe sections inside the vessel are cantilevered from 16 in. flanges bolted to nozzles on the vessel shell.

Thermal expansion of the brickwork is expected to be about 2% on the hot face. Consumable cardboard spacers are placed between all bricks at the hot face to allow for this growth. In addition, there is a provision for accepting 1 in. of differential movement in the vertical direction. At this sliding joint, the hot gas is isolated from the nitrogen jacket by means of a tongue-and-groove arrangement. The groove is a wide trough at the top of the incinerator filled with a crushable refractory, and the tongue is a pointed blade on the bottom of the hood which penetrates the refractory. A similar, though smaller, type of seal will accept a half-inch radial movement between the hood and each of the jacketed pipes. All water and air lines going through the vessel shell to internal components have provision for flexibility. Movement of the internals with respect to the vessel shell is accepted by using either internal flexible hoses or heavy reinforced rubber bellows installed at the nozzle flanges.

(d) Exhaust Gas, Scrubbing, and Pressure Control

The exhaust gases exit from the test vessel at about 3000°F and 100 psig. They must be cooled, cleaned, and depressurized before release into the atmosphere. Cleaning and cooling are accomplished in the scrubber. Depressurization occurs at the control valves which also serve to maintain a constant system pressure. After letdown, the gases pass up through a 28 in. diameter double-wall stack, which exhausts about 12 ft above the building roof line. Figure 12 shows a plan view of the gas outlet piping, and Figure 13 shows a schematic diagram of the gas flow. Throughout this section, lower-case letters in parentheses refer to items shown in Figure 12.

1) Water-Cooled Exit Piping. Hot exhaust gas is transferred from the refractory test vessel to the scrubber through five sections of water-cooled jacketed piping (h). Two of these sections begin inside the test vessel (at the hood), and each passes through a 16 in. diameter nozzle in the vessel shell. Outside the vessel they each connect to another section, which wraps around the vessel, and join together in a tee. The branch of the tee goes down and over to the venturi inlet of the scrubber. (Refer to Section 3.4.2.(a) for details of jacketed pipe design.)

2) Scrubber System. A wide range of scrubbing systems were considered for this project. After discussions with city officials on EPA requirements for Chicago, the Air Pol single-flooded venturi scrubber with a cyclonic demister was selected. Apart from being the lowest bid, the Air Pol unit had certain advantages over others:

- a) The design is compact.
- b) Gases can be rapidly vented through the scrubber in emergencies, without damaging the system.
- c) A guarantee on performance was included.

Exhaust gases enter a pressurized 4 in. diameter fixed venturi (i) flooded with water, the water being sprayed in tangentially. The gases are cooled by intimate mixing with the water, producing steam, and the resulting vapor is passed into a pressurized demister unit (j) which removes all water droplets together with any grit particles. A sludge gradually forms at the bottom of the demister. Periodically, the demister is blown down to remove this sludge.

a) Refractory test vessel	i) Shown: pair of 1 in. rupture discs
Below: venturi inlet
b) Slag tap vessel	j) Demister (broken line)
c) 12 in. rupture disc on slag tap vessel	k) 2½ in. safety relief valve
d) 2 in. safety relief valve	m) Gas pressure control valves (2)
e) 12 in. rupture disc on main process gas	n) Acoustical diffusers (2)
f) 6 in. differential pressure rupture disc	p) Stack
g) 10 in. rupture disc on nitrogen jacket	r) Water return manifold
h) Jacketed piping - 5 sections	s) Water supply manifold
→ normal gas flow	t) Water pressure control valves (2)
one below that shown
	u) Blast shield

Figure 12. Plan view of refractory test unit.

3) Pressure Control. The cool, clean gas then passes through a low noise control valve system which reduces the gas pressure to about 2 psi, and from there the gas passes to the stack. Two 3 in. Fisher control valves (m) are used in parallel. They are both controlled by one controller which sense the system pressure from several points in the test vessel (Figure 13). Pressure taps are located in the top of the slag tap notch and in the hood where plugging with slag is least likely. Each line will be purged with nitrogen periodically to keep it open. These two signals are averaged and sent to the controller. The controller output, a 3-15 psi signal, is sent to both control valves. One valve operates on a 3-9 psi input, while the other operates on a 9-15 psi input. This allows one valve to open fully before the other comes into operation. Either valve is capable of handling full normal operating flow, in the event that one should fail or need servicing during a test. The valve trim is made from 17-4 PH stainless steel and Stellite 6 for corrosion and wear resistance. The cage is designed for low noise. In addition, an acoustical diffuser (n) is installed just downstream of each valve. This combination assures that the noise level at a distance of 3 ft is below 85 db. All vessels upstream of the control valves are designed, nameplated, and National Board registered according to ASME, Section VIII, Division 1 rules.

There are several levels of redundancy in the pressure control system. (Items referred to in this paragraph are shown in both Figures 12 and 13.) Either or both of the control valves can be rapidly opened from the control room, or manually operated at the valve. If the system pressure rises too quickly for the control valves to handle, a 2-1/2 in. relief valve (k) mounted on the scrubber exit will open. During pressure relief, the flow rate through the scrubber could be very high, momentarily. This will cause flow noise and probably poor scrubbing action, but the gas would at least be relatively cool, which allows a standard relief valve to be used. A 2 in. relief valve (d) on the slag tap vessel is capable of operating at 650°F and can handle hotter gases for short periods of time. These relief valves will reclose following temporary excursions and allow operation to proceed.

Several rupture discs have been installed to further protect personnel and equipment against accidental overpressure. A pair of 1 in. diameter rupture discs (i) are located just upstream from the scrubber to relieve gas in the event of the venturi clogging. These are reverse buckling discs, which

Figure 13. Refractory test system pressure control schematic.

means that their opening pressure can be very close to the system operating pressure without causing premature failure. Three large conventional rupture discs provide the final level of protection. A 12 in. disc set at 140 psi is installed on both the slag tap vessel (c) and the jacketed piping leading from the inside of the test vessel (e). A 10 in. disc set at 150 psi and mounted on the top of the test vessel (g) provides for venting of the nitrogen jacket and additional protection for the test vessel. The rupture disc exhaust piping and the jacketed piping for normal exhaust (both shown on Figure 12) are supported by variable spring supports. Movement of the piping due to thermal expansion (mostly vertical) is accommodated by the springs without loss of load on the supports. The pipe leading to the 12 in. diameter main vessel rupture disc will not be water-cooled initially, although water sprays could be added if necessary. The main rupture disc is well away from any flowing gas stream, and far enough from the main gas piping that it should need no particular cooling. Thermocouples will be used to monitor the disc temperature. All discs are made of Inconel so that their bursting pressure is affected only minimally by increased temperature.

Standard wall steel pipe will direct vented gases from a ruptured disc directly up through the building roof, with adequate support to accept jet forces. This pipe will accept high-temperature gas, but only for sufficient time to allow relief of vessel pressure. The outlet of each vent pipe has a hinged cover, which keeps rain out, yet offers no resistance to flow during venting.

The pressure of the nitrogen blanket is held slightly above that of the test chamber gas (refer to Section 3.4.2.(e) describing the Nitrogen jacket for further control details). A 2-1/2 in. check valve is provided between the nitrogen blanket and the slag tap vessel. This valve, which opens only when the N_2 pressure is more than 5 psi above the slag tap vessel pressure, will help to equalize the pressure between the slag tap vessel and the test vessel if the slag tap notch should become partially or completely blocked. If the pressure difference should become quite large--by the sudden venting of one side through through a rupture disc, for example--the internal brickwork and coolers could be damaged. In order to protect against this event, a differential rupture disc (f) is installed in a 6 in. diameter line near the top of

the test vessel. This disc will open at 20 psi pressure difference in either direction, and quickly equalize the nitrogen jacket with the test chamber gas.

(e) Nitrogen Jacket

The space between the refractories and the test vessel shell is filled with nitrogen gas. Originally, it had been planned to control the nitrogen at a slightly higher pressure, ensuring that the process gas did not flow out to the vessel wall. After further examination of the N₂ system, however, it became questionable whether or not this differential pressure could be held. The gap formed between the incinerator and the hood may be too large to maintain even a small differential pressure without excessive N₂ flow.

It was decided to use a simple on-off control for the N₂ jacket and let experience dictate whether or not a differential pressure could be held, and if so, just how sophisticated the controls needed to be. The jacket pressure is controlled by a differential pressure gage with two set points. Nitrogen is continuously bled into the jacket space at a rate of 10 scfm. The first set point causes valves to open such that if the jacket pressure falls below the process pressure, nitrogen is injected into three areas of the jacket at a total flow rate of approximately 60 scfm. The second set point, set at a slightly higher differential pressure, will increase the flow rate to 210 scfm.

The N₂ jacket is vented through the 2-1/2 in. check valve into the slag tap vessel. The pressure in the slag tap vessel and the pressure of the process in the refractory test vessel are approximately equal due to the size of the slag tap notch. As the process drops, the slag tap vessel pressure will drop, and the N₂ jacket is vented into the slag tap vessel. In this way, when the system is depressurized during a shutdown, the N₂ in the jacket space is used for additional purging.

Bubble alumina was poured into the jacket space up to the top of the transition zone. This both helps to protect the hoses in the event that hot process gas leaks into the jacket and reduces the amount of N₂ needed to fill the jacket. Thermocouples on the test vessel shell and in the bubble alumina are used to alarm an overtemperature condition in the jacket.

(f) Refractory Liner System

The refractory liner system of the test unit was designed to operate for at least 500 hr before replacement. This required careful consideration of

refractory selection and cooling system elements. The final design was based on experience with slagging industrial processes and the experiments which Dr. Kennedy has conducted at Argonne National Laboratory.

Beginning at the base of the test unit (see Figure 7), the first refractory is a 90% alumina, calcium aluminate castable which was used to level the bottom and provide additional refractory backup of the hearth. Above this is a single block of anthracite carbon, blast furnace grade, which is 18 in. thick, embedded in a thin grout of the castable to distribute the load. The carbon distributes the heat from the base of the combustion chamber cooler along the wall, and also provides a stop for any molten iron which may form and dissolve the oxide refractory above.

The 9 in. walls and the 13-1/2 in. floor of the combustion chamber are made of 90% alumina, 10% chromia sintered bricks which were laid with mortar of equivalent composition. A plastic refractory of equivalent composition is used around the burner and lances. These bricks, and all others in the test unit, were laid by a professional refractory mason under the guidance of the manufacturer of the brick used. Bricks, mortar, and plastic in each section are all from the same manufacturer. A space approximately 1/2 in. thick was left between the walls and the channel cooler. This was rammed with a high thermal conductivity graphite paste to provide good thermal contact between brick and cooler.

The transition section is made of 84% alumina, 16% chromia sintered brick which is laid with the corresponding mortar. The copper coolers are embedded in a plastic refractory of equivalent composition. The walls of the transition section vary in thickness, the average being 9 in.

The test section for the shakedown run is made of blast furnace grade, superduty fireclay bricks and laid up with corresponding mortar. The bricks vary in thickness between 3-1/2 in. and 13-1/2 in. The cold face of the brick was coated with approximately 1/2 in. of high thermal conductivity graphite paste to provide good thermal contact between the brick and the stove coolers.

The incinerator and hood are designed as studded water walls. They are coated with a 90% alumina, 10% chromia plastic refractory. The coating is approximately 1 in. thick on the incinerator and approximately 2 in. thick on the hood.

Thermocouples are distributed throughout the refractory liner of the unit. These are placed in channels cut in the brick, which are then filled with 99.9% alumina cement. All noble metal thermocouples are in 99.9% alumina protection tubes, with the junction embedded in alumina cement at the end of the tube.

3.4.3 Slag Injection System

The purpose of the slag injection system is to introduce slag particles into the process in such a way that they are distributed evenly over the incinerator walls, which are heated sufficiently by the gas stream to allow the particles to adhere upon contact. Whether the particles become molten in flight towards the wall or whether they remain solid and adhere to the molten slag already covering the wall is of minor concern. The primary consideration is that the particles are sized properly so that upon exiting the injection nozzle, they neither fall directly to the bottom of the vessel, nor get carried off in the exit gas stream. Following the ORNL engineering review of the project, the calculated optimum particle size was increased slightly and the range narrowed to -8 to +14 mesh from the earlier value of -10 to +60 mesh.

The present slag injection system (Figure 14) is based on the conclusion that at least two gallons per minute of water could be injected at the upper portion of the incinerator section without adversely affecting either the temperature or the gas composition in the test section. As a result of this analysis, a system utilizing a slurry feeding concept has been incorporated into the refractory test system. In choosing a slurry system over a pneumatic system, the major considerations involved monitoring of system performance, serviceability, flexibility, and consequences of component failures.

The heart of the slag injection system is a Moyno six-stage positive displacement progressive cavity pump (Model 6M3) with a 1-1/2 hp mechanical variable-speed drive rated at up to 3 gpm at 200 psi discharge pressure. This unit is fed a 12% slurry by weight of slag in water from an open slurry mixing tank, and discharges through suitable valving along small-diameter tubing (1/2 in. maximum) to the slag injector located at the top center of the test unit. The spray tip of the slag injector produces a hollow cone spray pattern. The nozzle assembly is water jacketed and refractory insulated at the process end.

Figure 14. Slag transport system schematic.

With a maximum particle size of about 2 mm (0.080 in.), an orifice size of 0.250 in. was selected for the spray nozzle. At 2 gpm, the flow of slurry through a 0.250 in. orifice does not develop sufficient back pressure to achieve a suitable spray pattern. Consequently, provision has been made to introduce air into the slurry stream just prior to entering the vessel. This results in a mixed three-phase stream being injected through the spray nozzle--the water slurry being used to transport the particles to the top of the test unit at a controlled rate, and the air being used to regulate the shape and direction of the spray pattern without having to exceed the 2 gpm limit on the amount of water introduced with the slag.

At the other end of the system, the slag storage vessel holds 75 tons of dry, carefully sized slag which is loaded pneumatically from a delivery truck prior to the start of a test. This vessel stands vertically and unloads through an 8 in. diameter nozzle in its bottom head at an elevation of 30 in. above floor level. A 22 in. diameter pneumatic fluidizing funnel serves the dual purpose of keeping the slag flowing at the point of exit from the vessel as well as providing a flow of dry air through the vessel to carry away any moisture which may tend to accumulate inside. Material falls through the 4 in. neck of the fluidizing funnel by gravity, exiting into the hopper of a vibratory feeder until the level in the hopper backs up the material in the funnel neck. The feeder operates by electromagnetically induced vibration, and its controller varies the voltage to the feeder to permit control of the rate of slag feeding.

The slag discharged from the feeder drops onto a ribbed belt conveyor which carries the slag from a low point of about 12 in. above floor level to a height of about 5 ft, passing through the skirt of the slag storage vessel, and terminating above the slurry mixing tank. A final scalping screen located below the discharge end of the conveyor intercepts any unwanted oversize particles or contaminants before they fall into the slurry tank.

The slurry tank is sized to hold enough slurry to supply the Moyno pump for about 2 hr of run time in the event of an equipment failure which might interrupt delivery of slag to the tank. A worst-case situation would require slag to be manually transferred from the slag storage vessel to the slurry tank, but the frequency for this operation would not be more than about once every 1 to 2 hr. The slurry tank is 48 in. in diameter and about 36 in. high,

fabricated from 1/8 in. thick stainless steel with a 10 in. dished bottom. Six equal-spaced 5 in. wide baffles have been mounted inside and can be radially adjusted over a 1 in. range. Agitation of the slurry is provided by an axially mounted Lightning Series 90 turbine mixer driven by a 1 hp motor. The impeller is a four-blade 26 in. diameter unit with stabilizer fins turning at 68 rpm.

The slurry tank is fitted with a side tap connection to the slurry pump, located at a higher elevation than the settling level of the solids, to prevent overload of the pump should loss of agitation occur. Additional tank ports include a bottom drain and an overflow drain. Water is added to the tank on an intermittent demand basis and is monitored by several standpipe-isolated electronic level detectors. With the flow through the positive displacement slurry pump set at about 2 gpm, the vibratory feeder set to deliver 150 lb/hr of slag into the slurry tank, and the water level maintained within proper limits, the weight of slag delivered through the spray nozzle will closely match the 150 lb/hr requirement for the project. While the percent slurry being pumped at any given moment will vary slightly according to the water level in the slurry tank, on the average it will remain very close to the 12% level desired.

Pressure and flow control is arranged to best contend with possible line and nozzle blockage situations. Valves which routinely cycle open and closed on a flow of slurry are either weir diaphragm or rubber tube pinch valves. Under normal start-up, shutdown, or problem response situations, valve sequencing provides for a clear water flush of all slurry-carrying components, from the tank to the top of the test unit.

While the main burner is operating, air flows through the slag nozzle at all times to minimize heat transferred to the spray tip. As the test unit approaches slagging temperature, the Moyno pump is started, but pumps only clear water, which is bypassed to drain just before the injection nozzle. After reaching the correct temperature in the test section, the clear water output from the pump is also fed through the spray nozzle until temperature readings stabilize. At this point the feed to the slurry pump is changed from clear water to slurry.

During a run when the test unit is at operating temperatures, any problems with the slurry feeding system are handled in such a way as to minimize

the disruption of the testing conditions. If the flow of slurry must be interrupted, high-pressure water, which is also piped to the slag injection nozzle, can replace the flow of slurry to minimize any temperature variations in the process. This also takes place when slurry samples are taken near the test unit during a run.

Pressure in the slurry delivery line is monitored to indicate possible line or nozzle blockage. At about 175 psig back pressure, the bypass valve at the top of the vessel opens and the feed to the pump changes to plain water. If the pressure does not drop after this valve opens, a second bypass near the pump opens. Should pressure at the pump discharge rise to above 200 psig, a rupture disc will relieve the pressure to prevent pump damage. A pressure switch at the pump inlet is interlocked with the starter circuit to prevent operation of the pump if the suction head is not adequate.

Verification of proper operation of the slag injection system is accomplished through periodic sampling of the dry slag delivery rate into the slurry tank, as well as sampling of the delivery line at the test unit to determine both the solids content and the flow rate of the slurry entering the test unit.

3.4.4 Slag Tap Vessel/Slag Removal

(a) Functions

The main function of the slag tap vessel is to provide a space in which the molten slag exiting from the test vessel can be safely quenched, collected, and released from the pressurized test unit for disposal. In addition, the space within the slag tap vessel is utilized for several other purposes including

- a) Access to the slag notch area for installation and servicing of notch components (double-nose tuyere, gap cooler, etc.)
- b) Space for mounting and routing of water pipes to slag notch coolers
- c) Access to the slag notch for monitoring slag flow, and for removal of slag blockages using the slag tap torch
- d) Providing a large, relatively static gas space which can interact with both the process gases and the steam generated during slag quenching, so as to dampen any pressure pulsations during operation.

(b) Slag Quenching

The results of tests quenching molten slag in water at atmospheric pressure indicate that, by maintaining the water temperature in the slag tap vessel (shown in Figure 15) at 90°F or lower, the quenching process yields solid slag granules small enough for removal from the system as a dilute water slurry (<2% solids by weight). For safe and reliable quenching, a large volume of water is required relative to the volume of slag being quenched.

The point at which the molten slag from the test vessel runs off the refractory lip on the nozzle neck inside the slag tap vessel is about 12 in. above the normal water level and 4 in. away from the wall of the slag tap vessel. As the slag stream drops toward the water surface, two converging, solid stream water jets intersect the slag a few inches above the water surface. This action ensures that the size of the quenched slag granules remains small, despite variations in the flow of slag into the slag tap vessel.

Because of both the dynamic nature of the quenching process and the presence of molten slag in close proximity to the slag tap vessel wall, a steel liner is hung below the slag notch nozzle to afford protection to the vessel wall in this area. Four flat water-spray nozzles create a water wall effect to prevent formation of a built-up layer of frozen slag along the face of the liner.

(c) Quenched Slag Entrainment

Although the large volume of water (about 3500 gal) present in the slag tap vessel is essential to the safety of the quenching process, it becomes a problem when the task of suspension of the quenched solids as a dilute slurry is considered. Rather than expending the large amount of energy necessary to agitate all the water in the slag tap vessel, a system is utilized which selectively captures those granules of an acceptable size within a smaller agitated "catch pot" located about 18 in. below the water surface.

The catch pot encloses a volume of about 10 gal, is fitted with a cone bottom, and has a wide mesh, heavy wire cloth covered opening which slopes downward toward the center of the vessel. The screen allows a free exchange of water between the catch pot and the rest of the vessel, but intercepts any oversize solids which might not easily pass through the slurry discharge

Figure 15. Slag tap vessel arrangement.

lines. An inverted funnel is suspended near the center of the catch pot and connects to three separate slurry discharge lines, which are piped through the vessel shell to a hydroclone style solids separator, using suitable valving. By running three separate and progressively larger lines from the catch pot to the exterior of the vessel, the possibility of a shutdown resulting from a blockage of the quenched slag removal lines has been all but eliminated. Four small water-spray jets are fitted to the center of the cone at the bottom of the catch pot and are directed toward the inverted funnel above them. Slag granules passing through the wire cloth screen fall past the funnel and toward the bottom of the pot where these four spray jets direct them back upward toward the funnel inlet to the discharge lines.

The correct balance of water flow into the catch pot is essential for maintaining efficient solids removal. Under normal operation there is a minimum net flow of about 40 gpm through the screen into the catch pot. This flow entrains the particles being quenched directly above the pot and drives them through the screen. The flow of slurry out of the catch pot, induced by the system pressure, passes out along one of the three slag discharge lines, and is regulated by a heavy rubber tube pinch valve located between the vessel and the hydroclone.

This valve drops the pressure in the slurry exit line down from 100 psig to between 10 and 50 psig, depending on the desired flow through the hydroclone, which range from 35 to 90 gpm. The underflow of sludge from the Krebs rubber-lined hydroclone, consisting of 60-75% solids, discharges into small (2 yard) mobile hoppers, which are stored in the courtyard area. Clean water overflow from the hydroclone requires no further treatment and is piped directly to the city drain.

(d) Screen Backflush and Liquid Level Control

Periodic clearing of the catch pot screen is accomplished by backflushing with fresh water sprayed through two high-flow, full-cone nozzle mounted just below the screen and angled upward at about 45° toward the vessel centerline. During backflushing, flow to the hydroclone is temporarily interrupted in order to maximize the backflow through the screen. The fresh water used for backflushing brings the liquid level in the vessel up from its normal low level to its normal high level, at which point the flow through the slag discharge line is restored and backflushing ceases. A continuous flow of fresh

make-up water also flows into the vessel through the other spray nozzles and through a line to the bottom of the vessel. By regulating the flow of this make-up water to be slightly less than the flow of slurry exiting to the hydroclone, the water level in the vessel drops gradually to its normal low level, at which point another backflushing cycle begins. The desired frequency and duration of screen backflushing is determined by the spacing between the liquid level control probes in combination with the ratios of flow through the continuous make-up line, the slag discharge line, and the screen flush line.

The oversize solids cleared from the screen are dislodged onto a chute which slopes toward a second, larger collection pot located near the bottom center of the vessel. This pot holds about 8 ft³ of material and is removable through the 30 in. diameter nozzle at the top of the vessel during shutdowns. It has an open top and a perforated metal bottom for water drainage. Any quenched slag which escapes into the main volume of the vessel settles to the bottom where it is removed during scheduled breaks in the test run.

Water level control equipment also includes an externally mounted automatic liquid level gage, for visual indication, and two independently actuated drain lines--one for a back-up to the solids removal line, and the other an emergency drain to prevent the water level from rising to the height of the slag notch in the event of a valve failure or blockage in other lines. Both these drains connect to the side of the vessel at high enough elevations to prevent intake of settled solids.

(e) Gas Space/Nitrogen Purge

Because potentially combustible mixtures could accumulate in the slag tap vessel as a result of process gases passing through the slag notch, formation of hydrogen during slag quenching, or leaks in the oxygen and methane lines to the slag tap torch, the gas space in this vessel is continuously purged with nitrogen. An oxygen and combustible gas monitor also samples the nitrogen gas from this vessel and automatically increases the purge rate if these gases are detected. In order to minimize nitrogen consumption, the rate of purge is normally adjusted to a minimum of 20 scfm, of which half flows out through the slow vent at the top of the vessel, and the other half flows out through the slag notch into the test vessel. The nitrogen which flows through the slag notch into the test vessel counteracts the tendency for process gases from the

combustion chamber to be driven into the slag tap vessel, while the nitrogen vented out the top of the slag tap vessel sweeps out the otherwise static gas space and provides an appropriate flow of gas to be sampled by the gas monitor.

Connected in parallel with the normal nitrogen purge and slow vent lines are a rapid purge line and rapid vent line, both of which are activated by the gas monitor when preset levels of oxygen or combustibles are exceeded. If rapid purging does not sufficiently reduce the level of oxygen or combustible gas present within a specified time interval, a progressive controlled shut-down of the test unit is automatically initiated.

Protection of the slag tap vessel from overpressurization is accomplished using a 2 x 3 in. pressure relief valve set at 110 psig along with a 12 in. diameter rupture disc, both of which discharge to the atmosphere along a 12 in. diameter pipe which exits through the roof.

(f) Slag Notch

All components of the slag notch assembly (shown in Figure 16) are installed, piped, and serviced via the slag tap vessel. Beginning at the test vessel, the gap cooler (A) is mounted on the outside surface of the channel cooler and is cooled by a 2-1/2 turn, 3/8 x 3/4 in. rectangular copper tube (B) silver-brazed to its outer surface. The 15 in. diameter steel pipe (C), welded to the gap cooler at the 16.5° angle, provides a rigid mounting for the double-nose copper tuyere (D), at an optimized angle for maintaining slag flow. The 7 in. ID of this silicon carbide lined tuyere is reduced to about 4 in. by lining with a plastic refractory material (G). The thickness of this material at the bottom of the tuyere increases from 1 in. at the working point to about 2 in. at the back of the tuyere.

(g) Slag Tap Torch

A small (400,000 Btu/hr), moving, oxymethane burner to maintain a free-flowing slag stream through the slag notch was incorporated in the early design concept for the project. However, recent analysis indicates that the hazards associated with a moving burner and the cost to instrument such a unit for safe operation far outweighed the potential benefits of the concept. Consequently, a stationary slag tap torch, positioned near the drop-off end of the slag notch and angled toward the slag tap hole, is incorporated in the

Figure 16. Slag notch detail.

present design. This allows continuous flame monitoring with a stationary detector and a fixed location for the igniter.

The unit was selected by Process Combustion Corp. for this application is a standard design manufactured by Airco--a 1 in. ID gas fuel "Rocket" burner with a 36 in. long by 2 in. OD stainless steel, water-jacketed barrel.

The remaining slag notch equipment is installed inside a galvanized steel sleeve (F) which is held in place by a densely packed layer of Fiberfrax material (H) between the ID of the vessel nozzles and the OD of the sleeve. The four pipes for the double-nose tuyere and the three-notch cooling coils (E) are embedded in refractory material enclosed within this sleeve. All piping to the six cooling circuits of the slag notch are routed along the upper half of this space, where contact with molten slag is not a problem. The diameter of the slag notch increases from the rear end of the double-nose tuyere, reaching a maximum of about 22 in. at the slag tap vessel. This affords better access to the full length of the notch during operation of the slag tap torch and when repairing the refractory lining of the notch.

Recirculated cooling water is supplied to these six cooling circuits, as well as to the slag tap torch (I), from a small header mounted alongside the slag notch. A 3 in. diameter pipe from the main supply manifold enters the slag tap vessel through the 6 in. nozzle in the bottom head and connects to this header. Return lines for the six notch coolers are individually piped back to the main return manifold so that each circuit can be separately instrumented and monitored. These return lines exit the vessel through the 14 in. nozzle adjacent to the slag notch (see Figure 16).

3.4.5 Burner System

Procurement of the burner and lances caused great delays in the program. An exhaustive search for suppliers was conducted, but only three companies were willing to quote. There were three problems:

- 1) Continuous operation at 100 psig
- 2) High temperature of operation due to heat radiation within a small combustion chamber
- 3) Unclear definition on the required gas composition in the test vessel, and hence for the burner requirements. This was a major problem and was finally resolved with a letter from the project sponsor (see Section 3.2.1).

Once the gas composition problem had been resolved, specifications were drawn up for the burner, lances, and slag tap torch. A purchase order was placed with Process Combustion Corp. in Pittsburgh, Pennsylvania, and the burner system was supplied as follows:

- 1) Main Burner. The burner is a natural gas/O₂ burner rated at 10 million Btu/hr with a turndown ratio of approximately 5:1. The barrel is made of 316 SS and is water cooled (155 gpm). There is one 1-1/4 in. gas port down the middle surrounded by five 1/4 in. oxygen ports. All of the oxygen ports have carbide tipped rods for clearing any slag which may plug them. The burner is equipped with a viewport, a UV scanner which sights down the barrel, and a retractable high-intensity spark igniter. A 1 in. copper coil has been inserted around the burner to provide extra cooling (40 gpm) of the refractories in that area.
- 2) Lances. Both lances are water cooled (15-45 gpm) and have 310 SS tips. The natural gas lance will pass 0-200 scfm of gas whereas the air lance will pass 0-800 scfm of air. Both lances fit into blast furnace type copper monkeys which provide additional cooling to the refractories in those areas.
- 3) Slag Tap Torch. The slag tap torch is a standard natural gas/O₂ torch rated at 400,000 Btu/hr. It is made of 304 SS and is water cooled (10 gpm). It has a separate igniter which is inserted into the slag tap vessel through a side nozzle.
- 4) Control System. The main burner has an automatic control system which maintains a set stoichiometric ratio. When the firing rate of the burner is turned up or down manually, the stoichiometric mixture will be automatically controlled to remain at a preset value between 50% FSA and 100% FSA. An automatic purge cycle must be completed before ignition can be attempted. Once ignition has been attempted, a flame must be established within a specified length of time or the purge cycle will begin again. The burner is also equipped with an automatic 'low fire' condition which can be initiated by alarm conditions in the refractory test system. When in the 'low fire' mode, the burner operates at the lowest firing rate. When the burner shuts down, the purge cycle is automatically initiated. The control panel for the burner is located in the control room with an auxiliary start-stop station located at the burner system pipe rack. Status lights are also located on the main control panel along with shutdown pushbuttons.

The flow through the lances and the slag tap torch is set manually from the burner system pipe rack. The lances cannot be started without having the main burner lit and will shut down and purge automatically when the main burner shuts down. The torch will shut down automatically when the main burner shuts down, but may be started up again if it is needed to clear the slag tap notch. The start-stop stations for the lances and torch are located by the burner system pipe rack, with an auxiliary start-stop station for the torch located by the slag tap vessel viewport.

Many discussions were held with Process Combustion Corp. concerning the design of the burner system and, in particular, the control system. Because of the high cost of the burner system, some expensive safety features were eliminated. After discussions between IITRI and ORNL Review Team (Section 3.5), and after a preliminary hazards analysis report (Section 3.6.), it was decided that some of these safety features had to be reincorporated into the design. These features are:

- 1) A combustion chamber temperature monitor which allows the burner to be restarted without a purge cycle when the temperature is above the ignition point of the gas/O₂ mixture. This protects the igniter from being burned up and the refractories from being purged excessively by cold N₂. This was to be a manually selected feature based on the thermocouple readings in the combustion chamber bricks and the temperature of the exit gas.
- 2) A flame scanner on the slag tap torch with an automatic purge cycle similar to that on the main burner. Previously, the operation of the torch was to be entirely manual, with an operator watching the torch whenever it was lit.

3.4.6 Water Cooling System

As a consequence of the high temperatures present at various points within the test vessel (2000° to 4000+°F) and the presence of water-cooled metallic components located in direct contact with these process temperatures, the water-cooling system for the refractory test unit is designed to provide an uninterrupted flow of cooling water in all components at a level adequate to insure their survival, despite the occurrence of such inevitable events as power failures and equipment breakdowns. The major components of the water cooling system include:

- 1) 5500 gal water storage tank
- 2) 400 ton evaporative water cooling tower
- 3) 220/BHP/165 kW natural gas engine/generator set
- 4) 333 hp total pumping capacity (seven individual pumps)
- 5) Five major pressure control valves
- 6) 12 in. dia x ~20 ft supply and return manifolds. The cooling system is divided into two main subsystems: medium pressure/recirculated and high pressure/consumed. The seven water pumps consist of five medium-pressure and two high-pressure units which are powered as follows:

Main Power:

2 normally operating 125 psig x 500 gpm pumps
1 emergency 125 psig x 500 gpm pump
1 normally operating 150 psig x 100 gpm pump.

Generator Power:

2 normally operating 125 psig x 500 gpm pumps
1 normally operating 150 psig x 25 gpm pump.

Sufficient pumping capacity for a safe shutdown will remain, should either the generator or the main power fail. If main power fails, the control system can be switched on to generator power so that valves, meters, and gages will continue to function normally during the shutting down procedure.

Water is drawn from the storage tank, through individual suction lines to each pump, and fed to the vessel through two welded steel pipelines, as shown in Figure 17. One pipe, 8 in. in diameter, accepts all water from the medium-pressure pumps and transfers it to a vertical constant-pressure distribution manifold near the test vessel. From here, the water is fed through flexible rubber hoses to more than 30 water-cooling circuits within the vessel. The other pipe, 3 in. in diameter, accepts all the water from the high-pressure pumps for direct injection into the scrubber and slag tap vessels.

Each cooling circuit return line is instrumented with an electronic flow transducer, which connects to a meter on the control panel, and a thermocouple which feeds the data logger. The more critical circuits have temperature switch triggered alarms as well. Water from the cooling circuits flows back to a vertical return manifold and, from here, back to the storage tank through a 12 in. diameter pipe. The full flow of return water can be diverted to pass

Figure 17. Cooling water system schematic.

D PRESSURE GAUGE T1 THERMOCOUPLE T2 TEMPERATURE SWITCH F1 FLOW TRANSDUCER F2 FLOW SWITCH		L1C LIQUID LEVEL CONTROL T1C TEMPERATURE CONTROL		P1 PRESSURE CONTROL P2 PRESSURE CONTROL P3 PRESSURE CONTROL	
THE DESIGN REPRESENTS THE PRELIMINARY AND PROVISIONAL DESIGN INFORMATION GENERATED BY THE RESEARCH INSTITUTE AND SHALL NOT BE USED FOR CONSTRUCTION OR OPERATION OF ANY SYSTEM WITHOUT THE RESEARCH INSTITUTE'S APPROVAL.		DATE: 12/12/80 BY: J. C. B.		CHECKED: 12/12/80 BY: J. C. B.	
HITT RESEARCH INSTITUTE TECHNOLOGY CENTER CHICAGO, ILLINOIS 60610					
REFRACTORY TEST SYSTEM COOLING SYSTEM SCHEMATIC					
TOLERANCES UNLESS OTHERWISE SPECIFIED FRACTIONS & 1/16 DECIMALS & .005 DIMENSIONS & FITS: ANGULAR & 1°		SCALE: 1/2" = 1'-0" 1/4" = 1'-0" 1/8" = 1'-0" 3/16" = 1'-0" 1/2" = 1'-0" 3/4" = 1'-0" 1" = 1'-0" 1 1/2" = 1'-0" 2" = 1'-0" 3" = 1'-0" 4" = 1'-0" 6" = 1'-0" 8" = 1'-0" 12" = 1'-0" 18" = 1'-0" 24" = 1'-0" 36" = 1'-0" 48" = 1'-0" 60" = 1'-0" 72" = 1'-0" 84" = 1'-0" 96" = 1'-0" 108" = 1'-0" 120" = 1'-0" 144" = 1'-0" 168" = 1'-0" 192" = 1'-0" 216" = 1'-0" 240" = 1'-0" 264" = 1'-0" 288" = 1'-0" 312" = 1'-0" 336" = 1'-0" 360" = 1'-0" 384" = 1'-0" 408" = 1'-0" 432" = 1'-0" 456" = 1'-0" 480" = 1'-0" 504" = 1'-0" 528" = 1'-0" 552" = 1'-0" 576" = 1'-0" 600" = 1'-0" 624" = 1'-0" 648" = 1'-0" 672" = 1'-0" 696" = 1'-0" 720" = 1'-0" 744" = 1'-0" 768" = 1'-0" 792" = 1'-0" 816" = 1'-0" 840" = 1'-0" 864" = 1'-0" 888" = 1'-0" 912" = 1'-0" 936" = 1'-0" 960" = 1'-0" 984" = 1'-0" 1008" = 1'-0" 1032" = 1'-0" 1056" = 1'-0" 1080" = 1'-0" 1104" = 1'-0" 1128" = 1'-0" 1152" = 1'-0" 1176" = 1'-0" 1200" = 1'-0" 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through the cooling tower when required, and if the water temperature is still too high, fresh water is automatically added to the storage tank and an equivalent amount of hot return water drained from the system. Make-up water is automatically added according to a monitored combination of tank water level and water temperature. Should the make-up water, as well as operation of the cooling tower, be insufficient to keep the system temperature at 90°F or below, the system temperature will be allowed to rise, but the water will require chemical additives to avoid mineral deposit buildup in the coolers. The maximum acceptable temperature under these conditions would be about 120°F.

