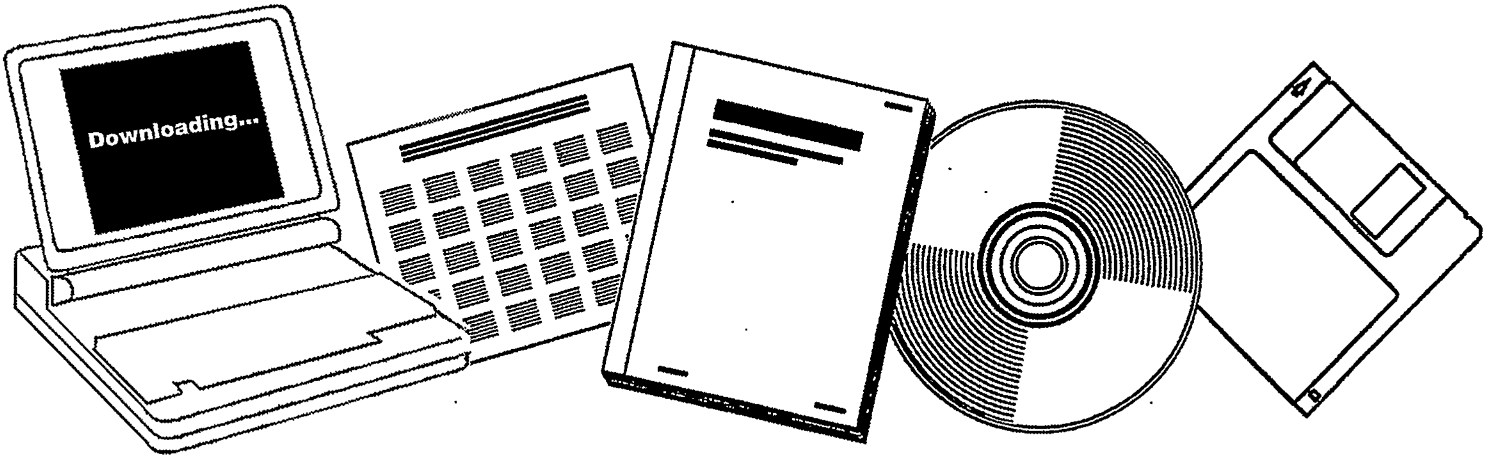
PRESTRESSED CONCRETE PRESSURE VESSELS CONCEPTUAL DESIGN/ECONOMIC ANALYSIS. R AND D REPORT NO. 114, INTERIM REPORT NO. 8

PARSONS (RALPH M.) CO.
PASADENA, CA

OCT 1978



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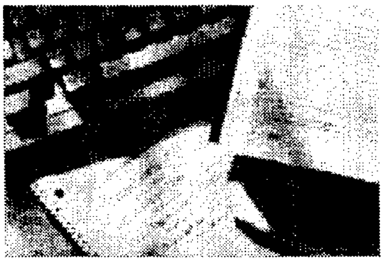

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PRESTRESSED CONCRETE PRESSURE VESSELS CONCEPTUAL DESIGN/ECONOMIC ANALYSIS

R and D Report No. 114, Interim Report No. 8

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October 1978

Work Performed Under Contract No. EX-76-C-01-1775

The Ralph M. Parsons Company
Pasadena, California

U. S. DEPARTMENT OF ENERGY

NOTICE

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

PREFACE

The U.S. Department of Energy is actively identifying and evaluating new technologies, as well as existing technologies in other fields, as they may be applied to improving the feasibility and economics of fossil fuel processing plants.

This study involves the conceptual design of commercial-sized prestressed concrete pressure vessels for coal conversion plant applications. The report addresses the design, constructibility and economics of these vessels compared with their steel counterparts.

Prestressed concrete pressure vessels (PCPV) are widely used today as storage tanks. PCPV design has been established and applied to some sixty (60) secondary containment vessels in use and under construction for nuclear power generating service.

While this work describes the benefits which may be obtained from prestressed concrete pressure vessels, such as:

- Benign failure characteristics
- Shorter construction schedules
- Minimum requirements for chromium and molybdenum
- More competitive procurements because thick steel plate is not required
- Less skilled labor for construction
- Lower capital investment than for steel vessels of comparable capacity

The report also addresses caveats in the further development of this technology, such as:

- Lack of design codes
- Lack of reliability analyses of cooling systems and refractory materials
- Lack of experience in thick-walled structural behavior of high temperature concrete pressure vessels

The following report increases the technology data base within the public domain and, it is hoped, stimulates interest in proceeding with further related research and development toward a more quantified assessment of prestressed concrete pressure vessels.

The contents of this report do not yet have the benefit of a detailed Department of Energy review.

David Garrett, P.E.
Technical Program Manager

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

ACI	American Concrete Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing Materials
bbl	barrel(s)
BPSD	barrels per stream day
Btu	British thermal units
CPM	critical path method
CS	carbon steel
DCF	discounted cash flow
dia	diameter
ΔP	differential pressure
E	expansion
f'_c	allowable compressive strength
FCI	fixed capital investment
HP	high pressure
hp	horsepower
Hz	Hertz-cycles per second
ID	inside diameter
Kip	1,000 inch pounds
ksi	thousand pounds per square inch
M	thousand
max	maximum
MEA	monoethanolamine
MM	million
MW(e)	megawatts of electricity
norm	normal
Parson	The Ralph M. Parsons Company
PCPV(s)	prestressed concrete pressure vessel(s)
PCRV(s)	prestressed concrete reactor vessel(s)
ppm	pounds per million
psi	pounds per square inch

psig	pounds per square inch gauge
rpm	revolutions per minute
S	shrinkage
scf	standard cubic feet
scfd	standard cubic feet per day
SS	stainless steel
TDA	total developed head
TPD	tons per day
TT	tangent to tangent
TYLI	T. Y. Lin International
VSL	VSL Corporation
wt%	weight percent

GLOSSARY OF TERMS

Axisymetric structure - A structure that is symetric in regards to an axis.

Bonded tendons - Tendons not free to move within concrete structure.

Compressive stress - Force per unit of area produced by contraction of m material.

Creep - Continuously increasing strain caused by long term constant load.

Fiber compressive stress - Compressive stress in outer fiber of element under bending.

Finite element analyses - A mathematical method of determining stresses by breaking the overall structure into a finite number of discrete elements.

Heat of hydration - Heat given off during curing of concrete by reaction of cement with water.

Isoparametric solid element - A type of finite element.

Isotropic material properties - The basic elastic constant, such as Young's Modulus or Poisson's ratio, is independent of direction of material.

Linear Analyses - An analyses using first order terms. Higher order terms are neglected in terms of mathematical analyses and in materials properties.

Non-linear Analyses - This analyses takes into account higher order terms or non-linear materials properties.

Orthotropic material properties - The basic elastic constant is dependent on direction of material.

Penetrations - Openings through pressure containing structure.

Plane strain - Strains occurring in a two-dimensional plane.

Plane strain analyses - An analyses using no higher order mathematical strain corrections.

Plane stress - Stresses occurring in a two-dimensional plane.

Tensile stress - Force per unit of area produced by elongation of material.

Transverse pressure - Pressure at right angles to the main force.

SECTION 1

INTRODUCTION

This report presents the results of conceptual designs and economic analyses for four types of large prestressed concrete pressure vessels (PCPVs) for use in coal conversion plants. It also compares the projected economics of the selected PCPVs with steel vessels in the same service.

The Ralph M. Parsons Company was the prime contractor for this study and T. Y. Lin International served as subcontractor with responsibility for the structural design of the PCPVs. The work was done under contract to the U.S. Department of Energy, Office of Assistant Secretary for Energy Technology, Division of Coal Conversion. The guidance of Mr. David Garrett of the Department of Energy is gratefully acknowledged.

The prime incentives for this study were preliminary assessments which indicated that:

- The development of PCPVs would permit the use of larger high pressure vessels than presently available in steel construction.
- PCPVs would provide an alternative to the use of steel vessels. This could be a major consideration if a large number of coal conversion complexes were to be constructed simultaneously to meet the goals of national plans. This alternative is particularly important because of the limited U.S. capability to produce many large high pressure vessels simultaneously.
- The use of PCPVs could reduce the fixed capital investment (FCI) of large coal conversion plants. The profitability of coal conversion plants is highly sensitive to the FCI; therefore a successful PCPV program would assist in making these plants economically viable.

To evaluate the potential advantages of PCPVs in coal conversion plants, the following study objectives were established:

- To develop preliminary designs, technical analyses of construction procedures and operating performance, and the projected economics for the following four PCPVs.
  - A coal dissolver and gas-liquid product separator vessel. The coal dissolver is a key vessel in coal liquefaction plants

  - A large absorber used to purify acid gas streams produced during liquefaction of high sulfur coals

  - A large high pressure gasifier complete with defined feed and product handling equipment.

  - A large high pressure gasifier installation modified to embed ancillary equipment, consisting of cyclones and flash dryers into the concrete structure

- To compare the projected economics of the PCPVs and steel vessels performing the same process services

- To recommend development work required to assure successful commercial performance of PCPVs

The four vessels studied were chosen from a large number of candidates; they represent a range of sizes and process duties selected to illustrate the potential advantages of PCPVs when used in large coal conversion plants.

The report which follows presents the design parameters used, projected economics when compared with steel vessels in the same service, the process duties for the separate vessels, details of the preliminary design as well as the construction procedures envisioned, an analysis of the technical and projected performance characteristics of the PCPVs, and recommendations for future work.

SECTION 2

SUMMARY

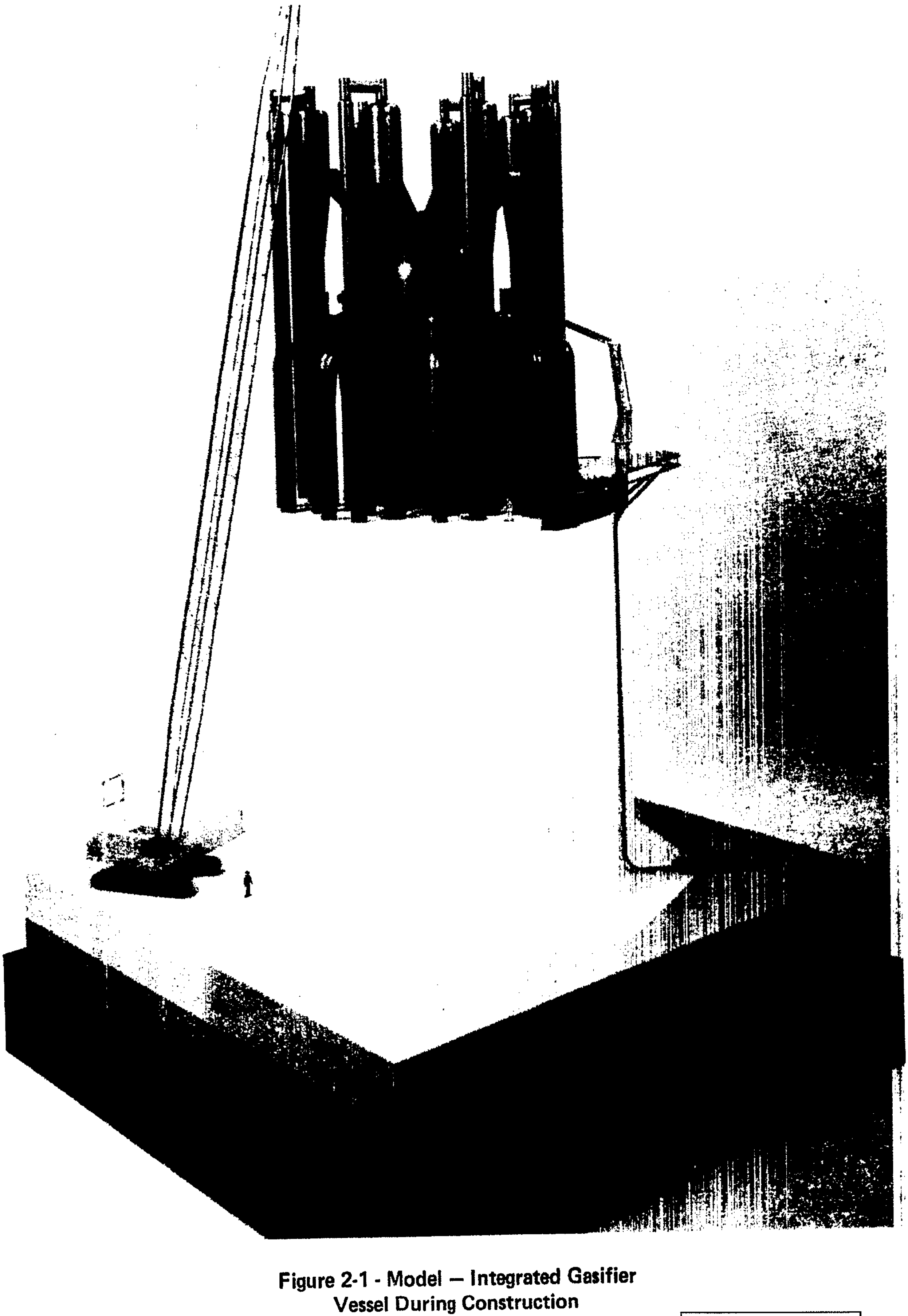

Figure 2-1 - Model — Integrated Gasifier Vessel During Construction

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SECTION 2

SUMMARY

INTRODUCTION

A study of the conceptual design and projected economics of four types of prestressed concrete pressure vessels (PCPVs) for use in coal conversion plants has been completed under contract EX-76-01-1775 with the U.S. Department of Energy. The designs and projected economics were then compared with alternative steel vessels when used in the same service. The results are summarized in this report.

The Ralph M. Parsons Company (Parsons) of Pasadena, California was the prime contractor and T. Y. Lin International of San Francisco, California served as subcontractor with responsibility for the structural design of the prestressed concrete pressure vessels.

The designs developed in this study were chosen to illustrate the potential of representative vessels selected from a large number of possible uses for PCPVs in coal conversion processes. The four PCPVs studied were: a dissolver-separator used to liquefy coal, an absorber used to purify gases, a coal gasifier reactor, and an integrated coal gasifier vessel. The vessels studied range from 23' 4" to 33' 4" inside diameter. They were each designed to replace one or more conventional steel pressure vessels with no change in the process flow from conventional practice. Figure 2-1 illustrates the projected size and characteristics of one of the vessels - note the 6-foot man for size comparison.

PCPV CHARACTERISTICS

For the orientation of those readers not completely familiar with PCPVs, they are structures wherein concrete, reinforcing steel, and high strength steel tendons are used to form the pressure containment shell. Well over 90 percent of the mass is concrete.

Prestressing means the intentional creation of permanent stresses in a concrete structure, for the purpose of improving its structural behavior under various load conditions. The prestressing forces can be applied by means of stressing the tendons. Figure 2-2 shows the general arrangement of the tendons in a PCPV. Similar to reinforced concrete, prestressed concrete involves combined action between the concrete and the prestressing steel tendons, and interaction between the internal prestressing force and the externally imposed loads. For PCPVs, the prestressing forces are applied by post-tensioning the steel tendons after the concrete has hardened. The post-tensioned tendons place the vessel in compression and enable it to resist the high operating pressures.

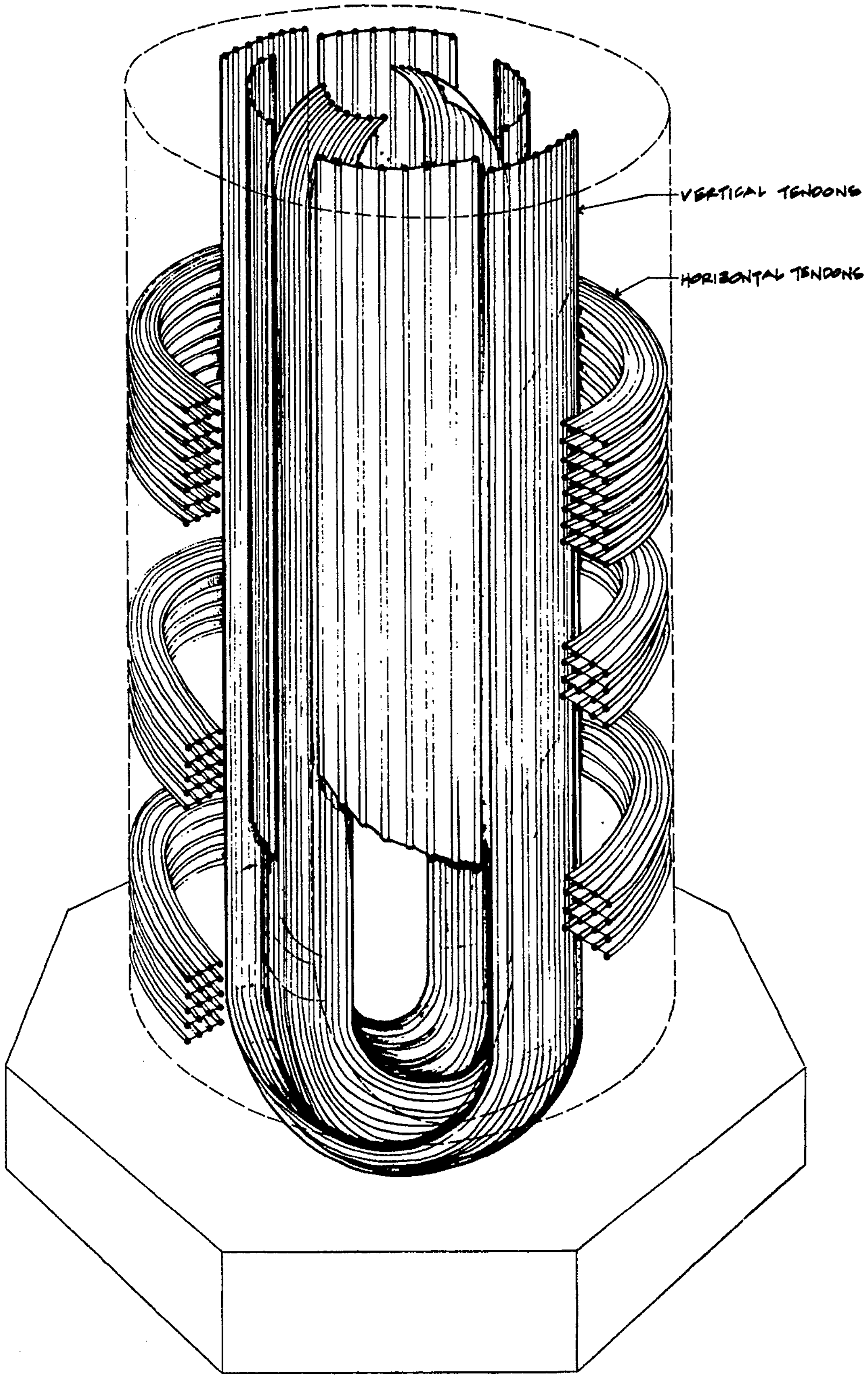


Figure 2-2 - Looping Tendon Arrangement Schematic

There are several additional elements required for a PCPV to perform successfully as a process pressure vessel. One of these is a metal membrane internal liner, which serves to prevent escape of process gases and liquids into the concrete structure. The metal membrane liner also serves as a form during concrete placement.

