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FOSSIL ENERGY

EVALUATION OF PRESTRESSED CAST IRON PRESSURE VESSELS FOR COAL GASIFIER

Final Technical Report

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DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

U. S. DEPARTMENT OF ENERGY

ABSTRACT

This report presents the results and conclusions from an evaluation study concerning the feasibility of using prestressed cast iron vessels (PCIV) as coal gasifier vessels. The study establishes the technical, economic and safety characteristics of coal gasification reactors based on the application of PCIV technology in the conceptual design of such a gasifier vessel. In addition, a comparison is made between the characteristics of prestressed cast iron vessels, prestressed concrete vessels (PCPV) and field fabricated steel vessels (FFSV) for a reference coal gasifier application is defined.

The evaluation indicates that prestressed cast iron vessels are feasible, inherently safe and are clearly competitive with prestressed concrete and welded steel vessels.

The results from an assessment of the various sections of the ASME Code which may be applicable to cast iron pressure vessels are also included. A draft design section for prestressed cast iron vessels patterned after existing sections of the ASME Code is presented as an Appendix to the report.

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REFERENCES

1. ERDA/CB&I Report No. FE-2009-13, "Cost Study, Shop Assembly vs. Field Assembly of Heavy Wall Coal Gasifier Reactor Vessels", December 1976.

2. Westinghouse Astronuclear Laboratory Report No. WANL 2445-1 (COO-2445-1), "Very High Temperature Reactor for Process Heat - A Technical and Economic Assessment", December 1974.

3. Ralph M. Parsons Co. Report No. FE-1775-20, "Prestressed Concrete Pressure Vessels Conceptual Design/Economic Analysis", October 1978.

4. Greenstreet, Oland, Callahan, Canonico, "Feasibility Study of Prestressed Concrete Pressure Vessels for Coal Gasifiers", ORNL-5312, Oak Ridge National Laboratory.

5. Metals Handbook, Volume 1, 8th Edition, 1961, American Society for Metals.

6. The Fundamentals of Iron and Steel Castings, 4th Edition, October 1968, The International Nickel Co., Inc., A. P. Craznebim.

7. 1978 Materials Selector, Volume 86, No. 6, November 1977, Materials Engineering.

8. Gray and Ductile Iron Castings Handbook, Gray and Ductile Iron Founders' Society, Inc., 1971.

9. Cast Iron: Physical and Engineering Properties, Butterworth and Co., 1976.

10. ASME Specification SA 278, Specification for Gray Iron for Pressure-Containing Parts for Temperatures up to 65°F.

11. ASTM Specification A48, Standard Specification for Gray Iron Castings.

12. ASTM Specification A247, Evaluating the Microstructure of Graphite in Iron Castings.

13. ASTM Specification A256, Compression Testing of Cast Iron.

14. ASTM Specification A438, Transverse Testing of Gray Cast Iron.

15. N. Janakiev, Mechanical Strength Parameters of Cast Iron with Lamellar Graphite and their Significance for the Design of Pressure-Carrying Reactor Components, Kerntechnik 19, Jahrgang (1977), No. 2.

16. P. Bastien, P. Azou, C. Winter, Influence De L'Hydrogene Introduit A Froid Dans Les Fontes, Fonderie 117, October 1955.

17. A Study of the Effects of High-Temperature High-Pressure Hydrogen on Low-Alloy Steels, API Publ. 945, June 1975, American Petroleum Institute.

18. W. A. Swansiger, R. G. Mushet, L. J. Weirick, W. Bauer, Deuterium Permeation through 309S Stainless Steel with Thin, Characterized Oxides, J. Nuc. Mats., 53 (1974).

19. Effect of Hydrogen on Behavior of Materials, A. W. Thompson and I. M. Bernstein, Eds., AIME, New York, 1976.

20. Prevention of Failures in Coal Conversion Systems, NBS Special Publication 468, Washington, 1977.

21. F. C. Schora and J. G. Patel, Design Considerations for Low-BTU Coal Gasification, ASM Conference on Materials for Coal Conversion Systems Design, Pittsburgh, 1976.

22. J. B. O'Hara, W. J. Lochmann and N. E. Jentz, Coal Liquification: Materials Systems Design, ibid.

23. Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants, API Publication 941, 1977.

24. A. J. MacNab, Report on Corrosion and Erosion of High BTU Gasifier Components, Metal Progress, Volume 112, No. 6, 1977.

25. C. L. Briant, Hydrogen Assisted Cracking of Sensitized 304 Stainless Steel, Met. Trans. A, Volume 9A, No. 5, 1978.

26. J. F. Lancaster, Materials for Petrochemical Industry, International Metals Review, Volume 23, No. 3, 1978.

27. Materials for Coal Conversion and Utilization (Third Annual Conference, Preliminary Procedings), CONF-781018, USDOE, Gaithersberg, 1978.

28. V. L. Hill and M. A. H. Howes, Metallic Corrosion in Coal Gasification Pilot Plants, Materials Performance, Volume 17, No. 6, 1978.

29. Preliminary Safety Analysis Report, Summit Power Station, Delmarva Power and Light Co., (Wilmington, Delaware).

30. G. D. Whitman, Interim Report on PCRV Thermal Cylinder and Tendon Failures, ORNL-TME-4763, December 1974.

31. D. A. Canonico, Second Interim Report on PCRV Thermal Cylinder Axial Tendon Failures, ORNL-TME-4764, November 1974.

32. V. Nicoloyeff, Tensile Tests of 2500-KIP Prestressing Tendons for the PCRV, GA-A14768 (UC-77), General Atomic Company, May 1978.

33. Taylor and Burrow, "The Basis of Design of Prestressed Concrete Pressure Vessels", Structural Concrete, pp. 225-268 (September, October 1966).

34. Prestressed Concrete Design and Construction Manual, Volume 1, DYK-BBR Prestressed Tanks, Inc., El Cajon, California.

1.0 INTRODUCTION

This report presents the results and conclusions of a design and evaluation study of a prestressed cast iron vessel (PCIV) for a coal gasifier application. The study was conducted for the U.S. Department of Energy, Division of Fossil Energy Programs and Division of Energy Storage Systems.

The primary objectives of the study were:

- To establish the technical, economic, and safety characteristics of coal gasification reactors based on the application of prestressed cast iron vessel technology.
- To evaluate these characteristics in comparison with those of coal gasification reactors based on welded steel and prestressed concrete pressure vessel technology.

The development of processes to convert coal to gaseous fuels that can substitute for the diminishing supply of natural gas is a high priority element in the Nation's quest for long term energy self-sufficiency. The use of such processes requires that attention be paid, at an early date, to the fabricability and practicality of the pressure vessels needed to contain the coal gasification reaction. It also is apparent that there is a high level of commonality between the design considerations for coal gasifier vessels and for high temperature thermal energy storage vessels.

The commercial development of coal gasification systems results in stringent requirements for the large pressure vessels to be used as gasifiers. In a commercial coal gasification system, the reactors might be 175 feet high and 30 feet in diameter and have eight inch thick walls if fabricated from welded steel. These sizes may very well affect the feasibility and cost of the commercial systems.

The maturity of pressure vessel technology follows the natural evolution of industrial development. Steel vessels are most mature, followed by prestressed concrete, and then prestressed cast iron. This evolving process results from industrial needs for vessels of increasing size, increasing severity of requirements, fabrication technology, economics and construction schedules.

Shop fabricated steel vessels are size limited primarily by transportation constraints; therefore, in large sizes significant field assembly and welding must be utilized. Steel vessel walls must also be designed to simultaneously satisfy all the functional requirements of leak tightness, pressure loads, compatibility with the thermal and fluid environment, and safety.

Prestressed concrete pressure vessels have evolved as one solution to the size constraints of steel vessels. Inherent in their design is the separation of functional requirements where a metal liner, with appropriate insulation and cooling, is used to provide leak tightness and to interface with the internal thermal and fluid environment. The concrete provides structural capability in a reduced thermal environment, while the prestressing tendons provide the tensioning force in an ambient environment to keep the concrete in compression. The redundancy of the prestressing tendons provides assurance of pressure capability and easy inspection. Some disadvantages of prestressed concrete vessels are: project schedular effects due to site construction needs, poor thermal-physical properties, complexity of the liner/cooling system needed to assure leak tightness and low concrete temperatures, and the large vessel outside dimensions. The technology status for prestressed concrete pressure vessels is such that they have been reduced to practice, in Europe and the U.S.A., for a number of applications.

A natural evolution to retain the best features of the prestressed concrete vessels while overcoming their disadvantages is to replace the concrete with prefabricated cast iron. In this type of vessel, cast iron "building blocks" are poured under factory quality assurance procedures at the foundry, shop machined, assembled at the construction site by appropriate stacking, and prestressed with tensioning systems similar to those used for prestressed concrete vessels. A PCIV in its basic form is illustrated in Figure 1.0-1.

The prestressed cast iron pressure vessel offers significant potential advantages in terms of technical, economic, and safety characteristics for large pressure

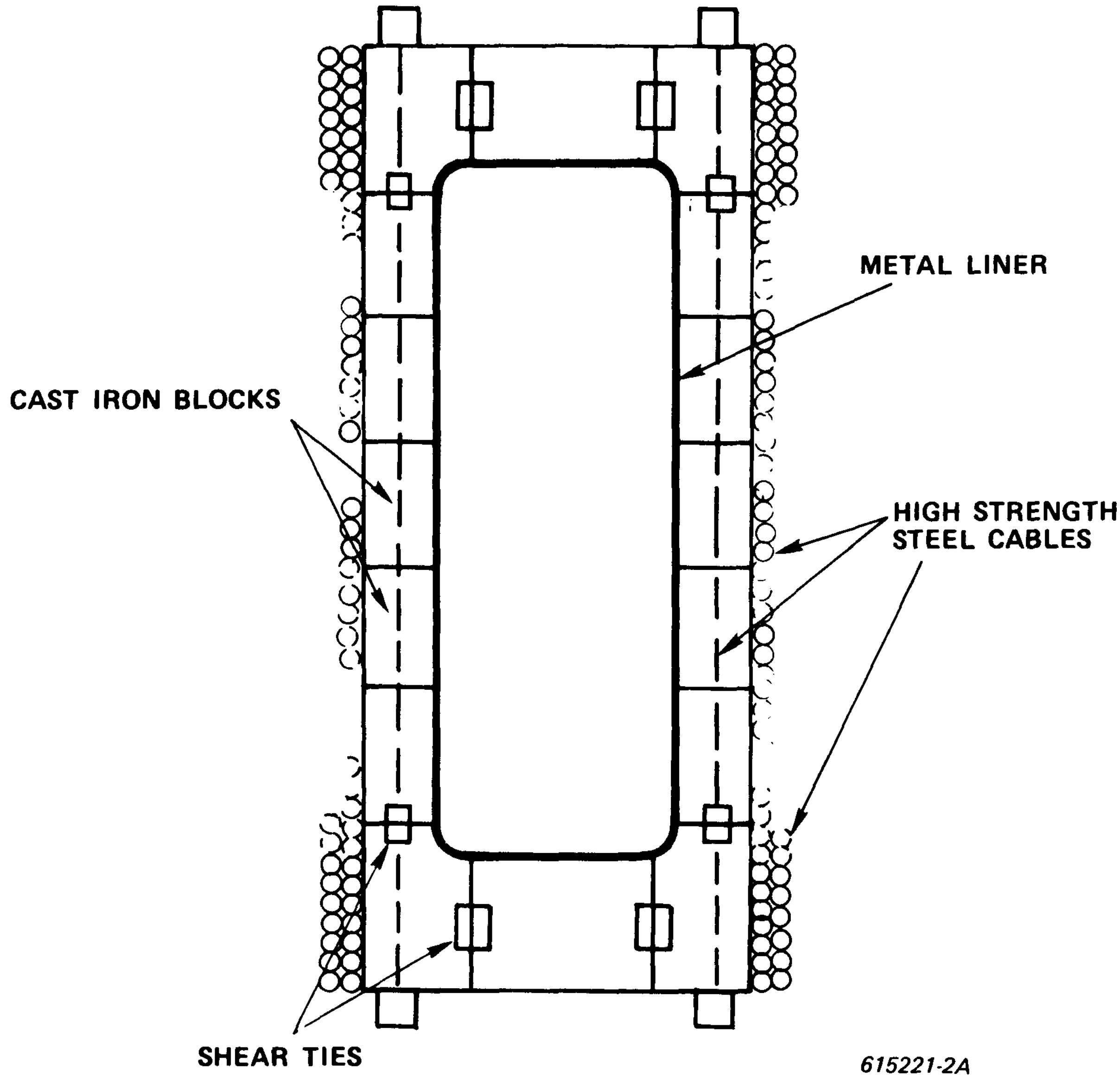

Figure 1.0-1. Basic Features of a PCIV

vessels. The technology has broad application to any industry requiring large pressure vessels, such as the chemical, petroleum, and similar industries, and may be particularly attractive in coal gasification and thermal energy storage applications where the pressure vessel can be a dominant factor in plant cost and feasibility. In addition, the PCIV is not size limited. It can be designed, manufactured, shipped and erected for any site to meet the requirements of the largest coal gasifier deemed economically desirable.

Another desirable feature of the PCIV is that it simultaneously lends itself to both standardization and flexibility. With a limited number of "building blocks", (i.e., circumferential sectors with and without piping penetrations), a multitude of vessel configurations can be constructed. The pouring and machining of the castings thereby becomes a standardized factory operation, analogous to an "assembly line", while the arrangement of the standard blocks for a particular process and plant size affords the flexibility to meet the requirements of individual installations. Since the PCIV is not a monolithic structure, it can also be field modified if it is necessary to change the location of a nozzle, repair damage, or, in the extreme, to disassemble the vessel for relocation or disposal.

With these and other potential advantages defined, the approach followed in this study was to establish representative top level requirements, derive and analyze a gasifier PCIV conceptual design, evaluate the applicability of existing technology, identify the ASME code modification that would be required to cover this type of vessel, and compare the PCIV characteristics to those of welded steel and pre-stressed concrete vessels for coal gasifiers. The PCIV design concept developed by this study is shown in Figure 1.0-2.

The Department of Energy Project Manager for this study was Mr. Thomas J. Nakley, Office of Fossil Energy Programs. The study has been conducted by the Westinghouse Advanced Energy Systems Division with Mr. Robert E. Thompson as Project Manager and Mr. Robert F. Lampe as the Principal Design Engineer.

Important subcontract contributions were provided by the Dravo Corporation Chemical Plant Division, through infusion of their expertise in field operational considerations into the design concept, and in definition and costing of foundation

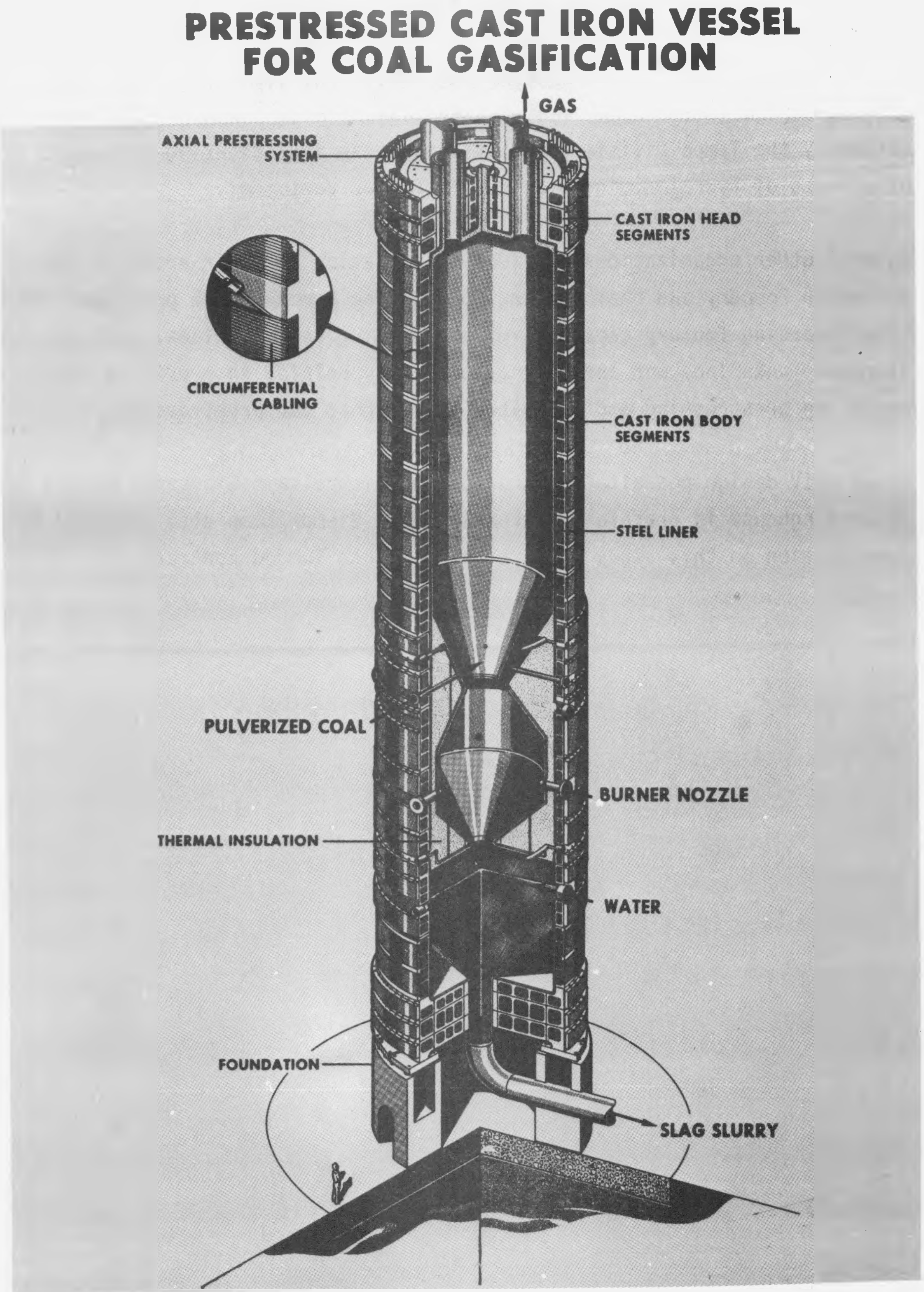

Figure 1.0-2. Coal Gasification PCIV

design and field operations. Other Westinghouse Divisions also participated in the study including ASME code study and pressure vessel design consultation by the Pressurized Water Reactor Systems Division, design and manufacturing consultation by the Tampa Division, and assistance in investigating the possibility of effects of hydrogen migration by R&D Center personnel.

Several other organizations provided consultation in their areas of expertise. Ironworth Foundry and Chambersburg Engineering Company both provided consultation regarding foundry capabilities and casting optimizations. Dyk BBR Prestressed Tanks Inc. and Inryco Inc. were very helpful in providing consultation regarding prestressing and estimates of the cost for prestressing.

Prior PCIV design consultation provided by Siempelkamp Giesserei GmbH & Company to Westinghouse is gratefully acknowledged. Siempelkamp also provided design consultation on this study under a Westinghouse funded contract.

2.0 SUMMARY AND CONCLUSIONS

2.1 SUMMARY

The contracted tasks have been accomplished as planned. The results of the study confirm the practicality of a prestressed cast iron vessel (PCIV) for coal gasifier vessel applications. Economic and other benefits have been determined to be obtainable with a PCIV when compared to field fabricated steel vessels (FFSV) and prestressed concrete pressure vessels (PCPV). It has been concluded that the necessary technology for implementation of a gasifier PCIV exists but that some materials and engineering data are needed to support ASME code approval. A demonstration of a PCIV as a coal gasifier is highly desirable in order to prove the readiness of PCIV technology. An intermediate development step of a scaled down vessel tested under expected operating conditions is recommended.

A Bi-Gas coal gasifier vessel with an internal diameter of 25 feet, tangent-to-tangent length of 125 feet, maximum operating pressure of 1200 psig, and an operating gas temperature of up to 2500°F was established as the reference case for this study. This case was selected so that the PCIV results could be directly compared with a prior study of FFSV for those conditions. A PCIV design concept was defined through an iterative process of concept identification and analysis. The PCIV concept was constrained to the same process and balance of plant interfaces as exist with a FFSV so that the PCIV results could be directly compared with the prior FFSV results. Casting and other material properties were investigated and defined. The ASME code modification necessary to specify criteria for the application were identified and a draft Section VIII, Division 3 prepared. Availability of the necessary technology was investigated and no major shortcomings were identified. Representative manufacturing procedures were defined. The field operations required to assemble and install the vessel were studied and defined in the full detail necessary to support evaluations. Cost estimates were prepared. The study results were assessed and compared with prior studes of FFSV and PCPV. The results were also interpreted in the context of other potential PCIV applications.

2.2 CONCLUSIONS

a. The reference case for which a PCIV has been studied (Bi-Gas coal gasifier vessel) has provided a good basis for evaluation of the characteristics and capabilities of a PCIV. The reference case included more difficult design requirements than would many other potential applications of a PCIV and therefore provided a stringent case for evaluations of feasibility.

b. A representative PCIV design concept has been defined and evaluated for the base case application. The PCIV has been determined to be highly practical and desirable for such an application.

c. Aspects of the design concept for which latitude exists for future design optimization have been identified. It is anticipated that such optimizations would further enhance the desirability of a PCIV for this application.

d. No fundamental problems have been identified that would preclude ASME code certification of a PCIV. The ASME code modifications necessary for PCIV implementation have been identified and a Section VIII, Division 3 draft prepared.

e. Significant capital cost reductions have been shown for the reference case PCIV compared to a field fabricated steel vessel (FFSV).

f. Detailed PCIV gasifier captial cost estimates of this study have indicated lower capital costs for a PCIV gasifier than those that have been estimated by others for a prestressed concrete pressure vessel (PCPV).

g. Realistic estimates of the PCIV capital cost reductions that will be shown by further PCIV optimizations indicate that installed PCIV costs will be at least 10 percent less than PCPV costs.

h. Site construction time required for a PCIV has been determined to be significantly shorter than for a FFSV or PCPV (23 months vs 48 months for a FFSV and 44 months for a PCPV for a two gasifier plant).

i. Overall time require for design, fabrication construction and test of a PCIV gasifier has been estimated to be 43 months, which is approximately the same as that required for either a FFSV or a PCPV.

j. Other design and total plant benefits that result from use of a PCIV have been identified and are discussed in the body of this report.

k. Interpretations of the PCIV design evaluations of this study have confirmed the premise that a PCIV is well suited for many larger vessel applications, particularly those where steel vessels become impractical or extremely expensive.

l. Interpretations of the study results in the context of the needs of other applications, such as for large thermal energy storage vessles, have indicated that a PCIV will be at least equally attractive for those applications.

m. No fundamental technology problems exist for PCIV application. However, there are needs for derivation of materials and engineering data, because of this new application of existing technology, for ASME code criteria and for general design use.

n. Further optimization and characterization of the baseline design concept would be beneficial in order to provide an enhanced documented base of PCIV design knowledge for use by potential appliers of PCIVs.

o. A demonstration scaled down PCIV that can be subjected to the important expected normal and off-design conditions is desirable in order to provide proof to potential users of the adequacy and predicatability of a PCIV. A demonstration vessel will also provide the knowledge for confirmation and for improvement of analysis, manufacturing and erection techniques and procedures.

3.0 PCIV BACKGROUND

In many respects, the maturity of pressure vessel technology and the emergence of new types of vessels follows the natural evolution of industrial development. This evolving process is forced by industry needs for increasing size, increasing severity of requirements, fabrication technology, economics and schedules. Steel vessels are the most mature because such vessels have been able to economically fulfill industry needs. Prestressed concrete vessels can be considered to be the next most mature. The need for vessels which are difficult to construct using steel is a relatively late developing need and this need was initially fulfilled through the use of prestressed concrete. More recently, cast iron has been determined to be a viable material with attractive properties for use in the body of prestressed vessels.

The first research on the feasibility of a prestressed reactor pressure vessel made of individual cast iron blocks was initiated in 1968 by Siempelkamp Giesserei Gmbh & Company in the Federal Republic of Germany. This work was initiated in conjunction with engineering work on the thermal shields for the 300 MW_E Thorium High Temperature Reactor (THTR) which was to be built at Schmehausen. The impetus for consideration of cast iron as a structural material was that its significantly better compressive strength and temperature capability than concrete appeared to offer the potential for improved economics in a large prestressed pressure vessel. The results of these initial investigations showed that a prestressed vessel using machined cast iron blocks instead of concrete was feasible and that capital costs and construction time could be reduced.

A 1:7.5 scale model of the THTR 300 PCIV was designed, analyzed, constructed and then tested in 1972. This model provided strong evidence for establishing the feasibility, practicality and structural safety of a PCIV. The criteria for assessment included the quality of fabrication, tolerances, prestressing system, ease of erection, level of achieved safety factors, and verification of structure analytic models. Overall dimensions of the model (Figure 3.0-1) were a height

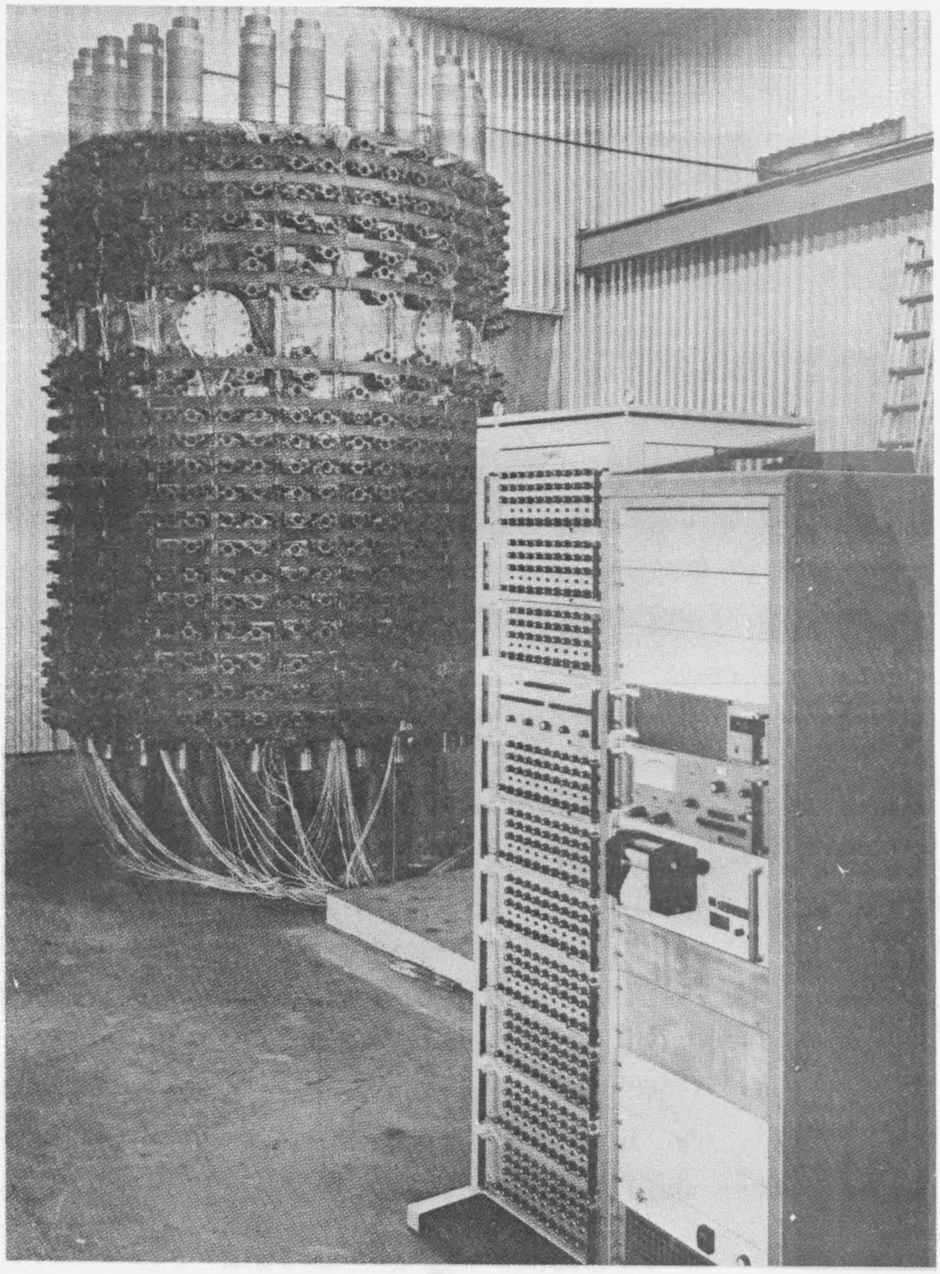

Figure 3.0-1. Fully Instrumented PCIV Model Prior to Testing

of ten feet and a diameter of 7.5 feet. The design pressure was 1130 psi, two times the working pressure of 565 psi. Other design criteria were the prestressing system tendons to be designed for three times the working pressure, a cast iron allowable stress of 1/4 of ultimate in undisturbed regions and 1/3 of ultimate in locally disturbed regions. Ambient temperature hydrostatic tests were conducted with gratifying results. Ten test cycles up to 665 psi (18 percent over the working pressure) were accomplished to demonstrate repeatability. These tests were followed by testing to the design pressure of 1130 psi and finally to 1305 psi (2.3 times the working pressure).

The test results compared very favorably with the structural analysis results. The conclusions drawn by Siempelkamp were:

- "The construction of the model and the test program carried out up to 90 bar proved that the PCIV technology is mature.
- The production of the single cast-iron blocks including their assemblage was easily established. Unforeseen difficulties did not occur.
- The good accordance between numerical analysis and test results obtained from two independent strain measuring devices, i.e., strain gauges and dial gauges, shows the PCIV technology lends itself very neatly to the present-day computing techniques.
- The subdivision of the PCIV into single structural components of materials which are selected according to the functions they have to fulfill, proved successful. The components employed are:
    - The cylindrical wall and the end slabs which are assembled of cast-iron blocks of high compressive strength
    - The prestressing system which consists of single wires of high tensile strength
    - The cooling system
    - The insulation
- This separation of functions is underlying the design of all PCIV conceptual designs."

Westinghouse Advanced Energy Systems Division investigated the attributes of the prestressed cast iron pressure vessel compared to other types of vessels in company funded studies of the nuclear Very High Temperature Reactor (VTHR) as a process heat energy source. These studies indicated clean cut advantages for a PCIV in the VHTR application. In a subsequent AEC funded study to make a technical and economic assessment of gas cooled reactors as a process heat energy source (Reference 2), Westinghouse evaluated and selected the PCIV as a superior alternative to other types of vessels.

Siempelkamp is currently in the process of building a PCIV for use as a helium reservoir for the emergency shutdown system of the THTR 300. This cylindrical vessel has an operating pressure of 3330 psi and a volume of 620 cubic feet. Because of its nuclear system usage, its design and testing is being subjected to all of the licensing and quality assurance requirements associated with primary nuclear systems. In this application the PCIV offers the very important additional benefit of enhanced burst resistance and therefore enhanced confidence of helium reservoir availability when needed.

These past efforts provided a good basis for consideration of PCIVs as a viable alternative for pressure vessels in many applications. The current study continues to enhance and support these considerations for the PCIV.

4.0 REFERENCE CASE AND REQUIREMENTS

Since this report involves the comparison of a PCIV with both welded steel and prestressed concrete vessels, it was necessary to select a given vessel design as a reference for making comparisons. The design chosen was the field fabricated welded steel gasifier vessel, described as Case A in Reference 1. This design is for a gasifier reactor vessel suited for use in a high pressure, two stage entrained coal gasification process that is very similar to the Bi-Gas process under development by Bituminous Coal Research, Inc. in the pilot plant at Homer City, Pennsylvania.

A summary type description of the welded steel reference case is given below, along with design requirements that have been established for designing competitive gasifier vessels. A more detailed description of the reference case is given in Report No. FE-2009-13, mentioned above.

4.1 REFERENCE CASE

The reference welded steel gasifier reactor vessel is a field fabricated vessel about 25 feet in diameter and 150 feet high. Figure 4.1-1 depicts this vessel and delineates many of the internal features that are designed for the Bi-Gas coal gasification process. This is a two-stage entrained solids gasification process. Coal is injected into the upper stage (Stage II) of the gasifier in a dry, finely pulverized state. Here the coal is subjected to hot (2700°F) reducing gases coming from the lower stage (Stage I) of the gasifier. The coal residence time in Stage II is eight seconds which is sufficient to partially convert the coal to gas. The gas leaving the Stage II contains coal particles (char) that have not vaporized and must be separated from the coal gas mixture by external cyclones and recirculated to Stage I. In Stage I the char is reacted with oxygen and steam at about 3000°F to form the reducing gas for Stage II. Coal ash melts in Stage I and falls as molten slag into a water filled quench tank located below Stage I.

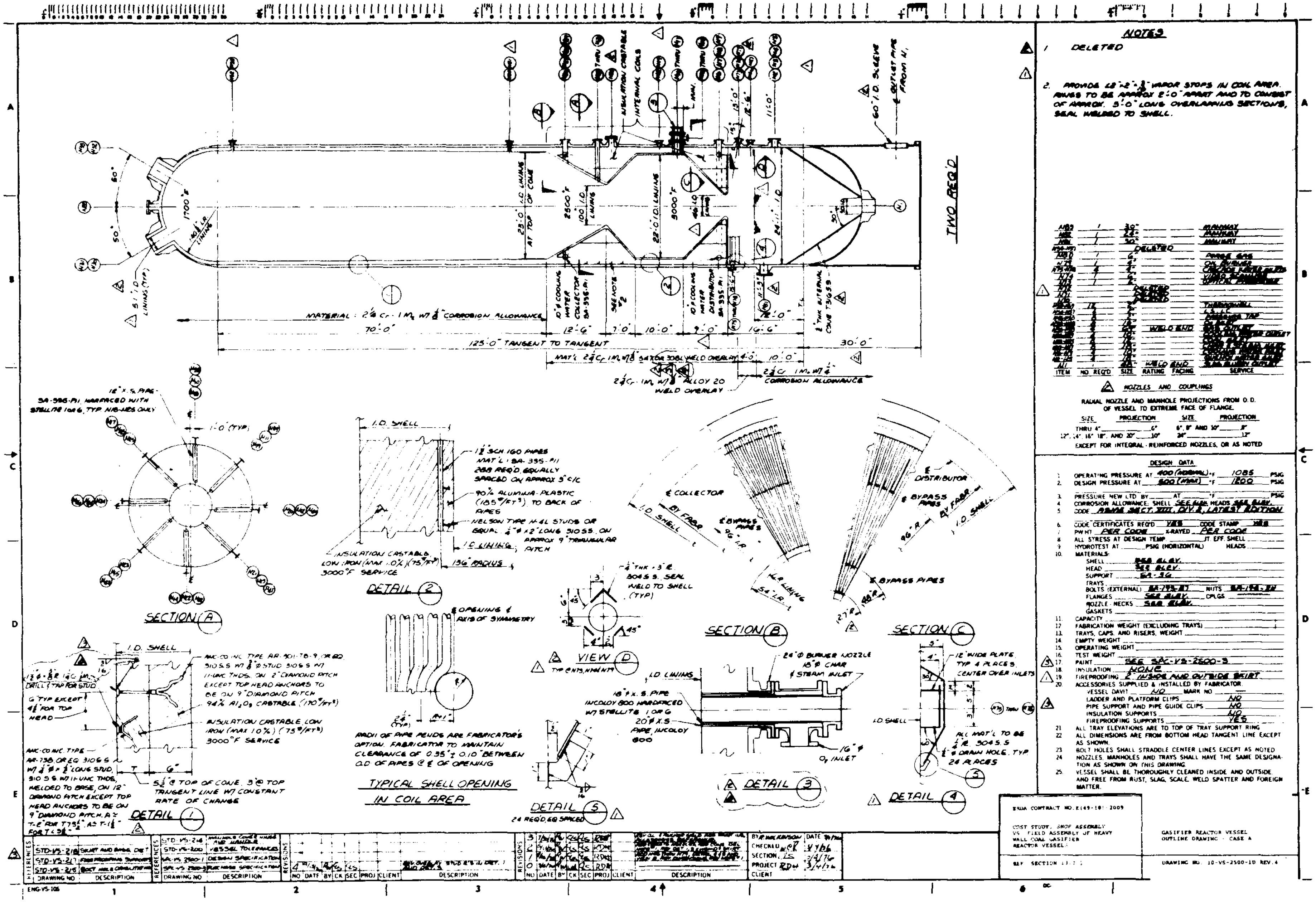

Figure 4.1-1. Field Fabricated Steel Vessel

The "welded steel" reference design is shown in Figure 4.1-1. It is based on a coal gasification process that nominally operates at 1080 psig pressure and 3000°F maximum temperature for the gas inside the gasifier reactor vessel. Structural design of the vessel is based on a design pressure of 1200 psig and a shell temperature of 500°F. Refractory insulation is used internal to the gasifier vessel to maintain the vessel wall operating temperature at 500°F maximum.

4.2 REFERENCE REQUIREMENTS

The design of the gasifier PCIV described in this report was based on the same requirements as those used in designing the field fabricated welded steel gasifier vessel for the Gillette, Wyoming site. These requirements are given in Reference 1 and are specified in Table 4.2-1 for the design and Table 4.2-2 for environmental conditions internal to the gasifier.

Figure 4.2-1 shows the nozzle and manway penetration requirements for the gasifier vessel. Figure 4.2-2 shows the most critical nozzles in the vessel and gives piping loads associated with each. (The source of these piping loads is Reference 1.)

The reference site for the gasifier vessel is near Gillette, Wyoming at an elevation of 4600 feet above sea level. The site is assumed flat and the soil undisturbed, with a load bearing capacity of 4000 pounds per square foot. Freeze protection is required to accommodate -40°F temperatures with a 30 mph wind. The frost line for design purposes is five feet below the surface. Wind conditions at the site are 12 mph (average) with 100 mph (peak) gusts but, of course, do not apply to vessels that are within enclosures. Site temperatures are 90°F (summer dry bulb) 65°F (summer wet bulb) and 15°F (winter dry bulb).

TABLE 4.2-1

DESIGN REQUIREMENTS FOR PCIV COAL GASIFIER VESSEL

Inside Diameter (PV Liner)	24'11"
Inside Height (tangent-to-tangent)	125 ft.
Operating Pressure (max.)	1200 psig
Operating Gas Temperature (max.)	3000°F
Operating Temperature (PV Liner)	≤450°F
Service Life	25 years
Gasification Process	"Bi-Gas"(3)
Coal Feed Rate (per vessel)	55,000 tons/day
Seismic Criteria	(None)
Applicable Design Standard	ASME Code (Modified)(1)
Internal Features	(2)
Component Transportation	Standard Railway
Wind Loads	None (Vessel Enclosed)

(1) Modifications necessary to cover PCIV technology were identified and documented as part of this report in Appendix A.

(2) See Design Case A of Reference 1

(3) Coal Gasification Process under development by Bituminous Coal Research, Inc. with Pilot Plant at Homer City, Pennsylvania.

TABLE 4.2-2

ENVIRONMENTAL CONDITIONS INTERNAL TO GASIFIER

	Composition in Kilomols Per Hour	
	Stage I	Stage II (Exit)
	3000°F	1780°F
	1090 psig	1085 psig
H_2	(Values not Available)	56
CH_4		26
CO		61
CO_2		36
H_2O		44
H_2S		3
NH_3		2
N_2		1
O_2		0

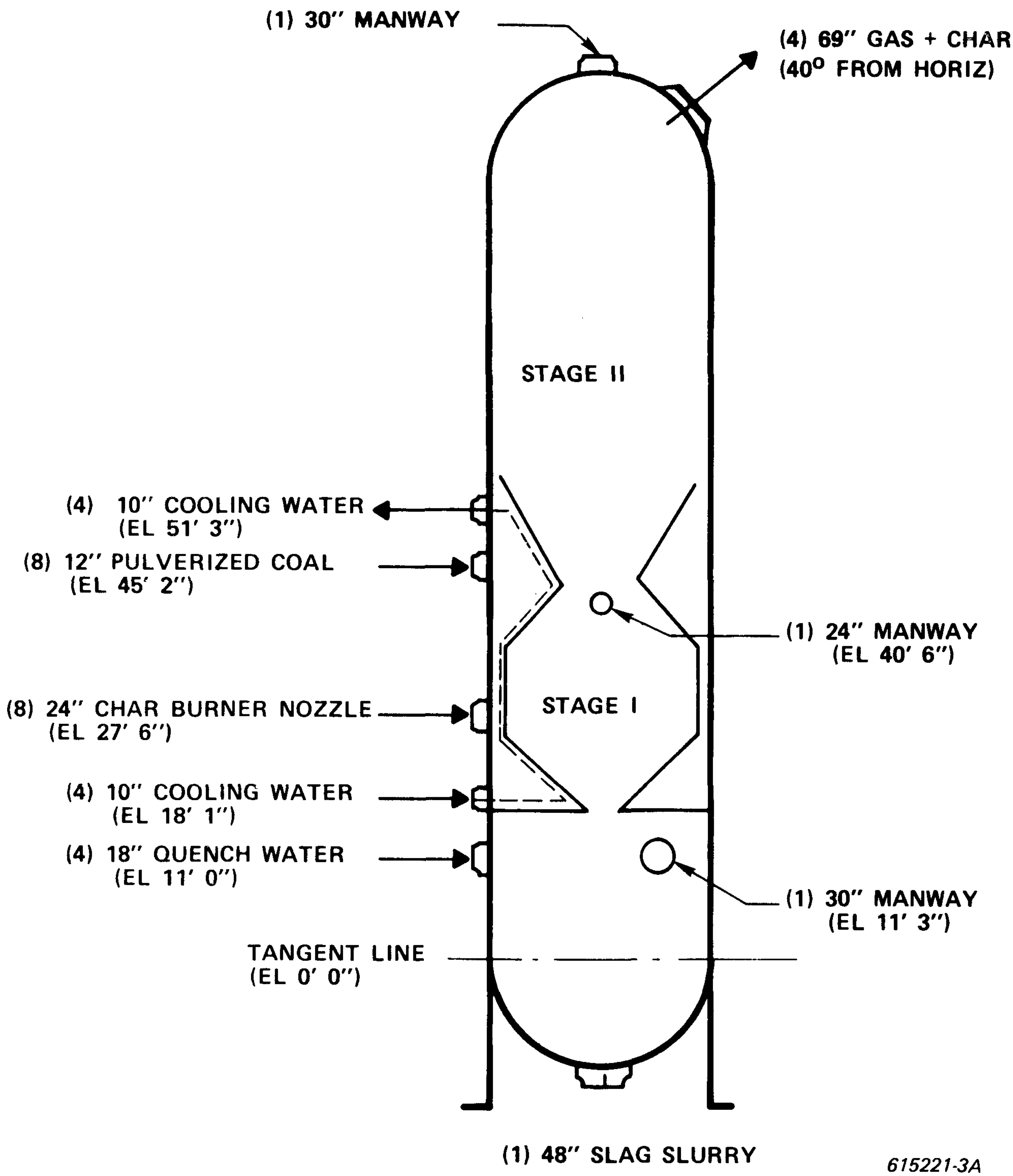

Figure 4.2-1. Penetrations and Geometric Requirements

Gas Outlet Nozzles (69")

F_R = 158,000 lbs.
F_T = 288,000 lbs.
M = 6,170,000 ft. lbs.
M_R = 262,000 ft. lbs.

Coal Inlet Nozzles (12")

F_R = 7,300 lbs.
F_T = 43,000 lbs.
M = 711,000 ft. lbs.
M_R = 563,000 ft. lbs.

Burner Nozzles (24")

F_R = 33,000 lbs.
F_T = 13,000 lbs.
M = 332,000 ft. lbs.
M_R = 97,000 ft. lbs.

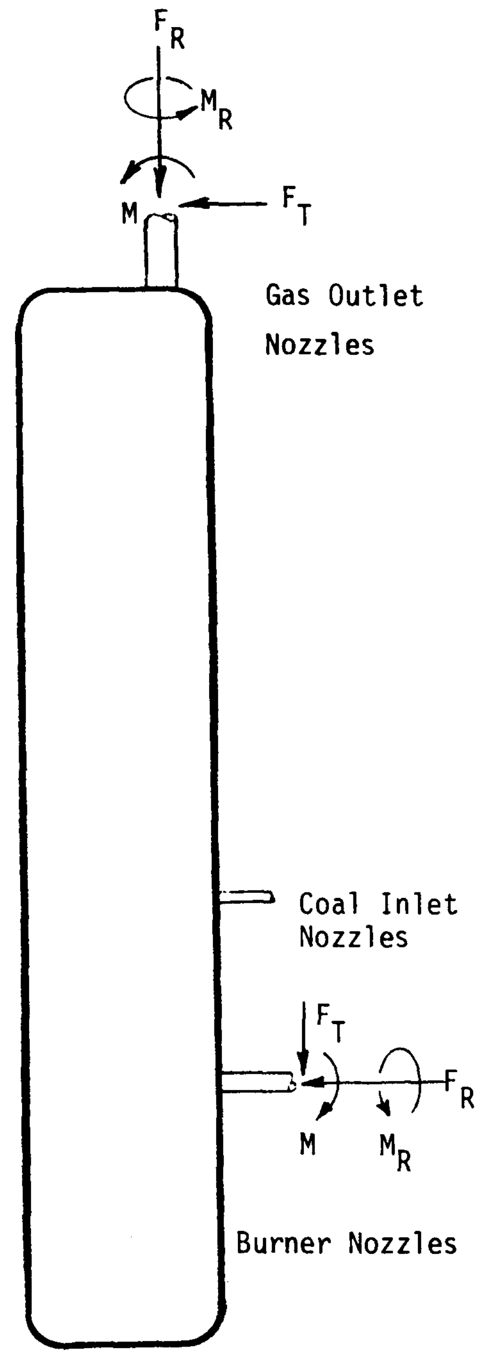

Figure 4.2-2. Piping Loads on PCIV Nozzles

4.3 DERIVED REQUIREMENTS

Certain requirements not previously established for the welded steel vessel were needed for designing the gasifier PCIV. These requirements were derived in such a way as to provide for the greatest practical degree of direct comparability between the PCIV study results and the results of similar studies of welded steel and prestressed concrete vessels. Comparisons should, therefore, be most meaningful while bringing into the comparisons the advantages and disadvantages inherent to the PCIV technology.

- Exit Nozzles - The four large nozzles at the top of the vessel through which process gas exists from the vessel are positioned vertically instead of at 50°F from the vertical as with the steel vessel. This simplification is permitted by the PCIV technology since a flat head is used.

- Length of Cylindrical Section - The tangent-to-tangent length of the cylindrical section of the vessel is increased to 129 feet (by adding four feet at the bottom). This increase in length is needed by the PCIV design using a flat bottom head in order to create proper slag drainage conditions.

- Transients - The vessel was designed to accommodate two startup/shutdown cycles per year for 25 years. The vessel is required to respond in an acceptable fashion to startup conditions where the full design pressure precedes any temperature rise and to shutdown conditions where internal pressure falls to ambient before any temperature reduction.

- Ambient Air Temperatures - The requirements stated in Section 4.2 define the most severe or "hot day" conditions that determine the size of any cooling system and its components. However, normal day conditions are not nearly so demanding. For these normal conditions, any cooling system must function satisfactorily at less than full capacity using ambient air at the following mean temperatures (Cheyenne, Wyoming):

Jan.	26.6°F	May	52.4°F	Sept.	58.2°F
Feb.	29.0°F	June	61.3°F	Oct.	47.9°F
Mar.	31.6°F	July	69.1°F	Nov.	35.5°F
Apr.	42.7°F	Aug.	67.6°F	Dec.	29.2°F

The annual mean temperature is 45.9°F.

5.0 CONCEPTUAL DESIGN OF PCIV

The prestressed cast iron vessel design described in this section was developed to utilize the beneficial properties of cast iron such as high strength, low cost and good machinability. High strength steel cables are used to hold together segmented cast iron body members that fit snugly around a leak tight stainless steel liner. The design developed allows the structural parts of the vessel to respond elastically to all expected short time loads. Thermal insulation and a forced air cooling system are used to keep thermally induced strains in the structural members of the vessel, i.e., the liner, body segments, heads and cabling, within acceptable limits. Relaxation of the prestressing cables and tendons that could occur for long-time tensile stresses are limited to a small amount <10% by careful selection of materials and by control of the prestressing material temperatures. To minimize costs and site construction time, factory operations were used instead of field operation wherever that appeared to be cost effective. The design permits the transportation of all members needed at the construction site by standard railway equipment. The cast iron members of the vessel were designed with relatively thick sections in order to constrain structural parts even if cracking were to occur from some overload condition. This enhances the safety aspects of the design and permits rather low strength cast iron to be used since the stress levels in such a design are low. Class 40 gray iron was selected.

5.1 GENERAL CONFIGURATION AND CHARACTERISTICS

The PCIV gasifier is basically a cylindrical vessel with thick flat heads at the top and bottom. It is shown pictorially in Figure 1.0-2. Figure 5.1-1 describes the general arrangement of members and represents the principal design drawing of the PCIV. The sidewall of the vessel is made from 14 rings of 8 body segments each.

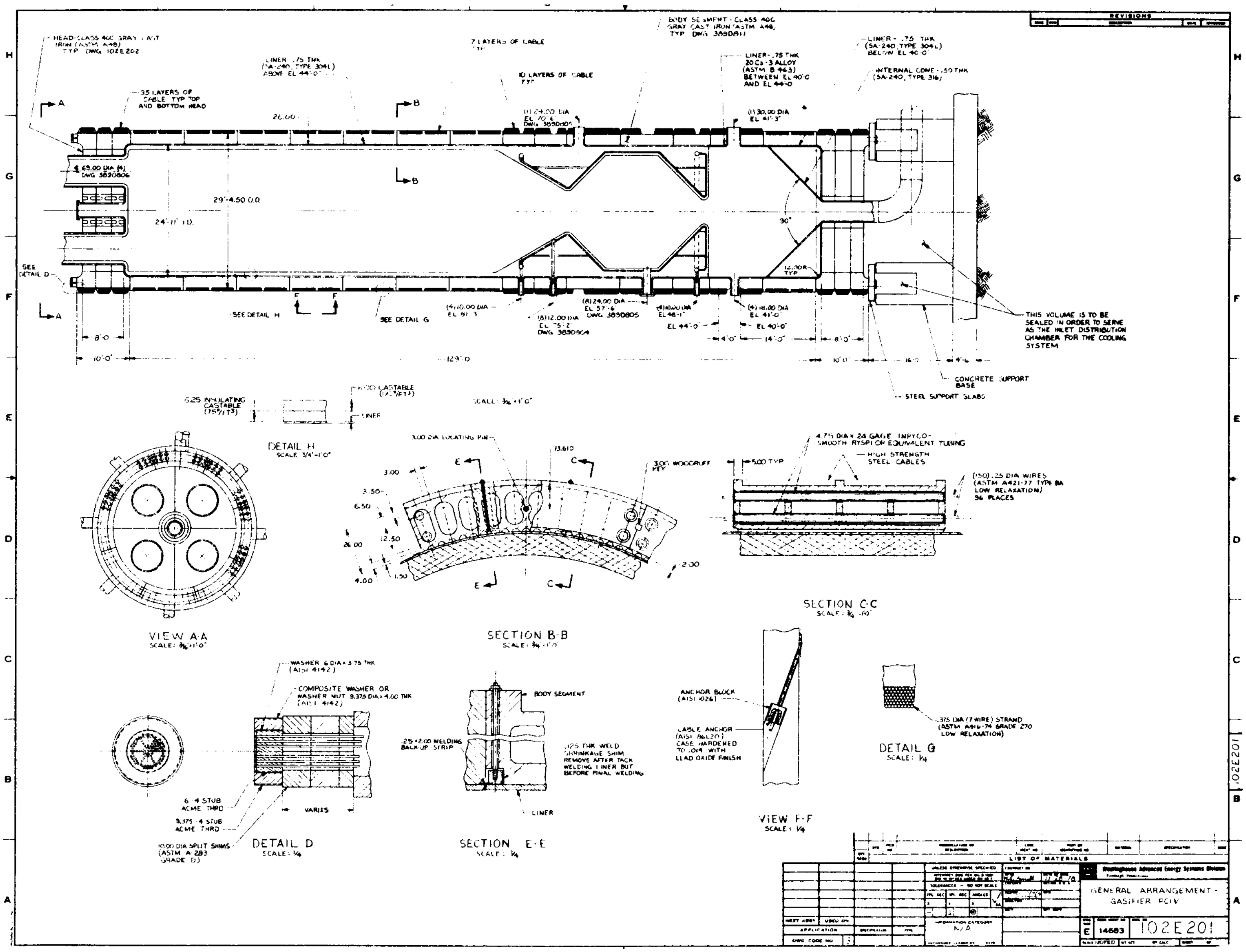

Figure 5.1-1. General Arrangement Gasifier PCIV

The sidewall design was developed to optimize the use of cast iron material while satisfying safety requirements. The overall radial thickness of the castings was determined by the need to use both an inner and outer circle of axial tendons. The radial spacing of the tendons was selected to provide sufficient space to permit the use of standard jacks during prestressing of the tendons.