(a) Water Pressure Control Valves

Five major valves are required to regulate the pressure and flow of cooling water at various points in the refractory test system. Three of these are connected to the medium-pressure (95-125 psig) circuit, and two are connected to the high-pressure (135-150 psig) circuit. These valves will be referred to as V1, V2A, V2B, V3, and V4 (see Table 3 and Figure 17).

(b) Recirculated Water

Five 60 hp/500 gpm electric pumps at 125 psig connect in parallel to the recirculated/medium-pressure water system. Of these five pumps, one is a backup, two are city-powered, and two are powered from a natural gas generator. During operation of the test unit, the pumping load is shared about equally between city and generator powered pumps. Normally, an excess of pump capacity will be on the line at all times, with a pressure-actuated bypass valve diverting the excess flow back to the holding tank (valve designation V1). The output from these pumps is manifold-connected to the 8 in. delivery line, which feeds the main cooling distribution manifold.

Since all of the cooling elements fed off this distribution manifold are inside the test vessel and exposed to 100 psig external pressure, by maintaining a maximum pressure of 95 psig in the water-cooling distribution manifold, any leaks which may develop in a cooling element or connection will be indicated by small amounts of gas flowing into the cooling circuit, rather than water flowing into test unit, which could be catastrophic. To regulate the manifold pressure at the desired 95 psig, the ~120 psig discharge from the delivery line is reduced with appropriate control valving. Fail-safe considerations dictate that this pressure reduction be accomplished through a

TABLE 3. REFRACTORY TEST UNIT COOLING SYSTEM CONTROL VALVES

Designation	Size, in. (connections)	Type	Pressures, psig			ΔP		Flows, gpm		Tight Closing	Proportional Band over Flow Range, % of Set Point	Failure Mode	Reqd. C_v at 100% Open
			Set Point	Inlet	Dis-charge	Norm	Min	Min	Max				
V1	2-1/2 to 3 (flanged)	Relief regulator (high performance)	125	80-125	1-5	120	75	100	600	Yes	3	Closed	50
V2A	4 (flanged)	Reducing control	95	75-100	72-95	25	3	500	1000	Optional	<1	Open	250
V2B	4 (flanged)	Reducing control	95	75-120	72-95	25	3	500	1000	Optional	<1	Closed	250
V3	1 to 1-1/2 (threaded)	Relief regulator (high performance)	145	145-135	72-95	50	40	0	90	Yes	3	Closed	14
V4	1-1/2 to 2 (threaded)	Relief regulator	135	145-135	100	45	35	0	90	Yes	10	Closed	20

Materials*	V1, V2A, V2B		V3, V4	
	Wetted Internals	S.S. and/or bronze	S.S. and/or bronze	
	Body	150 lb steel or 125 lb cast	150 lb steel	

*Suitable for untreated city water service.

minimum of two valves (designations V2A and V2B). This ensures that a fail-closed condition on one valve would not reduce flow below the minimum requirement for survival for all cooling elements and, at the same time, a fail-open condition would not allow the distribution manifold pressure to rise much over the test unit pressure of 100 psig. These two valves are completely independent, having separate controllers. They are large enough to pass adequate flow under partial loss of pumping capacity, when available differential pressure will be minimal, yet not so large as to cause overpressurization of the manifold should one valve fail full open. Two 4 in. valves, each with a C_v of ~250 satisfy these requirements--one is air to open, the other air to close.

3.4.7 Natural Gas Supply System

The gas system for the refractory test unit draws its supply from a dedicated 4 in. city gas main which is regulated to between 1-1/2 and 2-1/2 psig. A two-stage rotary compressor boosts this pressure to the 125 psig level required for delivery into the test unit. The 100 hp Fuller C70-70H unit which serves as the heart of the gas system is a positive displacement, sliding vane style unit, capable of delivering 300 scfm of gas at pressures of 130 psig. An automatic, water-cooled bypass loop from the discharge to the inlet of the compressor allows it to operate continuously at its 800 rpm fixed speed, despite the range of demand from the test unit. A 1 in. Fischer control valve with a three-mode controller regulates the flow through the bypass loop based on the pressure in the discharge line at the burner controls. With this type of regulation, the gas pressure supplied to the pipe rack for the burner, lances, and torch can be maintained within a range of 1 psi. Other major components of this system include:

- 1) An automatic, fail-closed, fired-rated, plug valve in the 4 in. supply line which opens only when the compressor is running and otherwise cuts off the gas supply at its source.
- 2) Oversized, 200 psig rated, coalescing style filter on inlet line.

The system instrumentation is optimized to balance the requirement of uninterrupted service with fail-safe performance for equipment protection. Monitoring of pressure and temperature readings from key locations in the system provides specific indication of both immediate and projected performance of the unit.

3.4.8 Air System

A source of high pressure (>125 psig) air for the refractory test unit is essential to the operation of both the incinerator section and the air lance. A small amount of air is also used by the slag injection system. This air is supplied by a pair of 125 hp Ingersoll-Rand reciprocating compressors, each rated for 500 scfm of output at 130 psig pressure. They are two-stage units with air cooled inter-coolers and water cooled after-coolers. Since the output of one compressor alone can adequately supply the test unit under most operating conditions, each unit provides full back-up for the other. Under normal conditions, both units operate alternately based on pressure demand at the receiver tank, which range between 125 and 130 psig, allowing a minimum duty cycle and lower operating temperature. Two automatically drained separators located between the after-coolers and the air receiver eliminate most of the condensate and oil entrained in the air.

A 6 in. pipe run from the air receiver at the tap house branches into one 4 in. run to the incinerator valves and one 3 in. run to the air lance controls of the pipe rack. The 140 cubic foot volume of the air receiver allows the compressor to operate in "constant speed" mode with the drive running continuously and the compressor pneumatically toggled between loaded and unloaded operation, based on the pressure in the air receiver. This eliminates the heavy load on the electrical system and increases the life of the starter contacts.

3.4.9 Oxygen System

An oxygen system to provide a maximum continuous flow of 300 scfm was required, and a standard system was leased from Air Products and Chemicals, Inc. The 9300 gal, horizontally mounted tank was installed on concrete foundations with 12 ambient vaporizers mounted alongside. The ambient vaporizers are adequate for supplying the full flow under normal weather conditions, and are supplemented by an electric vaporizer for cold weather operation. The complete system is surrounded by a high fence and is floodlit for security.

A 1-1/2 in. copper supply line feeds oxygen to the tap house where it joins with the burner pipe rack. This line is enclosed by steel channels for its full length, and a blocking valve is provided at the tank end of the line. This is remotely operated, requiring nitrogen pressure to remain open. The nitrogen feed line follows the oxygen line so that in the event of gross

mechanical damage to the oxygen line, the blocking valve will close automatically. As the tap house is an extension of the building, neither the oxygen line nor the natural gas line enters the main building, except at the lance and burner locations.

3.4.10 Nitrogen System

The dynamics of the refractory test system made it impossible to determine, with any accuracy, the amount of nitrogen that would be used. Leakage through the refractories and through the seal between the incinerator and the test section could not be determined. The number of unscheduled shutdowns, and therefore the amount of N_2 needed for purging the burner system, was also a factor of uncertainty. Discussions with the ORNL Review Team (Section 3.5) indicated that the amount of N_2 needed for purging the slag tap vessel was far greater than anticipated. Because of these reasons, a course of action was adopted as follows:

Approximate N_2 usage was calculated as closely as possible and was found to be about 80 scfm, continuous, and 300 scfm on an intermittent basis. The present LN_2 system at IITRI was used for the shutdown run. An appropriate liquid N_2 system with adequate vaporization will be leased and installed when test work is actually started at the facility.

3.4.11 Instrumentation and Controls

A block diagram of the refractory test system controls is shown in Figure 18. As indicated, there are four cabinets which house the controls for this system. These are the burner control cabinet, the pressure indicator/controller cabinet, the data acquisition system cabinet, and the main control cabinet. In addition, four small cabinets are located by the pipe rack for operation of the lances and the slag tap torch.

Burner System Controls. The burner system controls are described in Section 3.4.5.

Pressure Indicator/Controllers. Pressure throughout the refractory test system are monitored by Mon-O-Con indicator/controllers. These are modified pressure gages which are used on many of IITRI's high-pressure vessels because of their reliability. A complete Mon-O-Con consists of two parts: (a) an indicator set point unit and (b) a control unit.

Figure 18. Control system block diagram.

- a) The indicator set point unit is a pressure gage modified to contain independently adjustable set points, an internal lamp, a solid-state light-activated switch attached to each set point, and a light shield attached to the pressure gage needle.
- b) The control unit contains a power supply and one DPDT relay for each set point.

Figure 19 shows the operation of the Mon-O-Con. Four set points (A, B, C, D) have been arranged at random around the dial. Set points can be adjusted from the front of the gage by removing the dial coverplate. Connected to the pressure gage needle is a light shield which casts a continuously widening shadow as the pressure rises. In position 1, all set points are energized. In position 2, the pressure has risen such that set point A has been passed and the shadow cast causes its relay to become de-energized. Positions 3 and 4 show the operation of the light shield as the pressure continues to rise.

The Mon-O-Con gages with their control units are mounted in a control cabinet inside the control room. A list of pressures monitored by these units is given in Table 4. Since this means piping potentially dangerous gases into the control room, a gas detector is installed inside of this cabinet, a small fan vents the cabinet to the exterior of the control room, another gas detector is mounted on the control room ceiling, and flow limiters are installed on the lines to the control room.

Data Acquisition System. A Fluke 2240B data logger is the heart of the data acquisition system. A paper tape printer is an integral part of the unit and is available to the operator for data inspection. A compatible floppy disk system accumulates data for computer analysis. Data are output to the floppy disk unit at specified time intervals or under alarm conditions. Disks are used only once and then placed in a special envelope for insertion into a three-ring binder. In this way, all data accumulated throughout the program are permanently contained in a few folders. As the data logger scans the channels, the data are displayed on a CRT screen. This allows the operator to inspect several channels simultaneously without resorting to the printer. The printer, then, is only used when the operator desires a written record of the data.

Position 3

Position 4

Position 2

Position 1

Figure 19. Mon-O-Con operation.

TABLE 4. PRESSURE/INDICATOR CONTROLLERS

<u>Pressure Monitored</u>	<u>Number of Set Points</u>
Refractory test vessel process pressure	7
Refractory test vessel nitrogen jacket	4
Slag tap vessel	6
Air receiver	4
Gas compressor output	4
Oxygen supply	4
Incinerator air	4
Water supply manifold	4
Water return manifold	4

The data logger has been linearized for three different thermocouple types: Chromel/Alumel (Type K), tungsten-5% rhenium/tungsten-26% rhenium (Type C), and platinum-6% rhodium/platinum-30% rhodium (Type B). It has also been linearized to convert a flow transducer output into a gpm reading. Data taken from thermocouples were displayed and recorded directly in degrees Fahrenheit, and readings taken from the water flow transducers in the test section stave cooling elements were displayed and recorded directly in gpm.

The data logger monitors over 60 thermocouples distributed throughout the refractory test vessel (Figure 20). It also monitors thermocouples in the slag tap vessel, in the water-cooling circuits, and in the gas system. Various thermocouple measurements are compared against specified numerical limits during a scan. If a measurement exceeds its limits, the data logger activates an alarm relay which operates indicating lights and audible alarms and, in some cases, initiates shutdown modes. In addition to thermocouples, the data logger monitors the test vessel pressure, flow rates in the stave coolers, and the temperature rise of the water through the stave coolers.

The data logger, floppy disk unit, and CRT are all mounted in a single cabinet by the main control cabinet. Approximately 180 channels are presently used. With additional hardware, up to 1000 channels can be scanned by this unit.

- Chromel Alumel (Type K)
- ▲ Tungsten-5% Rhenium/Tungsten-26% Rhenium
- Platinum-6% Rhodium/Platinum-30% Rhodium
- x Platinel

Figure 20. Thermocouple locations in refractory test vessel.

Main Controls. The main controls can be broken down into two parts--the warning circuit and the control circuit. The warning circuit is a digital (TTL) latching circuit which takes as its inputs relay contacts indicating the status of the system. A fault in the system will close a relay contact which, in turn, will cause the warning circuit to flash a warning light on the control panel and on a diagrammatic board of the system. When the fault has cleared, the light will not flash, but will stay latched on until it is manually reset. This gives the operator time to take note of momentary excursions, several of which may occur simultaneously or in quick succession.

The warning circuit has been constructed to facilitate quick repair. Four latching circuits are built on each of twenty plug-in PC cards which can be quickly replaced. All integrated circuit chips are plugged into sockets to provide for quick card repair.

The control circuit is relay logic using plug-in (Potter-Brumfield series KRP) relays. Relay logic was used instead of a mini-computer so that the operators, who are not computer programmers, could be made more familiar with the control system. With relays, they are better able to troubleshoot problems and make repairs on their own, thus minimizing downtime.

The control circuit uses 233 relays which take inputs from pressure switches, limit switches, gas alarms, pushbuttons, and the burner system controls. The circuit operates twelve ancillary equipment starters, over 30 solenoid valves, audible alarms, and status and warning lights. It provides inputs to the warning circuit and the burner system interlock circuits. The relays are easily accessed through two side doors on the main control cabinet, and lights have been installed in the cabinets to simplify troubleshooting and repairs.

The main control panel consists of two 30 x 38 in. panels, which are mounted side by side on the front side of the main control cabinet. The left-hand panel has the start-stop pushbuttons for the pumps and compressors, various control pushbuttons, and over 200 warning and status lights (Figure 21). The right-hand panel has three flowmeters of different ranges for reading water flow rates in the cooling circuits. Along with each flowmeter is a bank of switches which selects the flow transducer which that meter will read. The right-hand panel also contains audible alarms which indicate warning and emergency conditions with pressure, temperature, flow, and the burner system.

(a) (left to right) Main burner control panel, pressure gage panel, and main control panel.

(b) (left to right) Pressure gage panel (partial), main control panel, flowmeter panel, and data logger, floppy disk memory, and CRT panel.

Figure 21. Control panels.

Finally, the right-hand panel has a space adjacent to the data logger for labeling the data logger channels.

3.4.12 Power

A new 2000 KVA transformer was installed inside the Materials Technology Building, and the refractory test system uses approximately one half of its capacity. In addition to this city power, a 175 kW natural gas fired generator provides power for two 60 hp and one 8 hp water pump continuously. This scheme provides sufficient cooling to the system in the event of either a city power failure or a generator failure. The generator is capable of providing 25 KVA for the controls and for emergency lights in addition to the power it supplies to the pumps. Although the refractory test system cannot be run in the event of a city power failure, generator power to the controls will provide for a controlled shutdown in which data can continue to be extracted.

The total power drawn by the refractory test system with all equipment running is in the neighborhood of 1200 amps, at 480 VAC, 3 phase.

3.5 PROJECT REVIEW BY OAK RIDGE NATIONAL LABORATORIES

During July 1980, a team of seven engineering personnel (Union Carbide) carried out a project review with particular emphasis on Tasks B and C.

Principally, this involved a three-day site visit at IITRI during which detailed discussions were held with all members of the design and project management team, followed by further telephone discussions.

The object of the review was to assess the adequacy of the program in three areas: technical, schedule, and estimated cost. The review of technical adequacy emphasized the questions: (1) Is it safe, and (2) will it work? The schedule was assessed for completeness and realism. The cost estimate review covered completeness, basis for estimate, appropriate escalation, and application of contingency.

The approach utilized in the review was as follows:

- 1) Assemble review team knowledgeable in areas of the program such as pressure vessels, burner systems, heat transfer, piping and gas systems, safety analysis, cost estimating, scheduling, etc.

- 2) Familiarize team with program design, schedule, and cost through reports, technical data, site visits, briefings by IITRI, and followup communication.
- 3) Compile list of concerns (technical, schedule, and cost) and review with IITRI.
- 4) Where indicated, investigate technical concerns by engineering analysis and/or calculations.
- 5) Summarize resultant concerns and appropriate recommendations, and review with program participants.

Although there appeared to be some definitive problem areas and certain other areas required considerably more detail design work, the review team expressed the feeling that the system design was appropriate for the application and, given adequate time and funding, would perform as intended. The safety of the system was of considerable concern, and apart from a strong recommendation that the Hazards Analysis be completed before construction was finished (see Section 3.6 of this report), much emphasis was placed on the proposed training and supervision of system operating personnel.

All the major points covered in the review report have been investigated, and further discussions have taken place with members of the review team. The exercise was extremely beneficial to the project, and it is hoped that a certain level of continuing contact will be possible in the future.

With regard to the technical aspects of the review, the following major points were raised, and have since been discussed and resolved:

- Leakage of hot gases through the bricks to the test vessel walls.
- The number of stages required on the Moyno slurry pump for adequate life.
- The spray nozzle for injection of slag into the hot gas stream.
- Slag particle size.
- Restart of main burner at temperature without a full nitrogen purge.
- Slag tap burner control system.
- Nitrogen purges and use of nitrogen throughout system.

Certain other major points were raised:

- Generation of mass and energy balances.
- Further thermal analysis to predict combustion temperatures and refractory wall temperatures in each section.
- Thermal analysis of upset conditions, and of the water-cooled piping and scrubber.
- Possible early failure of the main burner barrel nose.

Most of these points have also been addressed in the Hazards Analysis carried out by Hercules, Inc., subsequent to the design review, and alternatives or resolutions are summarized within the Hazards Analysis Report (see Appendix B of this report).

3.6 HAZARDS ANALYSIS

A top level fault tree analysis* was performed by IITRI in order to establish a basic control system design philosophy. Based on the results, the control system was designed to provide two levels of visual and audible alarms as well as three levels of automatic shutdown modes.

The first shutdown mode is called the burner 'turndown' or 'low fire.' When the burner system is tripped into this mode, the main burner goes to its minimum firing rate, the lances are turned off, the vessel depressurizes, and the slag injection system goes into a full bypass mode. This is the same as the 'low fire' mode except that the main burner is completely shut off. Both natural gas and O_2 are shut off at the burner system pipe rack. The final shutdown mode is the 'emergency shutdown', in which the entire system (with the exception of the water pumps) is completely shut down. In this case, both the natural gas and O_2 are shut off at the source. All shutdown modes can be initiated from the main control panel.

In addition to the control system considerations, the top level fault tree analysis provided some insight as to the rupture disc and relief valve sizing. It pointed out many of the dangers inherent in this type of a system and the care with which it must be designed.

*A brief explanation of a fault tree analysis is given in Appendix D.

As the design of the refractory test system neared completion, the IITRI design team performed a failure modes and effects analyses (FMEA). A sample sheet from this 29-page document can be found in Appendix E. Based on discussions with the ORNL Review Team, it was felt that the design of the system was sound and, with some modifications and additions, would be safe to operate. It was decided that an outside organization should do a formal analysis of the system. This would then mean that the refractory test system would have been reviewed by three separate groups: IITRI, Oak Ridge National Laboratory, and the contracted organization. After several quotations were received, Hercules Inc. (which is part of the Allegany Ballistics Laboratory) was contracted to do the Hazards Analysis.

All the required information was submitted to Hercules during a two-day on-site visit by them and amplified by subsequent telephone conversations and written communications. On October 2, 1980, Hercules visited IITRI and presented preliminary findings. Over 200 possibly hazardous events were considered and 49 were found to have a probability of 1×10^{-6} per hr or greater. These events were discussed in detail with Hercules during this visit. Changes in the design and/or operating procedures of the test facility were made which eliminated all hazards with greater than one in a million probability or which endangered personnel. These changes are incorporated in the final construction and operation of the facility. A further hazard analysis was made after completion to ensure that all modifications were incorporated satisfactorily without introducing additional hazards, and to insure that the procedures are sound and are carried out during operation. This Hazards Analysis Report forms Appendix B of this report.

3.7 OPERATING PERSONNEL

Safe operation of the refractory test unit is of paramount importance, and long discussions have been held on this subject both during the project review, and during the Hazards Analysis site visit. Major points to emerge from these discussions were:

- A comprehensive operating and maintenance manual must be provided for the operators.
- The operators must be formally trained.
- The operators must be adequately supervised at all times.

- Supervisors must be formally trained and given clearly defined responsibilities and authority.
- Comprehensive safety procedures must be set up and rigidly adhered to with penalties for noncompliance.

In general, this will require a departure from procedures used on smaller laboratory projects at IITRI, and pilot plant type procedures will dominate. This also applies to the working hours and shift schedules of operating personnel. A more formal arrangement than usual in laboratory-scale equipment will be necessary to ensure that this complex system is operated safely at all times.

3.7.1 Operating Manual

The Operating Manual was completed. It details normal operation of the unit, as well as the safety modes and calibration procedures. Reference lists of valves, flowmeters, thermocouples, and setpoints are included; it also details all emergency procedures to be followed.

3.7.2 Operator Training Program

Operation of laboratory equipment is usually the responsibility of technicians, with very little formal training, who learn by experience how to cope with problems as they arise. This refractory test system has a number of features which make the traditional laboratory approach unacceptable:

- Size and weight
- Complexity and size of subsystems
- 24 hr per day manual operation
- Large, pressurized system
- Gas/oxygen burner operating at pressure
- Molten slag being handled in quantity.

A formal training program was instituted to ensure that shift operators became fully conversant with the controls, maintenance, and possible hazards involved.

3.8 CURRENT STATUS

Construction of the test facility was essentially completed by July 31, 1981. A two-phase shakedown schedule of the test facility was developed by

IITRI and approved by DOE and ORNL. Phase I consisted of subsystem check-out and, also, work necessary to conform to the preliminary hazard analysis.

Phase II was the integrated check-out, shakedown, and the familiarization of the personnel with the operation of the facility. A progressive check-out and shakedown approach was formulated which moved from a low probability of any system failure to an increased probability of a failure. This approach also provided the operating team with time to familiarize themselves with the operation of the test facility.

Phase II was divided into tasks and was established as follows:

- Task 1 - Run cold at atmospheric conditions (compressors, pumps, generator, and slag injection and removal systems all run at same time to check entire system and familiarize personnel with operation).
- Task 2 - Run cold, but at a pressure of 100 psi.
- Task 3 - Assembly of auxiliary nozzle and equipment for low temperature heat-up of unit and dry out of refractories.
- Task 4 - Run through entire system with all burner systems to be fired at atmospheric conditions.
- Task 5 - Go through complete start-up procedure with Process Combustion Corp. representatives present.

Task 1 was completed without any observable problems. Task 2 was successfully completed with minimal problems. Task 3, assembly of auxiliary nozzle and equipment for low temperature heat-up of unit and dry out of refractories, was started immediately upon completion of Task 2.

The main burner supplied too much heat even at low firing to safely heat-up the test unit at approximately 100°-150°F per hour. In order to bring the unit up to a safe temperature (1500°F) to light the main burner, a North American "Aardvark 4492A" burner, a compact, high-velocity air heater, was purchased and installed in the test unit. With suitable sized gas accessories, the Aardvark can deliver air at any temperature from 300° to 1600°F. Even higher temperatures are possible with suitably constructed hot air delivery piping and heating enclosures. Air temperature of the discharge of the Aardvark must be high enough to overcome radiation losses in the transmission piping, and the piping must be compatible with these temperatures. Insulation can be applied to the transmission piping as long as this does not cause

excessive temperature buildup in the piping. A stainless steel smoke pipe was used as the transmission pipe to bring the hot air through the slag tap vessel to the main test vessel. The installation of this burner marked the completion of Task 3.

Task 4, run through entire system with all burner systems fired at atmospheric conditions, was successfully completed during the first week of January 1982. After a slow heat-up, using the Aardvark burner, to 900°F the main burner was ignited and run for 9 hr. During this time, both the air and gas lances were fired off satisfactorily and the test section bricks were heated up to 1600°F.

Task 5, go through complete start-up procedure with Process Combustion Corp. representative present, was successfully completed during the last week of January 1982. The unit was heated up slowly to 900°F using the Aardvark burner at which point the main burner was ignited. Using the main burner, the unit was brought up to a temperature of 2000°F and a pressure of 80 psi. As of the conclusion of this run, all systems with the exception of the slag injection system have been tested during integrated operation of the unit and have been found to operate satisfactorily. The slag injection system has been tested and found to be operational under cold conditions. While future problems may present themselves with the slag system, an improved design for the slag removal system has been drawn up and will be implemented if, in the future, the slag removal system should not work according to the design. This system allows regulation of the amount of slag removed by restriction of the hydroclone outlet as opposed to constriction of the pressure letdown valves, which could lead to clogging of the valves.

The report from Hercules, Inc., on the Hazard Analysis of the test facility and its operation was received during the first week of December 1981. A preliminary analysis of the report was given on October 15, 1981 by C. A. Angoli of Hercules, Inc., Allegany Ballistics Laboratory, Cumberland, Maryland. In their opinion, the test facility construction and operation procedure were satisfactory. However, they recommended a few items which they considered would be of benefit to the test facility. These are listed below:

- 1) Install audible and visual alarms from gas detectors outside of gas compressor enclosure and on the control panel - done.

- 2) Move gas compressor switch to outside of gas compressor enclosure - done.
- 3) Control room and gas compressor room exhaust fans should have flow switches - not to be done.
- 4) Both fans to start automatically - not to be done.
- 5) Overhead roof fan to start automatically - not to be done.
- 6) Additional gas alarms to be put on burner pipe rack - done.
- 7) Platform on top of vessel - designed
- 8) Face shields and breathing apparatus - purchased.
- 9) Flow switch for N₂ purge - not to be done.
- 10) Insulation around scrubber - done.
- 11) Level controls for slag tap vessel - designed and purchased.
- 12) Clock for control room - done.
- 13) Install limit switch on main burner gas and oxygen for gas lance purge valves and light on panel to indicate they are closed - not to be done.
- 14) Install controls on panel for slag tap vessel drain - done.

The final Hazard Analysis Report forms Appendix B of this report.

4. CONCLUSION

This operational test facility (see Figure 22), which was found to operate as designed, has been deeded to IITRI. At present, promotion is under way to encourage sponsorship of test work using this test facility.

Figure 22. Top and part of middle section of main test vessel.

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APPENDIX A
FINAL REPORT - TASK A

NOTE

FINAL REPORT, TASK A, CONCEPTUAL LINER DESIGNS

Pagination which is sequential but not consecutive is as follows:

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Abstract

1. Refractory materials used to line slagging coal gasifiers must have the necessary properties to resist gaseous atmospheric corrosion, solution by molten slag and erosion by particulate matter in the 2300⁰F to 3300⁰F temperature range. A ternary system diagram is used to classify oxidizing and reducing environments. Various ratios and phase diagrams are used to classify slags.
2. Details of design are presented to minimize loss of refractory by spalling.
3. Conceptual refractory lining designs are illustrated for the slagging zone of an 18 foot diameter gasifier for typical eastern and western coals.

Variations are shown to adapt these designs to cover a range of oxidizing and reducing conditions.

Cooling systems, slag taps and injection ports are discussed and illustrated.

4. The final choice of a lining should be based on the total cost of a lining system over the life of the coal gasifier.
5. A novel approach to slag removal is discussed and illustrated.
6. Recommendations are made to consider the findings of this study preliminary until they are confirmed by subsequent work on Phases B through F of this program.

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TASK ACONCEPTUAL DESIGNS FOR REFRACTORY LININGS OF SLAGGING GASIFIERS1.0 SUMMARY

This report documents the work done by the Arthur G. McKee Company under Task A, "Conceptual Designs" of DOE Contract No. ET-78-C-01-2785, "Design, Engineering and Evaluation of Refractory Liners for Slagging Gasifiers" between the United States Department of Energy and IIT Research Institute, 10 West 35th Street, Chicago, Illinois, 60616 under the direction of Mr. Wate T. Bakker, Division of Systems Engineering, Department of Energy, Germantown MD 20767.

The overall objective of this task was to develop refractory lining systems which will provide minimum refractory wear at low total heat loss.

Parameters and conditions affecting the conceptual design of refractory linings for slagging gasifiers have been explored. Lining designs have been developed which take advantage of refractory properties and which take into account, characteristics of raw materials and operating processes.

1.1 Character of Slagging Gasifiers

Slagging gasifiers comprise an important segment of second-generation coal gasification processes currently under investigation for production of medium Btu fuel gas and synthesis gas. Fortunately, the temperatures, atmospheres and slag compositions in slagging gasifiers are approximately the same as in ironmaking blast furnaces. The gas generated in blast furnaces has a heating value of about 85 Btu/SCF, whereas that of slagging gasifiers has a heating value from 100 to 300 Btu/SCF. Major differences in gas composition are expressed by the CO/CO₂, H₂/CO and H₂/H₂O ratios and by the CH₄ and N₂ concentrations in the gas stream.

Slagging gasifier concepts include Lurgi, Koppers-Totzek, Otto-Rommel, BI-GAS, Combustion Engineering, Babcock and Wilcox, Foster Wheeler, and Texaco. This list is only intended to indicate the general class of gasifiers to which this work might apply and is not comprehensive.

Slagging gasifier processes are designed to optimize two basic functions:

1.1.1 Continuous removal of liquid coal ash slag; and

- 1.1.2 Rapid high-temperature conversion of tars to carbon monoxide, hydrogen and methane.

Maximum operating temperature of these gasifiers varies from about 2300°F for current fixed bed systems to as high as 3300°F for some entrained bed systems. Operating pressures for these gasifiers range from atmospheric pressure to 1000 psi.

The high operating temperatures of slagging gasifiers cause unusual design, materials and operational problems with refractory linings. Close control of the temperature, the composition and the state of oxidation of the slag is essential to control the viscosity and affect optimum slag removal.

1.2 Special Features of Slagging Gasifiers

Attention has been given to the following details of slagging gasifiers, particularly as they affect the refractory lining.

- 1.2.1 Heat losses through the walls
- 1.2.2 Expected refractory life
- 1.2.3 Stress and strain in lining due to heat-up, cool down and thermal cycling
- 1.2.4 Design and construction of slag tap holes, internal supports and injection ports for coal, char, steam, air and/or oxygen
- 1.2.5 Reliability of cooling system
- 1.2.6 Usage of rejected heat
- 1.2.7 Effect of operating pressure on lining design

1.3 Parameters for Conceptual Design

Slagging gasifiers ranging in size from 10 to 30 feet ID have been considered. Conceptual designs of lining systems for 18 foot diameter slagging gasifiers are presented which can be scaled up or down to cover the full size range. A variety of coal feed stocks and gasification environments have been taken into account to make the results as useful as possible. Conceptual designs have been based on material properties available in the literature and refractory technology from related industries including blast furnaces, slagging boilers, high pressure chemical process reactors, glass tanks and both acid and basic refractory lined metallurgical refining furnaces.

1.4 Auxiliary Systems

All auxiliary systems which affect refractory performance have been considered.

- 1.4.1 Water cooling systems of three varieties are shown to protect refractories walls.
 - a. Copper plate coolers for heavy (over 18") brick walls
 - b. Cast iron stove coolers for intermediate thickness walls lined with brick or monolithic refractory materials
 - c. Studded tubes for thin walls protected by a layer of plastic refractory and slag
- 1.4.2 Water or air cooling systems are shown for oxide refractory bottoms and nonoxidizing heat transfer fluid cooling systems for carbon refractory bottoms. Both varieties have provisions to ventilate the under side of the refractory coolers to protect the foundation or the bottom of the containment vessel.
- 1.4.3 A conceptual design of a water cooled slag tap for the continuous removal of slag is included for each of the design variations.
- 1.4.4 Differential refractory expansion provisions are designed into the brick work to prevent shear failures between the bottoms and side walls. Cooling systems are designed to be compatible to minimize differential expansions due to temperature gradients. A procedure for providing the correct amount of expansion in brick linings is presented as an example in Paragraph 5.4.

1.5 Cost Considerations

- 1.5.1 The initial cost of the refractory lining for a slagging coal gasifier may only represent from two to fifteen percent of the cost of the complete reactor depending on the operating pressure. Two percent is for a high pressure gasifier to make SNG. Fifteen percent is for a gasifier operating at less than 15 psig to make low Btu gas. The refractory lining cooling system may add another eight to ten percent, bringing the total initial cost of the lining to from ten to twenty five percent of the cost of the complete reactor.
- 1.5.2 Since the lining may have to be replaced many times during

the life of the containment vessel, the total cost of the refractory lining should reflect the initial cost plus the total cost of all subsequent relines including consequential costs and the indirect cost of down time. When defined in this manner, the lining system may represent more than fifty percent of the total cost of the reactor.

- 1.5.3 The choice of a lining system should be based on an economic analysis which reflects the total cost of the lining system over the life of the coal gasifier. For example, a blast furnace bottom with the lowest initial cost may last from three to five years. The best carbon bottom, which may have an initial cost of twice as much, normally lasts over fifteen years. The carbon bottom, however, has the lowest total cost per ton of iron produced.

2.0 CONCEPTUAL DESIGN

Each coal gasification process and each classification of coal to be gasified has its own set of operating conditions and restraints. A conceptual design based on a complete evaluation of all refractory requirements for all gasification processes is beyond the scope of this Program. An examination of some of the common refractory lining problems encountered in slagging gasifiers illustrate the range of possibilities and include most of the problems expected to be found in the design of a lining for a slagging gasifier.

- a. Process atmospheric corrosion (oxidation or reduction). A simple procedure using atom fractions of carbon, hydrogen and oxygen in the process gas, plotted on a ternary system diagram is provided in paragraph 3.1 for making an initial judgement as to whether the atmosphere should be considered as oxidizing or reducing insofar as refractories are concerned.
- b. Coal ash corrosion (fluxing). The interrelation of refractory and slag properties are considered in paragraph 3.2.

All forms of corrosion depend on the operating temperature level. High temperatures are generally, but not always, more damaging than moderate temperatures.

- c. Erosion is related to corrosion and abrasion.
- d. A fourth consideration, spalling, depends on the thermal expansion and other physical properties of the brick, details of the design and installation of the refractories and temperature changes during start-up, during normal operations and during shutdown. Frequently, damage is cumulative, limiting the life expectancy of a lining to the number of such cycles.

Each of the above problems are treated in relation to the others because of the inter-action that is always present.

The presence of hydrogen must be taken into account because of its high conductivity and its effect on the conductivity of porous refractory materials.

The gasification step is highly endothermic, and part of the difference among processes depends on how energy is supplied to and removed from the gasifier, and how the temperature is controlled.

Fortunately, refractory requirements for coal gasification units are similar to those for certain metallurgical and chemical process vessels.

Experience in steel, nonferrous metals, chemical and glass plants can be used to establish estimated process /conditions.