Another important element is a cooling system plus insulating concrete which is necessary to control the structural concrete temperature whenever the metal liner temperature exceeds 200°F. Also, internal refractory is used when necessary to shield the metal membrane liner against very high temperature.

The general methods of PCPV design have been established. They are used routinely in the design of nuclear secondary containment vessels of which approximately 60 are under construction or in use today. These methods have also been applied to the design of prestressed concrete reactor vessels (PCRVs) used in the nuclear industry at pressures of the order of 600 psi and for vessels for storage of water, oil, LNG and coal. However, because of the higher operating temperatures and pressures, and the much thicker concrete walls for the coal conversion plant operations discussed here, some confirmatory tests should be performed to further substantiate the design.

DESIGN

The performance requirements for each of the vessels studied was defined; process flow diagrams showing stream compositions and flow rates as well as heat and material balances were developed and are presented. The equipment sizes (capacities) and materials of construction requirements were defined. For the dissolver-separator and gasifiers, the system studied included portions of the feed and product handling systems as well as the vessels; for the absorber comparison, only the vessels were included. These results provided the basis for designs, economic comparisons, and projected performance characteristics of the PCPVs and the steel vessels in the same process service.

Briefly, the characteristics of the vessels studied, and their use in coal conversion plants, were:

Dissolver-Separator

The dissolver-separator is a key vessel in coal hydroliquefaction processing; a similar process is under development at the SRC pilot plant located at Fort Lewis, Washington for the U.S. Department of Energy.

Figure 2-3 is a simplified cross sectional view of this PCPV. Here, the main process elements, the dissolver-separator vessels, operate at 850°F and 2,015 psig. The metal membrane wall is directly exposed to the process environment.

A key point is that one two-cavity PCPV would provide essentially the same capacity as eighteen (18) alternative steel vessels.

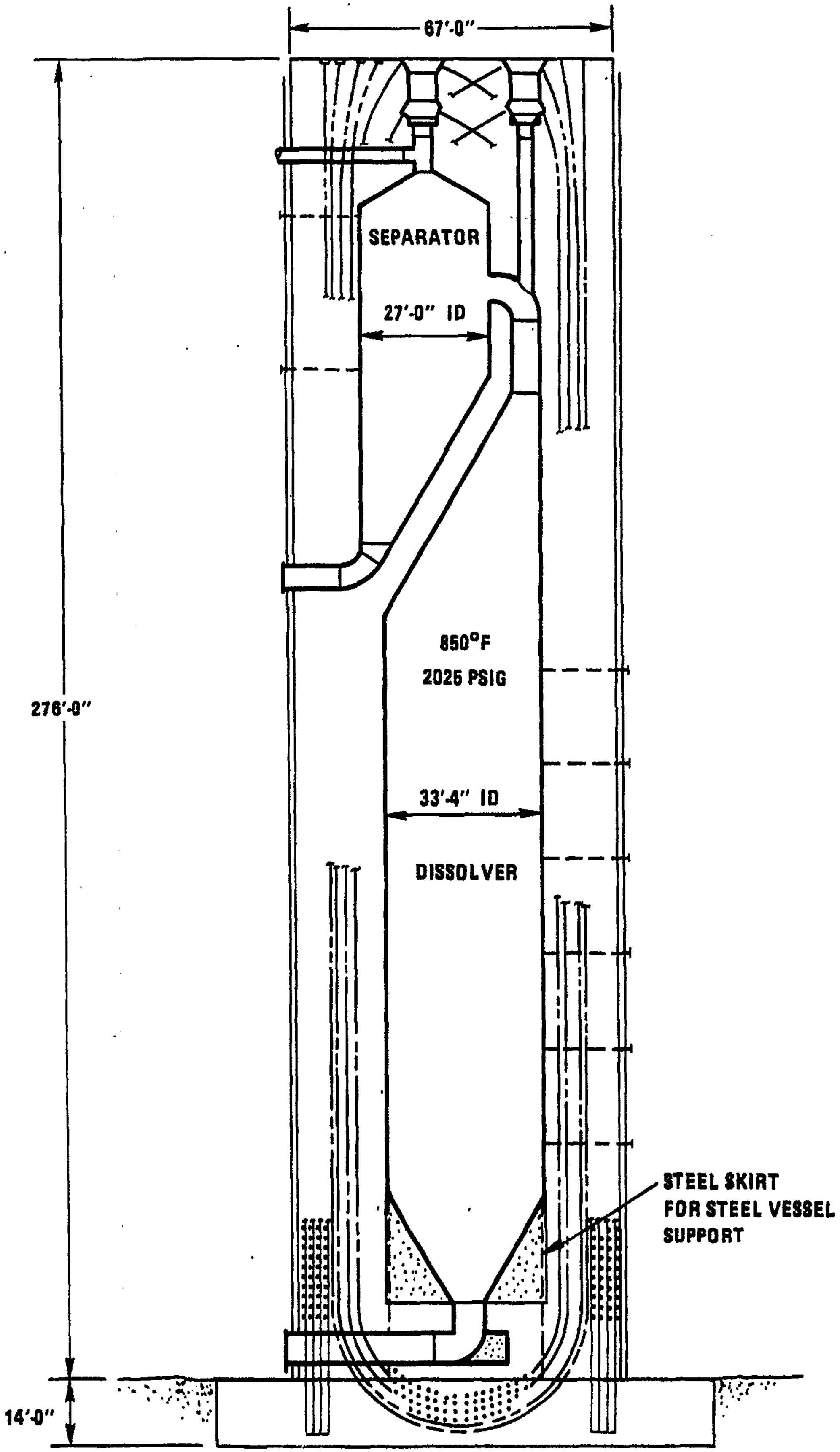


Figure 2-3 - Dissolver-Separator Vessel Sketch

Absorber

This vessel is used to purify gases produced in the dissolver-separator. The process design for this acid gas removal contactor originated in an earlier conceptual design published by Parsons. For this study only the absorber vessel was investigated.

A cross sectional view of this PCPV is shown in Figure 2-4. The vessel has internal trays and intermediate heads, which require carrying these loads into the concrete structure.

A key point is that one single-cavity PCPV would provide the capacity as six (6) steel absorbers.

Gasifiers

Coal is reacted with steam and oxygen in the gasifier at elevated pressure and temperature to produce fuel gas. The study scope covers from the point of feeding a coal-water slurry to the gasifier to the discharge of solids-free gas for further downstream processing. The design is based on a two-stage entrained gasification process. A typical similar process would be the Bi-Gas process being developed at Homer City, Pennsylvania for the U.S. Department of Energy; the lower stage of the gasifier operates at 3,000°F, at a pressure of 1,085 psig.

Two types of gasifier designs were developed. One was a gasifier reactor (Figure 2-5) and the second, termed an integrated gasifier, embedded close coupled ancillaries such as cyclones and flash dryers in the concrete (Figure 2-6).

Here a PCPV gasifier would have the same production capacity as a steel gasifier.

A summary comparison of the PCPV and steel vessel capacities and number of vessels is shown in Table 2-1.

Design parameters and procedures were defined for use in the comparative study. The study was based on a Gillette, Wyoming site. PCPV design and test procedures used engineering judgement in the absence of a code accepted for design of this type vessel for the proposed high pressure service. The guidelines and procedures used in the design are described in detail in this report. Additional details of preliminary design are presented, including materials specification, method of fabrication, and connections to ancillary equipment.

Analysis, plus review of previous tests of PCPVs, indicate that they tend to have a benign failure mode; this is an advantage in pressure process applications.

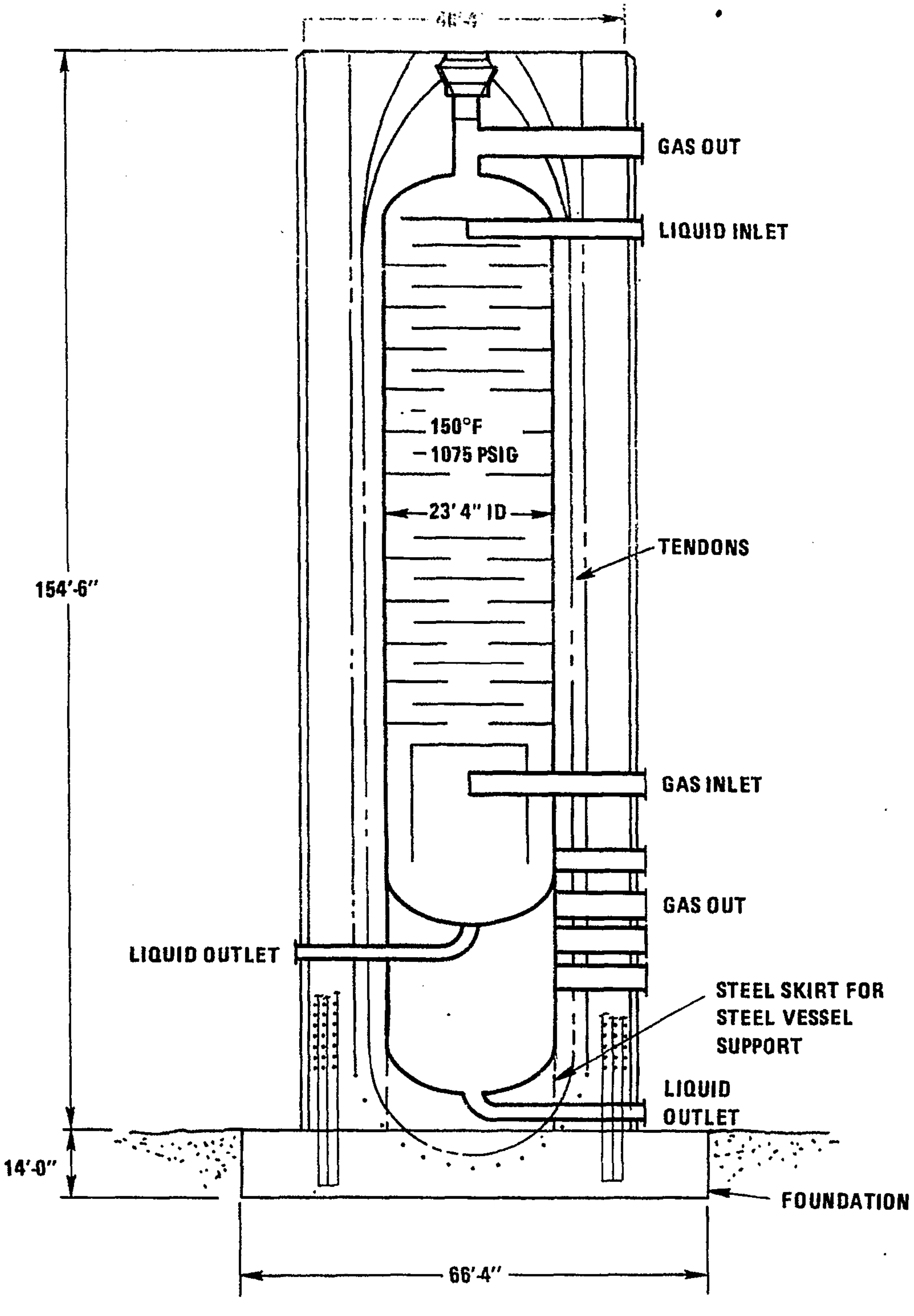


Figure 2-4 - Absorber Vessel Sketch

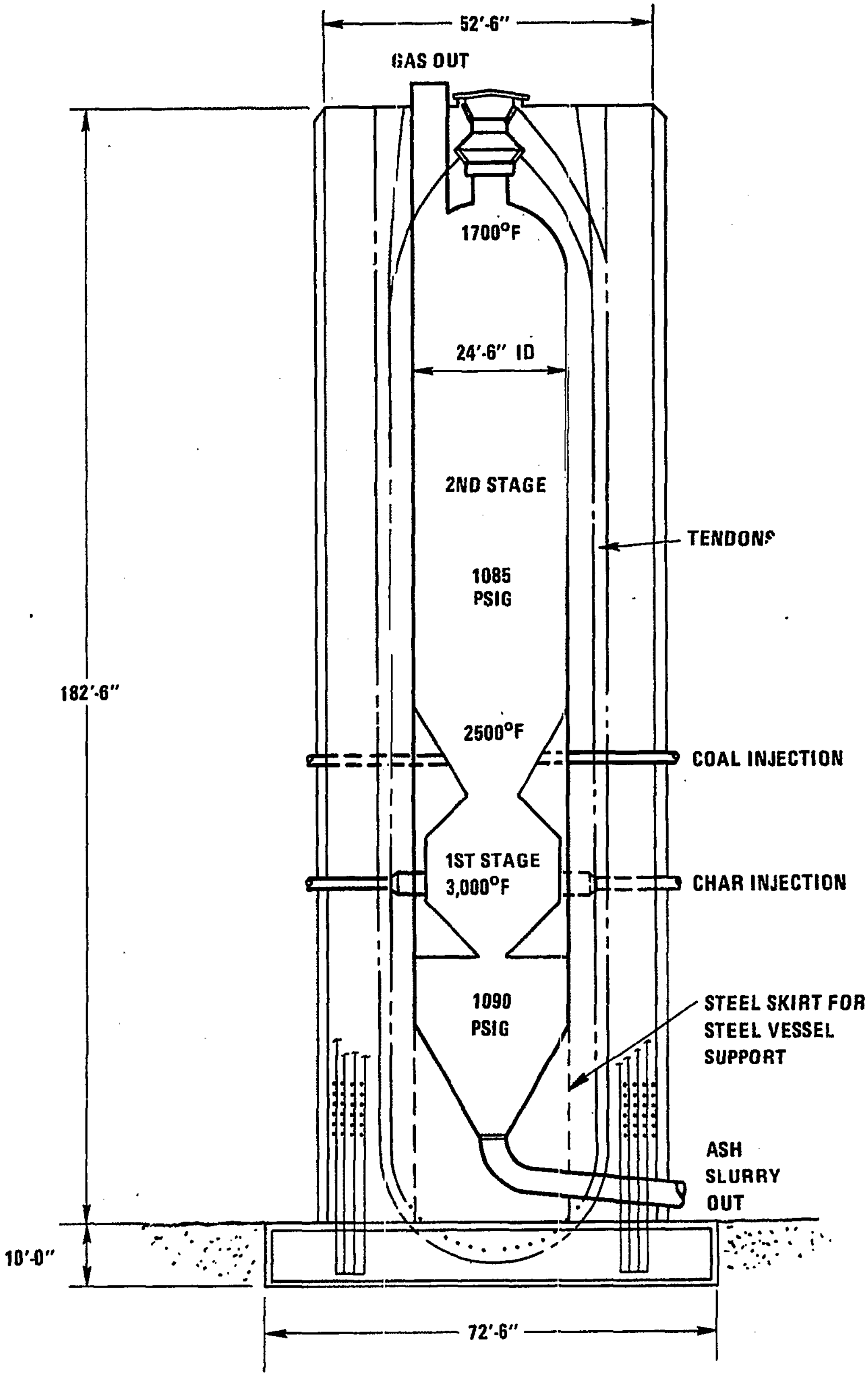


Figure 2-5 - Gasifier Vessel Sketch

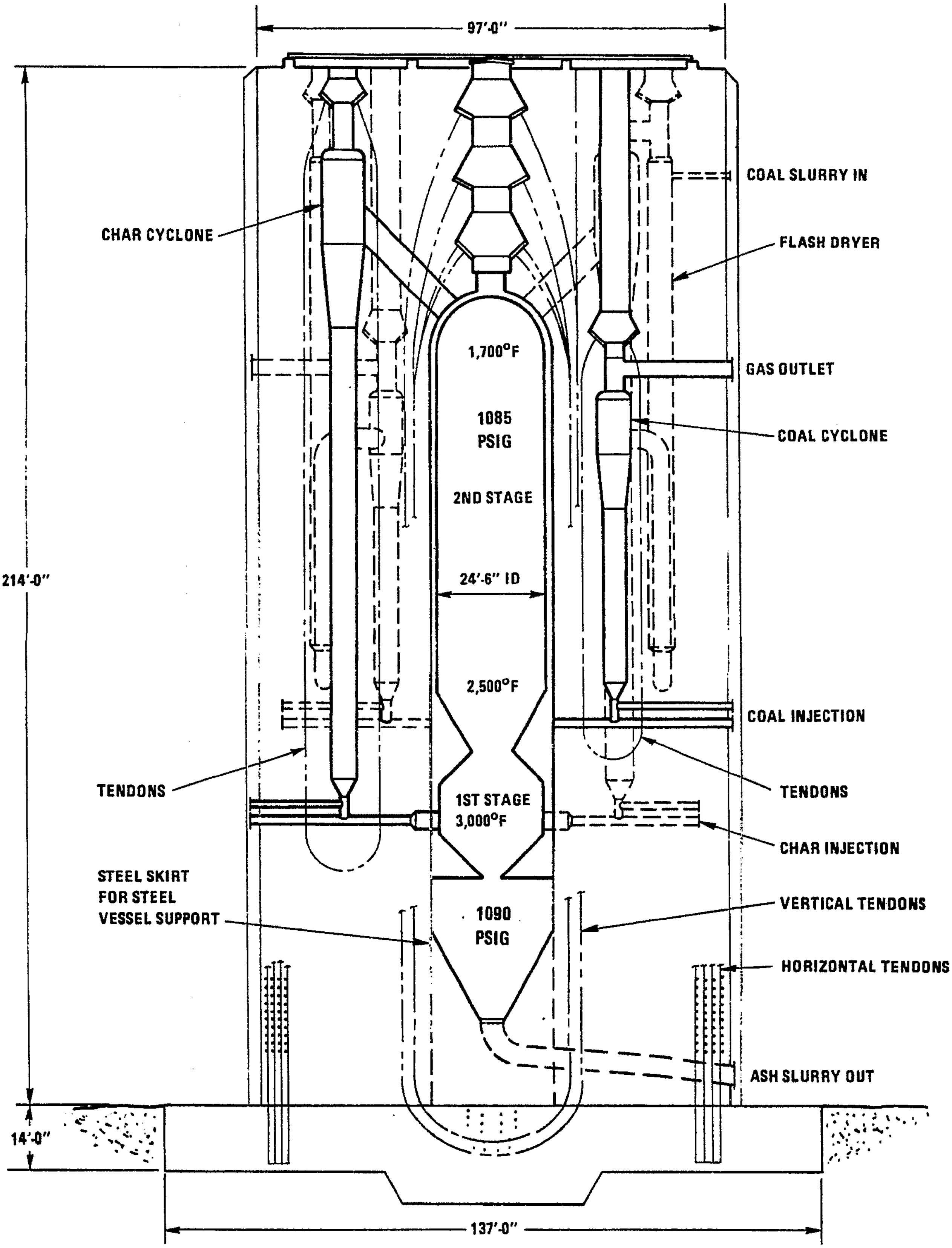


Figure 2-6 - Integrated Gasifier Vessel Sketch

Table 2-1 - Vessel Description Summary

Vessel	Type of Construction	Number of Trains	Capacity per Train	Number of Major Vessels per Train	Total Number Of Major Vessels
Dissolver-Separator	Steel	3	20,000 TPD of Coal	6	18
	PCPV	1	55,000 TPD of Coal	1	1
Absorber	Steel	3	23 million scf/hr	2	6
	PCPV	1	69 million scf/hr	1	1
Gasification	Steel	2	55,000 TPD of Coal	1	2
	PCPV-Gasifier Reactor only	2	55,000 TPD of Coal	1	2
	PCPV-Integrated Gasifier	2	55,000 TPD of Coal	1	2

CONSTRUCTION

Construction procedures, sequence and schedule were developed for the integrated gasifier, the most complex of the vessels. The preferred sequence includes site preparation, installation of foundation, on-site fabrication of thin-walled steel liners, concrete pours to encompass reinforcing steel (rebars) and ducts for the PCPV tendons, installation and tensioning of the tendons, pressure testing, refractory installation where required, and finishing operations. For the integrated gasifier, we estimate 61 months from project start to mechanical completion. The schedule for a single-cavity vessel might be 4-6 months shorter.