The castings were designed as hollow structures to reduce the amount of cast iron material, while still providing stability against buckling. The hollow parts of the castings also provide longitudinal passageways through which the axial tendons extend.

Having the axial tendons housed in the thickness of the sidewall also provides protection for the tendons against corrosion or physical damage. Tendons are located uniformly around the circumference of the vessel except at eight locations that are reserved for nozzle penetrations.

The height of each sidewall ring and the number of segments per ring are chosen to:

- keep casting size and weight at levels acceptable to foundries in the U.S. (approximately 40 tons).
- permit machining of individual castings and assembled sidewall rings.
- permit shipment of castings by standard railway.
- maintain ring hoisting weight to a practical level (~320 tons).

The PCIV uses a forced air cooling system to eliminate the leakage problems associated with water cooling systems. Cooling passages are provided on the inner surface of the cast iron segments (the surface facing the liner). Blower units located at ground level are used to force outside air into the enclosed region of the foundation. This region serves as a distribution chamber and feeds air to passages in the bottom head and subsequently to the flow passages in the sidewall. The upper head has a similar arrangement that allows a cooling air coming from the sidewall passages to cool and pass through the upper head. The air discharges from holes in the top of the upper head.

The upper and lower heads are essentially thick flat discs that are prestressed by circumferential cables to maintain states of compression in the heads even when loaded by vessel internal pressure. The heads are made from hollow castings to reduce weight while maintaining much of the stiffness of a solid head. Each head is composed of three layers that are shear tied together for bending strength.

Each head is composed of three layers so that hoisting equipment lifting capability requirements are only one-third as stringent as for a head composed of only one thick layer. Each head layer can, therefore, be assembled at ground level and hoisted into position. This is important since it eliminates the need for a temporary internal structure to support the upper head segments prior to wrapping, and also eliminates the need for wrapping at elevated positions on the vessel.

All cast iron members, whether in the head or sidewall, are designed with adequate margins to prevent cracking in service. The design uses configurations that can tolerate cracking and still maintain structural integrity since the loading approaches a condition of triaxial compression in the castings. This eliminates the need for inservice inspection of such members, and for normal operation, allows average primary stress levels up to 0.25 of the ultimate compressive strength (UCS) for compression and .20 of the ultimate tensile strength (UTS) for tension. (See Appendix A for discussion of allowable stresses).

In special regions where it may be impractical to use configurations that are inherently stable, large margins of safety are used to maintain the integrity of the cast iron. In addition, these regions are designed for inservice inspectability and with redundant features if practical. The large margins of safety are achieved by maintaining, for normal operation, average primary stress levels below .6 x UTS for compression and below .2 x UTS for tension. Stress levels during construction can be 30% higher since cycling is not a factor.

In a vessel that is built up by using many body segments as building blocks, there is a possibility that gaps will exist between the blocks even after the prestressing members have been installed to close the gaps. The gaps are related primarily to undersize dimensions that may be machined onto certain blocks. The possibility of gaps is essentially eliminated in the PCIV design by using rather large body segments and by holding reasonably close tolerances while machining the cast iron segments. The size of body segment should be large in order to provide sufficient length to accommodate the strain needed to close a gap without inducing a large compressive stress in the cast iron segments. Typical tolerances for machined segments are shown on Drawing 389D837 which is presented in Figure 5.1-3.

The vessel design uses castings that are approximately 10 x 10 x 4 feet or smaller to facilitate shipping. Casting weights are less than 40 tons which is well within the pouring and handling capabilities of several domestic foundries. The design permits eight sidewall castings to be assembled and prestressed to ground level thus forming one of several ring assemblies needed for constucting the cylindrical part of the vessel. (See Figure 5.1-2 for pictorial description of fabrication.) After ground level assembly and prestressing, each ring is hoisted into position at its proper elevation on the vessel being constructed. The head assemblies are done in a similar manner.

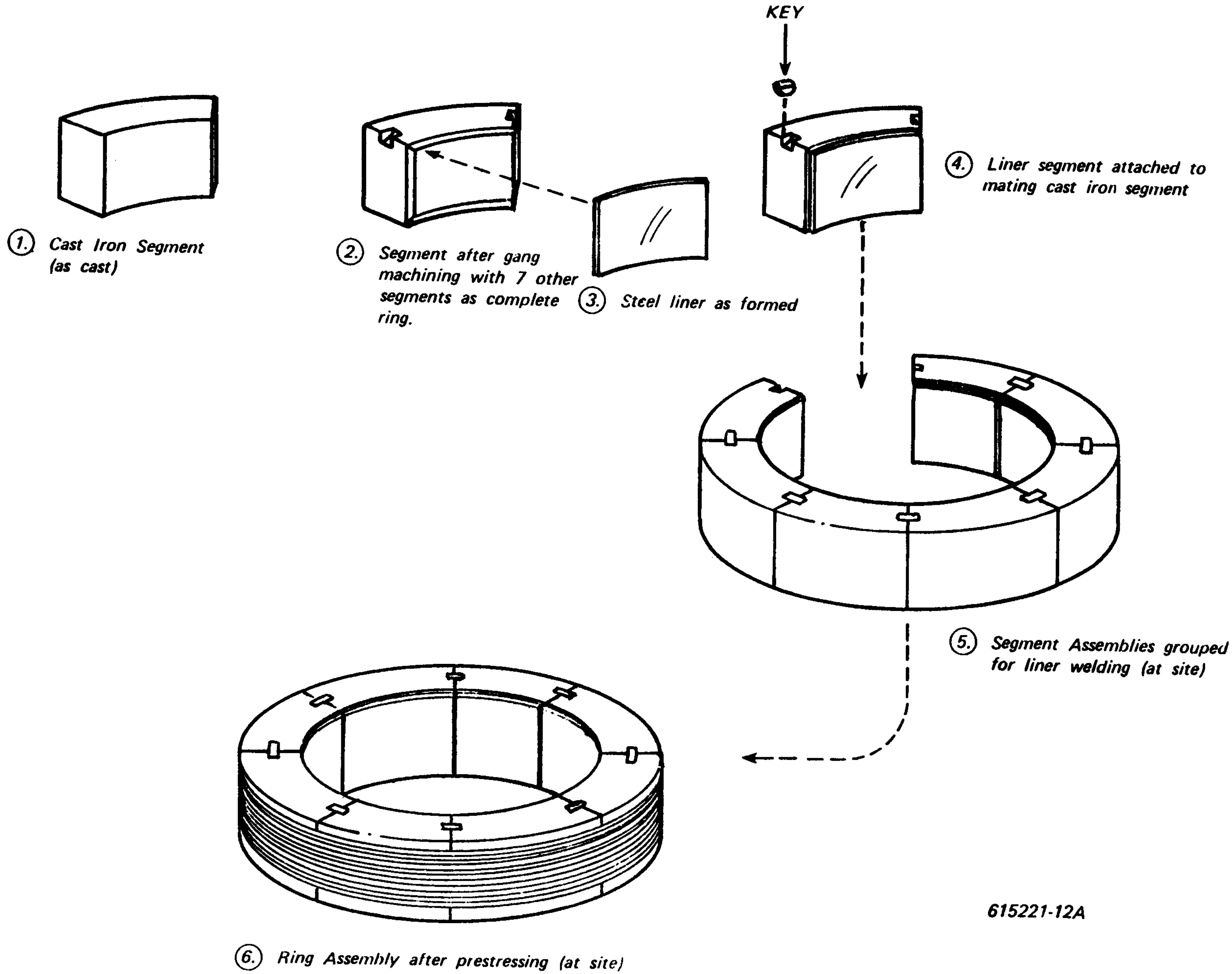

Figure 5.1-2. Method of Fabrication for PCIV

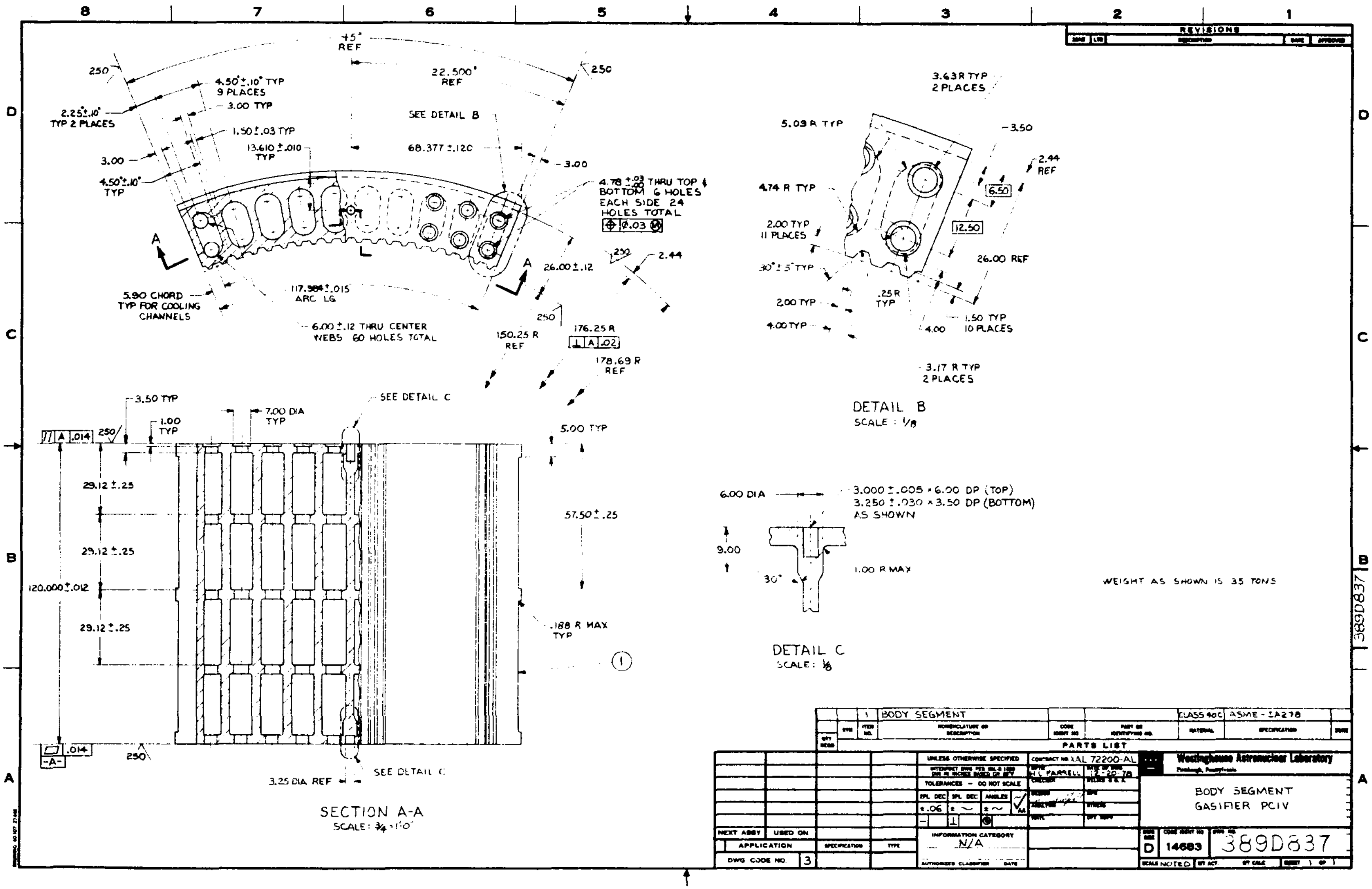

Figure 5.1-3. Cast Iron Body Segment

5.2 CONCEPTUAL DESIGN FEATURES

5.2.1 FOUNDATION

The foundation of the coal gasifier PCIV is basically a hollow concrete cylinder having a wall thickness of 8 feet. It is shown as part of the overall general arrangement for the PCIV in Figure 5.1-1. A more detailed description of the features of the foundation and vessel support structure is shown in Figure 5.2-1.

The design of the foundation is based on the criteria for a construction site at Gillette, Wyoming. For the foundation, the net soil bearing pressure is 4000 PSF and the concrete strength is 4000 PSI after 28 days or curing. Consistent with Reference 1, earthquake loadings are not a criterion. Wind loads are also not applicable since the vessel is installed within an enclosure.

As seen in the figures, the top of the footing for the foundation is level with the high point of the building floor. The anchor bolts shown are not required for strength but are used in leveling the steel slabs to form a good surface for seating the bottom head of the PCIV. If desired, the bottom head can be installed on the steel slabs prior to adjusting the leveling screws.

During construction non-shrink grout is to be poured beneath the steel slabs prior to installing the sidewall rings of PCIV on top of the bottom head. Sole plates are used just beneath the steel slabs in order to permit any radial expansion and contraction of the bottom head to take place, if that is required during operation of the coal gasifier.

In addition to providing support for the PCIV, the foundation serves as a distribution chamber for air that is used to cool the structural parts of the PCIV. For this reason, all pipes and ducts penetrating the 8 foot thickness of the foundation are sealed to prevent gross leakage of air from the space enclosed by the foundation. A pressure resistant steel door is used to provide access to the foundation area and also carry pressure loads that are created by 3 psig pressure.

The design of the foundation is such that it can be adapted to react earthquake forces, but will have to be properly sized in accordance with the magnitude of these forces.

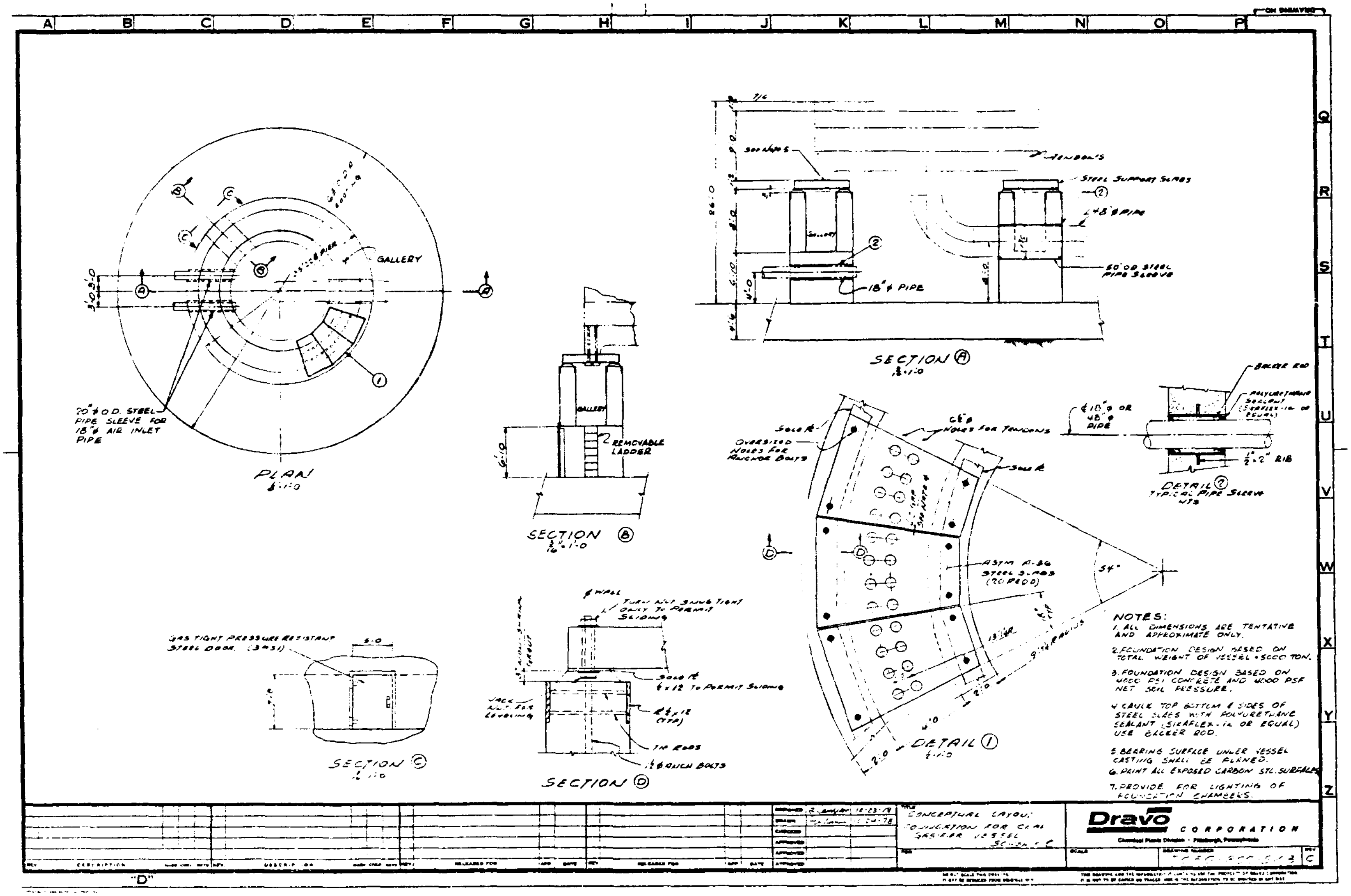

Figure 5.2-1. Foundation for PCIV

5.2.2 LINER

The liner for a PCIV is a leaktight membrane located at the inside diameter of the cast iron pressure vessel body. Its purpose is to prevent escape of fluid from inside the vessel and to provide support for thermal insulation attached to the inside surface of the liner. Pressure loads that are normally reacted by tension in welded steel pressure vessel shells are not carried by tension in the PCIV liner. Instead these loads are transmitted into the circumferential cabling by compression through the thicknesses of the liner and cast iron body segments. Tension in the cabling reacts the pressure loads.

The basic requirements for the vessel liner are the following:

- It must contain internal process fluids.
- It must be ductile so that some yielding may occur without cracks developing.
- Buckling is not permitted under normal operating conditions.
- It should be of a thickness that allows for the production of good quality welds.
- It should be thick enough to bridge internal pressure loading over discontinuities such as joints between body segments.
- Corrosion resistance must be sufficient to satisfy ductility and thickness requirements at end of service life.

The liner will be fabricated from 3/4 inch stainless steel plates which will be welded together. Anchor studs are used to attach the liner to the cast iron body segments to assure that liner strain patterns conform to the adjacent cast iron strain patterns. Depending on the PCIV design and the behavior of the cast iron wall, the modes of failure which the liner may encounter are those of buckling, tensile failure, shear connector failure, and fatigue failure. After a liner section has been assembled with 8 cast iron body segments and prestressed by the circumferential cables to form a ring assembly, the liner is in a state of hoop compression. The amount of this compression can be controlled within certain limits to create favorable stress conditions in the liner during the times when the vessel has internal pressure. The plan is to prestress the liner when it is in the ring with sufficient compression (about 10 ksi) to eliminate operation of the liner in the plastic range. For the sake of simplicity in this conceptual design analysis, however, it was assumed that the liner would be ring-assembled in the stress free state (with no hoop compression).

Using this assumption, the liner will be essentially in the stress free contact circumferentially with the cast iron body after the vessel has been prestressed axially. At that time the liner will be stressed axially in compression by the axial tendons to a level of about 17 ksi. This is less than the yield strength of about 21 ksi for the liner material at 200°F. To preclude buckling, the liner is restrained by anchor studs attached to the cast iron body at spacings of about 77 inches in both the circumferential and axial directions.

Again using the very conservative assumption stated above, at the design pressure of 1200 psi, the liner hoop membrane stress is over 31 ksi, which exceeds the yield stress of about 21 ksi. However, the liner is only intended to function as a leaktight membrane and not as a structural member. Indeed, experience with liners used in prestressed concrete reactor vessels and reported in References 4 and 33 indicates that such liners do operate in the post-yield stress state. It is only essential that the PCIV liner not be breeched when the vessel pressure reaches twice the design pressure. Since the liner can withstand strains in excess of 25% without rupturing, it appears that such strain levels could only be induced at a local level. The analysis of localized effects was considered outside the scope of this conceptual design study. It should be performed in sequence with the detailed design of the PCIV.

The anchor studs which attach the steel liner to the cast iron body provide both resistance to liner buckling and support for loadings which are perpendicular to the liner. They also resist forces parallel to the liner, which are created when a force imbalance occurs on opposite sides of an anchorage due to such factors as temperature differences, etc.

Since the liner will experience inelastic strains, fatigue must be considered. Since the total number of cycles over the lifetime of the plant is only 60, it is relatively easy to avoid fatigue problems. However, strain data for the liner should be expressed as strain histories which show maximum and minimum values of strain for significant loading conditions throughout its operational life. During detail design a fatigue analysis will be required but the results are not expected to change the conclusions of this study.

5.2.3 CYLINDRICAL SECTION OF VESSEL AND ITS CIRCUMFERENTIAL CABLES

The individual cast iron body segments are prestressed in compression by the circumferential cables which are prestressed in tension. The rings are then stacked one on top of the other to form the vessel and are subsequently held axially by the axial tendons. The axial tendons are prestressed in tension and compress the cast iron axially; consequently they further prestress the cast iron circumferentially since the vessel radial expansion (Poisson effect) is resisted by the circumferential cables. When the vessel is pressurized, the cast iron compression decreases while the circumferential cable tension increases. Thermally induced stresses occurring in the cabling and cast iron during operation will be negligible since the circumferential cables and the cast iron body will be essentially the same temperature. The liner, however, will have some thermally induced compression when going from prestressed to operating conditions since the expansion coefficient for the stainless steel liner is higher than for the cast iron vessel body. The magnitude of this stress is about 9 ksi at the hottest part of the vessel and proportionately less in other regions.

The maximum compressive stress in the cast iron body occurs in the pre-stressed state. The magnitude of the compressive prestress is sufficient to overcome any tensile stresses that might otherwise occur during the operational state. On the other hand, the maximum tensile stress in the circumferential cables occurs during operation when the vessel is pressurized.

The design of the PCIV was developed such that the following stress conditions are satisfied:

- The compressive prestress in the cast iron must be less than the cast iron compressive stress limit of 27.85 ksi.
- The cast iron circumferential compressive stress is zero when the vessel pressure is equal to the gapping pressure.
- The design stress in the circumferential cables (when the vessel pressure is equal to the design pressure) is limited by the cable stress allowable of 189 ksi.
- The stress in the cables is limited to the cable ultimate tensile stress when the vessel pressure is equal to the product of the design pressure and the factor of overall safety.

The stress conditions listed above impose conflicting requirements on the stresses in the cast iron and the cables and, consequently, on the design. While a high value for the cast iron prestress is necessary to assure that the vessel body will not gap, an excessively large value for this prestress will result in an unacceptably large value for the cable operating stress.

If p_i is the design pressure for the vessel, p_g is the pressure that would eliminate compression stresses in the cast iron body (i.e., it is the pressure required to initiate gapping between the cast iron ring segments), and p_f is the pressure that would initiate rupture of a circumferential cable, two factors of safety are defined:

F_g - the gapping factor of safety ($F_g = p_g/p_i$)

F_f - the factor of overall safety ($F_f = P_f/p_i$)

The PCIV design is based on a factor of overall safety (F_f) of 2, and a gapping factor of safety of 1.4 axially and 1.5 circumferentially. These safety factors are essentially the same as those used in PCPV's and are valid for two reasons: first, cast iron material behavior is more predictable compared to concrete and, second, cast iron does have tensile strenght compared to essentially (almost) zero tensile strength for concrete.

For the PCIV design under consideration, the cast iron vessel has an equivalent solid thickness of 9.2 in. in the circumferential direction. The stress equations indicate that the circumferential cable thickness cannot exceed 1.71 in. (beyond which the compressive prestress f_{cp} exceeds the cast iron allowable stress of 27.85 ksi) and cannot be less than 1.33 in. (below which the stress in the cast iron body will be such that gapping will occur for a gapping factor of safety of less than 1.5). Consequently the prestress system design is a cable thickness of 1.35 in. (corresponding to 7 layers of wrap) around the vessel body away from the nozzles and a cable thickness of 1.43 in. (corresponding to 10 layers of wrap) around the vessel body in the region of the penetration is adequate (see Figure 5.1-1). The larger cable thickness in the region of the penetrations is used to provide an additional margin of safety since the prestressing system does not exist in the planes of the nozzles.

Figure (5.2-2) shows the stress-strain diagram for the vessel with a 1.35 in. cable thickness; the diagram is approximately the same for a cable thickness of 1.43 inches also. When the cast iron ring segments are prestressed, the tensile stress in the cables is 152.89 ksi. This increases to 157.60 ksi when the vessel is assembled and the axial tendons are prestressed as well. The vessel compressive prestress in the fully assembled condition is 23.13 ksi. At the design condition, when the vessel internal pressure equals 1200 psi, the cable tensile stress increases to 185.86 ksi and the cast iron compressive stress decreases to 7.71 ksi. At the gapping pressure of 1800 psi, the cable tensile stress is 200.00 ksi and the vessel stress is approximately zero. If a linear stress-strain relationship is assumed for the cables to the rupture stress, the cable stress reaches the ultimate tensile strength of 270 ksi when the internal pressure is 2430 psi. This results in an overall factor of safety of F_f=2.025 for this PCIV design in the circumferential direction.

In Table (5.2-1), the circumferential direction stresses and strains in the cables and cast iron main body are listed for the different operational states.

Figure (5.2-3) shows the variation of circumferential cable stress and circumferential cast iron membrane stress with the vessel internal pressure.

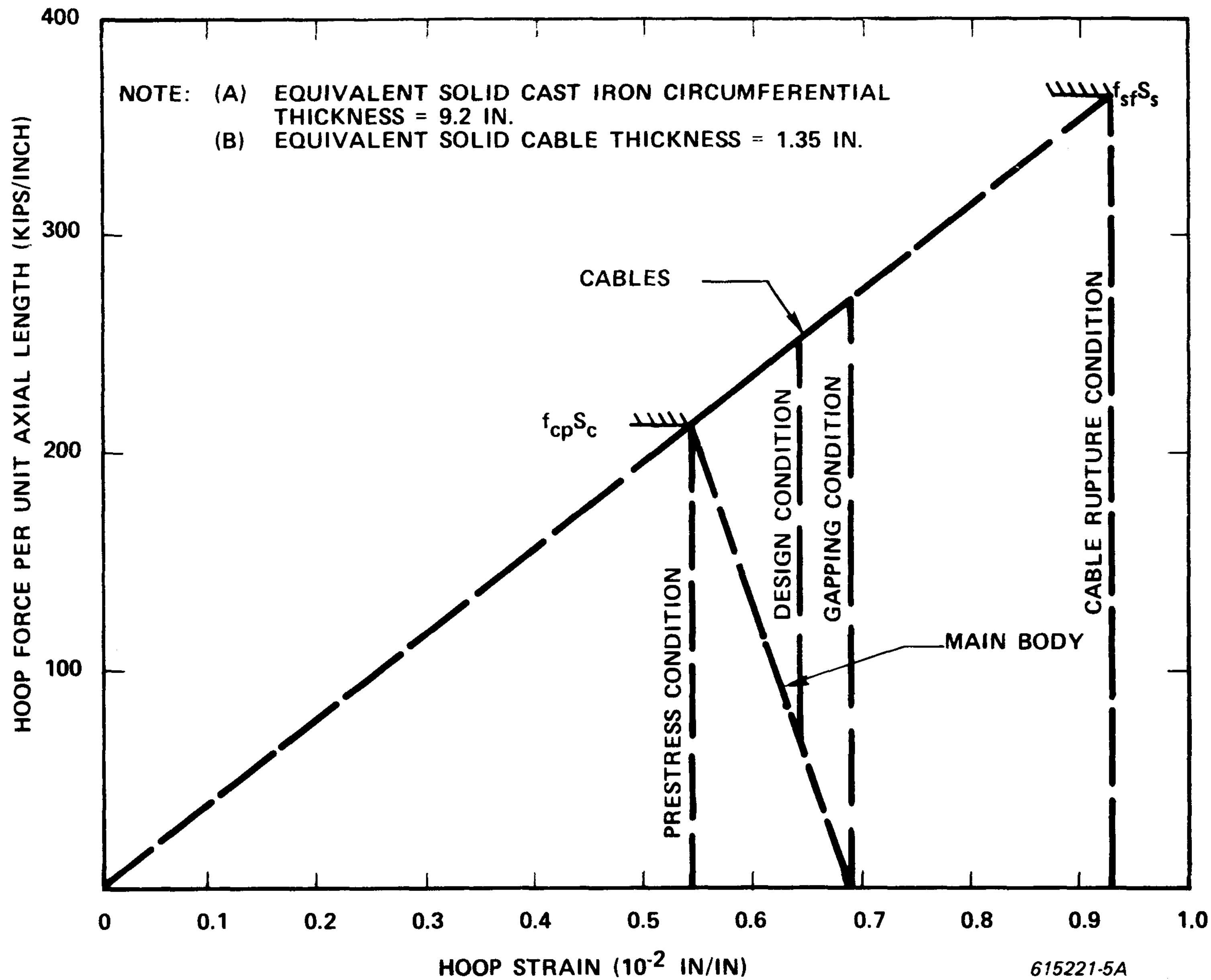

Figure 5.2-2. Stress Strain Diagram for PCIV Circumferential Design

TABLE 5.2-1

PCIV STRESSES, CIRCUMFERENTIAL DIRECTION

GENERAL

Stress Allowables: Cables - Ultimate Stress, f_f = 270 ksi

Allowable Stress, $f_{s,\ all}$ = 189 ksi

Cast Iron - Allowable Stress, $f_{c,\ all}$ = 27.85 ksi

Design Conditions:

Overall Factor of Safety: F_f = 2.0

Gapping Factor of Safety: F_g = 1.5

Design Pressures: p_i = 1200 psi

Operating Pressure: p_{op} = 1080 psi

Geometry:

Cast Iron Body Thickness (effective), s_c = 9.2 inches

Cable Thickness (solid), away from nozzle, s_s = 1.35 in.

PRESTRESS CONDITIONS

Ratio of interface pressure to design pressure

p_{int}/p_i = 0.212

Cast Iron Circumferential Prestress

f_{cp} = 23.13 ksi (compression)

Cable Prestress

f_{sp} = 157.60 ksi (tension)

Cable Prestress Around Cast Iron Ring

$f_{sp,\ r}$ = 152.89

Cable Prestrain Around Cast Iron Ring = 5.272×10^{-3} inches/inch

Cable Prestrain Around Cast Iron Vessel = 5.434×10^{-3} inches/inch

OPERATING CONDITIONS

Cable Stress at Operating Conditions = 182.33 ksi (tension)

Cast Iron Circumferential Stress at Operating Condition = 9.64 ksi (compression)

TABLE 5.2-1 (continued)

PCIV STRESSES, CIRCUMFERENTIAL DIRECTION

DESIGN CONDITIONS

Cable Stress at Design Condition = 185.87 ksi (tension)

Cast Iron Circumferential Stress at Design Condition = 7.71 ksi (compression)

GAPPING CONDITION

Cable Stress at Gapping Condition = 200.00 ksi

Cable Strain at Gapping Condition = 6.896×10^{-3} inches/inch

Cast Iron Circumferential Stress at Gapping Condition = 0.0 ksi (assumed in analysis)

CABLE RUPTURE CONDITIONS

Cable stress reaches the ultimate value of 270 ksi when the vessel internal pressure is 2430 psi, that is the factor of overall safety, F_f = 2.025.

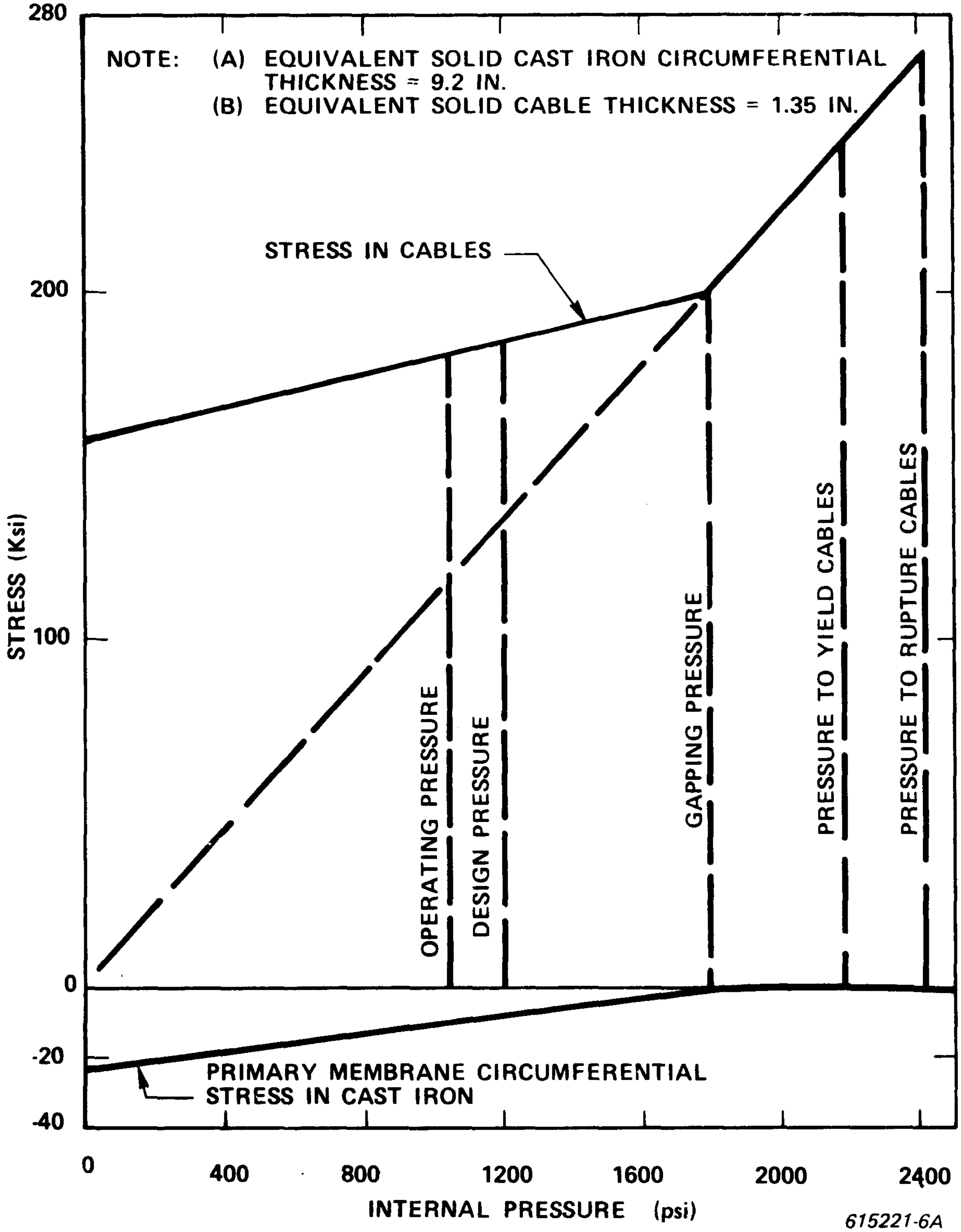

Figure 5.2-3. Sidewall Hoop Stresses versus Internal Pressure

The results of the PCIV sidewall circumferential stresses indicates that the stress levels in the cabling and cast iron body are well within the allowable stress values for these components. Also the stress levels in the stainless steel liner can be kept within the elastic range by controlling the amount of prestress compression induced into the liner while wrapping cabling around the outside of each body segment ring.

A cast iron vessel thickness of 8 inches and a cable thickness in the range 1.31 inches to 1.53 inches would also be acceptable. Such a design would have the advantage of reduced cost.

5.2.4 CYLINDRICAL SECTION OF VESSEL AND AXIAL TENDONS

When the cast iron prestressed rings are stacked one on top of the other and the heads are located in position, the vessel is prestressed axially by tensioning the axial tendons. The prestress in the tendons must be sufficient to react the force on the heads due to internal pressure loading. In reacting this force, the prestress in the tendons is sufficient to prevent the body from gapping due to longitudinal loads.

When the vessel is pressurized internally, both hoop and axial stresses are developed in the cast iron body and liner. Axial stresses are developed in the tendons and tangential stresses in the circumferential cabling. The vessel body biaxial stress effects are neglected since these are small. Although an axial temperature variation exists over the length of the vessel, thermal stresses are not directly considered in the analysis since they are relatively small and can be handled by superposition.

The design of the PCIV in the axial direction is governed by the same four stress conditions that govern the design in the circumferential direction (see Section 5.2.3). Similar to the stress state in the circumferential direction, the maximum compressive axial stress in the cast iron body occurs in the prestressed state while the maximum tensile stress in the axial tendons occurs during operation when the vessel is pressurized.

For the PCIV design under consideration, the cast iron vessel has an effective solid thickness of 12.6 inches in the axial direction, and a total cross-sectional area of 705 in^2 for the axial tendons. The variation of the tendon stresses and the vessel body axial stresses with the vessel internal pressure is shown in Figure 5.2-4. In the prestressed state, the tendons are stressed to 156.31 ksi in tension and the vessel body to 9.28 ksi in compression. When the vessel has a design pressure of 1200 psi, the tendon tensile stress increases to its allowable value of 168 ksi while the cast iron body axial compressive stress decreases to 2.83 ksi. The body compressive stress becomes zero, i.e., the body gaps axially, if the vessel pressure reaches 1.73 ksi; the gapping factor of safety is consequently 1.44. At this stage, the tensile stress in the tendons is 173.13 ksi. If a linear stress-strain relationship is assumed for the tendons to the rupture stress, the cable stress reaches the ultimate tensile strength of 240 ksi when the internal pressure is 2410 psi. This results in an overall factor of safety of 2.008 for this PCIV design in the axial direction.

In Table 5.2-2, the axial direction stresses in the tendons and cast iron main body are listed for the different operational states.

A decrease in the cast iron vessel axial thickness from 12.6 in. to 11.0 in., with the same quantity of tendons, would also be acceptable. Such a design would have the advantage of reduced cost and would, furthermore, have a gapping factor of safety of 1.5.

As shown in Figure 5.1-1 the axial tendons cannot be used in every "cell" position around the circumference of the vessel. In fact, only 48 of the 80 cell positions can be used because of the need for large diameter nozzles to penetrate the sidewall at several locations around the circumference. The structural effect from these blank areas, however, is rather insignificant because of the overall thickness of the cast iron body segments (about 30 inches) and the circumferential compression in the segments due to prestressing. (Section 5.2-6 has additional information on penetrations.)

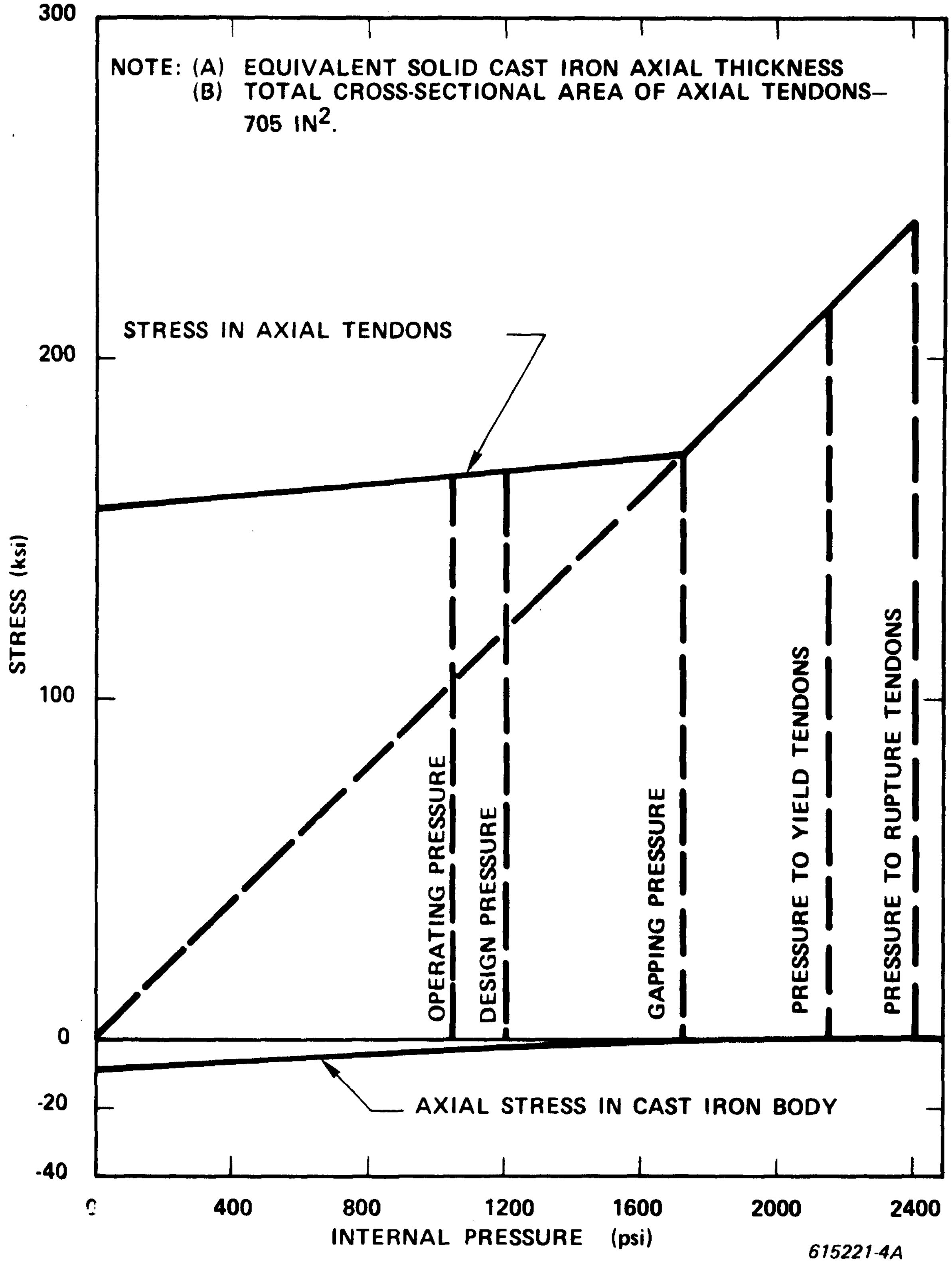

Figure 5.2-4. Sidewall Axial Stresses versus Internal Pressure

TABLE 5.2-2

PCIV STRESSES, AXIAL DIRECTION

GENERAL

Stress Allowables: Tendons - Ultimate Stress, f_f = 240 ksi

Allowable Stress, $f_{s,\ all}$ = 168 ksi

Cast Iron - Allowable Stress, $f_{c,\ all}$ = 27.85 ksi

Design Conditions:

Overall Factor of Safety: F_f = 2.0

Gapping Factor of Safety: F_g = 1.44

Design Pressure: p_i = 1200 psi

Operating Pressure: p_{op} = 1080 psi

Geometry:

Cast Iron Body Thickness (solid), S_{ca} = 12.6 inches

Tendon Cross Sectional Area = 705 in^2

PRESTRESS CONDITIONS

Cast Iron Axial Prestress

f_{cpa} = 9.28 ksi (compression)

Tendon Prestress

f_{pa} = 156.31 ksi (tension)

OPERATING CONDITIONS

Tendon Stress at Operating Conditions = 166.54 ksi (tension)

Cast Iron Axial Stress at Operating Condition = 3.64 ksi (compression)

TABLE 5.2-2 (CONT'D)

PCIV STRESSES, AXIAL DIRECTION

DESIGN CONDITIONS

Tendon Stress at Design Condition = 168 ksi (tension)

Cast Iron Axial Stress at Design Condition = 2.83 ksi (compression)

GAPPING CONDITIONS

Tendon Stress at Gapping Condition = 173.13 ksi

Cast Iron Axial Stress at Gapping Condition = 0.0 ksi (compression)

CABLE RUPTURE CONDITIONS

Cable stress reaches the ultimate value of 240 ksi when the vessel internal pressure is 2.41 ksi, that is, the factor of overall safety, F_f = 2.008.

5.2.5 CAST IRON HEAD AND TRANSITION SECTION

In this section, the cast iron head, its circumferential prestressing system, and the transition region between the vessel head and the vessel body are addressed. For initial sizing and to determine the stress levels in the vessel, the cast iron head, vessel body, and circumferential cables are all assumed to be solid homogenous bodies with no cavities. The solid thickness in each case was determined by calculating an effective thickness from the design geometry.

5.2.5.1 THE CAST IRON HEAD AND ITS CIRCUMFERENTIAL CABLES

One of the approaches to designing the PCIV head is based on the following logic: the cast iron head segments are prestressed in compression by the circumferential tendons, the head is subjected to bending stresses when the vessel is pressurized, and consequently the head thickness would be established on the condition that the sum of the compressive prestress and the compressive bending stress would equal the allowable compressive stress. The results of the design based on this approach indicate that for the required head thickness of 59.8 in, the required cross-sectional thickness of the circumferential cabling around the head is 13.62 in. This is about an order of magnitude larger than that around the cylindrical main body which is 1.35 inches.

Since the cost of tendons is approximately an order of magnitude greater than the cost of cast iron, on a per unit weight basis, it was desirable to explore the possibility of decreasing the quantity of tendons with, perhaps, an acceptable increase in the quantity of cast iron. The optimization could be performed in a cost effective manner.

Noting that increasing the head thickness will reduce the tensile bending stresses in the head due to pressure loading, it is seen that a lower compressive prestress needs to be applied to prevent the head segments from coming apart (gapping) on the tensile side of the head. Consequently, fewer cables are required to provide the prestress for a thicker head.

The actual head designed for the PCIV is shown schematically in Figure 5.2-5 and as a design layout in Figure 5.2-6. The actual PCIV head is 8 ft. thick and has about 60% voids. Therefore, setting h_{po} = 96 in. and h_{pi} = 60 in. (see Figure 5.2-5), and considering a plate radius of 176.25 inches, a pressure load of 1200 psi, a gapping factor of safety of 1.5, and a cable ultimate tensile strength of 270 ksi, it is seen that a cable solid ring thickness of 6.67 in. is required. Consequently 34 layers of cable staggered over 7 ft. of the head thickness and resulting in an equivalent solid ring thickness of 6.74 in. is adequate. This corresponds to a compressive prestress of 7.51 ksi in the cast iron and a tensile prestress of 187 ksi in the circumferential head cables. During operation, when the head is subjected to a pressure load of 120C psi, the maximum compressive stress in it (due to both the pressure load and the prestress) is 11.92 ksi.

5.2.5.2 DISCONTINUITY STRESSES AT THE HEAD TO VESSEL TRANSITION SECTION

When the PCIV is assembled, essentially no discontinuity stresses exist at the transition between the vessel head and the vessel body. However, once the vessel is pressurized, such stresses will exist.

For the vessel geometry under consideration, the membrane discontinuity hoop stress in the vessel body due to the discontinuity moment, discontinuity radial shear force, and pressure is determined to be 2.362p in compression. Here p is conservatively assumed to be the internal pressure; benefit from the interface pressure between the vessel and its circumferential cables is neglected. Consequently, the primary membrane circumferential compressive stress in the vessel body is 23.13 ksi during prestress, 25.96 ksi at the design condition of p = 1200 psi, and 27.38 ksi at the gapping condition (p = 1800 psi). These stresses are all below the primary membrane compressive allowable stress of 27.85 ksi for cast iron.

Bending stresses are also produced at the discontinuity. Again, conservatively, neglecting the interface pressure, the primary membrane plus bending stresses due to prestress and an internal pressure of 1800 psi (at the gapping condition) are 33.98 ksi in the axial direction, 29.78 ksi in the hoop direction, and 1.8 ksi in the radial direction; all in compression. These stresses are all below

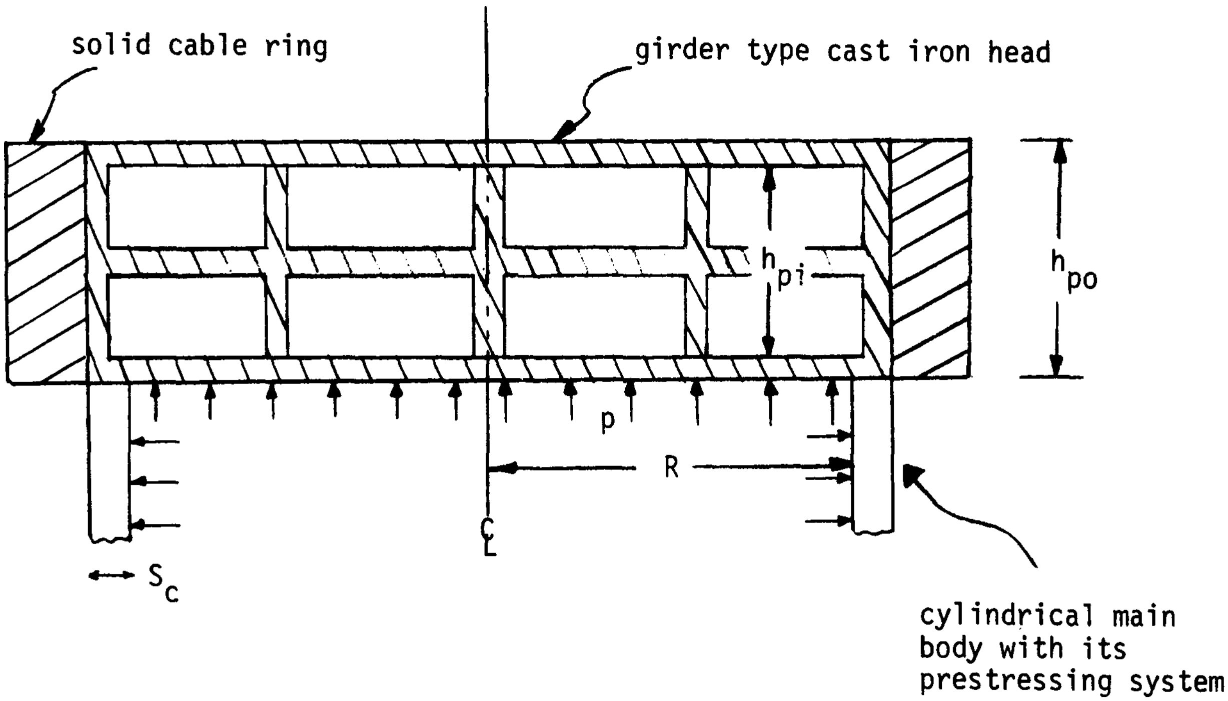

Figure 5.2-5. Schematic of Girder Type Head Structure

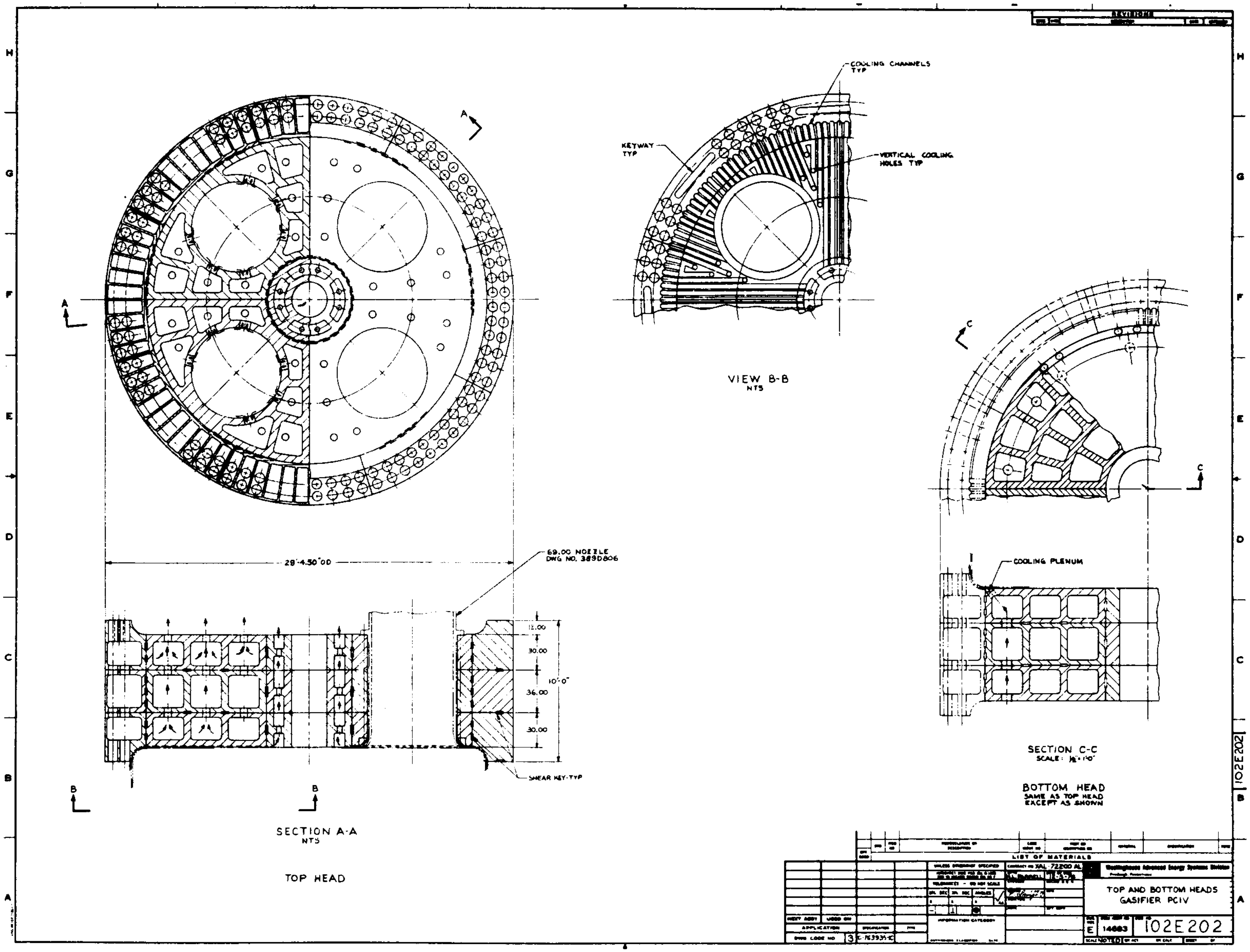

Figure 5.2-6. Layout of Top and Bottom Heads for PCIV

the primary compressive stress allowable of 41.44 ksi at a point. Consequently the vessel is deemed to be structurally adequate under the action of prestress, pressure, and discontinuity loads.