Various designs are presented for the linings of 18 ft. diameter coal gasification reactor vessels. These designs are applicable to commercial slagging coal gasifiers having inside diameters ranging from 10 to 30 feet.

The following variations are shown:

2.1 Carbon Refractory Linings

An all-carbon lining with brick walls and a block bottom is illustrated in figure 1 for strongly reducing atmospheres and slags which contain an appreciable amount of iron such as Baldwin Illinois or Montana Rosebud. An analysis of the ash in these coals is shown in Table 3.1, paragraph 3.3. The bases-to-acids ratios are 0.46 and 1.01 when iron is included as a base and are 0.14 and 0.56 when calculated on the usual blast furnace basis. The total iron oxide, expressed as Fe_2O_3 , is 18.4 and 22.1 percent. The atmosphere is likely to be strongly reducing if the object of the gasifier is to make low or medium Btu fuel gas or carbon monoxide-rich synthesis gas. For this purpose, partial oxidation would be carried out by use of from 35 to 45 percent stoichiometric oxygen and no steam. Air or oxygen would be used as the oxidant depending on the end use of the product gas. Unreacted carbon would be recycled. Since the atmosphere is strongly reducing, and there is substantial iron oxide present, some liquid iron and ferro-silicon can be expected to be found in the slag. This hot metal is difficult to contain by ordinary refractories. However, carbon refractories routinely give many years of service under similar conditions in the hearth of blast furnaces. Since the alkali content of the ash from these coals exceeds 2 percent, an alkali resistant grade of carbon should be used. The walls are shown 13-1/2 inches thick and are cooled with water in cast iron staves. The bottom is shown about 70 inches thick and is cooled with a nonoxidizing heat transfer liquid such as DOWTHERM A. The shape of the bottom, carbon thickness and high temperature heat transfer fluid have been selected to maintain a continuous layer of slag on the bottom between two and three times the thickness of that flowing down the walls.

2.1.1 The lining illustrated in figure 2 with a carbon block bottom and acid brick walls is intended for situations where the process atmosphere is not sufficiently reducing for carbon refractories to be used in the walls and flux stone is not used in the process. The walls could also be built of monolithic materials with properties similar to acid oxide brick. A temporary sacrificial layer of fire brick or monolithic refractory must be provided to protect the bottom during the initial operating period while the slag layer is building up. The shape of the bottom is calculated to maintain a layer of slag to protect the carbon from the process atmosphere at all other times.

- 2.1.2 The lining illustrated in figure 3 with a carbon block bottom and basic brick walls is intended for situations where the process atmosphere is not sufficiently reducing for carbon, the temperatures are exceptionally high and the slag is basic. The walls could also be built of monolithic materials with properties similar to basic oxide brick. Protection against oxidation of the carbon is the same as par. 2.1.1

2.2 Ceramic Oxide Refractory Linings

Acid and basic refractory oxide brick linings are illustrated in figures 4 and 5 for atmospheres which are not strongly reducing. The walls could also be built of monolithic materials with properties similar to the refractory oxide brick illustrated.

- 2.2.1 The lining shown in figure 4 is intended for acid slags such as might be expected from Dave Johnson Wyoming bituminous coal or Keystone Pennsylvania Appalachian coal without lime addition.

- 2.2.2 The lining shown in figure 5 is intended for basic slags such as might be expected from Montana Rosebud coal which has been fluxed with additional limestone.

Conditions within the slagging region of the gasifier dictate the choice of refractories which govern the design of the lining.

These designs are based on stove cooling of intermediate thickness. Heavy linings cooled with copper plates and thin linings cooled with steel studs are illustrated for comparison in figures 6 and 7. All variations are water cooled.

2.3 Slag Taps and Injection Ports

The long term containment of a average environment of a slagging coal gasifier inside a pressure vessel without discontinuities in shape and without openings would represent a challenge. Fortunately, it is a specific environment and not averages that have to be contained. Specific refractories are available for specific atmospheres ranging from highly oxidizing to highly reducing. None of them are suitable for all atmospheres. Likewise specific refractories are available for specific slags ranging from strongly acid to strongly basic. None of them are suitable for all slags. The real challenge is to protect the lining around an opening without compromising the integrity of the lining. Conceptual designs of slag taps and injection ports illustrate the problems and proposed solutions.

- 2.3.1 Slag taps are required to remove all of the residue that is left over after the hydrocarbons in the coal have been gasified. This could amount to 200,000 ton for an operating period of three years for a 2000 ton per day unit gasifying coal with ten percent ash. This service is expected to be trouble free and without benefit of repairs or maintenance.
- 2.3.2 The temperature of the slag as it flows through the slag tap should equal, or at least approach, the maximum temperature in the process. If it does not, some highly refractory masses of slag will eventually be softened and moved to where they will block the passage and the process will surely be shut down because a gasifier can not run very long after the slag tap has become inoperative.
- 2.3.3 The purpose of an injection port is to introduce something into the gasifier. The concentration and temperature of reacting materials within the vessel in the immediate neighborhood of an injection port is invariably different than elsewhere. This fact by itself is a serious disruptive influence. If the localized reaction is exothermic, the localized temperatures are higher. If it is endothermic because coal is being introduced, the localized atmosphere is likely to be highly reducing. If it is endothermic because steam is being introduced, the localized atmosphere is likely to be highly oxidizing at the prevailing temperature. Refractories which are perfectly suited and adequate for the average conditions within the gasifier may be totally inappropriate near an injection port.

2.4 Energy Recovery

Commercial gasifier designs may incorporate waste heat recovery systems to improve the overall energy efficiency of the process. Possible recovery of sensible heat and pressure energy from the exit gas and cooling systems needs to be anticipated during the design stages of a plant. The enthalpy of exit gases may be recovered in expander, gas, steam or combined cycle turbines to generate electrical power. Energy may be also recovered from cooling systems which are provided to cool the vessels and linings. The temperature in refractory walls may be maintained at levels which are satisfactory for the refractories by evaporative cooling. At the same time, heat loss through the lining can be reduced by maintaining a cold face temperature above that resulting from the more common water cooling. The thickness of the refractory for this construction is generally less than for a water cooled lining. The savings in refractory costs partially offsets the extra cost of evaporative cooling systems over water

cooling systems. The heat absorbed by evaporative cooling is normally removed at considerable expense by cooling towers or other costly means but could have some value for space heating or other purposes.

The temperature of refractory bottoms may also be controlled by high temperature organic heat transfer fluids such as DOWTHERM "A". It is theoretically possible to generate electrical power by such a system.

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FIGURE 1
CONCEPTUAL DESIGN
CARBON REFRACTORY LINING
SLAGGING COAL GASIFIER

FIGURE 2
CONCEPTUAL DESIGN
CARBON BOTTOM-ACID BRICK WALLS
SLAGGING COAL GASIFIER

FIGURE 3
CONCEPTUAL DESIGN
CARBON BOTTOM-BASIC BRICK WALLS
SLAGGING COAL GASIFIER

FIGURE 4
CONCEPTUAL DESIGN
ACID REFRACTORY LINING
SLAGGING COAL GASIFIER

FIGURE 5
CONCEPTUAL DESIGN
BASIC REFRACTORY LINING
SLAGGING COAL GASIFIER

FIGURE 6
CONCEPTUAL DESIGN
COPPER PLATE COOLED WALL
SLAGGING COAL GASIFIER

FIGURE 7
CONCEPTUAL DESIGN
STUDED MEMBRANE WALL
SLAGGING COAL GASIFIER

FIGURE 8

**CONCEPTUAL DESIGN
BOTTOM CONTOURS
SLAGGING COAL GASIFIER**

FIGURE 9

SLAG TAP HOLE
CARBON REFRACTORY LINING
SLAGGING COAL GASIFIER

FIGURE 10

TRANSVERSE CROSS SECTION
CARBON REFRACTORY LINING
SLAGGING COAL GASIFIER

FIGURE 11

**SLAG TAP HOLE
CERAMIC REFRACTORY LINING
SLAGGING COAL GASIFIER**

FIGURE 12
TRANSVERSE CROSS SECTION
CERAMIC REFRACTORY LINING
SLAGGING COAL GASIFIER

FIGURE 13

SLAG TAP HOLE
BLAST FURNACE STYLE
SLAGGING COAL GASIFIER

FIGURE 14
INJECTION PORT
BLAST FURNACE STYLE
SLAGGING COAL GASIFIER

3.0 GASIFIER OPERATING CONDITIONS

Service conditions for representative slagging coal gasifiers have been investigated with emphasis on processes for making low to medium Btu fuel gas and synthesis gas. These conditions have been characterized in such a way that an appropriate lining can be specified and designed. The most important factors to be considered in the selection of refractories for coal gasification environments over 2300°F are process atmospheric corrosion and corrosion by coal ash slag. Erosion is a function of gasifier's operating conditions and must be considered but generally does not govern a design. Spalling is not a function of normal gasifier operating conditions but is of concern to designers, refractory manufacturers and operators. All refractories suitable for use in coal gasification have a limitation on how fast they can be brought up to operating temperature. Blast furnace start-ups are planned to limit temperature rise of blast furnace quality brick to 150°F per hour. Coke ovens which are built of silica brick have very severe heating and cooling limitations through temperatures where phase changes occur in silica. This report is based on the understanding that appropriate limits on the rate of temperature change will not be exceeded.

3.1 Process Atmospheric Corrosion

The first consideration in designing a refractory lining for a slagging gasifier is to find a material that will stand up to the expected temperature in an atmosphere of hydrogen, steam, carbon monoxide, carbon dioxide, hydrogen sulfide and/or sulfur dioxide. The second consideration is to find a material that in addition to withstanding the high temperature process atmospheric corrosion, will also withstand the fluxing action of coal ash which may be either acidic or basic. The third consideration is to find a material that can withstand the erosion to which it will be subjected under operating conditions.

Reducing gases, primarily H₂ and CO will attack silica containing refractories at low pressures and high temperatures, while steam and CO₂ are aggressive at high pressures and high temperatures. In a reducing atmosphere, coal ash which contains iron is more corrosive to alumina-silica refractories than it is in an oxidizing atmosphere of the same temperature. Magnesite, on the other hand, may dissolve relatively large amounts of ferrous oxide in a reducing atmosphere without apparent damage. High pressure (1000 psig) steam-rich atmospheres tend to accelerate refractory deterioration. Lower pressure (0-100 psig) favor attack by hydrogen-rich atmospheres.

There is probably no one material which will meet all these requirements. High-alumina refractories which are inherently abrasion resistant and are inert to an acid slag, can usually

contain coal gasification atmospheres and will effectively resist attack by steam, the most aggressive agent at high pressures. Under some conditions it is necessary or desirable to include chromic oxide in the formulation of high-alumina refractories manufactured for coal gasification service. One purpose of the chromic oxide is to react favorably with ferrous oxide in preference to alumina. Another reason is to take advantage of the very high melting point of chromic oxide (over 4100°F) which is about 400°F higher than the melting point of pure alumina. Fortunately there are no low temperature eutectics in the alumina-chromic oxide system.

Corrosion of refractories by steam involves extraction of soluble oxides or hydroxides and formation of silicic acids from aluminosilicates. Since most pre-fired alumina refractories develop their strength and coherence through siliceous bonds, steam at elevated temperatures and pressures can readily cause softening and deterioration. High-alumina, cement-bonded materials, in which calcium aluminates bind the alumina or aluminosilicate aggregates, do not exhibit such surface deterioration and may be a better choice for lining some vessels than pre-fired materials of the same alumina content.

High-alumina materials which are phosphate bonded may also be preferred for some coal gasification applications. The extraction of phosphorus pentoxide, present as AlPO_4 , ($\text{Al}_2\text{O}_3 + \text{P}_2\text{O}_5 = 2 \text{AlPO}_4$) in hydrogen-rich atmospheres has not proved as damaging as previously predicted. This lack of reaction between phosphorus and hydrogen may indicate that coal gasification atmospheres with a high partial pressure of steam, are oxidizing with respect to phosphorus bonds and not reducing even though there is an apparent excess of hydrogen and carbon monoxide. Phosphate bonded materials still need to be checked out for coal gasification service under highly reducing conditions with very low partial pressures of steam.

The temperature and the oxidizing or reducing characteristics of the process gases as simultaneously expressed in terms of the ratios $\text{H}_2/\text{H}_2\text{O}$ and CO/CO_2 need to be established before the lining of a slagging gasifier can proceed. The partial pressure of steam in the gas must also be considered independently of the foregoing ratios. In order to classify a coal gasification atmosphere where the foregoing ratios are not known, it has been found useful to calculate the atom fractions of oxygen, hydrogen and carbon and plot them on a normalized ternary system diagram.

For this calculation, oxygen includes all atoms of oxygen in combustion air, steam and fuel except those bound in minerals forming the ash. Hydrogen includes all atoms of hydrogen in fuel and steam. Carbon includes carbon atoms in gaseous species plus solids and liquids if any.

For purposes of this discussion, it is convenient to classify atmospheres as oxidizing or reducing in terms of stoichiometric combustion ratios (FSA)* of pure hydrocarbons as follows:

<u>FSA</u>	<u>Atmosphere</u>
0-0.25	Reducing
0.25-0.50	Reducing/transition
0.50-1.00	Oxidizing/transition
over 1.00	Oxidizing

*FSA = Fraction of stoichiometric air

If the composition of the products of partial oxidation in a coal gasifier falls in the oxidizing/transition or the reducing/transition range of FSA values, the atmosphere may be either oxidizing or reducing depending on the temperature, pressure, minor constituents, relative reaction rates, etc. These conditions are shown graphically on the ternary system diagram of figure 15. Lines representing FSA = 1.0, FSA = 0.5 and FSA = .25 for any hydrocarbon, CH_n , containing no oxygen, can be found on lines drawn through a common point on an extension of the carbon-hydrogen axis with virtual coordinates, 1.33H, - .33 C.

The line connecting H_2O and CO_2 represents complete (stoichiometric) combustion of CH_n . The point found at the intersection of this line and the line through CH_n and O_2 defines the atom fractions of oxygen, hydrogen and carbon for FSA = 1.0

The line connecting $H_2O_{1/2}$ (.20 O, .80 H) and CO represents combustion of CH_n with 50 percent theoretical oxygen. The point found at the intersection of this line and line through CH_n and O_2 defines the atom fractions of oxygen, hydrogen and carbon for FSA = 0.5.

The line connection $H_2O_{1/4}$ (.11 O, .89 H) and $CO_{1/2}$ (.33 O, .67 C) represents combustion of CH_n with 25 percent theoretical oxygen. The point found at the intersection of this line and line through CH_n and O_2 defines the atom fractions of oxygen, hydrogen and carbon for FSA = .25.

The composition of raw materials and/or product gas of 30 coal gasification plants and pilot plants, which operate above 2000°F, is shown on the ternary system diagram in figure 15. In some cases, the atom fractions of carbon, hydrogen and oxygen were based on the volume percentages of CO, CO_2 , H_2 , H_2O and hydrocarbons in the product gas. The hydrogen, carbon and oxygen

atoms in sulfur compounds are also included. In other cases they were based on the weight and ultimate analysis of all raw materials used in the manufacture of the gas including moisture and oxygen in the coal and combustion air. Oxygen in the ash was not included.

The atmosphere is reducing in processes represented by atom fractions in the zone, $C - CO_{1/2} - H_2O_{1/4} - H_2$.

In the reducing/transition zone, $CO_{1/2} - CO - H_2O_{1/2} - H_2O_{1/4}$, other factors such as temperature, pressure and presence of sulfur and catalysts determine whether the atmosphere is oxidizing, neutral or reducing with respect to any particular refractory. The operating conditions for all of the 30 gasification processes shown on figure 15 fall in the reducing/transition zone.

The atmosphere is oxidizing in processes represented by atom fractions in the zone $CO_2 - O_2 - H_2O$. Products of combustion with excess air fall in the oxidizing zone.

In the oxidizing/transition zone, $CO - CO_2 - H_2O - H_2O_{1/2}$, other factors such as temperature, pressure and presence of sulfur and catalysts determine whether the atmosphere is oxidizing, neutral or reducing with respect to any particular refractory. The products of combustion under boilers, where less than stoichiometric air is used to suppress nitrogen fixation, fall in the oxidizing/transition zone.

The atom fractions can be calculated from the quantities and ultimate analysis of the materials going into the gasifier or from the volumetric analysis of the gas coming out. For multi-stage gasifiers, each stage must be treated as a separate gasifier if the atom fractions are to be useful in selecting suitable refractories.

In order to illustrate the procedure used to calculate the atom fractions, the following example is presented:

90 pounds of oxygen and 12 pounds of steam are used to gasify 100 pounds of coal. The 100 pounds of coal includes 3 pounds of moisture and 78 pounds of carbon. The hydrogen and oxygen content of the coal, excluding these elements in the moisture and ash, amount to 5.3 and 6.7 pounds. The products of (partial) combustion, expressed as a percent by volume are:

58 CO , 4 CO_2 , 25 H_2 , 4 H_2O , 3 CH_4 , 0.5 H_2S , 0.1 COS plus species which do not contain carbon, hydrogen or oxygen.

ATOM FRACTIONS BASED ON FEED

	<u>C</u>	<u>H</u>	<u>O</u>
100 pounds coal	78.0	5.3	6.7
90 pounds oxygen			90.0
15 pounds moisture		1.7	13.3
Total in pounds	78.0	7.0	110.0
Atomic weight	12.	1.	16.
Pounds/atomic weight	6.5	7.0	6.9
Atom Fractions	.32	.34	.34

ATOM FRACTIONS BASED ON PRODUCT

	<u>C</u>	<u>H</u>	<u>O</u>
58 CO	58		58
4 CO ₂	4		8
25 H ₂		50	
4 H ₂ O		8	4
3 CH ₄	3	12	
0.5 H ₂ S		1	
0.1 COS	.1		.1
Total	65	71	70
Atom fractions	.32	.34	.34

When this point is plotted on the ternary system diagram of figure 15, it is found to be in the transition/reducing zone, indicating that the more stable oxide refractories such as alumina, chromic oxide or magnesia would be appropriate as far as the atmosphere is concerned. Carbon refractories should also be considered. The atmosphere is probably too reducing for refractories which contain any free silica. The actual lining material to use would depend on the operating temperature and slag composition. The 90 pounds of oxygen used in this example is 37 percent of that required for complete combustion. The gas in this example has the

same degree of oxidation as a mixture of pure hydrocarbons (such as 3% methane and 97% benzene) oxidized with 42 percent of the amount of oxygen required for complete combustion.

3.2 Corrosion By Coal Ash Slag

Coal ash slag is very corrosive to most refractories. The eutectic formed when slag comes into contact with refractories has a relatively low melting point and will frequently cause further deterioration of a lining by dissolving the refractory itself. Liquid iron and sodium carbonate are especially corrosive to many refractories. Carbon refractories are good to resist liquid iron and molten slag, however carbon is not suitable for use in an oxidizing atmosphere. Fused cast alumina refractories will resist molten sodium carbonate but are subject to spalling.

Since all of these problems are related to temperature, it is important to take advantage of the conductivity of the refractory materials. High conductivity material is used in connection with cooling to freeze a layer of protective slag. Lower conductivity materials are used to maintain temperatures within acceptable limits.

In order for design work to proceed, the temperature, composition and state of oxidation of the slag must be known or assumed. The estimated viscosity as a function of these variables can be used as a basis for the design if measured values of viscosity are not obtainable.

All refractories except carbon and all slags may be divided into three classes based on their chemical composition: (a) acid, (b) amphoteric or neutral, and (c) basic. Examples of refractories, used for coal gasification, which fall in these classes are: alumina, chromic oxide and magnesia. The usual criteria for classifying refractories and slags is the

Bases-to-acids ratio; $B/A = (CaO + MgO + FeO + Fe_2O_3 + MnO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_3 + TiO_2 + P_2O_5)$

For some purposes a molar basis is used for this ratio; for other purposes, a simple weight basis calculation is made of lime plus magnesia divided by silica plus alumina. Ratios greater than unity are usually considered basic. In general, an acid refractory will resist an acid slag but will be attacked by a basic slag and conversely. The larger the difference between the B/A ratio of the refractory and slag, the more severe the attack. However, this is only a rough qualitative indication of the direction of the reaction. Temperature levels also have a great deal to do with what refractory will resist what slag.

If phase diagrams for all important systems for both refractory and slag are available, a more confident prediction can be made of reactions and reaction temperature. However, both refractories and slags at high temperatures may consist of several crystalline, amorphous and liquid phases which may not be in equilibrium and, in the case of slags, are changing with operating conditions. Unfortunately, phase diagrams are usually not available. If phase diagrams are available, the actual phases present are not necessarily known. It is therefore essential to assess slag resistance of refractories by tests or observation in service under conditions which are truly representative.

In a slagging gasifier, the residue of coal or char particles after gasification is an ash which melts, agglomerates and collects on the walls of the gasifier. There is an interchange of material between the slag and refractory until a dynamic equilibrium is reached which, in practice, may never occur. In the process, certain components in the slag, such as arsenic and alkalis can be concentrated in the refractory, and more importantly, in certain components of the refractory, especially grain boundary phases. These essential boundary phases may be fluxed in the slag and carried away.

Constituents of the refractory which are depleted by diffusion through a stable slag layer will be swept away by the flowing slag. Any upset in this condition such as an increased flow of slag or an increased heat flux causes a loss of the slag layer which protects the refractory surface. In case a stable slag layer does not develop, the slag will dissolve chemical constituents directly from the refractory as it moves down or across the surface of the refractory lining. Wastage is controlled by the solubility of the various refractory constituents in the slag, the total slag flow across the refractory surface and the length of time during which slag remains in contact with the refractory.

The slag composition will vary in different parts of the gasifier depending upon (a), temperature and oxidation/reduction characteristics of the process gas (b), the point in the process where the slag is released and (c), the contamination, if any, of refractory components previously fluxed. In the more reducing regions, the slag is often strongly reducing. The composition of the slag formed from the same coal burned in a boiler furnace under oxidizing conditions and condensed on water tubes is normally oxidizing.

The degree of oxidation of the slag is expressed in terms of the degree of oxidation of the iron.

$$R_{Ox} = \frac{Fe_2O_3}{Fe_2O_3 + 1.11 FeO + 1.43 Fe}$$

Studies of the flow of coal ash slags formed under oxidizing conditions (Cohen and Corey 1948) show that as slag cools below the liquidus, there is, at first, a small increase in viscosity due to partial crystallization. Further cooling causes a smooth increase in viscosity until a lower temperature is reached, where the viscosity increases greatly and the slag is apparently solid for low shear stresses. This temperature, T_{cv} , marks the transition between viscous and plastic deformation behavior as the result of the accumulation of crystals to form a "slush". A similar condition is believed to be found in coal ash slags formed under reducing conditions but at different temperatures.

The formation of a slag layer on refractory linings is due to the adhesion of molten ash which agglomerates to form a layer that eventually becomes thick enough to flow down the lining surface under its own weight. The thickness depends upon the density and absolute viscosity of the slag, the amount of slag flowing per unit width and the hydraulic gradient, 1.0 for vertical walls, $\sin \alpha$ for other surfaces; where α is the angle between the surface and the horizon. The temperature of the gas, the temperature of the hot surface of the refractory, the heat flux, the composition and degree of oxidation of the slag determine the density and viscosity of the slag. A cross-section of the slag layer is shown schematically in Figure 16. There are four zones and three interfaces: gas/flowing slag/frozen slag/refractory lining. The interface between the flowing slag and frozen slag is diffuse since the change in viscosity is continuous. When the hot face temperature of the lining is greater than T_{cv} , there is no frozen slag zone and when the gas temperature is less than T_{cv} , there is no flowing slag zone.

An approximate viscosity can be calculated for boiler slags and for some gasifier slags from the paper of Cohen and Corey (1948) if the slags do not contain particles of coal or char.

Typical slag compositions for a number of steel making processes and coals are shown in table 3.1. It may be seen that slags which form from Eastern coals are high in silica, alumina and iron oxide which makes them distinctly acid while the slags from Western coals are lower in iron oxide and may be either acid or basic. The carbon content of the slags is not given but can vary from zero to ten percent by weight or more.

The density of coal ash slag depends on the composition and temperature. If measurements are not available, it may be estimated by referring to "The Making, Shaping and Treating of Steel" (U.S. Steel 1971). Where flux additions are used to make

the ash more fluid or to partially desulfurize the gas, the composition and amount of flux are also required to define the problem.

3.3 Erosion

High velocity gas containing entrained char and ash, is very erosive and requires extremely wear resistant linings. For most gasifier designs, erosion is not a governing factor except in very localized areas where conventional erosion prevention design practices and available materials are believed to be adequate. Fortunately, most of the refractory materials, which are used to resist high temperature gaseous and slag corrosion, including high-alumina brick, have excellent physical properties to resist erosion. Graphite which is very soft is a notable exception. Silicon carbide is especially good to resist abrasion but has temperature limitations and is not suitable for use in an oxidizing atmosphere in the temperature range where slagging gasifiers operate.

Some other refractory materials which are very abrasive resistant when new, become subject to accelerated erosion after the physical and/or chemical properties have been altered during exposure to a corrosive atmosphere or corrosive slag. On the other hand, a layer of frozen slag may offer adequate protection to the otherwise inadequate erosion resistance of a particular material.

TABLE 3.1
COMPOSITION OF SLAG

	SLAG				COAL ASH			
	Basic Open Hearth	Iron Blast Furnace	Basic Open Hearth	Acid Open Hearth	Rosebud Montana	Balwin Illinois	Dave Johnson Wyoming	Keystone Penna.
CaO	45.9	41.0	7.5	5.4	21.1	7.1	9.6	1.6
MgO	6.2	8.0	3.7	0.1	6.2	1.0	2.1	0.9
Fe ₂ O ₃	4.3	0.3	4.6	3.6	4.7	*18.4	*3.9	*10.0
Fe O	11.1	0.8	42.8	22.3	16.0	*	*	*
MnO	6.3	0.7	15.8	11.3	**	**	**	**
Na ₂ O	**	**	**	**	1.2	0.9	0.4	0.4
K ₂ O	**	**	**	**	1.1	1.3	1.8	1.7
SiO ₂	17.7	35.0	19.2	54.2	35.0	42.0	55.6	51.1
Al ₂ O ₃	4.0	13.0	2.5	3.3	14.0	15.2	19.3	30.7
TiO ₂	**	**	**	**	0.7	1.0	0.4	2.0
P ₂ O ₅	2.6	0.1	2.5	0.1	0.1	0.2	1.5	0.1
S	0.06	0.70	0.09	0.05	0.33	3.56	1.28	0.56
B/A(1)	2.58	1.06	3.07	0.74	1.01	0.46	0.23	0.15
B/A (2)	2.40	1.02	0.52	0.10	0.56	0.14	0.16	0.03

* Reported as Fe₂O₃ --(Partial oxidation in a coal gasifier will result in substantial FeO)

** Not Reported

$$(1) \quad B/A = (CaO + MgO + Fe_2O_3 + FeO + MnO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2 + P_2O_5)$$

$$(2) \quad B/A = (CaO + MgO) / (SiO_2 + Al_2O_3), \text{ metallurgical basis}$$

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FIGURE 15

OXIDIZING, REDUCING
AND TRANSITION ZONES FOR
COAL GASIFICATION PROCESSES

FIGURE 16

IDEALIZED FLOW PATTERN
 SLAG ON REFRACTORY WALL
 WITH STABILIZED LAYER

4.0 REFRACTORY CHARACTERISTICS

For many purposes where refractories are used, the selection can be based on the service temperature and loading. Linings for coal gasifiers, on the other hand, are subject to such a variety of conditions that an in-depth analysis is necessary.

4.1 Refractory Failure Mechanisms

Material exposed in gasifiers and similar environments are known to fail by gaseous corrosion, slag corrosion, erosion and spalling.

- 4.1.1 Gaseous corrosion of high temperature refractory materials can occur at temperatures as low as 1350⁰F. Silicon carbide is subject to deterioration in oxidizing atmospheres at this temperature. The corrosive components of coal gasifier atmospheres include hydrogen, steam, carbon monoxide, hydrogen sulfide, sulphur dioxide, carbon dioxide, alkali vapors and aerosols.
- 4.1.2 Molten slag attacks all refractories presently used in slagging coal gasifiers unless they are water cooled to form a protective layer of frozen slag on the surface.
- 4.1.3 Erosion and abrasion by particulate matter is normally not a major problem in slagging gasifiers since most refractories are inherently abrasion resistant and the velocities in gasifiers are normally low except possibly at localized areas. Graphite refractories are soft and may need special protection.
- 4.1.4 Spalling and mechanical failure is difficult to characterize because it is usually not a factor, but when it is, the results can be catastrophic.

Thermal stresses in the lining is one cause of spalling. These stresses are particularly important at low temperatures during heat-up when the refractories are relatively brittle and when the maximum thermal gradients occur. Thermal stresses that can lead to low temperature spalling failures (Greaves, 1966) can be caused by three distinctly different loading conditions:

- a. Heating and cooling without external restraint
- b. Heating and cooling with external dimensional restraint
- c. Heating and cooling with external load restraint

Of these, the second causes the highest thermal stresses while the third can cause progressive failure as the load is transferred from one brick to another.

The effect of thermal stresses and the avoidance of premature failure due to spalling can be minimized by slow heating and cooling, properly providing for thermal expansion, and distributing the loads on the refractory. Provisions for thermal expansion and for distributing loads on the refractories have been taken into account in the conceptual design. Paragraph 5.4 illustrates an appropriate design procedure to minimize spalling in brick walls which are cooled with cast iron stove coolers. Similar provisions are recommended for other refractory brick walls. The organization responsible for the start-up and operations of the plant should maintain control over the rate of heating and cooling during start-up and shutdown. It is possible to incorporate a sacrificial inner lining to protect the permanent lining during initial heat-up and operations. This practice is recommended when carbon-containing refractories are used because it may not be possible to guarantee reducing conditions during start-up operations.

4.2 Basis for Choice of Refractories

The selection and use of refractories in gasifiers is governed by three factors:

- 4.2.1 Raw materials and process associated with the operation
- 4.2.2 Design and construction
- 4.2.3 Refractory properties

These factors are complex and interrelated. There are a multiplicity of design parameters and material properties which must be considered to make an optimum selection. This would appear to be a difficult if not hopeless task which indeed it is for a priori selection. The best basis for selection is previous experience but if this is not available, experience with refractories used in analogous situations and laboratory tests can serve as a guide for making an initial selection. The final selection usually depends upon a relatively few essential factors which dominate other less important considerations.

The final choice of refractories is dictated by cost and by conditions within the gasifier. The important

refractory characteristics which must be known as a function of temperature are:

- a. Resistance to oxidation by steam and CO_2
- b. Resistance to reduction by H_2 and CO
- c. Resistance to acidic and/or basic slags
- d. Resistance to liquid iron which may be saturated with carbon
- e. Resistance to carbon deposition and alkali attack
- f. Resistance to thermal shock
- g. Thermal expansion
- h. Thermal conductivity
- i. Strength, toughness and hardness

4.3 Refractories for Hot Wall Design

Slag attack is usually the major factor in determining refractory liner life for the hot wall design, also referred to as a thick lining, providing the refractory material is suitable for use in the gaseous environment at the existing temperatures. Since slag attack is primarily corrosion by solution of the refractory in the slag, the chemical composition of both slag and the refractory affect the refractory stability while the microstructure of the refractory and temperature level affects the rate of attack.

The refractory brick or monolithic material for the hot wall design must be inert to the process atmosphere and must have a high resistance to attack by molten slag at temperatures up to 3000°F or higher. Slag attack can be overcome by using materials which are not soluble in slag, i.e., which are thermodynamically stable with slag, or it can be retarded by minimizing or eliminating avenues to slag attack in the structure. The first defense suggests the use of neutral refractories, since they are resistant to attack by all types of slags. The second defense suggests:

- a) The use of large blocks of refractories with large grains, since joints and grain boundaries are preferentially attacked by slag and
- b) The use of low porosity materials to minimize the free surface and slag penetration.

Glass tanks are the major industrial furnaces with hot wall design. They must resist the attack of molten glass for campaigns lasting for years. The refractory lining is normally composed of large blocks of fused cast material. A similar approach can be used for slagging gasifier linings and experiments at Argonne and IITRI have shown that fused cast brick, either alumina or chrome-magnesia have outstanding resistance to molten slag.

However, fused cast bricks have relatively poor thermal shock resistance and tend to spall when subjected to sudden changes in temperature. These transients can be avoided in glass tanks because of the large mass of molten glass but are difficult to avoid in a gasifier which has a much lower thermal mass. Thus, fused bricks are not without limitations for gasifier use. Sintered brick on the other hand have superior thermal shock resistance characteristics.

Another approach to slag resistance, is to use sintered brick and to fill the pores with pitch or tar. These impregnated bricks may be more suitable for use in gasifiers than similar brick without impregnation, especially when the atmosphere is strongly reducing and the slag contains char particles or is saturated with carbon. Although tar impregnated brick have not been tested either in the laboratory or in a gasifier, bricks which have shown good slag resistance can be tar impregnated. There could be a risk if the temperature and reducing conditions of the process are already marginal for an oxide refractory.

4.4 Refractories for Cold Wall Design

The refractories for the cold or thin wall design must have sufficiently high thermal conductivity to allow sufficient heat to flow through the lining to freeze a layer of slag on the surface. Thermal conductivity information as a function of temperature is available from manufacturers of refractory materials. Graphite, followed by silicon carbide and amorphous carbon, has the highest thermal conductivity of any of the refractories normally considered for coal gasification service. Amorphous carbon and graphite refractories have been increasingly used with success in blast furnaces, a process very similar to coal gasification. The hearth and bosh which contain slag and iron are usually lined with amorphous carbon or graphite refractories and after a short break-in period, a stable lining thickness is reached. For use in coal gasifier linings, amorphous carbon or graphite should be covered with slag at all times since these materials would be oxidized by CO_2 and H_2O which are constituents of all coal gasifier atmospheres.

It has been observed by the author that when an iron-making blast furnace is blown out, there remains a thin layer of relatively

pure graphite between the iron pool and the refractory bottom. The iron in contact with this graphite has been determined to be saturated in carbon. Since this graphite layer is found in bottoms built of superduty firebrick as well as carbon, the origin of the carbon is believed to be from the blast furnace fuel and not from the lining. Likewise when firebrick are used to line the hearth and bosh walls of a blast furnace, a carbonaceous deposit replaces some or all of the brick. This deposit which contains from 25 to 50 percent carbon offers excellent resistance to corrosion.

4.5 Refractory Selection

The refractory selections are based on the operating conditions and refractory characteristics listed in the previous sections. The refractories which have been investigated include:

- 4.5.1 Carbon and graphite block, brick and ramming mix for reducing atmospheres, the presence of liquid iron saturated with carbon, and very high temperatures.
- 4.5.2 Magnesite and magnesite/chrome spinel for oxidizing and transition atmospheres, basic slags, molten metals, and high temperatures.
- 4.5.3 Chrome-alumina for acidic, neutral and some basic slags containing ferrous silicate, oxidizing and transition atmospheres and high temperatures.
- 4.5.4 Alumina and alumina-chrome for acidic and neutral slags, oxidizing and transition atmospheres and high temperatures.
- 4.5.5 Super duty firebrick and mullite for less severe conditions than enumerated above.

All of the refractories investigated except carbon and graphite are available in the form of fusion cast, sintered and chemically bonded brick and block. Compatible mortars are available and should be used for all recommended refractories. They are also available in the form of material which is rammed, cast, gunned or sintered into place for making monolithic linings without joints, parts of linings, sub-assemblies and/or patches. Cost factors including capital charges, life expectancy and expected maintenance requirements for each refractory will eventually determine what should be used for any particular application.