ECONOMICS

Fixed capital investments (FCI) and operating costs were estimated for the four PCPVs and compared with equivalent economic parameters for steel vessels in the same service. The projected FCIs are shown in Table 2-2.

Table 2-2 - Fixed Capital Investment Cost Summary

Vessels	Type of Construction	Total Number Major Vessels in Service	FCI ($ Million)	PCPV Percent Reduction in FCI Compared to Steel Vessel
Dissolver-Separator	Steel	18	420	0
	PCPV	1	130	70
Absorber	Steel	6	10	0
	PCPV	1	4	60
	Steel	2	255	0
Gasification	PCPV-Gasifier only	2	225	12
	PCPV-Integrated Gasifier	2	230	10

Comparative annual operating costs were estimated and the potential annual savings to be expected when using PCPVs. projected. The results are shown in Table 2-3.

Table 2-3 - Annual Operating Cost Savings

Vessel	Uniform Annual Cost Savings ($ Million)	Unit Cost Savings
Dissolver-Separator	90+	$0.20 per MM Btu of Feed Coal Energy
Absorber	2.2	$0.004 Per MM scf Gas Feed to Absorber
Gasifier	10.2	$0.013 Per MM Btu of Product Gas
Integrated Gasifier	8.5	$0.011 Per MM Btu of Product Gas

These savings are based on financial and project parameters consisting of a 12 percent discounted cash flow rate of return (DCF) on invested capital, and a 20-year plant operating life with an on-stream efficiency of 330 stream days per year.

CONCLUSIONS

The results of the study indicate:

- The design and construction of PCPVs was found to be generally within the present state of knowledge. Subscale testing should be performed to confirm some design judgements.
- The use of PCPVs can reduce the FCI requirements. To illustrate, substitution of a single PCPV for as many as 18 steel vessels might reduce the FCI by approximately 70 percent, amounting to as much as $300 million. Replacement of a single steel vessel with a PCPV can reduce the FCI by approximately 10 percent.
  - Thus, there is a definite economic incentive to carry further the development of PCPVs to demonstrate their technical feasibility and economic viability.
- PCPVs offer an alternative for construction of large scale coal conversion plants.
- Improved vessel safety performance is expected because of the benign failure characteristics of PCPVs.
- PCPVs have the potential to be operational in a shorter schedule than steel vessels.
- At the time of this writing, supply projections indicate that the materials of construction for PCPVs can be readily available in the U.S. while the capacity to fabricate and install large numbers of large heavy walled steel pressure vessels was found to be currently limited by the number of suppliers and availability of fabrication facilities.

There are a number of vessels in a coal conversion plant that could be constructed with PCPVs now. The state of the art, including the experience obtained in the nuclear industry, would be the basis for design and construction.

A three-part program designed to further develop PCPVs for still higher pressure operations, as described in this study, has been developed. The program includes:

- Part one: feasibility studies and demonstration plant programming
- Part two: experimental confirmatory tests
- Part three: design construction and operation of a demonstration scale PCPV.

The availability of PCPVs as an alternative to steel vessels can be an important factor if it becomes necessary to construct many large coal conversion complexes simultaneously. In that case, the availability of thick steel plate and the ability to fabricate a large number of steel thick-walled vessels simultaneously could be a limitation on the effectiveness of an aggressive national synfuels program.

RECOMMENDATION

The result reported here suggests that potential for use of PCPVs in coal conversion plants warrant further effort.

SECTION 3

PROJECT PARAMETERS

3.1 SCOPE OF WORK

The scope of work included development of the following items for four key PCPV types used in coal conversion plants, and comparison with steel and alloy vessels used in equivalent service:

- conceptual designs
- economic analyses
- technical analysis of design factors, construction and operating performance

3.2 VESSELS PLUS ANCILLARIES STUDIED

The designs developed in this study were chosen to illustrate the potential technical and economic advantages of representative vessels used in coal conversion plants. They were selected from a large number of candidates to illustrate the effects of operating under a wide range of temperatures, pressures and process stream configurations. They provided a range of sizes, operating conditions and configurations as illustrated in Table 3-1.

A description of the vessels and their ancillaries studied as well as their process functions follows.

3.2.1 DISSOLVER-SEPARATOR

The dissolver-separator is a key vessel in coal hydroliquefaction processing; a similar process is under development at the SRC pilot plant located at Fort Lewis, Washington for the U.S. Department of Energy.

Figure 2-3 is a simplified cross sectional view of this PCPV. Here, the main process elements, the dissolver-separator vessels, operate at 850°F and 2,025 psig. The metal membrane wall is directly exposed to the process environment.

This unit consists of a dissolver-reactor and a separator enclosed in a single PCPV structure. The dissolver-reactor has an inside diameter of 33 feet-4 inches and is approximately 198 feet in overall height. It is coupled to the separator located above the dissolver-reactor. The separator has an inside diameter of 27 feet and an overall length of approximately 60 feet.

This combination PCPV replaces three trains of steel dissolver-reactor vessels and steel separator vessels with each train consisting of three dissolver-reactors and three separators.[1] Thus, this one PCPV replaces 18 steel vessels; nine dissolver-reactors and nine separators of steel construction.

The process duty and the ancillaries included in the study are shown in Figure 3-1 located at the end of this section. The unit was designed to process 55,000 TPD of coal. A description of the processing follows; it represents a scale-up of a previously published conceptual design.[1]

A slurry containing about 30 wt% solids and with a solvent-to-coal weight ratio of approximately 3 is pumped with dissolver feed pumps 12-1501 with a discharge pressure of about 2,200 psig through the separator slurry feed exchangers 12-1310, and then to the dissolver preheater furnace 12-1401. The dissolver feed pumps are multi-stage centrifugal pumps with tungsten carbide hardfacing.

Hydrogen feed from the makeup hydrogen compressors 12-1801 and the recycle hydrogen compressor 12-1802 is combined with the slurry and the mixture heated to 700°F in preheater furnace 12-1401. The gas slurry mixture enters dissolver 12-2501 where an exothermic reaction takes place, dissolving the coal and raising the reaction temperature to about 850°F. The design slurry retention time is 15 minutes. The product mixture from the dissolvers consists of a vapor phase and a slurry phase consisting of hydrocarbon liquids and solid ash plus undissolved coal.

The two phases are separated in separator 12-1204. The vapor is partially cooled by heat interchange with the feed hydrogen in vapor feed gas exchanger 12-1303 before flowing to downstream process units. Recovered hydrogen-rich gas is used as part of the recycle hydrogen to the dissolver.

The slurry phase is cooled by interchange with the feed slurry steam in slurry feed exchanger 12-1310 before going downstream to units for further processing.

A closed loop cooling system using high-purity water is provided for cooling the exterior surface of the reactor vessel at the insulating concrete - structural concrete interface from the 850°F reactor operating temperature to a 200°F maximum structural concrete temperature. It consists of cooling water tubes, cooling water circulation pumps, air-cooled heat exchangers, water surge tank, necessary instrumentation and controls, and associated piping.

3.2.2 ABSORBER

The process design for this acid gas removal contactor used to purify gases produced in the dissolver originated in an earlier conceptual design published by Parsons.[1] For this study only the absorber vessel was investigated.

A cross sectional view of this PCPV is shown in Figure 2-4. The vessel has internal trays and intermediate heads, which require carrying these loads into the concrete structure. It is 23 feet-4 inches in diameter and approximately 130 feet in height, operating at 1,090 psig and 150°F. This vessel is equivalent in capacity to six steel columns of smaller diameter.

The process flow diagram is shown in Figure 32. The function of the unit is to remove about 1.85 vol% hydrogen sulfide and small amounts of carbon dioxide from an inlet gas stream which has about a 63% hydrogen concentration. This is accomplished by the countercurrent washing of the gas with a lean monoethanolamine (MEA) solution. The overhead gas from the absorber is routed to the lower knockout section of the vessel for separation of entrained liquid. The rich MEA solution containing H_2S and CO_2 leaving the absorber bottom is sent to regeneration and then recycled to the top of the absorber.

The PCPV absorber vessel has a capacity of six times that of each absorber of Reference 1. The original design required two 9-foot, 6-inch-diameter absorbers to handle the gas produced in processing 20,000 TPD of coal. The PCPV absorber could handle the gas from a plant processing 60,000 TPD of coal.

3.3.3. GASIFIERS

Two types of PCPV gasifier units were designed; one consisted of a gasifier vessel (Figure 25) and the second, referred to as an integrated gasifier vessel, embedded certain ancillary high pressure vessels consisting of coal and char cyclones, flash dryers, coal and char eductors, plus connecting piping, within the concrete structure; a cross section of the integrated gasifier is shown in Figure 2-6. The integrated design was conceived to be a potential improvement because of the reduction in the required wall thickness for the embedded ancillaries, these PCPVs serve the same process function as a large field fabricated steel gasifier described earlier.[2]

The gasification process flow scheme is the same for the gasifier vessel and the integrated gasifier vessel. The process scope covers from the point of feeding a coal-water slurry to the gasifier to the discharge of solids-free gas for further downstream processing. The process design shown in Figure 3-3 is based on a two-stage entrained gasification process. A typical similar process would be the Bi-Gas process being developed at Homer City, Pennsylvania for the U.S. Department of Energy.

The large, high-pressure gasifier vessel has an inside diameter of 24 feet, 6 inches and is approximately 150 feet in height. This vessel has an internal operating pressure of 1,095 psig and a metal shell temperature of 475°F. The operating temperature of the vessel is approximately 3,000°F in the lower (first) stage and from 2,500°F at the lower section to 1,700°F at the exit of the upper (second) stage. The shell temperature is maintained by castable refractory internal to the metal shell and by insulating concrete and a cooling system on the external side of the vessel metal shell.

Two gasification trains are provided, each designed to process 55,000 TPD of dry coal for a total of 110,000 TPD of dry coal.

The process flow scheme (Figure 3-3) is the same for both the PCPV gasifier reactor vessel and the integrated PCPV gasifier vessel cases. The feed coal is pulverized to about 70% through 200 mesh size and is slurried with water in an offsite facility that is not included in this study. The slurry consists of about 44.6 wt% dry coal and 55.4 wt% water.

The coal is pumped by centrifugal slurry circulating pumps -1501 to slurry feed pumps -1502. The multi-stage centrifugal slurry feed pumps, operating at about 1,250 psig, feed the coal to the gasifier vessel. Nine slurry feed pumps, eight operating and one spare, are provided. Each pump serves to feed one slurry feed heater, flash dryer, and coal injection point in the gasifier vessel.

Slurry feed heaters -1301 heat the slurry from about 60°F to 500°F. This temperature is just below the boiling point (554°F) of water at 1,080 psig. High pressure steam is used as the heating medium. These units reduce the heat load required in the subsequent flash drying operation.

The heated slurry is then injected into vertical flash dryer -1202. In this vessel, the water in the slurry is vaporized by direct contact with the hot 1,700°F gases from the gasifier vessel in a concurrent flow pattern. About 94% of the coal particles are separated from the steam-product gas in coal cyclones -2211.

The recovered dried coal particles at 600°F flow downward through flow metering instruments and are injected into Stage 2 of the gasifier vessel, -1203, through eight coal injectors.

The coal particles are contacted with the hot 3,000°F reducing gas flowing upwards from Stage 1 (lower stage) of the gasifier. The coal particles are rapidly heated and devolatilization and gasification takes place.

About 94% of the char is separated from the gas stream in char cyclones -2212. This char is metered and injected into the Stage 1 of the gasifier vessel. The remaining char is removed in the vertical flash dryer by contact with the slurry.

The char is tangentially injected into Stage 1 of the gasifier vessel by eight char injectors. Oxygen is also fed to the gasifier vessel by circumferential annuli around the coal-steam inlet nozzles. In this stage, most of the char is reacted with the oxygen and steam to form the highly reducing gas for reaction with the fresh pulverized coal in Stage 2.

The oxygen is supplied for the combustion reaction to form CO_2 to supply the heat for endothermic reaction between carbon and steam to form CO and H_2. The reaction temperature in this stage is approximately 3,000°F.

The molten ash slag and part of the unreacted char particles are flung against the wall by the centrifugal forces caused by the non-radial entry nozzles. The molten ash flows downward and out through the bottom nozzle. The molten ash slag is quenched and cooled in a water path. The char particles on the walls react with the oxygen and steam in the gasifier vessel.

The slag-water slurry at about 6 wt% slag is circulated by pump -1504 through slag cyclones -2213, recycle cooler -1302, and back into the water bath section of the gasifier vessel. The slag cyclone removes the ash slag from the circulating stream to produce a waste underflow product of about 30% solids concentration.

The process gas-steam mixture leaving coal cyclones -2211 is flow- and pressure-controlled. This gas, at about 600°F and containing some fine solid coal particles, is sent to venturi scrubbers -2214, for final solids removal before being sent to downstream processing. The separator diameters for each case were maintained at about the same diameter as the corresponding gasifier reactor vessels for reasons of consistency in shop versus field-fabricated vessels.

Four trains of venturi scrubber-separator units are provided to handle the total plant gas output. A recirculating cooling water loop is provided for the cooling coils in Stage 1 of the gasifier vessel. Cooling water is circulated by pump -1503 through the coils. A small amount, about 2-4%, of the water is converted to steam passing through the coils. This steam is separated in steam drum -1201 and is used as motive steam. The steam drum pressure is maintained at the same pressure as the gasifier vessel pressure to minimize the effects of a tube rupture.

A closed loop cooling system using high-purity water is provided for cooling the exterior surface of the gasifier at the structural concrete interface to 200°F. It consists of cooling tubes embedded in concrete, cooling water circulation pumps, air-cooled heat exchangers, water surge tank, necessary instrumentation and controls, and associated piping. The design of the cooling system is discussed in Section 6.5.

3.3 BATTERY LIMITS

The process equipment limits for each case have been described and are also indicated on process flow diagrams Figures 3-1, 3-2 and 3-3. The utilities in all cases are outside the battery limits. The economic comparisons were based on purchased utilities delivered to the process battery limits.

3.4 PLANT SITE AND CONDITIONS

The conceptual plant design and economic evaluation were based on a plant site conceived to be just outside Gillette, Wyoming (population 2,200). The site is about 80 miles southeast of Sheridan (population 12,000) and about 140 miles northeast of Casper (population 40,000).

The design was based on a level site with undisturbed soil. The soil load bearing capacity basis was 4,000 pounds per square foot. The soil geology basis was unconsolidated rock conglomerate for a depth of 10 feet. Sandstone with a load bearing capacity of 24,000 pounds per square foot underlying the conglomerate for a depth of 20 feet formed another design basis. This is followed by seams of coal ranging from 25 to 50 feet in thickness.

Other site condition bases were:

The plant elevation is 4,600 feet above sea level

The climatological conditions are:

Temperature	
Summer dry bulb	90°F
Summer wet bulb	65°F
Winter dry bulb	15°F
Design for freeze protection	-40°F with 50 mph wind
Design for frost line	5 feet below surface
Wind speed	
Average	12 mph
Peak gust	100 mph

The plant site is in Seismic Zone 1 as defined by the Uniform Building Code, with a B structural control level.