In the PCIV cast iron head, the maximum primary membrane plus bending stresses at the discontinuity due to prestress, gapping pressure, and the discontinuity loads are 12.91 ksi in the radial direction of 15.08 ksi in the hoop direction; both in compression. The allowable stress is 41.44 ksi; therefore the head is structurally adequate.

5.2.6 NOZZLES AND PENETRATIONS

In a typical welded steel pressure vessel, penetrations required for fluids to enter or leave the vessel are accomplished by essentially welding the external pipe to the periphery of a hole cut in the vessel wall. Metal thicknesses at and near the juncture are increased to provide structural reinforcement capable of transmitting piping loads into the vessel and to replace the weakness created by having a hole in the wall of the vessel. This design approach is fine for welded steel vessels but not for PCIV's having a thin metal liner instead of a thick vessel wall. The thin liner would buckle or tear from such loads. Therefore a different approach must be found for prestressed cast iron vessels.

The design approach chosen for the PCIV is one where piping loads are transmitted into the cast iron body of the vessel through an attachment arrangement design to transmit loads through bearing or compression into the cast iron Figures 5.2-7, 5.2-8 and 5.2-9 show such an arrangement for 12 inch, 24 inch and 69 inch nozzles respectively. It is important to transmit these loads through compression rather than tension since cast iron has a compressive strength about 3.5 times greater than the tensile strength. A typical pipe load, bending of the pipe, would be transmitted on the compressive side of the pipe, by bearing at the interface between the nozzle flange and the spot-faced surface of the cast iron body segment. On the tensile side of the pipe the load is transmitted from the nozzle flange into the attachment bolts and then through the bearing

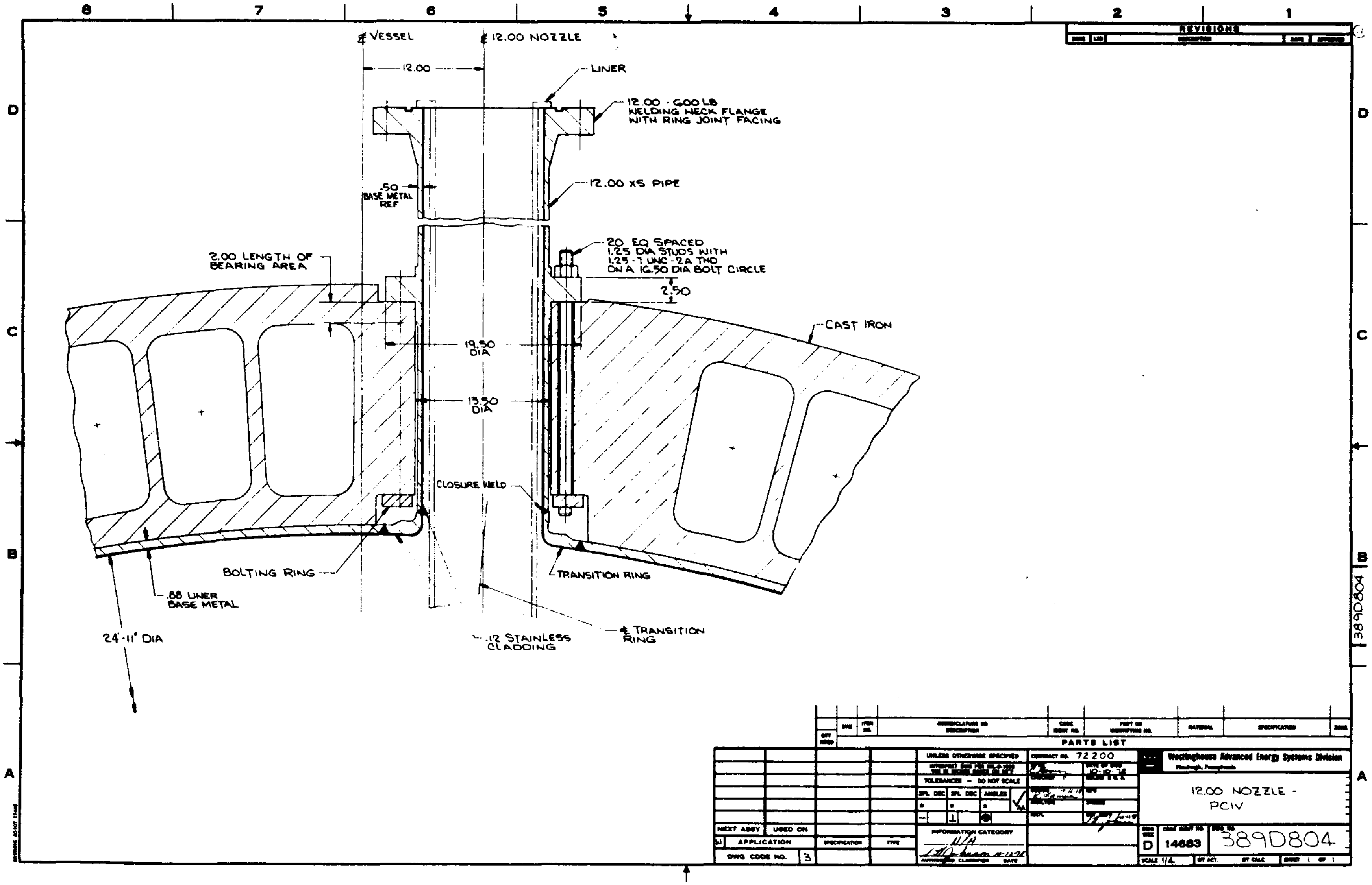

Figure 5.2-7. 12.00 Nozzle - PCIV

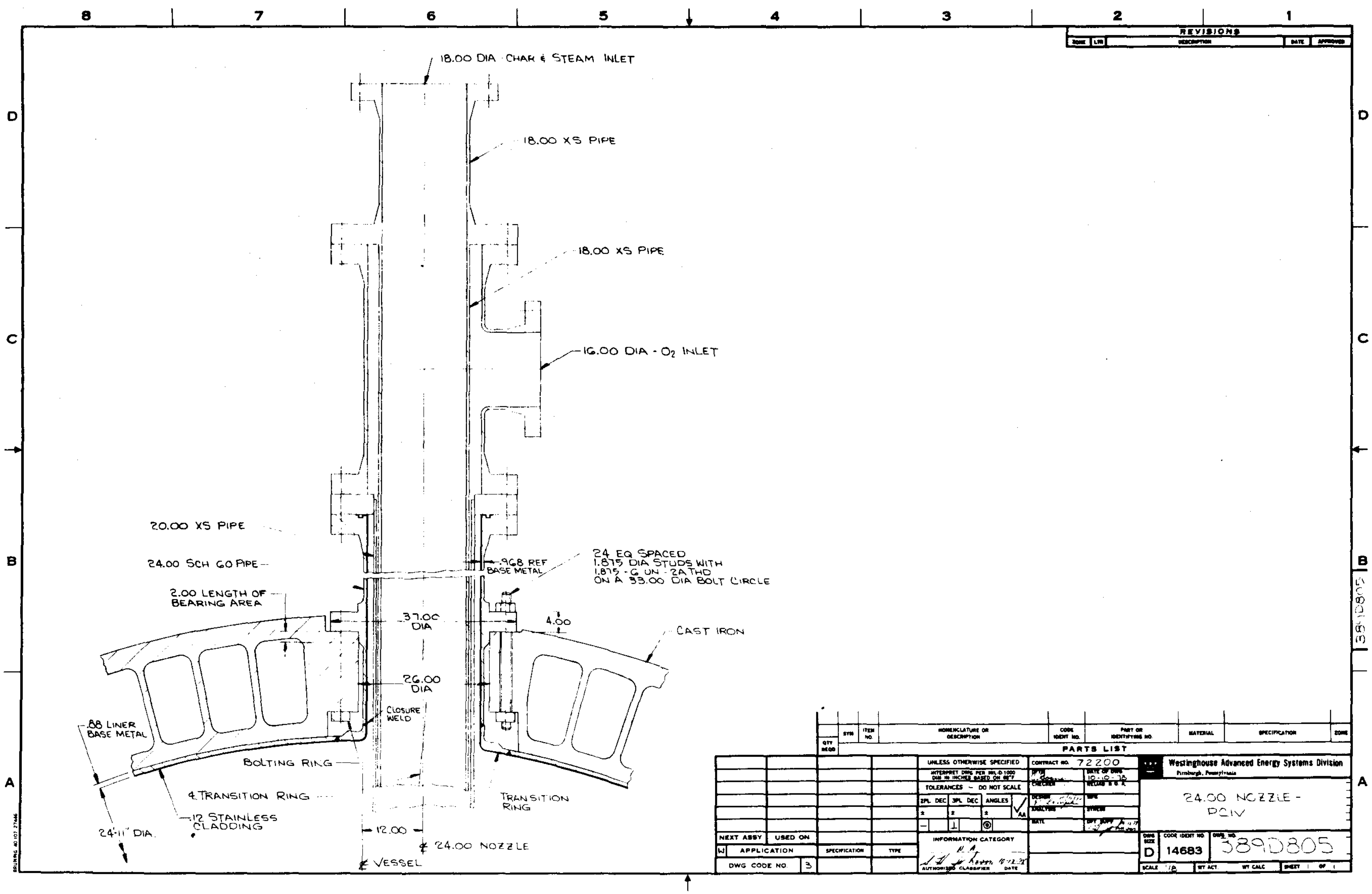

Figure 5.2-8. 24.00 Nozzle - PCIV

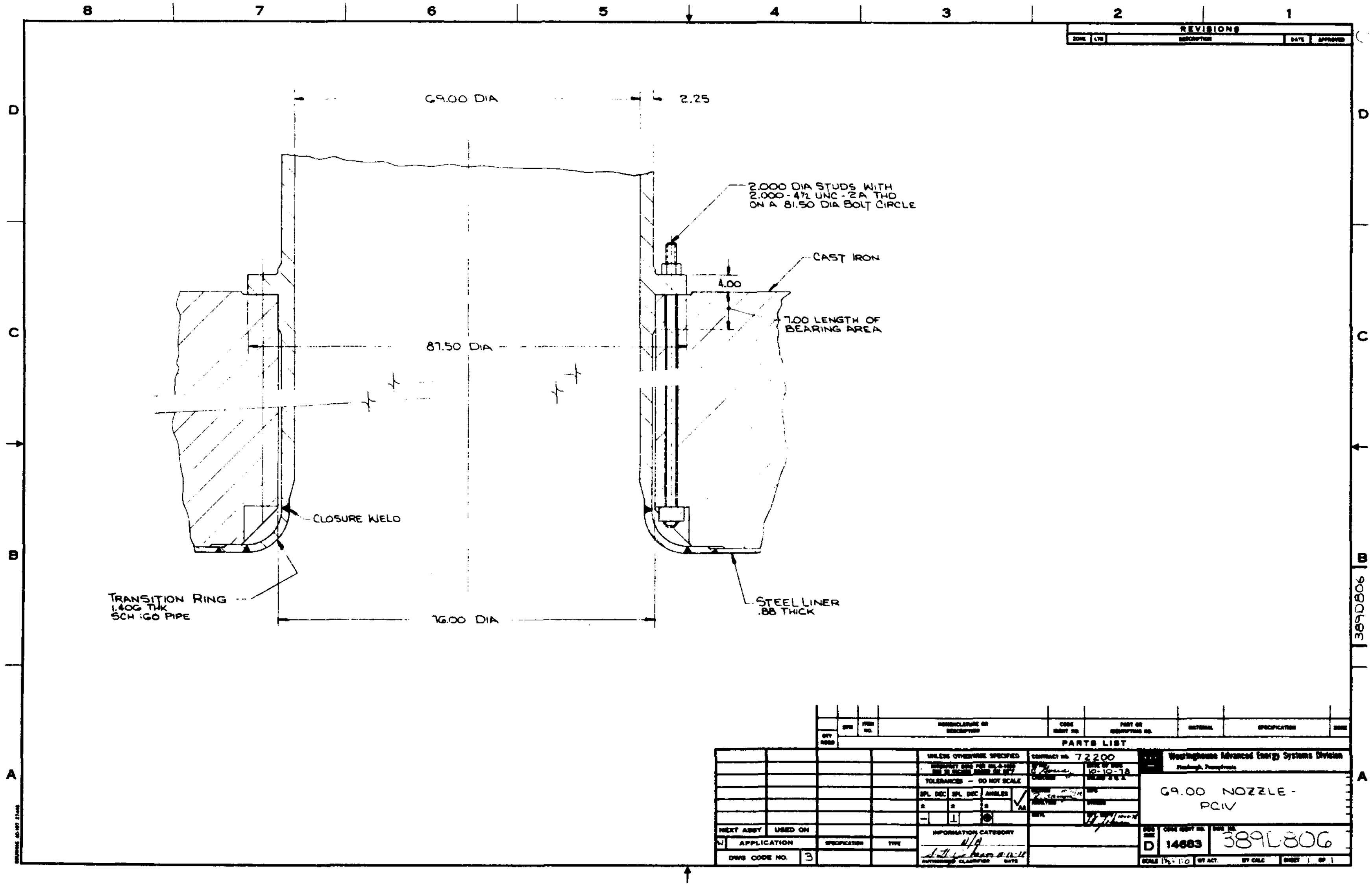

Figure 5.2-9. 69.00 Nozzle - PCIV

ring into the counterbored surface of the cast iron body segment by compression. Other loads such as longitudinal face, torsion and shear can also be transmitted by the attachment arrangement.

The nozzles themselves were designed to resist internal pressure without backup by the body of the PCIV. The wall thickness was sized in accordance with pressure piping rules in order to provide adequate strength. The transition piece that connects the nozzle to the liner is expected to also resist pressure loads without backup support from the cast iron body of the vessel.

The ability of the nozzle attachment designs to transmit the piping loads specified for the PCIV (see Section 4.0) was confirmed by analysis. Stress levels were about 80% of the allowable values for the 24 inch and 69 inch nozzles. The nozzle attachment for the 12 inch was analyzed to determine the strength of the attachment as related to the strength of the pipe itself. Results showed the attachment to be as strong or stronger than the pipe.

VESSEL PENETRATION

A description of the essential force system acting on the vessel penetration region is shown by the simplified sketch (Figure 5.2-10) of the cylindrical vessel region. This figure includes all the loading systems that stress the vessel penetration region, which are:

- Pressure System (p_i)
- Preload System: P_{ro} = pressure due to external wrapping; T_d = preload in casting due to tension in axial tendon.
- Local Piping Force System: F_t = nozzle shear force, F_r = nozzle axial load, M = nozzle bending moment, M_r = nozzle torque load
- Overall Vessel Shell (or head) forces: where T_v = vessel torque, P_v = vessel axial load due to pressure, weight and external pipeforces, M_v = vessel bending moment, S_v = vessel shear force.

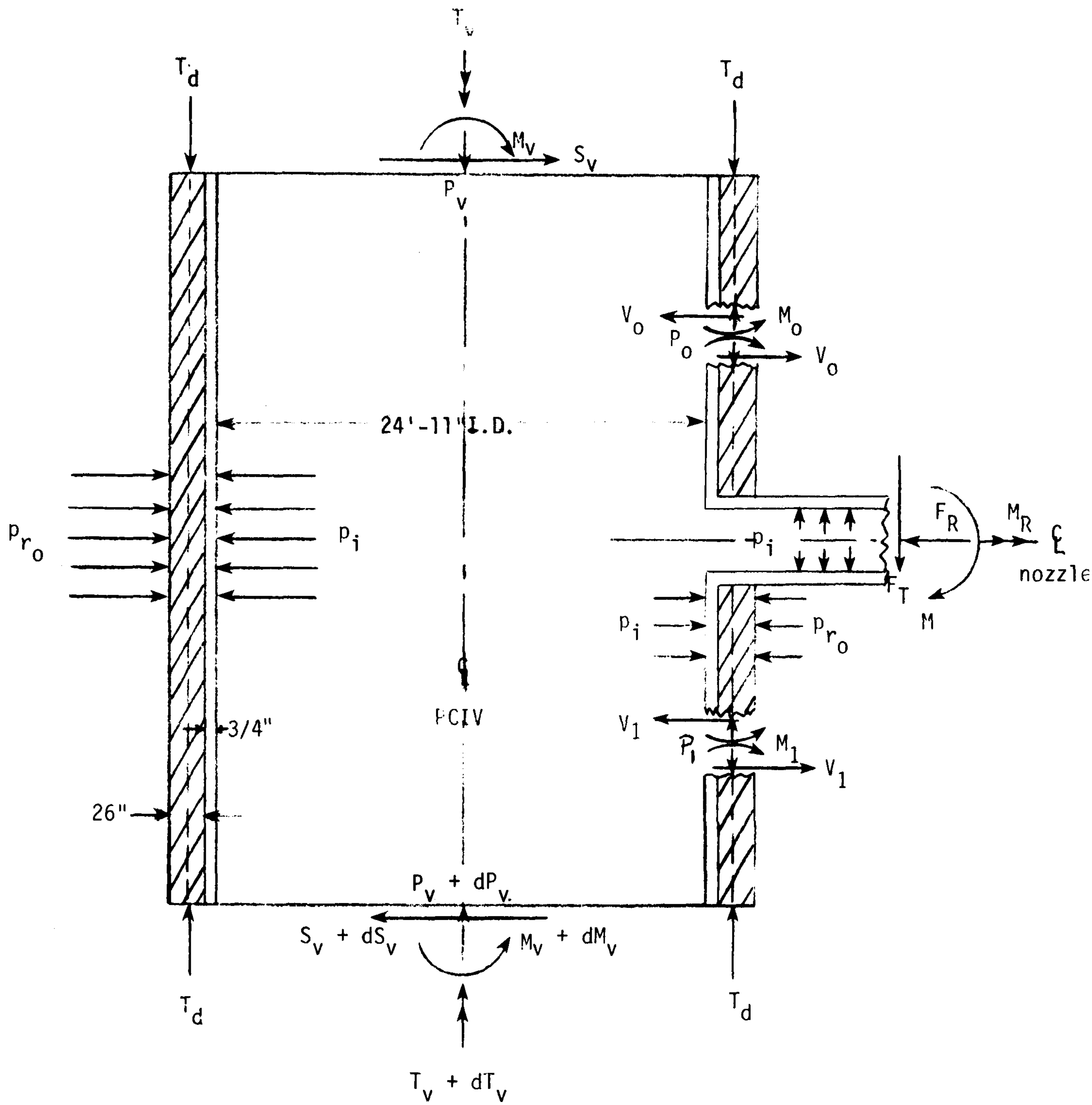

Figure 5.2-10. Forces on Vessel Penetration Region

Also, a similar system exists for the head region and follows essentially the same logic except for the change in configuration at the head penetration region.

The cylindrical portion (as well as the head) of the vessel penetration region will be exposed to all four loading systems mentioned previously such that superposition of the resulting stress systems will result in a net compressive stress in the casting sectors especially at mating surfaces. Also, the mating surfaces must resist shear to avoid slip displacement due to vessel shears (S_v and T_v), and local thickness shears (V_0, V_1) introduced by pipe forces (F_T, F_R, M, M_R). The shear transfer, depending on the magnitude of shears, can be resisted by friction, adhesive material, welding or by shear key provisions.

From the analytical work done, it was found that the penetrations in the wall and head of the PCIV do not weaken the structure beyond an acceptable level as determined by the hoop and longitudinal compression in the cast iron body. Extra wraps of prestressing cables in the regions where nozzles penetrate also help to maintain the pressure carrying strength in the vessel in the nozzle regions.

5.2.7 COOLING SYSTEM

The PCIV as designed conceptually for a coal gasifier application is subjected to internal hot gas of 3000°F in Stage I and about 2100°F average temperature in Stage II. Since these temperatures are too high for the structural parts of an ASME type pressure vessel, a cooling arrangement whether passive or active, must be used.

A passive cooling system that would use free convection and radiation from the outside of the vessel was considered but not selected primarily because of the difficulty in transferring heat radially past the prestressing members without raising their temperature significantly. Of course, if sufficient thermal insulation could be used inside the vessel, this approach could be used. The thickness of insulation required however is unacceptable primarily because of economics.

The cooling system selected is a forced air cooling system as depicted in Figure 5.2-11. Air is used rather than water to eliminate leakage problems during the service life of the vessel. Three blower units are mounted at ground level to force outside air into the enclosed area of the foundation. From this region the air flows thru the lower head, vertically upward through passageways provided in the sidewall of the vessel and filters outward through holes provided in the thickness of the upper head. The number of blowers required depends on outside air temperature since cold air provides better cooling than hot air. During normal operation two blowers are adequate for providing the cooling to keep the tendons and circumferential cabling below 140°F. On a hot day, the third blower is required because of the difficulty in cooling with 90°F inlet air.

Figure 5.2-12 shows a characteristic section of the vessel wall with materials and dimensions. Required cooling is provided by passing air through longitudinal cooling passages in the cast iron wall section. The passages are closely spaced around the vessel liner to provide uniform cooling of the cast iron wall. The passage positions provide necessary cooling for the entire cast iron wall section minimizing the temperature of both the vertical and circumferential prestressing members and eliminating significant temperature gradients in the cast iron.

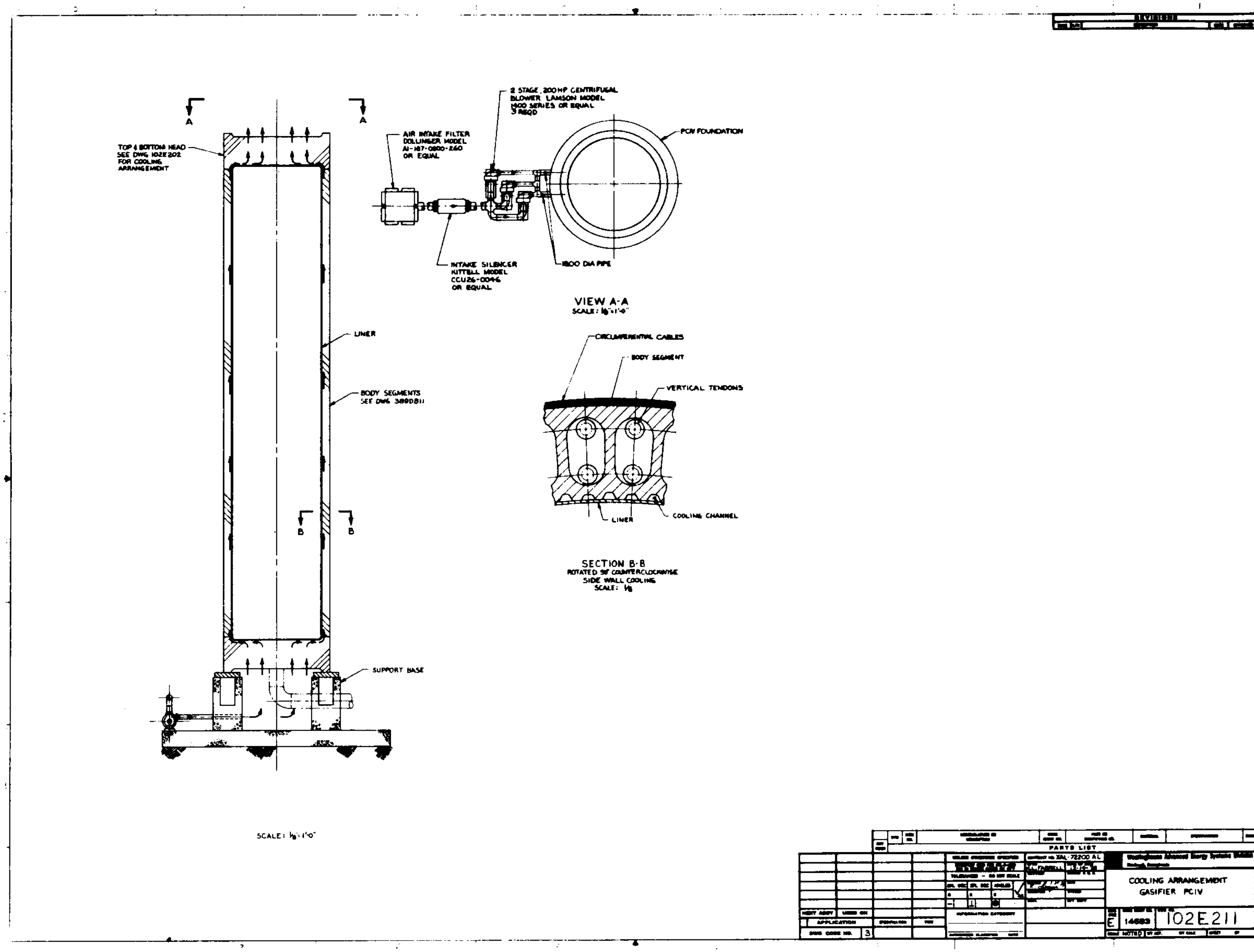

Figure 5.2-11. Cooling Arrangement Gasifier PCIV

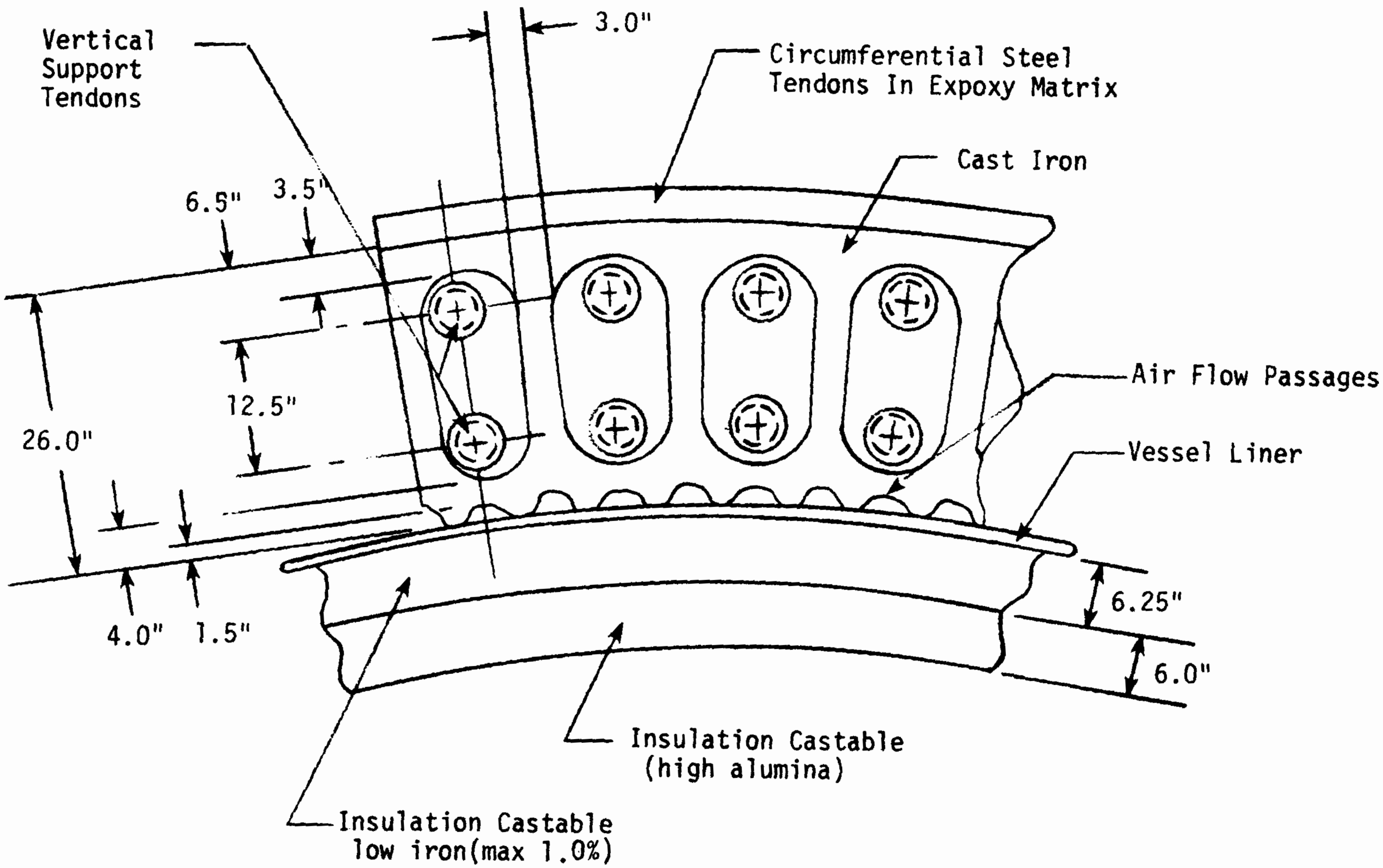

Figure 5.2-12. Cooling of PCIV Sidewall

The prime objective of the cooling system is to maintain the temperature of the highly stressed prestressing members below the maximum allowable operating temperature for these members (about 160°F). The maximum allowable temperature is determined from the stress relaxation characteristics of the material. This is a time and temperature related phenomenon and is duscussed in Section 5.3 along with experimental data and acceptable operating temperatures.

Cooling system requirements are derived from necessary heat flux removal to obtain desired temperature levels in the cast iron wall body and prestressing members. Ambient air entering the bottom of the vessel flows through the cooling passages and exits at the top of the gasifier. The limiting factor in the air cooling requirement is the allowable magnitude of the air temperature rise. Thus, on a "hot" day with a higher inlet air temperature, a greater flow is required and consequently higher horsepower is necessary to cool the vessel wall to desired levels. Two cases were considered; a nominal ambient condition of 50°F and a hot day having a temperature of 90°F. Vessel heat fluxes were calculated for the wall configuration in various sections of the vessel, e.g., Figure 5.2-13. Heat flows were calculated via conduction through the various structural materials comprising the vessel wall, forced convection in the cooling air passages and natural convection and radiation from the vessel surface to the ambient. Table 5.2-3 lists materials and thermal conductivities for the wall section of Figure 5.2-13.

TABLE 5.2-3

VESSEL WALL MATERIALS

Material	Wall Thickness	Thermal Conductivity
Castable Insulation (high alumina)	6.0 in.	8-10 $\frac{\text{Btu-in.}}{\text{hr ft}^2\ {}^{\circ}\text{F}}$
Castable Insulation (low iron)	6.25	1.54 - 1.84 1.65 (500 °F)
Stainless Steel Vessel Liner	0.75	112.8
Cast Iron (Hollow)	26.0	384
Steel Cables In Epoxy Matrix	2.8 (TYP)	207.4

The heat transferred to the air stream causes the bulk air temperature to rise. The air temperature increase is limited at the flow exit (top of the vessel) to insure desired wall temperature conditions. The required flows then dictate the necessary supply pressure and horsepower to overcome frictional effects in the air passages.

The PCIV design temperature limits on the prestressing members are 140°F for normal operation (50°F inlet air) and 160°F for hot conditions (90°F inlet air).

Figure 5.2-14 shows the horsepower required for a 90°F ambient air condition to limit the maximum prestressing member temperature to either 140°F or 160°F. The horse power required is plotted a function of insulation (low iron castable) thickness. Clearly, the case having the higher allowable discharge temperature significantly reduces the horsepower requirement. Also, it can be seen that small increments of insulation added to the inner wall of the vessel further decreases the required cooling horsepower. Figure 5.2-15 shows the cooling horsepower required as a function of insulation thickness for the normal day and hot day design conditions described above.

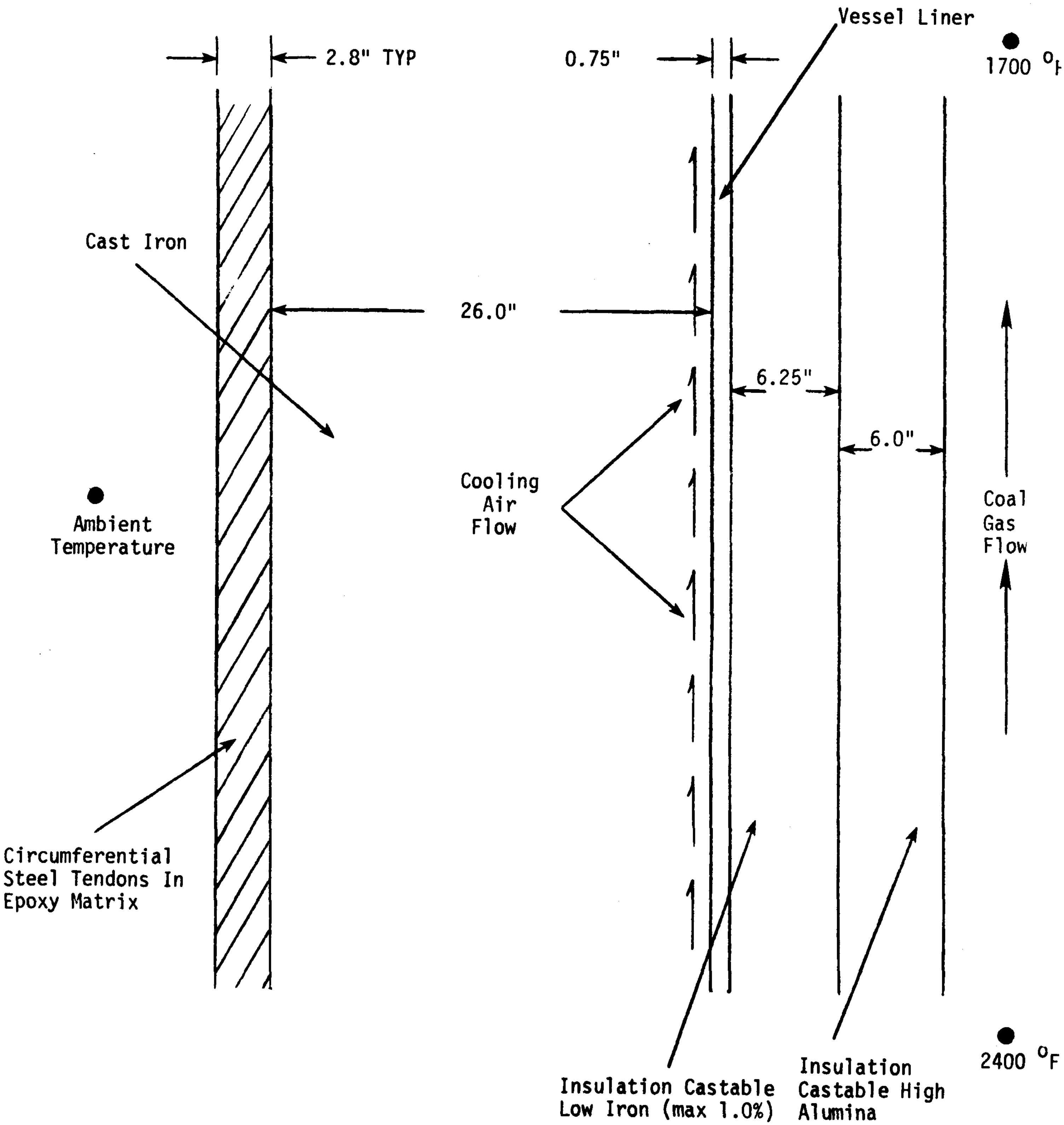

Figure 5.2-13. Composite of PCIV Sidewall

From the considerations on Figures 5.2-14 and 5.2-15, the conceptual cooling system design for PCIV was chosen to minimize costs. A low iron castable insulation thickness of 6.25 inches was chosen. This insulation thickness results in a cooling air flow rate of 50,000 cfm with resulting pressure drop of 2.2 psi and a blower output horsepower rating of 570 hp for the hot day design point (160°F). With the nominal 50°F ambient air and a 140°F maximum temperature the flow rate, pressure drop, and horsepower become 38,000 cfm, 1.4 psi, and 275 hp. Table 5.2-4 summarizes this information. Material temperatures expected during operation are shown in Table 5.2-5 along with allowable temperatures.

TABLE 5.2-4

COOLING SYSTEM REQUIREMENTS

Design Condition	Horsepower	Flow Rate (cfm)	Pressure Drop (psi)
90 ^{o}F ambient air inlet	570	50,000	2.2
50 ^{o}F ambient air inlet	275	38,000	1.4

In summary, the described cooling system will maintain the tendon temperatures below the design limit. Refinement of the cooling system design should allow horsepower requirements to be reduced to less than 400 hp. These refinements may include using the air space surrounding the vertical tendons as additional cooling passages and additional high quality thermal insulation.

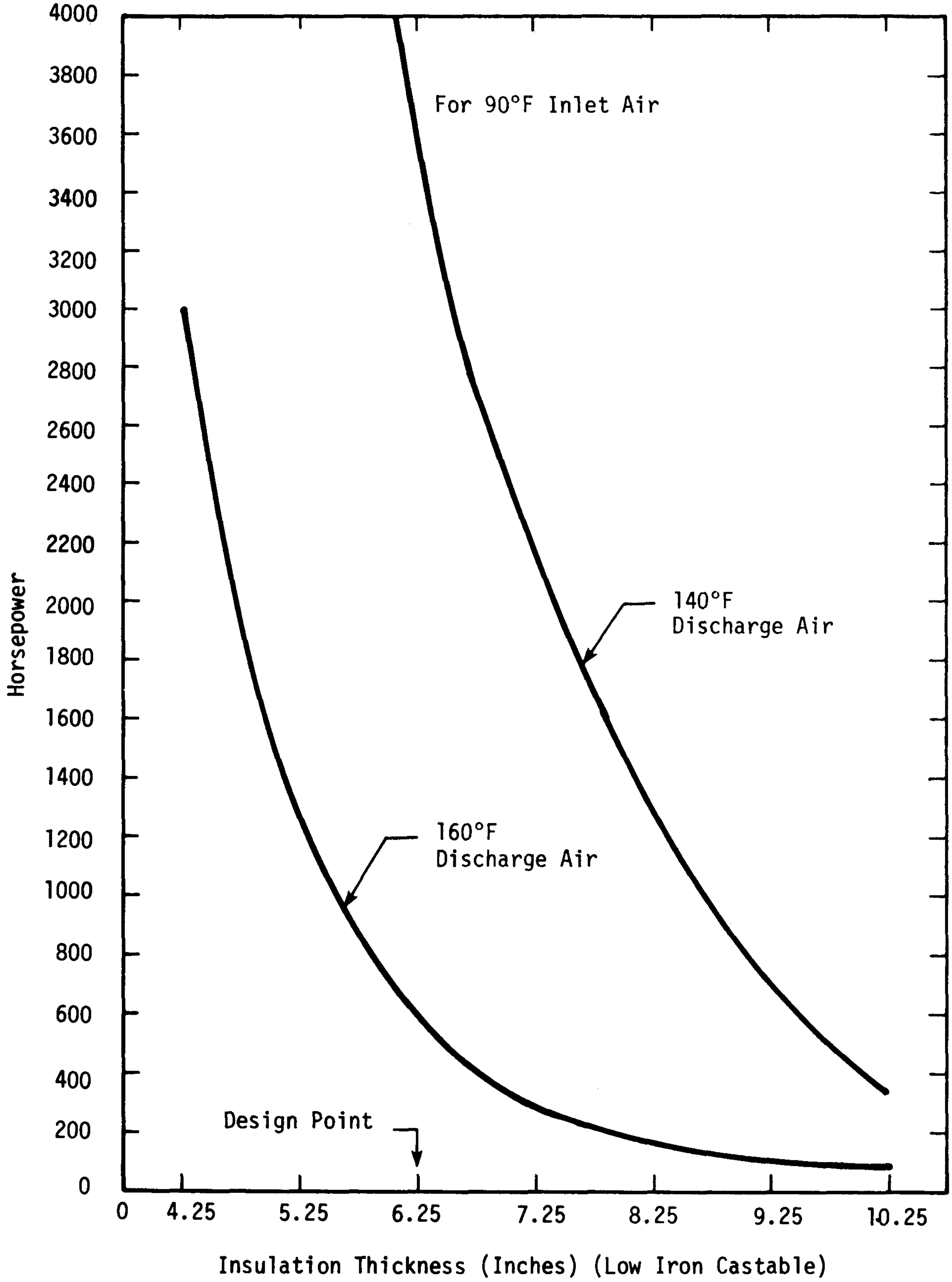

Figure 5.2-14. Variation in Aircooling Horsepower Requirements with Insulation Thickness for Two Air Discharge Temperatures

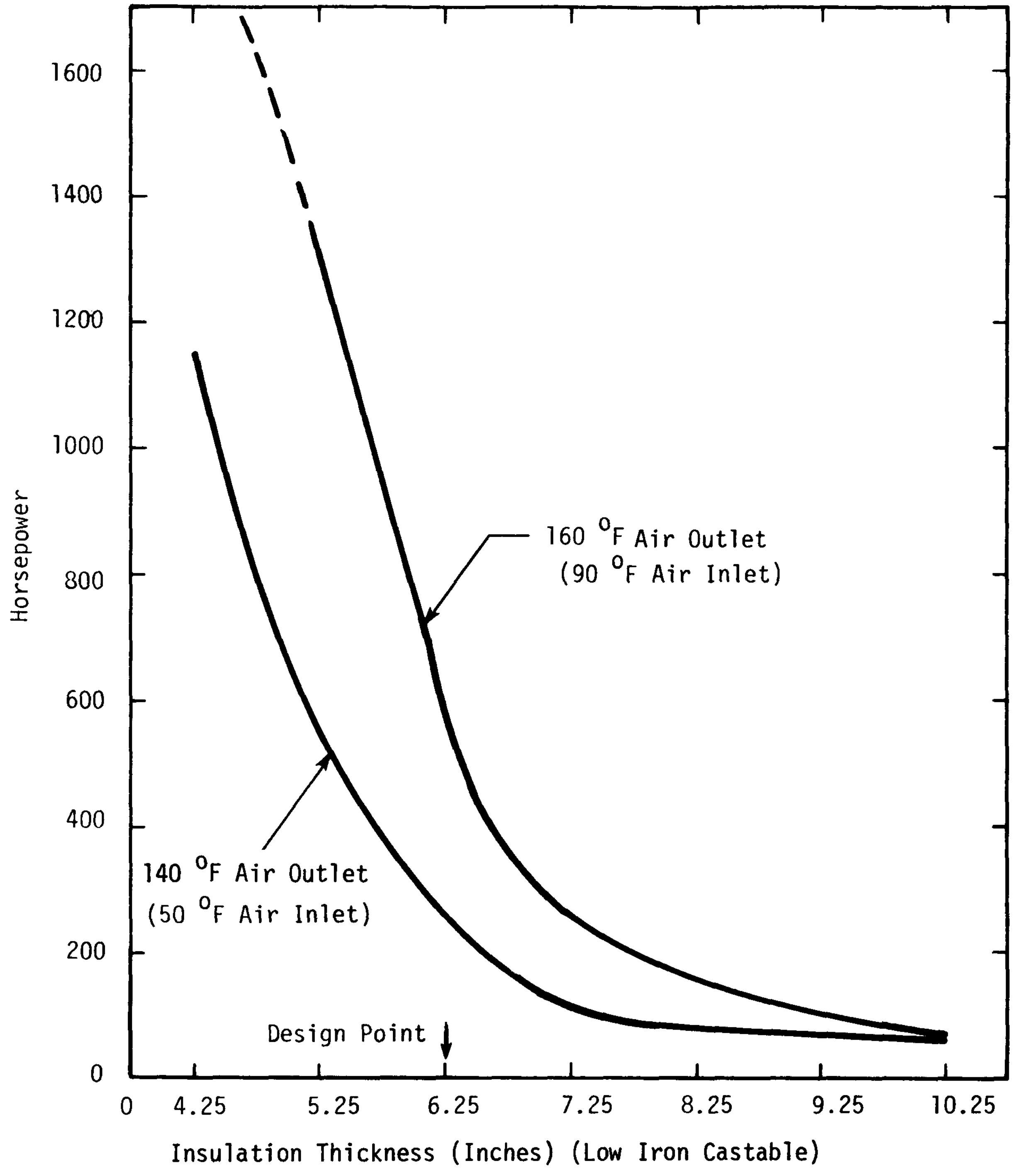

Figure 5.2-15. Air Cooling Horsepower Requirements for Normal and Hot Day Conditions

TABLE 5.2-5

PCIV MATERIAL TEMPERATURES

COMPONENT	TEMP LIMIT (°F)	MAX TEMP ON HOT DAY[2] (°F)	MAX TEMP ON NORMAL DAY[3] (°F)
Axial Tendon	140[1]	160	140
Circumferential Cabling	140[1]	150	130
Cast Iron Body	~500	170	150
Liner	>500	180	160
Insulation (Low Iron)	2600[4]	2100	2100
Insulation (High Alumina)	3000[4]	2400	2400
Insulation (Alumina Plastic)	3250[4]	3000	3000

(1) 160°F is limit for short duration events such as a hot day condition.

(2) A "hot day" consists of 90°F ambient air.

(3) A "normal day" consists of 50°F ambient air.

(4) Data from Reference 1.

5.3 MATERIALS

5.3.1 INSULATION

Within the scope of the present evaluation program, the insulation concept presented in the reference field fabricated steel vessel (FFSV) study was determined to be compatible with the conceptual PCIV design. No significant penalties were imposed upon the PCIV by utilizing the FFSV insulation concept intact, and no significant cost advantage could be identified which would result from changing the materials or their method of support from or application to the liner. Accordingly, the FFSV insulation concept was adopted essentially in its entirety. A description of the concept and summaries of the insulating material properties and characteristics, derived for the most part from Reference 1, is given below.

An insulating castable is installed in contact with the vessel liner throughout the Stage I (lower) and Stage II (upper) regions, varying in thickness from 6.25 in. in Stage II to that required to fill the entire volume between the vessel liner and the internal cooling coils and tubes in Stage I. This layer functions in concert with the internal and external cooling systems to maintain the vessel liner at an operating temperature of 200^{o}F or less. The material specified is a low-iron alumina-silica-calcia formulation as defined and characterized in Table 5.3-1 (A).

Interposed between the insulating castable layer and the process environment are layers of refractory working linings in both Stage I and Stage II. In Stage I, the as-constructed lining is a 3-in. layer of phosphate-bonded high-alumina plastic as described in Table 5.3-1 (B). This lining is directly exposed to the 3000^{o}F temperature and slagging conditions of the Stage I process region, and will partially or completely react with and be replaced by the slag. When the vessel is cooled down for maintenance or repairs, the plastic/slag layer will become highly vitrified and will experience severe spallation damage. Thus, the Stage I working lining will require complete replacement prior to each process restart. A 6-in. layer of alumina-silica castable, described in Table 5.3-1 (C), constitutes the working lining for Stage II. Due to the lower temperature and somewhat less aggressive chemical environment in most of the Stage II region,

TABLE 5.3-1

REFRACTORY CHARACTERISTICS

(A) INSULATING CASTABLE: STAGES I AND II

Chemical Analysis (Ignited Basis)

Ignition Loss:	0.7%
SiO_2:	33.6
Fe_2O_3:	0.7
Al_2O_3:	56.5
TiO_2:	0.8
MgO:	0.2
CaO:	5.8
Alkalies:	1.5

Technical Data

Service Temperature:	2600°F (1426°C) max.
Material Required for Estimating:	67 lb/ft^3
Predampening Water:	14 - 15%

Thermal Conductivity:

Mean Temperature (°F)	Mean Temperature (°C)	Mean Conductivity (BTU - in/ft^2-hr-°F)
500	260	1.65
1000	538	1.54
1500	816	1.84
2000	1093	2.39

Physical Properties

After Firing and Cooling:

Hours	Temperature (°F)	Temperature (°C)	Cold Crushing Strength (psi)	Cold Crushing Strength (kg/cm^2)	Linear Change* (%)
24	250	121	300-400	21-28	-
5	1700	927	150-250	10-18	0.6 - 0.8 S
5	2000	1093	100-200	7-14	0.6 - 0.9 S
5	2500	1371	300-400	21-28	0.6 - 0.9 S
5	2600	1427	300-400	21-28	1.0 - 0.5 S

*S = Shrinkage

TABLE 5.3-1 (CONT'D.)

(B) WORKING LINING: STAGE I (HIGH ALUMINA PLASTIC, PHOSPHATE BONDED)

Chemical Analysis (Calcined Basis)

Al_2O_3:	89.5%
SiO_2:	6.0
P_2O_5:	3.7
Alkalies:	0.2
Other Oxides:	0.6

Technical Data

Service Temperature: 3250°F (1788°C) max.

Material Required for Estimating: 185 lb/ft^3

Thermal Conductivity:

Mean Temperature (°F)	Mean Temperature (°C)	Mean Conductivity (BTU - in/ft^2-hr-°F)
≤ 1600	≤ 871	8.0
2000	1093	8.5
2500	1371	9.5
3000	1649	11.8

Physical Properties

After Firing and Cooling:

Hours	Temperature (°F)	Temperature (°C)	Modulus of Rupture (psi)	Modulus of Rupture (kg/cm^2)	Linear Change* (%)
24	450	232	1900	133	0.3 S
5	1500	816	2540	178	0.0
5	2000	1093	3580	251	0.2 E
5	2500	1371	4720	320	0.5 S
5	3000	1649	2570	180	0.0

Panel Spalling Loss:

3000°F (1649°C) Preheat 0 - 2%

Average Storage Life: 6 months

*S = Shrinkage
E = Expansion

TABLE 5.3-1 (CONT'D.)

(C) WORKING LINING: STAGE II (ALUMINA-SILICA)

Chemical Analysis (Calcined Basis)

SiO_2:	43.1%
Al_2O_3:	50.0
Fe_2O_3:	1.1
CaO:	3.2
MgO:	0.1
TiO_2:	2.3
Alkalies:	0.2

Technical Data

Service Temperature:	3000°F (1649°C) max.
Material Required for Estimating:	135 lb/ft^3
Predampening Water:	3 - 4%
Maximum Grain Size:	6 mesh
Thermal Conductivity:	< 10 BTU-in/ft^2-hr-°F

Physical Properties

After Firing and Cooling:

Hours	Temperature (°F)	Temperature (°C)	Modulus of Rupture (psi)	Modulus of Rupture (kg/cm^2)	Linear Change* (%)
24	230	110	680	48	0.0 - 0.1 S
5	1750	954	600	42	0.0 - 0.1 S
5	2000	1093	600	42	0.0 - 0.1 S
5	2500	1371	610	43	0.1 - 0.2 S
5	2700	1482	-	-	0.0 - 0.1 E

CO Disintegration Test:

100 hr unaffected - carbon spots
200 hr unaffected - carbon spots

*S = Shrinkage
E = Expansion

this lining is expected to be relatively durable and to require only localized repair after typical vessel shutdown cycles.

The insulation/working lining layers are supported by various stainless steel hangers or anchors welded to the vessel liner as described further in Section 5.3.2

5.3.2 LINER AND ATTACHMENTS

The function of the liner in the PCIV gasifier is to serve as an essentially impervious barrier layer between the high temperature, high pressure harshly corrosive process gases and the cast iron vessel body segments and steel prestressing members. Although the liner is covered internally with insulation over most of the vessel area, it must be assumed for material selection purposes that the insulation layers develop crack networks in service which permit direct localized access of the process gases to the liner. Thus, in selecting liner materials with acceptable corrosion resistance, any protection afforded by the insulation is ignored. Structurally, the liner does not function as a pressure retaining shell but rather as a membrane through which pressure loads are transmitted to the cast iron segments. Nevertheless, it must be capable of accommodating without fracture the plastic and elastic strains developed when it deforms into intimate contact with the cast iron during the initial startup heating and pressurization cycle, and must resist fracture and buckling during both operational pressure/temperature fluctuations and subsequent shutdown/restart cycles.

The reference composition of the process gas (combustion and reaction products plus residual reactants) at the gasifier Stage II exit nozzle conditions of 1780°F and 1085 psig was given previously in Table 4.2-2. This is reproduced in Table 5.3-2 together with calculated values for concentrations of the gas constituents and for their partial pressures adjusted to the 1200 psig design value for maximum vessel operating pressure. For simplicity, it was assumed that this gas composition is constant throughout the vessel above the nominal quench tank water level. Partial pressures were assumed to vary directly with temperature in accordance with the Ideal Gas Law. (These assumptions are quantitatively inconsistent with the reference operating conditions of 3000°F and 1090 psig given for the gasifier Stage I region, but this was taken into account during the material selection process.)