5.0 COOLING SYSTEMS

The refractory lining in a slagging coal gasifier protects the pressure vessel shell from the hostile gasification environment. Cooling systems are generally required for a satisfactory lining life, especially for large size reactors. The lining must resist corrosion by the gas atmosphere, solution by highly active slag and erosion by particulate matter. The temperature may be as high as 3300°F, which is above the maximum recommended service temperature for most commercial refractories without cooling. High temperatures, together with the corrosive and erosive action of process gas and slag, result in an extremely severe operating environment for refractories. With the possible exception of high pressure, service conditions in blast furnaces have been shown (Bakker 1978) to closely resemble those in slagging coal gasifiers. The similarities which he noted are: a coal-derived fuel is used, the atmosphere is highly reducing, gas is produced as a by-product, the temperatures range up to 3000°F, and the size is comparable to projected commercial gasifiers. Blast furnace slag, however, is subject to strict quality control for metallurgical reasons. Flux stone, added to maintain a fixed bases to acids ratio near unity, also maintains the viscosity at a uniformly low value for the prevailing temperature and oxidizing-reducing conditions. In addition, the slag or ash from slagging boilers is similar to that found in some gasifiers except that the oxidizing-reducing conditions of the atmosphere and the slag are different. Other commercial processes which contribute useful background to this program but less closely resemble gasifier conditions are open hearth furnaces, glass tanks, copper smelters, ammonia plants and carbon black plants. The information from these sources can be used to facilitate the design of coal gasifier linings and cooling systems.

5.1 Design Considerations

Refractory lining designs take into account cost, life expectancy, maintenance and serviceability. Cooling systems are an essential feature of all of these designs. Tentative designs have been made for:

- 5.1.1 Peripherally cooled linings using high conductivity refractories made from carbonaceous, acidic and basic materials
- 5.1.2 Copper plate cooled refractory brick linings
- 5.1.3 Water walls with a thin layer of monolithic refractory protection
- 5.1.4 Other details of lining design which have been considered include:
 - a. Heat losses through the lining including refractory walls and refractory bottoms

- b. Reliability of cooling systems for refractory walls and refractory bottoms
- c. Stress and strain in the lining during heat up, cool down and thermal cycling
- d. Design and construction of water cooled ports for injection of coal, char, steam, air and/or oxygen
- e. Design and construction of water cooled slag tap holes for continuous removal of slag and water cooled slag tap holes which can be closed for intermittent removal of slag from vessels with slag holding capability.

There are two traditional approaches to designing refractory linings to protect pressure vessel shells. These can be characterized as the cold wall design and the hot wall design on the basis of the thermal gradient through the refractory lining and the presence or absence of a solid slag layer on the hot face.

5.2 Hot Walls

The hot wall design features a means for establishing the hot face temperature during the design of the lining by variation in the lining thickness and conductivity of the lining materials, hence in the heat flow through the lining. Since there is no frozen slag layer, the refractory material is subject to the gaseous environment as well as the liquid slag.

The hot wall design keeps heat loss of the process to a minimum by using the minimum amount of cooling necessary to protect the steel shell.

Hot walls were preferred early in the evolution of blast furnaces. However, linings as thick as 6 feet were sometimes required and they eventually proved to be inadequate as furnace production was increased. Finally the last of the hot wall designed furnaces were replaced with water cooled thin walls.

5.3 Cold Walls

The cold wall design, also referred to as a thin lining, is based on cooling the slag so that it freezes to form a solid layer which protects the wall from the environment in the gasifier. Since the slag is a "viscous-solid", the reaction rate between it and the wall is very low and corrosion occurs very slowly.

Many industrial process plants, utility boilers and gasifier pilot plants have used cold wall designs in which slag is allowed to solidify directly on cooling tubes or cooling panels which have

studs to increase the heat transfer and provide mechanical support. However, this construction requires careful control of process conditions to avoid thermal transients which could melt through the slag layer. In addition, since the frozen slag is a glass at a temperature near its melting point, it may not be very resistant to erosion by lumps of solids such as may be found in a fixed bed gasifier. For these reasons, other processes, such as blast furnaces, interpose a layer of refractories between the cold wall and the environment.

Cold wall designs are based on the maintenance of an equilibrium slag thickness which protects the wall from attack. A design theory for a thin wall, water cooled, refractory lining for blast furnaces which was developed by Keonigh and Weidesmueller (1971) states that the equilibrium thickness, x , of a refractory lining is directly proportional to a minimum temperature, T_c , for chemical reaction between the slag and the refractory and inversely proportional to thermal conductivity, k , of the refractory.

$$x = C \frac{T_c}{k} \quad \text{where } C = \text{constant of proportionality}$$

The minimum temperature must be found by experiment, see for example, Herron & Baab (1975), while the thermal conductivity can be based on calculated temperatures and published data or by direct measurements.

For some refractories and some service conditions, the minimum temperature is so low that effective cooling is impossible. The selection of refractories with adequately high minimum temperature properties for this program has been guided by the work of Kennedy at Argonne National Laboratory. This work has provided minimum temperatures for use in the conceptual design.

The thermal conductivity of refractories is particularly important since even though the minimum temperature for the refractory under consideration is high, the thermal conductivity may be so low that effective cooling is still not possible or the equilibrium wall thickness may be too thin to offer protection during transient temperature increases. The selection of refractories must be based on the minimum temperature and the thermal conductivity which are consistent with practical rates of heat removal.

The more heat that is extracted thru the cold wall, the more the efficiency of the gasification process is reduced. Refractory linings minimize the heat loss since in general, the critical

reaction temperature between the slag and refractory is higher than between the slag and metal coolers. For example, silicon carbide has a critical reaction temperature of approximately 2200°F in slag tests while carbon steel reacts at 600°F and stainless steel at 1200°F.

The design of the thin wall lining (cold wall) is bounded by the minimum temperature required to prevent slag corrosion at the interface, the minimum thickness of the lining necessary for protection against thermal excursions, and the minimum thermal conductivity for practical cooling. In addition, for maximum energy efficiency, the heat removal from the lining should be minimized.

The thermal gradient through the refractory is controlled by the exposure of the coolers, the temperature of the cooling fluid and to a lesser extent by the flow of the cooling fluid. Thus, the slag layer which protects the refractory can be kept intact over a wide range of process temperatures.

Three cooling methods have been considered for the conceptual design of a thin-wall refractory lining.

- 5.3.1 Copper plate cooling is based on blast furnace practice, in which horizontal water-cooled copper plates are inserted in the lining. An example of copper plate cooling is shown in Figure 6.

The cooling ratio of copper plates is greater than other methods which have been considered except heavily studded membrane walls. The example shown in figure 6 has 200 percent cooling, calculated by dividing the area of contact between the plate and the refractory by the area of the hot face of the refractory lining associated with the plate. This allows greater cooling to be obtained than is possible with other cooling means suitable for linings of comparable thickness. However, there are also some disadvantages of copper plate cooling:

- a. The refractory lining must be relatively thick because the plates normally extend to the back of the wall. Other linings can be of minimum thickness for stability, wear or other reasons not associated with the cooler itself.
- b. Since the copper plates are not in uniformly continuous contact with the cold face of the lining, it is difficult to maintain a continuously uniform heat removal rate and hot face temperature.

- c. The plates may cause cracking in monolithic refractory linings.
- d. The cost of copper plate coolers is generally, but not always, higher than other cooling means.

5.3.2 Stave cooling, based on blast furnace practice, in which vertical water-cooled "staves" are inserted between the lining and the shell. Examples of stave cooling are shown in Figures 1-5. The cooling ratio of stave cooled linings is limited to about 1.20 depending on the diameter and lining thickness. The ratio for the lining shown in these examples is 1.13.

5.3.3 Studded membrane wall cooling is based on boiler practice. An example of studded membrane walls is shown in figure 7. The cooling ratio of the wall shown in this example is 2.00. This ratio could be increased by the use of more studs.

Analysis of the heat removal requirements for the refractory lining indicates that any of the above cooling methods can be used for most coal gasification processes but the costs and effectiveness are different. Both copper plate cooling and stave cooling are easily designed to obtain the desired cooling rates and to minimize heat removal from the refractory. Both methods have been successfully used in large refractory-lined reactors, such as blast furnaces.

In some cases, a shell is cooled by spraying water on it from the outside. This practice is sometimes used for industrial furnaces. It is very commonly used as an expedient to protect the steel when the refractory lining or the normal cooling is lost. In a slagging gasifier, the hot face of the refractory is covered by a flowing layer of viscous slag which can result in rapid corrosion. If the slag layer is too thin to protect the refractory, particulate matter may cause excessive erosion. Any temporary discontinuities (holidays) in the slag layer will allow the gas atmosphere to directly contact the refractory and subject it to the maximum temperatures of the gasifier and to oxidation or reduction by the hot gas.

All of the factors which affect slag viscosity except temperature are determined by process parameters including composition of raw materials. By controlling the slag/refractory interface temperature, the viscosity of the slag can be controlled. There exists a definite, though not linear, relationship between the amount of heat moving through a wall and its hot and cold face temperatures. For a given material with a given mean temperature, the greater the difference between the face temperatures, the more the heat flows between those faces.

The thickness of the refractory material in the direction of the heat flow, the thermal conductivity of the material and the heat flux determine the difference in temperature between the hot face and the cold face.

The thickness and thermal conductivity of a material can be traded off against each other in such a manner that a very thick, highly conductive material will allow the same movement of heat as a thin, low conductivity material for the same temperature difference. If the thickness of the various refractories is fixed, the amount of heat flow can be controlled by cooling the cold face thereby indirectly controlling the temperature of the hot face. Linings for the current generation of pilot plant gasifiers in the United States have all been based on cold wall design using either a refractory castable to protect the cooling tubes, based on chemical plant design practice, or directly exposing the cooling tubes and allowing slag build-up to protect them, as in slagging water-tube boiler design practice. Although blast furnaces and other large industrial processes normally use brick linings because of their better resistance to erosion and corrosion, pilot plant gasifiers have not done so because their small size makes brick lining very difficult to implement. Lead time for pre-fired or manufactured shapes has also been a factor for pilot plant programs which do not allow sufficient time for complete engineering to be done as is normal for commercial installations. However, brick is probably the more economical material to use over the long run for the linings of commercial size gasifiers, if a longer service life is realized from brick linings as has been the case in blast furnaces. For very large size gasifiers, the effect of scale reduces the apparent need to save energy. This is due to the fact that total heat release is proportional to the volume or cube of the characteristic dimension of a geometrically similar set of gasifiers whereas heat loss is proportional to the surface area or the square of the characteristic dimension. None the less, energy conservation is important and it is expected that large gasifiers will be lined if it does not result in more down-time or other over-riding conditions.

5.4 Spalling of Refractories

Spalling of refractory brick can be caused by inappropriate or lack of provisions for expansion. It is not good enough to simply allow for the expected expansion based on the average temperature rise of the refractory wall. Take, for example, the ring of refractory brick in the 13-1/2" "all key" wall lining for the 18 foot diameter gasifier illustrated in Figure 8. The inside and outside circumferences of this ring are:

$$\text{Inside } 18 \times 12 \pi = 678.6 \text{ inches}$$

$$\text{Outside } (18 \times 12 + 27) \pi = 763.4 \text{ inches}$$

If the hot face expansion is expected to be 1.20 percent and the cold face expansion 0.20 percent, based on the refractory properties and the temperature, these dimensions will change by the following amount:

$$\text{Inside } 678.6 \times .0120 = 8.1 \text{ inches}$$

$$\text{Outside } 763.4 \times .0020 = 1.5 \text{ inches}$$

If 6" brick are used and the average thickness of mortar used in setting these bricks is 1/16", these dimensions each increase by $763 / 96 = 8.0$ ". Taking the mortar and these anticipated expansions into account, the following dimensions should be used in detailing and ordering refractory brick.

$$\text{Inside } 678.6 - 8.1 - 8.0 = 662.5 \text{ inches}$$

$$\text{Outside } 763.4 - 1.5 - 8.0 = 753.9 \text{ inches}$$

Standard 13-1/2" x 6" x 3" keys are suitable for this lining and have the following dimensions:

The total number of shapes required is based on the outside dimension of 6" as follows:

$$753.9 / 6 = 125.7 \text{ brick (use 126)}$$

The inside dimensions work out to be:

$$30 \times 5 - 11/16 = 170.6 \text{ (X1)}$$

$$96 \times 5 - 1/8 = \underline{492.0} \text{ (X2)}$$

$$662.6 \text{ inches}$$

If the number of pieces of each shape had been selected from a handbook which did not take the expected operating temperature into account and the specific expansion properties of the

refractories to be used, there would not have been sufficient X2 keys furnished to allow for expansion of the hot face and it would be impractical or at best, very expensive, to correct this in the field by sawing or grinding the excess X1 keys.

To assure proper fit, and to prevent mortar from over filling the joints, spacers which will disappear before operating temperature is reached should be placed in each joint near the hot face.

The average cold joint spacing is:

$$\text{Inside} \quad (678.6 - 662.6) / 126 = 0.13"$$

$$\text{Outside} \quad (763.4 - 756.0) / 126 = 0.06"$$

Some of this is filled with mortar. The balance with spacers which will have disappeared when operating temperature is reached. Similar provision must be made between courses for localized vertical expansion. This ability to precisely control the expansion provision is one advantage manufactured brick have over monolithic linings.

6.0 REFRACTORY WALL DESIGN

The evolution of a conceptual design for the lining of a slagging gasifier as developed in this program illustrates some of the problems which have been perceived and the solutions which were found.

The vertical walls are all lined with sufficient refractory and cooled to maintain about one half inch of moving slag when the temperature and oxidizing conditions are such that the surface viscosity is in the range of 150-250 Poise.

A great deal of the available data on viscosity comes from power boiler experience where the atmospheres are oxidizing and from metallurgical slags where the bases and acids are in relatively equal proportions. Neither of these conditions are common in coal gasification plants.

The variation of viscosity with temperature is roughly logarithmic in nature. Under some conditions, a 200°F temperature difference corresponds to a 10 x difference in viscosity. For example, if 50% of the iron in a particular slag is in the ferrous oxidation state and the temperature is 2550°F, the viscosity is about 100 Poise. For a temperature of 2350°F this same slag has a viscosity of 1000 Poise.

The variation of viscosity with state of oxidation is also temperature dependent. For high temperatures (2700°F) the viscosities may differ by a factor of 10. For medium temperatures (2500°F) the viscosity may vary by a factor of 30. For minimum slagging temperatures of about 2300°F, the variation is about 100x.

The amount of iron in the slag has a large effect on viscosity. Under reducing conditions, a temperature variation of 600°F for a given viscosity value may be due to iron content in the ash. Under oxidizing conditions a variation of about 200°F for a given viscosity level may be due to the iron content.

Other factors which affect the viscosity of coal ash include the bases to acids ratio, the amount of silica in the "silica-plus-alumina" fraction and the amount of magnesia in the "lime-plus-magnesia" fraction. All of these relationships are temperature dependent and inter-related.

The wide range of coal properties and gasification processes has necessitated the development of the following lining configurations which are not mutually exclusive.

6.1 Copper Plate Cooled Brick Walls

Heavy (over 18") refractory walls are used to minimize heat loss. This concept is based on blast furnace practice. Copper plate coolers are imbedded in the wall to cool the brick. Refractories

considered suitable include super duty, mullite, high alumina and chrome-alumina brick. The cooling ratio defined as cooled surface area divided by heated surface area varies from 1.0 to 3.0. An example of heavy refractory walls with copper plate coolers is shown in Figure 8. The cooling ratio for the lining shown in this example is 2.00.

6.2 Stave Cooled Linings

Cast iron stave cooled linings are also based on blast furnace practice and experience. The approximate refractory thickness, t , for coal gasification service is:

$$t = 1/16 \times \text{Inside Diameter (For Diameters < 20 Feet)}$$
$$t = 9" + 1/40 \times \text{Inside Diameter (For Diameters > 20 feet)}$$

The actual thickness to use for a particular application will depend on the temperature of the operation, the composition and degree of oxidation of the slag and the conductivity of the refractory. These dimensions are somewhat less than are normally used in blast furnace service because the more aggressive atmosphere and slags found in coal gasification require more cooling.

- 6.2.1 Carbon refractory materials are recommended for the highest temperature service, providing the atmosphere is reducing at all times. An example of an all carbon lining for a coal gasifier is shown in figure 1.
- 6.2.2 Acid refractory materials suitable for use with cast iron stave cooled coal gasification reactors includes mullite, high-alumina, chrome-alumina and fusion cast variations of these materials. Proprietary monolithic refractory materials are also available with corresponding compositions. An example of an acid refractory brick lining with cast iron stave coolers is shown in figure 2.
- 6.2.3 Basic refractory materials suitable for use with cast iron stave cooled coal gasification reactors includes brick and proprietary monolithic materials containing magnesia and chromic oxide. An example of a basic refractory lining is shown in figure 3.

6.3 Studded Membrane Walls

Studded membrane walls are based on slagging boiler designs where a thin layer of alumina-chromic oxide refractory is held in place and cooled with studs welded to tubes. The ratio of cooling contact surface area to hot face area for studded membrane walls

varies from 1.50 to 3.00. An example of a studded membrane wall with a cooling ratio of 2.00 is shown in figure 7.

7.0 REFRACTORY BOTTOM DESIGN

The first attempt at making a conceptual design of the refractory lining of a slagging gasifier was based on a conical bottom with a central discharge. This configuration proved to be very difficult to implement. The depth of slag (t_2) on the bottom, near the walls, was estimated by the relationship:

$$t_2 = t_1 \sqrt[3]{\frac{\delta_1}{\delta_2}}$$

where t_1 = thickness of slag flowing down walls.

$\delta_1 = 1.00$ for vertical wall (sine 90°)

δ_2 = Slope of conical bottom adjacent to wall. (Away from the wall and particularly toward the discharge point, the slope is greater).

For Example If: $t_1 = 0.50"$

$\delta_1 = 1.00$

$\delta_2 = 0.10$

$t_2 = 1.08"$

The actual depth on the bottom would be greater because this relationship does not take the higher average viscosity found on the bottom into account. As the slag flows toward the center, the depth will be still greater because, for example, if the central opening is one fourth of the vessel diameter, the amount of slag per unit width will be at least four times that near the walls.

The greatest difficulty, however, was perceived to be the relatively great length around the lip of the discharge opening. For a 4.5 ft. opening, the slag would be flowing over a width of $4.5 \pi = 14$ ft. For an estimated slag "rate" of 14,000 pounds per hour for a gasifier of this size, this amounts to only one half ton per hour per foot of width. (In a blast furnace slag runner, the flow is about 250 tons per hour per foot of width or 500 times as much.) At this very low rate of flow, it is inevitable that the slag would solidify around most of the periphery until at some point in time, only a short distance would be free. Slag

originating near the wall of the vessel opposite the point where slag flows would have to travel a distance greater than the diameter of the vessel to reach the discharge. This greater length of flow reduces the effective slope to the point that the slag layer would become very thick and plug the opening. Furthermore, these conditions might result in a pool of stagnant liquid iron which could penetrate and destroy the refractory bottom and possibly result in an explosion if liquid iron comes in contact with cooling tubes containing water.

7.1 Slag Drainage

The recommended configuration for the bottom of a slagging gasifier is illustrated by figure 8. This drawing shows a horizontal section through the wall of an 18 foot diameter vessel near the bottom. The wall is made of 13-1/2" brick and cooled by forty eight cast iron stave coolers. The inside diameter of the wall is reduced to 16 feet by corbels in the brick work. The shape of the top surface of the bottom refractories is shown by contours. The contour interval of 2.4 inches is five percent of the 48 inch difference in elevation between the high point opposite the tap hole opening and the invert of the tap hole. An orthogonal set of lines show the direction slag is expected to flow in traveling to the tap hole.

- 7.1.1 The slope of the bottom has been calculated to result in an approximately equal depth of slag over all but a small area near the tap hole where the slope is uniform and the slag layer is progressively deeper.
- 7.1.2 The more or less uniform slag layer that is expected to form will provide some protection to the refractory bottom against the maximum process temperature, oxidation or reduction by the process atmosphere and accumulation of a pool of liquid iron.
- 7.1.3 The thickness of the slag layer on the bottom may be excessive unless considerable care is taken in the design. The difference in elevation between the high point and the low point should be equal to about one-fourth of the diameter for the average conditions found in a coal gasifier. This is five times as much as would be necessary if the slag were similar in composition to blast furnace slag and the atmosphere were similar to the products of combustion in a boiler.

The interface temperature between the refractory lining and the slag layer should be higher on the bottom than on the walls. This may be accomplished by making the thickness of the lining substantially greater on the bottom than on the walls, and by the use of high

temperature cooling fluid for the bottom in preference to water cooling.

7.2 Carbon Block Bottom

The conceptual design of a carbon bottom for a coal gasifier is shown in figures 1, 2, and 3. Figure 9 is a half-section of the carbon bottom through the tap hole. Figure 10 is a half-section through the carbon bottom taken at 90° from the tap hole. This design is preferred where the process atmospheres are sufficiently reducing and when gasifying coal which has a high iron content in the ash.

- 7.2.1 The carbon in contact with the slag is made in the form of vertical blocks 24 x 22-1/2" x about 3'-6" high. Two sets of horizontal graphite dowels are provided on the 24" sides to interrupt any tendency toward leakage between blocks. All surfaces are accurately machined. The tops are machined to match the contour lines shown in figure 8. Shop assembly and match marking is required to assure a proper fit.
- 7.2.2 The vertical blocks are supported on full length carbon "beams" 22-1/2 wide x 27" high x 21'-3" or less in length. All surfaces except ends are accurately machined, shop assembled and match marked.
- 7.2.3 The carbon bottom is cooled by a nonoxidizing high temperature heat transfer fluid such as DOWTHERM "A" which is a eutectic mixture of diphenyl and diphenyl oxide. This material is sold by the Dow Chemical Company. The atmospheric boiling point is 495°F and can be used for temperatures up to 750°F. This design is based on a maximum film temperature of 700°F. Other materials may be used providing they are stable at the design temperature and do not represent a hazard to carbon refractories should a leak occur. Tubes which contain this material should be completely welded and tested by freon or other means to be sure there are no leaks.
- 7.2.4 Forced ventilation ducts are provided under the carbon bottom cooling system to protect the supports or foundation from excessive temperatures. Air or inert gas can be used in the ventilation ducts.

7.3 Ceramic Brick Bottom

The conceptual design of a refractory oxide brick bottom for a coal gasifier is shown in figures 4 and 5. Figure 11 is a half-section through the slag tap hole. Figure 12 is a half-section taken 90° from the slag tap hole.

- 7.3.1 The inverted arch shown in figure 12 is an important feature of this design. The key shapes used in this cross section have been selected to prevent bricks from floating out and being carried away in the slag.
- 7.3.2 The depth of the bottom in this example is 60 inches, measured along lines of heat flux between the top of the brick and the top of the underhearth coolers. This much refractory thickness is necessary to maintain the slag temperature sufficiently high that it will flow to the tap hole without plugging. Water or air is satisfactory for use in the upper layer of coolers which is provided to protect the brick and maintain the desired shape of isotherms in the bottom. Air is recommended for use in the lower layer of coolers which is provided to protect the supporting structure or foundation from excessive temperatures.

8.0 SLAG TAPS AND INJECTION PARTS

8.1 Discontinuities

Discontinuities of any kind in the lining of a high temperature containment vessel represent potential hazards. In spite of careful design, construction, operation and maintenance, such features are frequently responsible for premature lining failures. Some of the contributing causes are:

- 8.1.1 Uncooled or undercooled refractories near openings tend to run hot, possibly resulting in loss of slag protection against corrosive atmospheres and slags.
- 8.1.2 Too much localized cooling tends to result in slag build-up, defeating the purpose of the opening and possibly resulting in the shut down of the entire operation.
- 8.1.3 High temperature gradients cause high strain gradients which correspond to high stress gradients. High stress gradients promote stress corrosion and gradual deterioration even though a catastrophic failure does not occur.
- 8.1.4 Special shapes required near openings in brick linings are usually manufactured by a different process or from different materials. The properties of these special shapes that may be different and cause trouble include composition, porosity, conductivity and thermal expansion characteristics.
- 8.1.5 Where different refractory materials are used around an opening, fluxing or other consequences of incompatibility may result.
- 8.1.6 Water coolers, when used, may leak causing rapid deterioration of all high temperature refractory materials.
- 8.1.7 Unprotected metal coolers may fail due to localized overheating when exposed to liquid metal or when fouled by improperly treated water.
- 8.1.8 Differential expansion between a pressure vessel and refractory lining causes strains in the refractory lining near all openings which may result in failure.

8.2 Slag Taps

Several means for slag removal were considered including:

- 8.2.1 Temporary storage of slag and periodic removal is similar to the blast furnace practice followed by the steel industry. This is feasible for coal gasifiers and may be preferred in some situations, especially when the slag contains liquid iron. A conceptual design of a blast furnace slag notch is shown in figure 13.
- 8.2.2 Continuous removal of slag through a central opening in the bottom of the gasifier is based on current coal gasification pilot plants which use this construction. This may be the least expensive to build but is probably the most expensive to maintain in an operable condition.
- 8.2.3 Continuous removal through an opening in the side of the gasifier is a development of this program. This scheme was selected for further development because it is not expected to require a crew of workers to open and close the cinder notch as practiced in the ironmaking industry. Even more important, continuous removal may not allow time for liquid iron to accumulate. An accumulation of liquid iron is both hazardous and expensive to tap from the bottom of the gasifier. Conceptual designs of tap holes for the continuous removal of slag from a gasifier are shown in figures 9 and 11.

8.3 Injection Ports

Injection ports in a coal gasifier have the same function as tuyeres in a blast furnace. Combustion air at temperatures exceeding 2000°F is routinely blown into a blast furnace through water cooled copper tuyeres. Steam, oxygen, fuel gas, liquid fuel and pulverized coal are also injected into blast furnaces through the tuyeres. The tuyeres are located near the bottom of the furnaces where the temperatures are at a maximum and in close proximity to liquid slag and liquid iron. Conceptual designs of a blast furnace tuyere and associated tuyere coolers are shown in figure 14.

- 8.3.1 Tuyeres should be made of relatively pure, high-conductivity copper. Specifications usually limit impurities and require a minimum thermal or electrical conductivity.
- 8.3.2 The cooling water velocity near the nose of a tuyere should be about 50 feet per second for temperatures similar to those found in a blast furnace. The cooling water velocity for the balance of the tuyere should be about 10 feet per second.

- 8.3.3 Cooling water should be treated as a minimum requirement and boiler quality water is usually a good investment.

9.0 CONCLUSIONS AND RECOMMENDATIONS

- 9.1 The design of a refractory lining system for a slagging coal gasifier should take into account.
 - 9.1.1 Oxidation or reduction of the refractory materials subject to the process atmosphere at the operating temperature.
 - 9.1.2 The corrosive action of the slag at the operating temperature.
- 9.2 The initial cost of the refractory lining system for a slagging coal gasifier may represent from ten to twenty-five percent of the cost of the reactor.

The total cost of the refractory lining system for a slagging coal gasifier including the total cost of all subsequent relines may represent more than fifty percent of the total cost of the reactor.

The final choice of a lining system should be based on an economic analysis which reflects the total cost of the lining system over the life of the coal gasifier.
- 9.3 The findings of this study are preliminary in nature and are subject to change, following completion of Phases B through F of this program.

APPENDIX B
HAZARDS ANALYSIS

HERCULES AEROSPACE DIVISION
HERCULES INCORPORATED
ALLEGANY BALLISTICS LABORATORY
CUMBERLAND, MARYLAND

HAZARDS ANALYSIS OF THE "AS BUILT"
EQUIPMENT FOR TESTING REFRACTORY
LINERS UNDER SLAGGING COAL
GASIFICATION CONDITIONS

- FINAL REPORT -

C. A. ANGOLI

DECEMBER 1981

PREPARED FOR
ILLINOIS INSTITUTE OF TECHNOLOGY
RESEARCH INSTITUTE
CHICAGO, ILLINOIS

WARRANTY AND DISCLAIMER

Within the scope of the work, Hercules warrants that it has exercised its best efforts in performing the hazard analysis contained herein, but specifically disclaims any warranty expressed or implied, that hazards or accidents will be completely eliminated or that any particular standard or criterion of hazard or accident elimination has been achieved if the findings and recommendations of Hercules Incorporated are adopted.

CAUTION

Conclusions presented in this Hazards Analysis report, are based upon the design, materials of construction, operating conditions, process materials, and procedures as they existed at the time of the analysis (or as they were presented to Hercules for analysis). If changes in any of these parameters occur in the future, the conclusions of the current Hazards Analysis may be invalidated.

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I. SUMMARY

A. OBJECTIVE

The objective is to provide a hazards analysis of the as-built equipment for testing refractory liners designed by IITRI and to provide recommendations for changes necessary to reduce the incident probability to the stated criteria.

B. CONCLUSIONS AND RECOMMENDATIONS

This is the second report related to hazards analysis of the refractory test unit. The first report covered the period when the unit was under construction. At this time, 150 events were identified as having the potential for either personnel injury or significant facility damage. Forty-two of these events had a probability of occurrence of 1×10^{-6} per hour or greater. Recommendations were offered to reduce or eliminate these.

The present study is a continuation of the analysis through the final construction phase.

The baseline probability of 1×10^{-6} per hour for the occurrence of a fire, explosion, or major release⁽¹⁾ incident was continued. An additional probability of 1×10^{-10} per hour was agreed upon as a guideline for incidents that could result in serious injury. In addition, a hazard severity vs. probability table was prepared to prioritize the items that need to be addressed to improve safety (see Table II).

The specific events that are of concern in the operation of the refractory test unit which can result in serious injury are as follows:

<u>Area</u>	<u>Potential</u>
I. Natural gas compressor room (125 psi gas)	Release of gas and fire or explosion.
II. N ₂ system	Operator asphyxiated due to excess N ₂ (leak)
III. Cooling water system	Loss of coolers resulting in steam explosion.
IV. Burner, lances, torch and related controls	Explosion resulting in injury and loss of equipment.

(1) Defined as a release of 60 SCF or more of natural gas in a building.

<u>Area</u>	<u>Potential</u>
V. Slag slurry feed system	Injury to eyes.
VI. Pressure control system	Rupture of vessel.
VII. Venturi scrubber	Serious burns.
VIII. Slag tap vessel	Explosion with injury and loss of equipment.
IX. Maintenance	Injury.
X. Operators	Create explosive condition.
XI. Start-up burner	Explosion with injury and loss of equipment.

In the analysis, 160 events were considered that could result in an explosion or serious injury. Of these events, six were found to have unacceptable probabilities of occurrence and severity; i.e., $> 1 \times 10^{-10}$ per hour and serious injury.

The specific recommendations for reducing the probability of these events to an acceptable level are as follows:

1. Event - Death or Injury Due to an Explosion in the Slag Tap Vessel

This event can occur due to two different sets of conditions: (1) if the iron in the slag becomes molten and flows into the water in the slag tap vessel, or (2) if the water level in the slag tap vessel rises and flows back into the main vessel.

Recommendations are:

- a. (1) Redundant determinations of gas, O_2 and air flow rates and redundant checks of instrument settings.
- (2) Inspection of the main vessel for free iron on each shutdown.
- b. (1) Installation of an independent high level alarm.
- (2) Provide an emergency shutoff valve on the water line to the slag tap vessel that can be operated from the control room.

2. Event - Explosion in Main Vessel Results in Injury and Equipment Damage

This event can occur due to the main vessel filling with an explosive mixture of natural gas and air or oxygen. In one situation, the Timer (T-2) or burner shutdown system fails and ignition does not occur within the allotted 15 seconds. The other situation is when the flame goes out during initial heatup with the temporary burner and the shutdown system fails to work.

Recommendations are as follows:

- a. Install a clock with second indication and instruct the operator to release the ignition button after 20 seconds and repurge the vessel as a manual check on the automatic system.
- b. Locate a portable combustible analyzer at the top of the main vessel during heatup to check the gases exiting the main vessel for combustibles.

3. Event - Injury Due to Opening a Pressurized Line

This event can occur if the slag slurry line to the top of the main vessel plugs and the operator fails to relieve the pressure before opening the line to clean out the blockage.

Recommendations are as follows:

- a. Operator to use safety procedures when working on pressurized lines; i.e., verify on pressure gauge that line is not pressurized
 - lockout Moyno pump
 - close valves at vessel
- b. Wear eye protection (goggles or face shield).

4. Event - Serious Burn Due to Contact With Hot Line

This event can occur if the operator makes contact with the hot, 300°F line from the venturi separator to the stack.

The recommendation is that this pipe line be insulated to protect personnel.

C. FUTURE WORK

This report concludes the hazard analysis of the slagging gasifier based on the information provided by IITRI. A list of these documents is attached in Appendix A. There is no further work planned for this system. At the time of the oral presentation there were a number of items to be completed to have the gasifier conform to the design. If these are not completed, the analysis would be invalid. (Gas alarms in the NG compressor room were not wired into the alarm circuitry, etc.)

The slagging gasifier is an experimental unit and there will be changes in design in the future. To ensure the safety of the unit, there needs to be an evaluation group set up by IITRI and DOE to review and evaluate these proposed changes.

An operator training program should be conducted by IITRI to inform the operators of how the system works, what the potential problems are and make them familiar with all the equipment, controls and alarms.

II. INTRODUCTION

A. BACKGROUND AND OBJECTIVES

IITRI has a contract with DOE to develop a unit for testing different refractories for use in slagging gasifiers. IITRI is in the final stages of construction and testing before starting operation of the equipment. The first test run will be a blast furnace simulation to obtain data on candidate refractory life for comparison to known information about these refractories in blast furnace operation.

The test facility will operate at high temperature (3000°-4000°F) and high pressure (100 psig) in a corrosive environment with flammable and potentially explosive gases present. The slag is introduced into the top of the main test vessel where it is melted. The melted slag then flows down the refractory, being tested countercurrent to a hot stream of incomplete combustion gases. The slag is collected in a tank near the bottom of the main test vessel. The flue gases from the top of the unit are scrubbed, cooled, and vented through a stack to the atmosphere.

IITRI has contracted for Hercules Incorporated (ABL) to perform an independent hazard analysis, P.O. 06092. This hazard analysis studied changes made to the process and controls since the initial hazards analysis was performed by Hercules Incorporated in 1980.

B. SCOPE OF THE ANALYSIS

The scope of this hazard analysis included the operation of the main test vessel, the slag tap vessel, the slag storage vessel and the scrubber during startup, running and shutdown. Interaction of the following subsystems was also in scope:

1. Natural Gas System - From the inlet of the gas compressor.
2. Oxygen System - From after the vaproization controls.
3. Nitrogen System - From after the vaporization controls.
4. Air System - From the inlet of the compressors.
5. Water System - From the city water inlet.
6. Slag Injection System - From the bottom of the slag storage vessel.
7. Slag Removal System - To the point of discharge into the hopper.

8. Burner System - To include the main burner, lances, and slag tap torch with their controls and interlocks.
9. Pressure Relief System - Including the stack, the pressure control valve, rupture disks, and relief valves.
10. Control System - Including interlocks, alarms, and shutdown modes.

Areas not included in the scope of this analysis were (1) the delivery of the nitrogen, oxygen, and slag to the respective storage vessels, (2) the discharge of gases from the stack, relief valves or rupture disks, and (3) conformance of the facility to OSHA Standards, environmental regulations or industrial hygiene requirements.

C. BASIS OF THE ANALYSIS

The basis of the analysis was the drawing packages, procedures, and other information furnished by IITRI as listed in Appendix A.