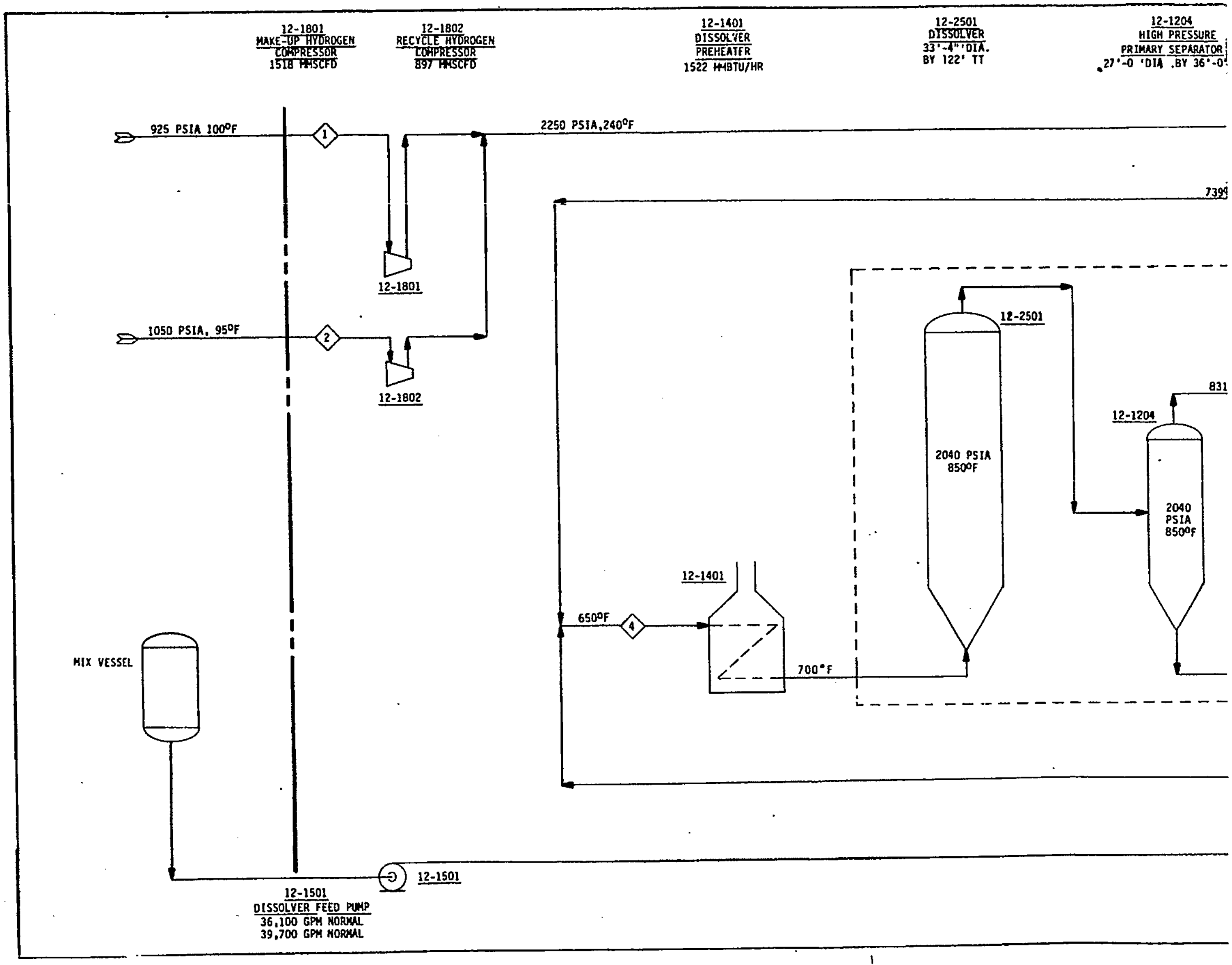
Because of the small population within 150 miles of the plant site, investments were based on a construction camp being established at the site. Prevailing labor rates and productivities in the area were utilized in the study.

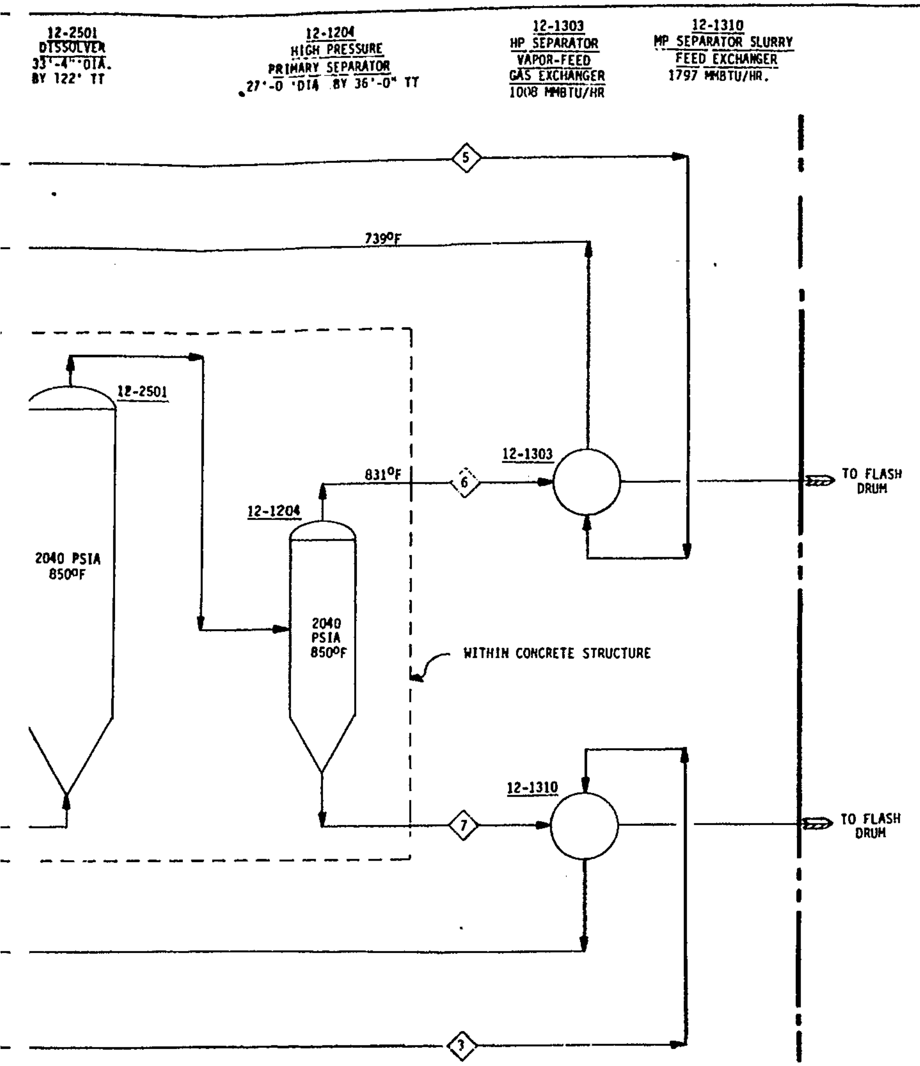
Supply of utilities such as electrical power, water, natural gas, and other fuels required for construction were based on availability at the site.

The site area is served by the Burlington Northern Railway. The site is also served by Interstate Highway 90, which is in good condition and has no special size or weight limitations. There is no waterway access to or near the plant site for delivery of materials.

Table 3-1 - Vessel Description

Vessel	Type of Construction	Number of Trains	Capacity per Train	Number of Major Vessels per Train	Total Number of Major Vessels	Temper-ature (°F)	Operating Pressure (psig)	Diameter
Dissolver-Separator	Steel	3	20,000 TPD of Coal	6	18	850	2025	33'-4" and 27'-0"
	PCPV	1	55,000 TPD of Coal	1	1			
Absorber	Steel	3	23 million scf/hr	2	6	150	1075	23'-4"
	PCPV	1	69 million scf/hr	1	1			
	Steel	2	55,000 TPD of Coal	1	2			
Gasification	PCPV-Gasifier Reactor only	2	55,000 TPD of Coal	1	2	1700-3000	1090	24'-6"
	PCPV-Integrated Gasifier	2	55,000 TPD of Coal	1	2			


12-1801
MAKE-UP HYDROGEN
COMPRESSOR
1518 MMSCFD
12-1802
RECYCLE HYDROGEN
COMPRESSOR
897 MMSCFD
12-1401
DISSOLVER
PREHEATER
1522 MMBTU/HR
12-2501
DISSOLVER
33'-4"'DIA.
BY 122' TT
12-1204
HIGH PRESSURE
PRIMARY SEPARATOR
27'-0 'DIA .BY 36'-0
925 PSIA 100°F
1
2250 PSIA,240°F
739
12-1801
1050 PSIA, 95°F
2
12-1802
12-2501
831
12-1204
2040 PSIA
850°F
2040
PSIA
850°F
12-1401
650°F
4
700°F
MIX VESSEL
12-1501
12-1501
DISSOLVER FEED PUMP
36,100 GPM NORMAL
39,700 GPM NORMAL



COMPONENT	① MAKE-UP HYDROGEN	② RECYCLE HYDROGEN	③ SLURRY TO DISSOLVER	④ SLURRY & GAS TO FURNACE	⑤ TOTAL HYDROGEN GAS	⑥ HP SEPARATOR VAPOR	⑦ HP SEPARATOR SLURRY
H_2 MOLES/HR.	132,590	94,308	---	226,898	226,898	103,460	9,989
N_2	1,827	945	---	2,772	2,772	1,681	1,090
CO	5,582	2,422	---	8,004	8,004	5,396	2,608
CO_2	166	---	---	166	166	1,142	199
NH_3	---	---	---	---	---	594	87
H_2S	86	---	---	86	86	3,451	423
H_2O	127	---	105	229	229	7,288	158
C_1	26,317	768	---	27,085	27,085	36,846	4,496
C_2	---	---	---	---	---	3,885	849
C_3	---	---	---	---	---	3,534	732
NC_4	---	---	---	---	---	1,274	300
IBP-200	---	---	---	---	---	310	95
200-400	---	---	---	---	---	1,791	1.387
400-450	---	---	---	---	---	388	533
450-500	---	---	---	---	---	285	509
500-600	---	---	285	285	---	586	1,687
650+	---	---	34,507	34,507	---	1,412	38,576
RESIDUE	---	---	37	37	---	---	70
ASH	---	---	126	126	---	---	126
COAL (MAF)	---	---	427	427	---	---	---
TOTAL MOLES/HR	166,696	98,442	35,488	300,626	265,138	172,735	63,916
LB/HR	909,536	296,750	19,866,890	21,073,176	1,206,286	2,491,344	18,581,832
BPD	---	---	1,097,886	---	---	---	1,100,316
MMSCD	1,518.213	896.589	---	---	2,414.8	1.578.8	---
MW	5.456	3.014	559.82	---	4.55	14.37	290.73
LB/GAL	---	---	10.340	---	---	---	9.650

Figure 3-1

0

PROCESS FLOW DIAGRAM
DISSOLVER - SEPARATOR
PRESTRESSED CONCRETE
PRESSURE VESSEL

THE RALPH M PARSONS COMPANY
PASADENA, CALIFORNIA

5435-6

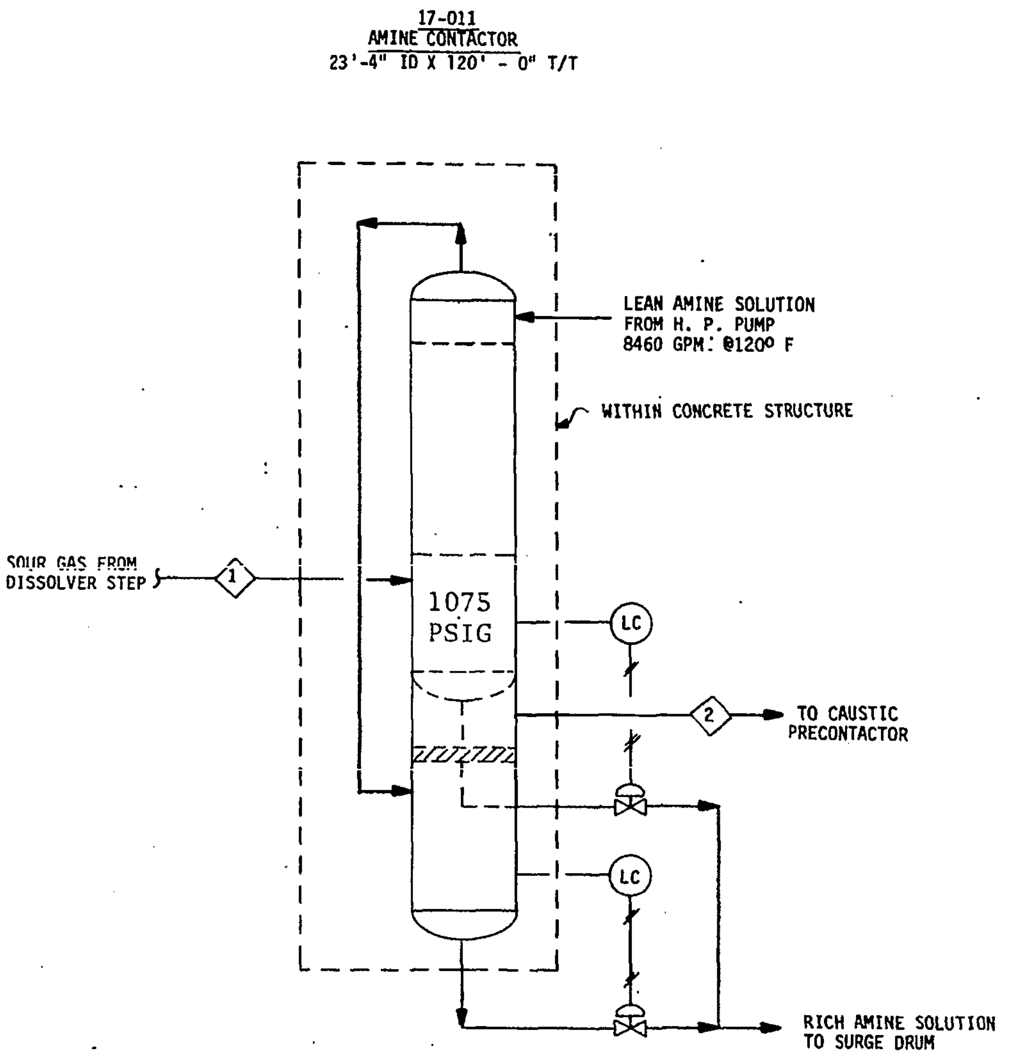
R-1-FS-2

0

3-9

3-9 (B)

(C)



COMPONENT	① GAS TO CONTACTOR	② GAS FROM CONTACTOR
H_2 Mols/Hr	113,756	113,598
N_2	2,803	2,798
CO	8,004	7,997
CO_2	1,173	---
NH_3	16	---
H_2S	3,371	---
H_2O	148	148
CH_4	41,650	41,587
C_2H_6	4,798	4,791
C_3H_8	4,285	4,280
C_4H_{10}	1,417	1,415
IBP-200°F	259	258
200-300°F	88	88
300-350°F	5	5
350-400°F	1	1
400-450°F	---	---
TOTAL MOLS/HR	181,773	176,966
LB/HR	1,816,392	1,647,375
MSCFH	69,078	67,158
M.W.	9,993	9.309