The PCIV gasifier is designed as a cold wall vessel with a maximum liner operating temperature of 200°F or less. At this temperature condensation of certain acidic and basic chemical species will occur at the liner inner surface, so that liquid phase corrosive attack must be considered in addition to compatibility

TABLE 5.3-2

PROCESS GAS CONDITIONS AT STAGE II EXIT NOZZLE

Temperature: 1780°F (971°C)

Total Pressure: 1085 psig

Constituent	Throughput (kilomol/hr)	Concentration (mol %)	Partial Pressure* (psig)
H_2	56	24.4	293.4
CH_4	26	11.3	136.2
CO	61	26.6	319.7
CO_2	36	15.7	188.6
H_2O	44	19.2	230.5
H_2S	3	1.3	15.7
NH_3	2	0.9	10.4
N_2	1	0.4	5.3
O_2	0	0	0

*Adjusted to 1200 psig total pressure (design value).

with the process gas. Since sulfur dioxide does not appear in the reference gas composition, condensation of polythionic and sulfuric acids is not predicted; this is fortuitous since corrosive attack by these acids is a major problem in many areas of coal conversion technology. The liquid phase species whose condensation is credible and which would be of concern from a corrosion viewpoint are carbonic acid and aqueous solutions of ammonium hydroxide and hydrogen sulfide, and possible derivatives of these.

A large body of technical literature exists in which the application of structural alloys in coal conversion and similar or related chemical process systems (petrochemical, hydrocarbon, etc.) is discussed in terms of past and current industry practice and experience as well as the results of completed and ongoing materials research and development programs. A representative collection of these publications is identified in References 19 through 28, and these were consulted in detail to provide backup to the selection task in this study. The results of this effort, combined with corporate experience in similar areas, indicates that the principal process gas constituents of concern are hydrogen sulfide and hydrogen, and that only the aqueous hydrogen sulfide solution has significant potential for serious liquid phase corrosive attack. By orienting the selection study toward alloys resistant to these media under the given conditions, compatibility with the remaining gas and liquid phase constituents was virtually assured (although this was, of course, verified when the final selection was made).

A variety of carbon and alloy steels, austenitic and ferritic stainless steels and other ferrous alloys; and nickel-and cobalt-base alloys were considered as possible liner material candidates. A tradeoff study involving considerations of corrosion and hydrogen damage resistance, mechanical properties, formability, weldability, availability and cost led to the selection of Type 304L stainless steel as the material to be used, in the form of 0.75-in. plate, for the liner over nearly the entire vessel area. For application in the immediate vicinity of the nominal quench tank water level, where the potential for liquid-phase corrosive attack is somewhat greater, the higher-alloyed 20 Cb-3 stainless steel in the same plate thickness was selected. The corrosion and hydrogen damage resistance of these alloys is adequate for the application in terms of their nominal chemical/metallurgical constitution, and their resistance to sensitization during welding and hot forming operations ensures that a susceptibility to selective intergranular corrosion will not be developed during fabrication and construction.

Five relatively well characterized hydrogen-induced damage processes must be considered when selecting carbon, alloy or stainless steels or other ferrous alloys for service in a hydrogenous chemical process environment. Each of these is briefly described below, and pertinent implications regarding the stainless steels selected for the PCIV gasifier liner are discussed in each case.

- Surface Decarburization: Hydrogen may react with carbon in solid solution at the alloy surface to form methane (CH_4) gas, which then diffuses away into the surrounding process gas atmosphere. The result is a reduction in strength and hardness in the alloy surface layer, accompanied by an increase in ductility. Dissolved carbon in the alloy interior then diffuses toward the surface to restore chemical homogeneity, so that if the carbon diffusion rate is high, the surface region is continuously replenished and the overall effect is slight. However, over an extended time period, if the carbon in solution is not replenished by decomposition of initially present carbide phases, the dissolved carbon content will become sufficiently low to produce a reduction in bulk alloy strength. Thus, in steels in which the concentration of initially present carbide phases is low, or in which their stability is very high, massive decarburization can eventually be accomplished with serious deterioration of strength properties. This process is not operative in austenitic stainless steels and thus is not of concern for the Type 304L and 20 Cb-3 PCIV gasifier liner materials selected here.

- Internal Decarburization (Hydrogen Attack or Hydrogen Damage): Hydrogen may diffuse into the interior of the alloy and react with carbon in solution to form methane gas. The methane cannot diffuse out of the steel, but rather condenses in and accumulates at voids and grain boundaries. This eventually results in the development of high localized internal stresses which may ultimately produce fissures, cracks or blisters in the member. Resistance to this process is provided by the addition of alloying elements having relatively strong tendencies to form stable carbides, thus minimizing the amount of carbon available in solution to react with hydrogen.

Chromium, molybdenum, tungsten, vanadium, titanium and columbium are the principal carbide-forming alloying elements used to provide resistance to internal decarburization. Due to their high chromium contents, austenitic stainless steels, including the Type 304L and 20 Cb-3 liner alloys selected here, are not susceptible to this damage process.

- Hydrogen Precipitation: At elevated temperatures, many ferrous alloys have an appreciable solid solubility for hydrogen, and this solubility increases with increasing hydrogen partial pressure; during extended operation at process conditions, hydrogen will diffuse into the alloy until an equilibrium concentration corresponding to this solubility is established. If the process system is rapidly cooled from this condition, especially without depressurization prior to cooling, the diffusion rate of hydrogen out of the alloy may not be high enough to compensate for the decreasing solubility and hydrogen will then condense internally at voids, grain boundaries and other imperfect lattice regions. As in the case of internal methane formation, this can result in the development of high localized stresses leading to fissuring, cracking or blistering. Although this process can operate to cause serious damage in austenitic stainless steels, it will not be a problem in the current PCIV gasifier design for two reasons. First, the difference in hydrogen solubility between the 200^{o}F maximum liner operating temperature and typical ambient atmospheric temperatures is relatively small; and second, the shutdown procedure for the gasifier is specified as initial depressurization at temperature followed by slow cooling, a sequence which provides ample time for outward diffusion of hydrogen as its solubility in the alloy decreases.

- Hydrogen Stress Cracking: In steels that have been heat treated to very high yield strength levels and then operated at high tensile stress levels in a hydrogen environment, a fracture mechanism analogous to (or perhaps identical to) stress corrosion cracking can operate to produce accelerated crack propogation terminating in sudden and unanticipated failure. Similar effects have been experienced and demonstrated in severely sensitized austenitic stainless steels, but these are not observed in unsensitized material. The sensitization-resistant 304L and 20 Cb-3 alloys selected for the PCIV are not subject to damage by this process.

- Hydrogen Embrittlement: A severe reduction of ductility and strength can be attributed to the presence of dissolved hydrogen in many ferritic alloys. This is not observed in austenitic stainless steels, however, and is thus of no concern for the PCIV liner materials.

Three approaches to implementing the selection of Type 304L and 20 CB-3 were examined; these were solid 0.75-in. stainless plate, 0.125-in. stainless clad on 0.625-in. carbon - 0.5 molybdenum steel, and 0.125-in. stainless clad on 0.625-in. plain carbon steel. The tradeoff in the clad plate cases is principally one of reduced starting material cost versus the additional cost of the cladding operation and a potential increase in welding process complexity. Cost studies were based on plates clad by roll bonding or explosive bonding; cladding by weld overlay was determined to be an unacceptable approach in this case because of the distortions to be expected in this relatively thin plate. In the clad plate cases, the resistance of the backing plate material to hydrogen damage must be separately assessed since hydrogen from the process gas will diffuse through the stainless clad and into the backing steel. Under the given operating conditions, the carbon - 0.5 molybdenum steel was found to have adequate hydrogen damage resistance but the plain carbon steel was judged to be marginal and was eliminated from further consideration for that reason. On a material cost basis, the stainless clad carbon - 0.5 molybdenum steel was found to have only a slight advantage over the solid stainless steel plate, and further consideration of welding complexity and cost and repair procedures for damaged plates produced a decision in favor of the solid stainless steel material.

Another liner material concept investigated in detail was an approximate analog to the reference FFSV concept; i.e., a liner made from 2.25 Cr - 1.0 Mo alloy steel plates having a 0.125-in. corrosion allowance in the upper Stage II portion of the vessel, a 0.125-in. Type 304L stainless steel cladding over most of the Stage I portion, a 0.125-in. Alloy 20 (an older version of 20 Cb-3 stainless steel) cladding over the region adjacent to the nominal quench tank water level, and a 0.25-in. corrosion allowance over the balance of the quench tank surface. Incorporation of such an analog in the PCIV gasifier design would have simplified the PCIV/FFSV cost comparison. However, this approach was rejected for two fundamental reasons; first, the unavoidable requirement for post-weld heat treatment of the 2.25 Cr - 1.0 Mo alloy steel is conceptually and economically incompatible with the fabrication/construction procedures and sequences developed for the PCIV gasifier; and second, the corrosion resistance of the unclad portions of a 2.25 Cr - 1.0 Mo liner operating at the cold wall design condition of less than 200^{o}F would be unacceptable in the presence of the anticipated condensed liquid species previously discussed.

Table 5.3-3 presents a summary of the four liner concepts discussed above and displays the most important characteristics and considerations involved in the tradeoff evaluation. All materials considered are accepted for use under Section VIII of the ASME code, and the liner weldability and weld cost assessment was based on Code requirements as well. Table 5.3-4 presents the properties of the selected liner materials, Type 304L and 20 Cb-3 stainless steels, used as input to the mechanical and thermal analysis portions of the PCIV gasifier design effort.

The stainless steel plates are joined into the liner configuration by arc welding along the vertical and horizontal seams. A conventional 37.5^o v-groove weld preparation will be machined on all plate edges, and a 1.0 x 0.25-in. backing strip will be tack welded to the outer surface of one of the two plates meeting at each seam. SA-240 Type 304L backup strips and AWS ER 308L filler metal will be used at each 304L/304L joint; ASTM B-463 (20 CB-3) backup strips and AWS ER 320 (20 Cb-3) filler metal will be used at each 20 Cb-3/20 Cb-3 joint; and SA 240 Type 304L backup strips and AWS ER 320 (CB-3) filler metal will be used at the 304L/20 CB-3 joints. Welding will be performed from the liner inner surface side by either the GMAW or SMAW process, using automatic procedures to the greatest extent possible. To ensure maximum resistance to corrosive attack by sulfur, localized inner surface areas from which the surface oxide has been removed either accidentally (scratches, gouges, etc.) or deliberately (wire brushing or slag chipping of weld bead surfaces, etc.) will be reoxidized by torch heating prior to installation of the refractory insulation layer.

Specification of materials for components attached to or contained within the PCIV liner was not given major attention in this study since the overall cost impact of making minor material variations would be negligible for current purposes. The following listing follows the recommendations of the FFSV reference design in most cases:

- Exit Nozzle and Inlet Duct Attachment Sections: Type 304L or 20 Cb-3 stainless steel.
  - To facilitate welding to the vessel liner, all nozzles and ducts will terminate at the liner interface with an attachment section made of the same stainless steel as the liner in each case. The remaining portions of these members, not treated in this study, would be made from lower cost materials with corrosion resistant claddings where required.

TABLE 5.3-3

SUMMARY OF FINAL LINER CONCEPT CHARACTERISTICS (200°F max. liner operating temperature)

CONCEPT	LINER ALLOY OR BACKING PLATE ALLOY	LINER/BACKING PLATE WELDING CONSIDERATIONS	CLAD ALLOY				CLAD ALLOY WELDING CONSIDERATIONS	GENERAL CORROSION ASSESSMENT	HYDROGEN SERVICE ASSESSMENT	CONCLUSION
			STAGE II	STAGE I	QTWL* REGION	QUENCH TANK				
SOLID STAINLESS STEEL	Liner Alloy *Stages II & I and Quench Tank:* Type 304 L stainless steel plate (SA-240 Type 304 L) QTWL*Region: 20 Cb-3 stainless steel plate (ASTM B463)	*Type 304L:* No pre-or post-weld heat treatment req'd. 20 Cb-3: 300°F preheat and interpass temperature, no post-weld heat treatment.		N O N E			N. A.	Acceptable	No limitations	Favored concept; recommended for PCIV gasifier.
STAINLESS CLAD LOW-Mo STEEL	Backing Plate Alloy 0.21 C - 0.90 Mn - 0.50 Mo st plate (SA-204 Grade A) Stages II & I and Quench Tank: Clad plate per SA-264 QTWL* Region: Clad plate per SA-265	No pre-or post-weld heat treatment req'd. for ≤ 0.625-in. thickness.	SA-240 Type 304L	SA-240 Type 304L	ASTM B463 20 Cb-3	SA-240 Type 304L	Type 304L: No pre-or post weld heat treatment required. 20 Cb-3: 300°F preheat and interpass temp., no post-weld heat treatment.	Acceptable	No limitation for this application.	Concept rejected for conceptual design, but should be reconsidered in detailed design phase.
STAINLESS CLAD PLAIN CARBON STEEL	Backing Plate Alloy 0.20 C - 0.90 Mn steel plate (SA-516 Grade 55) Stages II & I and Quench Tank: Clad plate per SA-264 QTWL* Region: Clad plate per SA-265	No pre-or post-weld heat treatment req'd.	SA-240 Type 304L	SA-240 Type 304L	ASTM B463 20 Cb-3	SA-240 Type 304L	Type 304L: No pre-or post weld heat treatment required. 20 Cb-3: 300°F preheat and interpass temp., no post-weld heat treatment.	Acceptable	Marginal for this application.	Concept rejected due to hydrogen service assessment.
ANALOG TO FFSV REFERENCE DESIGN	Liner or Backing Plate Alloy 2.25 Cr - 1.0 Mo steel plate (SA-387 Grade 22)	400°F preheat and interpass temperature, 1250°F post-weld heat treatment.	None	SA-240 Type 304L	ASTM B463 20 Cb-3	None	Pre-and post-weld heat treatment dictated by backing plate alloy requirements.	Not Acceptable	No limitation for this application.	Concept rejected due to post-weld heat treatment requirement and general corrosion assessment.

*QTWL = Quench Tank Water Level

TABLE 5.3-4

DESIGN PROPERTIES OF LINER PLATE ALLOYS

PROPERTY	ALLOY AND TEMPERATURE			
	Type 304L Stainless Steel		20 Cb-3 Stainless Steel	
	70^oF (21^oC)	200^oF (93^oC)	70^oF (21^oC)	200^oF (93^oC)
0.2% Yield Strength (ksi)	25	23	40	36
Ultimate Tensile Strength (ksi)	70	63	85	80
Elongation in 2 inches (%), min.	40	37	30	31
Modulus of Elasticity (M psi)	28.3	27.6	28.3	27.6
Poisson's Ratio	0.31	0.31	0.31	0.31
Density (lb/in^3)	0.29	0.29	0.29	0.29
Linear Thermal Expansion Coefficient ($^oF \times 10^6$)	9.6 avg.		8.31 avg.	
Thermal Conductivity (BUT-in/ft^2-hr-^oF)	113	120	81	90

- Cooling Coils: 1.25 Cr - 0.5 Mo Steel (SA 335 P11).

  - These coils will contain pressurized water and steam and may be exposed to the process gases, but their outer surface temperature should be high enough to preclude condensation. Under these conditions, the alloy content is sufficient to resist internal or external corrosion as well as hydrogen damage.

- Refractory Anchors: Type 310 Stainless Steel.

  - This material will provide adequate corrosion resistance and high temperature strength to effectively support the refractory insulation and working lining layers.

- Refractory Washers: Type 304L Stainless Steel.

  - This alloy will provide adequate corrosion resistance and is compatible with the liner alloys from weld attachment considerations.

- Quench Tank Cone and Exit Duct: Type 316L Stainless Steel.

  - This alloy will provide adequate general and intergranular corrosion resistance to the quench tank liquid and erosion resistance to the exiting entrained slag particles and other solids.

These latter material choices will be carefully reviewed and modified if necessary during the detailed vessel design phase.

5.3.3 BODY SEGMENTS

5.3.3.1 BACKGROUND

The recommended building block material for the pressure vessel body is gray cast iron. Gray iron is generally recognized as the least expensive of the cast ferrous metals; consequently, it is usually considered first when a casting is required (Reference 6). A property review of the material has indicated that it will perform adequately for coal gasifier PCIV applications.

The principal elements in gray iron are carbon and silicon (Reference 7). Carbon significantly reduces the melting point of iron. Silicon has a similar effect, but also promotes graphite flake formation upon solidification as opposed to that of massive hard iron carbide particles. Typical gray iron microstructures are composed of graphite flakes in a matrix of lamella ferrite and iron carbide (pearlite), or pearlite and ferrite. Phosphorous and sulfur are common impurities in gray iron, and both are controlled at low levels in engineering castings to avoid loss of strength. Manganese, another element found in gray iron, serves to reduce the deleterious influence of sulfur.

A charge of pig iron, scrap metal, recycled casting gates and risers, and coke is usually melted in a cupola furnace to produce gray iron; consequently, one or more of a wide range of tramp elements common to the scrap materials may also be present. Elements are also added to gray iron to enhance specific properties; for example, molybdenum is commonly used to improve strength and reduce the variation of strength with casting section size (Reference 6).

Excellent castability and machinability are two notable characteristics favoring selection of gray iron for the PCIV body. The review of casting and machining parameters presented for gray iron in Table 5.3-5, where comparison is made to cast steel, exemplifies this point.

The wide differential between pouring and solidification temperatures inherent to gray iron results in high fluidity, and the ability to produce castings of very complex shape and varied section thickness. The internal combustion engine cylinder

TABLE 5.3-5

GRAY IRON AND STEEL CASTING PARAMETER COMPARISON

PARAMETER	GRAY IRON	CAST STEEL
Pouring Temperature* (max)	2750^{o}F	3000^{o}F
Solidification Temperature * (min)	2075^{o}F	2700^{o}F
Solidification Shrinkage *	gray iron < <	steel
Furnace *	Cupola	Open hearth; electric
Machinability Index ** (Based on AISI B1112 Steel - 100)	110	55 - 70

*Reference 6

**Reference 7

block is an example of a complex gray iron casting which cannot be commercially produced from cast steel (Reference 6). Formation in gray iron of graphite, a phase exhibiting ~1/3 the density of iron, reduces the amount of shrinkage associated with solidification. Consequently, shrinkage defects are less likely in gray iron than in cast steel. The lower temperatures involved in the production of cast iron and its higher carbon content permits use of a cupola melting furnace where fuel (coke) and the charge are intimately mixed. This results in better process efficiency and lower cost than possible with cast steel where open hearth or electric furnace melting is required. Presence of graphite in the microstructure of gray iron enhances machinability, an important consideration since the PCIV body blocks must be finish machined to fairly close tolerances. A prestressed gasifier vessel fabricated from cast steel would be considerable more expensive than a PCIV.

Properties developed in a cast iron, particularly mechanical properties, are more dependent on the rates of solidification and subsequent cooling than on its composition (References 5, 8, 9). For example, the same composition could develop a high strength, hard, unmachinable white iron microstructure* when rapidly solidified and cooled, as might occur if cast as a thin section, but a lower strength, soft, very machinable gray iron structure** when more slowly solidified and cooled, as might occur if cast as a thick section. Consequently, gray iron specifications normally identify classes of material according to tensile strength level measured on a separately cast bar or an attachment to the casting, and do not impose major control over composition (References 10, 11). This allows the foundry personnel to achieve the required strength by adjusting composition to suit the size of the casting (Reference 8).

5.3.3.2 SELECTION

Gray iron of Class 40 C identified in specification ASME SA 278 (Reference 10) was selected as the PCIV block material. The basic requirement established by this selection is that a two-inch diameter test casting poured along with a PCIV casting exhibit a minimum tensile strength of 40 ksi. This is the largest

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*Typically massive iron carbide particles in a pearlite matrix

**Typically graphite flakes in a pearlite matrix test bar (type C) allowed by the specification without involving negotiations between purchaser and foundry. Several gray iron foundries have provided quotations for the PCIV body castings without indicating any problem with producing them to ASME SA 278, Class 40 C.

Some limits over sulfur and phosphorous content and carbon equivalent* are required in specification ASME SA 278 for Class 40 and stronger material used at or above 450^{o}F. Although the PCIV body castings will operate far below this temperature, this chemical control will still be imposed, since it will contribute to production of better grade material. A summary of PCIV body casting requirements is given in Table 5.3-6, Part (A).

An analysis of the cost to produce castings from a wide range of gray iron classes, and the return obtained in terms of compressive strength, was used as a guideline for selecting Class 40 gray iron as the PCIV body material. Casting cost was compared with compressive strength since this mechanical property is of paramount importance in the body material. The cost data included that of coremaking, moulding, shakeout, cleaning, scrap loss and casting metal, reported for a hypothetical 200 pound casting produced from Class 25 through 60 gray iron (Reference 5). Material class was determined from the tensile strength of separately poured 1.2 inch diameter test bars.

Results of the analysis are summarized in Figure 5.3-1 where the ratio of relative casting cost to minimum compressive strength (Reference 7) is plotted against gray iron class number. The best return in terms of compressive strength, indicated by the minima in the plot, falls in the range of Class 40 to 50 gray iron. Major reasons for obtaining lower returns for material above and below this class range are: the extensive use of costly alloying element additions is not offset by sufficient strength improvement in material above Class 50, while the lower compressive strengths of irons below Class 40 are not offset by significant reductions in casting cost. Class 40 gray iron was selected as the PCIV body material on the basis that machining costs, which remain relatively constant up to this class, increase significantly for stronger irons (Reference 5).

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*% C + .3 (% Si + % P)

TABLE 5.3-6

SPECIFICATION AND PROPERTIES OF THE PCIV BODY MATERIAL

(A) Specification

Material	Gray Cast Iron
Specification	ASME SA 278
Class	40 C
Test Casting	2 inch diameter (type C)
Test Specimen	1-1/4 inch diameter (type C)
Tensile Strength	40 ksi (minimum)
% P	0.25 (maximum)
% S	0.12 (maximum)
Carbon Equivalent*	3.8 (maximum)

(B) Design Properties **

Compressive Strength	3.5 x Tensile Strength
Shear Strength	1.4 x Tensile Strength
Elastic Modulus	18×10^6 psi
Fatigue Strength***	17.5 ksi
Poisson's Ratio	0.26
Thermal Expansion	$5.6 \times 10^{-6}/^{o}F$
Thermal Conductivity	384 BTU-in/ft^2-hr-°F at 200°F
Specific Heat	0.11 BTU/lb-^{o}F at 200^{o}F

*% C + 0.3 (% Si + % P)

**At room temperature except where otherwise noted

***Zero mean stress rotating beam test

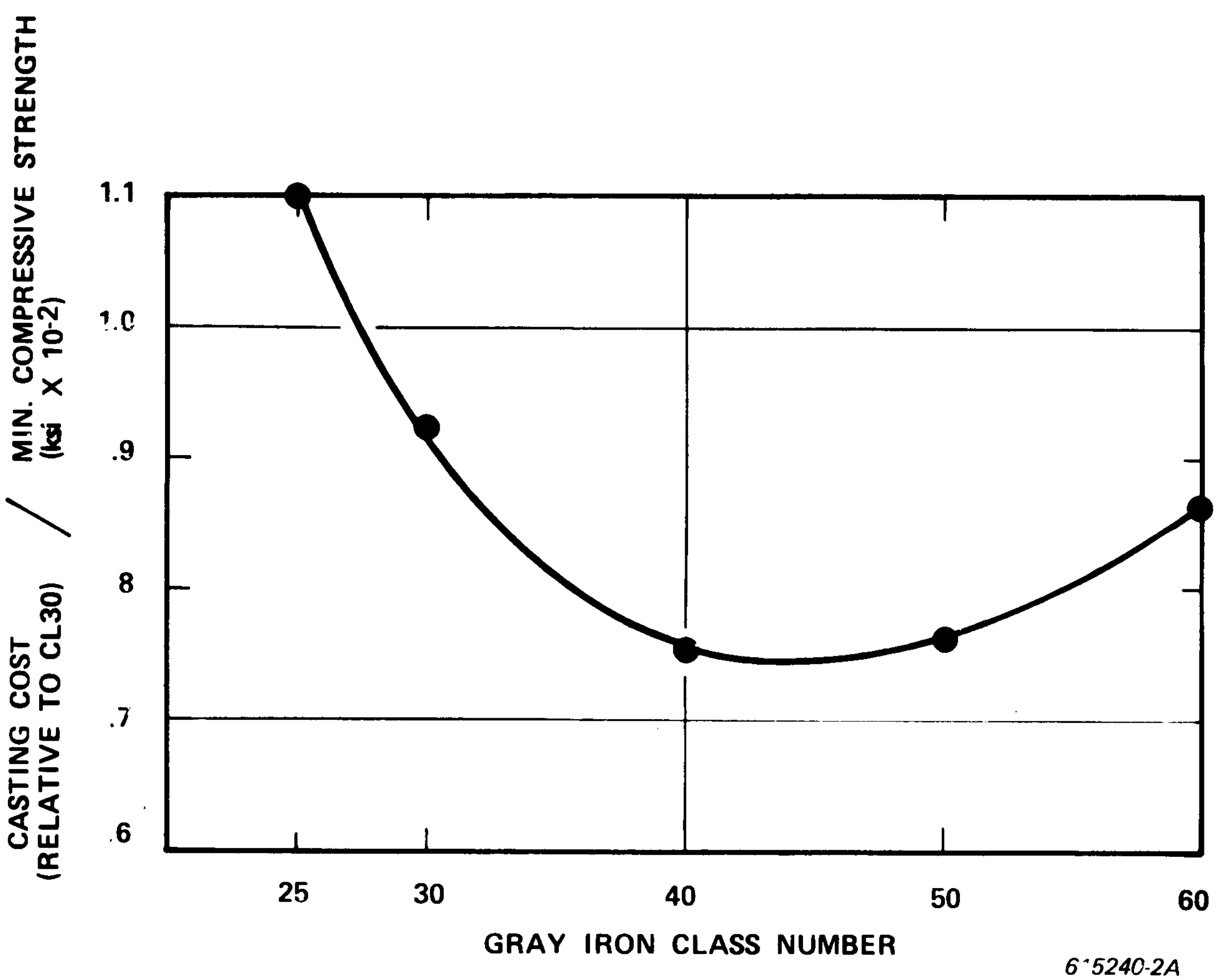

Figure 5.3-1. The Relationship of Casting Cost of Compressive Strength for Class 25 to 60 Gray Iron.

Class number and compressive strength were determined from 1.2 inch diameter separately cast test bars (References 5, 8). Casting costs were reported for a hypothetical 200 pound casting (Reference 5).

It is recognized, however, that the information summarized in Figure 5.3-1 constitutes only a preliminary basis for choosing a gray iron class for PCIV body application. The cost data used represented a hypothetical casting much smaller in size than a PCIV body casting. Some shift in the curve minima would be expected because of different costs involved in producing a PCIV casting. The method used to define the gray iron class will also influence the location of the curve minima. For example, if a test bar of diameter larger than 1.2 inch had been poured to classify tensile strength (class number) of the castings, the curve minima would be shifted somewhat in the direction of lower class numbers, since the bigger test bar will cool slower and be weaker. Optimization in the selection of a gray iron PCIV body material will require some refinement in the method of sampling to specify class number. The impact of this optimization on PCIV cost will be negligible, however, since a basic material change would not be involved.

5.3.3.3 PROPERTIES

Although gray iron having a minimum tensile strength of 40 ksi when poured as a two inch diameter Type C test bar is the recommended body material, the actual strength of the comparatively massive PCIV castings will fall below this level due to their slower cooling rate. An estimate of the strength developed in the body castings can be made using data reported for the dependency of the property on casting diameter, and consideration of cooling rate differences.

The decrease in room temperature tensile strength of Class 40 gray iron with increased casting diameter occurs according to the following approximate relationship (Reference 5).

1. $$T_c \sim 28 + \frac{24}{d} \ *$$

The dependency of strength on wall thickness for the internal webs and outer walls of a PCIV body casting will not follow this relationship since they

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*T_c = cast cylinder tensile strength (ksi); d = cylinder diameter $\geq$ 2 inches

approximate plates more so than cylinders, and will cool differently. The parameter $(V/A)^2$ is usually compared when estimating cooling rate differences for castings which differ in shape (Reference 9). This comparison, which is considered conservative (Reference 5), indicates that to have equivalent cooling for a plate and a cylinder, the thickness of the plate must be 1/2 that of the cylinder diameter. Modification of Equation 1 accordingly, to estimate plate strength yields:

$$2. \quad T_p \sim 28 + \frac{12}{t} \quad *$$

A tensile strength of ∿28 ksi is the lower limit estimated for Class 40 C gray iron when cast in very thick plate sections. The three inch thick radial webs in a body segment casting would be estimated to exhibit a tensile strength of ∿32 ksi.

The relationship between tensile strength and section thickness is plotted in Figure 5.3-2. Also plotted is the estimated dependency of compressive strength on section thickness obtained by modifying equation 2 for a factor of 3.5 difference between tensile and compressive strength. The ratio of compressive to tensile strengths of gray irons decreases from ∿4 to 3 as class number changes from 20 to 60 (References 8, 9), with 3.5 being typical of Class 40 material. The compressive strength relationship, given in Figure 5.3-2, indicates that ∿98 ksi is the lower limit estimated for Class 40 gray iron when cast in very thick sections. Webs of three inch thickness should exhibit ∿112 ksi compressive strength.

One of the inherent characteristics of gray iron is that its strength is relatively insensitive to temperature over the range from ambient to ∿600^{o}F. Decreases in tensile and compressive strengths are typically < 1 ksi for each 100^{o}F temperature rise in this temperature range (Reference 9). Consequently, loss of strength in the cast iron will be essentially negligible in the PCIV body since the operating temperature is less than 200°F.

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*T_p = cast plate tensile strength (ksi); t = plate thicknes $\geq$ 1 inch

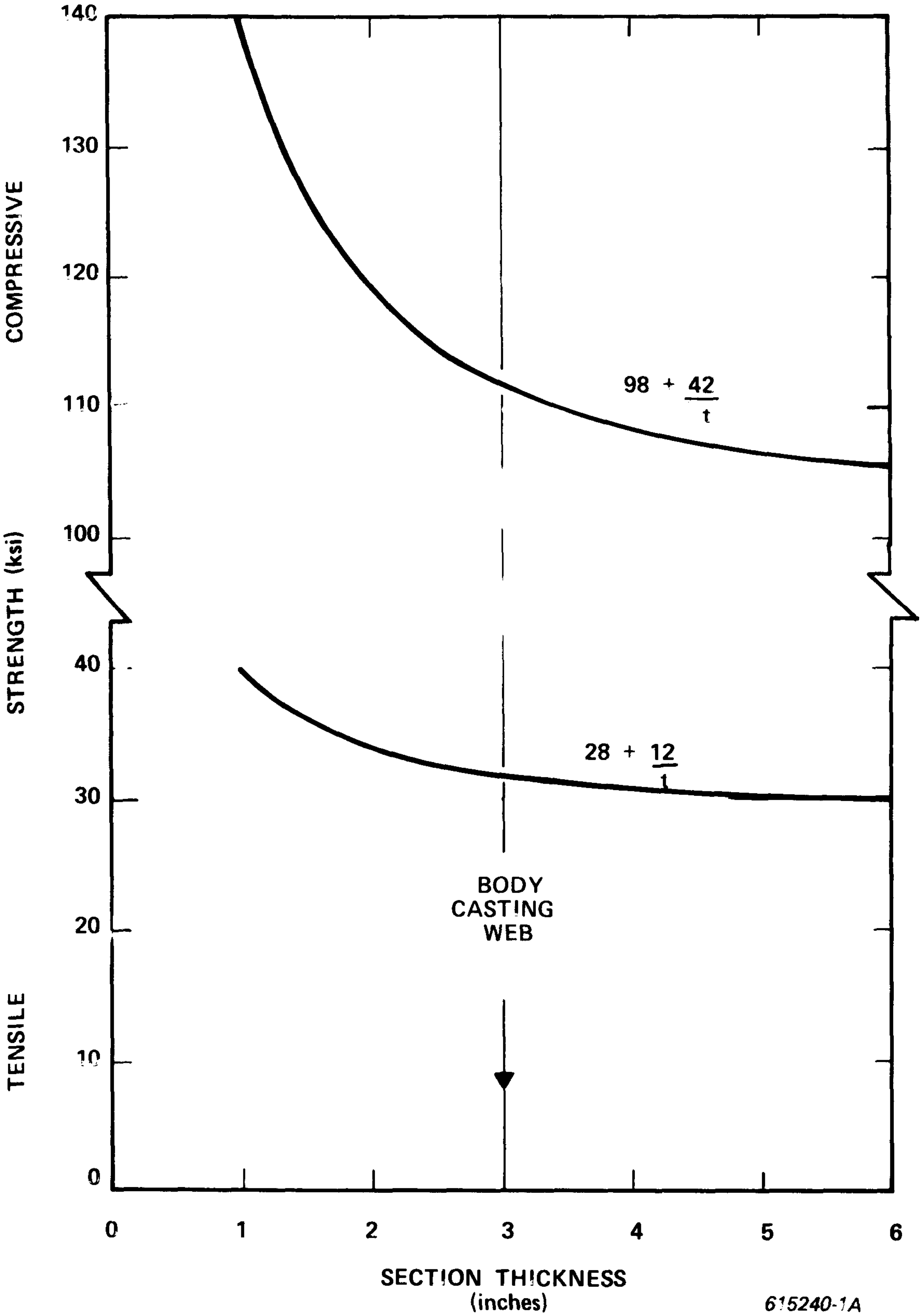

Figure 5.3-2. Estimated Dependency of Room Temperature Tensile and Compressive Strengths on Section Thickness for Class 40 C Gray Iron.

A specification and design property summary for the body material is given in Table 5.3-6 Part (B).

5.3.3.4 TEST AND INSPECTION REFINEMENT

Although a good specification base for gray iron exists (References 10,11,12,13 14), some further development and modifications are to be anticipated to cover gray iron for PCIV body castings. Non-destructive inspection is an area where test methods and acceptance criteria must be established. For example, to facilitate ultrasonic inspection, tighter chemical requirements or microstructural control may have to be imposed. Gray iron can exhibit a broad range of damping capacity depending upon carbon equivalent, strength and phosphorous levels, and microstructure (Reference 8). The gray iron class and chemical control recommended for the body castings will favor ultrasonic inspectibility, but some refinements could be necessary. The large sizes of body castings would make x-ray inspection difficult, but it might be considered.

Compressive properties are extremely important to the PCIV application of gray iron and should be measured. Use of a test bar larger than Type C, or direct sampling of the casting or an attachment, should be considered to obtain more representative mechanical property data. Also, a report that significant cracking occurs in gray iron during compression testing prior to reaching maximum strength requires evaluation (Reference 15). If substantiated, adjustment in the failure criteria used for gray iron may be required. An expanded discussion of test and inspection considerations as related to ASME code qualification of gray iron for PCIV application is covered in Appendix A.

5.3.3.5 CORROSION AND HYDROGEN DAMAGE

The corrosion resistance of gray iron is dependent primarily upon composition (Reference 8). Corrosion resistance is imparted by the high silicon content in unalloyed gray iron, and further enhanced by the small additions of Cr, Ni and/or Cu commonly used in moderately alloyed material. Although the overall corrosion resistance of gray iron is superior to that of unalloyed steel (Reference 8), the difference is not considered sufficient to permit 25 year

PCIV service without some surface protection against weathering. This can be provided by coating the external surface of the assembled PCIV with an industrial quality zinc filled primer and smooth finish topcoat. The topcoat will also serve to minimize adherence of particulate matter and facilitate cleaning operations.

The PCIV body segments will also have to be protected from corrosion during the time period between finish machining and vessel assembly. The application of a temporary rust preventative coating should suffice for this purpose. Solvent-base products containing dissolved rust inhibitors and film-forming materials which develop a continuous barrier upon solvent evaporation are commonly used for interim term surface protection of iron castings involving some outdoor exposure (Reference 8).

The processes by which hydrogen-induced damage can occur in ferrous materials were described in Section 5.3.2 and evaluated there with respect to liner materials. It is also necessary to consider potential hydrogen effects on gray cast iron. A description of these considerations for the various processes is given below; the conclusion is that hydrogen-induced damage will not occur in the PCIV body structure.

The quantity of process gas hydrogen diffusing thorugh the stainless steel PCIV liner, estimated from hydrogen permeability data on stainless steel (Reference 16), is about four liters (STP) per year or about 2.7×10^{-7} cfm. Upon exiting the liner outer surface, this hydrogen will emerge into the segment cooling channels containing air flowing at 32,500 cfm under typical 50°F atmospheric conditions. In view of the 10^{11} ratio between these rates, it is obvious that hydrogen cannot accumulate in any measurable concentration at the cast iron segment surfaces. Even if there were no cooling air flow at all, it is virtually inconceivable that hydrogen incident upon the segment surfaces at the above rate could have any measurable effect upon the massive cast iron structure.
Only if substantial leaks develop in the liner can a significant quantity of process gas hydrogen be postulated to have access to the cast iron segments. It is presumed here that such leaks would be detected and the vessel shut down for repair rather than operated for a significant time period with the leakage continuing.

With regard to decarburization damage processes involving the reaction of hydrogen with carbon to form methane, it is believed that unalloyed gray iron can be expected to behave similarly to plain carbon steels. Much of the carbon contained in such steels is dissolved in the ferrite phase, and that which is present in carbide form exists principally as Fe_3C which has relatively low thermodynamic stability. Plain carbon steels are only susceptible to hydrogen attack (internal decarburization) at conditions exceeding 400°F and 100 psig hydrogen partial pressure (Reference 17). The only carbon-containing phase is gray iron differing from those in plain carbon steel is graphite, which appears from free energy considerations to be more stable than Fe_3C; thus the susceptibility of gray iron to this damage process should at worst be about the same as that of the steel. Since the PCIV body segments will operate at 200°F or less, and since the maximum credible hydrogen pressure outside the liner is on the order of atmospheric pressure, it is concluded that the PCIV body segments cannot be affected by this hydrogen damage process.

Hydrogen precipitation is also not a credible hydrogen damage process for the gray iron segments. Even if substantial quantities of hydrogen were present during extended operation to equilibrate with the gray iron, the difference in hydrogen solubility between the 200^{o}F maximum segment operating temperature and typical ambient atmospheric temperatures is extremely small, so that relatively little precipitation could occur under any conditions. In addition, the gasifier shutdown procedure is specified as initial depressurization at operating temperature followed by slow cooling, a sequence which provides ample time for outward diffusion of hydrogen as its solubility in the cast iron decreases, even in the presence of severe bulk hydrogen leakage through the liner. Hydrogen stress cracking also appears to be a non-credible damage mechanism in the PCIV body segments, since the gray cast iron is neither heat treated to a high strength level (via the martensitic transformation) nor operated at a high tensile stress level.

Only the hydrogen embrittlement process, a severe loss of ductility and strength attributed to the presence of dissolved hydrogen, appears to merit any serious consideration as a cast iron degradation mechanism in the PCIV gasifier. Loss of ductility in gray iron, however, may be somewhat meaningless since the material is inherently brittle. The high carbon and silicon levels of gray iron, and the graphite flakes in its microstructure which act as stress-risers, combine to produce a material exhibiting typically less than 1/2% tensile elongation. Gray iron is suitable for PCIV segments because, as with the use of concrete in a prestressed concrete vessel, it will be maintained essentially under triaxial compression.

An extensive literature search uncovered only one reference work treating the influence of hydrogen on gray iron strength. In a study by Bastien, et al (Reference 16), four types of gray iron differing in tensile strength and microstructure were charged with hydrogen by corrosion and electrolysis in HCl. Room temperature tensile tests revealed a reduction in strength for hydrogen charged material of approximately 10% for three quarters of the cases examined, and a range spanning 3 to 28%. The tensile strength loss could be reversed by heat treatment at 122°F. The conditions under which hydrogen could interact with the PCIV body would differ signigicantly from those used in these experiments. In the PCIV case we have molecular hydrogen leaked or permeated through the liner and contacting cast iron segments operating below 200°F, whereas the experimental conditions involved mascent hydrogen liberated at the cast iron specimen surface by corrosion or electrolysis in HCl. In addition to the difference in the reference experiment versus PCIV actual conditions, it should be emphasized that the property loss determined experimentally was only ∿10% in the majority of cases, and involved tensile as opposed to compressive data, the latter being of greater significance to the PCIV design. Consequently, the relevancy of this work to the PCIV application of gray iron is questionable.

5.3.4 PRESTRESSING MEMBERS

The technology of prestressing members for PCIV structures, both in this conceptual study and as utilized in current practice in the European nuclear industry, is derived almost entirely from the corresponding technology which has been developed for prestressed concrete structures. Solid wire, multiwire strands or flat strips of high carbon steel, and long bars of alloy steel, are applied in various combinations and configurations as wrapped circumferential layers and as axial tendon assemblies to cylindrical or quasi-cylindrical vessels of all sizes. The layers or tendons are installed at ambient conditions under a very high tensile preload so that, under vessel operating conditions, the prestressing members provide the necessary reaction to the forces transmitted through the vessel liner and into the wall and head regions from the high pressure internal operating environment.

Selection of prestressing materials for the PCIV gasifier was based on specifications and practices accepted for prestressed concrete structures under Section III, Division 2 of the ASME Code. The axial tendons will be assemblies of 0.25-in. diameter high carbon steel wire conforming to ASTM A421, Type BA, Low Relaxation Quality. The circumferential wrapping will utilize 0.375-in. nominal diameter seven wire strand, formed from high carbon steel wires, conforming to ASTM A416, Grade 270, Low Relaxation Quality.

In manufacture, these wire materials are heat treated and stress relieved to develop a very high level of tensile strength combined with ductility adequate for the application. In the production of the low stress relaxation quality grades, the stress relief heat treatment is performed while the wire or strand is held under an applied tensile load, adding significantly to the cost of manufacture. The design mechanical properties of the axial wire and circumferential strand selected for the PCIV gasifier are compiled in Table 5.3-7. In addition to static short-term mechanical properties, the stress relaxation characteristics of these materials over the design operating temperature range must be known and carefully considered in the analysis of long-term vessel mechanical behavior. The data used in this study were obtained from Reference 29 and are reproduced in Figure 5.3-3. The curve shown for the 160°F maximum

TABLE 5.3-7

DESIGN PROPERTIES OF PRESTRESSING WIRE AND STRAND

PROPERTY OR CHARACTERISTIC	AXIAL MEMBER	CIRCUMFERENTIAL MEMBER
Size and Configuration	0.25-in. diameter Solid Wire	0.375-in. diameter 7-Wire Strand
Specification	ASTM A421 Type BA Low Relaxation	ASTM A416 Grade 270 Low Relaxation
Ultimate Tensile Strength or Load	240,000 psi	23,000 lbs
Yield Strength at 1% Elongation*	216,000 psi	20,700 lbs
Maximum Ultimate Elongation (%)	4.0	3.5
Modulus of Elasticity (M psi)	27.8	27.8
Mean Thermal Expansion Coefficient, 70 - 160°F ($^{\circ}$F x 10^6)	6.0	6.0
Mean Thermal Conductivity, 70 - 160°F (BTU-in/ft^2-hr-$^{\circ}$F)	333	333

*Note that this is a more conservative definition of Yield Strength than the familiar 0.2% offset criterion.

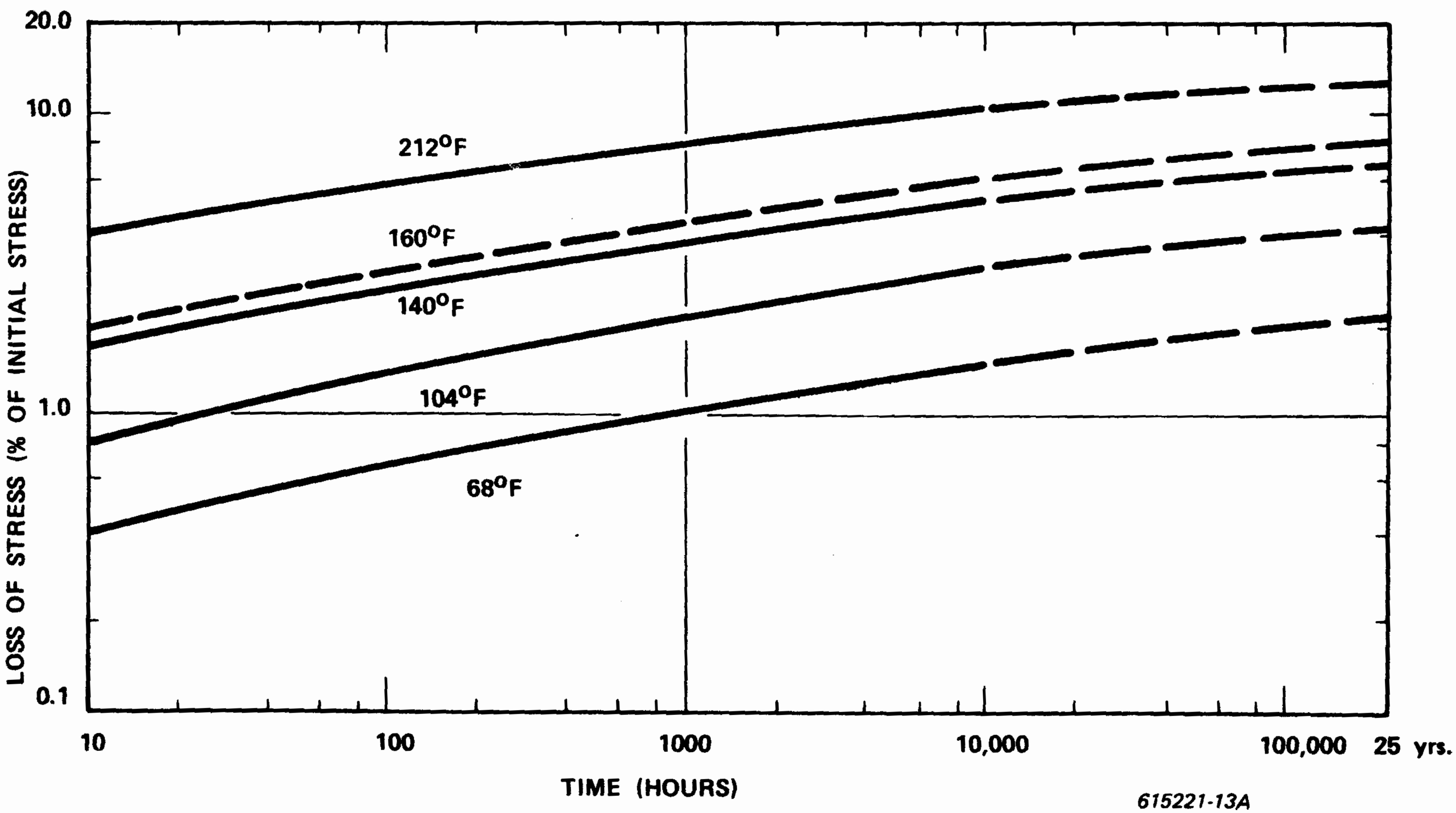

Figure 5.3-3. Design Stress Relaxation Properties of Prestressing Wire and Strand.

operating temperature of the PCIV gasifier prestressing members was obtained from the reference data by interpolation. This curve predicts approximately 8% relaxation of initial prestress* over the 211,000 hour (25 year) design life of the vessel. Under normal operating conditions where the prestressing operate at a members relaxation expected is less than 7%. (It should be noted that this data predicts stress relaxation resistance considerably in excess of the minimum requirements of the material specification designed above.)

Corrosion protection of the high carbon steel wire and strand is mandatory to prevent deterioration of the prestressing members over the 25 year vessel design life. In prestressed concrete structures, galvanized wire is frequently utilized to combat corrosion. Unfortunately, however, when wire heat treated to maximum strength is galvanized, exposure to the molten zinc galvanizing bath reduces the strength levels below the minimum values specified in ASTM A416 and A421. In addition, once the wire is galvanized, it cannot be given a heat treatment under tension to develop high stress relaxation resistance because the required heat treating temperature is above the 707°F melting point of zinc. Since the current PCIV gasifier design is based upon highest attainable strength and stress relaxation resistance in the prestressing members, galvanization was not used for this application.

When prestressing steel is imbedded in either concrete or grout, as is frequently done in concrete structures, it is possible for galvanic corrosion to produce serious deterioration in time periods far shorter than the intended service life. Water inescapably contained in the concrete or grout, containing various ions dissolved from the mix constituents, serves as the electrolyte; and variations in the localized stress level developed during the prestressing areas create regions of varying galvanic potential along the wire or strand, with the more highly stressed regions being anodic to those at lower stress levels. When galvanic corrosion proceeds under these conditions, the corroding anodic areas become reduced in cross section so that the stress on the remaining section increases, thus aggravating the situation. In addition, hydrogen is liberated at the cathodic regions which may then become available to promote

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*Initial prestress not exceeding 70% of ultimate strength.

hydrogen stress cracking or hydrogen embrittlement (discussed further below). To preclude the occurrence of this galvanic process, one current approach is to coat the prestressing wire or strand with an epoxy as it is being installed in the circumferential wrap layers or tendon assemblies. The epoxy is an electrical insulator which prevents galvanic corrosion from occurring, and also functions as a barrier to corrosion by direct chemical attack.

Prestressing steel used in axial tendon assemblies for concrete structures are usually protected from corrosion by application of a grease. The greased wire or strand may be additionally protected by a plastic covering. When the tendon assembly is enclosed in a duct (as in unbonded concrete structure tendons and the PCIV gasifier), additional protection is usually afforded by pumping the duct full of additional grease or grout after tendon installation. While this approach is conceptually attractive for its simplicity and relatively low cost, it has certain potential disadvantages with respect to application in the PCIV system. The very high strength steel wire and strand, operating under a high tensile stress, are susceptible to stress corrision in prestressed cast iron vessel in much the same way as in prestressed concrete vessels. In one study (References 30 and 31), severe stress corrision leading to failure of axial tendon assemblies was attributed to the presence of nitrate and/or carbonate impurities in the protective medium surrounding the tendon members. This would indicate a need for rigid composition and impurity specifications and controls if a grease is to be used in direct contact with the prestressing steel (The PCIV design uses epoxy in contact with the steel.) It is also not clear that a satisfactory grease with sufficient chemical stability and high viscosity can be identified for extended operation at the normal 140°F (maximum) prestressing member temperature.

Current PCIV practice in the European nuclear industry involves the use of a plastic coating, thought to be a polyurethane, which is applied to individual wires prior to installation and then additionally applied as a "potting" to circumferential wrapped layers and in the ducts surrounding axial tendon assemblies. However, the specifics of this approach were not available in sufficient detail to permit its consideration in this conceptual study.

Corrosion protection for the PCIV gasifier prestressing members is specified for conceptual purposes to be a layer of epoxy applied to the circumferential strands and axial wires during installation. Additional protection will be afforded by an outer layer of epoxy applied to each band of circumferential wrap and by filling the void volume in the axial tendon ducts with a column of grease. Selection of specific materials was considered to be outside the scope of this conceptual design phase. Variations in the final approach to corrosion protection of prestressing members will have relatively little impact on PCIV overall cost, so it is reasonable to defer the completion of this selection task to the detailed design phase of the program.

The final consideration with regard to prestressing member selection is the question of potential for hydrogen-induced damage. A description of the damage processes known to occur in ferrous materials was given in Section 5.3.2, and Section 5.3.3 contains a discussion on the credibility of accumulation of process gas hydrogen outside the vessel liner. Processes involving the reaction of hydrogen with carbon to form methane, as well as the hydrogen precipitation process, are not of concern here because of the low (160^{o}F max) operating temperature and credible hydrogen partial pressure ($\sim$1 atm) to which the prestressing members will be subjected. Hydrogen stress cracking and/or hydrogen embrittlement could occur under the given temperature and tensile stress conditions, but no credible access of measurable quantities process gas hydrogen to the prestressing steel can be postulated except under conditions of severe bulk leakage of process gas through the vessel liner. The conclusion is that hydrogen-induced damage to the PCIV gasifier prestressing members will not occur under the conditions of this conceptual study.

Other components of the PCIV prestressing systems, including cable anchors, anchor blocks, etc. are adapted intact from the practice of Reference 32. The axial tendon ducts will be made from galvanized steel tubing and require no unusual selection considerations.

6.0 MANUFACTURING

Based on the conceptual design drawings, a manufacturing plan defining the fabricating equipment, general setup procedures, and fabricating processes for the machining of the cast segments was prepared. The information contained herein describes the manufacturing effort and also serves as a basis for detailed manufacturing cost estimates. Shop activities, as opposed to field activities, are covered in this section.

6.1 MACHINING CAST IRON BODY SEGMENTS

- Establish setup points on the inside radius of each casting in order to distribute the excess material to be removed.
- Place the casting on a horizontal milling machine with the setup points resting on adjustable jacks on the machine table.
- Machine one face of the casting perpendicular to the setup points.
- Locate the casting with the machined surface flat on the mill table, and by using a fixture, machined to the correct end configuration of the casting, align the 45° angle on one side parallel to the machine cutter. (See Figure 6.1-1) Repeat this operation to machine the opposite 45° side to complete the machining of the interface angles.
- Place eight segments, making one complete ring (with the machined faces flat on the table) on a vertical boring mill. (See Figure 6.1-2) Adjust each 45° segment until each segment is flush against the adjacent segment and the eight, 45° segments are located on the center of table rotation. Machine the outside and inside diameters and face. Woodruff keyways are to be machined while the segments are grouped as a ring to provide assurance that they can be repositioned properly at the site. This manufacturing sequence will minimize any dimensional deviations incurred in machining the 45° sides. Each segment is serialized as to position in the final assembly.
- Set up the individual segments on a horizontal mill and bore the locating pin holes and cable tube holes.