The basis for incident probability was separated into two areas. For those events with a probability of occurrence greater than 1×10^{-6} /hr, specific recommendations were made for correcting the problem areas. For those events that have the potential for operator injury, a table was made relating probability and severity. Table II was constructed using the following groupings:

<u>Group</u>	<u>Probability</u>
1	$\geq 1 \times 10^{-4}$ /hr
2	$< 1 \times 10^{-4}$ to $\geq 1 \times 10^{-6}$ /hr
3	$< 1 \times 10^{-6}$ to $\geq 1 \times 10^{-8}$ /hr
4	$< 1 \times 10^{-8}$ to $\geq 1 \times 10^{-10}$ /hr
5	$< 1 \times 10^{-10}$ to $\geq 1 \times 10^{-12}$ /hr
6	$< 1 \times 10^{-12}$ to $\geq 1 \times 10^{-15}$ /hr
7	$< 1 \times 10^{-15}$ to $\geq 1 \times 10^{-20}$ /hr
8	$< 1 \times 10^{-20}$ /hr

<u>Category</u>	<u>Severity</u>
I	Permanent total disability up to and including death.
II	Permanent partial disability.

Category

Severity

III

Lost-time injuries, including
total temporary disability.

IV

First aid or no injury. This
category was not included.

Specific recommendations have been made for those incidents with a probability of 1×10^{-10} or greater with a severity in Categories I or II, or a probability of 1×10^{-6} or greater for Category III.

III. DISCUSSION

A. TECHNICAL APPROACH

The approach used for this hazard analysis was to divide the study into two tasks: (1) hazard evaluation, and (2) risk control.

1. Hazard Evaluation

Initially, the hazard analyst visited the site to review the equipment as constructed. In addition, discussions were held with IITRI personnel in which the hazards listed in the earlier report were reviewed. The changes that had been made were reviewed, as were areas where the final design had not yet been decided upon. The analyst was provided with the available information and as additional information became available, it was forwarded to Hercules. Telephone calls were made to clarify information about how various systems operated and to keep IITRI informed of those events that did not meet the criteria in the revised analysis.

Based on the information provided by IITRI, the hazard evaluation was conducted. The changes were incorporated into the analysis to determine the probability of each revised incident. Table II was developed to relate probability to severity. This table will assist IITRI and DOE in identifying those events which involve both a high probability of occurrence and significant severity - thus providing a basis for prioritizing corrective action.

In this part of the analysis, the combination of failures necessary to cause a particular hazard were developed. The severity of the event was then developed by considering the hazard, operator exposure, and equipment damage. The probability of the event was then determined from available failure rate data. In all cases where an explosive mixture existed, it was assumed that there was an ignition source present that would ignite the mixture. The incident probability was determined from the product of the causative factors or component failure mode probabilities necessary for the event to occur. In many cases, a number of different failure modes could produce the same end result and thus the probability was the sum of all the failures that could produce that particular situation.

On the fact sheets, which follow this section in Table I, the causative events, severity, and probability were developed. In the causative event column, the combination of events necessary to bring about the potential problem are listed. The event could be a single failure or a combination of failures that must occur together to bring about the hazardous situation. The severity is an estimate of the potential damage that could occur to the system and operators. The probability is determined from generic failure rates for the various components that combine to bring about a particular event. These numbers are then used to determine the probability of a particular event. Failure rate data can be found in Appendix B.

2. Risk Control

In this phase of the analysis, recommendations were formulated for correcting those hazards that do not meet the criteria. For events with a probability of occurrence greater than 1×10^{-6} /hr, specific recommendations are offered. For those events that are unchanged from the previous analysis, there will be no additional discussion beyond the recommendations on the fact sheets.

For those events in Categories I and II, specific recommendations are given for those events with a probability of 1×10^{-12} /hr or greater.

B. HAZARD ANALYSIS AND RECOMMENDATIONS

The following sections review each area of the process. This is done with a process description that describes equipment capacity and function. The next area reviews the design safety features that have been built into the system. Then the potential problems of the area and the severity are discussed. The last area to be discussed are specific incidents that could occur and recommendations to reduce the risk for that section of the process.

The system has been designed by IITRI to go to a less hazardous state if problems develop. There are three stages of these safety modes, which are:

- (1) An emergency shut down (ESD) can be initiated by the operator or by four predetermined conditions. These are low N₂ instrument supply pressure (< 40 psig), low N₂ supply pressure (< 125 psig), low pressure in the main vessel (< 75 psig) and high pressure in slag tap vessel (> 115 psig). When an ESD occurs, the natural gas compressor and the air compressors shut down, the slurry system shuts down, the natural gas, O₂ and air to the process is stopped and the pressure control valve opens.
- (2) A burner shutdown (BSD) can be initiated by the operator or by 26 abnormal conditions. These include loss of flame, closing of either the natural gas or oxygen shutoff valves, high combustibles or oxygen in the slag tap vessel or N₂ jacket area, high temperatures on various coolers, loss of the air compressors, low water flow to the venturi, low natural gas or oxygen pressure, high vessel pressure, low N₂ supply pressure, low pressure cooling water supply, low level-cooling water tank, gas compressor low oil level. When a BSD occurs, all gas, oxygen and air flows to the vessel are stopped, the pressure control valves open, the slurry feed switches to water from slurry.

- (3) The third mode is a burner turndown (BTD) which can be initiated by the operator or 12 abnormal situations. When the BTD occurs, the main burner drops into the low fire mode with stoichiometric oxygen, the pressure control system continues to operate, the lances and torch are shut down, the slurry system switches from slurry to water and air continues to the incinerator. The BTD system can be automatically activated by a high or low water level in the slag tap vessel, low flow on either venturi water supply line, low O₂, N₂, natural gas or air pressure, high combustibles in the stack, jacket or slag tap vessel or high cooler temperatures.

1. Natural Gas Compressor Room

a. Process Description

Natural gas is received from People's Gas at 2.0 ± .5 psi, supplied by a 4 in. gas main. The gas enters IITRI's system through a 4 in. plug valve operated by a nitrogen ("air") pressure signal. The valve, ASV-G426, is an air to open, fail closed valve that will close on an emergency shutdown. The gas then passes through a gas filter to remove any solid particles from the gas stream. This filter serves to protect the compressor.

The gas then enters a Fuller floating vane compressor where the gas is compressed in two stages to 123 psi for delivery to the burner system. The compressor is designed to compress 300 SCFM of natural gas from 1.5 to 123 psi using a 125 HP motor. The compressor is water cooled with additional cooling on the intercooler and aftercooler. The compressor has an automatic oiler to provide lubrication to the cylinders and reduce wear on the vanes.

The piping on the discharge of the compressor goes either to the burners or recycles back through a pressure controller to the inlet of the filter. This allows the excess gas to be recycled.

The room containing the compressor has a volume of 1,044 cubic feet and has two doors that provide access from the main building. Two of the walls are permanent building walls of block construction, while the remaining walls are wood partitions built to isolate the gas compressor room from other equipment and surroundings.

This system is shown schematically in Figure 1.

b. Design Safety Features

The natural gas compressor room has a number of safety features incorporated to protect the personnel and equipment.

Figure 1. Natural Gas Compressor Room Arrangement

The primary safety feature for a natural gas system is to provide a method of disrupting the inlet gas. An inlet gas valve, ASV-G426, is available as an N₂ operated, air to open, valve that fails closed and will close when an emergency shutdown would de-energize SLV-N380.

If a leak occurs in the system of a minor nature, adequate ventilation is necessary to remove the vapor to below an explosive concentration or if a massive leak occurs, the gas concentration must be reduced to a safe limit prior to personnel entering the room. Two fans are present in the room for this purpose.

The suction intakes for these two fans, are located in the compressor room, each fan with a capacity of 400 SCFM. The intake for one fan is directly over the compressor, while the other is located by the shutoff valve and filter. In a smoke test conducted by IITRI, it took the fans about five minutes to clear the room.

If a leak should occur in the natural gas system, there is a certain delay before the room can be exhausted of the resulting gas release. It is important that the sources of ignition for the flammable vapor are minimized. This would include heated surfaces or metal sparks. Shutdown occurs if compressor heating occurs. All electrical fittings meet the Electrical Code of Chicago. All tools and metal equipment should be of a nonsparking material, door hinges, etc., and building materials for walls should be nonabsorbent and offer no cavities for gas collection.

Several other features are present to minimize equipment failure that will create operator exposure to gas leaks, such as follows:

- Differential pressure monitoring across filter
- Oil system monitor

The following items will initiate alarms in the gas supply room, requiring operator interaction to correct the problem:

<u>Cause</u>	<u>Device</u>	<u>Sensor Location</u>
Low inlet pressure to compressor - 10 in. H ₂ O	PS 10L	Compressor suction
High inlet pressure to compressor - 50 in. H ₂ O	PS 10H	Compressor suction
High temperature compressor discharge - 325°F	TS 10	Discharge of second compressor stage

<u>Cause</u>	<u>Device</u>	<u>Sensor Location</u>
Low cooling water flow 5 gpm	FS 2	Cooling water flow from compressor and inter-cooler
Low oil level in lubricator	LL 1	On lubricator supply chamber
Lubricator belt broken or not moving	LS 1A	On lubricator belt
Gas leak 0.75% CH ₄ in air	Gas detector	North wall of compressor room
Gas leak 1.5% CH ₄ in air	Gas detector	North wall of compressor room
Low pressure 115 psi (warning alarm) 110 psi (emergency alarm)	W-3 Monocon gauge	Main gas line at burner controls

The following relief valves vent into a pipe that terminates at the top of the slag storage tank:

<u>Valve</u>	<u>Cause</u>	<u>Valve Location</u>
SRV-G430	38 psi - over-pressure discharge first stage	Before intercooler
SRV-G441	130 psi - over-pressure discharge second stage	Before aftercooler
SRV-G447	125 psi over-pressure gas recycle line	On recirculating gas line before ASV-G444

c. Potential Problems and Severity

Natural gas is explosive in the range of 5.0 to 15.0% in air. It can be ignited with a spark of 4.7×10^{-4} Joules, metal sparks or heated surfaces of 979°F. If a stoichiometric mixture is ignited, the rate of pressure rise and peak pressure will be 261 psi/sec and 94 psi. The hazard analysis of the natural gas system reviewed the equipment and design safety features

to determine (1) if adequate safety features are present, (2) the effect of process and safety equipment malfunctions on the probability of an incident, and (3) review the operating procedures for (1) operator actions that may influence safety, and (2) operator exposure to injury.

1 Gas Explosion

The main problem in the natural gas compressor room would be a gas leak that could lead to an explosion. A stoichiometric ratio of natural gas and air in the compressor room would produce a pressure of 94 psi that would result in death and destroy building walls for a distance of 100 ft. Thus any gas explosion would result in severe injury and equipment damage.

A gas leak can develop in a number of different ways resulting in the release of different quantities of gas and potential problems, such as

- (a) A small gas leak (1 SCFM or less) could develop at GV-G440 or other connections. If the fans are operating, there would be no gas buildup and there would be a flammable concentration only within a few inches of the leak. If the fans are not operating, it would take about 2 hours to build up an explosive concentration in the room which would be detected by the gas detectors and shutdown the compressor.
- (b) A gas leak of about 30 CFM could develop at a gasket on CV-G429 or a leak at the high pressure head gasket (part 1021) due to failure or improper maintenance when installed. If the fans were operating, there would be an explosive concentration around the leak that would be below the lower flammable limit in the exhausted air. Due to the air turnover, leak site, and detector locations, the gas detectors may not detect the gas leak. If the fans are not operating, it would take about two minutes to produce an explosive concentration in the room. The failure of the gas detectors to detect or shutdown the compressor would result in an explosive mixture that could cause severe injury and equipment damage.
- (c) A rupture of the compressor would result in the release of 80 SCFM of gas into the room even if the detectors shutdown the compressor. Thus, an explosive concentration would exist until the fans could clear the room (about one minute).

The other area for problems is with the gas compressor. Failure of the lubricator, loss of cooling water, or overpressurization problems can result in damage to the compressor. Monitors are provided to provide warning if problems develop and the operator is to take hourly readings to check that the equipment is operating properly.

These potential problems were reviewed in the hazard analysis, with a resulting probability of an incident of 8.4×10^{-11} . The specific analysis is summarized in Table I, Section A.

The following recommendations are presented to increase the safety of the operation:

- (a) Post signs on both doors, reading "DO NOT ENTER WHEN ALARM IS SOUNDING."
- (b) When either alarm sounds, the main gas valve should be closed and the operators should wait at least five minutes before entering the room. The detection of the gas means that there exists an explosive quantity of gas in the room and the problem should be corrected before proceeding with normal operation.
- (c) Audible alarms connected to the gas detector should be located outside the compressor room so that the operator can hear the alarm before entering the compressor room.
- (d) The gas detector should be checked at least once a week and maintenance done before each test run.
- (e) At the time of the oral presentation, the gas detectors were not connected into the alarm panel or the compressor shutdown circuitry. This must be done or the analysis is not valid.
- (f) At present, only one fan has a flow switch indicating when it is operating. The other fan should be connected to an alarm to indicate when it is not operating.

TABLE I

**IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET**

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
A. Natural Gas System Compressor and Auxiliaries in Compressor Room	Release of natural gas and formation of a flammable/explosive mixture in compressor room.	1. a) Packing seal leaks (1 CFM) and b) Fan not turned on and c) Failure of detector or operator ignores alarm and d) Failure of 2nd detector to detect or shutdown compressor	Fire causing equipment damage and operator burned.	7.8×10^{-11}	Alarms for gas detectors should be located outside compressor room. Door to room needs to have a sign stating, <u>"DO NOT ENTER WHEN ALARM SOUNDING."</u>
		2. a) Gasket leak (30 CFM) and b) Fan not turned on and c) Failure of detector or operator ignores alarm and d) Failure of 2nd detector to detect or shutdown compressor	Fire/explosion results in loss of equipment and possible serious injury or death.	1.4×10^{-15}	When alarm sounds the main gas valve should be closed and the operator should wait at least 5 minutes before entering. The fans must be operating

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
A. Natural Gas System Compressor and Auxiliaries in Compressor Room (Cont'd.)		<p>3. a) Catastrophic failure of compressor (300 CFM) or valve or piping and b) Failure of second detector to detect or close valve and shut-down compressor</p>	Explosion causes building damage and possible loss of life	6.4×10^{-12}	<p>Alarms for gas detectors should be located outside compressor room. Door to room needs to have a sign stating, "DO NOT ENTER WHEN ALARM SOUNDING."</p> <p>When alarm sounds the main gas valve should be closed, the operator check that the fans are operating and wait at least 5 minutes before entering.</p>

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
A. Natural Gas System Compressor and Auxiliaries in Compressor Room (Cont'd.)	Overheating of compressor	4. a) Loss of cooling water and b) Failure to detect and c) Failure of interlock	Compressor damage.	1.3×10^{-11}	Calculation indicates that flammable concentration will not exist 10 feet beyond NG vent.
	Overpressurization of compressor	5. a) By-pass pressure control valve fails closed due to loss of instrument air or Control failure or Solenoid valve failure and b) Relief valves fail to relieve.	Compressor damage.	1×10^{-7}	
		6. a) Gas vented from compressor and b) Inversion keeps gas from dispersing and c) Sufficient concentration present for ignition by transformers.	Fire causes loss of transformer and some building damage.	Not credible	

2. Oxygen Supply System

Oxygen is necessary in the process to obtain the desired temperature and atmosphere. The requirement is for a maximum continuous flow of 300 SCFM. The system to deliver oxygen is shown in Figure 2.

a. Process Description

A standard system was leased from Air Products and Chemicals, Inc. In the system, liquid oxygen is stored in a 9600 gallon horizontal tank. The liquid oxygen flows from the storage tank through twelve ambient air vaporizers to the temperature/pressure control manifold. There is an electric vaporizer for use in cold weather when the ambient air vaporizers may not meet the demands. The controls are designed to supply up to 300 SCFM of O_2 at 125 psi and 70°F. The O_2 flows through ASV-X253 to the burner control panel. ASV-X253 is an air to open N_2 operated valve. The O_2 flows through a copper pipe inside a channel box for protection. The pipe and channel is ~ 100 feet long, traveling along the fence.

b. Design Safety Features

The oxygen supply system has the following safety features incorporated into the design:

- (1) Six relief valves located on the liquid lines
- (2) Dual pressure/temperature control manifolds
- (3) Remote shutoff valve that fails closed and can be closed manually from the control room.
- (4) A Monocom pressure gauge system, W1, that has a series of pressure sensors that activate various alarms, as follows:
 - (a) At 110 psi, the automatic burner turndown system will activate reducing the O_2 demand.
 - (b) At 115 psi, a low O_2 supply pressure alarm will sound.
 - (c) At 130 psi, the high O_2 supply pressure warning alarm will sound
 - (d) At 140 psi, the high O_2 supply pressure emergency pressure alarm will sound and activate the shutdown of the main burner.

In addition, there are low temperature alarms, that (a) at 40°F give a warning is given, and (b) at 25°F sound an emergency alarm.

Figure 2. Oxygen Supply System

c. Potential Problems and Severity

The potential problem with this system is an O₂ leak that results in a fire.

The path of the oxygen line was reviewed in consideration of the places where gas would accumulate, the sources of fuel or incompatible substances. Failure to keep the grass cut or storage of flammable material along side this line could lead to a severe fire. The results of this analysis are summarized in Table I, Section B. The probability of the event occurring is $1 \times 10^{-9}/\text{hr}$.

Abnormal oxygen flow and other problems are reviewed in the burner system.

d. Recommendations

The recommendations are as follows:

- (1) Train the operators to close the remote shutoff valve ASV-X253 any time a leak or fire develops along the O₂ line. After shutting the valve, then notify the fire department if a fire has occurred and take action to limit damage.
- (2) Keep the area around the O₂ tank and lines clear of weeds and combustible materials.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
B. Oxygen Supply System	<p>Rupture of oxygen line with possible fire or explosion</p> <p>Other potential problems due to oxygen system are discussed with burners and main vessel problems</p>	<p>1. Failure of the pressure/temperature control system and Rupture of line</p>	Fire - injury	1×10^{-9}	Operators should be trained to shut off all valves first in case of a fire and then take steps to extinguish the fire.

3. Compressed Air System

a. Process Description

Air is compressed in two Ingersoll-Rand two-stage reciprocating compressors to 125 psi. Each compressor is driven by a 125 HP motor and each delivers about 500 SCFM of air. The air is cooled by aftercoolers and goes to a 4 x 12 ft receiving tank as shown in Figure 3. From here, the air goes to the incinerator section and the air lance.

b. Design Safety Features

There are a number of safety features designed to protect the air compressor system. These include relief valves, one on each compressor stage and one, SRV-A-214, on the air receiver. Temperature alarms on the discharge of each compressor provide a warning alarm at 300°F (TS-3 and TS-5) and an emergency alarm at 350°F (TS-2 and TS-4).

The air receiver has a low air pressure warning alarm of 115 psi and a low air pressure emergency alarm of 105 psi that activates the automatic burner turndown system. In addition, there is a high air pressure warning alarm set at 125 psi.

Each air compressor has an overload warning alarm to indicate high current usage by the motor and an alarm to indicate loss of power due to fuse or circuit breaker being open.

Each compressor has an oil pressure switch that will shut-down the compressor on low oil pressure.

c. Potential Problems

The main problems with the compressors would be those incidents that would lead to compressor damage such as loss of lubricating oil, overpressurization, or motor failure due to overheating. These problems do not pose a direct hazard to the operators but will have a definite effect on the ability to operate the gasifier as designed. Two items are identified, such as compressor overheating or overpressurization with a probability of 1.3×10^{-11} and 2×10^{-17} , as shown in Table I, Section C.

The loss of air to the process would not result in a more hazardous condition but would result in failure to melt the injected slag and undesirable gases being vented to the atmosphere.

d. Recommendations

The recommendations for the air compressors are as follows:

Figure 3. Compressed Air System

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
C. Air System Compressor and Auxiliaries	Overheating of air compressor	1. a) Loss of lubricating oil and b) Failure to detect and c) Failure of interlock	Compressor damage.	1.3×10^{-11}	
	Overpressurization of air compressor	2. a) Failure of relief valve and b) Failure of interlock and c) Failure to detect and d) Failure of pressure control valve	Compressor damage.	2×10^{-17}	
	Other problems due to air system are discussed with burner and main vessel problems				

- (1) Take readings as required and correct problems when they develop.
- (2) Follow the operating and maintenance manual for changes and repairs.

4. Nitrogen System

a. Process Description

Liquid nitrogen is stored in a 650 gallon vessel from which it flows through a vaporizer to the N₂ system. It is planned to replace the present vessel with a 9000 gallon vessel in the near future. The system layout is shown in Figure 4.

The nitrogen is used as instrument air to control the "air" operated valves throughout the system. For the control system the N₂ is at a pressure of 50 to 75 psi. High pressure N₂ is supplied to the igniters, the slag injection system, the slag removal system, the N₂ jacket, and to the burners and lances for purging.

b. Safety design Features

The N₂ supply is critical to the operation of the control valves. A Monocon gauge system is used and has a series of low pressure set points. When the pressure drops to 55 psi, an alarm sounds and the system automatically goes into the burner turndown mode. A further drop to 50 psi will sound another alarm and result in the system going into the burner shutdown mode. If the pressure continues to drop to 40 psi, the system will go into an emergency shutdown mode.

On the high pressure N₂ line, there is another series of alarms set at < 155 psi warning, < 145 psi emergency and < 125 psi which activate the emergency shutdown mode.

c. Potential Problems and Severity

The inadvertent closing of a valve on the N₂ system could result in loss of N₂ purge flow, N₂ jacket flow or loss of control N₂ to a valve resulting in equipment damage. An N₂ leak in the piping east of the main vessel could create an oxygen deficient atmosphere in the main vessel room.

d. Specific Incidents and Recommendations

- (1) HSV-N368 fails closed or R-N402 fails closed or HVV-N370 fails open to vent and PS-W4 fails to work or the shutdown system fails and the operator fails to notice low pressure problems with the instruments.
- (2) An N₂ line ruptures in a confined area and operator enters and the operator is not wearing his O₂ deficiency meter or the O₂ deficiency meter fails resulting in the operator's death.

Figure 4. Nitrogen System

The specific incidents and their probability, are given in Table I,
Section D.

Recommendations are as follows:

- (1) O₂ deficiency alarms should be calibrated daily, battery check done weekly and fuel cell checked before each run.
- (2) The procedure for putting the N₂ instrument system into service must be followed. There should be two operators doing this to check that all the valves are opened.
- (3) Keep all people who have no need to be in the area of the gasifier out. One of these individuals could accidentally close or change a valve that could result in loss of control to part of the system.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
D. Nitrogen System	Operator overcome by breathing N ₂ when N ₂ line breaks	1. a) N ₂ line breaks and b) Operator present or enters area and c) Sufficient confinement and d) Operator not wearing low O ₂ detector or O ₂ detector fails	Operator injury or death.	8x10 ⁻¹³	Oxygen deficiency alarm should be calibrated daily by operator, battery checked once a week and fuel cell checked before each test run.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
D. Nitrogen System (Cont'd.)	Loss of N ₂ for instruments	2. a) HSV-N-368 fails closed or R-N 402 fails closed or HVV-N 370 fails open to vent and b) PS-W4 fails to work or Shutdown system fails and c) Operator fails to notice low pressure problems with instruments	Loss of N ₂ to instruments and inability to control system resulting in equipment damage.	4.5×10^{-13}	Procedure for putting instrument N ₂ system to work must be followed. Need to keep out individuals not connected to unit as they could accidentally close an N ₂ valve causing a loss of control and take hours to find.

5. Cooling Water System

a. Process Description

The cooling water system consists of a 5500 gallon storage tank, a cooling tower, seven pumps, piping, control valves and 40 cooling circuits, as shown in Figure 5.

The low pressure recirculated water is pumped from the storage tank by five 500 GPM, 60 HP centrifugal pumps at a pressure of 125 psi. The pressure is reduced to about 95 psi at the supply manifold before going through the coolers on the main vessel. The water returns through a 12 in. line back to the storage tank. As the water temperature increases, the cooling tower is put on line. If the cooling tower is not able to provide sufficient cooling, then a dump valve will open, draining part of the returning water to the sewer. This will then require that more water be supplied to the storage tank from the water main.

The high pressure, consumed water has two pumps, one of 100 GPM capacity at 150 psi and one of 25 GPM capacity at 150 psi, that supply water to the venturi scrubber and the slag tap vessel.

The 25 GPM high pressure pump and two of the 500 GPM low pressure pumps run on power supplied by a natural gas driven generator. This generator, which operates all the time the system is running, provides that cooling water is available if a city power failure should occur and allows for a controlled shutdown of the system.

b. Design Safety Features

The cooling water system has a number of safety features built into the system; PS-1 and PS-7 on the high pressure water system alarm at 130 psi and PS-2 through PS-6 on the low pressure water system alarm at 95 psi.

The cooling water tank has a low city water pressure switch, PS-16 set at 15 psi, a low flow switch on the make-up water FS-3 set at 50 GPM and three level controls. Liquid level switch, LL-2, controls the level of the water in the storage. If the water level drops below LL-3 an alarm will sound. A further drop in level will activate LL-9 and cause the system to go into an automatic burner shutdown.

The cooling water pressure to the supply manifold is controlled at 95 psi. As the pressure in the system will be about 100 psi, this should result in gas leaking into the cooling water. The water supply manifold pressure will activate a low water pressure warning alarm at 75 psi and an emergency water pressure alarm at 70 psi.

Figure 5. Cooling Water System

The following is a list of flow and temperature setpoints and their action:

<u>Cooling Circuit</u>	<u>Normal Flow, gpm</u>	<u>Low Flow, gpm</u>	<u>Action</u>
Main Burner	155	150	Burner shutdown
Methane Lance	10	6	Lance shutdown
Air Lance	10	6	Lance shutdown
Slag Tap Torch	12	8	Torch shutdown

<u>Cooling Circuit</u>		<u>Set Point, °F</u>	<u>Action</u>
1. Main Burner	Data Logger	95	Burner turndown
	No. 7		if not corrected
	Temp. Switch	100	Burner shutdown
2. Port Block	TS-33	115	BTD*
3. Air lance	Data Logger	95	BTD*
	No. 9		
	Temp. Switch	100	Lance shutdown
4. Methane Lance	Data Logger	95	BTD*
	No. 10		
	Temp. Switch	100	Lance shutdown
5. Air Monkey	TS-35	115	BTD*
6. Methane Monkey	TS-34	115	BTD*
7. Castable Coil	TS-23	115	BTD*
8. Channel Coolers (4)	DL No. 14	115	BTD*
	DL No. 17	180	BSD**
9. Notch Gap Coil	DL No. 19	115	BTD*
10. Iron Tap Coil		115	BTD*
11. View Port Coils (2)	TS-23	115	BTD*

* BTD = Burner turndown ** BSD = Burner shutdown

<u>Cooling Circuit</u>		<u>Set Point, °F</u>	<u>Action</u>
12. Notch Tuyere Nose	TS-20	115	BTD*
13. Notch Tuyere Body	TS-21	115	BTD*
	DL No. 15	150	BSD**
14. Notch Coils (3)	DL No. 18	110	BTD*
	TS-14 and -15	125	BSD**
15. Slag Tap Torch	DL No. 6	95	BTD*
	Temp. Switch	100	Torch shutdown
17. Plate Cool- ers (4)	TS-16 to -19	115	BTD*
	TS-24	150	BSD**
19. Stave Cool- ers (8)	TS-13	115	BTD*
	TS-16	180	BSD**
20. Crescent Cooler		115	BTD*
22. Water Wall	TS-13	115	BTD*
	DL No. 12	150	BSD**
26. Slag Injec- tion Nozzle	TS-7	115	BTD*
	DL No. 5	150	BSD**
27. Hood	TS-12	115	BTD*
	DL No. 12	150	BSD**
28. Exit Pipes, Int.	TS-12/-13	115	BTD*
	DL No. 12	150	BSD**
29. Exit Pipes, Ext.	TS-8 and -9	115	BTD*
	DL No. 11	150	BSD**

*BTD = Burner turndown **BSD = Burner shutdown

c. Potential Problems and Severity

The safety feature that is of primary concern with the cooling water system is that a malfunction results in an orderly shutdown. Each of the control loops were reviewed to determine component or system failures that would negate this function. It was determined from the analysis that the probability of losing this safety feature is 5×10^{-6} /hr. The analysis is summarized in Table I, Sections E and F. The critical components in this system are as follows:

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
E. Cooling Water System	Loss of cooler	1) a) Error in connecting cooling water inlet or outlet line and b) High cooling water temperature occurs in cooler and c) Operator tries to correct and d) Turndown/shutdown system fails to work	Loss of cooler, possible leak of water into main vessel with steam explosion	1×10^{-11} EST	Check each series of water connections by opening only those valves to be certain that water lines are properly connected. All water lines are to be coded for ease of identification.
		2) a) High cooling water temperature occurs in cooler and b) Operator opens a wrong valve due to procedure or typing errors and c) Turndown/shutdown system fails to work	Same as E-1.	1×10^{-11} EST	Procedure needs to be checked against actual valves and for possible typing errors. There are over 600 valves in the system. Operators to be trained to double check valves and systems when problems develop.

**IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET**

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
E. Cooling Water System	Loss of cooler due to hose failure	3. a) Inlet hose not fastened securely and b) Fail to find while pressure checking water lines and c) Hose comes off and high temperature switch or burner turn-down system fails to operate	Loss of cooler, temporary end of test.	1×10^{-12} (EST)	Pressure test all cooling water systems to be certain that hoses are properly secured. Operator to use care when walking through water spills.
		4. a) Outlet hose not fastened securely and b) Fail to find while pressure checking water lines and c) Hose comes off, operator fails to shut-down system	Loss of cooling water, possible water damage to equipment, operator slips on wet floor and is injured.	1×10^{-9} (EST)	Same as E-3.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
F. Main Vessel Cooling Water	Loss of equipment due to loss of cooling water	1.a) Loss of city power due to blackout or Breaker tripped	Possible loss of coolers	1×10^{-3}	Test to determine water loss to various coolers. Main burner critical, need to know before actual operation to plan how to adjust cooling water flow if critical.
		2.a) Loss of city power due to blackout or Breaker tripped and b) Failure of shutdown system	Loss of coolers and major equipment damage	1×10^{-7}	
		3.a) Generator shutdown	Possible loss of coolers	7×10^{-6}	Back-up by city power See F-1.
		4.a) Generator shutdown and b) Loss of city power due to blackout or Breaker tripped	Major equipment damage	7×10^{-9}	
		5.a) Pump fails	Possible loss of coolers	3×10^{-5}	Three other pumps on line. See F-1.

(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
F. Main Vessel Cooling Water (Cont'd.)	Loss of equipment due to loss of cooling water	6. a) Hot water drain valve fails open due to valve failure or control failure but A limiting flow orifice has been installed	No problem	---	See F-8.
		7. a) Loss of make-up water due to low city pressure and b) Level indicator (LL-3) fails to alarm and c) Level indicator (LL-9) fails to operate and shutdown burner	Possible loss of coolers	6.4×10^{-16}	
		8. a) Hot water drain valve fails open due to valve failure or b) Makeup water supply is less than water draining and c) Operator fails to take action to correct situation and	Major loss of equipment	8.8×10^{-17}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
F. Main Vessel Cooling Water (Cont'd.)	Loss of equipment due to loss of cooling water	8. d) Level indicator (LL-9) fails to operate and shutdown burner			
		9. Rupture of piping on supply side.	Major loss of equipment	2×10^{-11}	
		10. Rupture of piping on return side	Probable loss of coolers	2×10^{-11}	
		11. a) Loss of make-up water due to FCV-W3 failing closed because of control failure or Valve failure and b) Level indicator (LL-3) fails to indicate low level and c) Level indicator (LL-9) fails to shutdown burner	Major loss of equipment	6×10^{-18}	
		12. a) Level indicator fails (LL-3) and b) Level indicator (LL-9) fails to shutdown burner	Major loss of equipment	6.4×10^{-13}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
F. Main Vessel Cooling Water (Cont'd.)	Loss of equipment due to loss of cooling water	13. LP pump pressure control valve fails open	Possible loss of coolers	7×10^{-5}	Flow reduction should be no worse than loss of one pump.
		14. a) LP pump pressure control valve fails open and b) Failure of turndown/shutdown system	Possible loss of coolers	7×10^{-9}	
		15. Puncture of water tank by forklift handling drums stored under water tank	Loss of coolers	1×10^{-12}	Consider installing protective barrier around tank. Consider storing drums elsewhere.
		16. a) One LP pressure control valve fails closed due to tap line leaking or Loss of instrument air or Valve failure and b) Other pressure control valve fails closed due to tap line leaking or	Loss of coolers	2.4×10^{-14}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
F. Main Vessel Cooling Water (Cont'd.)	Loss of equipment due to loss of cooling water	16. Loss of instrument air or Valve failure and c) Failure of shutdown system			

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
F. Main Vessel Cooling Water (cont.)	Loss of equipment due to loss of cooling water	17. HP pump pressure control valve (134 psi) fails due to valve failure or Valve sticks	Damage to venturi/scrubber slag tap vessel	1×10^{-5}	Will be flow to scrubber from other sources
		18.a) Small leak in cooler due to inadequate cooling or Poor construction or Leak in connecting piping due to fitting failure or Poor assembly and b) Check valve fails to open	Possible loss of coolers. Steam in jacket.	3×10^{-10}	Check all systems for leaks when installed.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
F. Main Vessel Cooling Water (cont.)	Loss of equipment due to loss of cooling water problem	19. a) Large leak in cooler due to poor construction and b) Failure to discover or c) Large leak in connecting piping due to fitting failure and d) Failure to discover	Steam explosion	1.8×10^{-12}	
	Cooling water leak in N ₂ jacket area	20. a) Cam-lock connections made on water lines in N ₂ jacket area and the ears are wired down and b) System air checked for leaks and depressurized and c) System checked for leaks with water and d) Due to error when fastening connectors leak of sufficient size requires shutdown of unit to fix	Water damage to refractory, steam produced in jacket area	1×10^{-6} (est)	) Double check all connections to be sure that locking ears are closed and wired down.

Control relay 74 - activating burner turndown
system

Relay 38 - activating burner shutdown
system

If this system should malfunction, the burner will continue to operate until the operator takes action.

The cooling system is subject to malfunction or human error in several areas which would require activation of the emergency shutdown procedure. The potential problems are that hoses may be connected to the wrong cooler, valves may be mislabeled, hoses may fail, power failure, pump failure, loss of make-up water, piping failure, and leaks. The severity would be a function of the particular situation.

Several typical problem areas are as follows:

(E-1) Water hoses connected to wrong cooler and high temperature develops and operator unable to correct and turndown/shutdown systems fail to work.

(E-2) High cooling water develops in a cooler and operator tries to correct but valve mislabeled or incorrect procedure and turndown/shutdown systems fail to work.

(F-1 and -2) Loss of city power.

(F-3) Loss of generator.

(F-4) Loss of generator and loss of city power.

(F-7 and -8) Low supply of make-up water and LL-3 fails to alarm, or operator ignores and LL-9 fails to shutdown burner system.

(F-9 or -10) Piping failure.

(F-15) Water tank punctured by forklift.

(F-16) V2A (ATC) fails closed and V2B (ATO) fails closed.

In the cooling water system, for example, there could be a loss of water in the storage tank and the level alarm LL-3 fails to alarm or the operator ignores the alarm and the level continues to drop to the point where LL-9 fails to activate the burner shutdown system. This could result in damage to the coolers. The reduced water flow and increased temperatures should result in the burner turndown system being activated.

The common components for almost every problem with the cooling water system are Control Relay 74 (CR 74), which activates the burner turndown system and Relay 38 (R 38), which activates the burner shutdown system.

d. Recommendations

- (1) Check to insure that turndown and shutdown systems work before each run.
- (2) Verify that each water circuit is labeled correctly. This can be done by opening the valves for a particular circuit only and verifying that there is flow through that circuit. No flow would indicate that an inlet or outlet line was not properly connected.
- (3) A three-way check needs to be made between the drawings, procedures, and the actual valves in the plant to be certain that the valves are numbered correctly and that the drawings and procedures agree.
- (4) Pressure test the cooling water system for leaks before starting the burner.
- (5) IITRI has conducted a test of the cooling water system by having four pumps on line and suddenly dropping two pumps off to see if some of the coolers would be starved for water. The test indicated that the flow distribution remained satisfactory.
- (6) Consideration should be given to installing a protective barrier around the water storage tank or moving the supplies stored there to another location to prevent puncture of the tank by a forklift.