Figure 3-2

REV NO	CUST APPR.	DATE	REVISION	BY	PROC ENGR	CHECK	CHIEF PROC. ENGR	CHIEF OPER ENGR	PROC DIR.
0				SRD					

PROCESS FLOW DIAGRAM
ABSORBER
PRESTRESSED CONCRETE
PRESSURE VESSEL

THE RALPH M. PARSONS COMPANY PASADENA, CALIFORNIA	JOB NO. 5435-6	DWG. NO. R-1-FS-3	REV. 0

DC- DT-

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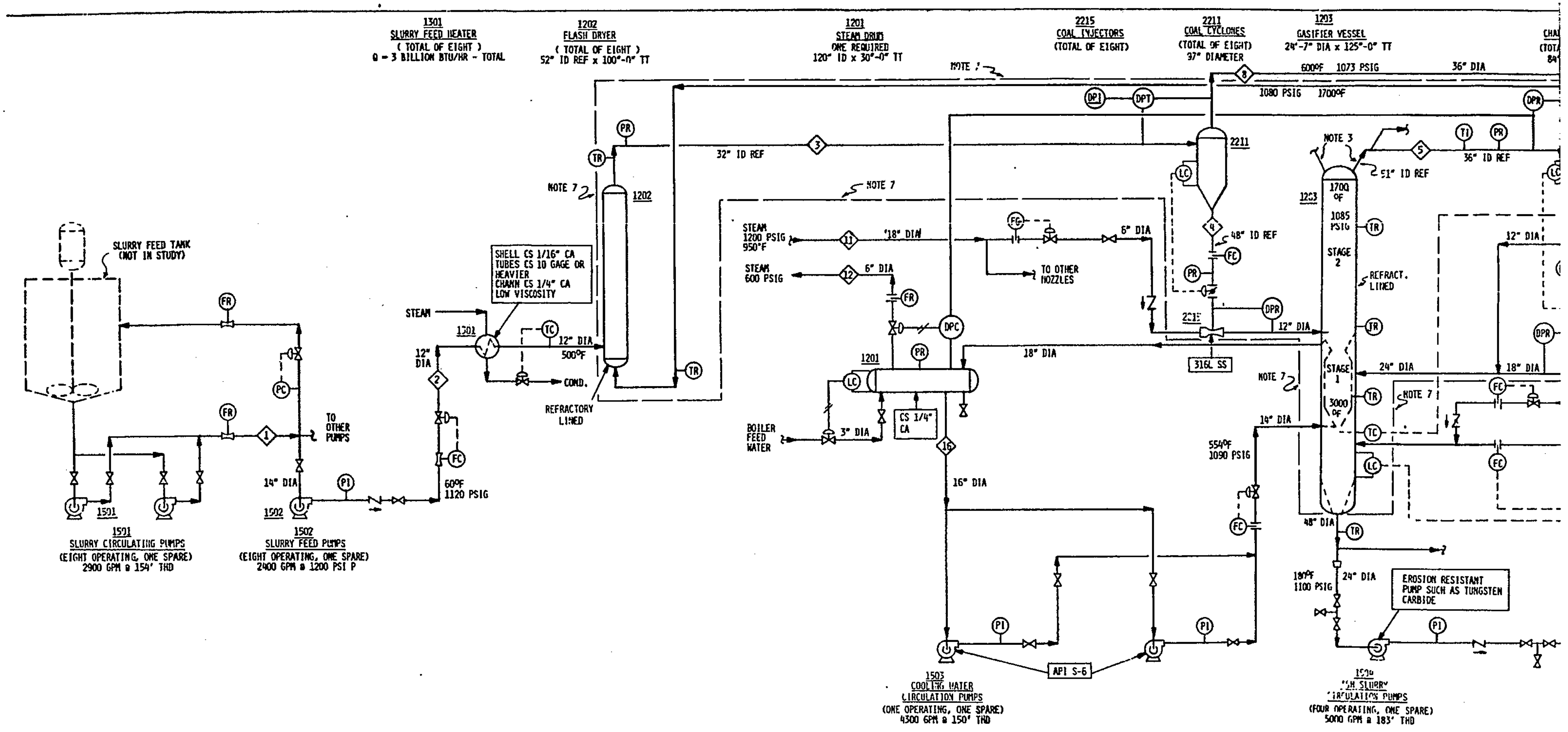
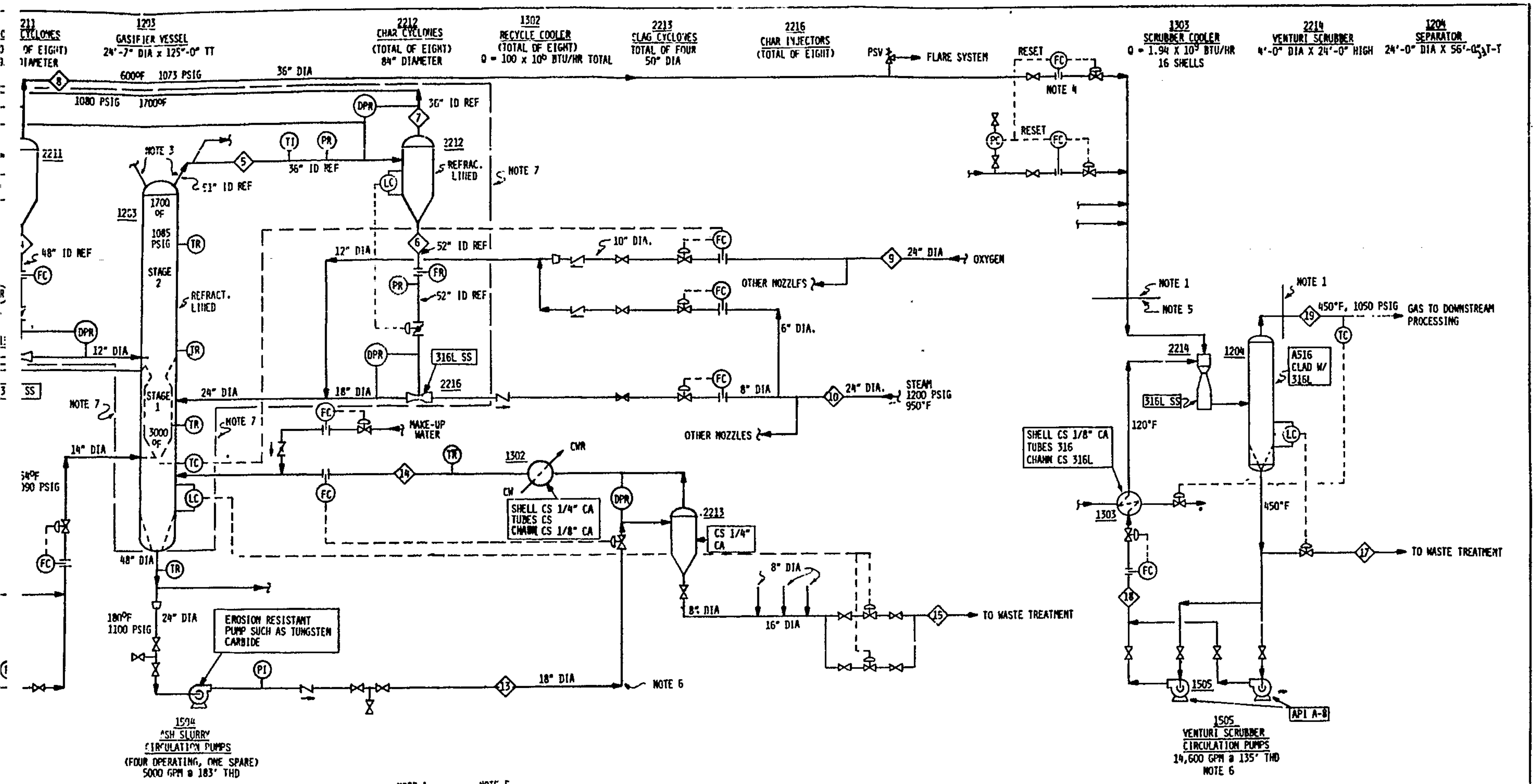


STREAM NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1
GASES MOLS/HR																
H_2	-	-	113,310	-	113,310	-	113,310	113,310	-	-	-	-	Note 2	Note 2	Note 2	-
CH_4	-	-	51,230	-	51,230	-	51,230	51,230	-	-	-	-				-
CO	-	-	132,460	-	132,460	-	132,460	132,460	-	-	-	-				-
CO_2	-	-	72,070	-	72,070	-	72,070	72,070	-	-	-					-
H_2O	-	-	408,880	-	87,950	-	87,950	408,880	-	101,760	50,880	1,940				-
H_2S	-	-	5,270	-	5,270	-	5,270	5,270	-	-	-	-				-
NH_3	-	-	4,200	-	4,200	-	4,200	4,200	-	-	-	-				-
N_2	-	-	1,320	-	1,320	-	1,320	1,320	1,320	-	-	-				-
O_2	-	-	-	-	-	-	-	-	64,570	-	-					-
Total Mols	-	-	788,740	-	467,810	-	467,810	788,740	65,890	101,760	50,880	1,940				-
Total Lbs	-	-	15.58 x 10^6	-	9.80 x 10^6	-	9.80 x 10^6	15.58 x 10^6	2.10 x 10^6	1.33 x 10^6	0.92 x 10^6	35,000				-
SOLIDS AND LIQUIDS LBS/HR																
C	3.96 x 10^6	3.28 x 10^6	3.50 x 10^6	3.30 x 10^6	3.50 x 10^6	3.29 x 10^6	220,000	196,600	-	-	-		32,600	1,600	31,000	-
H	.27 x 10^6	0.22 x 10^6	0.22 x 10^6	0.21 x 10^6	-	-	-	13,400	-	-	-		-	-	-	-
O	.52 x 10^6	0.43 x 10^6	0.43 x 10^6	0.40 x 10^6	-	-	-	25,500	-	-	-		-	-	-	-
N	.07 x 10^6	0.06 x 10^6	0.06 x 10^6	0.06 x 10^6	-	-	-	3,800	-	-	-		-	-	-	-
S	.22 x 10^6	0.18 x 10^6	0.18 x 10^6	0.17 x 10^6	-	-	-	10,900	-	-	-		-	-	-	-
Ash	.72 x 10^6	0.60 x 10^6	0.66 x 10^6	0.62 x 10^6	1.08 x 10^6	1.02 x 10^6	60,000	35,800	-	-	-		549,300	28,500	540,800	-
H_2O	7.15 x 10^6	5.92 x 10^6	0.14 x 10^6	0.13 x 10^6	-	-	-	8,200	-	-	-		8.92 x 10^6	7.60 x 10^6	1.26 x 10^6	1.57
Total	12.91 x 10^6	10.69 x 10^6	5.19 x 10^6	4.89 x 10^6	4.58 x 10^6	4.31 x 10^6	270,000	294,200	-	-	-		9.52 x 10^6	7.60 x 10^6	1.83 x 10^6	1.57
Total Lb/Hr	12.91 x 10^6	10.69 x 10^6	20.77 x 10^6	4.89 x 10^6	14.38 x 10^6	4.31 x 10^6	10.07 x 10^6	15.87 x 10^6	2.10 x 10^6	1.33 x 10^6	0.92 x 10^6	35,200	9.52 x 10^6	7.60 x 10^6	1.83 x 10^6	1.57

3-13 (A)

3-13 (B)



NOTE 1 NOTE 5

11	12	13	14	15	16	17	18	19
-	-				-			113,310
-	-				-			51,230
-	-				-			132,460
-	-				-			72,070
50,000	1,940	Note 2	Note 2	Note 2	-	Note 2	Note 2	747,470
-	-				-			5,270
-	-				-			4,200
-	-				-			1,320
-	-				-			-
50,000	1,940				-			1,127,330
0.92 x 10^6	35,000				-			12.67 x 10^6
-	-	32,600	1,600	31,000	-	97,300	378,000	2,000
-	-	-	-	-	-	6,600	25,800	130
-	-	-	-	-	-	12,600	49,200	250
-	-	-	-	-	-	1,900	7,300	40
-	-	-	-	-	-	5,400	21,000	110
-	-	549,300	28,500	540,800	-	17,700	69,000	360
-	-	8.92 x 10^6	7.60 x 10^6	1.26 x 10^6	1.57 x 10^6	1,458,000	5,677,400	80
-	-	9.52 x 10^6	7.60 x 10^6	1.83 x 10^6	1.57 x 10^6	1.60 x 10^6	6.23 x 10^6	2,970
0.92 x 10^6	35,000	9.52 x 10^6	7.60 x 10^6	1.83 x 10^6	1.57 x 10^6	1.60 x 10^6	6.23 x 10^6	12.68 x 10^6

NOTES:

1. ALL FLOW RATES TOTAL FOR TRAIN. TWO TRAINS REQUIRED.
2. DISSOLVED GASES ARE NOT INCLUDED AS THEY ARE RECOMPRESSED INTO MAIN GAS STREAM.
3. FOUR NOZZLES ON GASIFIER VESSEL TWO PARALLEL BRANCH LOOPS FROM EACH NOZZLE.
4. PRESSURE CONTROLLER TO RESET FLOW CONTROLLERS FOR EIGHT PARALLEL PATHS.
5. FOUR PARALLEL TRAINS TO HANDLE GAS FROM TOTAL PLANTS (BOTH TRAINS).
6. ONE LOOP SHOWN, FOUR LOOPS TOTAL.
7. ALL EQUIPMENT WITHIN THIS AREA TO BE IN PRESTRESSED CONCRETE PRESSURE VESSEL.

Figure 3-3

0	INITIAL ISSUE	RR

PROCESS FLOW DIAGRAM
GASIFIER
PRESTRESSED CONCRETE CONCEPT

THE RALPH M. PARSONS COMPANY
PASADENA, CALIFORNIA

JOB NO	DWG NO	REV
5435-6	R-1-FS-1	0

3-13 (C)

(D)

SECTION 4

ECONOMICS

The estimated capital requirements and operating costs are presented in this section. All economics are based on fourth quarter 1977 dollars. Estimates are provided for four types of PCPVs and four types of steel vessels in equivalent process service. The projected economics for PCPVs and steel vessels are then compared.

4.1 FIXED CAPITAL INVESTMENT

4.1.1 SCOPE

Preliminary fixed capital investments were developed for the following vessels:

- Dissolver-Separator: A PCPV containing a large dissolver vessel and separator in a single cavity plus an alternative case of nine steel dissolver vessels and nine separators as described in Section 3.2.1.
- Absorber: A single large PCPV and an alternate case of six steel absorbers as described in Section 3.2.2.
- Gasifier: Two PCPVs and an alternate case of two steel field fabricated vessels as described in Section 3.3.3.
- Integrated Gasifier: Two PCPVs in which ancillaries are embedded in the concrete structure and an alternate case of two steel field fabricated vessels as described in Section 3.3.3.

4.1.2 SUMMARY

Table 4-1 presents a summary of the system characteristics and the estimated fixed capital investments (FCI). It also summarizes the percent reduction in FCI potential when using PCPVs as an alternate to steel vessels.

The greatest potential savings was for the dissolver-separator case in which one dual cavity PCPV essentially replaced eighteen separate steel vessels. For orientation, this single PCPV would serve a coal conversion complex with a production capacity of the order of 300,000 barrels of oil equivalent based on the reference 2 conceptual design results.

The potential reduction in the dissolver-separator fixed capital investment system is approximately $300 million, amounting to about 70 percent reduction.

The potential savings in the case of the absorers is about $6 million, this time a significant 60 percent reduction in FCI. For the gasification comparisons, the potential FCI reduction was indicated to be about 10 percent; the integrated gasifier, the more complex vessel, showed no economic advantage over the gasifier reactor system.

4.1.3 PROCEDURES

This is a preliminary type estimate whose accuracy is considered to be -10, +25 percent. The estimate includes the cost of equipment, field direct and field indirect costs, sales tax, engineering fee, and home office services.

4.1.4 BASIS FOR ESTIMATES

The basis for the estimate for each system is discussed in the following paragraphs.

4.1.4.1 Dissolver-Separator Vessels

The process limits for this case were from the suction side of dissolver feed pumps 12-1501 and compressors 12-1801 and 12-1802 to the discharge of partially cooled vapor from exchanger 12-1303 and liquid from exchanger 12-1310 as described in Figure 3-2.

Three trains of steel dissolvers and separators with each train consisting of three 12 foot-6 inch diameter dissolvers and three 9 foot-0 inch separators were compared with one train of a 33 foot-4 inch diameter PCPV dissolver and a 27-foot diameter separator. This one PCPV train has a capacity of about 92 percent of that of the three trains of steel vessels.

The estimate for the PCPV dissolver-separator case was based upon new ancillary equipment specifications for a single-train plant. Equipment costs were obtained by a combination of in-house and vendor pricing. The dissolver-separator shell is constructed of 1/2-inch SA-387-C12 steel with an internal cladding of SB-409-800H material.

The major equipment list, including design operating conditons, equipment size/capacity and materials of construction are listed in Table 4-2 for the PCPV and Table 4-3 for the steel vessels.

4.1.4.2 Absorber

One 25 foot-4 inch diameter PCPV absorber column was compared with six 9 foot-6 inch diameter steel vessels. The total inlet gas capacity of the units is the same in each case as described in Figure 3-2. The steel absorber vessels are amine contractors -1101 of Unit 17, dissolver acid gas removal, of the Oil/Gas report.[1] Two of these absorbers per train were required in that study. Only the absorber vessels were included in the study.

The reference 2 steel contactor price was escalated to fourth quarter 1977 and multiplied by six. The foundation costs for the six vessels was added to the vessel cost to give the estimated total FCI.

4.1.4.3 Gasifier Vessels

The gasification process flow scheme for the gasifiers is shown in Figure 3-3. The scope covers from the point of feeding a coal-water slurry to the gasifier to the discharge of solids-free gas for further downstream processing. The same process limits were used in all comparisons of PCPVs versus steel vessels.

In the case of steel vessels, the FCI estimate was based upon the results reported for field-fabricated heavy-wall coal gasifier reactor vessels.[2] The equipment list for this case is shown in Table 4-4. The estimate was escalated to December 1977 dollars.

For the PCPV gasifier reactor case, the estimate differs from the steel case as follows:

(1) A 1/2-inch SA-204 shell is substituted for the original thick wall reactor vessel. An integrated shell cooling system was added.

(2) Cooling water surge drum, pumps, and air cooler were added to provide a shell cooling coil system.

(3) The original concrete foundation for the thick-wall vessel was replaced by the concrete containment structure including all appurtenances, i.e., crane, elevator, davits. Concrete foundations were added for the cooling system equipment.

(4) The original steel structural steel account for the steel vessel design was adjusted because some of the original structure and all of the siding are replaced by the concrete containment structure. The same is true for painting and insulation.

(5) All other direct and indirect accounts remain unchanged except those that area product of direct labor, and these were changed to reflect the adjustments in items (1) through (4).

(6) The estimate is for a two-train plant.

An equipment list for the PCPV gasifier reactor is presented in Table 4-5.

The PCPV integrated gasifier case is a modification of the steel case as described below.

(1) A 1/2-inch SA-302 shell is substituted for the original thick-wall reactor vessel. An integrated shell cooling system was added.

(2) The heavy-wall vessels, flash dryer, char cyclone, and coal cyclone were replaced by 1/2-inch SA-204 shells. An integrated shell cooling coil system was added to the above shells.

(3) Cooling water surge drum, pumps, and cooler were added to the scope to provide an auxiliary vessels cooling system.

(4) The original concrete foundation for the thick-wall vessel was replaced by the concrete containment structure including all appurtenances, i.e., crane, elevator, davits. Concrete foundations were added for the cooling system equipment.

(5) The original gasifier steel supporting structure was deleted; it is replaced by the concrete containment structure.

(6) All other direct and indirect accounts remain unchanged except those that are a product of direct labor, and these were changed to reflect the adjustments in items (1) through (5).

The integrated gasifier equipment list is shown in Table 4-6.

4.1.5 BASIS FOR COST CATEGORIES

The estimating procedures used for each cost category are detailed below:

A. Major Equipment Costs

The PCPV costs were based upon material takeoffs and construction labor requirements. The costs of the principal metal components - steel liner, cooling tubes, tendons and duct work - were obtained by vendor pricing. The costs of concrete and reinforcing steel (rebars) were based upon historical in-house experience combined with vendor pricing.

The costs of other major equipment such as pumps, compressors and heat exchangers were based on vendor pricing, combined with historical in-house experience.

B. Constructed Cost

The constructed cost for major equipment items, other than the PCPV's, was estimated by applying a historically derived experience factor to their purchased equipment cost. This factor includes the field direct and indirect costs.

1. Field Direct Materials, Labor and Other Direct Costs

Field direct costs include:

(1) Concrete, structural steel, piping, instrumentation, and electrical.

(2) Labor for construction of the various units.

(3) Other direct costs such as miscellaneous freight, instrument checkout and run-in services, soils investigation, nonproductive time, and taxes that cannot be allocated to specific unit areas but are considered direct costs.

The labor costs reflect fourth quarter 1977 average hourly rates for the site area and expected labor productivity for that area. The estimate is based on the work being performed during a standard work week defined as five 8-hour days, Monday through Friday. No provisions for premium costs for scheduled overtime work is included. However, an allowance for limited nonscheduled overtime has been included.

2. Field Indirect Costs

Field indirect costs include:

(1) Temporary construction facilities and costs related to the job and its working conditions, including craft subsistence, housing and transportation.

(2) Field administration and field office expense.

(3) Construction equipment, small tools, and consumables.

(4) Payroll taxes, insurance, union welfare, fringe benefits, permits, and bonds.

C. Home Office Costs

Engineering-construction home office costs include management and administration, process and project engineering, construction support, design, drafting, accounting, estimating, scheduling, cost engineering, procurement, expediting, inspection, stenographic, clerical, engineering construction fee, overhead, and direct expenses such as printing, reproduction, computer charges, communications, and travel.

D. Spare Parts

Costs for spare parts are included in working capital.

E. Sales Tax

3 percent sales tax and/or use tax is included for materials and equipment.

F. Escalation

Escalation for the period after the fourth quarter 1977 is not included.

G. Contingency

No contingency is included.

H. Exclusions from Fixed Capital Investment Estimate

The following cost items are excluded from the estimate:

(1) Owner's expenses connected with project.

(2) All taxes, except sales and payroll taxes.