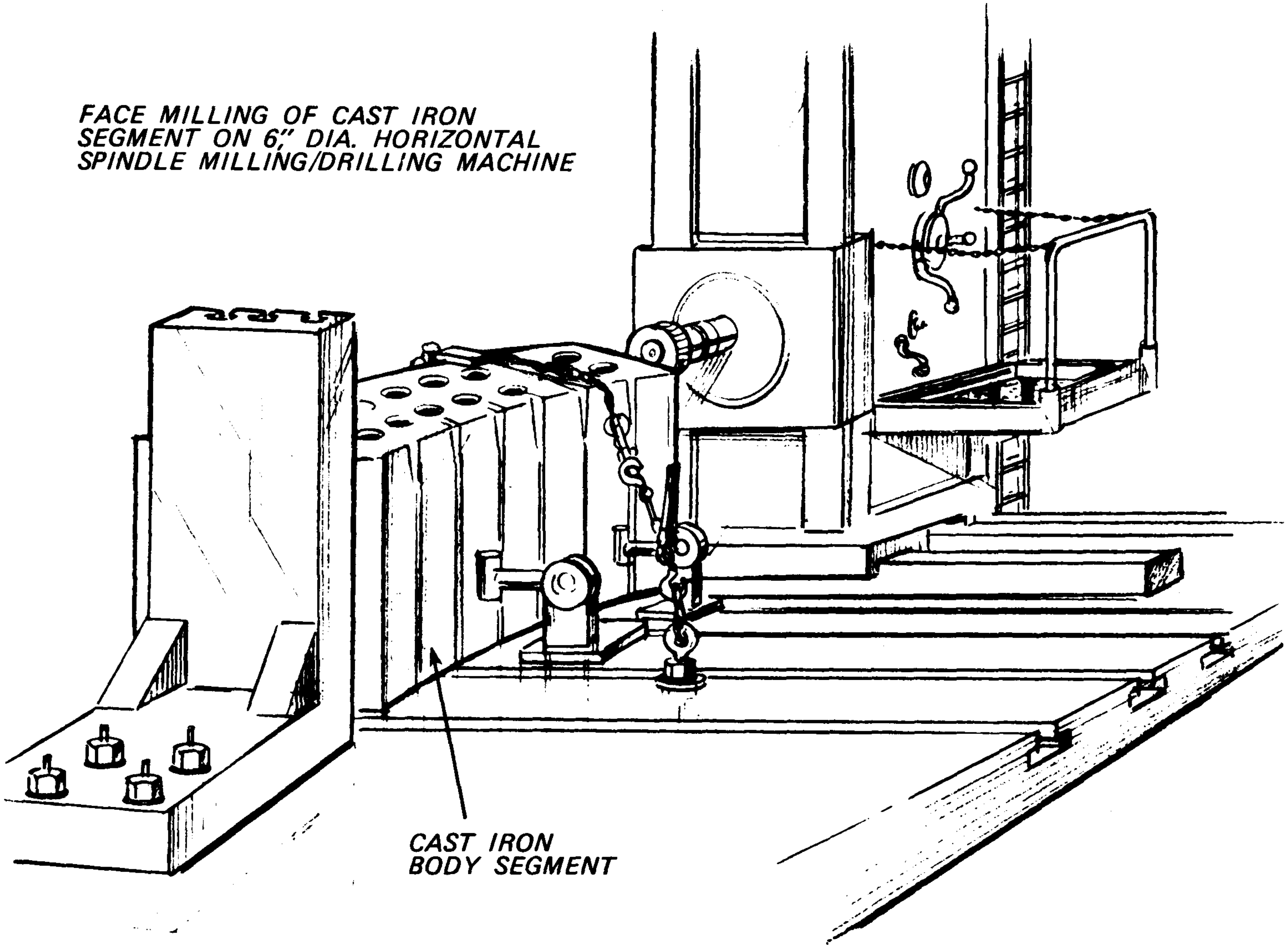

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Figure 6.1-1. Face Milling of Cast Iron Segment on Horizontal Milling Machine

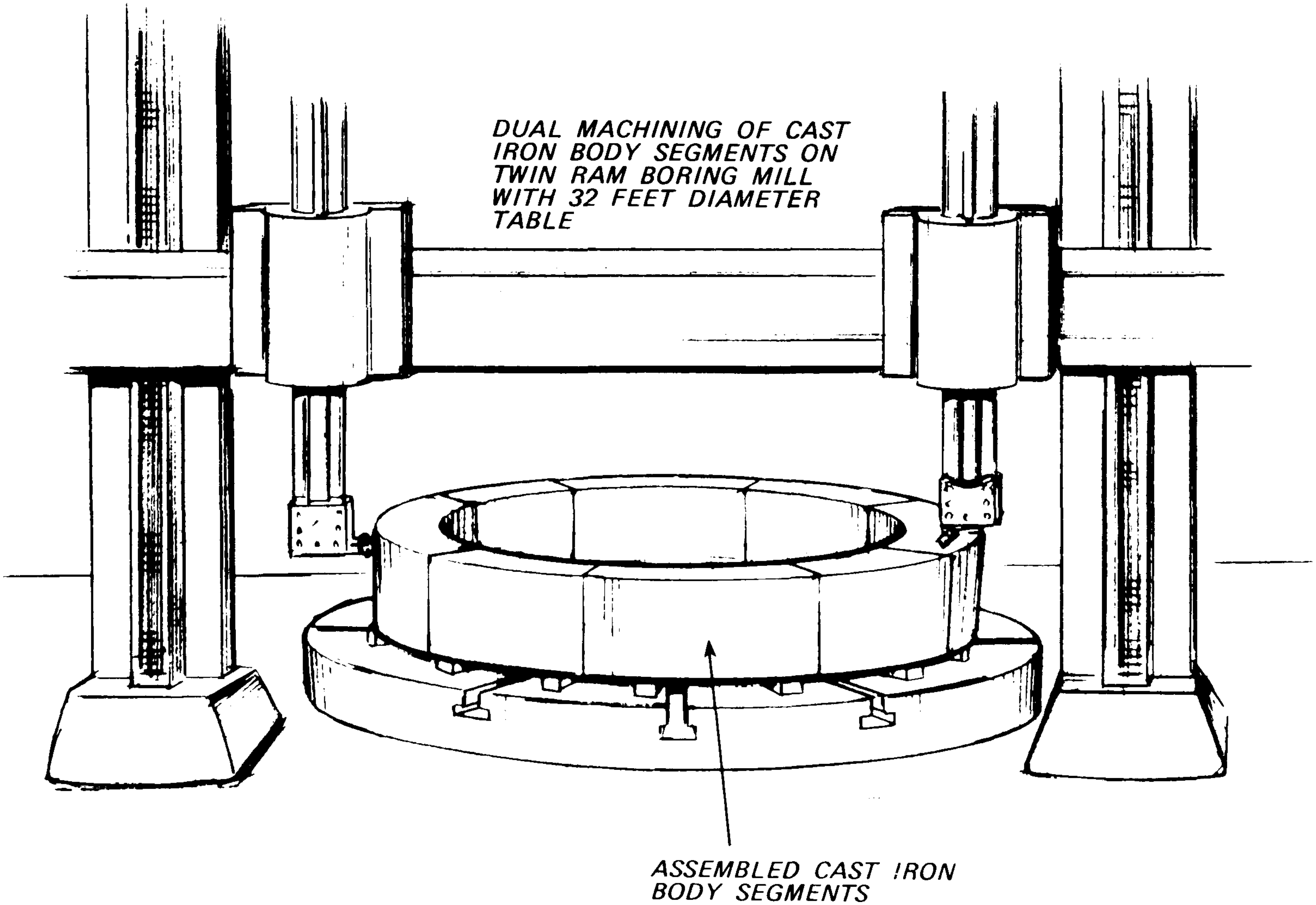


Figure 6.1-2. Dual Machining of Cast Iron Body Segments

- Set up drill and bore the attachment bolt holes and nozzle openings.

6.2 MACHINING BODY LINER SEGMENTS

- Set up each liner plate while in the flat state on a horizontal mill and machine weld preps on both edges of the 10 foot width.
- Liner sections that require nozzle transitions will be laid out showing the location of the transition opening. Plasma cut the opening leaving adequate stock to finish machine the opening after the sections have been formed.
- Roll form the liner segments.
- Match fit each liner segment to the mating cast iron body segment. Transfer the locations of the bolt attachments, nozzle openings and chord distance from the cast segments to the liner segments.
- Machine the nozzle transition opening and weld preps that were not previously machined.
- Weld the finish machined bolt attachments and nozzle transitions to the liner segments. All backing strips will be field installed and task welded into position.

6.3 MACHINING NOZZLES

- The welding neck flange has the seal ring groove and weld prep turned at the appropriate diameters. Holes are drilled in the weld neck flange on the drawing bolt circle.
- The slip on flange has the inside diameter bored and the weld prep turned on each end. Holes are drilled at the correct bolt circle.
- The bolting rings are drilled and tapped on the bolt circle and depending on the size are plasma arc cut from solid material or roll formed and welded. Cleanup machining is performed on the welded and burned out areas.
- The transition rings for the smaller nozzles are contour machined from solid cutouts while the larger rings are contour machined from rolled and welded sections assembled to allow stock for finish machining.

- The larger size nozzle pipes are roll formed and welded and all sizes will have weld preps machined on each end. The larger pipes are turned to cleanup the outside diameter to suit the flip flange inside diameter.

- The slip-on flange is fitted and welded to the nozzle pipe as required.

- The welding neck flange is fitted and welded to the nozzle pipe as needed.

- The bolting ring is assembled to the cast iron body and the assembled nozzle pipe is inserted through the cast iron body and welded to the transition ring. The studs are then assembled and bolted through the cast iron body and flange to the bolting ring.

6.4 ASSEMBLY OF BODY SEGMENTS

- Assemble the cast iron body segments and mating liners. Install the bolting studs and torque as required.

- Install the nozzles and weld to complete the assembly of the nozzle, liner and cast iron body segments. The body segments will be complete for shipment to the erection site.

6.5 MACHINING TOP AND BOTTOM CAST HEAD SEGMENTS

- The machining is basically identical to process used for the cast iron body segments.

6.6 FABRICATION OF THE HEAD LINERS (TOP AND BOTTOM)

- The head liners will be fabricated in eight, 45° segments to make each 360° head.

- The plate material will be plasma cut to the desired configuration with excess stock on the outside diameter for roll or die forming the 12 inch radius.

- Following the forming operation, each segment will be machined to attain the correct side angles; weld preps will be completed on all sides and the center and 69 inch nozzle opening will be finished machined.

6.7 ASSEMBLY OF THE HEADS AND HEAD LINERS

The assembly of heads and liners will be a total field effort in accordance with the following assembly plan.

- The head liner sections (eight, 45° sections) will be positioned on a flat surface and welded to fabricate the total 360° heads. Welding will be done from both sides on each seam to eliminate the need for backing strips.

- Fit and weld the nozzle transitions.

- Installing the bottom head liner is simply a matter of lifting the head liner, placing it in the nest formed by the cast head and welding the nozzle to the transition.

- Installing the top head and liner. Position the cast head segments to form the lower section (1 of 3 sections). Wrap the cable and pre-stress the section. Assemble the head liner and the section. Studs will be welded to the head liner for attaching the head liner and the cast head segments. Once the two assemblies are joined the studs will hold the liner to the cast segments while being lifted into position. Once the lift has been completed, weld the head liner to the body segment liners, position the two remaining cast head sections, assemble and weld the top head nozzles.

7.0 FIELD OPERATIONS

The PCIV design was developed in such a way that foundry and machine shop operations were maximized in order to minimize field operations at the construction site. This approach led to an overall manufacturing and assembly plan based on fabricating building blocks at the machine shops that could be shipped to the construction site and assembled in an efficient manner to form a complete prestressed cast iron vessel. The overall plan selected was one that does not require stress relieving operations at the construction site. The costs and delays associated with such operations were evaluated against the extra cost of using a stainless steel liner. It was found to be cost effective to use the stainless steel liner (which can be welded without post weld heat treating) instead of one of the lower cost steels that would require stress relief in the field. The principal reason for avoiding stress relief is to avoid the high temperatures that are involved. It did not seem practical to use the building block approach mentioned earlier along with stress relief heating because of the difficulty in keeping the prestressing members cool during the heating process.

Another consideration that was evaluated in the selection of the overall manufacturing and assembly plan was circumferential prestressing. Many prestressed concrete structures, mainly water storage tanks, are prestressed circumferentially by using a winding machine that travels around and around the poured concrete body of the tank, laying cabling down under tension as it travels around the outside of the tank. While the same approach could be used for constructing a PCIV it was not selected as the preferable method because of the height of the coal gasifier vessel and the difficulty involved in performing such operations in a safe and cost effective manner.

The field operations involved in the overall manufacturing and assembly plan selected for constructing the PCIV gasifier are described below. In this description, emphasis is placed on covering the operations that are considered unique to the construction of a PCIV rather than try to describe those operations that are typically used in constructing welded steel, or prestressed concrete vessels.

Field operations planned for the construction of the PCIV gasifier separated into the following major categories:

- Receipt and Storage
- Positioning for Assembly
- Liner Welding at Grade
- Circumferential Prestressing
- Final Positioning
- Liner Welding in Place
- Longitudinal Prestressing
- Completion

These categories are described in general terms in paragraphs 7.1 thru 7.8. The sequencing of construction operations is given in chart form in Figure 7.0-1. Scheduling of field operations is shown in bar graph form in Figure 7.0-2. The schedule covers the construction of either one or two vessels since the welded steel reference gasifier plant utilizes two vessels.

7.1 RECEIPT AND STORAGE

Components and materials needed for construction of the PCIV are received from rail (or possibly truck) shipment and stored on site until such time when they are to be actually used. Finished castings for the heads and sidewall of the vessel along with prestressing system materials are recieved on temporary trackage adjacent to the erection area as shown in Figure 7.1-1. Castings and other heavy items are off-loaded by derrick or general construction crane and

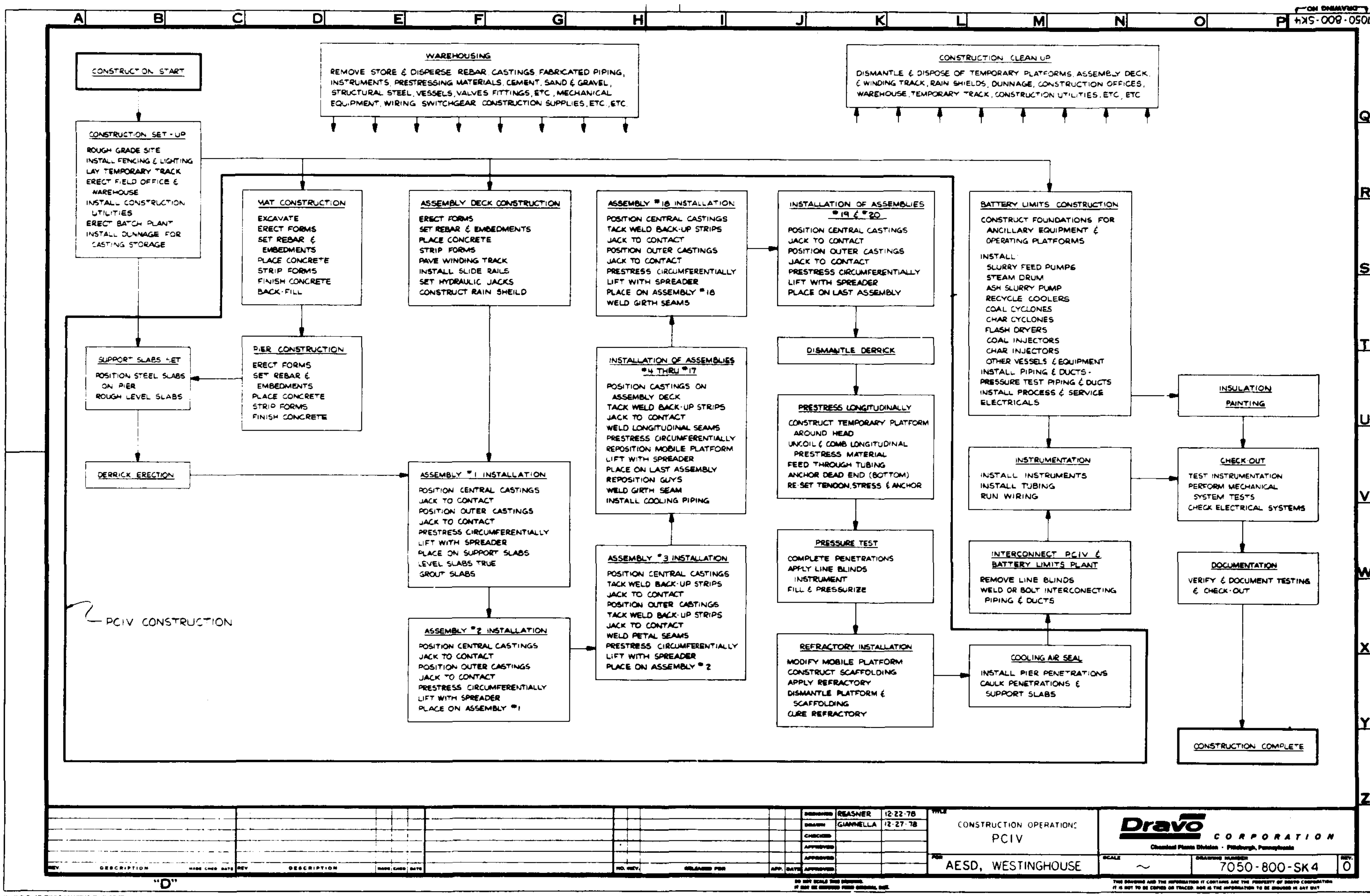


Figure 7.0-1. Construction Sequence Chart

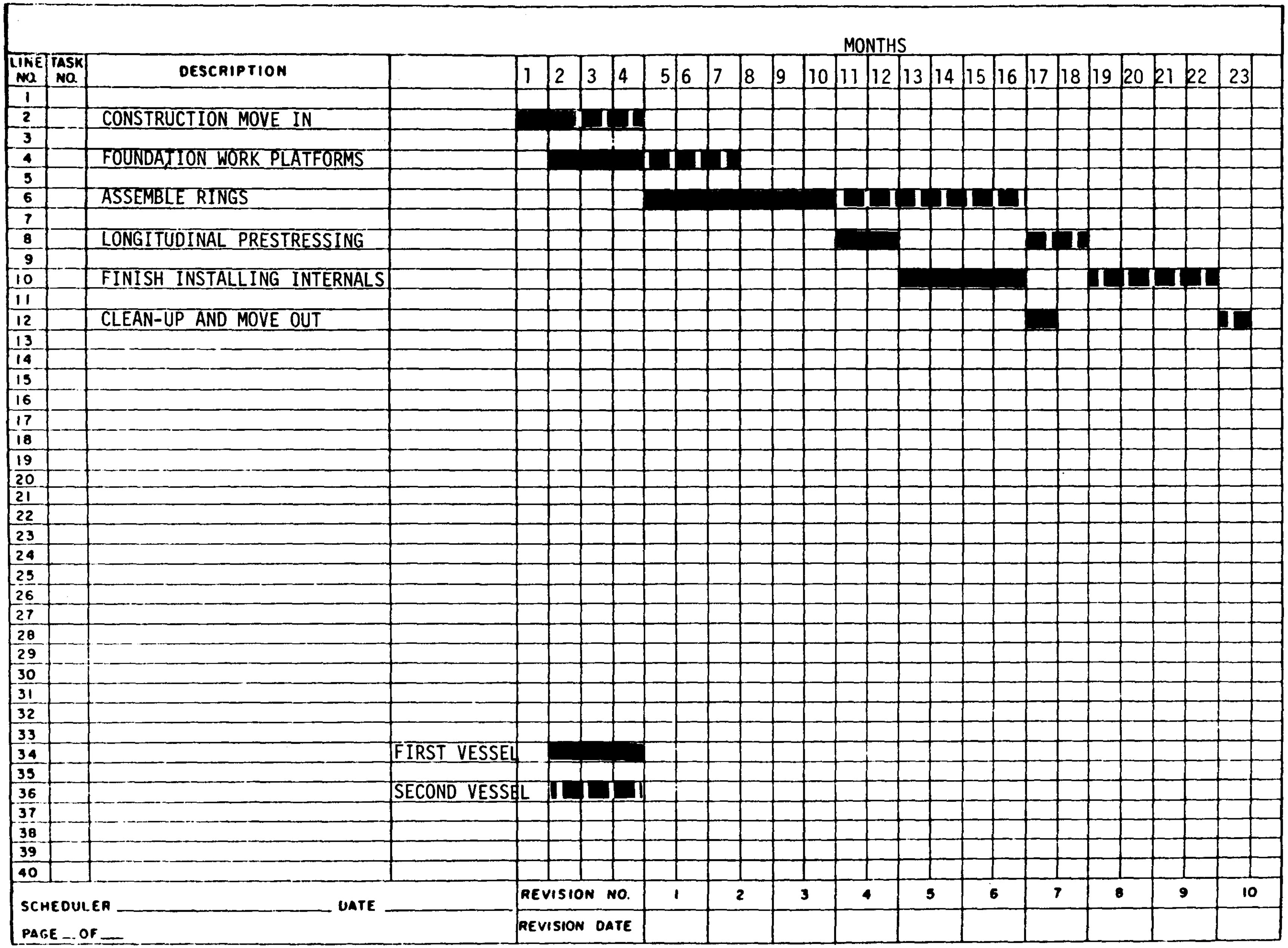


Figure 7.0-2. Schedule of Field Operations (Prestressed Cast Iron Pressure Vessel)

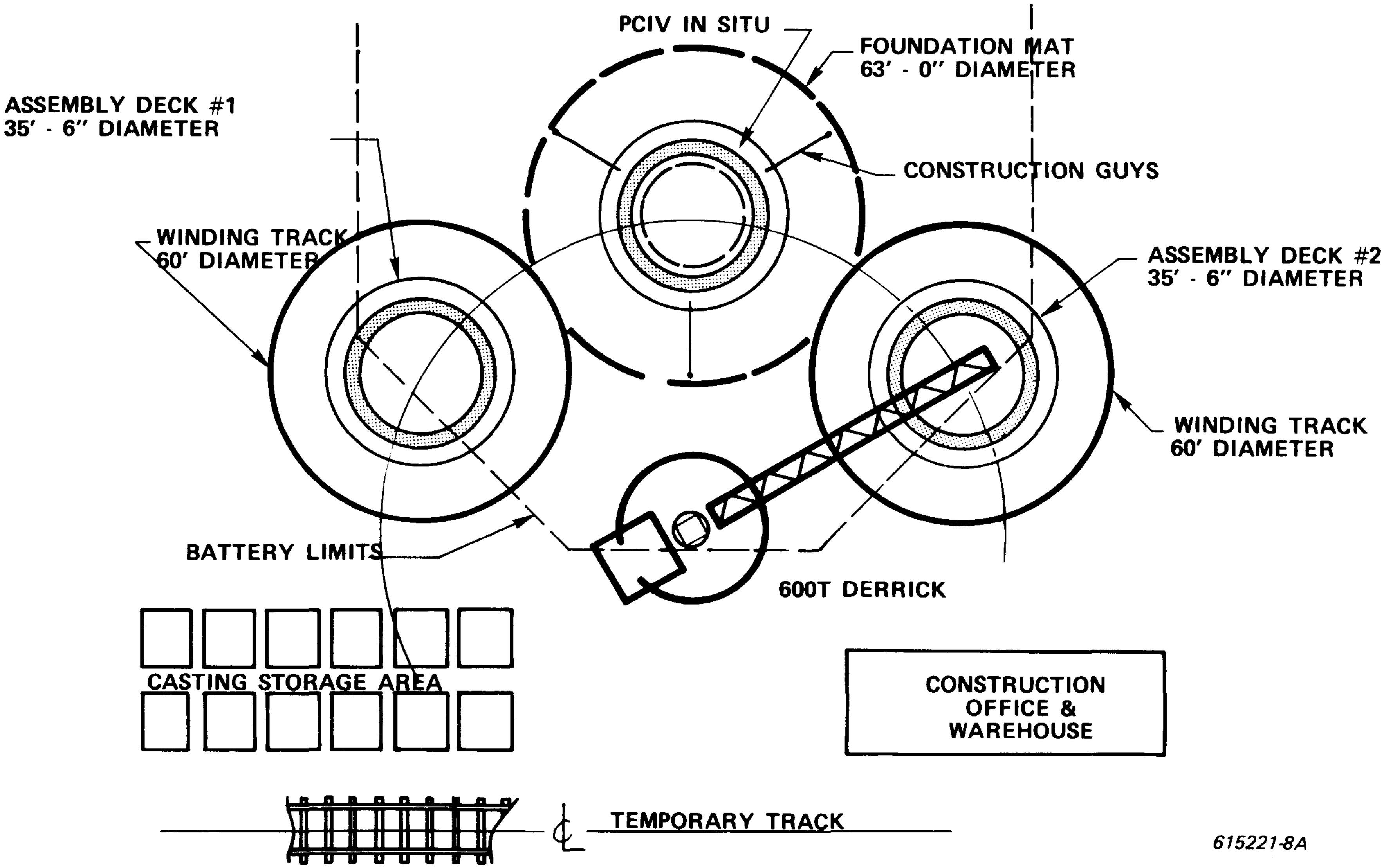


Figure 7.1-1. Construction Area - Plan View

stored on timber dunnage in the staging area. Prestressing material such as strand reels and tendon loops are off-loaded by general mobile construction equipment and warehoused for protection. The "building block" castings are received throughout most of the construction period since it takes a considerable length of time to cast and machine and shop assemble each building block.
As shown in Figure 7.1-1 two assembly decks are used for constructing ring assemblies. This arrangement reduces construction time since prestress winding can be done on one ring while positioning and keying can be done on the other.

7.2 POSITIONING FOR ASSEMBLY

The castings must be positioned on the assembly deck in such a way as to form a ring for prestressing. Prior to moving the castings to the assembly deck, any protective coatings or coverings on the castings are removed. Horizontal backup strips not previously fastened to the liner plates are tack welded in position. Temporary lumber spacers are fastened to the mating surfaces of the castings to provide protection from accidental bumping. Castings for a specific assembly are placed on the assembly deck in final position relative to each other but separated by spacers. The castings are identified as to position in the PCIV by numbers indicating ring number and azimuthal position.

CYLINDRICAL SHELL ASSEMBLIES

After the eight castings comprising a cylindrical assembly are rough positioned and spacers removed, hydraulic jacks slide the castings to proper contact. Positioning keys are inserted to maintain proper alignment radially. The arrangement is illustrated in Figure 7.2-1. Note the use of a lightly tensioned cable at the top of the assembly to ensure stability and the availability of repositioning jacks if mating is less precise than desired.

HEAD/BOTTOM LAMINAR ASSEMBLIES

The procedure for positioning castings in laminar assemblies is similar to that for cylindrical assemblies except that two steps are required; the inner castings are brought to contact first and the exterior ring of casting second.

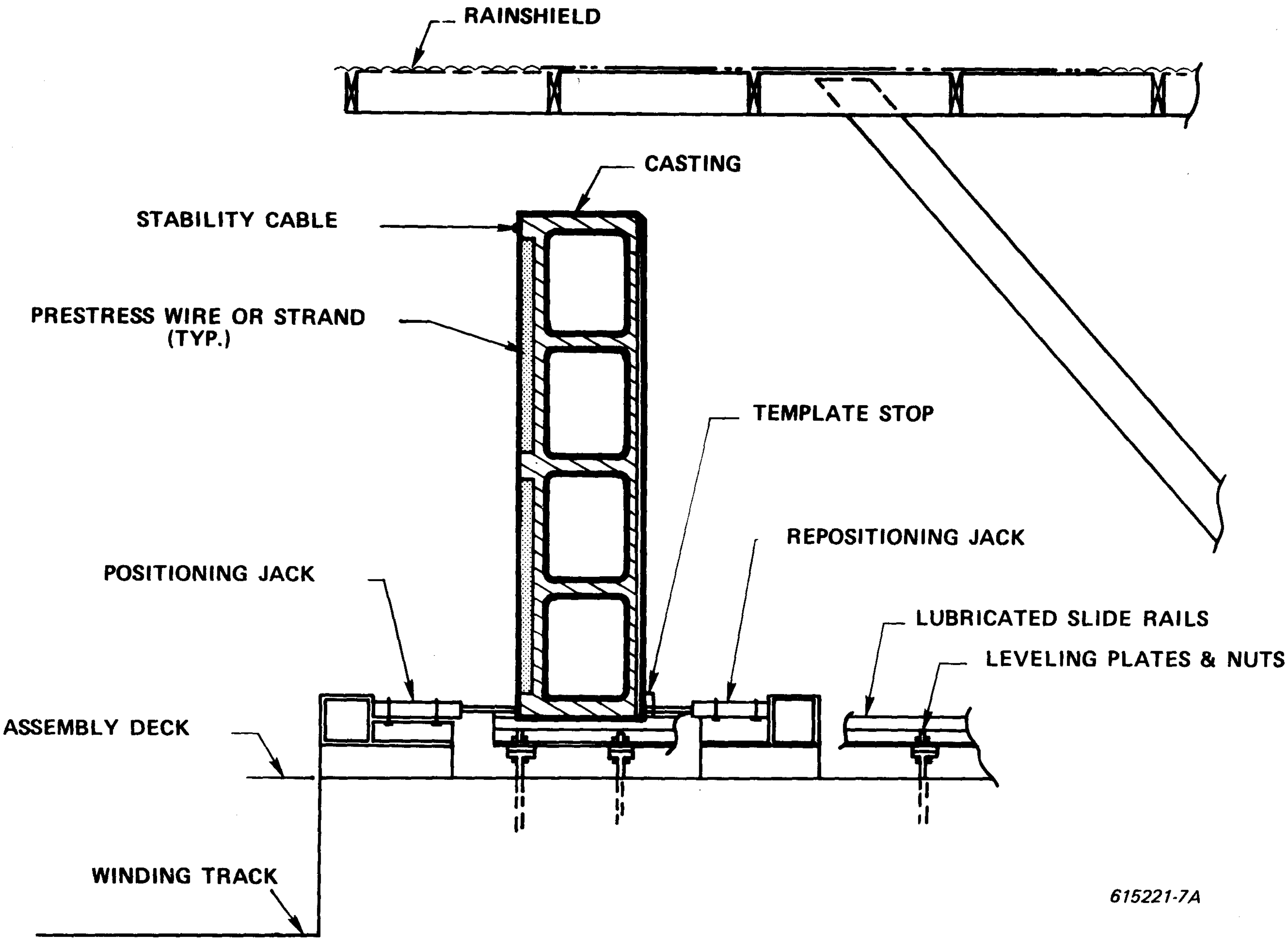


Figure 7.2-1. Construction Operations on Assembly Deck

7.3 LINER WELDING AT GRADE

Eight liner sections are joined together by welding to form a cylindrical ring or course of the cylindrical part of the vessel. This welding is done while the cast iron body segments are held together as a ring on the assembly deck at ground level but prior to prestressing. Backup strips are used behind each joint in order to separate the cast iron from the weld joint and to make sure that the root pass of the weld is of good quality. The welding is done by using a vertical motion welding machine using the MIG process or equivalent. As shown in Figure 7.2-1 a light pre-assembled rain shield over the assembly deck permits the welding to be done "in the dry". Dye penetrant is used to test the weld joints for quality. Weld shrinkage in the liner rings is not a problem since prestressing of the cast iron body segments produces enough hoop strain to compensate for the shrinkage and get good contact between the liner and cast iron members.

7.4 CIRCUMFERENTIAL PRESTRESSING

Circumferential prestressing is done at ground level and is started by anchoring the free end of 7 wire strand (coiled on a reel) in a slot of a casting rib. A winding machine (plus reel) moving around the assembly lays the strand in the rib cavity at a constant, controlled tension load. (An alternate arrangement has the strand-winder stationary and the assmebly of ring segments on a rotating turntable.) On completion of a single layer, the end is anchored in a slot of the casting rib at that location. No splicing between cable lengths is permitted.

The key element in doing circumferential prestressing is the strand winding machine. The machine selected for circumferential prestressing the PCIV sidewall and head assemblies is basically the same as that shown in Figures 7.4-1 and 7.4-2. As described in Reference 34 the machine is a large capacity wrapping machine that has been developed to apply large prestressing forces to cylindrical structures under extremely close force tolerances such as may be required for nuclear reactors and pressure vessels, large storage tanks, large diameter high pressure pipe, etc. The cylindrical structure may either be rotated while the tensioning mechanism is kept stationary or the tensioning mechanism may be rotated around the cylindrical structure, such as shown in the photo on this page.

The tensioning mechanism may either be supported from the ground, or supported from the top of the wall, or may be supported from a temporary or permanent ring beam attached to the wall. Structures requiring short completion times may be wrapped with several machines operating at the same time at different levels. Technical information about the machine is also given in Figures 7.4-1 and 7.4-2.

THE DYK II STRAND-WINDER

DYK

To satisfy the demand for correct tensioning of super large P.C. tanks, DYK designed and developed what undoubtedly is the world's largest and most versatile tank wrapping machinery.

Features found in the DYK I strandwinder can also be found in the DYK II strandwinder. In addition this machinery is capable of stressing nuclear reactors, LNG and LPG tanks and large or small diameter pipe.

The set-up for LNG and LPG tanks would be similar to the arrangement for the 40.5 ft high tank at Cerritos, CA, shown below. For very tall tanks the machinery will be hanging from an independently driven overhead carriage.

Wrapping of strand in cylindrical slots on reactor walls can readily be accomplished by moving the stressing-head assembly up and down inside the machinery while maintaining the level of the DYK II winder at certain predetermined elevations.

Large or small prestressed pipe may be stressed on a turntable driven by the DYK II winder.

MAIN FEATURES OF THE DYK II STRANDWINDER

1. Maximum applied force: 20,000 lbs.
2. Application tolerance: ±400 lbs.
3. Automatic continuous electronic stripchart recording of applied force is made during tensioning.
4. Continuous visual digital read-out of applied force verifies strip-chart recording.
5. The wire can be tensioned or detensioned, either at standstill or in motion, to any value between 0 and 20,000 lbs.
6. The desired force in the strand is maintained regardless of whether the machine travels in the forward or in the reverse direction.
7. The strand can be spaced electronically, through automatic or manual means, by lowering the entire machinery with the support cables.
8. The strand can be spaced electronically, up or down, through automatic or manual means, in 0.005" increments, by moving the stressing-head assembly up and down inside the machinery with screw-drive means.
9. Maximum vertical displacement of stressing-head assembly inside the machinery is 60".
10. Maximum continuous operating speed: 400 ft/min.
11. Stress tolerance can be maintained at full operating speed for any radial variation up to 18" in cylindrical slot depths.
12. Machinery can wrap strand, wire and flat steel.

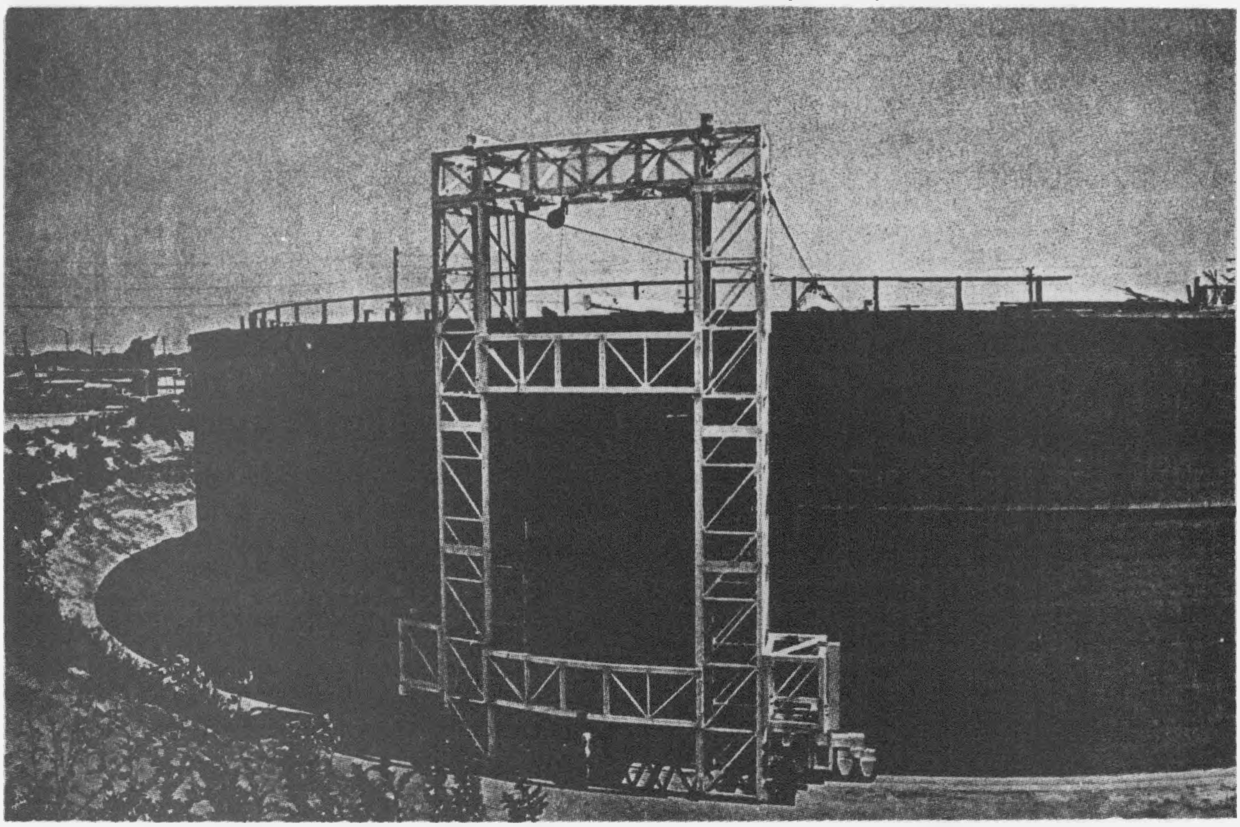
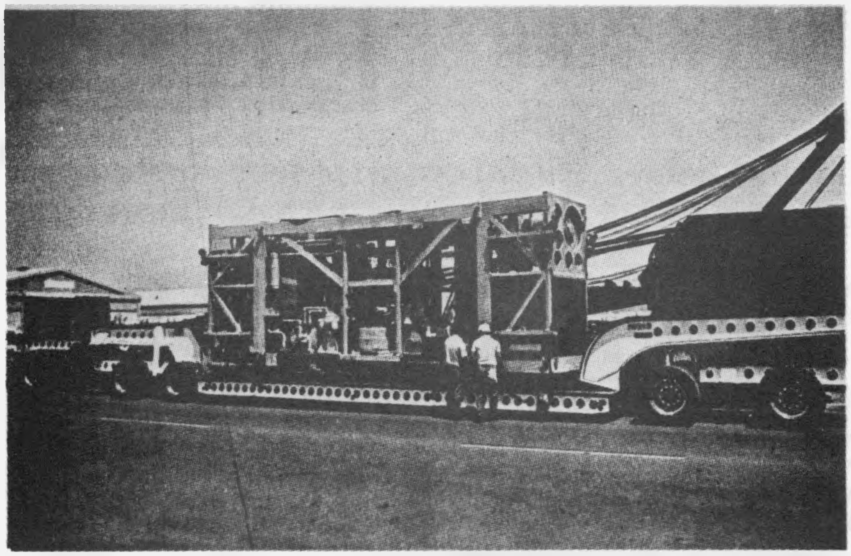


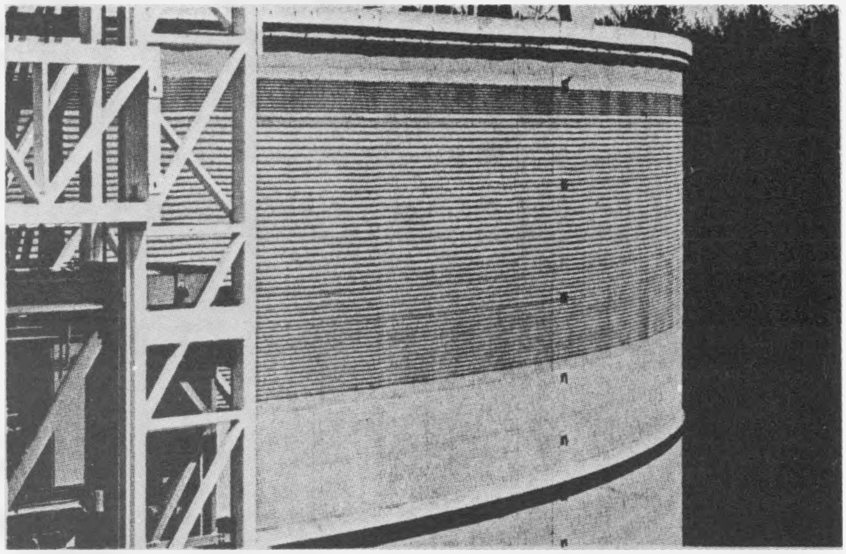
Figure 7.4-1. Circumferential Strand Winding Machine

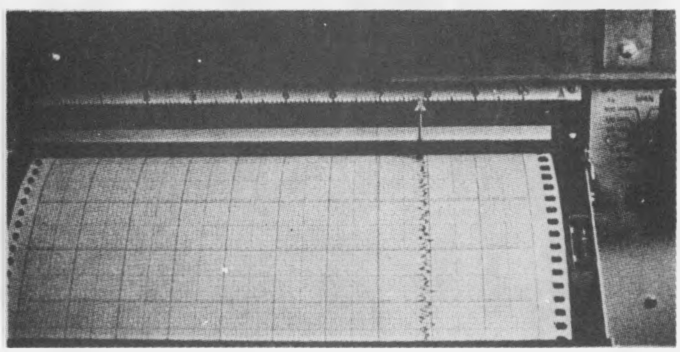
DYK



TRANSPORT OF DYK II POWER ASSEMBLY ON LOW BED TRAILER

AUTOMATIC ELECTRONIC SPACING MEANS INSURED PROPER SPACING OF WRAPPED STRAND. NOTE LOCK-OFF POCKETS IN WALL SPACED AT ONE REEL INTERVALS.





CLOSE-UP PHOTO OF STRIP-CHART RECORDING WHILE STRANDWRAPPING IS IN PROGRESS.

Figure 7.4-2. Transport, Spacing and Recording Features of DYK II Strand Winding Machine

7.5 FINAL POSITIONING

Steel support slabs bridging the gallery in the foundation pier are rough leveled by jack nuts on the anchor bolts. A pre-fabricated spreader frame is attached to the bottom-most assembly (which is the lower plate of the bottom head) and the two moved by derrick onto the support slabs. Positioning is done by means of guide pins. The assembly is leveled true and the support slabs are brought to proper contact by adjusting jack nuts. The support slaps are grouted and the remaining two bottom head assemblies are similarly positioned by spreader, derrick and guide pins.

In the same manner, cylindrical assemblies are stacked one-by-one to full height, guyed intermittently against accidental dislodgment during stacking. An interior mobile platform, supported on lugs welded to the liner, serves the dual function of a viewing platform from which to direct the derrick operator and as access for girth welding. A view of this operation is shown in Figure 7.5-1.

Laminar assemblies for the top head are stacked in much the same fashion as for the bottom head.

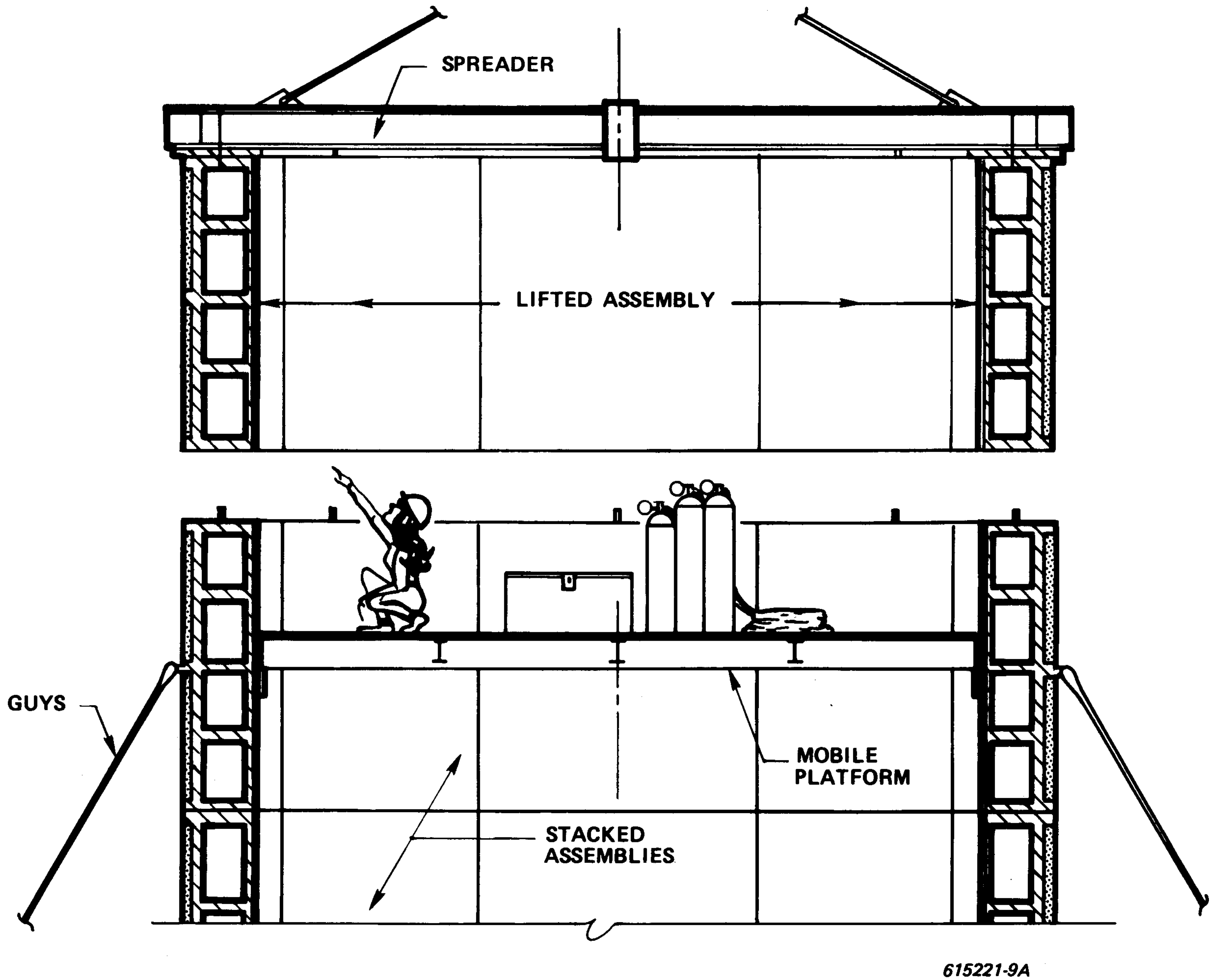


Figure 7.5-1. Assembly Stacking of Body Rings

7.6 LINER WELDING IN PLACE

Girth welds are done individually after each vessel body ring assembly has been hoisted and set in position at its appropriate elevation. The welds are made totally from the inside of the vessel by welders working on a mobile platform with manual torches.

Petal welds are made manually (down) for the bottom head and manually (up) for the top head working from the mobile platform inside the vessel.

After welding is completed the mobile platform is modified to a smaller diameter and hung from cables inside the vessel. This permits its use as a work platform to install internal cooling coils and thermal insulation on the inside of the vessel.

7.7 LONGITUDINAL PRESTRESSING

In order to longitudinally prestress the PCIV, vertical tendons must be installed at 96 locations near the outside diameter of the vessel. Each tendon consists of 150 steel wires each being .25 inches in diameter and approximately 153 feet in length. For installation a temporary work platform is constructed around the periphery of the upper head at an elevation even with the top surface of the head.

The tendons are received at the construction site in the as-coiled condition. The coils are about 8 feet in diameter and stored on special racks that have been designed for shipment and storage of the tendons. The coiled tendons are transferred one at a time to the tendon uncoiling reel which is positioned on the platform at the top of the vessel. The tendons are then uncoiled, combed and winched thru vertical passageways formed by metal conduit sections that have been previously assembled into the wall of the vessel (see Figure 7.7-1). This operation pulls each tendon far enough thru the vertical passageway to expose a length of the tendon wires in the gallery area below the vessel. This excess length permits the wires to be installed in a "field anchor" member and each wire button-headed by the use of a machine that is available for that purpose. Button-heads were previously made on the wires at the opposite (or top) end while the wires were being assembled to the "shop anchor" member. A winch located at the top of the vessel is now used to pull each tendon upward until the field anchor seats against its bearing plate that is exposed in the gallery at the bottom of the vessel.

After threading a permanent bushing onto each shop anchor, a stressing jack is used as shown in Figure 7.7-2 at the top of the vessel to pull on the bushing. This produces tension in the tendon since the button heads at the bottom end of the tendon wires prevent upward motion. The stressing jack elongates the tendon sufficiently to allow split shims to be inserted under the bushing thereby holding the elongation. The thickness of the shims (about 10 inches) is predetermined to produce the proper amount of axial prestress in the vessel.

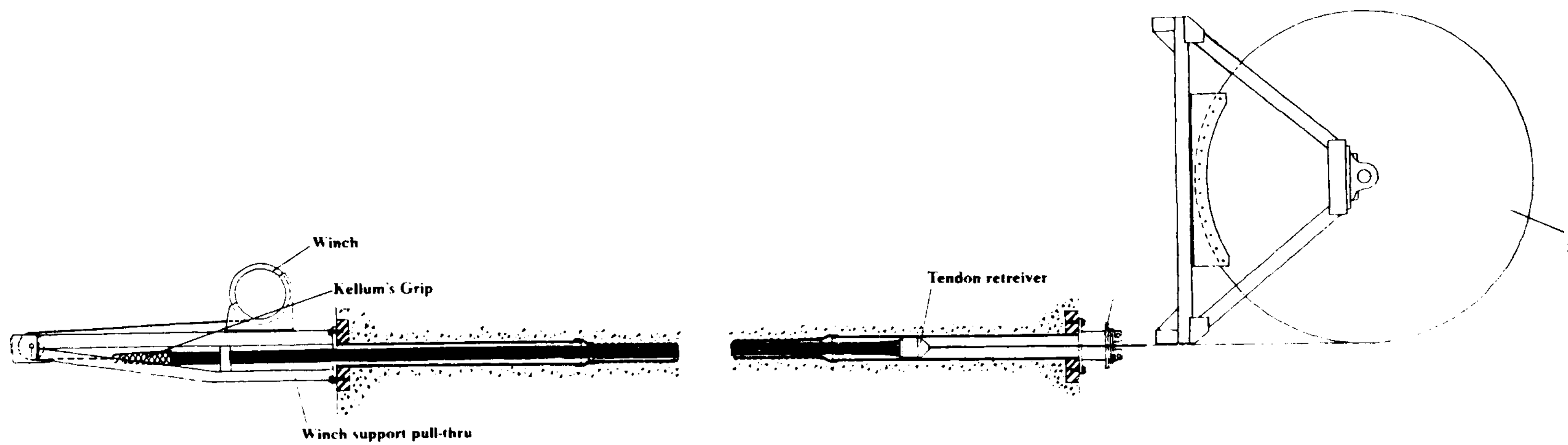


Figure 7.7-1. Installation of Axial Tendons

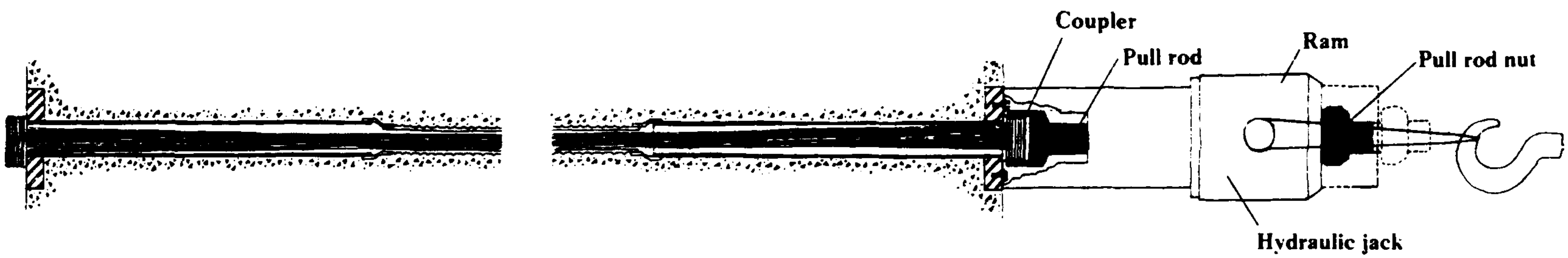


Figure 7.7-2. Applying Axial Prestress

For corrosion protection of the tendon wires and anchors, caps are placed over the top and bottom anchors so that grease can be forced into the conduit and caps, thus forming permanent corrosion protection.