6. Burner System

a. Process Description

The burner system, shown in Figure 6, consists of the main burner, methane and air lances, slag tap torch, and the related controls. The burner system was designed by Process Combustion Corporation and is unique. The burner is constructed of stainless steel and is designed to burn natural gas and O₂ at 125 psi, producing 10 million Btu/hr at full capacity. It also has the capacity of operating at reduced O₂ levels to supply a reducing atmosphere to the refractory test chamber. The burner is cooled with a water jacket and the flame is monitored with a Honeywell ultraviolet scanner.

The methane lance was designed to allow up to 200 SCFM of natural gas to flow into the main vessel. The air lance is designed to allow up to 800 SCFM of air to flow into the main vessel. The addition of natural gas and air through the lances increases the quantity of heat that can be put into the main vessel and allows further control of the atmosphere inside the refractory.

The slag tap torch is designed to burn 250 SCFM of natural gas with 625 SCFM of O₂. The torch is to be used to keep the slag molten and flowing out of the main vessel and into the slag tap vessel. It is aimed to direct its flame at the notch the slag flows through.

b. Safety Design Features

The safety design features include the following:

- (1) Honeywell Ultraviolet Scanner with a self-checking unit.
- (2) Check valves in the natural gas, O₂, N₂, and air lines.
- (3) N₂ purge lines to each line with solenoid valves that open with burner shutdown.
- (4) The O₂ and natural gas lines to the main burner have double block and bleed solenoid valves. The bleed lines vent to atmosphere outside the building and away from any equipment.
- (5) The natural gas line has the following:
 - (a) A low flow switch, < 40 SCFM.
 - (b) A low pressure switch, < 105 psi.
 - (c) Low differential pressure between gas and vessel 10 psid or less, automatic shutdown.

Figure 6. Burner System

- (d) High pressure switch > 140 psi, automatic shutdown.
 - (e) Low differential pressure between N₂ and vessel 10 psid or less, automatic shutdown.
 - (f) High cooling water temperature > 100°F, automatic shutdown.
 - (g) Low cooling water flow < 150 GPM, automatic shutdown.
- (6) The O₂ line has the following safety devices:
- (a) Differential pressure switch between O₂ and natural gas line more than 6 psid, automatic shutdown.
 - (b) Low pressure switch < 105 psi, alarm.
 - (c) Differential pressure switch between O₂ and main vessel 10 psid or less, automatic shutdown.
 - (d) High pressure switch > 140 psi, automatic shutdown.
- (7) The methane lance line has the following safety devices:
- (a) Low flow switch < 12 SCFM, alarm.
 - (b) Low pressure switch < 105 psi, alarm.
 - (c) Low differential pressure switch between gas line and main vessel 10 psid or less, lance shutdown.
 - (d) Low differential pressure between N₂ (purge) and main vessel 10 psid or less, lance shutdown.
 - (e) High cooling water temperature > 100°F lance shutdown.
 - (f) Low cooling water flow < 6 GPM, lance shutdown.
- (8) The air lance line has the following safety devices:
- (a) Low pressure switch < 105 psi, alarm.
 - (b) Low flow switch < 70 SCFM, alarm.

- (c) High cooling water temperature
100°F, lance shutdown.
- (d) Low cooling water flow < 6 GPM,
lance shutdown.
- (9) The slag tap torch has the following safety
devices:
 - (a) Low flow switch gas < .05 SCFM,
alarm.
 - (b) Low flow switch O₂ < .05 SCFM,
alarm.
 - (c) Low differential pressure O₂ line
and slag tap vessel 10 psid or less,
torch shutdown.
 - (d) low differential pressure N₂ (purge)
and slag tap vessel 10 psid or less,
torch shutdown.
 - (e) Low differential pressure gas to O₂ gas
more than 6 psid below O₂, torch
shutdown.
 - (f) High cooling water temperature 100°F,
torch shutdown.
 - (g) Low cooling water flow < 8 GPM, torch
shutdown.
- (10) Additional safety devices include:
 - (a) Automatic purge cycle before burner
can be ignited.
 - (b) Stack gas and O₂ analyzers show
low O₂ (< 5%) and combustibles
(< 0.75%) before igniter can be
activated.
 - (c) Start-up in low flow mode only
(limit gas to vessel).
 - (d) Igniter timer - must ignite within
15 seconds or shutdown and repurge.

c. Potential Hazards

The potential hazards with this system are (1) failure to detect loss of flame and subsequent filling of the combustion chamber with gas,

(2) failure of the purge system to clear the burner before restart after shutdown, and (3) failure of the timer system allowing early restart attempts.

These events can result in operator injury due to the proximity of the operator to the burner when restart is attempted, or loss of the refractory due to internal explosion.

The failure events that could lead to the undesired events were analyzed as having a probability of occurrence of 1.49×10^{-8} /hr. The analyzed data are summarized in Table I, Section G.

d. Specific Incidents and Recommendations

(G-21) Burner fails to ignite on demand and T-2 timer fails to shutdown igniter allowing explosive concentration to develop and delayed ignition results in an explosion and operator injury. Probability is 1.4×10^{-8} /hr. It is recommended that the operator be instructed to hold the igniter button no longer than 20 sec. Provide a clock by the igniter. If the flame on relay has not come during this time, release the igniter, repurge, and restart.

(G-2) Gasket at natural gas line check valve fails releasing about 30 SCFM of gas and fan is not on and detectors fail to detect gas leak with resulting fire/explosion killing operator and severely damaging burner controls.

(G-4) O₂ piping fails between check valve and burner and hot gases flow back out of main vessel and operator is present and seriously burned.

(G-22 and -23) Flammable mixture is present in main vessel after an emergency shutdown, purge timer (T-1), or low N₂ pressure (R-11), or automatic purge relay (R-5) fails and the stack combustible analyzers, G5 and G6, fail to detect and stack O₂ analyzers, G13 and G14, fail to detect high O₂.

(G-29) Low flow of cooling water to main burner and flow and temperature shutdown systems fail and operator fails to shutdown system with alarm and burner fails, dumping cooling water into the main vessel, destroying vessel and killing operator.

(G-32) N₂ purge solenoid valve on O₂ line (N-332) fails open, flameout occurs, and shutdown system fails, resulting in combustible buildup in main vessel that could explode with serious injury.

(G-34) Slag freezed over O₂ holes reducing O₂ flow and operator fails to notice reduced flow and flameout occurs and shutdown system fails, resulting in combustible buildup in main vessel that could explode with serious injury.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
G. Main Vessel Burner System	Release of natural gas and/or oxygen with formation of a flammable mixture around burner control panel.	1. a) Packing leaks (1 CFM) and b) Operator smells but fails to fix and c) Inadequate ventilation and d) Failure to detect gas buildup	Fire causes control damage operator may be burned.	6.4×10^{-10}	Any time gas is in the line to the burner the main fan is to be operating. The area around the gas lines should have a number of gas detectors that give audible alarms. Operators should check all gas lines for leaks once per shift.
		2. a) Gasket failure (30 CFM) and b) Inadequate ventilation and c) Failure to detect leak	Fire/explosion causes loss of control panel and serious injury.	1.1×10^{-11}	
		3. a) Catastrophic piping or valve failure (300 CFM) and b) Inadequate ventilation and c) Failure to detect leak	Explosion causes extensive equipment and building damage and loss of life.	6.4×10^{-15}	Same as 1. above.

TABLE I
(CONTINUED)

HTRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (cont'd.)	Release of a flammable gas mixture by main vessel.	4. a) Failure of rigid piping between check valve and main burner and b) Leak large enough to allow backflow of gases from main vessel and c) Operator present	Operator overcome by gases (possible loss of life). Fire destroys equipment.	5×10^{-11}	Visually inspect piping between main burner and check valves after each run. Limit need of operators to be at main burner when operating.
		5. a) Failure of rigid piping between check valve and main vessel and b) Leak large enough to allow backflow of gases from main vessel and c) Operator present and d) Failure of Emergency Shutdown system	Loss of life and extensive equipment damage.	2.5×10^{-16}	Same as 4. above.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

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EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
G. Main Vessel Burner System (cont'd.)	Release of a flammable gas mixture by main vessel. Oxygen and natural gas flow to main vessel when burner flames out due to loss of natural gas flow to main burner (NG flows to vessel through lance). Flammable mixture is present in test vessel. Ignition by hot refractory.	6. a) Leak at valve flange between check valve and main vessel and b) Inadequate ventilation and c) Failure to detect	Fire causes control damage and possible operator injury.	1.2×10^{-11}	Fan to be operating when gas in lines. Lines to be pressure checked after being opened.
		7. a) Flow control valve fails closed or hand valve downstream fails closed or check valve fails closed and b) Flame safeguard fails to shutoff both O_2 and NG to lance and c) High pressure interlock fails to shutoff both O_2 and NG and d) Low ΔP interlock fails to shutoff both O_2 and NG and	Explosion results in damage to vessel and auxiliaries. Possible injury to operator.	1.5×10^{-14}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (cont'd.)	Release of a flammable gas mixture by main vessel.	<p>7. e) Flow control system fails to shutoff both O_2 and NG and f) NG low flow alarm sounds and operator fails to take action.</p> <p>8. a) Valve upstream of PSH 27 but downstream of PSL 26 in natural gas line fails closed and b) Flame safeguard fails to shut both O_2 and natural gas and c) Low ΔP interlock fails to shut both O_2 and natural gas and d) Flow control system fails to shut both O_2 natural gas and e) NG low flow alarm sounds and operator fails to take action.</p>	Same as 7.	3.3×10^{-19}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)		9. a) Bleed valve in natural gas line fails open and b) Flame safeguard fails to shut off both O ₂ and NG and c) Low ΔP interlock fails to shut off both O ₂ and NG and d) Low P interlock fails to shut off both O ₂ and NG	9. Same as 7	3.9x10 ⁻¹³	
		10. a) Hand valve upstream of flow element fails closed and b) C-1 contactor fails closed preventing O ₂ block valves from operating and c) NG lance solenoid valve fails open and d) Flow control system fails to shutoff both O ₂ and NG	Same as 7	1x10 ⁻²²	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)	Oxygen flows to vessel when burner flames out due to loss of natural gas flow to main burner. Oxygen rich atmosphere exists in vessel and exit gases.	<p>10. e) NG low flow alarm sounds and operator fails to take action</p> <p>11. a) A valve downstream of PSH 27 in natural gas line fails closed and b) Flame safeguard fails to shutoff O₂ only and c) High ΔP interlock fails to shutoff O₂ only and d) Flow control system fails to shutoff O₂ only and e) O₂ analyzers fail to detect high O₂ level in stack and f) NG low flow alarm sounds and operator fails to take action</p>	Fire in system due to thermal ignition of any combustible contaminants or buildup in gas system ducts.	1.5x10 ⁻²²	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)		12. a) Valve upstream of PSH 27 but downstream of PSL 26 in natural gas line fails closed and b) Flame safeguard fails to shutoff O ₂ only and c) Low ΔP interlock fails to shutoff O ₂ only and d) Flow control system fails to shutoff O ₂ only and e) O ₂ analyzers in stack fail to detect high O ₂ level and f) NG low flow alarm sounds and operator fails to take action	Same as 11	8.3x10 ⁻²³	

TABLE I
(CONTINUED)

HTRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)		13. a) Bleed valve (SV 7) in natural gas line fails open and b) Flame safeguard fails to shut off O ₂ only and c) Low ΔP interlock fails to shut off O ₂ only and d) O ₂ analyzers fail to detect high O ₂ level	Same as 11	9.6x10 ⁻¹⁷	
		14. a) Hand valve upstream of flow element in natural gas line fails closed and b) Flame safeguard fails to shut off O ₂ only and c) Low ΔP interlock fails to shut off O ₂ only and d) Flow control system fails to shut off O ₂ only and e) O ₂ analyzers fails to detect high O ₂ level and	Same as 11	3.5x10 ⁻²⁹	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)		14. f) NG low flow alarm sounds and operator fails to take action	Same as 11	7×10^{-26}	
		15. a) Loss of natural gas supply and b) Low ΔP interlock fails to shut off O_2 only and c) Flame safeguard fails to shut off O_2 only and d) Flow control system fails to shut off O_2 only and e) O_2 analyzers fail to detect high O_2 level and f) NG low flow alarm sounds and operator fails to take action			
	Formation of high level of combustibles in main vessel	16. a) Loss of natural gas flow to main burner only and b) NG lance shut off solenoid valve fails open	High rate of combustion causes overheating of incinerator hood and possible damage	1.5×10^{-11}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
G. Main Vessel Burner System (Cont'd.)	High level of combustibles in test vessel	16. and c) Operator fails to respond to low flow alarm or notice the lance flow light on			
		17. a) Valve downstream of PSH 25 in oxygen line fails closed and b) Flame safeguard fails to shut off NG and c) Low ΔP interlock fails to shut off NG and d) Low flow alarm sounds and operator fails to take action	High rate of combustion causes overheating of incinerator hood and possible damage.	2.2×10^{-12}	Determine what minimum flow is necessary to activate alarm.
		18. a) Valve upstream of PSH 25 and downstream of PDSL 24 fails closed and b) Flame safeguard fails to shut off NG and c) Low ΔP interlock fails to shut off NG and	Same as 17.	4.8×10^{-13}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.)	Flammable mixture of gases present in main vessel	18. d) Low O ₂ flow alarm sounds and operator fails to take action	Same as 17	2.4x10 ⁻¹⁰	
		19. a) O ₂ bleed valve (SV 9) fails open and b) Flame safeguard fails to shut off NG and c) Low ΔP interlock fails to shut off NG			
		20. a) Hand valve upstream of flow element in O ₂ line fails closed or loss of O ₂ supply and b) Flame safeguard fails to shut off NG and c) Low O ₂ current flow alarm sounds but operator takes no action	Same as 17	1x10 ⁻¹⁴	
		21. a) Burner fails to ignite on demand and			
			Ignition could cause explosion damaging equipment and causing injury.		

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

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EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)	Burner started with flammable mixture in vessel	21. b) Control system fails to shut off flow (Ignition time T-2 fails)	Same as 21.	4.5×10^{-11}	Training to emphasize that operators are not to start-up if analyzers show combustibles or O_2 present.
		22. a) Flammable mixture in vessel after emergency shutdown and b) Igniter enabled without a purge and c) Combustible analyzers fail to detect or control shutdown system fails and d) O_2 analyzers fail to detect or control shutdown system fails			
		23. a) Flammable mixture in vessel after emergency shutdown and b) Low N_2 pressure for purge (R-11 or T-1 fails) and	Same as 21.	9.5×10^{-11}	Same as 22.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.)		23. c) Low N ₂ pressure fails to activate burner shutdown or control shutdown system fails and d) Combustible analyzers fail to detect or control shutdown system fails and e) O ₂ analyzers fails to detect or control shutdown system fails			
		24. a) Burnout of igniter and b) Operator uses slag tap torch to try to light main burner			
		25. a) Main burner goes out and b) Flame detector sees slag tap torch flame			

No longer feasible as slag tap torch is not moveable.

No longer feasible as slag tap torch is not moveable.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
G. Main Vessel Burner System (Cont'd.)	Production of a flammable/explosive gas mixture in refractory chamber	26. a) Flame detector fails to sense loss of flame and b) Self-checking unit relay fails and c) Temperature of unit is below 1200°F and d) Operator fails to take corrective action	Gases may ignite explosively with equipment damage and injury.	2×10^{-16}	Check flame detector before each run. Training to stress that action be taken to protect system.
	Burner fuel/oxygen ratio in error - high fuel ratio could reduce FeO _x , flame snuffed out too much NG	27. a) Natural gas flow control system offset - high flow or Oxygen flow control system offset - low flow or Error in setting bias ratio	Wrong gas mixture for test, possible equipment damage.	1.5×10^{-3}	Provide a second check of the bias ratio setting. Use daily balance of feed and stack analysis to check flows. Calibrate flow control system before each run.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.)	Burner fuel/oxygen ratio in error - low fuel ratio	28. a) Natural gas flow control system offset - low flow or Oxygen flow control system offset - high flow or Error in setting bias ratio	Same as 27.	1.5×10^{-3}	Same as 27.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Mixer Vessel Burner System (Cont'd.)	Burner fails to shutdown on loss of cooling water. Loss of integrity and water into vessel	29. a) Low flow or loss of cooling water to main burner and b) Burner control system (flow and temperature) fails to shutdown burner and c) Operator ignores alarms and fails to shutdown burner	Loss of burner probable steam explosion due to water leak. Possible injury.	1×10^{-11}	Operator training has to emphasize operator action when cooling water problems develop (burner turndown or shutdown).
	Burner fails to shutdown on high cooling water temperature	30. a) High cooling water temperature and b) Interlock fails to turndown burner and c) Emergency overtemperature reached with failure of shutdown system and d) Operator fails to take action	Burner failure dumps water into vessel with steam generation and possible end of test.	8.6×10^{-16}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Mixer Vessel Burner System (Cont'd.)	Burner fails to shutdown when flameout occurs due to high vessel pressure. Combustible gases present in main vessel	31. a) Pressure in vessel exceeds burner supply pressure and b) Flame out occurs (normal) and c) Burner control system fails to shutdown burner	Overpressurization of system. Potential F/E with equipment damage and operator injury or death.	5.3×10^{-27}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.)	Burner fails to shutdown if flameout occurs due to N ₂ purge valve failing open and putting a flammable mixture into main vessel	<p>31. and d) Slag tap relief valve fails closed and e) Scrubber relief valves fail closed</p> <p>32. a) N₂ purge valve fails open and b) Flameout occurs and c) Burner control system fails to shutdown burner</p>	Combustibles present in main vessel may be ignited explosively, equipment damage injury.	1.1x10 ⁻¹¹	There are two lights on main burner control panel that could be set up to indicate when N ₂ purge valves are open.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
3. Main Vessel Burner System (cont.)	Attempt to start burner without igniter (high temperature start) and delay in achieving ignition occurs. Combustible gases accumulate in main vessel.	33.a) Failure of optical pyrometer and b) Thermocouple failure and c) Error by supervisor in giving word to attempt high temperature start.		Will not be able to do.	The lock switch on the control panel will be deactivated and no hot startup without purging will be attempted.
	Production of an explosive gas mixture in chamber due to frozen slag restricting O ₂ flow.	34.a) Design of burner allows slag to freeze over opening reducing O ₂ flow and b) Operator fails to notice reduction in O ₂ flow and c) Loss of flame and d) Failure of shutdown system to stop NG flows	Explosion in test vessel with equipment damage and personnel injury.	6x10 ⁻¹¹	Inspect burners and lances on each shutdown to determine if there is a slag buildup problem and if corrective action is necessary.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Air Lance		<p>35.a) Design of lance allows slag to freeze over opening reducing air flow</p> <p>and</p> <p>b) Operator fails to notice possible equipment damage.</p>	Loss of air will result in higher temperature in incinerator section with possible equipment damage.	1×10^{-6}	Same as 34.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
G. Main Vessel Burner System (Cont'd.) Incinerator	Flammable gas mixture goes out stack	36. a) Frozen slag plugs incinerator air holes reducing air flow and b) Operator fails to notice reduced air flow/temperature in incinerator and c) Stack gas analyzer fails to detect and turn down burner and d) Stack gas analyzer fails to detect combustibles and shutdown burner	Release of flammable/toxic gas to atmosphere.	4×10^{-13}	
		37. Start-up of main burner in full flow	-	-	System has been changed so that start-up must be in the low flow mode.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch	Oxygen flow to torch continues when loss of NG flow occurs. High O ₂ concentration in slag tap vessel.	38. a) Valve downstream of flow control valve in NG line closed by error or failure and b) Interlock system fails to detect and c) Flow switch fails to alarm or operator error and d) Flame detector fails to shutdown torch and e) Vessel O ₂ analyzer fails to shutdown and f) Vent O ₂ analyzer fails to work or operator ignores alarm and g) NG valve is reopened	Possible explosion causing equipment damage and injury.	5x10 ⁻¹⁸	
		39. a) Valve upstream of PSL 112 shut or loss of NG supply and b) Interlock fails to shut off O ₂	Same as 38.	5x10 ⁻¹⁸	

TABLE I
(CONTINUED)
IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Ves- sel Burner System (Cont'd.) Slag Tap Torch		39. and c) Flow switch fails or operator error and d) Flame detector fails to shut off O ₂ and e) Vessel O ₂ analyzer fails or operator error and f) Vent O ₂ analyzer fails or operator error			
	NG flow to torch continues when loss of O ₂ flow occurs causing high combustibles in slag tap vessel	40. a) Valve downstream of flow control valve in O ₂ line closed by error or failure and b) Flow switch fails or operator error and c) Flame detectors fails to shut off torch and d) Vessel combustibles detector fails to shut down and	Possible explo- sion causing equipment damage and injury.	5x10 ⁻¹⁸	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch		<p>40. e) Vent combustibles detector fails or operator error and f) Valve is reopened</p> <p>41. a) Valve upstream of PSL 106 fails closed or loss of O₂ and b) Interlock fails to shut off torch and c) Flame detector fails to shut off torch and d) Flow switch fails or operator error and e) Vessel combustible detector fails or operator error and f) Vent combustible detector fails or operator error</p>	Same as 40.	5x10 ⁻¹⁸	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch	Torch does not shutdown on failure to ignite. Combustible mixture in vessel	42. a) Igniter fails to ignite and b) Timer (T-4) fails to open or (C-6) relay fails closed and c) Operator holds ignition button for 5 minutes and d) Vessel combustible detector fails and e) Vent combustible detector fails	Possible explosion with equipment damage	3.7×10^{-19}	Operator training to emphasize that no burner be started with combustibles or O ₂ showing on detectors.
		43. a) Flammable mixture in Slag Tap Vessel and torch activated due to purge timer failure and b) G1B gas detector fails or shutdown system fails and c) G2B gas detector fails or shutdown system fails and	Possible explosion with equipment damage.	2×10^{-11}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch		43. d) G9B O ₂ detector fails or shutdown system fails and e) G10B O ₂ detector fails or shutdown system fails			
	Torch fuel rich, high combustibles present	44. a) High NG pressure or Low O ₂ pressure that PS 20 fails to detect and b) Flow switch 33 fails to detect and c) Combustible analyzer system fails to detect	Possible explosion	1.9×10^{-12}	
	Torch fuel lean, high O ₂ concentration	45. a) Low NG pressure or b) High P interlock fails to shut down and c) NG flow switch (FS-32) fails to detect and d) O ₂ analyzer system fails to detect	Excess O ₂ in slag tap vessel and vent.	1.9×10^{-16}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch (Cont'd.)	Torch fails to shutdown due to cooling water problems	46. a) Reduced cooling water flow to torch due to pump or control valve failure and b) Low flow switch or Relay fails to shutdown torch and c) High temperature switch or Relay fails to shutdown torch and d) Operator fails to respond to alarm	Loss of torch and water sprays onto notch freezing slag.	5×10^{-13}	
		47. a) Cooling water to torch - high temperature and b) High temperature interlock fails to shutdown torch	Loss of torch and water sprays onto notch freezing slag	1×10^{-7}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch (Cont'd.)	Torch fails to shutdown when flamout occurs due to high pressure. Buildup of flammable mixture.	48. a) Pressure in slag tap vessel exceeds torch supply pressure. and b) Flameout occurs (normal) and c) Torch control system fails to shutdown torch and d) Operator inaction and e) Relief valve on Slag Tap vessels fails closed	Equipment damage and possible operator injury.	3.3×10^{-17}	
		49. a) N ₂ purge valve to O ₂ or NG line to torch fails open and b) Failure of flame detector to shutdown torch and c) O ₂ /combustible analyzer system fails to detect	Same as 48.	7×10^{-14}	
	Flammable/explosive gas mixture develops in slag tap vessel	50. a) Leak in NG tubing to torch and b) Combustible analyzer system fails to detect or shutdown torch	Potential explosion. Damage to slag tap vessel possible operator injury.	7.4×10^{-15}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) Slag Tap Torch (Cont'd.)	Flammable/explosive gas mixture develops in slag tap vessel	51. a) Leak in O ₂ tubing to torch and b) O ₂ analyzer system fails to detect or shutdown torch	Potential explosion. Damage to slag tap vessel possible operator injury.	7.4×10^{-15}	
	Unable to move slag tap torch	52. Slag tap torch is now mounted in one position so this situation no longer is applicable.	---	---	
	Torch fails to shutdown when main burner shuts down and flammable mixture introduced with torch going	53. a) Torch operating and b) Shutdown of main burner and c) Torch fails to shutdown and d) Operator fails to notice that torch is operating and e) Igniter fails to light off main burner but torch flame does	Minor explosion with refractory and possible equipment damage.	1×10^{-11}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) NG Lance (Cont'd.)	Lance fails to shutdown when main burner shuts down and flammable mix- ture intro- duced with torch going	54. a) Main burner shuts down and b) Interlock fails to shut off NG flow to lance and c) Combustible detec- tors fail to detect or Combustible detector alarm sounds but operator does not understand or takes wrong action and d) ASV-G448 fails to close on burner shut- down	Combustible in main vessel - possible explo- sion in hood area	2×10^{-14}	Operators to be trained to check that all gas and air flows have stopped when burner shutdown occurs.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) Natural Gas Lance (Cont'd.)	Lance fails to shut off when cooling water flow low or temp. high	55. a) Low cooling water flow or high cool- ing water temp. and b) Interlock fails to shut off lance	Loss of lance. Possible steam explosion.	8.3×10^{-12}	
		56. a) High cooling water temperature and b) Interlock fails to turn down burner and c) Emergency overtem- perature reached with failure of shutdown system and d) Operator fails to take action	Same as 55.	8.6×10^{-16}	
	Production of a flammable/ explosive gas mixture in re- fractory cham- ber	57. a) Methane lance N ₂ purge valve fails open due to coil burnout	Unknown gas com- position. Low temperature.	8.1×10^{-5}	Loss of methane flow would result in less heat produced in incinerator and alter the test conditions. Not a credible hazard.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) Natural Gas Lance (Cont'd.)	Production of a flammable/ explosive gas mixture in refractory chamber	58. a) Methane lance flow indicator was in- correctly calibrated or Calibration changed over time. High temperature in incinerator area - hood damage.	Unknow gas com- position.	4.0×10^{-5}	Check of flow meter on 6 months basis to verify calibration.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
G. Main Vessel Burner System (Cont'd.) Air Lance (Cont'd.)	Lance fails to shutdown when main burner shuts down	59. a) Main burner shuts down and b) Interlock fails to shutoff air to lance and c) O ₂ detector fails to detect or O ₂ detector alarms but operator fails to take proper action	Air cools refractory faster than desired, possible thermal shock	4.9x10 ⁻⁸	
		60. a) Low cooling water flow or high cooling water temperature and b) Interlock fails to shutoff lance	Possible loss of lance	8.3x10 ⁻¹²	
		61. a) High cooling water temperature and b) Interlock fails to turndown burner and c) Emergency overtemperature reached with failure of shutdown system and d) Operator fails to take action	Loss of lance	8.6x10 ⁻¹⁶	

TABLE I
(CONTINUED)

HTRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
G. Main Vessel Burner System (Cont'd.)	Production of a flammable/explosive gas mixture in refractory chamber	62. a) Air lance N ₂ purge valve fails open due to coil burn-out or Control failure	High combustion rate in incinerator - hood damage.	8.1 x 10 ⁻⁵	Recommend light to indicate when N ₂ purge valve opens and procedure for operator to do when this occurs.
Air Lance (cont'd.)		63. a) Air lance flow indicator was incorrectly calibrated or b) Calibration changed over time	Same as 62	4 x 10 ⁻⁵	Recommend initial calibration of flow-meter & periodic rechecks - twice a year.

(G-43 and -44) Flammable mixture develops in slag tap vessel that detectors G1, G2, G9, and G10 fail to detect and torch is ignited with explosion.

Recommendations are as follows:

- (1) Any time gas is on line to burner the main fan is to be operating. Have alarm to indicate when fan is not operating. This could be tied into Monocon gas gauge, W-3, that alarm sounds if fan is not operating when gas pressure reaches 30 psi.
- (2) Check for leak on each shift, and if leaks are found, shutdown and repair - do not delay fixing.
- (3) Checkout shutdown system that all components work properly, C1, C2, and C4 are of particular concern as these can allow gas and O₂ into the main vessel.
- (4) Determine what minimum flow for O₂ IAL is and adjust if too low.
- (5) Operator training to emphasize that before igniting burner or torch, check to assure that combustible analyzers and O₂ analyzers are operating and indicating in the safe range.
- (6) Calibrate flow control instruments before each run.
- (7) The main burner is a unique design that has not been tested previously. A failure of the cooling water jacket would be capable of releasing up to 155 GPM of water into the main vessel. The resulting pressure surge would blow all relief protective devices and destroy the vessels. The pressure surge would be above 400 psi and the rupture pressure of the vessel is 300 psi. Any indications of reduced flow or increased temperature of the cooling water on the main burner should require an immediate activation of the Burner Turndown system (BTD) until the problem is resolved. On each scheduled shutdown, the main burner must be inspected for signs of potential failure.
- (8) There are spare lights on the main burner control panel section that could be set-up to indicate when either N₂ purge valve N332 and N334 is open.
- (9) Inspect the burners and lances on each scheduled shutdown to determine if a slag buildup is causing problems in restricting flow.

- (10) Operators to be trained to check that all gas and air flows have stopped whenever a burner shutdown occurs.
- (11) Check all flow meters for calibration before each run.

7. Incinerator Section

a. Process Description

Air is added to the main vessel in the incinerator section. The air reacts with the hot incomplete combustion gases producing CO₂, H₂O, and heat that melts the slag injected at the top of the incinerator. The air flow to the incinerator is measured by an orifice plate and controlled by an ASV-A228 air to open, fail closed, valve.

b. Design Safety Features

The air pressure at the incinerator is monitored with a high warning pressure setpoint of 125 psi, a low warning pressure of 115 psi, and a low emergency warning pressure of 105 psi.

The cooling water on the incinerator is monitored with a warning alarm when the cooling water reaches 115°F and if not corrected, results in an automatic burner turndown. If the cooling water temperature reaches 150°F, it would result in an automatic burner shutdown.

The stack O₂ analyzers monitor the exiting gases and alarm when the O₂ level reaches 5% and an emergency alarm and burner turndown occurs when the O₂ level reaches 12%.

c. Potential Problems and Severity

The main problem is the loss or reduction of air flow to the incinerator resulting in less temperature increase, insufficient heat to melt the slag and release of CO to the atmosphere. There is no direct operator hazard but the test results would be affected if the slag was not melted. The probability of problems in the incinerator section is 1.3×10^{-8} /hr (see Table I, Section H).

d. Specific Incident and Recommendations

(H-3) Air line ruptures in the hood area and the O₂ analyzers fail to detect and the turndown/shutdown system fails.

Recommendations are as follows:

- (1) Calibrate flow instruments before each run.
- (2) Check air lines in hood for signs of damage on each shutdown.
- (3) Calibrate O₂/combustible analyzers every week.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
H. Main Vessel Incinerator	Flammable/explosive gases exit process	1.a) Loss of air flow or Reduction of air flow due to compressor system problems and b) Failure of turndown/shutdown system	Flammable/toxic gases to atmosphere	1.2×10^{-9}	
		2.a) Air add valve fails closed due to solenoid failure or Control failure and b) Failure of turndown/shutdown system	Flammable/toxic gases to atmosphere	1.1×10^{-8}	
		3.a) Rupture of air line in hood and b) Failure of analyzer to detect and c) Failure of shutdown system	Flammable/toxic gases to atmosphere	2.6×10^{-12}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
H. Main Vessel Incinerator (cont.)	Flammable/explosive gases exit process	4.a) Incinerator air flow indicator gives wrong reading due to calibration error or Operator error in setting and b) Stack gas analyzers fail to detect	Flammable toxic gases to atmosphere	4.1×10^{-10}	Pressure check hood to see if leaks can be found. Due to porosity of refractory studs holding refractory in position, and slag freezing on a cold surface this is probably no problem.
	Overheating of hood due to loss of refractory	5.a) Air leak under castable refractory due to poor assembly and b) Failure to find with testing	Probable loss of hood	1×10^{-9} est.	

8. Slag Slurry Feed System

a. Process Description

The slag is stored in the Slag Storage Vessel, a tank 8 ft. in diameter and 36 ft. high that holds 75 tons of slag. The slag, which will vary in composition from run to run, has a maximum particle size of 2mm. The slag is fed by a vibratory feeder into a ribbed conveyor belt at a rate of about 150 lbs. per hour. The conveyor discharges the slag into an agitated slurry make-up tank 4 ft. in diameter and 3 ft. high. A water slurry that is 20% by weight slag, is made up in the tank which has an agitator and automatic level control.

The slurry is pumped from the slurry tank to the top of the main vessel by a Moyno six stage PD pump. The slurry flows through a 1/2 in. diameter, high pressure hose and is sprayed through a hollow cone spray nozzle onto the side walls of the incinerator. High pressure air is added with the slurry to obtain the proper spray pattern without introducing excess water.

The piping for the slurry system includes a sampling/by-pass line and a recirculating by-pass line back to the slurry tank. This system layout is shown in Figure 7.

b. Design Safety Features

The slurry feed system has the following safety features. Flow switch, FS-5, alarms at 0.5 GPM with normal flow being 2 GPM. Pressure switch, PS-9, alarms at 105 psi on the slurry discharge line. Pressure switch, PS-8L, alarms at 160 psi opening the sampling by-pass, stopping the slurry feed, and opening the water feed to the pump suction. In addition, water flows directly to the spray nozzle to keep it clean and cool. If the pressure rises to 180 psi, PS-8H opens the recirculating by-pass.

There is a rupture disc on the pump discharge that relieves at 200 psi back to the slurry tank.

c. Potential Problems and Severity

The potential problems are slag stuck in storage tank, plugged slurry lines, plugged spray nozzles, gas leaks, and hose failure. The severity could vary from a minor injury to, if the circumstances are right, death of an operator. The probability of serious operator injury is 1×10^{-8} /hr. (See Table I, Section I.)

d. Specific Situations and Recommendations

(I-2) Slurry line plugs and operator does not release pressure on line and operator opens line without proper safety equipment, resulting in slag blinding operator. The probability is 1×10^{-8} /hr.

Figure 7. Slag Slurry Feed System

TABLE I
(CONTINUED)
IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
I. Main Vessel Slag Slurry Feed System	Operator injury due to problems with the slag handling system	1. a) Slag does not come out of storage vessel due to bridging and b) Operator unable to break bridge and c) Operator opens bottom of tank and d) Nobody is on safety watch and e) Slag breaks loose trapping operator	Operator injury/death	1×10^{-12} (est.)	Operators to wear designated safety equipment and follow safety procedures when working on equipment. Work is to be done only with approval of supervision.
		2. a) Slurry line plugs and b) Operator does not release pressure on line and c) Operator opens line without proper safety equipment	Operator injury	1×10^{-8}	Same as I-1 above.
		3. a) Spray nozzle plugs in main vessel and	Operator knocked off vessel	1×10^{-13} (est.)	Consider platform on top of vessel, emphasize following all safety procedures.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
I. Main Vessel Slag Slurry Feed System (Cont'd.)	Operator injury due to problems with the slag handling system	<p>3. b) Unable to open using HP water or N₂ and</p> <p>c) Main vessel left pressurized and</p> <p>d) Operator attempts to remove nozzle without proper safety equipment and</p> <p>e) Supervision not present</p> <p>4. a) Spray nozzle plugs in main vessel and</p> <p>b) Unable to open using HP water or N₂ and</p> <p>c) Vessel depressurized but burner on low fire and</p> <p>d) Operator works without proper safety equipment and</p> <p>e) Supervision not present</p>	Operator overcome by toxic gas	1x10 ⁻¹³ (est.)	Consider platform on top of vessel, emphasize following all safety procedures.