(3) Client's local, state, and federal permits.

(4) Premium time costs, except nonscheduled overtime premium.

(5) Piling and unusual foundation conditions.

(6) Process licensing fees.

4.1.6 TOTAL CAPITAL REQUIREMENTS

In addition to the fixed capital investment, certain capital requirements were included. These are start-up costs, construction financing and provision for working capital.

4.1.7 FIXED CAPITAL INVESTMENT COMPARISON

4.1.7.1 Dissolver-Separator

The estimated FCIs for the PCPV and steel dissolver separator systems are presented in Table 4-7. The results indicate a potential saving of $300 million when eighteen steel vessels are replaced by one PCPV. Approximately $180 million of this savings is in the equipment subtotal and the remainder is in piping and ancillary savings.

4.1.7.2 Absorber

A comparison of the FCIs for the PCPV and steel units is presented in Table 4-8. The bulk of the 60 percent reduction in FCI results from significantly lower cost of the metal vessels accounts for the PCPV.

4.1.7.3 Gasifiers

FCI comparisons for the steel and two PCPV gasifier configurations are shown in Table 4-9. The estimated FCIs for the two PCPV types are similar, and projected to be about 10 percent less than the steel vessel case. The results indicate that the major equipment subtotal for the PCPV tends to be lower than for steel, with the material subtotal equal or greater. The field indirects are about the same for each case.

4.1.8 PRODUCT COST COMPARISON

4.1.8.1 Procedures

The product cost directly related to operation of the separate units was compared. The comparison did not include such items as raw materials nor catalyst and chemicals costs which are presumed to be equal for the PCPV and steel vessel cases.

The comparisons included estimates for working capital and the capital investment burden account. The working capital was based upon 30 days coal inventory, no product inventory, 4 percent of FCI for spare parts inventory, 30 days accounts receivable, 30 days budget for current expenses and 30 days credit for accounts payable.

The capital investment burden account includes a 12 percent after tax return on investments. Federal and state income taxes are based on a combined rate of 52 percent after a depreciation allowance using the double declining balance method and a 10 percent investment tax credit assuming 90 percent of the fixed capital investment is eligible.

Start-up costs were estimated at 7 percent of the FCI.

The profits were based on a 12 percent discounted cash flow rate of return on investment and a 20-year plant operating life at an operating rate of 330 stream days per year.

The operating labor cost was based on a wage rate of $7.50 per hour with a payroll burden of 35 percent. Property taxes and insurance was costed at 2.75 percent of FCI and G&A overhead at 1.5 percent of manufacturing cost. The plant overhead was estimated to be 60 percent of operating and maintenance loan. Maintenance is calculated at 4 percent of the fixed capital investment with 40 percent applied to labor and 60 percent applied to materials.

The cost of utilities was:

Electrical power = \$0.04/Kw-hr
Steam = \$3.50/M lb
Cooling water = \$0.60/M gal.
Process water = \$0.30/M gal.
Fuel gas = \$3.00/MM Btu

4.1.8.2 Results

The results of the comparison, expressed as Equivalent Uniform Annual Cost Savings when using PCPVs, is presented in Table 4-10. Also shown are unit savings expressed as savings per unit coal feed to the dissolver-separator, unit gas feed to the absorber, and unit product energy content (Btu) for the gasifiers.

The results indicate significant potential savings for the use of a single large PCPV dissolver-separator as an alternative to eighteen steel vessels; this savings is indicated to be approximately \$5.06 per ton of coal feed, amounting to about \$90 million per year for a plant feeding 55,000 TPD of coal to the dissolver. For the absorber, the annual savings is projected to be about \$2.2 million on an investment of approximately \$4 million for the PCPV vis-a-vis \$10 million for six steel vessels. When comparing the gasifiers, where a single PCPV would be an alternative to a single steel gasifier, the annual savings potential is predicted to be \$10 million on an investment of the order of \$225-250 million.

The results indicate that for those cases where large PCPVs can be used in coal conversion plants, they offer the promise of significant savings and deserve consideration for future commercial.

Table 4-1 - Fixed Capital Investment Comparison

Vessel	Type of Construction	Number of Trains	Capacity per Train	Number of Major Vessels per Train	Total Number Of Major Vessels	FCI ($ Million)	Percent Reduction in FCI Compared to Steel Vessel
Dissolver-Separator	Steel	3	20,000 TPD of Coal	6	18	430	0
	PCPV	1	55,000 TPD of Coal	1	1	130	70
Absorber	Steel	3	23 million scf/hr	2	6	10	0
	PCPV	1	69 million scf/hr	1	1	4	60
Gasification	Steel	2	55,000 TPD of Coal	1	2	255	0
	PCPV-Gasifier Reactor only	2	55,000 TPD of Coal	1	2	225	12
	PCPV-Integrated Gasifier	2	55,000 TPD of Coal	1	2	230	10

Table 4-2 - Equipment List, PCPV Dissolver-Separator

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Vessels					
12-2501	1	Dissolver	850°F operating temperature 2,025 psig operating pressure	33'-4" dia x 122'-0" TT	See drawing D-01-VS-10, 11,12
12-1204	1	HP separator (with dissolver)	850° operating temperature 2,025 psig operating pressure	27'-0" dia x 36'-0"	See drawing D-01-VS-10, 11,12
12-1205	1	Circulating water surge drum	200°F design temperature 5 psig design pressure	9'-0" dia x 18'	CS
Heat Exchangers and Fired Heaters					
12-1303	20	HP separator vapor feed gas exchanger	1,008 x 10^6 Btu/hr duty	Type DEU 52" x 192" 4,564 ft^2 each	A-387GR221 308 clad shell; 321 SS tubes
12-1310	18	HP separator slurry feed exchanger	1,797 x 10^6 Btu/hr duty	Type DEU 9,392 ft^2 each	A-387GR22 308 SS clad shell 321 SS tubes

One train only required.

Table 4-2 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
12-1311	1 bay	Circulating water air cooler	23.72 x 10^6 Btu/hr duty; cools 1,900 gpm of water from 175°F to 150°F	18' x 40'	CS
12-1410	1	Dissolver-Preheater fired heater	15.22 x 10^6 Btu/hr duty; heats slurry/gas mixture from 650°F to 700°F	Cabin type	321 SS tubes
<u>Pumps</u>					
12-1501	5	Dissolver feed pump	10,000 gpm each max; 2,225 psi ΔP; liquid specific gravity 1.241 @ 60°F; liquid slurry 450°F; 25% coal and 75% liquids	10 x 22 3-stage turbine drive, 15,300 hp	CS stellite
12-1502	2	Water circulation pumps	1,900 gpm each water; 200' TDH; 5 psig suction; 150°F inlet temperature	8 x 10 x 17 130 hp	CS
<u>Compressors</u>					
12-1801	2	Makeup hydrogen compressor	705 x 10^6 scfd each; 2,235 psig discharge; 910 psig suction at 100°F; gas 5,456 mol. wt; turbine drive	Multi-stage centrifugal 50,000 hp	SA-4340
12-1802	2	Recycle hydrogen	415 x 10^6 scfd each; 2,235 psig discharge; 1,035 psig suction at 95°F; gas 3.014 mol. wt; turbine drive	Multi-stage centrifugal	SA-4340

One train only required.

Table 4-3 - Equipment List, Steel Dissolver-Separator

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Vessels					
-2501	3	Dissolver	2,025 psig operating 850°F operating	12'-6" dia x 122'-0" TT	A-387GR22 308L overlay
-1204	3	HP primary separator	2,025 psig operating 850°F operating	9'-0" dia x 36'-0" TT	SA-387GR22 308 SS overlay
Heat Exchangers and Fired Heaters					
12-1303	1	HP separator vapor feed gas exchanger	335×10^6 Btu/hr duty; 1 shell 53"/16" Shell: 2,015 psig, 831°F Tubes: 2,235 psig, 739°F	45,200 ft^2	A-387GR22 308L clad shell 321 SS tubes
12-1310	3	HP separator slurry feed exchanger	200×10^6 Btu/hr duty; 2 shells 60"/60' Shell: 2,025 psig, 850°F Tubes: 2,235 psig, 637°F	32,400 ft^2	A-387GR22 308L clad shell 321 SS tubes
12-1401	3	Dissolver-preheater	169×10^6 Btu/hr duty; 2,225 psig, 700°F	12' x 45' x 55' Cabin type	321 SS tubes
Pumps					
12-1501	3	Dissolver feed pump	4,010 gpm; 3,000' TDH; 7,600 hp; 451°F operating temperature		CB Stellite

Three trains of the above equipment are required.

Table 4-3 - (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Compressors					
12-1801	2	Makeup hydrogen compressor	225×10^6 scfd each; 2,235 psig discharge, 910 psig suction at 100°F; gas mol. wt = 5.456; turbine drive	Reciprocating 14,000 hp each	SA-4340
12-1802	1	Recycle hydrogen compressor	296×10^6 scfd; 2,235 psig discharge, 1,035 psig suction at 95°F; gas mol. wt = 3.014; turbine drive	Reciprocating 13,600 hp	SA-4340

Three trains of the above equipment are required.

Table 4-4 - Equipment List, Conventional Steel Gasifier

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Vessels					
1202	1	Steam drum	1,200 psig at 650°F	120' dia x 30'-0" TT	SA-516
1202	8	Flash dryer	1,200 psig at 500°F shell 1,200 psig at 2,000°F refractory	52" ID refractory x 100'-0" TT, 9" refractory	SA-516 shell refractory
1203	1	Gasifier	1,200 psig at 500°F shell 1,200 psig	24'-11" ID shell x 125' TT	SA-387 grade 22 class 2 with 308L weld overlay
1204	2	Separator	To remove 90+% of coal solids from gas stream at 600°F and 1,070 psig; outlet gas 450°F Gas 7.79 x 10^6 lb/hr at 19.75 mol. wt; solids 147,000 lb/hr	24'-0" dia x 56'-0" TT	SS clad
Exchangers					
1301	8	Slurry feed heater	To heat 1.34 x 10^6 lb/hr of coal slurry from 60°F to 500°F with 1,050 psig steam quench = 400 x 10^6 Btu/hr Shell Tubes Design pressure 1,175 1,140 Design temperature 567 600	57-720 CEN with 9,159 ft^2 tube surface each	CS shell CS tubes

Equipment shown is for one train; two trains are required.

Table 4-4 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
1302	8	Recycle cooler	To cool 960,000 lb/hr of water containing less than 1% solids from 180°F to 110°F; inlet pressure 1,200 psig (max); 6 each = 67.2 x 10^6 Btu/hr	60-288-CET with 9,859 ft^2 tube surface each	CS shell CS tubes
1303	32	Scrubber cooler	Remove 1.94 x 10^9 Btu/hr of heat Inlet water 450°F; outlet water 120°F; total process flow 6.23 x 10^6 lb/hr	41-720 FTS 10,120 ft^2/shell	CS shell CS tubes
Pumps					
1501	9	Slurry circulation	2,900 gpm at 154' TDH with 48% coal solids at 70% -200 mesh; 60°F inlet; atmospheric pressure	10 x 14 x 20 DSJH 1,150 rpm 170 hp	Erosion-resistant wear parts
1502	9	Slurry feed	2,400 gpm at 2464' TDH with 48% coal solids at 70% -200 mesh; 60°F and 50 psig inlet	8-stage DVMX 1,750 rpm 2,400 hp	Erosion-resistant wear parts
1503	2	Cooling water	4,300 gpm at 150' TDH; inlet temperature 556°F; inlet pressure 1,200 psig (max)	220 hp	CS
1504	5	Ash slurry circulation	5,000 gpm at 183' TDH; inlet pressure 1,200 psig (max); inlet temperature 180°F; water contains 6 wt% slag solids at 95% -20 mesh	12 x 16 x 22 DSJH 1,150 rpm 350 hp	Erosion-resistant wear parts

Equipment shown is for one train; two trains are required.

Table 4-4 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
1505	2[a]	Scrubber circulation	14,600 gpm of water at 450°F with 9% fine coal solids TDH 134' Inlet pressure 1,070 psig norm 1,200 psig max	Integral motor Canned pump 600 hp	SS
<u>Special Equipment</u>					
2211	8	Coal cyclone	Separate coal solids at 70% -200 mesh from 600°F gas stream; inlet pressure 1,080 psig (norm) 1,200 psig (max); solids 648,000 lb/hr; gas 1.95 x 10^6 lb/hr; mol.wt = 19.8; solids removal 94-1/2%	97" dia refractory lined; ΔP = 6 psi	CS refractory lined
2212	8	Char cyclone	Separate char solids at 60% mesh from 1,700°F gas stream; inlet pressure 1,084 psig (norm) 1,200 psig (max); solids 572,500 lb/hr; gas 1.225 x 10^6 lb/hr; mol. wt = 20.9; solids removal 94%	84" dia refractory lined, ΔP = 4 psi	CS refractory lined

[a] Provide one spare pump to handle both trains.
Equipment shown is for one train; two trains are required.

Table 4-4 (Contd)

Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
2213	4	Slag cyclone	Separate ash slag solids from water stream; inlet pressure 1,200 psig (max); inlet temperature 180°F; slag size 80% -20 mesh; slag specific gravity 2.3; solids removal 95%; solids 150,000 lb/hr; water 2,230,000 lb/hr; desired solids concentration 30%	Model D-50-1200, 50' dia x 136" long, ΔP = 8 psi	Abrasion-resistant lining
2214	2	Venturi scrubber	Water condensed 1,458,000 lb/hr	4'-9" dia x 24'-0" high	SS clad
2215	8	Coal injectors	To inject 611,250 lb/hr of 70% -200 mesh coal into gasifier; motive force 1,200 psig, 950°F steam; desire 10 psi ΔP across injector; discharge pressure 1,085; coal temperature 600°F	14" type 420	Stellite/ tungsten carbide with CS
2216	8	Char injectors	To inject 538,750 lb/hr of 60% -200 mesh char into gasifier; motive force 1,200 psig, 950°F steam; desire 10 psi ΔP across injector; discharge pressure 1,085 psig; char temperature 1,700°F	20" type 420	Stellite/ tungsten carbide with CS

Equipment shown is for one train; two trains are required.

Table 4-5 - Equipment List, PCPV Gasifier

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Vessels					
1201	1	Steam drum	1,200 psig at 650°F	120" dia x 30'-0" TT	SA-516
1202	8	Flash dryer	1,200 psig at 500°F shell; 1,200 psig at 2,000°F refractory	52" ID refractory x 100'-0" TT; 9" refractory	SA-516 shell refractory
1203	1	Gasifier (concrete)	1,200 psig at 500°F shell; 1,200 psig	24'-7" ID shell x 125" TT	See drawings D-01-VS-30 and 31
1204	2	Separator	To remove 90+% of coal solids from gas stream at 600°F and 1,070 psig; outlet gas 450°F Gas 7.79 x 10^6 lb/hr at 19.75 mol. wt; Solids 147,000 lb/hr	24'-0" dia x 56'-0" TT	SS Clad
1205	1	Cooling water surge drum	5 psig design 200°F design	9' dia x 18' TT	CS

Equipment shown is for one train; two trains are required.

Table 4-5 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Exchangers					
1301	8	Slurry feed heater	To heat 1.34 x 10^6 lb/hr of coal slurry from 60°F to 500°F with 1,050 psig steam quench = 400 x 10^6 Btu/hr Design pressures and temperatures: Shell: 1,175 psig, 567°F Tubes: 1,140 psig, 600°F	57-720 CEN with 9,159 ft^2 tube surface each	CS shell CS tubes
1302	8	Recycle cooler	To cool 960,000 lb/hr of water containing less than 1% solids from 180°F to 110°F; inlet pressure 1,200 psig (max); 6 each = 67.2 x 10^6 Btu/hr	60-288-CET with 9,859 ft^2 tube surface each	CS shell CS tubes
1303	32	Scrubber cooler	Remove 1.94 x 10^9 Btu/hr of heat; inlet water 450°F; outlet water 120°F: total process flow 6.23 x 10^6 lb/hr	41-720 FTS 10,120 ft^2/shell	CS shell SS tubes

Equipment shown is for one train; two trains are required.

Table 4-5 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
1304	1 bay	Gasifier cooling water air cooler	Air cooler to remove 20 x 10^6 Btu/hr of heat from circulating water	15' x 20'	CS
<u>Pumps</u>					
1501	9	Slurry circulation	2,900 gpm at 154' TDH with 48% coal solids at 70% -200 mesh; 60°F inlet; atmospheric pressure	10 x 14 x 20 DSJH, 1,150 rpm 170 hp	Erosion-resistant wear parts
1502	9	Slurry feed	2,400 gpm at 2,464' TDH with 48% coal solids at 70% -200 mesh; 60°F and 50 psig inlet	8-stage DVMX 1,750 rpm 2,400 hp	Erosion-resistant wear parts
1503	2	Cooling water circulation	4,300 gpm at 150' TDH; inlet temperature 556°F; inlet pressure 1,200 psig (max)	220 hp	CS
1504	5	Ash slurry circulation	5,000 gpm at 183' TDH; inlet pressure 1,200 psig (max); inlet temperature 180°F; water contains 6 wt% slag solids at 95% -20 mesh	12 x 16 x 22 DSJH, 1,150 rpm 350 hp	Erosion-resistant wear parts

Equipment shown is for one train; two trains are required.

Table 4-5 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
1505	2[a]	Scrubber circulation	14,600 gpm of water at 450°F with 9% fine coal solids; TDH 134' Inlet pressure: 1,070 psig norm 1,200 psig max	Integral motor Canned pump 600 hp	SS
1506	2	Gasifier cooling	725 gpm at 250' TDH @ 150°F each; 5 psig suction pressure	3 x 4, 13 LTC 65 hp	CS
<u>Special Equipment</u>					
2211	8	Coal cyclone	Separate coal solids at 70% -200 mesh from 600°F gas stream; inlet pressure 1,080 psig (norm) 1,200 psig (max); solids 648,000 lb/hr; gas 1.95 x 10^6 lb/hr; mol. wt = 19.8 solids removal 94-1/2%	97" dia refractory lined $\Delta P = 6$ psi	CS refractory lined
2212	8	Char cyclone	Separate char solids at 60% mesh from 1,700°F gas stream; inlet pressure 1,084 psig (norm) 1,200 psig (max); solids	84" dia refractory lined $\Delta P = 4$ psi	CS refractory lined

[a] Provide one spare pump to handle both trains.

Equipment shown is for one train; two trains are required.