7.8 COMPLETION

After closing off the nozzles, a hydrostatic water test is made to ensure the structural integrity of the vessel under pressurized conditions.

Following the hydro-test, refractory is applied using interior scaffolding for application to top of cooling piping and the modified mobile platform for the upper portion.

After air ducts through the foundation pier are installed, the support slabs over the gallery and the ducts are caulked to form a plenum below the vessel.

8.0 COST AND SCHEDULE ESTIMATES

8.1 COST ESTIMATES

Estimates of the total fixed capital investment cost have been derived for manufacturing, erecting and preparing the reference PCIV gasifier for use. All costs were determined in terms of fourth quarter 1978 dollars.

A ground rule for preparation of these estimates was that the same type of assumptions as were made in the Reference 1 study should be utilized whenever possible so that as direct a comparison as possible could be made of PCIV and FFSV costs. One result of this ground rule was that, although this study is directed at the vessel only, it was necessary to also estimate the costs of the internal components so that the total costs would be for a comparable equipment scope. Another result of this ground rule was that the same construction site, near Gillette, Wyoming, was assumed.

It was the intent in deriving these estimates that the PCIV costs derived should be as realistic as possible but should tend toward conservatism rather than optimism. It should also be recognized that many of the features of the design concept described in Section 5.0 have not been optimized for low cost. Further design to lower costs is certain to be fruitful. Therefore, the PCIV cost estimates shown in Tables 8.1-1, -2, and -3 should be viewed as being conservatively high. The accuracy of the overall total cost estimate is judged to be such that the actual costs may be as much as 20 percent lower to 10 percent higher than estimated.

These cost estimates apply to the construction of a single gasifier at the assumed construction site. The components of the gasifier shown in Figure 5.1-1 were studied and casting and other raw material costs determined through discussions with potential vendors. In the case of the castings, detailed drawings were provided to foundries and discussed with them. Quotes were obtained from five U.S. foundries. No unusual spread existed in the quotes and an average pattern cost and an average casting cost was then used as input to the overall

TABLE 8.1-1

MATERIAL AND MANUFACTURING COSTS ($1000)

(One PCIV Gasifier)

	Raw Mat'l.	Mfg.	Complete
Castings	4,929	2,435	7,364
Liner Sections	700	285	985
Internal Components	227	322	549
Nozzle Transitions	64	109	173
Nozzles & Attachments	609	201	810
Bolts, Conduit, Backing Strips	82	200	282
Welding & Attachment of Nozzles	13	173	186
Air Cooling Sys. Hardware	100		100
Shipping	146	450	596
	6,870	4,175	11,045

TABLE 8.1-2
FIELD ERECTION COSTS ($1000)
(One PCIV Gasifier)

	SUB-CONTR.	PURCHASED MAT'L FREIGHT	LABOR (W/BURDEN)	TOTAL
DIRECT CONSTRUCTION COSTS				
Site Work & Prep	80		26	106
Assembly Area		49	110	159
Foundation		264	208	472
PCIV Erection		1	383	384
Circum. Prestressing	1,657			1,657
Longitud. Prestressing	626			626
Internal Insul.	558			558
Electrical & Misc.	3	1	1	5
PCIV Cooling			40	40
	2,924	315	768	4,007
INDIRECT CONSTRUCTION COSTS				
Temporary Construction	20	74	38	132
Construct. Equipt.		692	22	714
Tools & Supplies		36		36
Other Craft Labor			67	67
Constr. Mgmt. & Non-Manual			293	293
Misc. Field Expense		95		95
Construct. O.H.		50		50
	20	947	420	1,387
PROCUREMENT AND INSURANCE				40
			TOTAL	5,434

TABLE 8.1-3

COST SUMMARY ($1000)
(One PCIV Gasifier)

Raw Materials Costs	6,870
Manufacturing Costs	4,175
Field Direct Construction Costs	4,007
Field Indirect Construction Costs	1,387
Field Procurement and Insurance	40
TOTAL CONSTRUCTION COSTS	16,567
Engineering and Fee	1,742
TOTAL COST	18,224

gasifier cost. Costs of shipping the castings to the machine shops were determined using a representative shipping distance and planning on four castings loaded onto each rail car.

The necessary machining operations and procedures were derived as discussed in Section 6.0, and the resulting costs derived for machining of the castings, forming of the liner segments, manufacture of the nozzle transitions, attachment of the liner segments to the casting, and for the other manufacturing operations. These costs were estimated by determining the operations and machine times required and by applying representative U.S. costing rates. Shipping costs were then determined using representative rail shipping distances to the Gillette, Wyoming construction site.

Table 8.1-1 summarizes the costs of the major gasifier components delivered to the construction site. These costs include gasifier internals but do not include certain PCIV costs, such as prestressing materials, which are included as part of the field erection direct costs.

The field operations necessary were studied by the Dravo Corporation, Chemical Plants Division, and a cost estimate for the field erection operations derived. In preparing this estimate, Dravo utilized their extensive experience in performance and costing field construction operations, and obtained expert advice and cost estimates from others in specialized areas such as for subcontractors for the prestressing operations. In particular, valuable assistance regarding prestressing operations and costs were provided by Inryco, Inc. and by Dyk BBR Prestressed Tanks, Inc.

Included in the field operation costs are the costs of constructing the gasifier from the Table 8.1-1 equipment received at the construction site. The costs include site preparation, railroad spur, temporary construction facilities, gasifier foundation, assembly and installation of the PCIV rings, welding of the liner segments and nozzles, prestressing and corrosion protection, hydrostatic test, installation of gasifier internals and insulation, removal of the temporary concrete foundations, and other miscellaneous construction related costs. The field costs include the materials for foundation, prestressing steel, and insulation. Also included are the field indirect costs.

A summary of the costs for one PCIV gasifier is shown in Table 8.1-3. The Total Cost includes 10 percent added for engineering and fees, consistent with Reference 1.

8.1.1 COST REDUCTIONS

As a result of formulating the conceptual design of a PCIV and evaluating its merits, it became clear that certain features of the design could be changed or modified in such a way that cost reductions would result. These areas of potential cost reduction identified by this study, but which would require additional effort to confirm and quantify, are discussed below:

- Amount of Cast Iron Material - In the conceptual design, the sidewall configuration of the cast iron body segments was established to provide stability in the event that a crack existed in the material and also to keep stress levels below allowable limits for cast iron. However, since the stability of the cast iron is not marginal and since the maximum stress is well below the allowable limits, it is apparent that some reduction in the amount of cast iron used in the body segments can be made. Lower weight will also reduce shipping costs. An alternate approach that would yield an important cost reduction, would be to use a lower strength and consequently lower cost cast iron material.

- Cooling Passages through Castings - The casting configuration used in the conceptual design utilizes a surface on the inside radius that has vertical grooves cast in place to provide passage for air coolant flow. A more attractive configuration is one where the castings are cored in the vertical direction in such a way that passage of the conduits for the tendons is provided and also passageways for cooling air flow. This will reduce the cost of the castings and also permit thinner liners to be used since the liner thickness in the conceptual design is dictated by the bending strength required to bridge internal pressure loads across the vertical flow passages in the castings.

- Less Machining - The sidewall castings, as designed, require machining essentially all over. It appears possible to design the castings with features that eliminate the need for some of the machining, possibly on the inside or outside curved surfaces.

- Nozzle and Nozzle Attachment Design - The nozzles that enter the vessel, either through the sidewall or the head, must be carefully designed to withstand the loads imposed while maintaining the stresses imposed on the cast iron within acceptable limits. The nozzle concepts derived in this study show that the design requirements can be filfilled, but the nozzle concepts have not yet been optimized for cost. The nozzles are recognized to be relatively expensive design solutions which can be optimized to reduce material and labor costs.

- Vertical Tendons - There are various types of vertical tendons that can be used in a PCIV and a representative type has been included in the reference PCIV design concept of this study. The type was selected because of its assured acceptability. However, there are other candidate types which have the potential for reducing the material and/or erection cost of the axial prestressing system. One such candidate utilizes solid bar type tendon sections joined together by threaded couplings as the sidewall is constructed. Optimization of the vertical tendons for cost during detail vessel design is expected to be beneficial.

- Circumferential Cables - As with the vertical tendons, there are various types of circumferential prestressing systems that can be used in a PCIV and a representative type has been included in the reference PCIV design concept. One alternate type of system that may be particularly attractive in a PCIV application utilizes flat strip material instead of strands. Optimization of the circumferential prestressing system to minimize cost while fulfilling the needs of the PCIV is expected to be beneficial.

- Corrosion Protection for Prestressing Members - An epoxy material was selected for corrosion protection in the reference PCIV design concept because its application and performance for corrosion protection is well established. However, its expense is significant and there are other candidate design solutions such as the use of galvanized cables which provide inherent corrosion protection.

- Head Design - The bottom and top heads of the PCIV conceptual design contain 1500 tons of cast iron in 78 machined pieces. The cost of material and machining associated with these heads is therefore an important portion of the total PCIV cost. Alternate simpler head designs utilizing fewer blocks, fewer nozzle or alternate head configurations appear certain to reduce costs but require more detailed design study to assure suitability.

Each of the above potential areas would require more detailed design of the PCIV gasifier to confirm and quantify the cost reductions. Although each area for cost reduction appears to be realistic, it is unrealistic to assume that the total of all reductions can be achieved in actuality. Therefore, although the sum of the estimated reductions is on the order of 20 percent of the total PCIV gasifier cost, a lesser cost reduction of 10 percent ($1.9 million) appears realistically achievable.

8.2 SCHEDULE

Among the major elements determining the time required for a PCIV gasifier are engineering, preparation of casting patterns, casting of the blocks, machining of the blocks and liner segments, and site construction activities. A schedule for these activities for the installation of one gasifier is shown in Figure 8.2-1. This schedule was derived using the pattern making and casting delivery schedule estimated by the foundries that were consulted and the estimated schedules for manufacturing and site construction activities discussed in Sections 6.0 and 7.0.

The pacing items for the Figure 8.2-1 schedule are an accomplishment of the vessel design engineering, pattern making and delivery of sufficient castings to allow start of machining operations, machining of the castings and liner segments, and completion of site erection activities. Figure 8.2-1 shows that a PCIV allows the majority of activities to be accomplished away from the construction site and that the construction site activities are reduced to a relatively short portion of the total time required.

Because most of the PCIV fabrication activities are accomplished off-site under shop conditions, the latitude exists to use alternate shops if problems should develop with one shop. The latitude also exists to utilize more shops to shorten the machining time and therefore to shorter the overall schedule.

The schedule for supply of the castings was derived considering utilization of two foundries and representative casting supply rates as quoted by foundries for these blocks. More foundries could be utilized if desired, in order to avoid too great a reliance upon a few suppliers, but use of more than two would not improve the overall since other factors are more determining.

The machining activity has the most determining effect on the overall schedule but is also the activity which can be improved the most through design to enhance manufacturability. The schedule shown in Figure 8.2-1 assumes the use of five pairs of boring mills. It is also expected that a similar schedule could be maintained using fewer mills with the design modifications, which

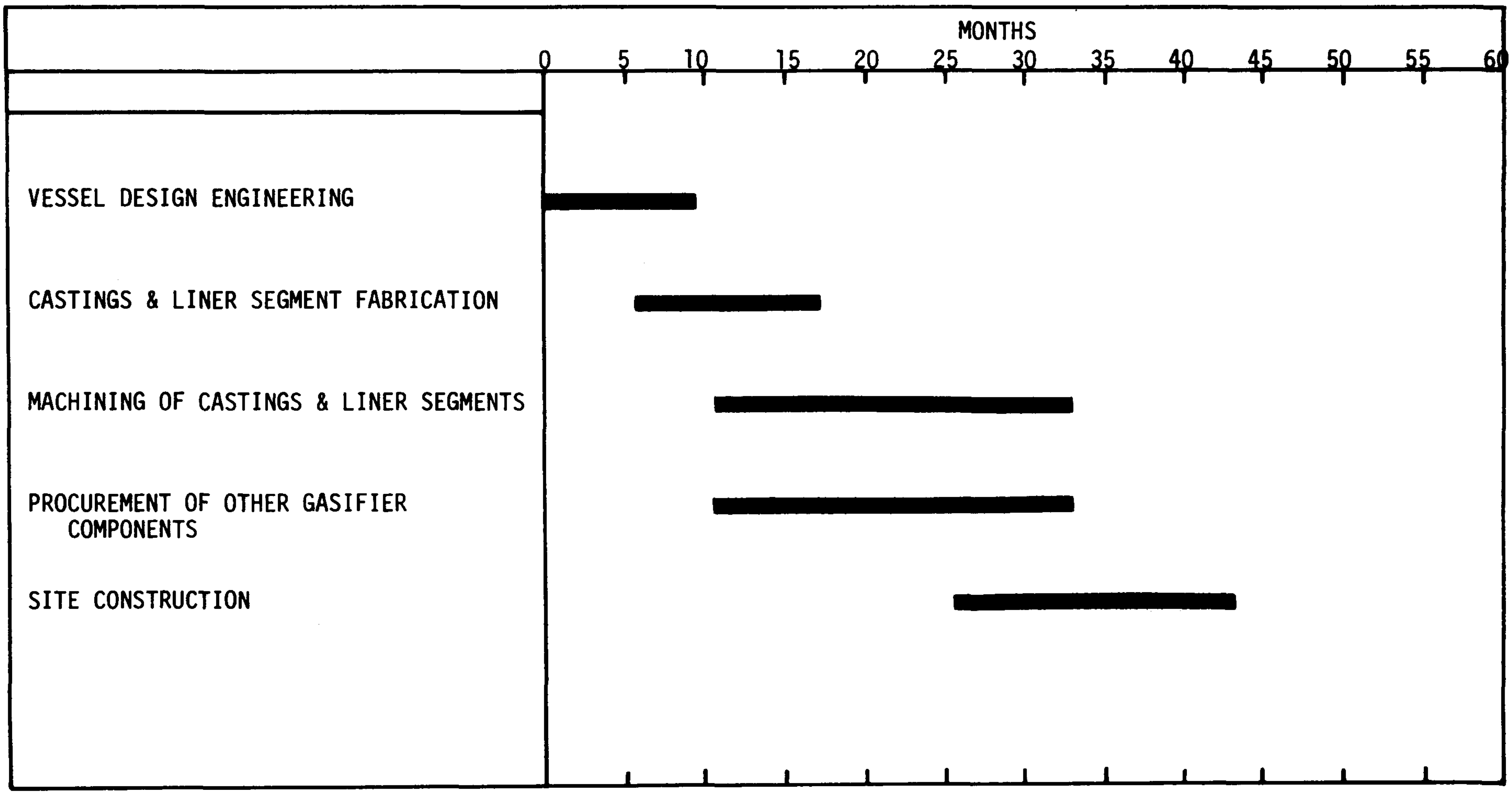


Figure 8.2-1. Overall Schedule for One PCIV Gasifier

will improve manufacturability and lower cost. As discussed elsewhere in the report, it appears that the walls can be redesigned to significantly reduce the machining required on the inside and outside curved surfaces.

Because of the latitude that a PCIV provides to optimize for particular needs the overall schedule shown in Figure 8.2-1 should be considered to be conservative rather than exact. It can be considered to be a baseline for general considerations and for identification and evaluations of improvements.

9.0 EVALUATION AND INTERPRETATION OF RESULTS

The specific design results, that are discussed in other sections of this report, have been evaluated in terms of availability of the necessary technology and their impact upon suitability of a PCIV for coal gasifier applications. In addition, because of the potential applicability of a PCIV to a wide range of other application, the study results have also been interpreted in the context of their implications for other PCIV applications. This section of the report summarizes the evaluations and interpretations of the study results.

The reference Bi-Gas coal gasifier application has been found to be a good base case for evaluation of the viability of a PCIV as a candidate type of pressure vessel. The reference case has sufficiently severe internal process conditions and sufficiently large dimensions to require examinations into all important PCIV design aspects. It is also a reference case which can be used as a basis for evaluations regarding PCIVs in general.

9.1 TECHNOLOGY EVALUATION

Through the processes of developing the reference design concept, consultation with organizations expert in various specific critical design areas, and through derivation of a draft ASME design code it has been determined that there are no fundamental technologies needed for a PCIV which are not available. The PCIV concept is essentially a new combination of technologies that have already been individually applied in other applications. However, the new use of these technologies in the PCIV application does result in the need for derivation of materials and engineering data that have not been needed for past applications of the same technologies.

Some areas where additional data engineering and materials are desirable are identified in the following portions of this section.

9.1.1 OVERALL

In general terms, the engineering and materials data that are needed are of the type that give the desired confidence in a specific vessel design; i.e., that the vessel will be suitable for its intended purpose and also that its design is reasonably optimum.

Some additional engineering studies to provide the engineering knowledge regarding the advantages and disadvantages of various design trade-offs would be very helpful in providing design guidance for specific applications. Such engineering studies would help to quantify the merit of cost and schedule improvements that were identified in Section 8.0 Another area that should be investigated is that of the effects of vessel size and internal conditions on the advantages and disadvantages of a PCIV as compared to the other candidate types of vessels. Because the design and use of PCIVs is still at an early point on the learning curve, such engineering studies can be expected to provide significant improvements in the base of knowledge for a moderate effort.

Construction and test of a demonstration vessel with representative internal pressure and temperature conditions is desirable in order to assure acceptance and use of PCIVs by process plant designers. A demonstration vessel need not be full size, but should be of sufficient size to allow verification manufacturing, assembly, prestressing and corrosion protection techniques. The test vessel would provide demonstrations of satisfactory, predictable temperatures, stresses and strains in the major components making up the walls, heads and nozzles. A demonstration vessel will allow testing to be accomplished over a range of internal conditions such as overpressure and overtemperature conditions to verify suitability under unusual circumstances. A demonstration vessel will thus provide both confidence and design data and can be an important factor in making the benefits of a PCIV available for use.

9.1.2 MATERIALS

The maximum non-damaging compressive stress is defined as the stress level which, when obtained, does not degrade the specified tensile strength of the cast iron material. This effect is important in regions of the vessel where discontinuities occur or where the stress may cycle between compression and tension during transient conditions. A materials testing program would be beneficial in order to determine this compressive strength as a function of thickness, temperature and material (class type) variations. A suggested testing method is identified in the cast iron materials section of the draft PCIV code. This information is necessary to substantiate the design criteria specified in the draft code.

The current material specifications for gray cast iron (ASME 278 and ASTM A-48) clarify the grade of cast iron via a separately cast test sample. This test sample presumably indicates the tensile strength of the actual casting. A technology review indicates that material strength properties vary according to cooling rate/section thickness. A 4-inch diameter casting will exhibit a tensile strength approximately 6 Ksi below that of a 2 inch casting, poured at the same time from the same material heat. This example is indicative of the effects of specifying a two-inch diameter test specimen to control the load carrying capability of a large casting. A materials test program is desirable to correlate test specimen size and strength with actual casting strength. In addition to this correlation effort, the strength variation across the section thickness would aid in determining the triaxial stress state as a function of thickness.

Generally, the cast iron segments when prestressed will be in a compressed state. This suggests that the tensile strength capability of the cast iron would not be utilized. However, some sections of the vessel (i.e., head/cylindrical section interface) create discontinuities in which tensile stresses may be developed. These tensile stresses would develop due to start-up/shut-down cycles and/or pressure fluctuation cycles. The cyclic loading effects may become significant depending on the user's application or design. Fatigue design curves are not presently available for the cast iron materials. A materials development program is therefore necessary to define the test method, test the materials and correlate the data for design purposes. In this test program it may be necessary to investigate cyclic loading other than the reversed bending cases since the vessel primarily carries a compressive stress and cyclic loading is not always reversed. Therefore it may be necessary to bias the cyclic loading toward the compressive stress direction. Even though fatigue may not be a problem in the coal gasification vessel design, any high cyclic loading application could induce a fatigue situation and materials fatigue data are desirable.

The design criteria for gray cast iron are based on the general physical properties and current technology. The variation in strength, brittleness and non-linear stress-strain curves of gray cast iron present unique considerations when designing and analyzing the PCIV concept. In general, the compressive strength of cast iron is between three and four times the tensile strength. For this wall sections undergoing uniaxial compressive loading, the design is limited by shear failure. The shear strength of cast iron is usually between one and 1.5 times the tensile strength. This condition exists because of the lateral displacement of the thin section under uniaxial compression. Increasing the thickness of the section reduces the shear effect and approaches a hydrostatic condition. Because of these effects two sets of design criteria have been specified in the draft PCIV code. The unconstrained and constrained criteria represent the thin wall and thick section conditions, respectively. Due to the limited amount of data, the design criteria are preliminary. The materials verification program identified earlier will aid in verifying the present design criteria. Clarification of the design criteria is important to insuring adequate safety factors have been applied.

Stress relaxation data as a function of temperature for the prestressing materials are limited. Additional data are necessary to evaluate candidate materials and/or operating temperature of the prestressing systems. The prestressing material temperatures have been limited to 140°F in the coal gasifier conceptual design except under hot day conditions when 160°F has been used as the limit. Some thermal energy storage systems may require higher temperature allowables, and additional stress relaxation data are therefore desired to evaluate life of prestressing steel tendons under these conditions.

9.1.3 CAST IRON REPAIR

During the casting process some holes and cracks may develop in the body segments. Some of these holes and/or cracks will be removed as the segment is machined. It may be necessary to repair any remaining holes or cracks after machining. Specific repair methods and procedures must be developed in order to produce quality castings on an economic basis. Weld repair or plug repair may be possible methods used to repair defective castings. An effort is necessary to evaluate these methods and/or any other methods to repair defective castings. Procedures for the approved method or methods will be developed for incorporation into the draft PCIV code.

9.1.4 FACTORS OF SAFETY

Prior to prestressing, there are gaps in the circumferential direction between the block that constitute the main body. During prestressing, the tendon system is loaded in tension and the main body is strained in compression so that the forces are in equilibrium. When the PCIV is subjected to internal pressure, the main body loses some of its compression and the tension in the prestressing system is increased. When the internal pressure is equal to the so called gapping pressure, the main body loses all its prestressed compression and the gaps between the blocks in the circumferential direction reappear. A factor of safety in gapping, F_g is applied to assure that the main body does not lose its compression. For a PCIV with liner, it is desirable that the liner not lose its integrity unless the tendons have significantly yielded. Thus the design limits are controlled by the tendons. Fracture of the tendons is prevented by providing a factor of safety, F_f, sufficiently above gapping. The basic factors of safety are:

- F_g - against gapping, and is the ratio of gapping pressure to design pressure.
- F_f - factor against tendon failure, and is the ratio of pressure necessary for tendon failure to design pressure.

The factor of safety for gapping may vary depending on design and operation conditions. A code article should be included in the PCIV code so that the gapping factor is defined at an acceptable value. Currently, it is recommended that a minimum gapping factor of safety of 1.2 be established until additional information can be obtained to justify a change. Gapping of the main body of the vessel leads, in the case of a PCIV without liner, so leaking and subsequently a loss of internal pressure. For the PCIV with liner, the liner may lose its integrity when the tendons begin to yield. Leaking could also occur during the yielding. It should be noted that gapping safety factor, F_g, need not be exactly the same for axial and circumferential cables. The axial direction F_g may be somewhat lower than the circumferential direction. In this manner, the mode of gapping may be controlled by the designer.

Because of the importance of these design factors, further investigations are desirable to substantiate the acceptability of them.

9.1.5 INSPECTION

Specifications covering nondestructive inspection for internal casting defects, and defining types and conditions of defects which would be cause for rejection or recommendation for repair, will have to be developed for the PCIV castings. The size, weight, assembly methods and complexity of these castings makes X-ray inspection difficult, while the high damping capacity of gray iron will impair ultrasonic testing. Magnetic particle testing would be suitable for detection of surface defects, but simple unaided visual inspection may be adequate to detect this condition in the cast material. Presently, it appears that ultrasonic testing represents the most likely inspection method. International technology recommends use of ultrasonic inspection with a four inch by four inch grid pattern. Statistical quality control methods can be used on the castings to eliminate the need for 100 percent inspection. An evaluation of the ultrasonic inspection method is necessary to assure its acceptability as the primary inspection method. In addition, inspection criteria must be established to identify the types of condition of defects which should be rejected or repaired. Once the technology for inspection and the acceptance criteria are established a standard can then be included in the PCIV code.

9.1.6 NOZZLES

The reference PCIV design includes a liner to protect the cast iron body segments from corrosive gases and maintain the leak tightness condition. The liner becomes the inner skin of the vessel and provides a means to connect nozzles for flow through the vessel. Specifications do not now exist to control the design of the vessel in regions where penetrations through the cast iron body segments and prestressing system occur. The intent of paragraphs from Section VIII Division 2 have been applied in this study to control and design the penetrations into the vessel but development of specific rules relative to these types of penetrations is necessary to insure consistency and safety of the vessel.

9.2 INTERPRETATION OF RESULTS

In addition to the specific design results that are discussed in other sections of this report, some general interpretations have resulted from this study which may be of use to others. The intent of this section is to document this general information and to clarify the rationale use in arriving at some of the conclusions.

There are advantages to use of stainless steel as a liner material such as its compability with process gas and an easing of the field erection operations. Results from the evaluation study indicate that stainless steel can be used as a PCIV liner material even though its thermal expansion characteristics are considerably higher than those of cast iron. This characteristic tends to put compressive stress into the liner as the temperature of the liner and cast iron body rises, and tension as the temperature drops. The stresses can be kept within acceptable limits by keeping the temperature of the liner and cast iron body members essentially the same, and by limiting the temperature rise of both. The results of this effect are beneficial since it permits many different types of steel to be considered as liner material candidates and allows an optimized material to be selected.

The reference PCIV design was formulated with design features and construction techniques that allow the liner to be fabricated in contact with the cast iron body of the vessel. This is a very desirable characteristic since it eliminates the need for any filler material such as grout to fill irregular spaces between the liner operates at essentially the same temperature as the cast iron because of the good contact and thermally induced stresses in the liner are therefore greatly reduced.

Prestressed cast iron pressure vessels can be constructed with penetrations large enough to satisfy most size requirements. Also, normal piping loads can be safely transmitted into and reacted by the body of the vessel. Therefore conventional nozzle sizes and normal piping loads can be satisfactorily accommodated in a PCIV. Nozzles can be built into the sidewall and head of the PCIV have been designed so that they do not significantly disturb the normal stress patterns in the vessel.

Configurations were devised for the cast iron members of the PCIV which produce stress patterns in the members that approximate triaxial compression. The configurations have no slender features. This is important in order to eliminate buckling as a possible cause of failure and also to make sure that the structural integrity (ability to carry compressive loads) of the cast iron members is maintained even if cracks were to develop in the cast iron. It follows that inservice inspection of the cast iron members is not required to assure safety. Operational expense and delays associated with shutdowns for inservice inspections are therefore minimized for PCIV's.

The body of the reference PCIV gasifier is designed to be cooled by forcing air through passages provided for that purpose. Analysis indicates that this type of cooling is practical instead of water cooling. The impact of this result is that the vessel can be operated throughout its service life without problems of water leaks occurring and causing costly shutdown periods.

The head configuration that resulted from the conceptual design effort is rather complicated and expensive. The head is laminated into three sections in order to permit reasonably sized hoisting equipment to be used for installation at the erection site. The advantage of the laminated head design is that it permits each layer of the head to be prestressed by circumferential wrapping at ground level instead of at the elevated installed position. The disadvantage of the head design is that the head is rather complicated and expensive to fabricate. It, therefore, represents one area of the gasifier PCIV that should be reevaluated for possible changes to reduce cost and complexity of the vessel.

Circumferential prestressing is accomplished by continuous wrapping at ground level of individual ring sections of the PCIV. An alternate approach is to position body segments individually at the proper level on the PCIV being built and to continuous wrap with circumferential cabling at that elevation. This approach is not as attractive as ground level wrapping, particularly on tall vessels, because of the difficulties in holding the segments secure and in a winding machine-track combination capable of doing the wrapping at such elevations. Therefore, circumferential wrapping should be done at ground level, with the cabling being laid directly against the cast iron body members. This approach is also advantageous because it approximates production line procedures and eliminates any hazards of prestressing at elevated positions.

Inherent safety of the PCIV results from the redundancy of the axial and circumferential prestressing systems. These systems provide the primary load carrying capacity of the vessel. The system also maintains the position of the cast iron segments and the liner. Insulation is attached to the liner to control the temperature in the cast iron and prestressing steel system. The vessel forced air cooling system insures that the prestressing steel temperature remain below the range where stress relaxation is significant.

Design, fabrication, construction and inspection aspects of the reference application are consistent and prototypic of current technology. A test vessel has been built and tested by Siempelkamp which has provided some verification and qualification of the PCIV concept. The safety aspects of the PCIV conceptual design are consistent with the draft PCIV code which is patterned after the other sections of the widely accepted ASME Code.

Formal expansion of the code by ASME to include such provisions can reasonably be expected. Official coverage of the PCIV in the Boiler and Pressure Vessel Code will encourage commercial usage of the PCIV.

The PCIV technology is also adaptable to applications other than the coal gasifier for which this evaluation study was primarily focused. One such application is for thermal energy storage systems. The draft PCIV code has been developed in a general fashion to accommodate various applications within the specified safety restrictions or constraints. Design conditions will vary according to the type of application, therefore specific considerations must be investigated prior to deciding on a specific concept. Thermal environment relative to the prestressing system appears to be the critical aspect when discussing various applications.

The evaluation study results indicate that for some applications where large pressure vessels are required, the vessel should be designed to minimize heat loss from the vessel. This is probably best done by adding insulation inboard of the

PCIV liner. The resulting radial temperature profile is nearly flat through the liner, cast iron and cabling thicknesses. Designs that utilize thermal insulation between the liner and cast iron or between the cast iron and cabling present an approach that may be advantageous in applications other than coal gasification.

A PCIV is distinctly different from a steel vessel in one important aspect. The liner contains the internal fluid and the pressure is carried by external tension members. The shell of a steel vessel must fulfill both functions simultaneously. The PCIV arrangement gives greater flexibility in choosing a liner material that is compatible with the internal environment and materials other than those recognized as structural materials by the ASME code may be acceptable. This is advantageous to the PCIV approach because of compatibility with the process and for possible cost advantages.

PCIV's can be designed so that the liner operates in compression or a low state of tension during normal operation. Steel vessel shells must operate in a higher state of tension to keep the wall of the shell from becoming too thick. The advantage of operating the liner in compression or a low state of tension is that its resistance to fatigue and stress corrosion problems is greatly enhanced. This can be a very important characteristic insofar as prolonging the life of a vessel that is subjected to a cyclic operation or have a corrosive internal environment.

Because a PCIV is constructed from "building blocks", this type of vessel appears to be particularly appropriate for very large vessels. None of the results of this study indicate that any size limitations have been approached. Much larger diameter vessels, where steel vessels would be more difficult to fabricate, appear to be practical and cost advantages for PCIVs are expected to be more pronounced for large diameter vessels.

10.0 COMPARATIVE ASSESSMENTS

One of the objectives of this study was to evaluate PCIV characteristics in comparison with those of coal gasification reactors based on welded steel and prestressed concrete pressure vessel technology. This section of the report includes results of comparisons that are not discussed elsewhere in the report.

Vessel Type Experience

Of the three types of vessels, there is of course the greatest amount of experience with the steel vessel. There is a lesser, but still important, base of experience with the prestressed concrete pressure vessel (PCPV). As discussed in Section 3.0, the base of actual experience with PCIV is the least of the three types. However, the PCIV also benefits from the experience in circumferential and longitudinal prestressing systems that has been gained in construction and use of PCPVs. In fact, the PCIV can be considered to be primarily a newer combination of older types, i.e., prestressing systems and cast iron, for which extensive experience exists. As discussed in Section 9.3, there are no fundamental technologies which are needed for implementation of a PCIV gasifier, but there are needs for materials and engineering data and vessel demonstration. It has been judged that there is sufficient, direct and related experience to assure successful PCIV implementation in a coal gasifier application.

Cost Comparisons

One of the most important bases for comparison of the various candidate types of vessels is that of cost. It is usually necessary, because of lack of data, to attempt to use cost data from vessels designed for different applications and then to interpret and to normalize these data to some common basis for comparison. In order to avoid some of the pitfalls of such an approach, the Department of Energy directed at the outset of this study that the reference case would be the same as the field fabricated steel vessel (FFSV) case of the Reference 1 study already completed by Chicago Bridge & Iron Company. This PCIV study was therefore conducted using similar installation assumptions as for steel vessels. It was also assumed to be a requirement that the same interfaces with the rest of the system should be maintained whenever possible. It is therefore possible to make meaningful direct comparisons of FFSV and PCIV costs, with the only adjustments being those necessary to account for dollar inflation since the 1976 Reference 1 study.

In addition, a study of Prestressed Concrete Pressure Vessels (PCPV) was performed for the Department of Energy by The Ralph M. Parsons Company (Reference 3). That study examined four different PCPV applications, one of which was that of a replacement of the FFSV gasifier. These data were therefore also available for use in cost comparisons although some adaptations of data were necessary since the PCPV design was not completely constrained to the same plant interfaces as the FFSV installation and the plant costs were also grouped differently.

In order to obtain a good indication of relative costs of the three types of vessels, the cost estimates resulting from the PCIV study have been compared against the cost data published in References 1 and 3 regarding FFSV and PCPV costs. In both of these references, costs are presented in terms of total cost of a plant that includes two gasifiers but without separately grouping all of the costs associated with the individual gasifier. The published data have therefore been interpreted and the appropriate gasifier related costs extracted to allow direct comparisons with the PCIV gasifier costs.

For the purpose of this comparison, the gasifier costs include the necessary site preparation, foundation, the vessel itself, vessel testing, all piping penetrations, the gasifier internal equipment and insulation, any necessary vessel auxiliary equipment such as cooling systems, and field indirect costs and fees. Costs from References 1 and 3 have been escalated to provide a common basis of fourth quarter of 1978 dollars for the comparisons. Table 10.0-1 shows the results of these comparisons.

It can be seen that the PCIV gasifier costs for a plant utilizing two gasifiers have been estimated to be double the costs of a single PCIV gasifier. There could possibly be some reduction in the site assembly costs, but the two gasifiers in the Reference 1 plant layout appear to be too far apart to make effective dual use of site facilities. Therefore, for conservatism, the cost of two PCIV gasifiers has been assumed to be exactly double the cost of a single PCIV gasifier.

As shown in Table 10.0-1, direct comparisons, on as close to a one-to-one basis as possible, show a significant cost advantage for both types of prestressed vessels with a further two percent improvement for the PCIV. Of course, caution must be exercised in evaluating comparisons such as these. Even though the scopes of the systems for which estimates are made are the same, there are invariably differences in the assumptions when each of the three systems have been estimated by different organizations. In addition, the estimates are just that - "estimates," with some associated uncertainties. In the case of the PCIV it is believed that the estimated costs are probably high because, as discussed in Section 8.3, of the assumptions and methodology applied in deriving them.

The comparisons of capital costs shown in Table 10.0-1 show the expected significant cost benefits of PCIV versus field fabricated steel vessels for large pressure vessel applications such as this reference case coal gasification reactor. These benefits are in addition to those that accrue because of the reduction in site construction time through use of a PCIV. The reduction in site construction time can have an important effect on total plant economics.

TABLE 10.0-1

COMPARISON OF CAPITAL COSTS

- 2 Parallel Gasifier Trains -

	Cast Iron PCIV	Concrete PCPV	Steel FFSV
Total Gasifier Related Capital Costs			
- (Millions of 4th Quarter 78$)	36.4	39.4	51.1
- Relative to FFSV	71%	77%	100%

TABLE 10.0-2

COMPARISONS OF CAPITAL COSTS

- 2 Parallel Gasifier Trains -

(Including Estimated Achievable PCIV Cost Reductions)

	Cast Iron PCIV	Concrete PCPV	Steel FFSV
Total Gasifier Related Capital Costs			
- (Millions of 4th Quarter 78$)	32.8	39.4	51.1
- Relative to FFSV	64%	77%	100%

The differences between PCIV and FFSV costs are expected to be more pronounced for larger vessels, especially those that require even thicker walls. The separation of vessel functions into a fluid containment membrane and a separate pressure containment and strength section provides economics that become even more significant as vessel size and shell thickness increase.

The direct comparisons of costs shown in Table 10.0-1 are in actually only part of the data that must be used. Considerations must also be given to the likelihood of cost reductions that are likely to result from further design maturity. As discussed in Section 8.0, the PCIV cost estimates derived in this study have been derived in a manner such as to be realistic for the design concept considered. However, since this is the first detailed study of a PCIV for an application such as the coal gasification reactor, the design concept and the associated cost estimates have not had the benefits of successive design iterations to properly minimize costs.

Figure 10.0-1 illustrates the general cost trends that can be confidently expected. The relative costs from Table 10.0-1 are plotted on Figure 10.0-1, along with an approximation of the relative quantity of the number of large steel vessels, PCIV's and PCIV's built. There is a large background of experience for FFSV because of their extensive use as pressure vessels in the past. There is also a significant amount of experience with PCIV's, but still less with FFSV. As discussed in Section 3.0, there is a significant background for PCIV's but, until this study, no serious design for such as the coal gasifier application had been accomplished. Relative to the PCPV and FFSV, a much smaller number of PCIV's have been constructed.

Typical "learning curve" effects exist for all three types of pressure vessels. When the typical learning curve effects are combined with the data of Table 10.0-1 to reflect the relative experience with each type of vessel, relationships such as that shown in Figure 10.0-1 result. The fact that this study has shown equivalent costs for a PCIV and a PCPV, even though this PCIV study has been only the first step towards implementation, is in itself important.

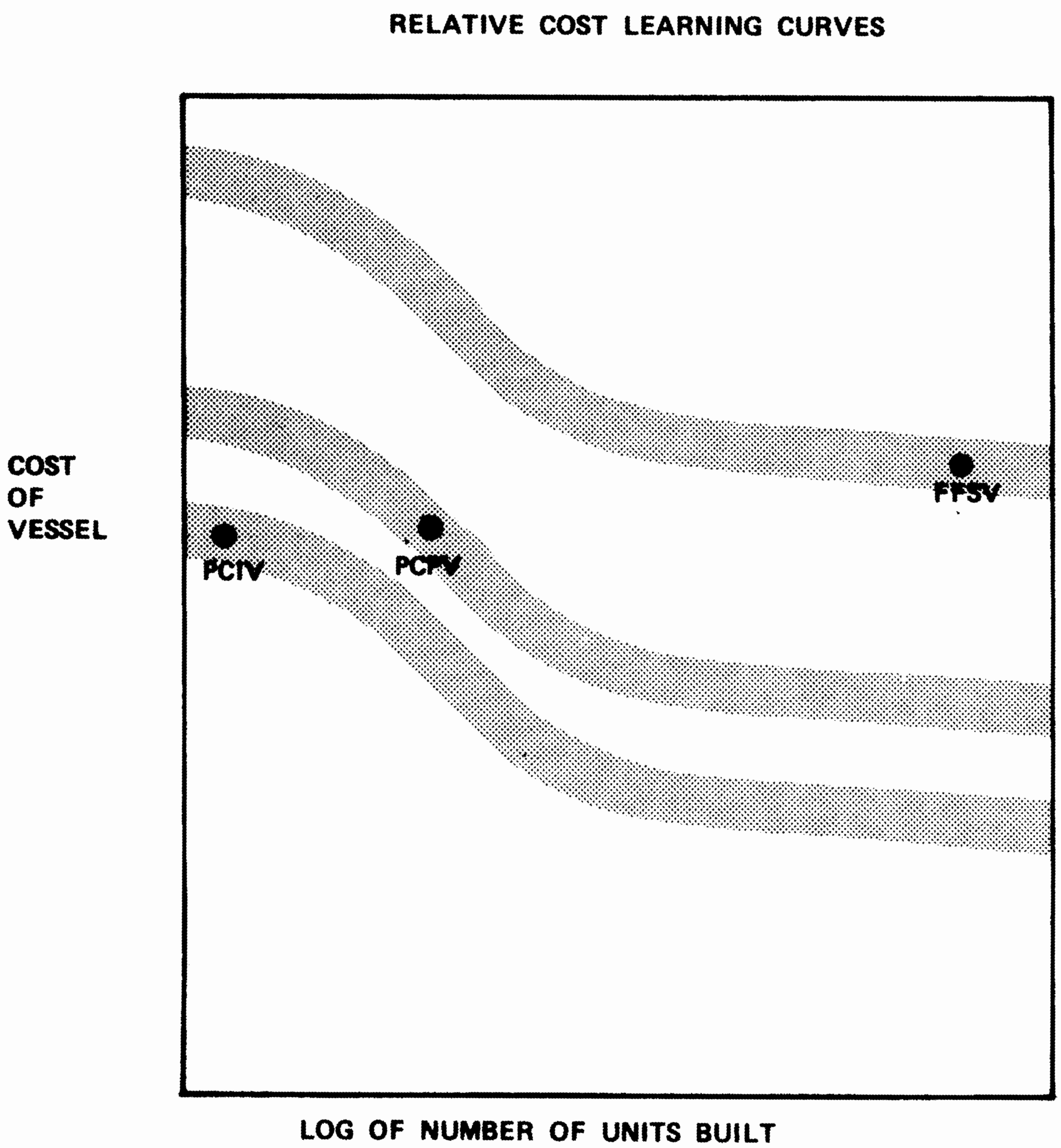


Figure 10.0-1. Relative Cost Learning Curves

Three facts indicate that important cost reductions will result from use of a PCIV instead of a PCPV.

1. The general equivalence of incompletely optimized PCIV costs with optimized PCPV costs for the same application.

2. The relative position of PCIV and PCPV costs on their respective "learning curves."

3. Specific modifications to the gasifier PCIV design concept that have already been identified, and discussed elsewhere in this report, to reduce cost coupled with a general review to estimate the level to which costs could reasonably be expected to be reduced.

As a result of the considerations of Item 3, above, the cost comparisons of Table 10.0-2 were derived. The lower PCIV gasifier related costs were somewhat conservatively estimated because it was recognized that further design studies may show some costs to be increased. It is a carefully considered judgment, however, that the cost comparisons of Table 10.0-2 are reflective of the actual comparison of true PCIV costs when compared with FFSV and PCPV designs having the same level of maturity. Table 10.0-2 is therefore believed to be the best indication of the relative cost benefits.

Site Construction Schedule

In some plants the length of time required for construction of the vessel can be the pacing item in the plant construction program. In these cases, a reduction in vessel construction time can be of importance in reducing overall plant costs.

Reference 1 showed a site construction time of 48 months for the two FFSV gasifiers, considering from the start of vessel site preparation through vessel insulation. Reference 3 indicated a 44 month schedule for similar activities for PCPV gasifiers. This study has shown a site construction schedule of 23 months for two PCIV gasifiers.

The significant reduction in site construction time with a PCIV is obtained because much of the labor associated with construction of a gasifier vessel is accomplished before site activities must commence and some can continue to be accomplished in parallel with site activities. Fabrication of the cast iron blocks can be accomplished through parallel efforts at several foundries and machine shops. The same is not true for FFSV and PCPV construction since these vessels must be built with a preponderance of labor at the construction site.

Inherent Safety Characteristics

All three types of vessels can certainly be considered to be safe. However, prestressed vessels in general have desirable inherent safety characteristic because of the redundancy of the tendons and cables provides additional protection against rupture. Instead of a sudden and complete rupture that can occur with a steel vessel if rupture pressure is reached, individual tendons and cables would rupture without initiating a sudden catastrophic total rupture. This failure mode gives a warning of an ultimate rupture that would not be given prior to the rupture of a steel vessel.

Use of cast iron instead of concrete offers an additional safety advantage in a prestressed vessel. Separation of the body material, the blocks, due to strains in the cables and tendons, can occur without permanent damage to the block material. That is, gaps can be opened between the blocks and after the internal pressure has been relieved, the walls will return to their original configuration. The same is not true for concrete which could fracture and possibly fragment under similar conditions.

Another characteristic of cast iron that can be important in providing enhanced safety is that of its higher temperature capability than concrete. In the event of system failures such as excessive internal process temperature, local insulation failure, or loss of vessel cooling, the higher temperature capability of cast iron provides an extra margin of safety.

Constructability

Two reasons why the constructability of the PCIV is better than for the FFSV or the PCPV are:

- Potential labor problems that could inhibit construction can be circumvented to a large degree in PCIV construction since alternative foundries and machine shops can be used to keep hardware moving, even in the event of labor shortages at a given foundry or machine shop. Labor problems at the construction site are also less severe since construction time is less and fewer construction personnel are required at the site.
- Quality control and repair work can be more easily and efficiently done on the PCIV components since most of this work can be done under shop controlled conditions rather than field conditions. Field welding quality control on the PCIV is limited to that required on the thin liner rather than the thick vessel wall of the FFSV. Field quality control of cast iron segments is not required but the same is not true for the rebar and concrete needed for the PCPV.

Availability (Reliability and Maintainability)

At this time it does not appear that there should be any significant difference in availability for the three types of vessels for this application. This general equivalence is in itself important since it would indicate that the other PCIV benefits can be obtained without a penalty in vessel availability.

Code Considerations

The FFSV has the advantage of steel vessel experience and an ASME code that is already in existence to use as a basis for the vessel design. The PCPV technology has been proven and applied for reactor vessels according to the ASME Section III, Division 2 Code. An ASME code for PCIV does not exist yet and must be prepared and approved to promote commercialization of the concept. This PCIV study has shown that appropriate ASME code requirements can be fulfilled by a PCIV and ASME code approval can be predicted with confidence.

In-Service Inspectibility is not required for any of the three concepts (FFSV, PCPV or PCIV) for the non-nuclear applications. The draft PCIV code has been based on this premise and closely follows the ASME Section VIII, Division 2 philosophy. Inspection and testing of PCIV and PCPV liners are similar to the FFSV inspection technology (Section VIII, Division 2). However, prestressing steel system inspection follows the PCPV inspection techniques (Section III, Division 2).

Applicability to Larger Vessels

Larger vessels with their associated requirement for thicker walls for the same internal pressure represent a class of applications where the PCIV is expected to have distinct advantages. Larger vessels can be constructed without requiring fabrication of larger cast iron blocks than are required for the reference application of this study. The wall of a very large PCIV can be made up of concentric rings, if necessary. No major problems with prestressing are foreseen. In fact, a concrete vessel for this same reference size gasifier application already requires prestressing over much larger dimensions than the reference PCIV. Procedures for machining the cast iron blocks can also be adapted to the needs of blocks for larger inside diameters.

This capability to adapt the PCIV construction to larger vessels without introducing new problems of wall thickness fabrication, quality control, difficult or expensive corrections of construction errors, etc. is an important PCIV characteristic.

APPENDIX A

ASME CODE CONSIDERATIONS FOR PCIV's

(Under Separate Cover)

APPENDIX B

ADDITIONAL STRESS AND THERMAL EVALUATIONS

This appendix to the report on "Evaluation of Prestressed Cast Iron Vessels for Coal Gasifiers" covers some analytical evaluations that were done in addition to those described in the main body of the report. The information may be of a rather detailed nature, but is documented in this appendix to serve primarily as a reference for future work to be done on PCIV technology.

Stress related information is given in B1 and thermal in B2.

B1 PCIV STRESS EVALUATIONS

B1.1 INTRODUCTION

The prestressed cast iron vessel (PCIV) is cylindrical and consists of a thin membrane liner surrounded by the cast iron blocks which form the main body and which are held together by a prestressing system composed of cables. The PCIV may be designed to one of three different concepts: the cold going vessel wherein thermal insulation is provided on the inside diameter of the liner so that the liner, the main body and prestressing cables all operate at a low temperatures; the hot going vessel with cold going cables wherein insulation is located between the main body and the cables so that the main body is at a higher temperature than the cables; and the hot going vessel with hot going cables wherein thermal insulation, if used, is provided outside the main body and the cables so that all parts of the vessel operate at a relatively high temperature.

In this study, the cold going PCIV is addressed. The hot going vessels with cold going cables and with hot going cables are not considered because of thermal stress fears and material uncertainties related to stress relaxation of the cables at relatively high temperature.

BI.2 THE PCIV IN THE CIRCUMFERENTIAL DIRECTION

Prior to prestressing, there are gaps in the circumferential direction between the blocks that constitute the main body. During prestressing, the cable system is loaded in tension and the main body is strained in compression so that the forces are in equilibrium. When the PCIV is subjected to internal pressure, the main body loses some of its compression and the tension in the prestressing system is increased. When the internal pressure is equal to the so-called gapping pressure, the main body loses all its prestressed compression and the gaps between the blocks in the circumferential direction reappear. A factor of safety in gapping, F_g, is applied to assure that the main body does not lose its compression. For a PCIV with liner, it is required that the liner not lose its integrity unless the cables have yielded. Thus the design limits are controlled by the cables. The basic factors of safety are:

F_g : against gapping, and is the ratio of gapping pressure to design pressure.

F_F : factor against tendons failure, and is the ratio of pressure necessary to initiate tendon failure to design pressure

Assuming that the circumferential cables and cast iron body are made of solid homogeneous cylinders and denoting their thicknesses by S_s and S_c, respectively, the prestress in the cables is given by

$$f_{sp} = S_c f_{cp}/S_s \tag{B1}$$

where f_{cp} is the hoop compressive prestress in the cast iron body. One notes that the cable prestress as given by equation (B1) is for the vessel when assembled. For the cables wrapped around the cast iron body ring segments the prestress is given by

$$f_{sp,r} = E_s \left\{ \frac{f_{sp}}{E_s} - \gamma_c \frac{f_{cpa}}{E_c} \right\} \tag{B2}$$

where γ_c is the Poisson's ratio for cast iron, f_{cpa} is the axial compressive stress in the cast iron, and E_s and E_c are the material moduli for the cables and cast iron, respectively. In equation (B2), the second term in parentheses makes allowance for the additional strain that will be imposed on the circumferential cables due to the Poisson effect when the axial tendons are also prestressed.

When the vessel is pressurized, an interface pressure develops between the cast iron body and the circumferential cables and is given by (see Reference 1)

$$p_{int} = p\left[1 + \frac{(1 - \nu_s/2)}{(1 - \nu_s/2)} \; \frac{E_d \; S_c}{E_s \; S_s}\right]^{-1} \qquad \text{(B3)}$$

and where γ_s is the Poisson's ratio for the cables, R is the internal radius of the vessel, and p is the internal pressure. Equation (B3) is valid for a thin cylinder only.

The stresses in the cast iron vessel and in the circumferential cables during operating conditions are approximated by

$$\sigma_c = (p - p_{int}) \; R/S_c - f_{cp} \qquad \text{(B4)}$$

$$\sigma_s = \begin{cases} (p_{int} R + S_c f_{cp})/S_s ; \; p \leq F_g p_i \\ p\,R/S_s ; \; p \geq F_g p_i \end{cases} \qquad \text{(B5)}$$

In both the above expressions, the first term represents the pressure contribution to the stresses during operation while the second respresents the prestress.

The design of the PCIV should be such that the following conditions are met:

$$\begin{aligned} &f_{cp} \leq f_{c,\, all} \\ &\sigma_c \leq 0, \text{ for } p = F_g p_i \\ &\sigma_s \leq f_{s,\, all}, \text{ for } p = p_i \\ &\sigma_s \leq f_f, \text{ for } p = F_f p_i \end{aligned} \qquad \text{(B6)}$$

where $f_{c,\,all}$ and $f_{s,\,all}$ are the allowable stresses in the cast iron and cables, respectively, and f_f is the ultimate tensile strength of the cables.

The stress equations (B6) and (B5) impose conflicting requirements on the design. While a high value for the cast iron prestress, f_{cp}, is necessary to assure that the vessel body will not gap, an excessively large value for f_{cp} will result in an unacceptably large value for the cable operating stress σ_s.

Setting the cast iron compressive stress equal to zero when the pressure is equal to the gapping pressure, yields from equation (B4) and (B5)

$$f_{cp} = F_g p_i \left\{ 1 - p_{int}/p_i \right\} R/S_c \tag{B7}$$

$$\sigma_s(p) = \begin{cases} \dfrac{R}{S_s}\left[p(p_{int}/p) + F_g p_i \left\{ 1 - p_{int}/p_i \right\} \right] ; & p \le F_g p_i \\ \\ \dfrac{Rp}{S_s} & \end{cases} \tag{B8}$$

Equation (B7) gives the circumferential prestress in the cast-iron required to assure that it will not gap below the gapping pressure, and equation (B8) gives the tensile stress in the cables at any value of the vessel internal pressure.

B1.3 THE PCIV IN THE AXIAL DIRECTION

When the cast iron prestressed rings are stacked one on top of the other and the heads are located in position, the vessel is prestressed axially by tensioning the axial tendons. The prestress in the tendons should be sufficient to overcome any tensile stresses which might develop axially in the vessel body during operation; and consequently to prevent the body from gapping in the axial direction.

When the vessel is pressurized internally, both hoop and axial stresses are developed in the cast iron while only axial stresses are developed in the tendons. The vessel body biaxial stress effects are neglected since these are small. Although an axial temperature variation exists over the length of the vessel, thermal stresses are not considered in the analysis as they are negligible. In the following analysis development, it is assumed that the liner is not stressed axially in the prestressed state.