TABLE I
(CONTINUED)
IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
I. Main Vessel Slag Slurry Feed System (Cont'd.)	Operator injury due to problems with the slag handling system	5. a) Slurry feed system goes down and b) Check valve fails open and c) Valve in sampler line leaks and d) Gas back flows exiting at sampler	Fire causes damage to slurry feed system and electrical gear with possible operator injury	1.4×10^{-12}	
		6. a) Failure of hose and b) Check valve fails open and c) Operator sprayed by slurry or hot gases	Operator injured or burned	9×10^{-13}	

Recommendations are:

- (1) Release pressure before working on lines or equipment that are pressurized.
- (2) Wear proper safety equipment, face shield or goggles.
- (3) Work to be done only with approval of supervision.

(I-1) Slag bridges in bottom of slag storage tank and when unable to free slag, operator opens bottom of tank and nobody on safety watch and slag breaks loose trapping operator.

(I-3 and -4) Spray nozzle plugs and operator unable to open line while not using proper safety equipment.

(I-5) Slag feed system goes down and check valve CV-S513 fails open and valve in sampler line leaks, allowing hot gases to exit at sampler.

(I-6) Hose fails and check valve fails and operator sprayed by slurry or hot gases.

Recommendations are as follows:

- (1) Operators to be aware of IITRI procedures for working on pressurized lines and equipment.
- (2) Consider installing a platform at the top of the main vessel for safety when working on top of the main vessel.
- (3) Operators to wear proper safety equipment and follow safety procedures at all times.

9. Main Vessel Problems

a. Process Description

Molten slag flows down the refractory walls to collect at the bottom of the main vessel. The slag then flows through the slag tap notch into the slag tap vessel, as shown in Figure 8.

An N₂ jacket is maintained between the refractory and the shell of the main vessel. The N₂ pressure is kept at 100 + 5 psi to protect the cooling water hoses and coolers from condensed acid gases and leaks of hot gases into the jacket area.

b. Design Safety Features

The safety features of this part of the process include the following:

- (1) An optical instrument to measure the slag in the discharge from the slag tap vessel. A decrease in solids would result from pluggage of the slag tap notch.
- (2) Monocon gauge W-2 which gives an N₂ jacket pressure warning at 100 psi and an emergency warning at 110 psi.
- (3) The differential pressure rupture disc between the N₂ jacket and the pressure gas which has a DP rating of 20 psi.
- (4) The combustible analyzers and O₂ analyzers will activate an automatic burner turndown at 0.75% CH₄ or 5% O₂ and a burner shutdown at 1.5% CH₄ or 12% O₂.
- (5) The N₂ check valve will allow higher pressure N₂ to flow from the jacket into the slag tap vessel.

c. Potential Problems and Severity

The potential problems are pluggage of the slag tap notch results in the building up of molten slag in the main vessel, low pressure in N₂ jacket area, high pressure in N₂ jacket area, and failure of analyzers to detect combustibles or O₂ in jacket area.

In most cases, the severity would be loss of the refractory and the end of the test. The probability of a failure resulting in loss of refractory is 5×10^{-6} /hr. (See Table I, Section J.)

Figure 8. Main Vessel Arrangement

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
J. Main Vessel Miscellaneous	Hole in refractory	<p>1. Air or methane lance gas stream impinges on opposite wall eroding through refractory due to loss of swirler or Insufficient turbulence to breakup HP gas stream</p> <p>2. a) Slag tap notch plugs due to slag freezing or Broken piece of refractory in hole and b) Unable to reopen hole and c) Slag melts and pours into quench water creating pressure surge (steam explosion) and d) Solids monitoring instrument in outlet line fails to operate or detect low solids level</p>	<p>Erosion of refractory</p> <p>Possible damage to main burner. Relief/rupture disc protects slag tap vessel but sudden depressurization causes loss of refractory integrity</p>	<p>No problem as gas velocity should be ~3 ft/sec at wall</p> <p>2×10^{-15}</p>	<p>Need to check that slag is flowing and stop slag feed if problems occur until notch is reopened.</p>

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous	High ΔP across refractory	3. a) High ΔP results from low pressure on jacket side due to loss of N_2 flow because valve closed or A leak/rupture of the slag notch pressure tap line to N_2 PCV and b) N_2 leakage from jacket to atmosphere is greater than process gas leakage from core to jacket and c) Situation not detected or corrected by ΔP switch and d) Pressure balance not restored by flow through differential pressure rupture disc	Loss of refractory, end of test.	1×10^{-13}	Loss of refractory may result in failure of cooling water lines or hot gases may destroy the hoses with the end result being large water leaks that could result in a steam explosion.
		4. a) High ΔP results from low pressure on jacket side due to premature failure of N_2 rupture disc and	Loss of refractory and end of test	2×10^{-10}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous (continued)	High ΔP across refractory	4. b) N_2 supply capability exceeded and c) Situation not corrected by ΔP switch and d) Pressure balance not restored by differential pressure rupture disc	Loss of refractory and end of test.	2×10^{-10}	
		5. a) High ΔP results from low pressure on jacket side due to abnormal N_2 leak from vessel and b) N_2 supply capability exceeded or Failure to increase flow and c) Emergency ΔP sounds - operator fails to reduce vessel pressure and d) Pressure balance not restored by differential pressure rupture disc	Loss of refractory and end of test.	1.8×10^{-11}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous (continued)	High ΔP across refractory	6. a) High ΔP results from high pressure on jacket side due to high N_2 pressure as valve fails open, bad seat or Control failure and b) N_2 check valve capacity exceeded or N_2 check valve fails closed and c) Situation not corrected by ΔP switch and d) Pressure balance not restored by differential pressure rupture disc	Loss of refractory and end of test	1.3×10^{-18}	
		7. a) High ΔP results from high process gas pressure due to gas PCV's (both) failing closed and b) N_2 supply capability exceeded and c) Situation not corrected by ΔP switch and	Loss of refractory and end of test	6.6×10^{-13}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Ves- sel Miscel- laneous (continued)	High ΔP across re- fractory	<p>7. d) Pressure balance not restored by differential pressure rupture disc</p> <p>8. a) High ΔP results from low process gas pressure due to gas PCV fail open and b) N_2 check valve capacity exceeded or N_2 check valve fails closed and c) Pressure balance not restored by differential pressure rupture disc</p> <p>9. a) High ΔP results from low process gas pressure due to slag tap vessel purge valve failing open and b) N_2 check valve capacity exceeded or N_2 check valve fails closed and</p>	<p>Loss of re- fractory and end of test</p> <p>Loss of re- fractory and end of test</p>	<p>5×10^{-9}</p> <p>4×10^{-10}</p>	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous (continued)	High ΔP across re- fractory	9. c) Pressure balance not restored by differential pressure rupture disc 10. a) High ΔP results from low process gas pressure due to premature failure of a rupture disc and b) N_2 check valve capacity exceeded or N_2 check valve fails closed and c) Pressure balance not restored by differential pressure rupture disc	Loss of re- fractory and end of test.	5×10^{-6}	Inspect rupture discs after each run for signs of wear or fatigue
	Damage to equipment re- fractory	11. a) N_2 pressure control valve fails open due to diaphragm rupture resulting in high flow to slag tap vessel and N_2 jacket and b) Operator fails to re- spond to alarms	Possible loss of refractory	1.3×10^{-7}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
J. Main Vessel Miscellaneous (Cont'd.)	Thermal damage to vessel wall and/or equipment between refractory and vessel wall	12. a) Process gas enters jacket through differential rupture disc connection due to premature failure of rupture disc and b) Sufficient gas enters to cause damage if not detected and c) Situation not detected/corrected by jacket analyzer and d) Situation not detected/corrected by 2nd (emergency) jacket analyzer.	Damage to vessel water lines and coolers, may necessitate the end of the test	2×10^{-12}	
		13. a) Process gas enters jacket when differential rupture disc fails due to operator error and b) Sufficient gas enters to cause damage if not detected and	Damage to vessel water lines and coolers, may necessitate the end of the test	4×10^{-10}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous (Cont'd.)	Thermal damage to vessel wall and/or equipment between refractory and vessel wall (Cont'd.)	13. c) Situation not detected/corrected by jacket analyzer and d) Situation not detected/corrected by 2nd (emergency) jacket analyzer	Damage to vessel water lines and coolers, may necessitate the end of the test	4×10^{-10}	
		14. a) N ₂ check valve fails open and b) Sufficient gas enters to cause damage if not detected or corrected and c) Situation not detected/corrected by 1st jacket gas analyzer and d) Situation not detected/corrected by 2nd jacket gas analyzer	Damage to vessel water lines and coolers - need to end test	1.2×10^{-13}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous	Thermal damage to vessel wall and/or equipment between refractory and vessel wall	15. a) Loss of air to incinerator and b) Gas backflows through air lines and c) Hoses fail due to overheating in hood allowing process gas to enter jacket and d) Sufficient gas enters to cause damage and e) Situation not detected/corrected by 1st jacket analyzer and f) Situation not detected/corrected by 2nd jacket analyzer	Damage to vessel and cooling system	4×10^{-10}	

TABLE 1
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
J. Main Vessel Miscellaneous (continued)	Thermal damage to vessel wall and/or equipment between refractory and vessel wall	6. a) Loss of refractory integrity due to expansion and contraction so that N ₂ flows in and process gas flows out and b) Sufficient gas enters to cause damage if not detected or corrected and c) Situation not detected/corrected by 1st jacket gas analyzer and d) Situation not detected/corrected by 2nd jacket gas analyzer	Damage to vessel and cooling system.	4×10^{-9}	Operation will determine if this is a problem.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
J. Main Vessel Miscellaneous (continued)	Leak at flange damages vessel and burns operator	17. a) Flange not properly tightened after heat-up burner and equipment removed and b) Operator fails to find or check for leaks while pressurizing system and c) Operator burned by hot gases escaping at slurry spray nozzle	Operator burned.	1×10^{-9} (EST)	Need to double check all nozzles used for heat-up.

d. Specific Incidents and Recommendations

(J-2) The slag tap notch plugs and the operator is unable to open the notch and the solids monitor fails to detect the low solids and the slag melts through (150 lbs. of slag) and flows into the water creating enough steam to cause the slag tap vessel to fail.

N₂ leak from jacket to atmosphere and N₂ supply exceeded and operator fails to respond to differential pressure alarm and differential pressure rupture disc fails to rupture and restore pressure balance.

N₂ jacket overpressured due to control failure and N₂ check valve unable to handle flow and differential pressure setpoint does not activate burner turndown/shutdown.

Operator error caused differential rupture disc to fail and analyzers fail to detect combustibles or O₂ in jacket area.

Recommendations are as follows:

- (1) Monitor for measuring slag in slag discharge need to be installed. Operator should check that slag is flowing three to four times each hour. If there is no slag flow, stop the slag feed and correct the situation before continuing run.
- (2) Check all flanges on main vessel daily for possible leaks.
- (3) Check N₂ check valve between main vessel and slag tap vessel to be certain that it is working properly and inlet is not plugged on each shutdown.
- (4) Inspect rupture discs before each run and replace if signs of wear or damage.
- (5) Operators to be trained to bring up both vessel and jacket pressure slowly and evenly to prevent rupture of DP rupture disc.
- (6) Calibrate analyzers at least once a week.
- (7) If problems develop, have operator switch to burner turndown mode to try to correct problem or start cooling down system. Going to the burner shutdown or emergency shutdown modes may be hard on the refractory and result in a premature end of the test.

10. Pressure Control System

a. Process Description

There are two pressure control valves, PCV-C 579 and 580, located between the scrubber and the stack. These valves fail open, which reduces the pressure when an abnormal situation occurs. The valve location in relation to the system is shown in Figure 9.

b. Design Safety Features

The following safety features are part of the pressure control system:

- (1) C-581 is an 8" relief valve set at 105 psi venting above the roof.
- (2) T-555 is a 2" relief valve set at 110 psi venting above the roof.
- (3) A 12" 140 psi rupture disc is located on the slag tap vessel discharge line and vents above the roof.
- (4) A 12" 140 psi rupture disc is located on the process gas exiting the main vessel that vents above the roof.
- (5) Two 1" 120 psi rupture discs are located on the process gas line to the scrubber that vent above the roof.
- (6) A 10" 150 psi rupture disc is located on a line from the N₂ jacket that vents above the roof.
- (7) A 6" 20 psid rupture disc is located between the main gas line and the N₂ jacket line.
- (8) N₂ purge to slag tap vessel to prevent backflow of combustible gases into the slag tap vessel.
- (9) Combustible and O₂ analyzers on the slag tap vessel.
- (10) Monocon gauges are set to have the following alarms:

Figure 9. Pressure Control System

a W-8 Slag Tap Vessel

low emergency @ 75 psi

low warning @ 85 psi

high warning @ 95 psi

high emergency @ 105 automatic burner shutdown

115 emergency burner shutdown

b W-9 Slagging Zone Pressure

low emergency @ 75 psi

low warning @ 85 psi

high warning @ 95 psi

high emergency @ 100 psi

burner shutdown @ 115 psi

emergency shutdown @ 120 psi

(11) If the slagging zone pressure is greater than the slag tap vessel pressure, a burner shutdown will occur.

(12) If the slagging zone pressure is less than the slag tap vessel pressure, a burner shutdown will occur.

(13) If the pressure in the main vessel reaches 140 psi, the O₂ and natural gas control valves will close.

c. Potential Problems and Severity

The potential problems are failure of the control valves, failure of the relief valves, failure of the rupture discs, failure of the analyzers, and failure of the shutdown system.

In most cases, the severity would relate to probable loss of refractory and equipment damage. Where relief valves, rupture discs and shutdown systems would fail to operate at high pressures, 140 psi, there could be serious operator injury. The probability of refractory loss is 1.2×10^{-7} /hr and of serious injury 8×10^{-11} /hr. (See Table I, Section K.)

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
K. Pressure Control System	Loss of refractory integrity due to sudden pressure drop/rise	1. a) Both pressure control valves fail open due to solenoid failure or Loss of instrument air or Controller failure and b) N ₂ check valve capacity exceeded or N ₂ check valve fails closed and c) Differential pressure rupture disc fails to operate	Loss of refractory end of test.	6x10 ⁻¹⁰	
		2. a) Both pressure control valves closed due to solenoid failure or Control failure or Pressure sensing line ruptures or Dirty valves due to scrubber problems and b) N ₂ flow to jacket unable to match pressure increase	Loss of refractory end of test.	3x10 ⁻¹⁴	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
K. Pressure Control System (cont'd.)	Loss of refractory integrity due to sudden pressure drop/rise	2. and c) Failure of ΔP switch and d) Pressure balance not restored by differential pressure rupture disc			
	Loss of refractory integrity and possible vessel damage due to fluctuating pressure	3. a) Fluctuating pressure control due to valves not working properly or Dirty valves from scrubber problems and b) Pressure switch does not respond or Operator fails to take corrective action	Loss of refractory, possible equipment damage end of test	1×10^{-7}	
Pressure Relief	Refractory and material damage due to loss of pressure	4. a) Scrubber relief valve does not re-seat after use and b) N_2 check valve capacity exceeded or N_2 check valve fails closed and	Loss of refractory, end of test.	2.8×10^{-10}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
K. Pressure Relief Control System (cont'd.)	Refractory and waterwall damage and possible damage to vessels due to relief valve failure	<p>4. c) Pressure balance not restored by differential pressure rupture disc</p> <p>5. a) Scrubber relief valve or slag tap vessel relief valve stuck shut and b) Pressure switch does not activate system shutdown and c) Pressure balance not restored by differential pressure rupture disc</p>	Loss of refractory possible equipment damage.	4×10^{-15}	
Rupture Discs	Damage to refractory and waterwall due to pressure relief system	<p>6. a) Premature failure of jacket RD or slagging zone RD or either exit pipe RD and b) Relief valve has not worked and c) Pressure switch fails to shutdown system and d) Pressure balance not restored by differential pressure rupture disc</p>	Loss of refractory possible cooler damage.	2×10^{-15}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
K. Pressure Relief Control System (Cont'd.)	Damage to refractory, water-wall and possibly to vessels	7. a) Relief valve on exit line fails to work and b) Relief valve on slag tap vessel fails to work and c) Rupture disc does not work at designated pressure and d) Pressure switch fails to shutdown system	Loss of refractory, possible cooler damage, end of test. Possible explosion with equipment damage and injury or loss of life	2×10^{-20}	
Rupture discs					
Slag tap vessel	Damage to slag tap vessel, internals and main vessel refractory	8. a) Slag tap relief valve (SRV-T555) fails to reseal after use, sucking flame from main burner into slag tap vessel and b) Low pressure emergency shutdown fails to work and c) Operator fails to shutdown system in response to low pressure alarm	Slag tap vessel and internals damaged, refractory damaged and end of test	2.8×10^{-13}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
K. Pressure Relief Control System (Cont'd.) Slag Tap Vessel	Damage to slag tap vessel, internals and main vessel refractory	9. a) Premature failure of slag tap rupture disc sucking flame from main burner into slag tap vessel and b) Low pressure emergency shutdown fails to work	Slag tap vessel and internals damaged, refractory damaged and end of test	2.5×10^{-11}	
		10. a) Slag tap vent dump valve (ASU-T562) fails open due to a control failure and b) Flame from main burner sucked into slag tap vessel and c) Low pressure emergency shutdown fails to work	Slag tap vessel and internals damaged, refractory damaged and end of test	1.7×10^{-10}	
		11. a) Pressure reducing control valve (PCV-T558) fails open due to control failure and b) Failure of vent gas analyzer to detect combustibles present due to drawing flame into vessel	Slag tap vessel and internals damaged, possible damage to refractory	6.8×10^{-17}	

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EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
K. Pressure Relief Control System (Cont'd.)	Damage to slag tap vessel, internals and main vessel refractory	11. and c) Failure of vessel gas analyzer to detect combustibles and d) Low pressure emergency shutdown fails to work	Slag tap vessel and internals damaged, possible damage to refractory	6.8×10^{-17}	
Slag Tap Vessel (Cont'd.)		12. System changed, no longer applies			
Slag Tap Vessel Vent Valve	Possible explosion and/or damage to slag tap vessel and equipment from overpressurization and high temperature	13. a) Slag tap vent valve (PCV-T558) fails closed due to diaphragm failure and b) Pressure switch fails to shutdown system and c) Relief valve fails to work and d) Rupture disc fails to operate	Loss of slag tap vessel, due to explosion. Probable personnel injury/death	2×10^{-21}	
		14. a) Slag tap vessel N ₂ purge add system fails closed due to PCV-N305 closed or	Loss of slag tap vessel, due to explosion. Probable personnel injury/death	8.2×10^{-11}	Consider flow switch in N ₂ line.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
K. Pressure Relief Control System (Cont'd.) Slag Tap Vessel Vent Valve (Cont'd.)	Possible explosion and/or damage to slag tap vessel and equipment from overpressurization and high temperature	14. HSV-N-313 closed or HSV-N-312 closed or CV-311 fails closed and b) No combustibles detected by slag tap vessel analyzer and c) Failure of operator to take proper action and d) Vent detector fails to detect combustibles			
Slag Tap Vessel N ₂ Purge Vent Line Pressure Control Valve	Combustibles not detected	15. a) Covered by K-14 & 16 16. a) Slag tap pressure control valve fails closed due to rupture of diaphragm and b) No flow to slag tap analyzer and c) Analyzer on vessel fails to detect combustibles and	Loss of slag tap vessel, due to explosion. Probable personnel injury/death	6.4×10^{-13}	Check calibration twice a week.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
K. Pressure Relief Control System (Cont'd.)	Combustibles not detected	16. d) N ₂ purge system not working			
Slag Tap Vessel N ₂ Purge Vent Line Pressure Control Valve (Cont'd.)					

d. Specific Incidents and Recommendations

Pressure control valves fail open or relief valves open prematurely or fail to reseal or rupture discs fail prematurely, resulting in sudden depressurizing of the system and loss of the refractory.

Pressure control valves fail closed and relief valves fail to open and rupture discs fail to burst and pressure shutdown system fails resulting in failure of equipment and loss of life.

(K-11 & 13) Pressure control valve PCV-T558 fails and analyzers fail to detect combustibles and shutdown system fails.

(K-14) Failure of N₂ purge to slag tap vessel due to problem with PCV-N305 or HSV-313 or HSV-N312 or CV-311 and analyzers fail to detect combustibles.

Recommendations are as follows:

- (1) Calibrate analyzers at least once a week.
- (2) Check rupture discs before each run for signs of wear or corrosion.
- (3) Check relief valves once a year.
- (4) Install a N₂ flow switch in N₂ purge line to slag tap vessel.

11. Venturi Scrubber System

a. Process Description

The hot, >2000° gas from the main vessel, as shown in Figure 10, comes into the scrubber where water is sprayed at a rate of 25 GPM into the gas stream. The gas and water then flow to the separator where the water is separated from the cooled gases, 300°F. The gases then pass through the pressure control valves to the stack. The water level in the separator is maintained by a level controller that operates flow valve FCV-WC180 and allows the water to flow to the drain.

b. Design Safety Features

The following are the safety features of the venturi scrubber system:

- (1) Flow switch, FS-6, high pressure water flow to the scrubber activates at 15 GPM or less with alarm and automatic burner turndown.
- (2) Flow switch, FS-7, low pressure water flow to the scrubber, activates at 10 GPM or less with alarm and automatic burner turndown.
- (3) If both flow switches, FS 6 & 7, are activated then an automatic burner shutdown will occur.
- (4) Flow switch, FS-8, on the discharge of the water from the scrubber activates an alarm if the flow out of the separator drops below 15 GPM.
- (5) Data logger temperature #3, scrubber water temperature, alarms at 210°F and if not corrected, an automatic burner turndown will occur.
- (6) Data logger temperature #4, scrubber gas temperature, alarms at 350°F and if not corrected, an automatic burner turndown will occur.

c. Potential Problems and Severity

Potential problems in the scrubber area are loss of water to the scrubber or piping that could result in overheating and failure of the piping. Another potential problem is an operator being seriously burned if he contacts the exit line from the separator. (See Table I, Section L.)

Figure 10. Venturi Scrubber System

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
L. Venturi	Venturi/scrubber fails due to overheating	1. a) Loss of HP water to venturi due to fouling or Plugged line or Valve closed or Both HP pumps down and b) Flow switch 6 fails to activate burner turn-down and c) Loss of LP water to venturi due to failing or Plugged line or Valve closed and d) Flow switch 7 fails to activate burner turn-down and e) Operator fails to act on low level or low flow alarm from scrubber	Loss of venturi/scrubber	1.7×10^{-16}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
L. Venturi (Cont'd.)	Venturi/scrubber fails due to overheating	2. a) Reduced water flow to venturi due to fouling and b) Flow Switch (FS 6 or 7) fails to turn down burner system and c) Flow Switch (FS-8) fails to activate alarm	Loss of venturi and scrubber	1.7×10^{-12}	
		3. a) Jacketed water line fails and b) Operator fails to respond to temperature alarm	Loss of venturi and scrubber	1×10^{-12}	
	Operator seriously burned on hot piping	4. Operator trips or falls on second deck making contact with piping from scrubber to stack (gas in pipe is 350°F)	Operator receives serious burns	1×10^{-4}	Insulate the line to protect personnel from potential injury.

d. Specific Incidents and Recommendations

(L-4) Operator makes contact with the hot pipe (300-350°F) from the scrubber to the stack and is severely burned. There is very little room to move on the second level and it would be very easy for an operator to make contact with this hot line. The probability is 1×10^{-4} per hour.

It is recommended that this line be insulated to protect personnel from burns in case of contact.

Other recommendations are that the flow switches and thermocouples on this system be checked and calibrated before each run.

12. Slag Tap Vessel

a. Process Description

The Slag Tap Vessel (Figure 11) is a 6 ft. diameter, 16 ft. high tank rated at 155 psi. The vessel will be about half full of water for quenching slag coming from the main vessel.

The molten slag flows through the slag tap notch and drops into the water in the slag tap vessel. While dropping the slag is sprayed with water to help fracture it into small pieces. The small pieces of slag are fluidized and flow out of the vessel to a hydrocone which separates the solids and the water. The slag is collected in hoppers for disposal while the water goes to a drain. The pressure in the vessel forces the dilute slurry, about 2% solids, out the discharge lines.

A level controller monitors the level in the tank and controls the water flow in and out. Water is added continuously through a series of sprays. In addition, water is added through a two-way valve, ASV-WS158, either to the screen back flush line at lower levels or through the continuous make-up line. Water flows out through the slurry outlet line and automatic valve ASV-S528. In addition, a high water level opens ASV-WR169 in the back-up drain line while a higher water level opens ASV-WR171 in the emergency drain line.

b. Design Safety Features

The following are the safety features of the slag tap vessel:

- (1) Two-inch relief valve set at 110 psi.
- (2) Twelve-inch rupture disc rated at 140 psi.
- (3) Combustible and O_2 monitor in vapor space that will activate burner turndown if warning conditions occur (0.75% CH_4 or higher and/or 5% or higher O_2).
- (4) Combustible and O_2 monitor of purge gas that will activate burner turndown as stated above.
- (5) Automatic burner shutdown if any monitor detect 1.5% CH_4 or 12% O_2 .
- (6) An automatic burner turndown occurs if either a high or low water level develops in the vessel.

Figure 11. Slag Tap Vessel

- (7) Temperature switch, TS-30, in the water will alarm when the water temperature rises to 105°F and if not corrected an automatic burner turndown will occur.
- (8) Temperature switches, TS-31 & 32, in the vapor space will alarm when the gas temperature reaches 150°F and if not corrected, an automatic burner turndown will occur.
- (9) A N₂ purge system that adds N₂ to the vapor space through valve, PCV-N305, to maintain an inert atmosphere in the vessel. If combustibles or O₂ is detected, a higher rate of purging will take place until the atmosphere returns to normal.

c. Potential Problems and Severity

The potential problems in this vessel are molten iron flowing into the water with an explosion destroying equipment and killing operators, water rising into the slag tap notch with a possible explosion, drain lines open allowing gases to vent into pit by vessel, buildup of slag and insufficient N₂ purge to vessel.

The severity in many cases would be severe operator injury or death. In other cases there would be internal damage to the equipment that would delay further operation until repaired. The probability of serious injury is 1.6×10^{-9} /hr. (See Table I, Section M).

d. Specific Incidents and Recommendations

(M-1) Molten iron is produced in main vessel due to a very reducing atmosphere and when iron contacts water in slag tap vessel, explosion results. Probability is 1×10^{-9} per hour.

Recommendations are as follows:

- (1) Calculation of natural gas and oxygen ratios be made independently by two engineers.
- (2) Flow instrumentation be calibrated and checked before each run.
- (3) Operator to set NG to O₂ ratio and supervisor to check that it has been set properly.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
M. Slag Tap Vessel (Miscellaneous)	Physical Explosion	1. a) Ratio of NG to O ₂ is set high or Instrument error and b) NG to lance flow decreases or Air to lance flow decreases and c) Operator fails to notice change and correct lance flow and d) Gas in main vessel is sufficiently reducing to produce molten iron which flows into slag tap vessel with resulting explosion	Loss of slag tap vessel. Operator injury.	1x10 ⁻⁹	Instrumentation to be calibrated and checked before each run. Operator to be checked on NG to O ₂ ratio. Supervision to check O ₂ and air flows against calculated valves. Inspect bottom of main vessel on each shutdown to determine if free iron is present.
	Wall exposed to temperature above design limits	2. a) Loss of water curtain due to loss of water to slag tap vessel and b) Hot slag flows onto shield eating a hole through the shield and	Loss of slag tap vessel	3x10 ⁻¹⁴	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
M. Slag Tap Vessel (Miscellaneous)	<p>Wall exposed to temperature above design limits (continued)</p> <p>Water into notch/main vessel</p>	<p>2. c) Hot slag makes contact with vessel wall and causes failure</p> <p>3. a) Emergency drain not working due to failure of probe LL 6 to de-energize R-29 when liquid contact probe or Relay R-29 stays energized or N-423 positioned wrong or</p>	Explosion - loss of equipment, serious injury.	6×10^{-10}	Install independent high level sensor and alarm to warn operator of high level in slag tap tank.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
M. Slag Tap Vessel (Miscellaneous) (Cont'd.)	Water into notch/main vessel	<p>3. Solenoid SLV-N422 fails to open or ASV-WR171 fails to open or HSV-WR170 fails closed or not opened and</p> <p>b) Backup drain not working due to valve failure ASV-WR169 or Solenoid SLV-N424 fails closed or MO-W425 positioned wrong or HSV-WR168 fails closed or not opened or Level probe LL 6 fails or Relay R-29 stays energized and Level probe LL 5 fails or Relay 28 stays energized or Level probe LL 7 fails or</p>			

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
M. Slag Tap Vessel (Miscellaneous) (Cont'd.)	Water into notch/main vessel	<p>Relay 30 stays energized or</p> <p>3. Relay CR63 fails open and</p> <p>c) R10R fails to open or</p> <p>Motor fails to close valve or</p> <p>LL6 fails or</p> <p>Motor 280 valve fails to close or</p> <p>ASV-WS158 fails open to backflash position or</p> <p>R-30 fails closed or</p> <p>MON-415 positioned wrong or</p> <p>LL 7 probe fails or</p> <p>Solenoid SLV-W414 fails open and</p> <p>d) Operator inaction/error due to LL6 fails or</p> <p>R-28 fails closed or</p>			

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
M. Slag Tap Vessel (Miscellaneous) (Cont'd.)	Water into notch/main vessel	Operator fails to take correct action when alarm sounds			
	Leak of hot gases	4. a) Failure of fitting or Failure of flange gas-ket and b) Failure to detect leak	Operator injury due to contact with hot gases	5.4×10^{-9}	Check all flanges for leaks when pressurizing vessels. Operators to make periodic checks when operating (once per day).
	Loss of water flow to slag tap vessel	5. a) Failure of valves or control in water feed piping and b) Slurry outlet valve fails to close and c) Low level alarm fails or operator fails to take corrective action	Water temperature in slag tap vessel increases steam buildup relief valve or rupture disc operate, may delay test	3.5×10^{-16}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
M. Slag Tap Vessel (Miscellaneous) (Cont'd.)	Leak of flammable gases from slag tap vessel lines	6. a) Emergency drain line open due to control or valve failure and b) Water level drops below exit pipe and c) Gases vent to drain and d) LP alarm sounds, operator takes no action and e) LP emergency shutdown fails to operate and f) High temperature vapor space alarm fails or Burner turndown system fails to operate	Flammable gases vent into pit where slag tap vessel located, possible overheating of vessel	1.7×10^{-16}	Operator training to include work on handling unusual situations and what action is to be taken.
		7. a) Slurry outlet line open due to control or valve failure and b) Backup drain line open due to control or valve failure and	Flammable gases exit at slurry hopper and drain, possible fire or operator injury vessel may overheat	6.2×10^{-21}	

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS / REMARKS
M. Slag Tap Vessel (Miscellaneous) (Cont'd.)	Leak of flammable gases from slag tap vessel lines	7. c) LL 5 fails to alarm and d) Water level falls below slurry lines and e) LP alarm sounds, operator fails to take action and f) LP emergency shutdown fails to operate			
	Explosion in slag tap vessel	8. a) Hot water in slag tap vessel results in large slag pieces that fill vessel and b) Unable to remove slag and c) Water volume reduced	Increase in pressure that may cause relief valve or rupture disc to activate	5×10^{-11}	The energy in the slag may generate steam and high pressure but would not be capable of causing a physical explosion.
		9. a) Fluidizer not working due to line failure and b) Unable to remove slag and c) Water volume reduced and d) Water temperature increasing	Increase in pressure that may cause relief valve or rupture disc to activate	5×10^{-11}	Same as 8. above.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
M. Slag Tap Vessel (Miscellaneous) (Cont'd.)	Overheating of slag tap vessel	10. a) When heating up with the main burner in-sufficient N ₂ purge gas flows into STV allowing hot gases to be drawn back into STV and b) Detection of gases and c) Failure of purge system to increase N ₂ flow and d) High temperature alarm sounds but operator fails to act	Damage to slag tap vessel and equipment	6.3×10^{-11}	Consider flow switch in N ₂ purge feed line as recommended in K-14.

- (4) Supervision to review log sheets and check O_2 and air flow against calculated values.
- (5) Inspect the bottom of the main vessel on each shutdown to determine if free iron is present. If found, steps need to be taken to correct the situation.

(M-3) Level control failure allows water level to increase into notch area with a resulting explosion. (See fault tree in Appendix D.) The probability is 6×10^{-10} per hour.

Recommendations are as follows:

- (1) Install an independent high level sensor and alarm to alert the operator to the high level. The gage tube may be too dirty to determine the level and if the level is high, unsafe to try to determine where the level is.
- (2) Provide operator with an automatic valve located near PCV-WS156 to close in emergency.
- (3) The five-way manual valves can easily be set the wrong way. A means of identifying the position of the valve ports must be secured to the valve for ease of determining how the valve is set.

Other recommendations are:

- (1) Check all flanges when pressurizing vessels and once a day while operating.
- (2) Consider gas flow detectors in both drain lines.
- (3) Install flow switch in N_2 purge feed line.

13. Maintenance

a. Process Description

Maintenance will be a regular part of the slagging gasifier. Poor maintenance will result in frequent failures of the equipment resulting in unnecessary downtime. The gasifier will be taken apart and reassembled at certain points to determine how the refractory is doing. These shutdowns will occur at 100, 250, 500 and 1000 hours and will involve extensive maintenance.

b. Design Safety Features

The safety features for maintenance are the IITRI safety procedures and supervisors. By using the safety procedures and the experience of supervision, the system can be maintained in a safe manner.

c. Potential Problems and Severity

There are many potential problems that can develop during maintenance and the severity can vary depending upon circumstances. Some areas of concern are the N₂ jacket and welding on lines or equipment that has not been properly purged of gas. The probability of serious injury is $1 \times 10^{-8}/\text{hr}$. (See Table I, Section N.)

d. Specific Incidents and Recommendations

(N-1) A leak develops in the N₂ jacket area and an operator/mechanic passes out due to inhaling N₂.

(N-2) Welding is done on a gas line without proper preparation and explosion results.

Recommendations are as follows:

- (1) All safety procedures are to be followed at all times.
- (2) Check vessels for normal atmosphere before entering.
(Prepare entry permit.)
- (3) Have safety watches when entering confined spaces.
- (4) Prepare a Hot Work Permit with appropriate sign-off before welding or other similar work is done.
- (5) Do not weld on lines in place if possible. If it is necessary to weld in place, consider an inert purge on line.
- (6) Use slings in good shape when moving heavy pieces of equipment by crane.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/REMARKS
N. Maintenance Procedures	Equipment shut-down due to problem in jacket area (water, leak, etc.)	1. a) Supervisor fails to check jacket atmosphere and b) Operator/mechanic tries to ascertain problem without safety watch and c) Individual passes out due to inhalation of N_2	Operator injury/death	1×10^{-11} (EST)	Safety procedures must be followed at all times including when maintenance is done.
	Work on line Containing Gas	2. a) Welding is to be done to repair or modify a line that contained natural gas and b) Line not properly purged and c) Supervisor fails to test for explosive mixture before allowing work to proceed and d) Sufficient gas present to seriously injure operator	Operator injured	1×10^{-8}	Procedures for maintenance must be followed. Where possible, do not weld with lines in place or have inert purge on line. Have a hot work permit that spells out each step that must be done.

14. Operator Training and Control Panel

a. Process Description

The IITRI control panel for the slagging gasifier has over 200 lights and alarms. These provide the control room operator with information that certain areas of the process are not within the desired control limit. Many alarms will activate either a burner turndown or burner shutdown mode to protect the system.