Table 4-5 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
2212 (Contd)			572,000 lb/hr; gas = 1.225×10^6 lb/hr; mol. wt = 20.9; solids removal 94%		
2213	4	Slag cyclone	Separate ash slag solids from water stream; inlet pressure 1,200 psig (max); inlet temperature 180°F; slag size 80% -20 mesh; slag specific gravity 2.3; solids removal 95%; solids 150,000 lb/hr; water 2,230,000 lb/hr; desired solids 30% concentration	Model D-50-1200 cyclones 50" dia; ΔP = 8 psi	Abrasion-resistant lining
2214	2	Venturi scrubber	Water condensed 1,458,000 lb/hr	4'-9" dia x 24'-0" high	SS clad
2215	8	Coal injectors	To inject 611,250 lb/hr of 70% -200 mesh coal into gasifier; motive force 1,200 psig 950°F steam; desire 10 psi ΔP across injector;	14" type 420	Stellite/tungsten carbide with CS

Equipment shown is for one train; two trains are required.

Table 4-5 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
2215 (Contd)			discharge pressure 1,085 psig; coal temperature 600°F		
2216	8	Char injectors	To inject 538,750 lb/hr of 60% -200 mesh char into gasifier; motive force is 1,200 psig, 950°F steam; desire 10 psi ΔP across injector; discharge pressure 1,085 psig; char temperature 1,700°F	20" type 420	Stellite/tungsten carbide with CS
2217	1	Crane	Located on top of gasifier vessel for servicing	30-ton capacity	CS

Equipment shown is for one train; two trains are required.

Table 4-6 - Equipment List, PCPV Integrated Gasifier

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
Vessels					
1201	1	Steam drum	1,200 psig at 650°F	120" dia x 30'-0" TT	SA-516
1202	8	Flash dryer	1,200 psig at 500°F shell, 1,200 psig at 2,000°F refractory	See drawings D-01-VS-1 and 2	See drawings D-01-VS-1 and 4
1203	1	Gasifier	1,200 psig at 500°F shell, 1,200 psig	24'-7" ID shell x 120' TT	See drawings D-01-VS-1, 4, and 5
1204	2	Separator	To remove 90+% of coal solids from gas stream at 600°F and 1,070 psig; outlet gas 450°F; gas 7.79 x 10^6 lb/hr at 19.75 mol. wt; solids 147,000 lb/hr	24'-0" dia x 56'-0" TT	SS clad
1205	1	Cooling water surge drum	5 psig design; 200°F design	22' dia x 44' high	CS
Exchangers					
1301	8	Slurry feed heater	To heat 1.34 x 10^6 lb/hr of coal slurry from 60°F to 500°F with 1,050-psig steam quench = 400 x 10^6 Btu/hr	57-720 CEN, with 9,159 ft^2 tube surface each	CS shell CS tubes

Equipment shown is for one train; two trains are required.

Table 4-6 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
			Shell Tubes Design pressure, psig 1,175 1,140 Design temperature, of 567 600		
1302	8	Recycle cooler	To cool 960,000 lb/hr of water containing less than 1% solids from 180°F to 110°F; inlet pressure 1,200 psig (max); 6 each = 67.2 x 10^6 Btu/hr	60-288-CET with 9,859 ft^2 tube surface each	CS shell CS tubes
1303	32	Scrubber cooler	Remove 1.94 x 10^9 Btu/hr of heat; inlet water 450°F; outlet water 120°F; total process flow = 6.23 x 10^6 lb/hr	41-720 FTS 10,120 ft^2/shell	CS shell
1304	6 bays	Gasifier cooling water air cooler	Air cooler to remove 166 x 10^6 Btu/hr of heat from circulating water	Forced-draft, each bay 10' x 40'	CS
Pumps					
1501	9	Slurry circulation	2,900 gpm at 154' TDH with 48% coal solids at 70% -200 mesh; 60°F inlet; atmospheric pressure	10 x 14 x 20 DSJH, 1,150 rpm, 170 hp	Erosion-resistant wear parts
1502	9	Slurry feed	2,400 gpm at 2,464' TDH with 48% coal solids at 70% -200 mesh; 60°F and 50-psig inlet	8-stage DVMX, 1,750 rpm, 2,400 hp	Erosion-resistant wear parts
1503	2	Cooling water Circulation	4,300 gpm at 150' TDH; inlet temperature 556°F; inlet pressure 1,200 psig (max)	220 hp	CS

Equipment shown is for one train; two trains are required.

Table 4-6 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
1504	5	Ash slurry	5,000 gpm at 183' TDH; inlet pressure 1,200 psig max; inlet temperature 180°F; water contains 6 wt% slag solids at 95% -20 mesh	12 x 16 x 22 DSJH, 1,150 rpm, 350 hp	Erosion-resistant wear parts
1505	2[a]	Scrubber circulation	14,600 gpm of water at 450°F with 9% fine coal solids; 134' TDH; inlet pressure 1,070 psig normal; 1,200 psig max	Integral motor canned pump 600 hp	SS
1506	2	Gasifier cooling water pumps	13,500 gpm at 250' TDH @ 150°F each; 15 psig suction pressure	18 x 20 x 30, 1,000 hp	CS
<u>Special Equipment</u>					
2211	8	Coal cyclone	Separate coal solids at 70% -200 mesh from 600°F gas stream; inlet pressure 1,080 psig (norm) 1,200 psig (max); solids 648,000 lb/hr; gas 1.95 x 10^6 lb/hr; mol. wt = 19.8; solids removal: 94-1/2%	See gasifier drawings D-01-VS-1 through 5	See drawings and take-offs
2212	8	Char cyclone	Separate char solids at 60% mesh from 1,700°F gas stream; inlet pressure 1,084 psig (norm) 1,200 psig (max); solids 572,500 lb/hr; gas 1.225 x 10^6 lb/hr; mol. wt = 20.9; solids removal: 94%	See gasifier drawings D-01-VS-1 through 5	See drawings and take-offs

[a] Provide one spare pump to handle both trains.

Equipment shown is for one train; two trains are required.

Table 4-6 (Contd)

Item Number	Number Required Per Train	Description	Design Conditions	Size and Type	Materials
2213	4	Slag cyclone	Separate ash slag solids from water stream; inlet pressure 1,200 psig (max), inlet temperature 180°F; slag size 80% -20 mesh; slag specific gravity 2.3; solids removal 95%; solids 150,000 lb/hr; water 2,230,000 lb/hr; desired solids 30% concentration	Model D-50-1200 cyclones, 50" dia x 136" long ΔP = 8 psi	Abrasion-resistant lining
2214	2	Venturi scrubber	Water condensed: 1,458,000 lb/hr	4'-9" dia x 24'-0" high	SS clad
2215	8	Coal injectors	To inject 611,250 lb/hr of 70% -200 mesh coal into gasifier; motive force 1,200 psig, 950°F steam; desire 10 psi ΔP across injector; discharge pressure 1,085 psig; coal temperature 600°F	14" type 420 (see gasifier drawings D-01-VS-1 through 5)	Stellite/ tungsten carbide with CS
2216	8	Char injectors	To inject 538,750 lb/hr of 60% -200 mesh char into gasifier; motive force is 1,200 psig, 950°F steam; desire 10 psi ΔP across injector; discharge pressure 1,085 psig; char temperature 1,700°F	20" type 420 (see gasifier drawings D-01-VS-1 through 5)	Stellite/ tungsten carbide with CS
2217	1	Crane	Located on top of gasifier vessel for servicing	30-ton capacity	CS

Equipment shown is for one train; two trains are required.

Table 4-7 - Dissolver-Separator Fixed Capital Investment Comparison
($ Million)

Costs	PCPV Dissolver-Separator	Steel Dissolver-Separator
Equipment		
Steel Vessels	7	155
Heat Exchangers and Heaters	27	55
Pumps	5	11
Compressors	13	15
Equipment Subtotal	52	236
Piping and Other Installed Costs	62	192
Concrete Containment Structure	14	-
Total Fixed Capital Investment	128	428
Say	130	430

Table 4-8 - Absorber Fixed Capital Investment Comparison
($ Million)

Costs	PCPV Absorber	Steel Absorber
Vessels	1.3	9.8
Concrete	2.6	0.1
Total Fixed Capital Investment	3.9	9.9
Say	4	10

Table 4-9 - Gasifiers Fixed Capital Investment Comparison
($ Million)

Costs	PCPV Integrated Gasifier	PCPV Gasifier Only	Steel Gasifier
Major Equipment			
Steel Vessels	4	12	12
Heat Exchangers	26	26	25
Pumps	18	17	17
Separation Equipment	47	53	55
Reactors	9	9	37
Major Equipment Subtotal	104	117	146
Material			
Concrete	24	7	1
Piping	63	59	69
Structural Steel		3	7
Other Bulk Materials	9	10	1
Material Subtotal	96	79	78
Field Indirects and Other	29	28	29
Total Fixed Capital Investment	229	224	253
Say	230	225	255

Table 4-10 - Savings Using PCPVs as an Alternative to Steel Vessels

Item	Dissolver-Separator		Absorber		Gasifier Only		Integrated Gasifier	
	Uniform Annual Cost ($ Million)	Feed Coal ($/MMBtu)	Uniform Annual Cost ($ Million)	Feed Gas ($/MMscf)	Uniform Annual Cost ($ Million)	Product Gas ($/MMBtu)	Uniform Annual Cost ($ Million)	Product Gas ($/MMBtu)
<u>Operating Costs</u>								
Operating Labor and Materials	-0.512	-	0.062	-	-	-	-	-
Maintenance	10.732	-	0.240	-	1.158	-	0.977	-
Utilities	-1.227	-	-	-	-0.025	-	-0.142	-
Plant Overhead	2.326	-	0.088	-	0.278	-	0.234	-
Property Tax and Insurance	7.381	-	0.165	-	0.796	-	0.671	-
G and A	0.293	-	0.008	-	0.033	-	0.027	-
Savings Subtotal	18.993	0.043	0.563	0.001	2.240	0.003	1.767	0.003
<u>Capital Burden Costs</u>								
Capital Investment	46.080	-	1.029	-	4.970	-	4.193	-
Working Capital	1.484	-	0.035	-	0.165	-	0.136	-
Income Taxes	26.062	-	0.585	-	2.815	-	2.374	-
Savings Subtotal	73.626	0.166	1.649	0.003	7.950	0.010	6.703	0.009
Total Savings	92.619	0.209	2.212	0.004	10.190	0.013	8.470	0.011

SECTION 5

PCPV CHARACTERISTICS AND HISTORY

This section briefly describes the basic characteristics of Prestressed Concrete Presure Vessels (PCPVs) and their history.

5.1 CHARACTERISTICS

A prestressed concrete pressure vessel (PCPV) is a structure wherein concrete, reinforcing steel, and high strength steel tendons are used to form the pressure containment shell. Well over 90 percent of the mass is concrete.

Prestressing means the intentional creation of permanent stresses in a concrete structure, for the purpose of improving its structural behavior under various load conditions. The prestressing forces can be applied by means of stressing the tendons. Figure 2-2 shows the gneral arrangement of the tendons in a PCPV. Similar to reinforced concrete, prestressed concrete involves combined action between the concrete and the prestressing steel tendons, and interaction between the internal prestressing force and the externally imposed loads. For PCPV's, the prestressing forces are applied by post-tensioned tendons places the concrete in compression and enables it to resist the high operating pressures.

There are several additional elements required for a PCPV to perform successfully as a process presure vessel. One of these is a metal membrane internal liner, which serves to prevent escape of process gases and liquids into the concrete structure. The metal membrane liner also serves as a form during concrete placement.

Another important element is a cooling system plus insulating concrete which is necessary to control the structural concrete temperature whenever the metal liner temperature exceeds 200°F. Also, internal refractory is used when necessary to shield the metal membrane liner against very high temperature.

5.2 HISTORY

The general methods of PCPV design are well established. The American Society of Mechanical Engineers (ASME) Pressure Vessel Code, Section III, Division 2, covers the requirements for PCPV nuclear containment vessels and nuclear reactors in the United States. Intensive work is underway in many countries to further the use of PCRVs for nuclear work. Sixteen prestressed concrete reactor vessels (PCRVs) are in operation. Five more have been constructed and are being prepared for operation.

The general characteristics of some of these PCPVs are given in Table 5-1.[3] In addition to the full scale PCRVs, over 50 major subscale models of PCRVs have been built and tested to determine and establish their characteristics.

Among the PCRV designs presently under way in the United States are the GCR design for a multi-cavity 900 megawatt (electrical) PCRV, a gas-cooled fast reactor (GCFR), a multi-cavity nuclear reactor for process heat, and a high temperature gas-cooled reactor (HTGR) for direct cycle gas turbines.

Experimental and design work is underway in Germany and Austria for PCPVs using a 300°C (572°F) hot liner design. Design and model testing is underway in Great Britain for PCRVs for liquid metal fast breeder reactors.

In addition to the PCRVs, over 60 prestressed concrete pressure vessels are either in operation or being constructed as containment vessels for nuclear reactors. PCPVs have also been used for storage of liquefied natural gas (LNG), coal silos, and for other liquids. Prestressed concrete is very widely used in bridge and building construction throughout the world.

Table 5-1.- Constructed Prestressed Concrete Reactor Vessels

Plant	Location	Vessel Type	No. of PCRV's	Internal Dimensions		Design Pressure (psi)	Temperature[a] (°F)	Operational	Prestress Method	Power Output [MW(e) net]
				Dia (ft)	Length (ft)					
G2 - G3	France	Horizontal Cylinder	2	46	52	220	120	Yes	Wire Tendons - Linear	30
EDF-3	France	Horizontal Cylinder	1	62	66	440	770	Yes	Strand Tendons - Linear	480
St. Laurent	France	Vertical Cylinder	2	62	119	440	440-460	Yes	Strand Tendons - Linear	480
Bugey	France	Vertical Cylinder	1	56	126	676	440	Yes	Wire Tendons - Linear	550
Oldbury	Great Britain	Vertical Cylinder	2	77	60	385	475	Yes	Strand Tendons - Helical	300
Wylfa	Great Britain	Sphere	2	96	96	423	480	Yes	Strand Tendons - Linear	590
Dungeness B	Great Britain	Vertical Cylinder	2	65.5	58	478	555-1250	Yes	Wire Tendons - Linear	600
Hinkley Point B	Great Britain	Vertical Cylinder	2	62	63.5	615	550	Yes	Strand Tendons - Helical	625
Hunterston B	Great Britain	Vertical Cylinder	2	62	63.5	615	550	No	Strand Tendons - Helical	625
Hartlepool	Great Britain	Multi-cavity Cylinder	2	43[b]	60[b]	644	600-1200	No	Wire Tendons - Linear and Wound	625
Vandellos	Spain	Vertical Cylinder	1	62	119	440	440-460	Yes	Strand Tendons - Linear	480
Schmeirn-hausen	Germany	Vertical Cylinder	1	NA	NA	NA	NA	No	NA	NA
Fort St. Vrain	United States	Vertical Cylinder	1	31	75	845	750	Yes	Wire Tendons - Linear	330

Notes: [a] Temperature given is maximum for internal insulation.
[b] Dimensions are for major reactor cavity.

SECTION 6

PCPV DESIGN

6.1 VESSEL FUNCTIONAL REQUIREMENTS

6.1.1 GENERAL

The specific functional requirements for the PCPV's were defined by outline drawings for each of four cases consisting of a dissolver-separator, an absorber, a gasifier-reactor and an integrated gasifier. These requirements are described in the following subsections.

In addition to these specific functional requirements for each vessel, operational and construction considerations were defined. These considerations included:

- Site location - This is described in Section 3.4.
- Construction - The PCPV's are to be designed such that they may be built using existing technology and equipment. The field construction time is to be minimized. Interference between construction labor crafts shall be kept to a minimum to increase laborproductivity.
- Accessibility is to be provided to the vessel internals for inspection and repair of vessel and components.

6.1.2 DISSOLVER - SEPARATOR

The dissolver-separator vessel outline and materials requirements is shown on Figure 6-1. This vessel operates at 2025 psig pressure and 850°F with a design condition of 2225 psig and 857°F.

The vessel membrane liner is constructed of 1/2-inch thick ASTM A387 grade 22 class 2 (2-1/4 Cr - 1 Mo) steel clad with 0.109-inch of ASTM SB-402-8001A (Incalloy) alloy. The liner will be exposed to the process environment. The corrosion constituents of most concern are hydrogen sulfide (H_2S) and hydrogen (H_2). The 2-1/4 Cr - 1 Mo steel and alloy 800 will resist attack by H_2. The clad alloy provides protection against H_2S. A 1/16-inch corrosion allowance was provided for the 2-1/4 Cr - 1 Mo material as it should experience negligible corrosion.

Access to the vessel interior is provided by two manways at the top and a removable spool-piece at the bottom inlet nozzle. Instrument connections are provided throughout the length of the vessel.

Longitudinal plate fins of ASTM A387 grade 22 class 2 are welded to the exterior vertical straight surfaces of the membrane wall. These fins serve four functions. They:

- Provide an anchorage between the metal membrane wall and the structural concrete.
- Provide a heat transfer path between the metal liner and the water cooling tubes.
- Serve as forms for casting of insulating concrete during construction.
- Act as stiffeners during the erection of the vessel.

As the vessel is operating with a metal liner wall temperature of 850°F and with an upper limit of 200°F placed on the structural concrete, an external water cooling system is provided. This system consists of circulating cooling water through one inch diameter cooling tubes located between the plate fins in the straight vertical sections and at each stud for the other areas. The high purity cooling water is recirculated through a closed loop cooling system consisting of air coolers, surge tank and recirculating pumps. The cooling system cooldown rates are given in APPENDIX B.

The plate fins and cooling tube details are shown in Figure 6-2.

For the curved and irregular surfaces of the vessels and piping, the system described in the Oak Ridge report[3] is used. This system consists of using concrete anchorage studs and attaching the cooling water tubes to these anchors.

6.1.3 ABSORBER

The absorber vessel outline is shown on Figure 6-3. This vessel operates at 1075 psig pressure and 150°F with design conditions of 1183 psig and 175°F.

The vessel shell, flanges and nozzles are constructed of 1/2-inch thick SA-516-70 carbon steel as negligible corrosion is expected. The internal trays are constructed of ASTM A240 type 304 stainless steel with a 1/8-inch corrosion allowance.

Manways are provided at the top of the vessel, the lower part of the absorber section and in the separating section. Necessary instrument connections are provided throughout the vessel.