If A_t is the total cross-sectional area of the axial tendons and S_{ca} the equivalent solid thickness of the cast iron in the axial direction, the axial compressive prestress in the cast iron is given by

$$f_{cpa} = A_t f_{pa}/2\pi R S_{ca} \qquad \text{(B9)}$$

where

f_{pa} is the tensile prestress in the axial tendons.

When the vessel is subjected to an internal pressure p, the axial strains developed in the cast iron body and the tendons are the same. Additionally the sum of the axial forces developed in the cast iron and tendons must equal $p\pi R^2$. Consequently, the summation of axial stresses in the cast iron and the tendons due to the pressure is given by:

$$\sigma_{cp} = p\pi R^2/(E_t A_t/E_c + 2\pi R S_{ca}) \qquad \text{(B10)}$$

$$\sigma_{tp} = E_t \sigma_{cp}/E_c$$

where

E_t and E_c are the elastic moduli for the tendons and cast iron, respectively.

The axial stresses in the cast iron and the tendons during operation are therefore given by:

$$\sigma_{ca} = \sigma_{cp} - f_{cpa} \tag{B11}$$

$$\sigma_t = \begin{cases} \sigma_{tp} + f_{pa} \ ; \ p \leq F_g p_i \\ p\pi R^2/A_t \ ; \ p \geq F_g p_i \end{cases} \tag{B12}$$

From equations (B10), (B11), and (B12), the cast iron axial compressive prestress f_{cpa} can be found on the condition that $\sigma_{ca} = 0$ when $p = F_g p_i$. Equations (B9) through (B12) now define the stress states in the cast iron and axial tendons in the operational condition subject to the following stress constraints:

$$\begin{aligned} & f_{cpa} \leq f_{c,\ all} \\ & \sigma_{ca} \leq f_{s,\ all}, \text{ for } p = F_g p_i \\ & \sigma_t \leq f_{s,\ all}, \text{ for } p = p_i \\ & \sigma_t \leq f_f, \text{ for } p = F_f p_i \end{aligned} \tag{B13}$$

B1.4 THE PCIV HEAD

The prestressed cast iron head is laminated through its thickness and, additionally, consists of segments in the circumferential direction. In the assembled state the segments are held together in compression by prestressed circumferential cables to form each laminated segment. These are then held together by shear keys to form the PCIV head such that the head essentially behaves as a homogenous isotropic circular flat plate.

The level of compressive prestress imposed on the head by the circumferential cables should be such that no tensile stresses occur in the head when the vessel is pressurized. Furthermore, the sum of the compressive prestress and the compressive bending stress created by the pressure load should not exceed the allowable compressive stress for the head material. These are the stress constraints on the design of the PCIV head.

Assuming that the head is a flat circular plate simply supported at the edges and subjected to a pressure load p, the maximum bending stress is given by (for a value of 0.28 for Poisson's ratio)

$$\sigma_{max} = 1.23\ pR^2/s^2 \qquad \text{(B14)}$$

where R is the radius of the plate, and s is the thickness of the plate (assumed to be solid). In reality the head has cavities and will more likely resemble a girder type plate as shown in the schematic (Figure 5.2-5). For such a plate, the equivalent solid thickness is given by (Reference 2).

$$s^2 = (h^3_{po} - h^3_{pi})/h_{po} \qquad \text{(B15)}$$

where h_{po} and h_{pi} are as indicated in Figure (5.2-5).

If the stress in the head circumferential cables in the prestress condition is f_{sp} and the thickness of the cable ring is S_{sp} (assumed to be solid and homogenous), the compressive prestress exerted on the head is given by:

$$\sigma = f_{sp}\ S_{sp}/(R + S_c) \qquad \text{(B16)}$$

Setting the pressure load as $p = F_g p_i$ where p_i is the design pressure and F_g the gapping factor of safety, and setting f_{sp} equal to the allowable cable stress (i.e., $f_{sp} = 0.7\ f_{sf}$, f_{sf} is the ultimate cable tensile strength), equations (B14), (B15), and (B16) yield on simplification:

$$S_{sp} = 1.757\ F_g\ p_i\ (R + S_c)R^2 h_{po}/[f_{sf}\ (h^3_{po} - h^3_{pi})] \qquad (B17)$$

Equation (B17) gives the desired thickness of the cable ring around the PCIV head.

B1.5 DISCONTINUITY STRESSES AT THE HEAD TO VESSEL TRANSITION SECTION

When the PCIV is assembled, essentially no discontinuity stresses exist at the transition between the vessel head and the vessel body. However, once the vessel is pressurized, such stresses will exist. Discontinuity moments and radial shear forces are created and these are given by (Reference 3).

$$M_o = \frac{\left\{ \dfrac{pR^3\lambda^2 D_2}{4D_1\ (1+\nu)} + \dfrac{2pR^2\lambda^3 D_2 t_1}{t_2(1-\nu/2)\ [Et_1 + 2RD_2\lambda^3(1-\nu)]} \right\}}{\left\{ 2\lambda + \dfrac{2R\lambda^2 D_2}{D_1\ (1+8)} - \dfrac{\lambda Et_1}{Et_1 + 2D_2\lambda^3 R(1-\nu)} \right\}} \tag{B19}$$

$$V_o = M_o \left\{ 2\lambda + \frac{2R\lambda^2 D_2}{D_1\ (1+\nu)} \right\} - \frac{pR^3\lambda^2 D_2}{4D_1(1+\nu)} \tag{B20}$$

where

$$\lambda = \left[3(1-\nu^2)/R^2 S_c^2 \right]^{1/4}$$

$$D_1 = E_c S^3{}_{cp}/12(1-\nu^2)$$

$$D_2 = E_c S^3{}_c/12(1-\nu^2)$$

The cast iron vessel membrane discontinuity maximum stresses in the circumferential direction are now given by (Reference 3):

$$s_2 = \left[\frac{pR}{S_c} + \frac{2M_o}{S_c}\ \lambda^2 R - \frac{2V_o}{S_c}\ \lambda R \right] \tag{B21}$$

Similarly the vessel bending discontinuity stresses in the longitudinal direction are given by (Reference 3):

$$s^1{}_1 = \left[\frac{1.932\ V_o}{\lambda S^2{}_{ca}} - \frac{6M_o}{S^2{}_{ca}} \right] \tag{B22}$$

The maximum bending discontinuity stresses in the cast iron head in the radial and circumferential directions are given by (Reference 3):

$$s_r = \left[\frac{V_o}{S_{cp}} - \frac{3}{8}\,\frac{pR^2}{S^2_{cp}}\,(3 + \nu) - \frac{6M_o}{S^2_{cp}}\right] \tag{B23}$$

$$s_t = \left[-\frac{3}{8}\,\frac{pR^2}{S^2_{cp}}\,(3 + \nu) - \frac{6M_o}{S^2_{cp}}\right] \tag{B24}$$

In the various equations of this section, E and ν are the modulus of elasticity and the Poisson's ratio, respectively, for cast iron.

B1.6 LINER

Depending on the PCIV design and the behavior of the cast iron wall to which the liner is attached, the modes of failure which the liner may encounter are those of buckling, tensile failure, shear connector failure, and fatigue failure.

B1.6-1 LINER BUCKLING

In the current PCIV design, it is intended that the liner be in stress free contact with the cast iron vessel wall in the assembled state. Consequently, no circumferential prestress is applied on the liner and buckling due to an external pressure is not a consideration. However, as the PCIV design firms up (during the subsequent phases of the PCIV study) it may be determined that it is necessary to prestress the liner circumferentially. If such is the case, liner buckling due to an external circumferential pressure will have to be considered and References (4) and (5) will be useful in the stability analysis In the former reference buckling due to pressure loading only is considered, while in the latter buckling due to thermal effects is considered.

In the current PCIV design, the liner is prestressed axially by the axial tendons, and consequently liner buckling in the axial direction is a consideration. Using the analysis of Reference (6) where the metal liner is assumed to be of inifinite length constrained circumferentially by anchors connecting the liner to the surrounding wall, the buckling load is given by:

$$P = (1 + \frac{1}{8}\tan^2\alpha)\ 9\pi^2 EI/(4R^2\sin^2\alpha) \qquad \text{(B25)}$$

where E is the Youngs modulus, I the moment of inertia, R the radius, and 2σ the angle between two circumferential anchors. If ε is the axial strain developed in the liner due to the axial compressive load, the required angle between two circumferential anchor studs needed to preclude buckling is approximated by:

$$\phi_p = 2.5t/(R\sqrt{\varepsilon}) \qquad \text{(B26)}$$

so that the required circumferential spacing between two anchor studs is given by $R\phi_p$. In equation (B26), t is the liner thickness.

B1.7 NOMENCLATURE

F_g - gapping factor of safety

F_f - factor of overall safety

E_s - Youngs modulus for cables

E_t - Youngs modulus for tendons

E_c - Youngs modulus for cast iron

γ_s - Poisson's ratio for steel

γ_c - Poisson's ratio for cast iron

$f_{s,\,all}$ - allowable tensile stress for cables

$f_{c,\,all}$ - allowable compressive stress for cast iron

f_f - ultimate tensile strength for cables and tendons

s_c - cast iron vessel equivalent circumferential thickness

s_{ca} - cast iron vessel equivalent axial thickness

R - radius of vessel

S_s - equivalent thickness of vessel cable ring

S_{sp} - equivalent thickness of head cable ring

A_t - cross-sectional area of axial tendons

s - equivalent thickness of head

h_{po} - external dimension of girder type head

h_{pi} - internal dimension of girder type head

t - liner thickness

ϕ_p - angle between the two circumferential anchor studs required to preclude liner buckling

f_{cp} - circumferential prestress in vessel

f_{cpa} - axial prestress in vessel

f_{sp} - circumferential prestress in cables

$f_{sp,\, r}$ - circumferential prestress in cables around cast iron ring segment

σ_c - circumferential stress in cast iron vessel

σ_s - circumferential stress in cables

σ_{cp} - axial prestress in cast iron vessel

σ_{tp} - axial prestress in tendons

σ_t - axial operating stress in tendons

σ_{ca} - axial operating stress in cast iron vessel

σ_{max} - maximum bending stress in head

σ_{lt} - tensile stress in liner

M_o - discontinuity moment

V_o - discontinuity radial force

S_2 - discontinuity circumferential membrane stress in vessel

S^1_1 - discontinuity longitudinal bending stress in vessel

S_r - discontinuity radial bending stress in head

S_t - discontinuity circumferential bending stress in head

P - axial buckling load of liner

B1.8 REFERENCES

1. Lamkin and Brehm, "Analytical Stress Analysis Solution for a Simplified Model of a Reactor Fuel Element", Nuclear Technology, Vol. 27, pp. 273-285 (October 1975)

2. Gilli, Beckmann, and Schilling, "Thermal Energy Storage Using Prestressed Cast Iron Vessels (PCIV)," COO-2886-2, ERDA Office of Conservation, Contract No. EY-76-C-02-2886 (June 1977)

3. Roark, "Formulas for Stress and Strain," Third Edition, McGraw Hill (1954)

4. Yamamoto and Matsubara, "Buckling Strength of Metal Lining of a Cylindrical Pressure Vessel," Bulletin of Japanese Society of Mechanical Engineers, Volume 12, No. 51, pp. 421-428 (1969).

5. Bucciarelli and Pian, Transactions of the ASME, Series E, Volume 34, No. 4, p. 979 (1967)

6. Chan and McMinn, "The Stabilization of the Steel Liner of a Prestressed Concrete Pressure Vessel," Nuclear Engineering and Design, 3, pp. 66-73, (1966)

B2 PCIV THERMAL EVALUATIONS

B2.1 INTRODUCTION

Conceptual designs of a Prestressed Cast Iron Pressure Vessel (PCIV) for coal gasification include a cooling system. Process temperatures as high as 3000 ^{o}F occur inside the reactor vessel outlined in Figure 1. However, support tendons in the wall structure must operate at a relatively low temperature ($\sim$ 140 ^{o}F) to insure that stress relaxation is limited in the tensioning cables which comprise the tendons. During the course of the PCIV program several vessel designs were considered to meet the cooling requirements. This memorandum discusses various aspects of thermal analysis efforts to study the proposed cooling schemes. Analysis of the final design is presented in the first part of this report. Summaries of options and analyses pertaining to the final design as well as early conceptual designs are discussed later in the memorandum.

B2.2 ANALYSIS

B2.2.1 THERMAL COOLING - FINAL DESIGN

The support tendon cooling problem is basically twofold in nature due to the fact that the vessel has two types of tensioned support cables, axial and circumferential. Figure 2 shows the circumferential tendons wrapped around the outer vessel structure with the axial support tendons running vertically along the vessel within the cast iron wall. In the final design, the circumferential tendons lie in contact with the outer vessel wall. Thus, the thermal problem essentially requires cooling the entire cast iron wall to provide a controlled temperature for both the axial and circumferential tendons.

The wall cooling scheme for the final PCIV Conceptual Design is outlined in Figure 3 showing a characteristic section of the vessel wall with materials and dimensions. Cooling is provided by passing air through small cooling passages in the cast iron wall section. The passages or "scallops" are closely spaced around the vessel liner to provide uniform cooling of the cast iron wall. The passage positions provide necessary cooling for the entire cast iron section minimizing the temperature of both the axial (vertical) and circumferential support tendons and eliminating significant temperature gradients in the cast iron.

The prime objective of the cooling system is maintaining the support tendons at or below maximum allowable operating temperatures. Cooling system requirements are derived from necessary heat flux removal to obtain desired temperature levels in the cast iron wall. Ambient air enters the bottom of the vessel, flows through the cooling passages and exits at the top of the gasifier. The limiting factor in the air cooling requirement is the allowable magnitude of the air temperature rise caused by heat transfer to the air stream. The air temperature increase is limited at the flow exit (top of the vessel) to insure desired wall temperature conditions. The required flows then dictate the necessary pressure drop and horsepower to overcome frictional effects in the air passages.

Thermal modeling was conducted using the Westinghouse Tap-A analysis code.(1) Heat flows were calculated via conduction through the various structural materials comprising the vessel wall, forced convection in the cooling air passages and convection and radiation from the vessel outer surface to the ambient. The model employed the following boundary conditions on the vessel walls:

1. The inner wall surface temperature is the same as the coal gas stream temperature.
2. Radiation and natural convection to the ambient occur on the outer surface of the vessel. Equivalent convective coefficients(2) on the vessel surface were input as a function of the vessel outer surface temperature as follows:

$$h_n = 0.19\,(T_s - T_a)^{0.33} \tag{1}$$

$$h_r = 0.00684\,(\varepsilon)\left[\frac{\frac{(T_s + T_a)}{2} + 460}{100}\right]^3 \tag{2}$$

where

T_s = vessel outer surface temperature, ^{o}F

T_a = ambient temperature, ^{o}F

ε = outer wall emissivity ($\sim$0.4 - 0.9 assumed)

h_n = natural convection coefficient, $\frac{Btu}{hr\ ft^2\ {}^{o}F}$

h_r = equivalent radiation coefficient, $\frac{Btu}{hr\ ft^2\ {}^{o}F}$

An alternative set of equations to study the heat transfer characteristics of the various vessel wall components is outlined in Section B2.2.4.

The following correlation[2] was employed to simulate various cooling air flows on the air passages detailed in Figure 4.

$$h = 0.024\ C_p \frac{(G)^{0.8}}{(D_i)^{0.2}} \qquad (3)$$

where:

h = convective heat transfer coefficient, $\frac{Btu}{hr\ ft^2\ {}^{o}F}$

C_p = specific heat, $\frac{Btu}{lb_m\ {}^{o}F}$

G = mass velocity, $\frac{lb_m}{ft^2}$

D_i = equivalent passage diameter, in.

The correlation is based on fully developed flow inside the cooling passage.

The desired result is the necessary cooling horsepower requirement for air flow through the air passages. Referring to Figure 5, the basic energy and continuity equations[3] apply.

$$\dot{q} - \dot{w}_s = \frac{\partial}{\partial t}\int_{V} e\rho dV + \int_{S}(e + \frac{P}{\rho})\,\rho\,\bar{v}\cdot d\,\bar{s} \qquad (4)$$

where:

$$e = u + \frac{V^2}{2g_c} + Z\frac{g}{g_c} = \text{total fluid energy}$$

$$\frac{\partial}{\partial t}\int_{V}\rho dv + \int_{S}\rho\bar{v}\cdot d\,\bar{s} = 0 \qquad (5)$$

For a steady state incompressible flow condition, a modified Bernoulli equation describes the cooling air stream flow.

$$\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} + \frac{V_2^2 - V_1^2}{2g_c} + (Z_2 - Z_1) + H_L = 0 \qquad (6)$$

where H_L is the frictional head loss term.

The mass flow rate of air is calculated from the convective coefficient expression. A corresponding Reynolds Number and roughness parameter based on the cast iron passage wall then determine the passage friction factor, f, from the Moody curves.(4) The frictional head loss is calculated from the Darcy-Weisbach expression:

$$H_L = \frac{fL}{D}\,\frac{V^2}{2g_c} \qquad (7)$$

where:

L = the passage length, ft

D = equivalent passage diameter, ft

V = air velocity

The frictional head loss imposes a pressure drop in the air stream.

$$\Delta p = \rho H_L \qquad (8)$$

The air stream pressure change and volumetric flow rate determine the necessary horsepower to drive the cooling air. The horsepower is calculated based on the following relationship.

$$Hp = \frac{\Delta P \cdot Q}{\eta} \quad (9)$$

where

ΔP = pressure drop

Q = volumetric flow rate

η = blower efficiency, (80%-90% assumed)

Thermodynamic properties are strong function of temperature. Thus calculations were based upon the assumption of a incompressible flow condition in which the air properties were evaluated at the average temperature and pressure of the air stream. This assumption is valid for moderate values of ΔP.

Calculations included estimates of frictional heating of the air stream. Frictional heating becomes important in high velocity air flows. The work input to the air results in a bulk air temperature rise, thus decreasing the effectiveness of the air stream heat removal. Therefore, in the true case, more air flow and consequently greater horsepower is necessary to appropriately cool the vessel wall to desired levels. Estimates were based on converting the ideal horsepower (without viscous heating) into an equivalent air temperature rise (heat load). A corrected flow rate and horsepower were then determined.

The allowable air temperature rise to meet the tendon maximum dictates the required mass flow rate of air. The air flow determines the appropriate heat transfer coefficient to remove the necessary heat flux from the vessel wall. Calculations are based on the energy (enthalpy) balance in Equation (10).

$$\dot{q} = \dot{m} \, C_p \, (\bar{T}_{a_2} - \bar{T}_{a_1}) \quad (10)$$

where

$\dot{q}$ = heat transferred to the air stream, $\frac{Btu}{hr}$

$\dot{m}$ = mass flow of air $\frac{lb_m}{hr}$

C_p = specific heat $\frac{Btu}{lb_m\ ^oF}$

$\bar{T}_a$ = bulk air temperature, ^oF

T_{a1} = air inlet, T_{a2} = air outlet

The frictional heating estimates are calculated via the following:

$$\dot{q} = \dot{q}_v + \dot{q}_{fh} \qquad (11)$$

$$\dot{q} = q \cdot A_p \qquad (12)$$

$$\dot{q}_{fh} = Hp_{ideal} \qquad (13)$$

where

$\dot{q}_v$ = vessel heat flow rate $\frac{Btu}{hr}$

q = vessel heat flux $\frac{Btu}{hr\ ft^2}$

A_p = passage area ft^2

$\dot{q}_{fh}$ = equivalent frictional heating heat load $\frac{Btu}{hr}$ (from conversion of ideal horsepower without frictional heating effects)

Calculations are based on heat flows through various sections of the vessel. For example, Figure 6 shows a typical wall cross section in the gasifier stage of the vessel. The wall structure is similar to a design by Chicago Bridge and Iron Co. [5] The heat flows in this section are based on the average temperature of the gas stream (2050 ^oF) and an average insulation thickness (4.25" of low iron castable). Heat flux calculations in other vessel sections are referended to the gasifier stage model. Details are discussed with the results in Section 2.2. Table B2-1 on the following page lists materials and thermal conductivities[6] for the wall described in Figure 6.

TABLE B2-1 VESSEL WALL MATERIALS

Material	Wall Thickness	Thermal Conductivity
Castable Insulation (high alumina)	6.0 in.	8-10 $\frac{\text{Btu-in.}}{\text{hr ft}^2\ ^{o}\text{F}}$
Castable Insulation (low iron)	4.25 (average)	1.54 - 1.84 1.65 (500 ^{o}F)
Stainless Steel Vessel Liner	0.75	112.8
Cast Iron	26.0	384
Steel Tendons In Epoxy Matrix	2.8 (TYP)	207.4

B2.2.2 SCALLOP FLOW COOLING REQUIREMENTS

Two design cases were studied: a nominal ambient inlet condition of 50 ^{o}F and a "hot" day having a temperature inlet of 90 ^{o}F. The desired maximum allowable tendon temperature is 140 ^{o}F occurring at the top of the vessel as the cooling air temperature increases. Figure 7 represents the required horsepower for both design cases as a function of insulation (low iron castable) thickness, used for its high thermal resistance.

The addition of quality insulation to the inner vessel clearly reduces the required horsepower. The 4.25 insulation thickness is the average value used by CBI(5) in the upper stage of the gasifier. (The CBI design basically uses the liner temperature as the vessel wall limit thus obviating the need for a cooling system.)

However, even with additional insulation, cooling requirements are still excessive for the hot day condition. Further reduction in required cooling may be achieved with increasing the 140 ^{o}F maximum temperature. Since the hot day condition occurs for only short periods of time, the effect of a higher allowable operating temperature was considered. Higher allowable temperatures permit a higher air stream temperature rise which reduces the necessary cooling. Figure 8 shows the required cooling horsepower for the hot day condition extrapolated to the maximum temperatures of 150 ^{o}F and 160 ^{o}F, again as a function of increased insulation thickness. Clearly, the 160 ^{o}F maximum requires the least cooling. Further increases in the allowable temperature limit are prohibited by the stress relaxation problem in the tendon cables. One practical selection of design limits would involve utilizing the highest allowable maximum temperature, 160 ^{o}F, on the hot design day and the 140 ^{o}F maximum for the nominal design condition. Results are shown in Figure 9.

The thermal feedback of frictional heating is indicated by the fact that the higher the required horsepower, the larger the viscous heating effect. For simplicity, frictional horsepower effects were calculated for a set of horsepower and heat flux data (e.g. 150 ^{o}F maximum with 90 ^{o}F inlet air) to establish an actual vs ideal horsepower relationship. All horsepower calculations are proportioned similarly. For example, Figure 10 shows the cooling horsepower with and without frictional heating for the 160 ^{o}F maximum and 90 ^{o}F inlet case. The preceeding curves indicate regions of high horsepower. Due to the assumption of incompressible flow the high horsepower values resulting from high velocity and pressure drop are inaccurate and not applicable. However, the lower curve sections in the region of design selection, are applicable.

From the considerations on the preceding figures, the conceptual cooling system design for the PCIV was chosen as a trade-off of required cooling horsepower and vessel insulation thickness. A low iron castable insulation thickness of 6.25 inches was selected. This insulation thickness results in a cooling air flow rate of 50,000 cfm with resulting pressure drop of 2.2 psi and a blower output horsepower rating of 570 hp for the high temperature ambient design point (160 ^{o}F). With the nominal 50 ^{o}F ambient air and a 140 ^{o}F maximum temperature the flow rate, pressure drop, and horsepower become 38,000 cfm, 1.4 psi, and 275 hp, respectively. Table B2-2 summarizes the cooling system hardware requirements.

TABLE B2-2 COOLING SYSTEM REQUIREMENTS

Design Condition	Horsepower	Flow Rate* (CFM)	Pressure Drop (psi)
90^{o}F ambient air inlet	570	50,000	2.2
50^{o}F ambient air inlet	275	38,000	1.4

Numerous computer simulations of the vessel heat flow characteristics and air passage effectiveness were conducted to arrive at the choice of design point. Various insulation thicknesses, heat transfer coefficients, air temperatures and vessel boundary conditions were studied. Figure 11 shows the vessel air stream heat flux removal as a function of insulation thickness and heat transfer coefficient. The bulk air stream temperature is 115 ^{o}F. Clearly, the insulation thickness is dominant in reducing the vessel heat flux. Additional insulation thus requires less cooling air flow. Figure 12 shows the effect of air stream temperature. Obviously, the colder the air temperature, e.g. nominal vs. hot day conditions, the better the heat removal thus dictating a lower air flow rate and lower horsepower requirement.

*Corrected to standard conditions at 4600 ft-proposed gasifier site- 12.43 psia, 42.6 ^{o}F-Reference (2), via air flow adjustment.

An example of resultant wall temperature distribution for a given air flow through the scallop cooling passages is shown in Figure 13. High air flows effectively cool the entire cast iron wall section and minimize temperature gradients in the cast iron. The case shown has 90 ^{o}F inlet air at 57,000 cfm resulting in an outer vessel temperature of 108 ^{o}F for the inlet to the Stage II gasifier having an inner boundary temperature of 2400 ^{o}F. The wall temperatures are low due to the low air temperature in the scallop passages at that point along the vessel. The maximum air stream temperature occurs at the top of the vessel (air flow exit). Consequently, the heat flux removal is lowest at the air flow exit. Figure 14 illustrates this fact by showing the heat flux to the air stream as a function of inner vessel boundary temperatures and insulation thickness. Figure 15 shows the air stream heat removal as a function of axial position along the Stage II gasifier. The increasing air stream temperature from the bottom to the top of the vessel prevents wall hot spots from occurring despite higher inner vessel boundary temperatures in the lower stages of the vessel.

The required air cooling flows to achieve the 160 ^{o}F maximum on the hot design day and 140 ^{o}F maximum during nominal operation are shown as a function of insulation thickness in Figure 16. The air flow rates include the viscous heating effects discussed previously. Again, the insulation thickness is the dominant factor in the cooling scheme. Figure 17 shows the vessel wall temperature distribution at the top of the Stage II section for the hot design condition (90 ^{o}F inlet air) and 50,000 cfm air flow.

The cooling requirements in Table B2-2 results in various maximum temperatures throughout the vessel wall. Table B2-3 lists the noted allowable and maximum temperatures for the various materials comprising the vessel structure.

TABLE B2-3 PCIV WALL MAXIMUM TEMPERATURES

Component	Design Limit (^oF)	Hot Design Day[1]	Nominal Design Day[2]
Axial Support Tendon	(160)[3] 140	160	140
Circumferential Support Tendon	(160)[3] 140	150	130
Cast Iron	------[4]	170	150
Stainless Steel Liner	------[4]	180	160
Castable Insulation (low iron)	2600[5]	2100	2100
Castable Insulation (high alumina)	3000[5]	2400	2400
Castable Insulation (alumina plastic) Stage I	3250[5]	3000	3000

(1) Hot design day, 90 ^oF air inlet.

(2) Nominal design day, 50 ^oF air inlet.

(3) 160 ^oF maximum - short preiods of time (hot day)
140 ^oF maximum - constant operation (nominal day)

(4) To date no limit imposed on cast iron, liner

(5) CBI data - Reference (3)

The design constraints are footnoted. Note that the temperature gradient in the cast iron is limited to ~ 20 ^oF by the cooling system. The axial support tendons run slightly hotter than the circumferential tendons due to their proximity to the vessel liner; however, the cooling system still meets the temperature limits of both support tendons.

B2.2.3 ADDITIONAL COOLING CONCEPTS

Several optional schemes were considered in an attempt to reduce the cooling horsepower requirements for the PCIV. The first idea involved changing the cooling air inlet from the bottom of the vessel to the Stage II section of the gasifier shown in Figure 18. Since the largest heat flux from the vessel occurs in this section, 80% of the total cooling air could be passed along Stage II to the hot gas exit while the remaining 20% of the air flow would flow along lower vessel sections. While the hot combustion process occurs in Stage I, sufficient water cooling is provided to reduce the net vessel heat flux in this section. The benefit of proportioning the air cooling in this manner is reducing the air flow path length, the frictional losses and consequently the required cooling horsepower.

Figure 19 shows the estimated horsepower requirement for the hot and nominal design days again as a function of additional insulation. Clearly the cooling requirement decreases. However, despite reductions in required cooling horsepower, the liability of extra cost exists in the new air flow inlet, air flow proportioning (80/20) and necessary external piping.

Another cooling option is the use of alternate air flow passages. For example, consider the air "cell" space surrounding the axial support tendons shown in Figure 20. Several analyses were conducted using variable amounts of low iron castable insulation (e.g. 2 inches <u>less</u> than the current design) and passing the cooling air through the air "cell" space surrounding the vertical support tendons. Since wall support bulkheads within each cell occur at intervals along vessel length, the air stream must pass through the bulkheads. Figure 21 shows the necessary cooling requirement for the hot design day, with 90 ^{o}F ambient air inlet and 140 ^{o}F maximum temperature, as a function of percent cell flow area through the bulkheads. While frictional losses occur as the air stream expands and contracts through the series of bulkheads, cooling horsepower reductions are still noticeable compared to the smaller "scallop" air passages located next to the vessel liner. The results of Figure 21 were calculated for ideal flow expansion and contraction through 80 bulkheads. Horsepower requirements may decrease further by reducing the number of bulkheads. Figure 22 shows the resulting cooling horsepower for 20 bulkheads.

Clearly, options exist to refine the current cooling system and reduce the air cooling requirements of the present design by varying the flow passages with the added potential of decreasing insulation thickness on the inner vessel. More work is required to conduct a detailed analysis to establish precise design choices in subsequent phases of the PCIV program. Calculations in this study were based on estimates of frictional effects, average air thermal properties, etc., to establish basic conceptual design guidelines. Cooling loads and requirements may vary depending on changes in vessel parameters (e.g. air passages, efficiencies, or viscous effects, flow compressibility, etc.

B2.2.3 EARLY CONCEPTUAL DESIGNS

Several early vessel designs considered various positioning for both the axial (vertical) and circumferential support tendons. The major difference compared to the final design was the placement of the circumferential tendons. The nature of the circumferential tendon wrapping is important. For example, several designs included support "shoes" for the circumferential tendons shown in Figure 23. Basically, the shoes insulated the tendons from the outer wall of the vessel. Thus, the temperature control of the axial support tendons became the main issue in the cooling scheme. The cooling problem solution was one of isolating the axial tendons from the highly conductive cast iron wall with a thin gauge radiation "shield" which could also serve as a mounting structure for the tendons. Cooling air could then be passed through the annulus between the radiation shield and the tendon itself.

The cooling scheme was described by a model involving several simultaneous nonlinear equations. Referring to Figure 24, energy balances were conducted on the various materials between the vessel liner and axial support tendon yielding the following:

Wall:

$$\frac{K_w A_w}{X_w}(T_1 - T_w) = \frac{K_a A_a}{X_a}(T_w - T_s) + \varepsilon_w \sigma A_w F_{ws}(T_w 4 - T_s 4) \tag{14}$$

Shield:

$$\frac{K_a A_a}{X_a}(T_w - T_s) + \varepsilon_w \sigma A_w F_{ws}(T_w 4 - T_s 4) = \varepsilon_s \sigma A_s F_{st}(T_s 4 - T_t 4) + h_s A_s (T_s - T_a) \tag{15}$$

Tendon:

$$\varepsilon_s \sigma A_s F_{st}(T_s 4 - T_t 4) = h_t A_t (T_t - T_a) \tag{16}$$

Air:

$$\frac{K_w A_w}{X_w} (T_l - T_w) = \dot{m} C_p (T_{a2} - T_{a1}) \qquad (17)$$

Defining $T_a = \frac{T_{a2} + T_{a1}}{2}$ (18)

The 5 equations above have a total of 5 unknowns:

- T_w Wall temperature, ^oF
- T_s Shield temperature, ^oR
- T_t Tendon temperature, ^oR
- T_a Average air temperature
- T_{a2} Exit air temperature

The known quantities are:

- T_{a1} Inlet air temperature, ^oF
- T_l Liner temperature, ^oF

The convective coefficient[2] for the air is:

$$h = 0.024\ C_p \frac{(G)^{0.8}}{(D_i)^{0.2}} \qquad (19)$$

where D_i is the annulus gap dimension. As in previous discussions, the convective coefficient is a function of the air flow rate, $\dot{m}$. The cooling criterion is the limit on the exit air temperature, T_{a2}, to insure that the axial tendon remains below 140 ^oF.

$$T_{a2} = T_{a1} + \frac{K_w A_w}{X_w \dot{m} C_p} (T_l - T_w) \qquad (20)$$

Analyses were conducted with various specified liner temperatures and shield arrangements to study hot and cold designs. A summary of the basic results is outlined in Figures 25 and 26.

Clearly, from Figure 25, increasing liner temperatures rapidly increases the cooling requirement which favors a cold design. As discussed previously, the 90 ^{o}F ambient inlet condition requires significantly more horsepower than the 50 ^{o}F nominal case due to magnitude of the allowable air temperature rise. Figure 26 illustrates that for a given liner temperature, cooling requirements may be reduced by increasing the annulus gap between the vertical tendon and the radiation shield, decreasing the velocity and frictional effects in the air stream. The results indicate that the most efficient reduction of the axial tendon cooling requirement involves decreasing the vessel wall temperature; e.g. adding more insulation or using wall air cooling passages such as the air cells discussed in Section 2.2.

B2.2.4 ALTERNATIVE EQUATIONS

The following Equations describe the heat flows through the vessel wall (Refer to Figure 3).

(1) $$\frac{K_i A_i}{X_i} (T_i - T_1) = \frac{K_{s1} A_{s1}}{X_{s1}} (T_1 - T_2)$$

(2) $$\frac{K_{s1} A_{s1}}{X_{s1}} (T_1 - T_2) = \frac{K_{ci} A_{ci1}}{X_{ci1}} (T_2 - T_3) + \frac{K_a A_{sc}}{X_{sc}} (T_2 - T_3) +$$

$$\varepsilon_{sc} \sigma A_{sc} F_{sc-ci} (T_2^4 - T_3^4) +$$

$$h_n A_{sc} (T_2 - T_3) + h_f A_{sc} (T_2 - T_a)$$

(3) $$\frac{K_{ci1} A_{ci1}}{X_{ci1}} (T_2 - T_3) + \frac{K_a A_a}{X_a} (T_2 - T_3) + \varepsilon_{sc} \sigma A_{sc} F_{sc-ci} (T_2^4 - T_3^4) +$$

$$h_n A_{sc} (T_2 - T_3) + h_f A_{sc} (T_2 - T_a) = h A_{sco} (T_3 - T_a) + \frac{K_{ci} A_{ci2}}{X_{ci2}} (T_3 - T_4)$$

(4) $$\frac{K_{ci} A_{ci2}}{X_{ci2}} (T_3 - T_4) = \frac{K_a A_a}{X_a} (T_4 - T_5) + \varepsilon_{ci} \sigma A_{ci} F_{ci-ci} (T_4^4 - T_5^4) +$$

$$h_n A_a (T_4 - T_5) + \frac{K_{ci} A_{ci3}}{X_{ci3}} (T_4 - T_5)$$

(5) $$\frac{K_a A_a}{X_a} (T_4 - T_5) + \varepsilon_{ci} \sigma A_{ci} F_{ci-ci} (T_4^4 - T_5^4) + h_n A_a (T_4 - T_5) +$$

$$\frac{K_{ci} A_{ci3}}{X_{ci3}} (T_4 - T_5) = \frac{K_{ci} A_{ci4}}{X_{ci4}} (T_5 - T_6)$$

(6) $$\frac{K_{ci} A_{ci4}}{X_{ci4}} (T_5 - T_6) = \frac{K_{sz} A_{sz}}{X_{sz}} (T_6 - T_7)$$

(7) $$\frac{K_{s2}A_{s2}}{X_{s2}}(T_6 - T_7) = h_t A_o (T_7 - T_{ao})$$

(8) $$h_t = h_r + h_n$$

(9) $$h_n = 0.19\ \Delta T^{0.33}$$

(10) $$h_r = 0.00684\ (\varepsilon)\left[\frac{\frac{T_i + T_i}{2} + 460}{100}\right]^3$$

(11) $$T_a = \frac{T_{a1} + T_{a2}}{2}$$

(12) $$\frac{K_{s1}A_{s1}}{X_{s1}}(T_1 - T_2) = \dot{m}\ C_p\ (T_{a2} - T_{a1}) + \frac{K_{ci}A_{ci1}}{X_{ci1}}(T_2 - T_3)$$

(13) $$h_f = 0.024\ C_p\ \frac{[G]^{0.8}}{D_i^{0.2}}$$

Nomenclature used in the equations above is outlined on the following page.

a = air

a_1 = air inlet

a_2 = air outlet

a_o = outer ambient

c_i = cast iron

c_{i1} = liner to scallops

c_{i2} = scallop to cell

c_{i3} = inner cell to outer cell

c_{i4} = cell to circumferential tendon

f = forced convection

n = natural convection

r = radiation

t = total convective coefficient

s_1 = liner

s_2 = circumferential tendon

s_c = scallop-liner area

s_{co} = scallop-cast iron area

i = inner vessel

1 = inner liner

2 = outer liner

3 = scallop-cast iron

4 = cast iron-cell

5 = outer cell

6 = cast iron-circumferential tendon

7 = outer vessel

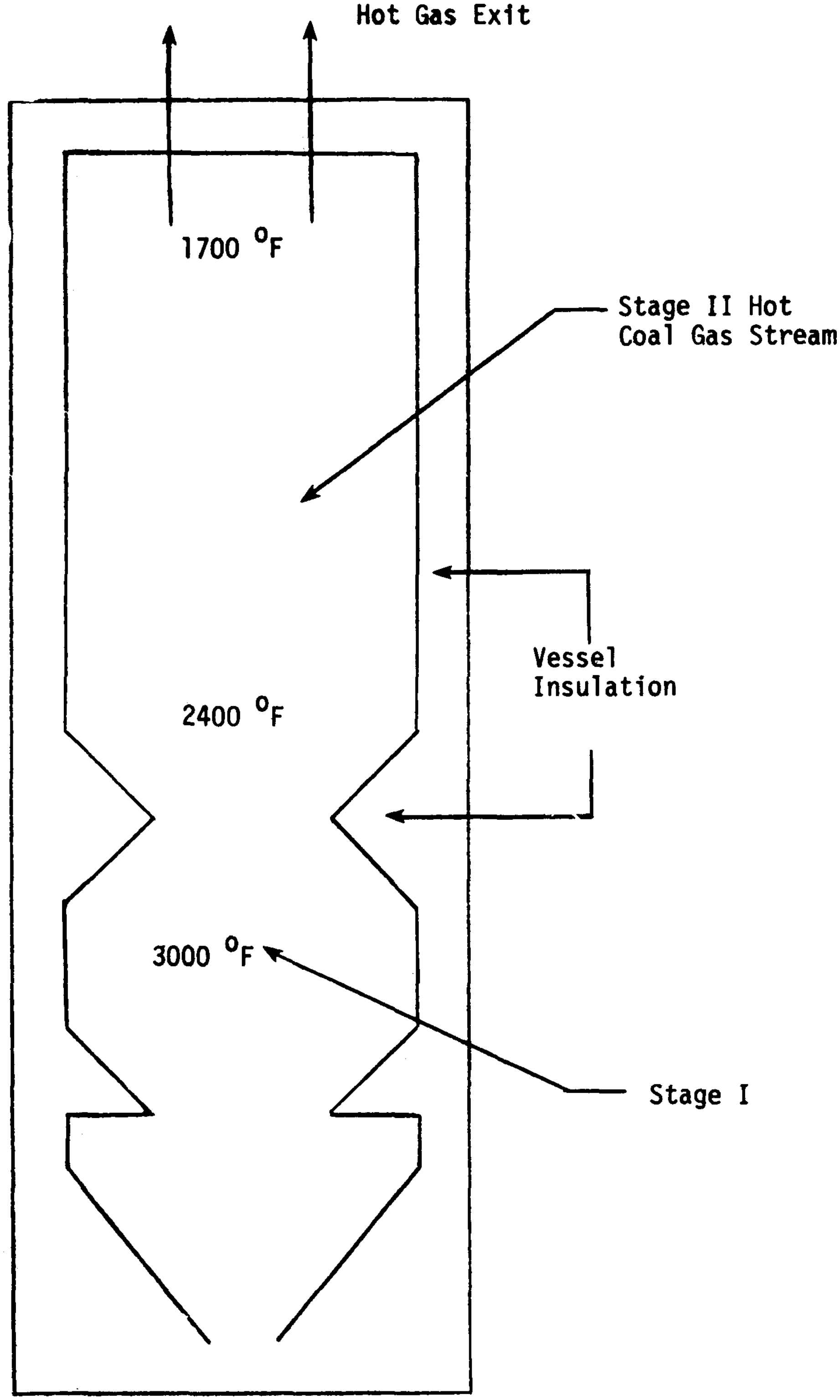
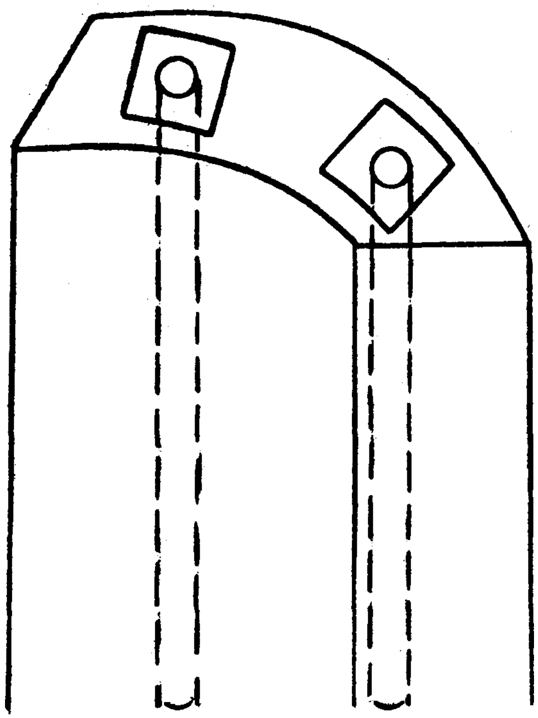
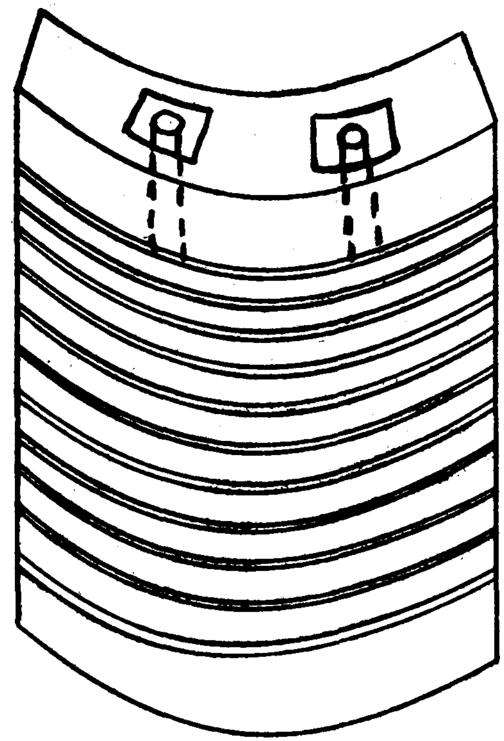


Figure 1 CROSS SECTION OF REACTOR VESSEL FOR COAL GASIFICATION



Axial (Vertical) Support Tendons Within The Vessel Wall Structure



Circumferential Support Tendons On The Outer Vessel Wall

Figure 2 PCIV SUPPORT TENDONS

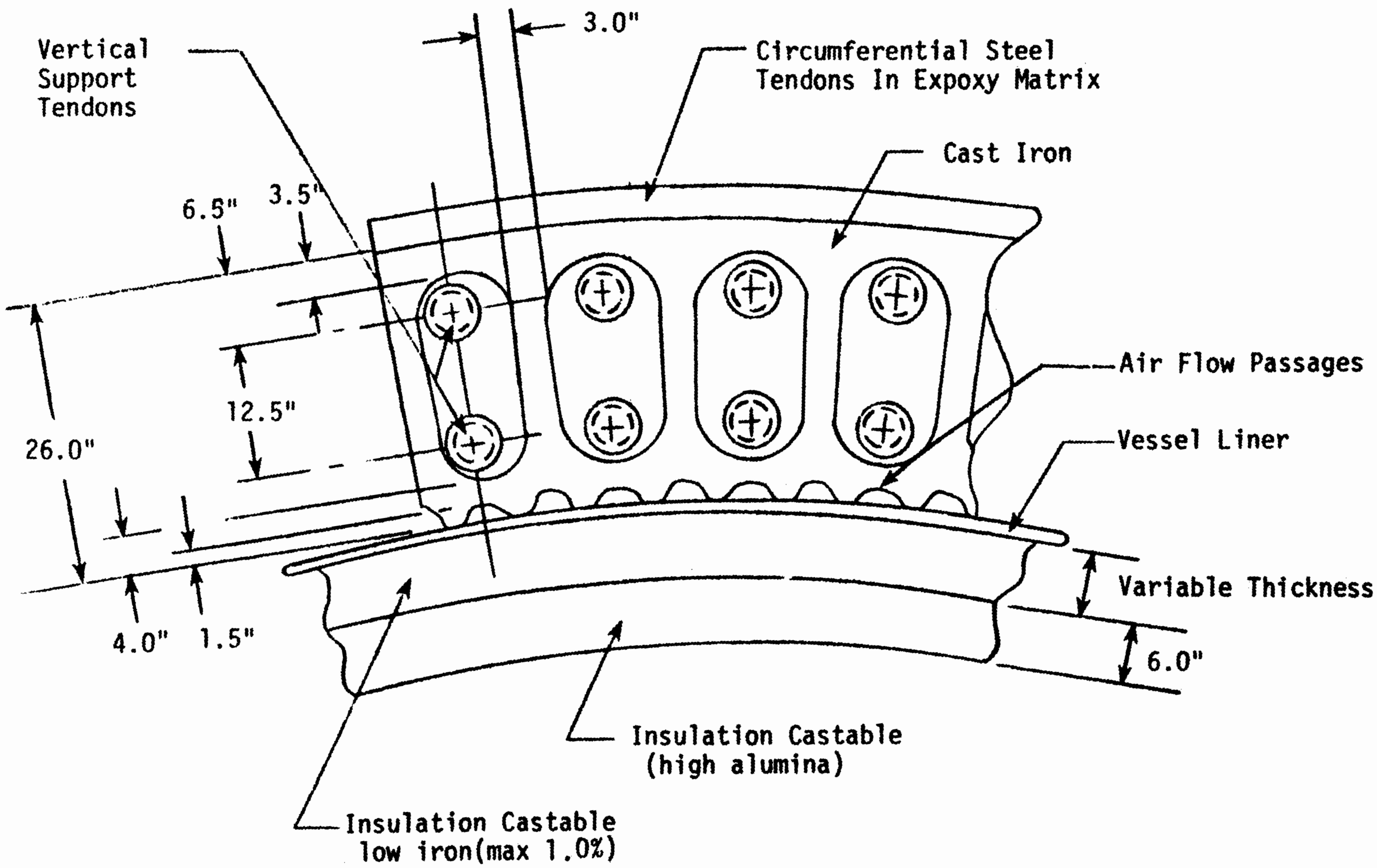


Figure 3 PCIV WALL DESIGN CROSS SECTION

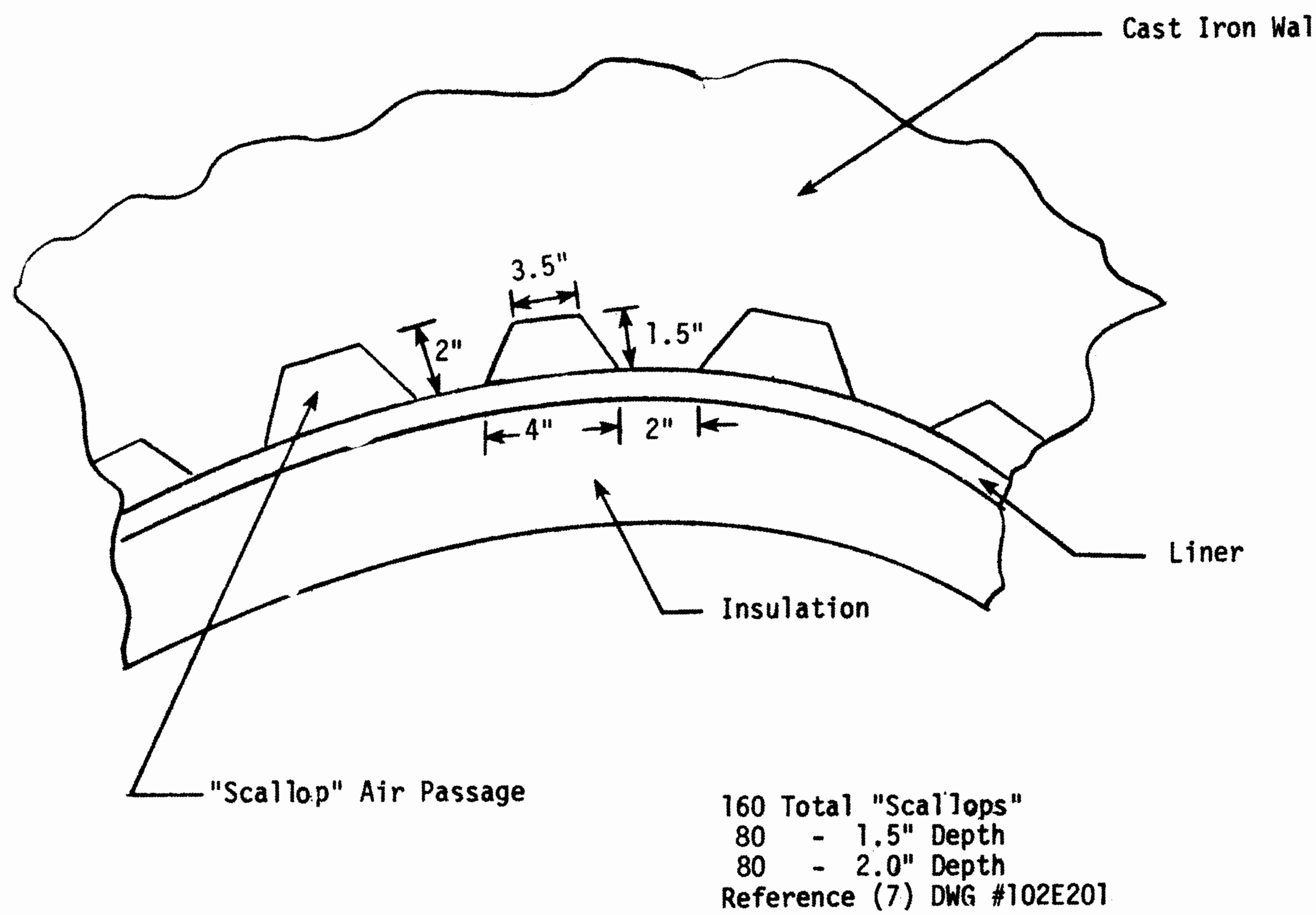
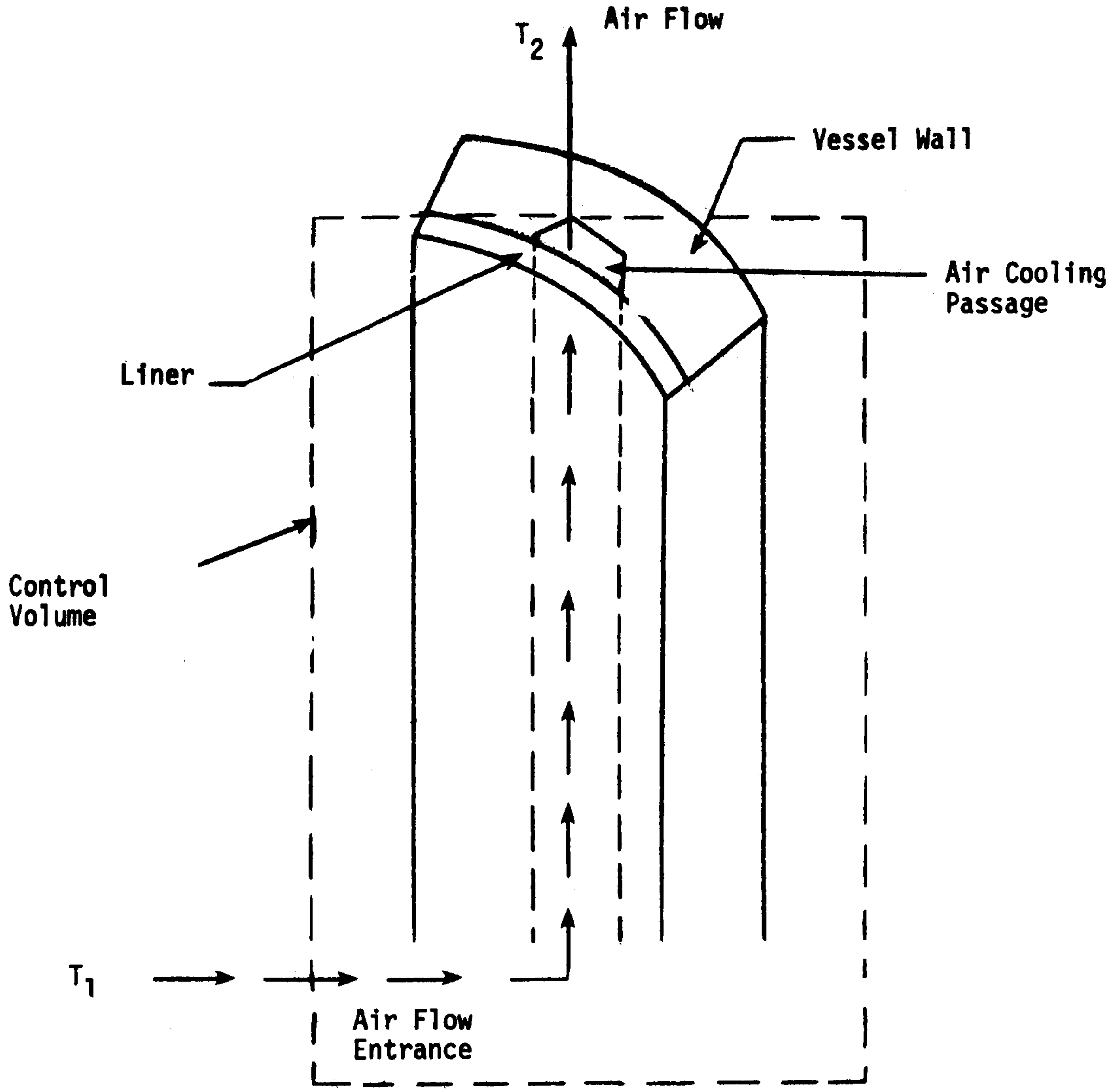