The second operator is responsible for the operating equipment out in the area. He must check the pumps, compressors, generator, change slag hoppers, monitor slag flow and other work as designated.

b. Design Safety Features

The safety features are the automatic responses of the control system to abnormal conditions. In addition, the operators provide additional monitoring and can initiate action to bring the system to a safe condition.

c. Potential Problems and Severity

The potential problems are poor operator training and lack of information to control the process. In most cases, the operator is not able to observe changes. The level controls for the water tank and the slag tap vessel do not tell the operator where the level is unless it is high or low enough to actuate an alarm. Thus, the operator cannot see a trend and work to change it before a problem develops. He can only react after the alarm sounds. (See Table I, Section 0.)

d. Specific Incidents and Recommendations

(0-1) A gas leak develops in the Monocon panel and the gas detector fails and the fan is not running. A fire results in damaged controls and burns to the operator.

(0-3) The operator is confused by a multitude of alarms and the shutdown systems fail and operator takes no action with resulting equipment damage and possible injury.

Recommendations are as follows:

- (1) A strong operator training program is needed to make the operators familiar with the system and how it operates. Emphasis needs to be placed on putting the gasifier in a "safe" mode and then correcting problems. This will reduce the chance of equipment damage and operator injury along with more time to correct the problem.

IITRI SLAGGING GASIFIER HAZARDS ANALYSIS FACT SHEET

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- (2) All detectors need to be checked at least once a week.

15. Start-Up Burner

a. Process Description

To initially heat the refractory at a low rate, a special burner will be used. The burner is inserted in the manhole on the slag tap vessel with a long pipe that extends into the main vessel through the notch. The methane and air lances are removed and an ultraviolet scanner is inserted in one and a thermocouple in the other. The slag injection setup is removed from the top of the main vessel so the gases can exit there.

The burner is ignited and the refractory heated at up to 50°F per hour until the limits of this burner are reached, expected to be around 700°F. Then the system is returned to normal and heatup continued using the main burner. The gas and air are to be supplied to the burner at 16 ounces of pressure.

b. Design Safety Features

The following are the safety features of the startup burner system:

1. Low pressure gas and air minimizing the quantity of gas available.
2. Flame monitoring and automatic shutdown on loss of flame.
3. Direct operator supervision of heat-up.

c. Potential Problems and Severity

The main problems would be leaks, and failure of the shutdown system. Due to the low pressures involved if a problem developed, there would be limited equipment damage but the operator could be seriously burned. The probability of injury is 3.7×10^{-10} /hr. (See Table I, Section P.)

d. Specific Incidents and Recommendations

(P-2) Loss of flame and failure of the shutdown system and failure of the operator to notice temperature decrease. The probability is 1.7×10^{-10} per hour.

It is recommended that:

1. A portable gas detector be placed at the top of the main vessel.
2. The main fan be operating whenever gas is in the lines.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
P. Start-up Burner	Gas leak at external piping	1. a) Flexible hose leaks and b) Operator fails to smell leaking gas or find leak and c) Operator burned in resulting fire	Operator sustains minor burns, putting out fire	1.8×10^{-10}	Pressure check gas lines before start-up.
	Concentration of combustible gases in main vessel	2. a) Loss of flame and b) Failure of flame detector to shutdown on loss of flame and c) Operator fails to notice temperature change	Possible explosion if mixture ignited	1.7×10^{-10}	Consider placing portable gas detector in vent at top of main vessel.
	Concentration of combustibles in main vessel	3. a) Pressure switch fails to detect high gas pressure and b) Flameout occurs and shutdown system fails to close gas valve and c) Operator fails to notice changes	Possible explosion if mixture ignited	2.2×10^{-12}	Same as for P-2.

TABLE I
(CONTINUED)

IITRI SLAGGING GASIFIER
HAZARDS ANALYSIS FACT SHEET

EQUIPMENT ITEM	POTENTIAL PROBLEM	CAUSATIVE EVENTS	SEVERITY	PROBABILITY	RECOMMENDATIONS/ REMARKS
P. Start-up Burner (continued)	Concentration of combustibles in main vessel (continued)	4. a) Low air pressure switch fails and b) Flameout occurs and shutdown system fails to close gas valve and c) Operator fails to notice changes	Possible explo- sion if mixture ignited	2.2×10^{-12}	Same as for P-2.

TABLE II

IITRI SLAGGING GASIFIER
SEVERITY VS. PROBABILITY

Probability	Severity		
	CATEGORY I Permanent Total Disability and/or Death	CATEGORY II Permanent Partial Disability	CATEGORY III Lost Time Injury to Total Temporary Disability
$\geq 1 \times 10^{-4}$			L-4
$< 1 \times 10^{-4}$ to $\geq 1 \times 10^{-6}$			
$< 1 \times 10^{-6}$ to $\geq 1 \times 10^{-8}$		F-21, I-2, ,	
$< 1 \times 10^{-8}$ to $\geq 1 \times 10^{-10}$	M-3, M-1	P-2	B-1, F-1, J-17, M-4, P-1, E-4, N-2
$< 1 \times 10^{-10}$ to $\geq 1 \times 10^{-12}$	A-3, E-1, E-2, F-2, F-4, F-32, F-43, I-1, K-14, N-1, O-3, F-34, F-29	F-22, F-44, P-3, P-4, F-23	A-1, F-6, I-5, E-3
$< 1 \times 10^{-12}$ to $\geq 1 \times 10^{-15}$	A-2, F-3, F-7, F-9, F-49, F-50, I-3, I-4, K-16, D-1	F-51, F-54	I-6, O-1
$< 1 \times 10^{-15}$ to $\geq 1 \times 10^{-20}$	F-5, F-8, F-10, F-26, F-38, F-39, F-40, F-41, F-48, K-7, M-6	F-42, F-45 F-30, F-56, F-61, F-55, F-60	
$< 1 \times 10^{-20}$	F-31, K-13	M-7	

APPENDIX A

INFORMATION UPON WHICH ANALYSIS IS BASED

The hazard analysis of the slagging gasifier was based on the drawings and information furnished by IITRI. The initial information was obtained in 1980 for the previous analysis.

Part of the information was received at the time of the initial visit on 7-23-81. Additional information was received on 8-17, 9-1, 9-9, 9-22, 9-25, and 10-5. The oral presentation was given on 10-15, at which time it was found that several safety items were not connected into the alarm and protective system.

CUSTOMER INFORMATION RECEIVING RECORD

CONTRACT 96752 CUSTOMER IITRI AO 8634

SLAGGING GASIFIER

SHEET NO. 1 OF 8

IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
-	Cinder monkey - Copper	C
M6043 A-501	Mtg. arrangement copper (monkeys)	
-	Burner nozzle assembly	
A-118	Copper cooler type C	
A-119	Copper cooler type B	
A-120	Copper cooler type A	
-	Sketch of seal between jacketed pipe and inc.	
D6160 D-014	Refractory test unit with hood change	
-	EEP/sight window model 55400 2"	
-	List of drawings	
A-605	Slag notch end view tuyere/gap cooler coil	
-	Spray System bulletin 129B	
-	Spraying Systems data sheet 10394	
-	Slag delivery line sketch	
(2 sheets) A-124	Bottom head cooling coil	
C-125	Channel cooler assembly	
D-127	Inner wall channel weld't channel cooler	
D-128	Cover plates channel cooler	
D-131 (2)	Stave cooler assembly	
D-121	Proposed water wall incinerator	
-	Sketches of water wall incinerator	

5 S CODE: A. Item to be returned at Contract closeout - Proprietary
 B. Item to be returned at Contract closeout - Unclassified
 C. Item for information only - Return not required

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CONTRACT 96752 CUSTOMER IITRI AO 8634

SHEET NO. 2 OF 8

IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
-	Incinerator cap	C
-	Incinerator cap (3)	
C-133	Jacketed piping layout	
B-134	Jacketed piping section 1	
A-135	Jacketed piping section 2	
A-136	Jacketed piping section 3R & 3L	
A-137	Jacketed piping section 4	
A-040	Water supply manifold	
D-145	Exit gas control valve piping 2 sheets	
(A) P-3742-3	P.C.C./bloom O ₂ /NG burner	
P-3955-3	Compressed air lance	
P-3954-3	Nat. gas (water cooled) lance	
A P-3764-3	Arrangement of burner on test vessel	
A P-3994-3	Slag lance support details	
D P-3794-3	Elementary diagram main burner and lances	
D P-3771-3	P&I for main burner and lances	
B-050	Pressure control schematic	
-	4150 & 4160 series type 657 Fisher controls 3582 & 3583 series design EC, EAC, ES, EAS	
B P-3894-3	Pipe rack - bottom portion	
-	Slag removal schematic	
D-703	Refractory test sketch cooling schematic	

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CONTRACT 96752 CUSTOMER IITRI AO 8634

SHEET NO. 3 OF 8

DATE RECEIVED	IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
8-20	B-313	Oxygen system flow diagram	C
	C-311	Air system	
	C-312	Compressed gas system	
	D-309	Main flow diagram - gas	
	E-701	Cooling pipe layout (2 sheets)	
	-	Gas seal and tie rod details	
	E-204	Plan and elevation of air system	
	-	Slag composition	
	3014	Inland steel engineering standards	
	D-111	Slag nozzle layout	
	-	Letter of Aug. 6, 1980 to E. E. Hoffman from R. A. Bradley	
		on slag composition and gasifier atmosphere	
	C-013	Refractory test unit layout	
	A-302	Refractory test vessel thermocouple positions	
	-	Gasifier procedures manual "Preliminary"	
		Slag feed system conceptual design	
	C-304	Power distribution diagram	
	C-305	Main control panel - assembly	
	D-314	Auxiliary equipment power Sheet 1	
	-	Auxiliary equipment power Sheet 2	
✓	-	Gas comp. air comp. starter circuits Sheet 3	↓

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SHEET NO. 4 OF 8

[illegible]

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CUSTOMER INFORMATION RECEIVING RECORD

CONTRACT 96752 CUSTOMER IITRI AO 8634

SHEET NO. 5 OF 8

DATE RECEIVED	IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
4-80	D2-1	General arrangement separator & venturi	C
	-2		
	7L-8279-A	5' test vessel	
	-1		
	7L-9082-A	Slag storage vessel	
	-2		
	7L-8279-B	Additional details	
	-1		
	7L-8326-A	Slag tap vessel	
	-1		
	7M-8326-A	Additional details	
	-1		
	7M-9082-A	Additional details	
	7M-9082-C	Clip details	
	-1		
	7M-9082-B	Manway details	
	-1		
	7M-8326-B	Manway details	
	-	Smeeth-Harwood - copper casting specifications	
	-	Memo G. Booth to R. Firestone Copper Coolers 6-17-80	
	-	Memo G. Booth to A. Tulis Blast Furnace Run 8-8-80	
	-	Memo C. Kennedy to R. Firestone Atmosphere for Tests 6-26-80	
	-E		
	P-3771-3-	P&I for burner and lances revision by IITRI	
	Eng. sum-		
	mary shts	21 sheets - description of burner parts	
	C-606	Slag delivery stem schematic	
	Teledyne	Data sheets 9700 analyzer system	
	Letter	C. Hales to C. Angoli 9-12-80 Letter of transmittal and response to questions	
	D-048	Equipment room layout	
↓	3-2-79		
	Sht. 2	Gasifier scatter shield details	↓

STATUS CODE: A. Item to be returned at Contract closeout - Proprietary
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CONTRACT 96752 CUSTOMER ITRI AO 8634

SHEET NO. 6 OF 8

[illegible]

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B. Item to be returned at Contract closeout - Unclassified
C. Item for information only - Return not required

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CONTRACT 96752 CUSTOMER IITRI AO 8634

SHEET NO. 7 OF 8

[illegible]

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CONTRACT 96732 CUSTOMER IITRI AO 8634

These drawings were received after the agreed deadline and all items were not considered.

SHEET NO. 8 OF 8

[illegible]

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CUSTOMER INFORMATION RECEIVING RECORD

CONTRACT 96752 CUSTOMER IITRI AO 8707

SHEET NO. 1 OF 5

DATE RECEIVED	IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
7-23-81		Second Annual Tech. Progress Report - Slagging Gasifiers	C
		Letter and Attachments May 29, 1981, D. L. Lennon to C. Hales	
		Letter to E. J. Scheel from C. Hales 7-16-81, Refractory Test Unit	
		Comments on Drawings from E. Scheel of Davy McKee	
	980	Info. Bulletin on Teledyne Instrument	
	333	Info. Bulletin on Teledyne Instrument	
	322	Info. Bulletin on Teledyne Instrument	
	122	Info. Bulletin on Teledyne Instrument	
	1st Draft	Operating Manual (Partial)	
	M6043-E323	Process Flow Diagram	
		Test Vessel Heat and Mass Flows	
	M6043 B-313	Oxygen System Flow Diagram	
	M6043 C-312	Compressed Gas System	
	M6043 C-206	Oxygen Piperack Layout	
	M6043 C-207	Compressed Gas Piperack Layout	
	M6043 D-311	Air System	
	M6043 D-321	N ₂ System Schematic	
	M6043 D-606A	Slag Delivery System Schematic	
	M6043 D-607	Slag Tap Vessel System Schematic	
	M6043 D-309	Main Flow Diagram - Gas	
✓	M6043 C-401	Scrubber System	✓

STATUS CODE: A. Item to be returned at Contract closeout - Proprietary
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CONTRACT 96752 CUSTOMER IITRI AO 8707

SHEET NO. 2 OF 5

DATE RECEIVED	IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
7-23-81	M6043 D-703	Refractory Test System Cooling System Schematic	C
	M6043 D-707	Cooling System Layout As-Built	
	M6043 D-314 Sht 1	Control Circuit Diagram Ancillary Equip. Power	
	Sheet 2	Control Circuit Diagram Ancillary Equip. Power	
	Sheet 3	Control Circuit Diagram City Water Pumps & Fan Circuit	
	Sheet 4	Control Circuit Diagram Gen. Powered H ₂ O & Slurry Pump	
	Sheet 5	Control Circuit Diagram Gas Comp., Air Comp.	
	Sheet 6	Control Circuit Diagram Water Tank & Slag Injection	
	Sheet 7	Control Circuit Diagram Monocon Relay Outputs	
	Sheet 8	Control Circuit Diagram Data Logger Outputs	
	Sheet 9	Control Circuit Diagram Start-up Sequence	
	Sheet 10	Control Circuit Diagram	
	Sheet 11	Control Circuit Diagram	
	Sheet 12	Control Circuit Diagram	
	Sheet 13	Control Circuit Diagram	
	Sheet 14	Control Circuit Diagram	
	Sheet 15	Control Circuit Diagram Warning Circuit I/O	
	Sheet 16	Control Circuit Diagram Lamp Test/Reset Circuit	
	Sheet 17	Control Circuit Diagram Lamp Test/Reset Circuit	
	Sheet 18	Control Circuit Diagram Audible Alarms	
	Sheet 19	Control Circuit Diagram Audible Alarms	

STATUS CODE: A. Item to be returned at Contract closeout - Proprietary
 B. Item to be returned at Contract closeout - Unclassified
 C. Item for information only - Return not required

CUSTOMER INFORMATION RECEIVING RECORD

CONTRACT 96752 CUSTOMER IITRI AO 8707

SHEET NO. 3 OF 5

[illegible]

STATUS CODE: A. Item to be returned at Contract closeout - Proprietary
B. Item to be returned at Contract closeout - Unclassified
C. Item for information only - Return not required

CUSTOMER INFORMATION RECEIVING RECORD

CONTRACT 96752 CUSTOMER IITRI AO 8707

SHEET NO. 4 OF 5

DATE RECEIVED	IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
3-17-81	Memo	To T. Angoli from J. Lamoureux dated August 13, 1981	
	M6043 Sht. 1		
	D-314	Control Relay Functions	
	M6043 Sht. 2		
	D-314	Control Relay Functions	
	M6043		
	D-305	Main Control Panel Assembly	
	M6043 Sht. 8		
	D-314	Data Logger Outputs	
	M6043		
	E-620	Slag Tap Torch Mounting Layout	
	M6043		
	D-633	Slag Injection Nozzle	
	M6043 Rev. A		
	D-606A	Slag Delivery System Schematic	
		Circuit Revisions for Slag Tap Vessel Level Controls (3 Sheets)	
		AARDVARK Burner Information (5 Sheets)	
	M6043		
	E-323	Process Flow Diagram	
		Fan Capacities	
		Set Points Monocon Gauges (4 Sheets)	
		Set Points Data Logger Alarms (3 Sheets)	
		Set Points Pressure Switches (4 Sheets)	
		Set Points Temperature Switches (4 Sheets)	
		Set Points Flow Switches (4 Sheets)	
↓		Set Points Gas Detectors (3 Sheets)	

STATUS CODE: A. Item to be returned at Contract closeout - Proprietary
 B. Item to be returned at Contract closeout - Unclassified
 C. Item for information only - Return not required

CUSTOMER INFORMATION RECEIVING RECORD

CONTRACT 96752 CUSTOMER IITRI AO 8707

SHEET NO. 5 OF 5

DATE RECEIVED	IDENT. NO.	ITEM DESCRIPTION	STATUS CODE
8-1-81		Operating Manual Sections 1, 2 & 3	C
9-9-81		Information on 5-Way Valves	C
9-22-81		Operating Manual Section 4	C
9-25-81		Information on Monitoring the Slag Content of the Slurry	C
		Discharge from the Slag Tap Vessel	
10-5-81		Operating Manual Section 1.1 Revised	C
10-16-81		Honeywell Bulletins	
		95-8269 - Ultraviolet Flame Detector Model C-7076A	
		95-8270 - Dynamic Self-Check UV Amplifier Model R-7476A	
		95-8271 - Flame Amplifier Module Model ESP5075	

STATUS CODE: A. Item to be returned at Contract closeout - Proprietary
 B. Item to be returned at Contract closeout - Unclassified
 C. Item for information only - Return not required

APPENDIX B

FAILURE RATE DATA

1. Control valve	$7 \times 10^{-5}/\text{hr}^{(1)}$
2. O ₂ analyzer	$6.4 \times 10^{-4}/\text{hr}^{(1)}$
3. Flow switch	$1.3 \times 10^{-4}/\text{hr}^{(1)}$
4. Solenoid valve	$4.8 \times 10^{-5}/\text{hr}^{(1)}$
5. Flame failure detector (UV)	$1.9 \times 10^{-4}/\text{hr}^{(1)}$
6. Flow meter	$1.15 \times 10^{-4}/\text{hr}^{(1)}$
7. Level measurement	$1.9 \times 10^{-4}/\text{hr}^{(1)}$
8. Optical pyrometer	$1.1 \times 10^{-3}/\text{hr}^{(1)}$
9. Controller	$3.3 \times 10^{-5}/\text{hr}^{(1)}$
10. Diff. pressure trans.	$2.0 \times 10^{-4}/\text{hr}^{(1)}$
11. Relay	$5 \times 10^{-6}/\text{hr}^{(2)}$
12. $\sqrt{\text{Ext.}}$ transformer	$1 \times 10^{-6}/\text{hr}^{(2)}$
13. Pressure switch	$4 \times 10^{-5}/\text{hr}^{(1)}$
14. Flame failure detector (elec.) 2 relays and 1 transformer	$1.1 \times 10^{-5}/\text{hr}^{(2)}$
15. Relief valve leaks	$1 \times 10^{-5}/\text{demand}^{(6)}$
16. Level indicator	$8 \times 10^{-7}/\text{hr}^{(4)}$
17. Gasket failure	$1.8 \times 10^{-5}/\text{hr}^{(4)}$
18. Valve ruptures	$1 \times 10^{-8}/\text{hr}^{(5)}$
19. Loss of cooling water to NG comp., human error	$1 \times 10^{-3}/\text{hr}^{(\text{Est.})}$
20. Loss of instrument air (N ₂) (human error, tank empty)	$1 \times 10^{-3}/\text{hr}^{(\text{Est.})}$
21. Pipe rupture $\leq 3"$	$1 \times 10^{-9}/\text{hr}^{(6)}$

APPENDIX B
(CONTINUED)

22.	Shutdown device fails on demand	$1 \times 10^{-4}/\text{demand}^{(5)}$
23.	Generator failure	$7 \times 10^{-6}/\text{hr}^{(2)}$
24.	Pump failure	$3 \times 10^{-5}/\text{hr}^{(6)}$
25.	>6 in. pipe rupture	$1.8 \times 10^{-9}/\text{ft yr}^{(5)}$
26.	Slag bridges	$1 \times 10^{-2}/\text{hr (Est.)}$
27.	Line plugs	$1 \times 10^{-2}/\text{hr (Est.)}$
28.	Slurry nozzle plugs	$1 \times 10^{-2}/\text{hr (Est.)}$
29.	Check valve fails - leaks back	$1 \times 10^{-6}/\text{hr}^{(4)}$
30.	Ball valve leaks	$1.4 \times 10^{-4}/\text{hr}^{(4)}$
31.	Random failure of rupture disc	$5 \times 10^{-6}/\text{hr}^{(2)}$
32.	Check valve fails to open	$1 \times 10^{-4}/\text{demand}^{(6)}$
33.	Hose failure, heavily stressed	$4 \times 10^{-5}/\text{hr}^{(2)}$
34.	Operator present (operator will be near the main vessel about half the time)	$5 \times 10^{-1}/\text{hr (Est.)}$
35.	Hole plugs due to freezing	$1 \times 10^{-2}/\text{hr (Est.)}$
36.	Hole plugs due to broken refractory	$1 \times 10^{-3}/\text{hr (Est.)}$
37.	Loss of slag flow not recognized	$1 \times 10^{-1}/\text{hr (Est.)}$
38.	Unable to open slag tap hole	$1 \times 10^{-2}/\text{hr (Est.)}$
39.	Operator error	$1 \times 10^{-3}/\text{hr}^{(5)}$
40.	Relief valve fails to open on demand	$1 \times 10^{-5}/\text{demand}^{(6)}$
41.	Pressure control valve fails to open	$1.3 \times 10^{-4}/\text{hr}^{(4)}$
42.	Loss of city power	$1 \times 10^{-3}/\text{hr (Est.)}$
43.	Breaker failure	$1 \times 10^{-5}/\text{hr}^{(2)}$
44.	Heat exchanger failure	$1.8 \times 10^{-6}/\text{hr}^{(6)}$
45.	Fitting failure	$3 \times 10^{-7}/\text{hr}^{(6)}$

APPENDIX B
(CONTINUED)

46.	Flow measurement (fluids) indicating variable area flowmeter	$3.9 \times 10^{-5}/\text{hr}^{(1)}$
47.	Unable to open spray nozzle with H.P. water	$1 \times 10^{-1}/\text{hr}$ (Est.)
48.	Ball valve leaks	$1.4 \times 10^{-4}/\text{hr}^{(4)}$
49.	N ₂ leakage greater than gas leakage	0.5/hr (Est.)
50.	N ₂ check valve capacity exceeded (depends upon circumstances 2-1/2" line cannot match flow of larger lines)	0 or 1 (Est.)
51.	In J-10 differential pressure rupture disc unable to restore balance (venting too fast)	1 (Est.)
52.	Check valve fails open	$3 \times 10^{-7}/\text{hr}^{(6)}$
53.	Loss of refractory integrity due to heating and cooling	$1 \times 10^{-2}/\text{hr}$ (Est.)
54.	Failure of jacketed pipe	$1 \times 10^{-10}/\text{hr}^{(6)}$
55.	Low nitrogen pressure	$1 \times 10^{-3}/\text{hr}$ (Est.)
56.	Level probes	$2.5 \times 10^{-5}/\text{hr}^{(1)}$
57.	Water hose not fastened properly	$1 \times 10^{-3}/$ (Op. error) ⁽⁵⁾
58.	Slag breaks loose	$1 \times 10^{-2}/\text{hr}$ (Est.)
59.	Failure of solids monitor	$1 \times 10^{-4}/\text{hr}^{(5)}$
60.	Failure of time delay relay	$4.5 \times 10^{-6}/\text{hr}^{(4)}$
61.	Igniter failure	$1 \times 10^{-3}/\text{hr}$ (Est.)

1. S. N. Anyakora, G.F.M. Engel and F. P. Lees, "Some Data on the Reliability of Instrument in the Chemical Plant Environment," The Chemical Engineer, London, 255, pp 396-404, Nov. 1971.
2. A. E. Green and A. J. Bourne, Reliability Technology, John Wiley and Sons, Ltd. London 1972.
3. Nonelectric Reliability Notebook, Hughes Aircraft Company, RADC-TR-69-458, Final Technical Report, March 1970.
4. Farada Part X, Sept. 1970, Fixed Ground Equipment.
5. S. Alallah, "Assessing and Managing Industrial Risk," Chemical Engineering, pp 94-103, Sept. 8, 1980.
6. Reactor Safety Study, Appendices III & IV, U. S. Nuclear Regulatory Comm., Oct. 1975.

APPENDIX C

SAMPLE CALCULATIONS

The following calculations have been selected to illustrate how the event probabilities were obtained:

F-21	(a) Igniter failure	1×10^{-3}
	and	
	(b) T-2 timer fails closed	4.5×10^{-6}
	or	
	Burner shutdown system fails	1×10^{-5}
	$1 \times 10^{-3} \times (1 \times 10^{-5} + 4.5 \times 10^{-6}) =$	$1.4 \times 10^{-8}/\text{hr}$
K-10	(a) Slag tap vent dump valve ASV-T562 fails open	3.3×10^{-5}
	and	
	(b) Flame from main burner drain into slag top vessel	1
	and	
	(c) Emergency shutdown system fails to work	5×10^{-6}
	$3.3 \times 10^{-5} \times 1 \times 5 \times 10^{-6} =$	1.7×10^{-10}

APPENDIX D

FAULT TREE IN INCIDENT M-3

A fault tree was developed for incident M-3, steam explosion occurs in slag tap vessel due to water entering notch. This was done to aid in the analysis due to the number and type of valves and the functioning of the control system. This analysis showed that the vessel could overfill by the failure of both level controls as the most probable failure.

U-4

APPENDIX C

LETTER FROM SPONSOR SPECIFYING ALLOWABLE
GAS COMPOSITION

ARGONNE NATIONAL LABORATORY

9700 South Cass Avenue, Argonne, Illinois 60439

Telephone 312/972-5120

June 26, 1979

TO: Ross Firestone

FROM: Christopher Kennedy CRK

SUBJECT: Recommended Atmosphere for Corrosion Tests

In order to proceed with the design and fabrication of the IITRI test facility, Cris Hales (IITRI) has asked DOE to specify the test atmosphere. A survey of atmospheres in coal-gasification plants, done by Mel Greaves (McKee), has been presented in IITRI's second quarterly report. The atmospheres are expressed on a C-H-O triangle (see Fig. 1) and fall within the shaded area. Where available, I have also gathered data from slagging gasifiers (some of it based on exit gas compositions) and plotted it in a similar fashion. Included for reference are gas analyses from several ANL slag tests and the "DOE" standard atmosphere (as required in IITRI's proposal). Note that although ANL's tests were conducted using only methane, air, and oxygen, the gas analyses do not fall on the CH_4 -O tie line, but are deficient in H (possibly due to loss of some H_2 while sampling and storing prior to the analysis).

The initial design of the IITRI test facility was also based on firing with natural gas, oxygen, and air, with the possibility of char injection through the gas burner. Without char injection, we would expect the atmosphere to fall somewhere on the line between CH_4 and O. Thus, by sub-stoichiometric combustion, it should be easy to simulate the "DOE" atmosphere. However, the H/C ratio of this atmosphere is ~ 4 , whereas the available data indicate that slagging pilot plant atmospheres range from 2.5 to 0.7. The atmospheres in the shaded area cannot be duplicated precisely by natural gas, air, and oxygen. To reproduce these atmospheres would require large amounts of coal (or carbon black) to be injected (through burners or mixed with the slag) and would entail significant additional expense.

In light of these considerations, I submit that the critical parameter to control is the ferritic content (wt % Fe_2O_3 /wt % $\text{Fe}_2\text{O}_3 + 1.11$ wt % $\text{FeO} + 1.43$ wt % Fe) of the slag. The ferritic content will affect the viscosity of the slag and its mode of corrosion of the refractories. Keeping in mind the objectives of this program, as stated in the IITRI proposal, and the current budgetary limitations, I therefore recommend that the test facility be fired with natural gas, air, and oxygen in proportions that will result in a ferritic content in the slag of between 5 and 35%. Based on the data from

June 26, 1979

the pilot plants and ANL experiments, it would appear that 40-80% FSA (fraction of stoichiometric air) will produce the desired ferritic content. However, it should be noted that precise predictions of the atmosphere-ferritic content relationship are impossible because of nonequilibrium conditions and unknown kinetics.

As previously stated, the atmosphere produced by natural gas, air, and oxygen will be 10-20% higher in hydrogen than in some slagging gasifiers. If sufficient funding is available in the future, I would recommend that coal be injected to reduce the H/C ratio and provide a more prototypic atmosphere. --

Approved By

W. T. Bakker
Wate Bakker, Acting Chief
Materials Engineering Branch
Division of Systems Engineering

CK:smh

APPENDIX D
FAULT TREE ANALYSIS
(from First Annual Report)

APPENDIX D

FAULT TREE ANALYSIS

(from First Annual Report)

This refractory testing system is an experimental arrangement involving highly combustible gases held at high temperature, under pressurized conditions. In addition, the size of the system is well beyond the scope of normal laboratory-scale equipment. These two factors combined are of critical importance when the safety of the system is considered.

In order to help ensure safe operation at all times, it was decided that a basic hazard analysis should be carried out for the system and its operation. As the logic in the analysis closely parallels the logic of the control system, the two are mutually dependent and may be developed together in the early stages. This has been done by means of a Fault Tree Analysis, for the entire system, and will be followed by a closer analysis of the events leading to an explosion, as well as an analysis on the events of an explosion within the refractory test vessel.

The Fault Tree or Logic Diagram (Figure D-1) is a very useful and comprehensive method of system safety analysis, and can be applied to all levels of complexity. The method is used to determine how a given accident, or any other specified, undesired event can be brought about. The causes of the undesired event can be traced to any required level of detail to identify the individual basic failures, or the interplay of combinations of basic failures that could cause the undesired event. These basic failures are not limited to hardware components. They can be human actions, environmental factors, or combinations of these.

An immediate result of such an analysis is a highly visible graphic representation of all basic failures and the paths whereby they can combine to create the undesired event. The method can also be used quantitatively. If data are available for the probability of occurrence of the basic failures, it is possible to calculate the probability of occurrence of the undesired event. In so doing, it is also possible to identify those basic failures that are

Figure D-1. Sample fault tree.

more critical, and the most critical paths, in order that priorities can be established for taking corrective action.

The technique of Fault Tree Analysis was first developed at the Bell Telephone Laboratories in 1962. The objective at the time was to identify all causes or combinations of events that could lead to an inadvertent launch of a Minuteman missile. The technique was subsequently further developed and applied to various other systems at the Boeing Company, and further development of the method is still in progress.

In this particular case where time and funding for such analysis must be minimized, parts of the system must be overdesigned, while other parts have several levels of redundancy, to compensate for possible gaps in the analysis. This would be an expensive route to follow in a large production plant, but is the most economical, and the safest, solution for experimental equipment such as this refractory test unit.

Another factor with experimental equipment is that changes are made frequently during the course of the project, and an expensive full analysis may have many inaccuracies by the time the safety systems which may be overlooked and lead to problems. A balance must be obtained between depth of analysis and the accuracy of the final predictions. The philosophy for the refractory test unit was that enough analysis should be done to identify all the higher levels of hazard, then back-up systems would be used to avoid them, with audio-visual alarms to identify each level that is reached.

APPENDIX E
WATER SYSTEM ANALYSIS

WATER SYSTEM ANALYSIS

Component	Failure Mode	Possible Cause	Immediate Effect	Safety Controls	Controlled Response	Uncontrolled Effect on System
Hot water drain valve (NC)	Closed	Coil burnout Control failure	None	None	None	None
Hot water drain valve	Open	Not seated Valve failure Controls failure	Water level drops	Level controls Indicating lights Audible alarm	Manual Add valve opens	Possible loss of water inventory
			Normal operation	Level controls Indicating lights Audible alarm	Normal operation	
Add valve (NO)	Open	Coil burnout Controls failure	Cold water into tank	Level controls Indicating lights Audible alarm	Drain excess water Manual response	Tank overflow Excess water usage
Add valve (NO)	Closed	Sticks shut Controls failure	Water level drops	Level controls Indicating lights Audible alarm	Manual response	Slow draining of water tank
Level control		Level failure Controls failure	Water level drops	(2) Back-up level controls Indicating lights	Back-up controls restore normal operation at lower level until manual valves are operated	Slow draining of water tank
LP pump pressure control valve (125 psi) (NC)	Closed	Pressure tap line leaking	High pressure in supply line	Downstream valves	Downstream regulation	Pumps operate above most efficient pumping pressure
LP pump pressure control valve (125) (NC)	Open	Valve failure	Supply manifold pressure low	Pressure gage/ switch Indicating lights Audible alarms	Controlled system Turndown or shutdown	Reduced cooling circuit flow Possible overheating
Manifold pressure control valve (95 psi) (1)-NO, (1)-NC	Open	Pressure tap line leaking Valve failure Instrument air loss	Supply manifold pressure slightly high	Second valve Pressure gage/ switch Indicating lights Audible alarm	Second valve closes Manual response	Slightly increased flow
Manifold pressure control valve (95 psi) (1)-NO, (1)-NC	Closed	Pressure tap line leaking Loss of instrument air, Valve failure	Supply manifold pressure slightly low	Second valve Pressure gage/ switch Indicating lights Audible alarms	Second valve opens Manual response	Reduced cooling circuit flow, possible overheating
HP pump pressure control valve (145 psi) (NC)	Closed	Pressure tap line leaking	Supply line pressure high	Pressure switch Indicating light Audible alarm	Normal operation	Increased flow
Individual pump (HP or LP pump)	Off	Motor overloads Pump valves off	None	Pressure switch Indicating lights Audible alarm	Bypass valve closes	Slightly reduced, but safe, pumping capacity

WATER SYSTEM ANALYSIS (cont.)

Component	Failure Mode	Possible Cause	Immediate Effect	Safety Controls	Controlled Response	Uncontrolled Effect on System
Water loss		City supply low	Loss of make-up water	Pressure switch	Controlled shutdown system	Cooling circuits operated at elevated but safe temperature
Generator	Off	(See generator)	Generator powered pumps out	City powered pumps	Controlled shutdown or turndown	System shutdown
City Power	Off	Blackout Breaker tripped	City powered pumps out	Generator powered lights	System shutdown	System shutdown
HP pump pressure control valve (134 psi) (NC)	Open	Stick open Valve failure	Loss of water to venturi and slag tap vessel	Flow switches Pressure switches Temperature switches Indicating lights Audible alarm	System shutdown	Scrubber rupture Possible slag tap vessel damage
City water rise	Pressure loss	High area demand	Loss of make-up water Water inventory loss	Pressure switch Level controls Indicating light Audible alarm	System shutdown Close drain valves Continue to use hot water	Cooling circuit temperature Possible overheating and damage to vessel internals. Possible vessel damage.
Cooler or hose fitting temperature	Small leak	Inadequate cooling or failed fitting	Process gas into water Cooling circuit temperature rise	T/C alarm on data logger Temperature switch in critical elements Indicating lights Sight glass	Burner turndown Manual response	Cooling circuit over Possible boiling of water or cooler damage
Cooler or hose fitting	Large leak	Inadequate cooling or failed fitting	Water into vessel and process gas into cooling circuit Possible steam explosion	Temperature switch Flow indicators Pressure gage/switch Δ switch Indicating light Audible alarm	Burner shutdown	Possible internal damage and possible vessel shell damage.