Plate fins and studs are provided in the exterior face of the metal membrane liner. These serve to anchor the metal membrane to the structural concrete, carry the internal load to the concrete, and as a structural aid during vessel erection.

No external cooling system is provided as the vessel operates below the 200° maximum allowable structural concrete temperature.

6.1.4 GASIFIER

The gasifier vessel outline and materials requirements is shown in Figure 6-4. This vessel operates at about 1085 psig in the gasification sections and about 1090 psig in the lower slag quench section. The operating temperature in the lower stage (stage 1) is about 3000°F. The operating temperatures in the upper stage (stage 2) range from about 2500°F at the lower part to 1700°F at the upper exit. The metal liner operating temperature is 475°F. The design conditions for the vessel shell are 500°F and 1200 psig.

The vessel wall is constructed of 1/2-inch thick ASTM A204 grade C alloy steel. This material was selected because code stress relieving is not required for this thickness. A 204 grade C contains 1/2% molybdenum which provides some protection should the internal refractory fail and the metal membrane become exposed to high temperature and high pressure hydrogen. The 1/2% molybdenum containing ASTM A335 grade P1 and ASTM A336 class F1 nozzles and flanges were selected for the same reason. A 1/16-inch corrosion allowance was selected because it is believed these components will experience negligible corrosion. The vessel has an internal refractory lining to protect the metal from the very high operating temperatures. The original working lining of the lower stage consists of about 3 inches of 90% alumina phosphate bonded plastic and is backed up with internal water cooling coils. The plastic will react with the molten ash slag and gradually will be replaced by the slag. The frozen plastic/slag layer is the only refractory in this stage.

The working lining in the upper stage is a 94% alumina high density castable where thickness tapers from 5 inches at the lower section to 4 inches at the top. An insulating castable of low iron content and 75 pounds per cubic foot density is installed behind the working lining. Its thickness tapers from 4 inches at the lower end to 2 inches at the top. The function of the insulating castable is to lower the temperature to 475°F at the metal membrane wall. The castable is supported by stainless steel anchors in 12-inch square pitch centers. The refractory and internal cooling coil details are shown in Figure 6-5.

Two cooling systems are provided for the gasifier-reactor. The first system is for the cooling of the internal refractory in the lower stage of the gasifier. This system operates at gasifier pressure and generates some low pressure steam. The second cooling system (external cooling system) is for the protection of the structural concrete from the 475°F temperature of the metal membrane wall. Its function and design is similar to that of the dissolver-separator (Section 6.1.2) and is described there.

6.1.5 INTEGRATED GASIFIER

The integrated gasifier outline is shown in elevation in Figure 6-6 and in plan in Figure 6-7. Embedded in the concrete structure is the gasifier and certain ancillary equipment consisting of eight parallel sets of char cyclones, coal cyclones, flash dryers, coal injectors, char injectors and associated connective piping.

The gasifier design is identical to that of the gasifier (Section 6.1.4) and is described there. The ancillary equipment operating conditions are shown in Figure 3-3 of Section 3.3.3. The metallic components of the ancillary equipment are constructed of 1/2-inch ASTM A204 grade C alloy steel which contains 1/2% molybdenum. The operating conditions for the ancillary equipment is above 200°F, therefore a single component high density castable 94% alumina refractory is installed internally with stud type refractory anchors and cooling coils located externally. Inlet steam, internal refractory cooling system, and process feed piping is insulated externally. The refractory and cooling system schematic are shown in Figures 6-8 and 6-9.

6.2 PCPV DESIGN

6.2.1 GENERAL

This section describes the basic design of the structural containment portions of the PCPVs. The specific designs are described in the following subsections.

The designs follow the general concepts described in Section 5 "History and Characteristics". The designs developed here use embedded horizontal circumferential and vertical steel tendons bonded within steel ducts.

The tendons utilized in the design consist of 55 strands of 1/2-inch diameter cable, with each strand rated at 270 ksi conforming to ASTM A-416. The tendons are enclosed in 6-inch diameter thin wall tubing.

The spacing of horizontal tendons is at 24 inch vertical centers. The number of tendons are reduced in lower stress areas, such as the top and base of the PCPV. Each tendon forms a complete 360° loop around the vessel. The tendons are anchored to opposite sides of buttresses located on the external face of the PCPV and then placed under tensile stress. A typical view is shown in Figure 6-10.

The vertical tendons have the same strength characteristics as the horizontal tendons. They form a loop from the top of the vessel, around the base, to a corresponding opposite top location. The vertical tendons also supply the strength support for the top closure penetrations. The number and location of the vertical tendons is dependent upon the specific vessel design.

A typical general closure plug design is shown in Figure 6-11. A typical closure plug support details are given in Figure 6-12. This design is similar to that described in the Oak Ridge report.[4]

Typical details for the nozzle penetrations are given in Figure 6-13. These designs carry the externally imposed load back into the concrete structure.

The dissolver-separator, gasifier, and the integrated gasifier require external cooling to limit the structural concrete to a maximum temperature of 200 F. The water cooling system and anchorage system was discussed in Section 6.1.2 dissolver-separator. Typical liner and concrete details for the cooling system are given in Figure 6-12. The insulating concrete at the liner membrane is Portland cement based with a lightweight aggregate with a 28 day compressive strength of 5000 psi.

The recommended structural concrete used is type II Portland cement based concrete. Brief specifications for the insulating and structural concrete are given in Appendix D.

An elevator, stairs, and working davits are provided for each PCPV. Also provided are necessary airplane warning lights and normal lighting.

6.2.2 DISSOLVER-SEPARATOR

The overall vertical cross-section and external elevation of the PCPV is shown in Figure 6-14. The lower section and foundation plan are shown in Figure 6-15. The consolidated plan view is shown in Figure 6-16.

The overall height of the PCPV is 276 feet and its diameter is 67 feet. A 20-ton gantry crane is provided to remove the top closures from the vessel.

A total of 128 vertical tendon loops are installed. The attachment point for eight loops is at the two closures (four for each closure). The remaining 120 loops are attached at the top head. Almost 1100 horizontal tendons are used. These tendons range from four at two foot centers at the top and bottom sections to eight in the major portion of the PCPV. The horizontal tendons are attached at eight buttresses.

The steel skirt shown in Figure 6-14 is provided for erection of the steel membrane vessel liner.

Reinforcing steel is provided as necessary through the structure for stress distribution.

6.2.3 ABSORBER

A vertical cross section and elevation of the PCPV is shown in Figure 6-17. The consolidated plan is shown in Figure 6-18.

The PCPV has 28 vertical tendon loops and over 200 horizontal tendons. Most of the horizontal tendons are arranged at three tendons at each 2-foot vertical distance. The horizontal tendons are attached at three buttresses at the outer periphery of the vessel. A 10-ton gantry crane is provided for removal of the top closure.

6.2.4 GASIFIER

A vertical cross section and elevation of the PCPV is shown in Figure 6-19. The closure plug design and consolidated plan is shown in Figure 6-20. This vessel requires 32 vertical loops and over 300 horizontal tendons, the majority of which are arranged in 4 tendons per horizontal row. The horizontal tendons are anchored at four buttresses.

A 30 ton gantry crane is provided for removal of the top closure plug.

6.2 INTEGRATED GASIFIER

A cross section and elevation view of this PCPV is shown in Figure 6-21 and in top plan in Figure 6-22. This PCPV is 97 feet in diameter by 214 feet tall.

The complexity of the structure is indicated by the plan cross-sections shown in Figure 6-23. The central gasifier vessel requires 32 vertical tendon loops. The coal cyclone requires 4 loops, and the char cyclone and flash dryer each require 2 loops.

The closure plug and access to the gasifier is shown in Figure 6-24. Closure plugs are provided for each coal cyclone, char cyclone and flash dryer. The necessary closure support is provided by the vertical tendons around each of these vessels.

It requires about 660 horizontal tendons, the majority of which are arranged in double rows of four every two feet. Eight buttresses are used for anchoring the tendons.

A 30-ton gantry crane is provided for removal of the top closures of the various vessels.

6.3 PCPV STRUCTURAL DESIGN METHODS

A number of methods were used in the design of the PCPV structural components. The first method used to establish the feasibility of the design was Lame solution for thick walled cylinders.[5] An example of this analysis is shown in Figure 6-25. The results of this analysis indicated the structural feasibility of the PCPV since the stresses within the vessel could be controlled mainly by varying the wall thickness and amount of prestressing.

In stress analysis, T. Y. Lin's proprietary computer program OPSSAP was used. The program is a modification of the computer program SAPIV.[6] It is capable of analyzing two and three dimensional finite element systems for static and thermal loads. Program OPSSAP utilizes a large capacity active column type of equation solver which offers a wide latitude in node numbering sequence as well as improvement in solution efficiency. This particular feature is essential for the crack analysis. Its element library includes beam, truss, boundary, two and three-dimensional finite elements, with orthotropic and isotropic material properties. The two-dimensional finite element can be either with or without incompatible modes, for plane stress, plane strain and axisymmetric analyses. The three-dimensional finite element can be either an 8-node incompatible mode brick element, or an improved 8-to-21-node higher order curved isoparametric solid element. An example of the results of the analysis is shown in Figure 6-26.

For thermal analysis, the computer program DOT 7 was used. The program DOT applies the finite element technique to the linear and nonlinear analysis of steady state and transient heat transfer within two-dimensional planar or axi-symmetric structures. It includes time-dependent material properties, boundary conditions, and internal heat generation. Figure 6-27 illustrates the results of the analysis.

To facilitate the computer analysis, pre-processors for the coordinate and finite element mesh generation, and post-processors for the graphic display of results were prepared and employed.

6.4 PCPV DESIGN ANALYSIS

6.4.1 DESIGN CONSIDERATIONS

A number of factors were considered in the design of the PCPV's. These included shrinkage, creep, heat of hydration, bonding of the tendons, refractory failure and cooling water failure. Other factors such as seismic wind, foundation, and vessel system were also investigated.

The effects of some of the main factors are briefly discussed below:

- Shrinkage caused by prolonged drying of the hardened concrete can be a serious problem in a structure involving massive quantities of concrete. To reduce this effect, and the heat of hydration as discussed later, concrete will be cast in small lifts, although this will have the disadvantage of greater amount of plastic shrinkage at the surface of the wet concrete, and the increase of the number of cold joints where differential shrinkage can take place. The method of concrete placement took this factor into account.

- Creep - Due to the confined nature of the concrete, creep may have a beneficial effect on the PCPV because creep permits the redistribution of the internal stresses to take place. This is particularly important in areas subjected to high local stresses, and where elastic movement is restrained, e.g., at the junction between the foundation mat and the vessel wall. Creep movement in the vertical direction will induce an axial force on the internal cells and vertical pipes. This force is, however, relatively insignificant and may be coped with (a) by anchoring system of the steel cell lining and of the pipes, and (b) by vertical steel reinforcement.

- The heat of hydration during the setting of concrete is a major problem in large-scale construction in concrete. During the construction of a massive concrete structure, due to the heat of hydration the concrete temperature will rise rapidly above the temperature at pouring, and will remain at the higher level for a long time. For the purpose of this study, the internal temperature of the concrete vessel at the unstressed stage is taken as the temperature due to the heat of hydration at some ten days after the concrete is poured. A transient heat transfer analysis was carried out to obtain the temperature distribution for subsequent stress analysis. The selected concrete has a low heat of hydration and a one week period is allowed between concrete pours.

- Bonding of Prestressing Tendons - For safety reasons, unbonded tendons have been almost exclusively used in nuclear power containment vessels in the USA and elsewhere, to enable cable tension to be monitored and corrected if necessary. However, unlike a nuclear vessel, a coal conversion PCPV does not have the problem of radioactivity, and the escape of gas and vapors into the atmosphere will not have the catastrophic consequences a nuclear vessel has. Bonded tendons were selected in this design as they have the advantages of: better crack control, better protection against weather, better heat resistance and virtually no maintenance.

- Prestressing - For ease of construction and economy, circumferential prestressing tendons will form a 360° loop around the vessel, with both ends anchored on the same buttress. The disadvantage of a complete loop is the disproportionately large prestress loss in the cables. However, this disadvantage could be outweighed by a number of advantages in favor of the 360° loop, as evidenced by its use in a number of new PC vessels.

  The circumferential prestressing of a PCPV may be affected by either embedded sheathed cables or by surface-wound wires or strands. Each has its pros and cons, with the former having the advantage of better protection against corrosion, and the latter the advantage of economy of cost and construction time. In this design embedded cables are used.

- Plug Design and Layout - The design and the layout of the plugs take into consideration the many requirements that include strength, heat dissipation, minimum interference with tendon layout, and ease of installation and removal. The design was made generally along the lines of the design as proposed in the Oak Ridge Report[3]:

- Penetration-Outlet Design Consideration - There are two major considerations in the penetration-outlet design. The first one is the re-spacing of the horizontal prestressing tendons; the second is the anchorage support around the penetrating pipes.

Since the concrete wall of a PCPV is much thicker than the ordinary nuclear containment vessel the skipping of horizontal tendons does not create serious stress problems. Therefore, in the present PCPV study, the penetrations are designed in such a way that they are located as close as possible within a narrow band at a given elevation. Horizontal tendons are omitted within that band. Adequate mild steel reinforcements are then added at that region to distribute localized stress. The design of anchorage support around the penetrations is a complex problem. The pipes carry externally imposed loads in addition to the internal temperature and pressure. To simplify the design, it has been assumed that the same pipe sections outside of the vessel wall, extend into the concrete wall for a distance of 4 ft minimum. Gusset plates or studs are welded to the pipes, with steel reinforcement interwoven around them, to serve as support anchorage and to prevent spalling. In order to ensure that the stresses in the pipes are not excessive within this critical portion, the pipes are modelled as beams on elastic foundation.

- Steel Liner and Anchorage System - The steel liner and anchorage system for the pipes and vessels to be embedded in the concrete have been designed primarily as (a) heat barrier, and (b) structural form for erection and for the concreting of the PCPV. The strength of the liner has been neglected in the design of the vessel. Nevertheless it has to be designed to take some stress during operation since it is anchored to the concrete.

- Metal Membrane Wall Overheating - A failure of the internal refractory in the cooling system could cause a failure of the metal membrane liner wall. Three refractory failure cases were investigated. In the worst case, it would require an hour to raise the cooling water temperature 5°F and the steel membrane would remain intact. If a complete cooling water failure occurred, heat transfer calculations indicate that the metal wall temperature will rise from 500°F to about 900°F in about one hour. The details of these analyses are given in Appendix C.

6.4.2 DESIGN CRITERIA

A. Code References and Applicabilities

The design of reinforced concrete structures and concrete pressure vessels is generally governed by the following two codes:

a. American Concrete Institute (ACI) Standard 318-71, Building Code Requirements for Reinforced Concrete.

b. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 2, Code for Concrete Reactor Vessels and Containments, 1977.

It was determined early in the study that the existing ASME Section III Code did not meet the needs for coal conversion PCPV's. This was primarily because of differences in safety design requirements and operating conditions.

A new set of design criteria was then developed for these coal conversion PCPV's by T. Y. Lin International.

B. New Design Criteria

The new set of design criteria is based upon serviceability, behavior and safety requirements rather than on allowable stresses governed by elastic conditions.

It is recognized that the new design criteria represent new grounds which could not be fully covered within the time available, nor the scope of study. For this reason, much reliance has to be placed on past practice and experience of the behavior of prestressed concrete, as well as on engineering judgment, to develop a set of design criteria which would be proven correct by subsequent work. The new design criteria is based first on an adequate factor of safety against failure, while insuring at the same time the proper behavior of the vessel under operating conditions, including possible overpressure. They will not be constrained by empirical values of allowable stresses, as these are meant for pressure structures of a different type. Under the action of prestress alone, the membrane stress in the PCPV is set at a much higher value than usually applied for secondary nuclear containment vessels which are usually limited to membrane compressive stress of about 1,500 psi. Coal conversion PCPV are different vessels in that they have much thicker walls, and the concrete in the walls is essentially confined. It is the confined state of the concrete that imparts a much greater compressive strength to the concrete, in this case, from the usual 5,000 psi to the order of 15,000 psi. The confined state will also alleviate problems associated with shrinkage and creep.

As far as can be determined, there seems to be no reason for not increasing the allowable membrane stress in compression to at least 2,500 psi, although this value gives an apparent safety factor of 2 for a 5,000 psi concrete, and less than 2 if stress concentrations and temperature and creep effects are taken into account. This factor of safety will be more than sufficient at ultimate failure because the amount of prestress can never be greater than the amount that is first applied.

- Membrane Stresses - The average stress across the critical section of a vessel, for lack of a better term, is herein defined as the membrane stress. The determination of membrane stress is an important and convenient check on the gross factor of safety.

For simplicity, this stress is computed across a two-dimensional section without considering the three-dimensional nature of the problem. The membrane stress produced by prestressing should be greater than that produced by the internal pressure, with a factor greater than unity. In the case of a nuclear containment vessel, the factor used is on the order of 1.1 or 1.15. This means that under a test pressure of more than 1.15 times the design internal pressure, the membrane pressure will be overcome by the internal pressure statically, and the vessel will crack. This sane factor appears reasonable for coal conversion PCPVs.

- Allowable Local Compressive Stress - This is more complex and difficult to assess, because under confined conditions crushing of concrete is almost impossible to occur, and a localized high compressive stress may mean nothing more than a high local strain. Because concrete is ductile in compression, especially when confined, there seems to be little need for an upper limit for compressive stress. With concrete confined in three dimensions, there is practically no way for concrete to fail even at a compressive stress much higher than its cylinder strength.

- Allowable Local Tensile Stress - Because excessive tensile stresses in a PCPV subjected to high internal pressures and temperatures are practically unavoidable, a more realistic criterion for these special structures is not whether tensile cracks are permitted, but whether such cracks will diminish its structural capability. In a coal conversion PCPV, the tension cracks are mostly confined to the exterior region of the concrete wall. This is because internal pressures and temperatures cause membrane tensile stresses throughout the vessel wall.

- New Stress Criteria for PCPV - For the PCPV under study, the computed tensile stresses due to internal pressures and temperatures can be quite high without causing adverse effect on the structural integrity, stability, and the performance of the vessel. This and other considerations, particularly those relating to the behavior and functional requirements of the vessel, justify the adoption of the following design stresses and load factor for this study design:

Load factor	= 1.10 to 1.15
Allowable confined state membrane compressive stress	= 2,500 psi