Figure 4 "SCALLOP" AIR PASSAGE DETAILS



Air Stream Temperature Change = ΔT = $(T_2 - T_1)$

Figure 5 AIR COOLING PASSAGE SCHEME

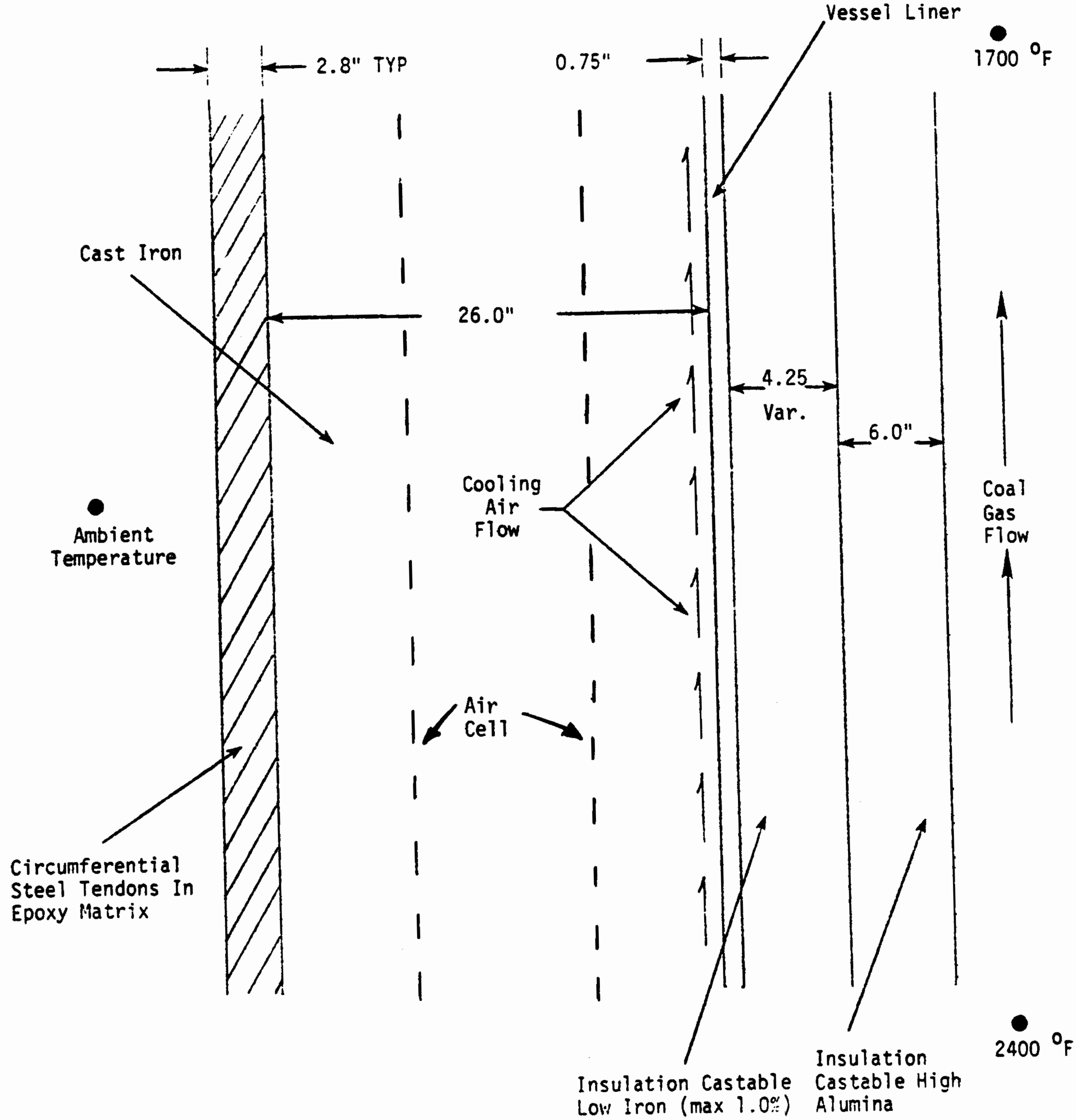


Figure 6 VESSEL COMPOSITE WALL GASIFIER REGION

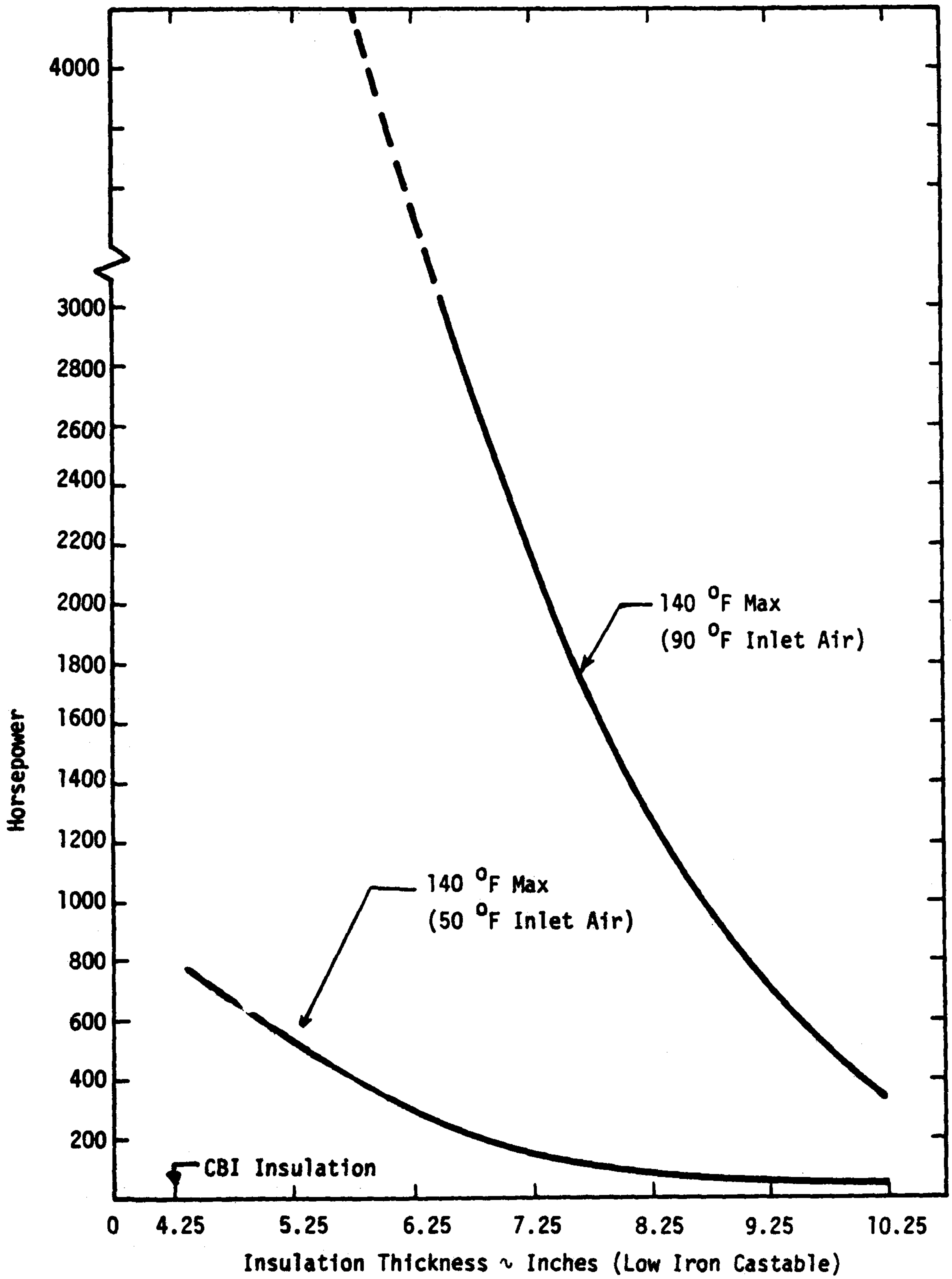


Figure 7 AIRCOOLING HORSEPOWER FOR THE HOT AMBIENT CONDITION, 90 °F INLET AND NOMINAL AMBIENT, 50 °F INLET TO MEET THE 140 °F MAXIMUM CONDITION

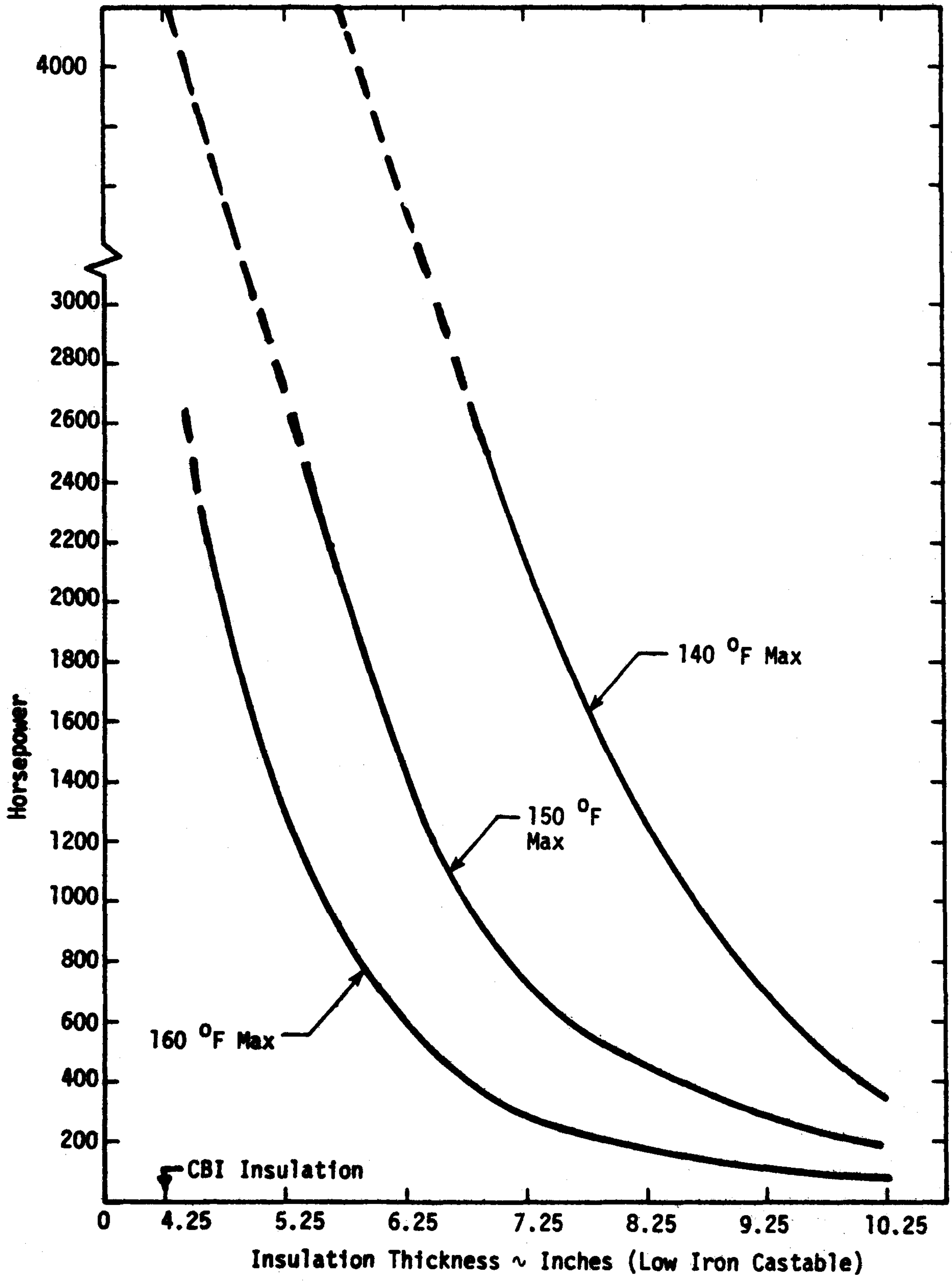


Figure 8 AIRCOOLING HORSEPOWER FOR THE HOT AMBIENT CONDITION ~ 90 °F INLET AIR AND 140 °F/160 °F LIMIT TEMPERATURES

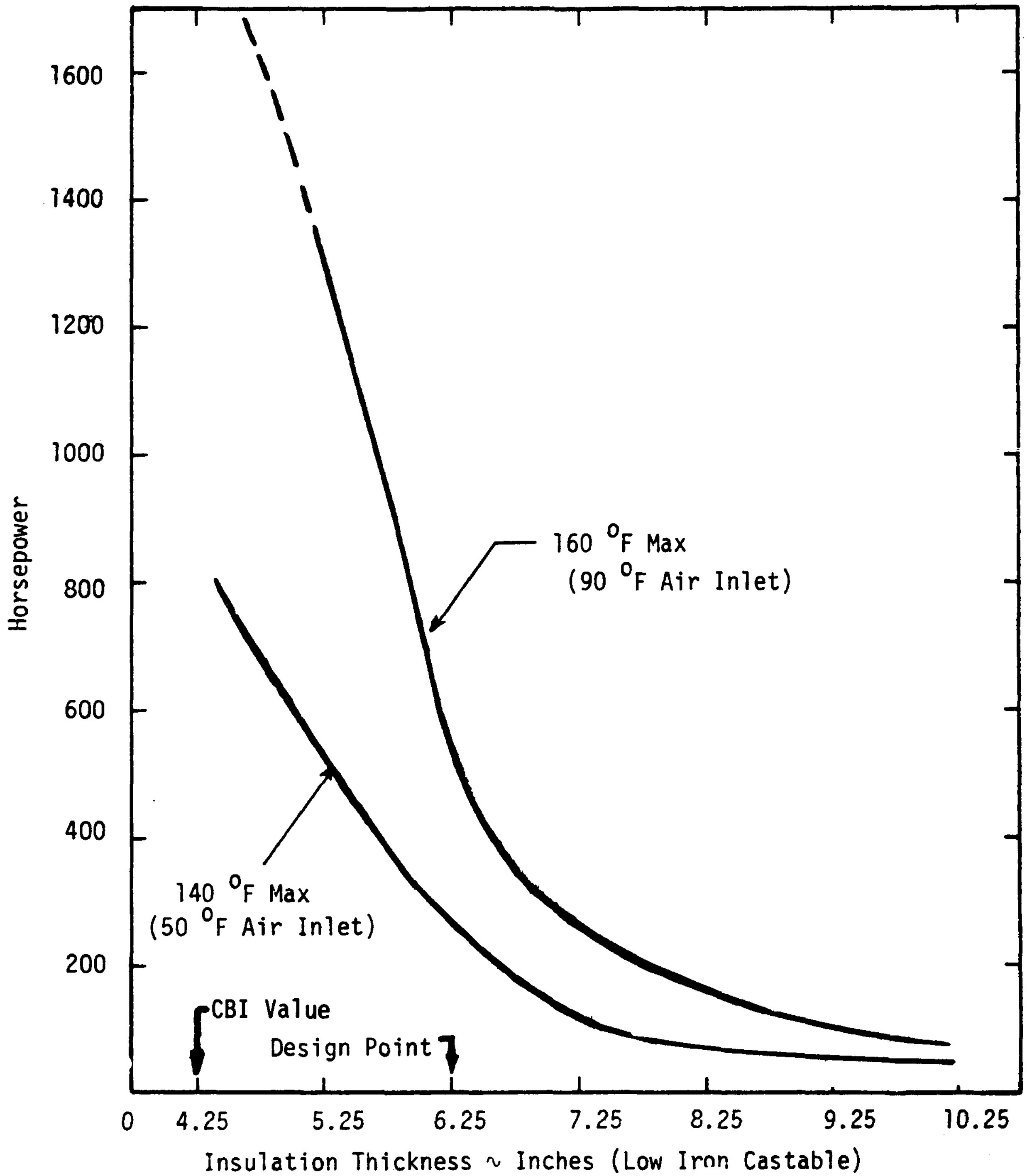


Figure 9 DESIGN AIR COOLING REQUIREMENTS FOR 160 °F LIMIT WITH 90 °F AIR INLET AND 140 °F LIMIT WITH 50 °F AIR INLET

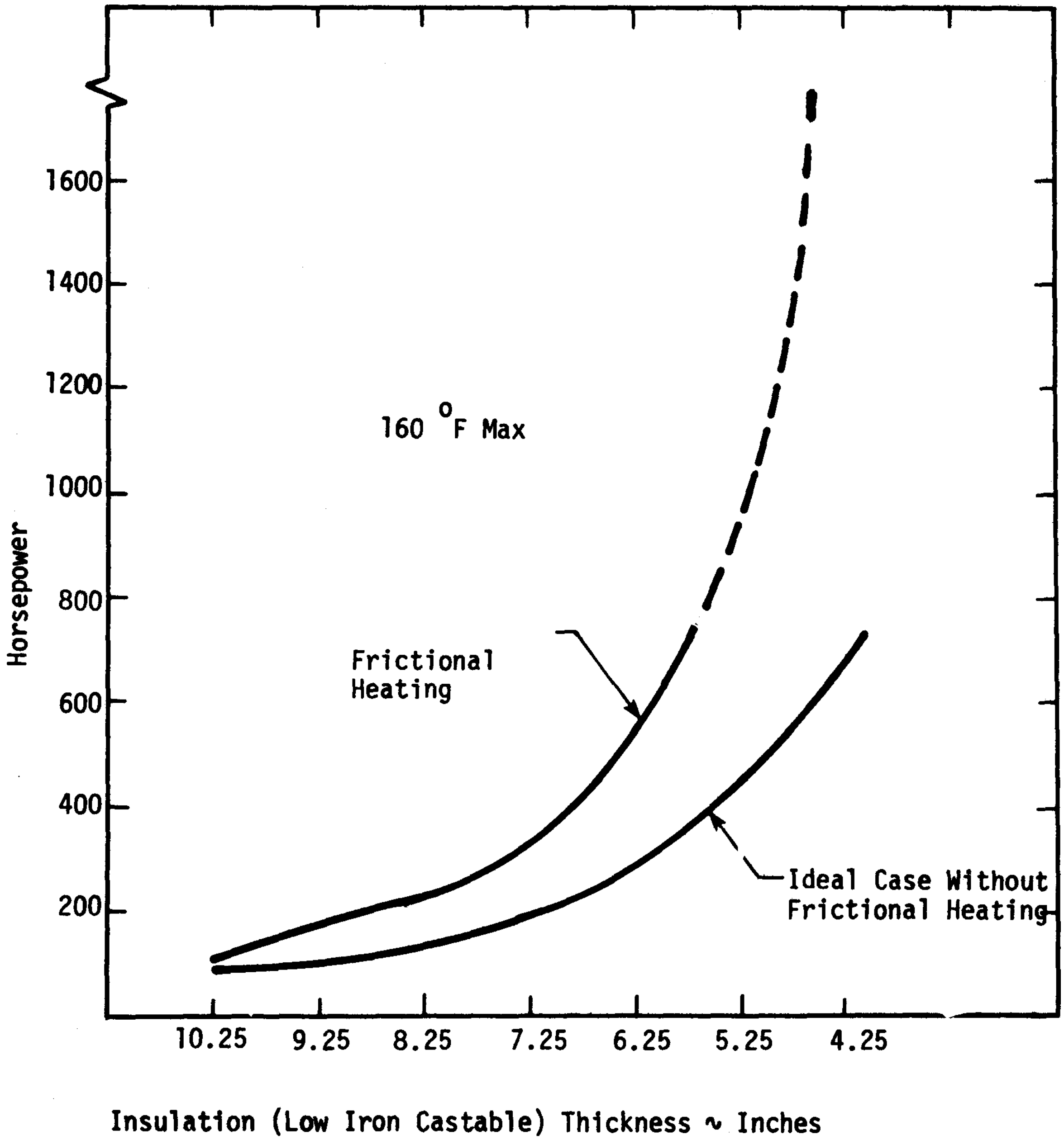


Figure 10 ESTIMATED HORSEPOWER REQUIREMENTS CALCULATED WITH/WITHOUT FRICTIONAL HEATING EFFECTS: 160 °F MAX, 90 °F INLET AIR

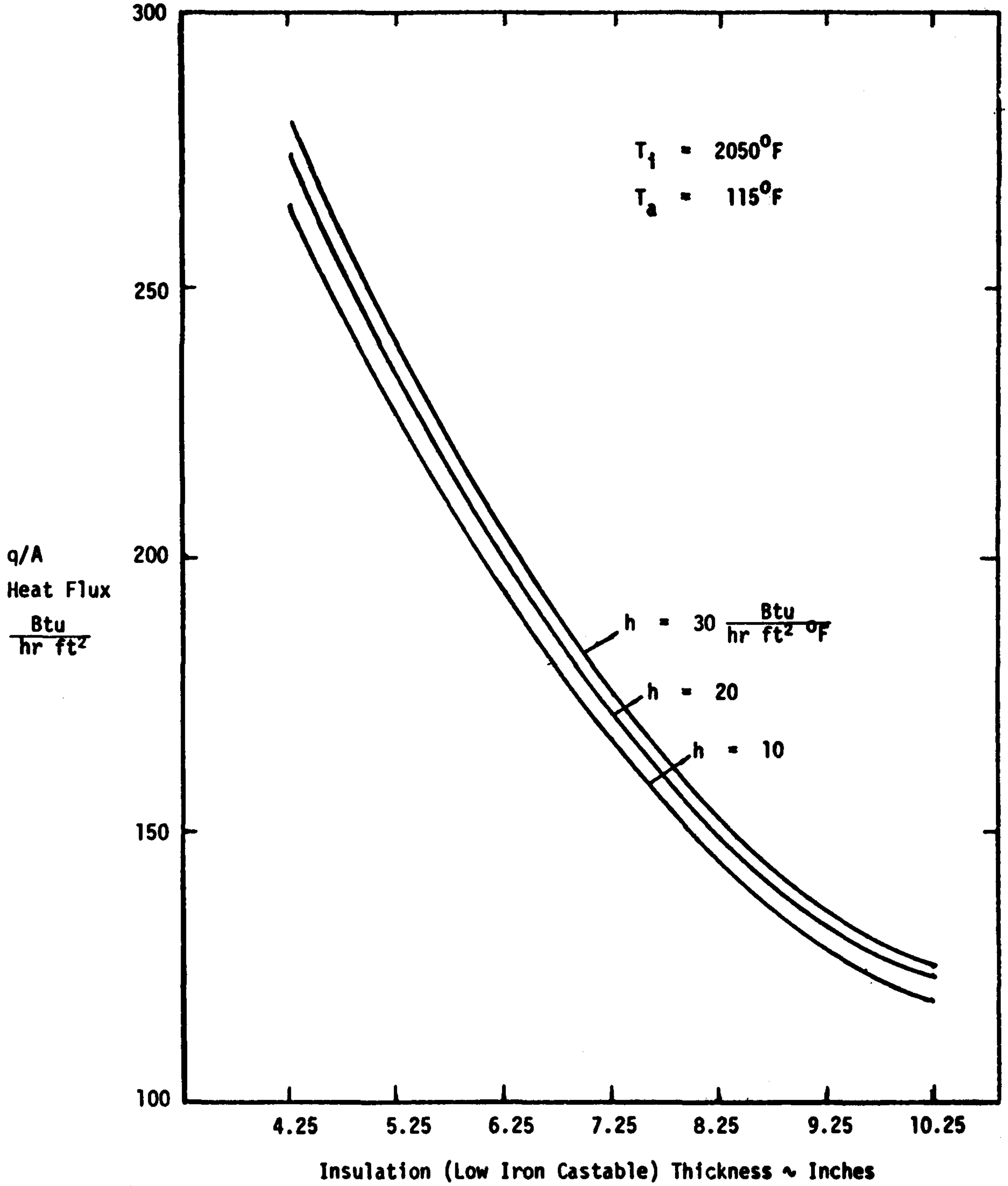


Figure 11 VESSEL HEAT FLUX REMOVAL AS A FUNCTION OF HEAT TRANSFER FILM COEFFICIENT AND INSULATION THICKNESS FOR THE MID SECTION OF THE STAGE II GASIFIER

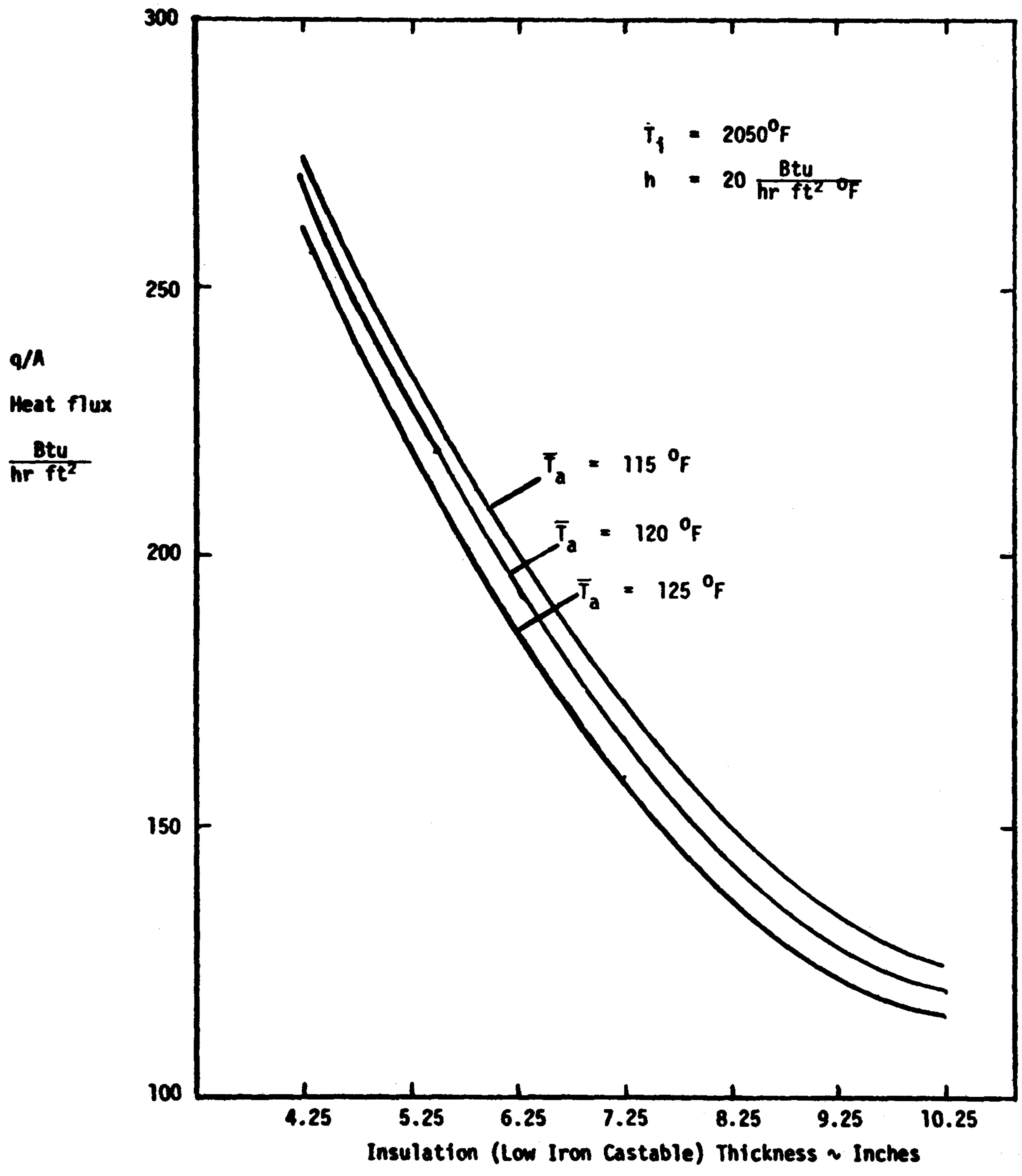


Figure 12 VESSEL HEAT FLUX REMOVAL AS A FUNCTION OF AIR STREAM TEMPERATURE AND INSULATION THICKNESS, MID SECTION STAGE II

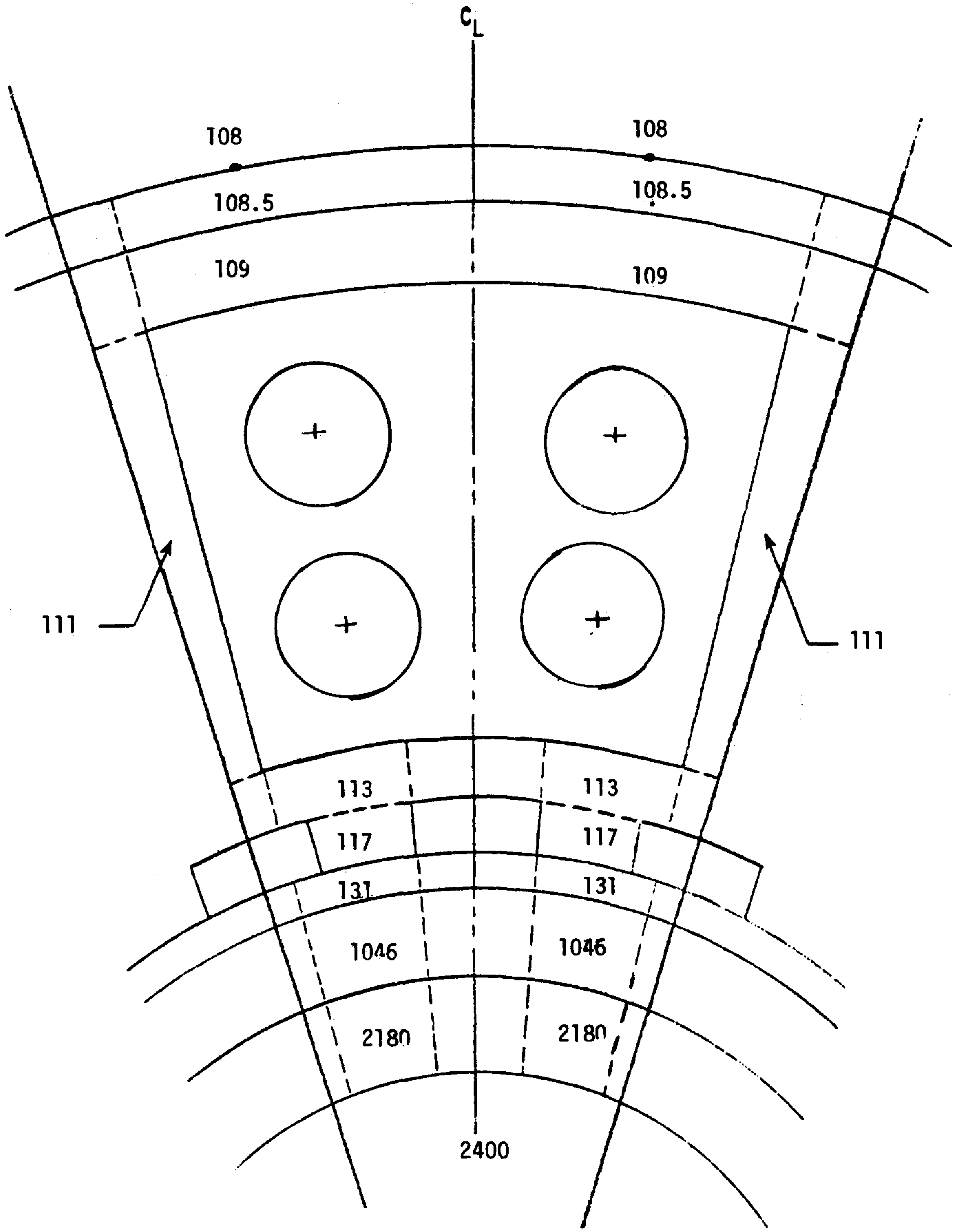


Figure 13 TYPICAL WALL TEMPERATURE DISTRIBUTION (^oF) USING 90 ^oF INLET AIR, 5.7 x 10^4 CFM COOLING FLOW THROUGH SCALLOPS WITH INNER VESSEL AT 2400 ^oF

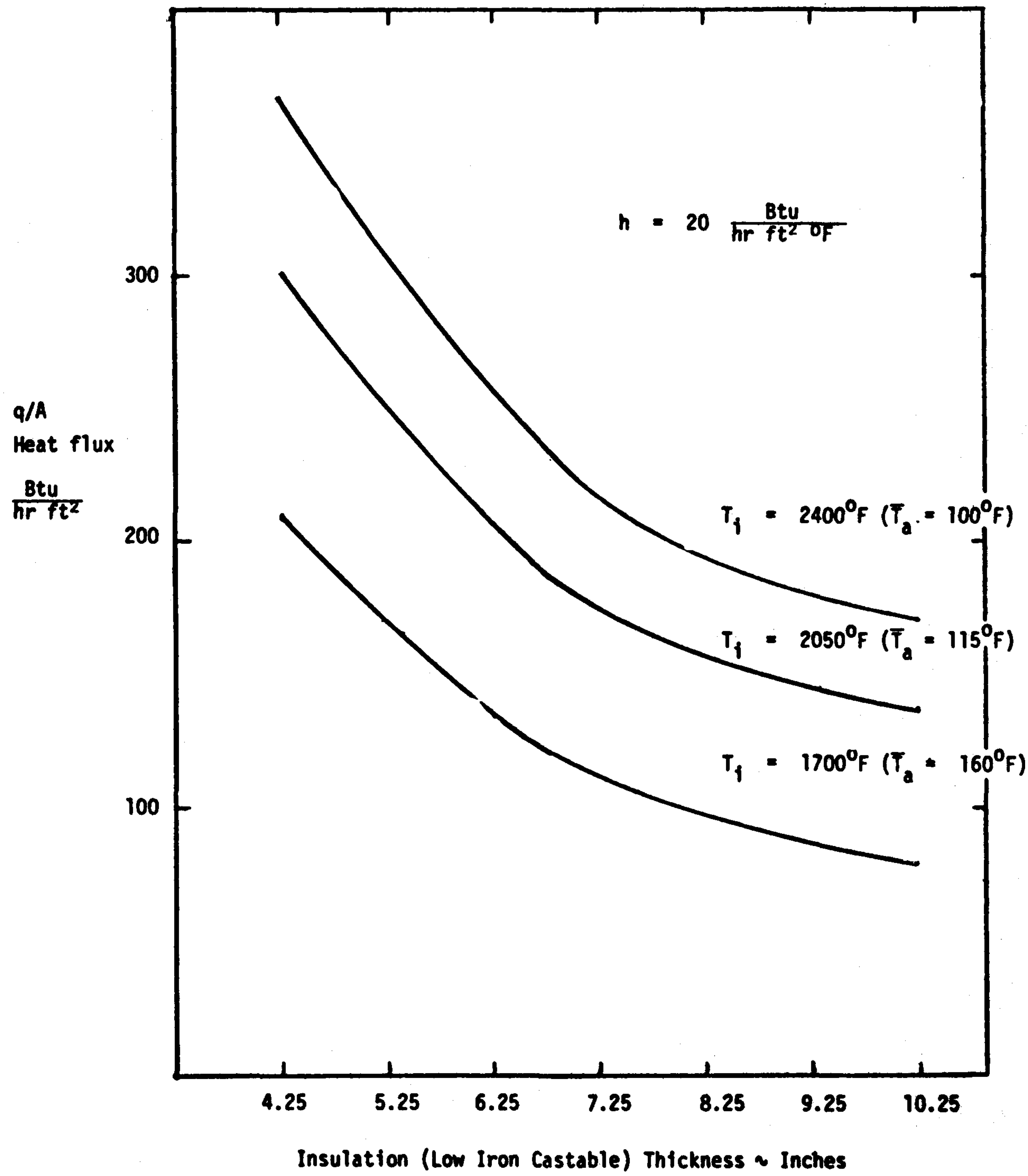


Figure 14 VESSEL HEAT FLUX REMOVAL AS A FUNCTION OF VARIOUS INNER VESSEL BOUNDARY TEMPERATURES AND INSULATION THICKNESS (STAGE II GASIFIER)

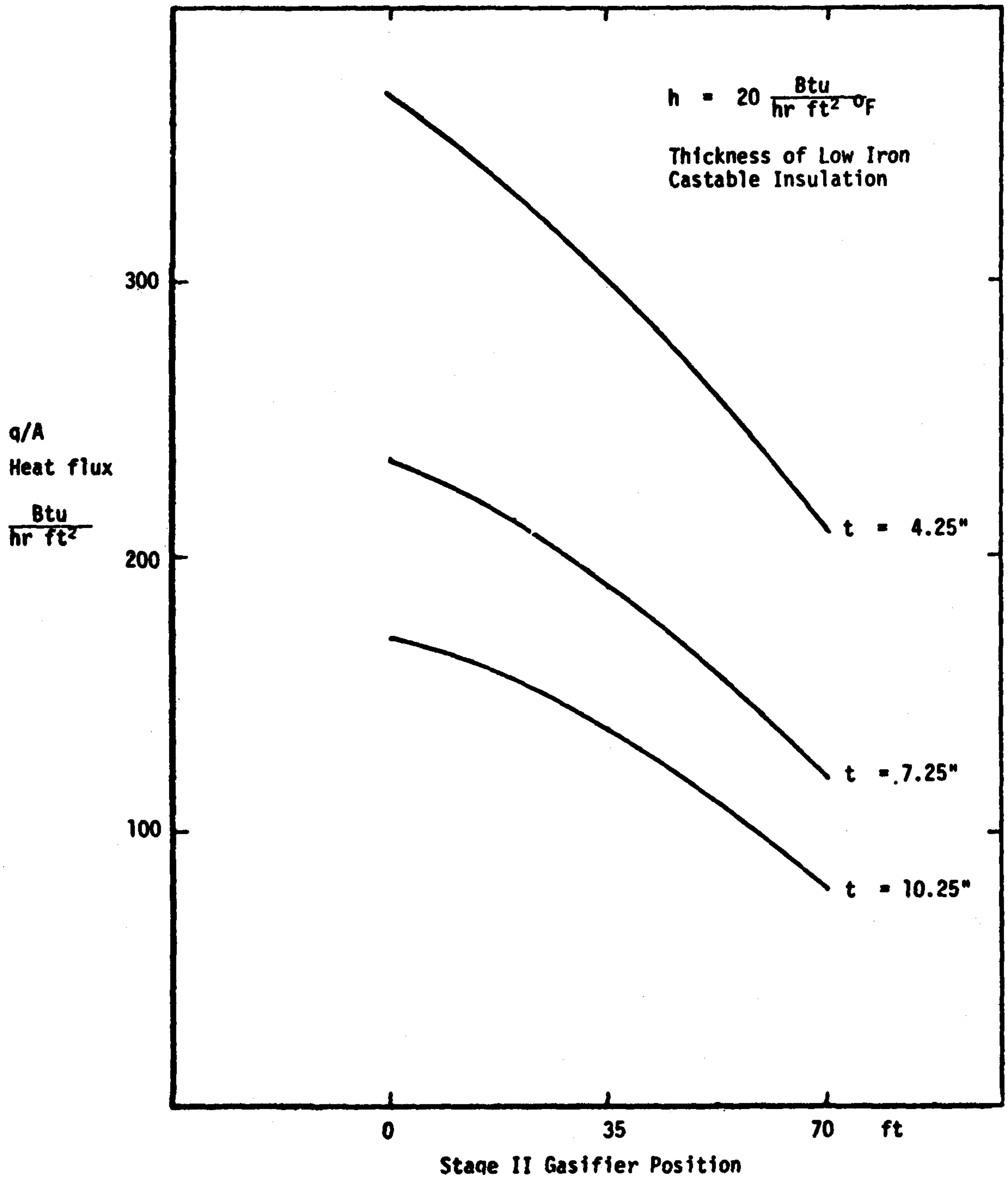


Figure 15 VESSEL HEAT FLUX REMOVAL AS A FUNCTION OF AXIAL POSITION ALONG THE STAGE II GASIFIER FOR VARIOUS INSULATION THICKNESSES

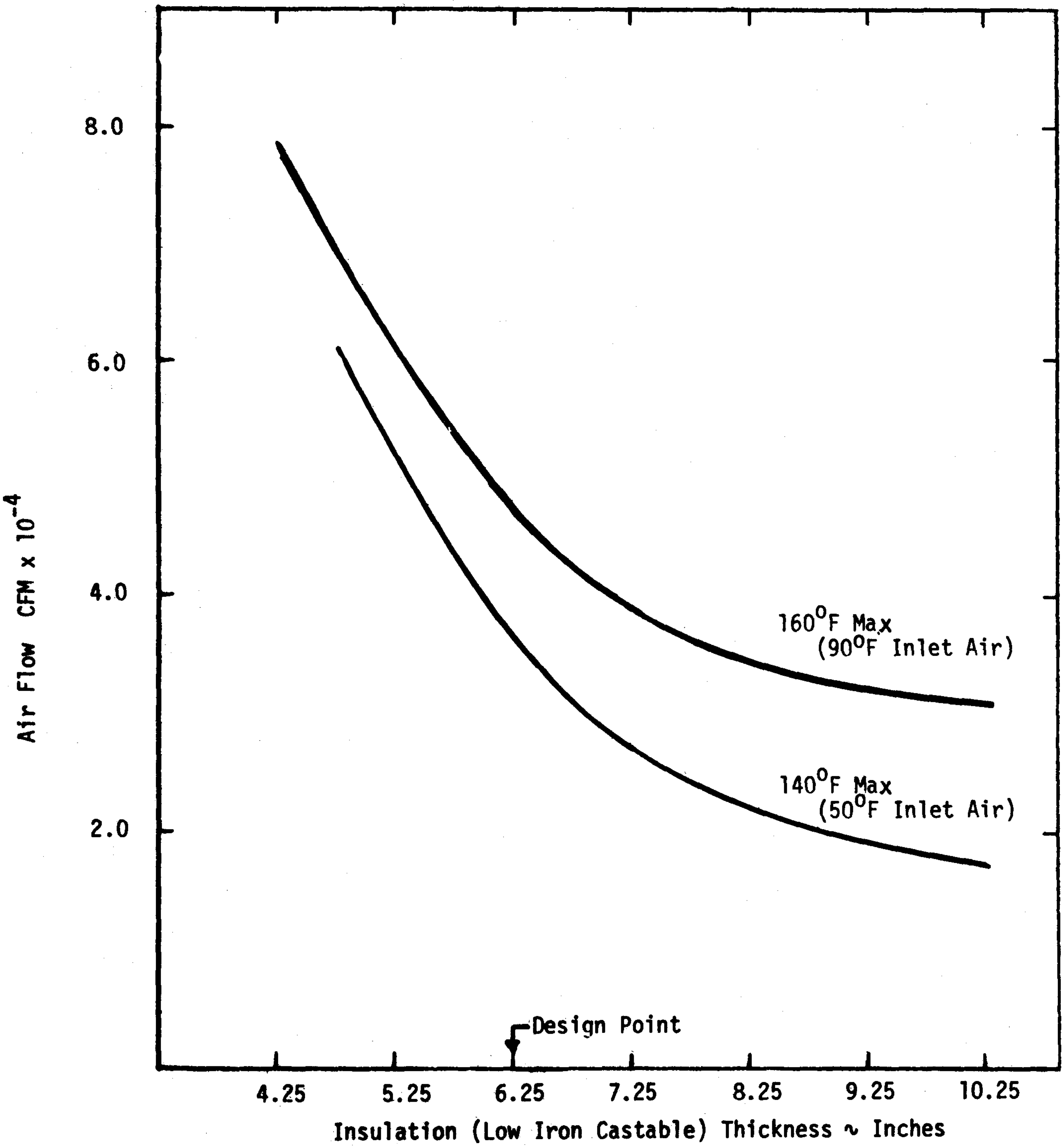


Figure 16 REQUIRED AIR FLOW FOR THE HOT AND NOMINAL DAY OPERATIONS TO OBTAIN THE 160 °F/140 °F MAXIMUM TEMPERATURES AS A FUNCTION OF INSULATION THICKNESS

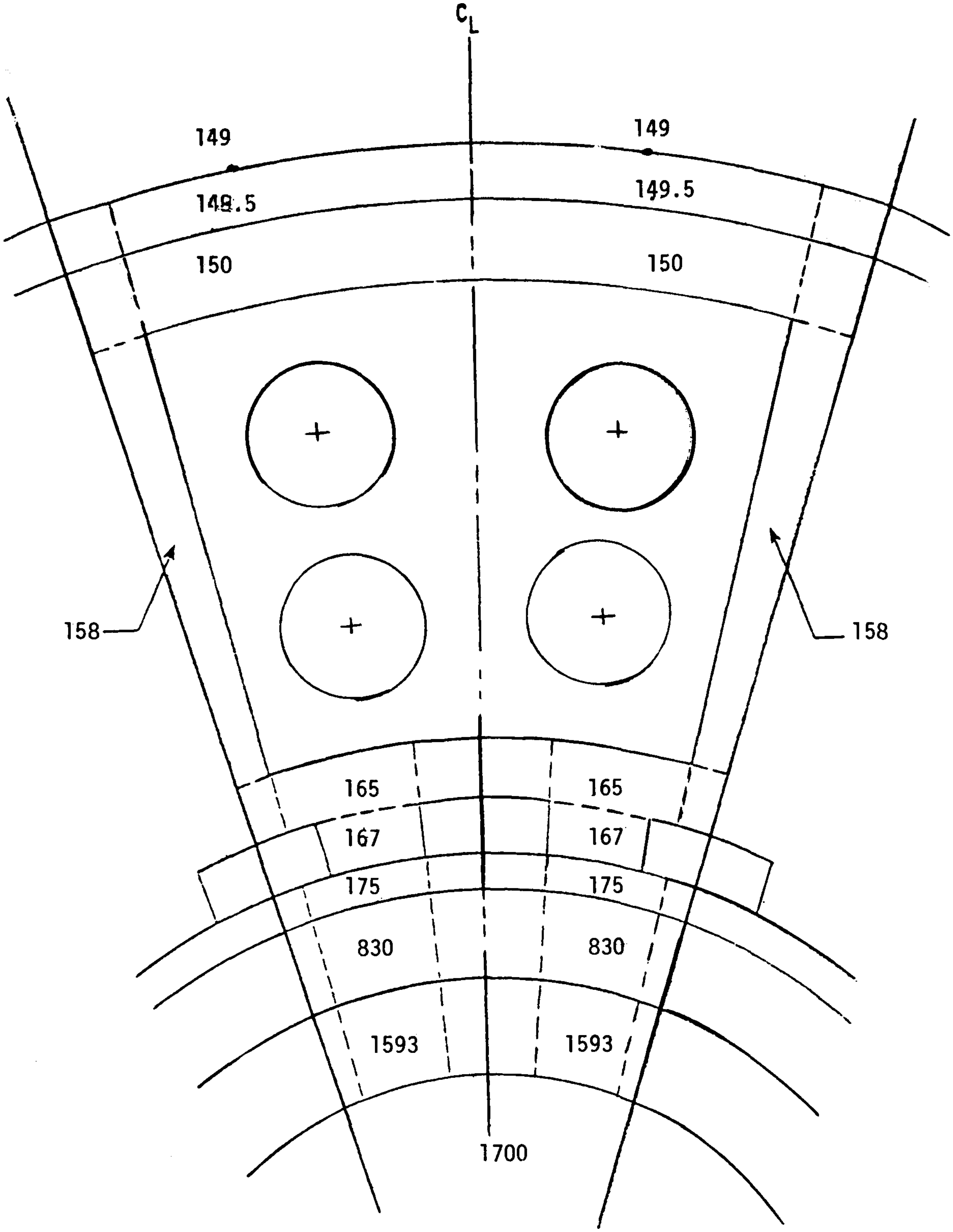


Figure 17 WALL TEMPERATURE DISTRIBUTION (°F) USING 90 °F INLET AIR, 5.0 x 10^4 CFM COOLING FLOW THROUGH SCALLOPS WITH INNER VESSEL AT 1700 °F AND 6.25" LOW IRON CASTABLE INSULATION

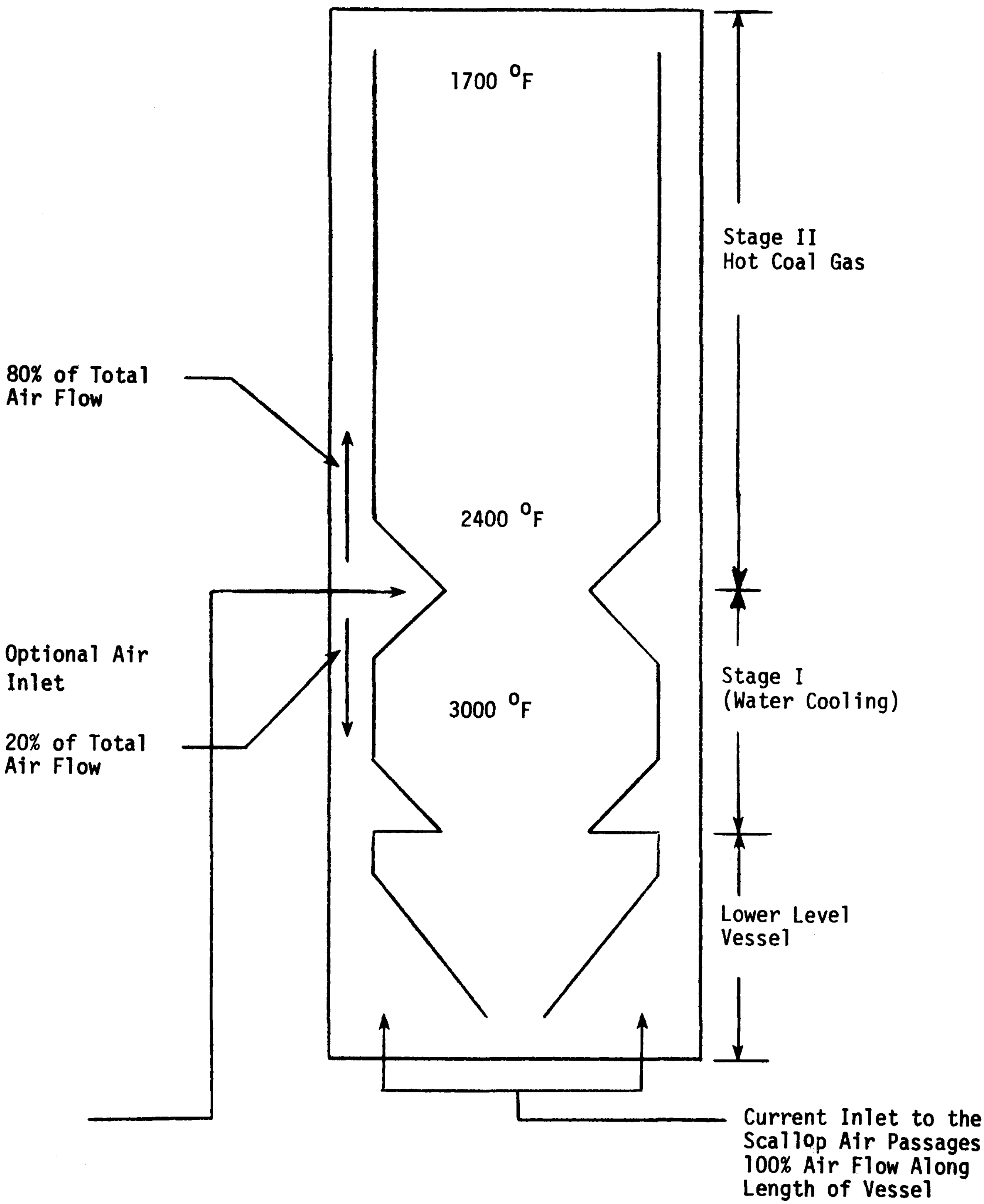


Figure 18 COOLING OPTION-AIR FLOW INLET TO STAGE II SECTION

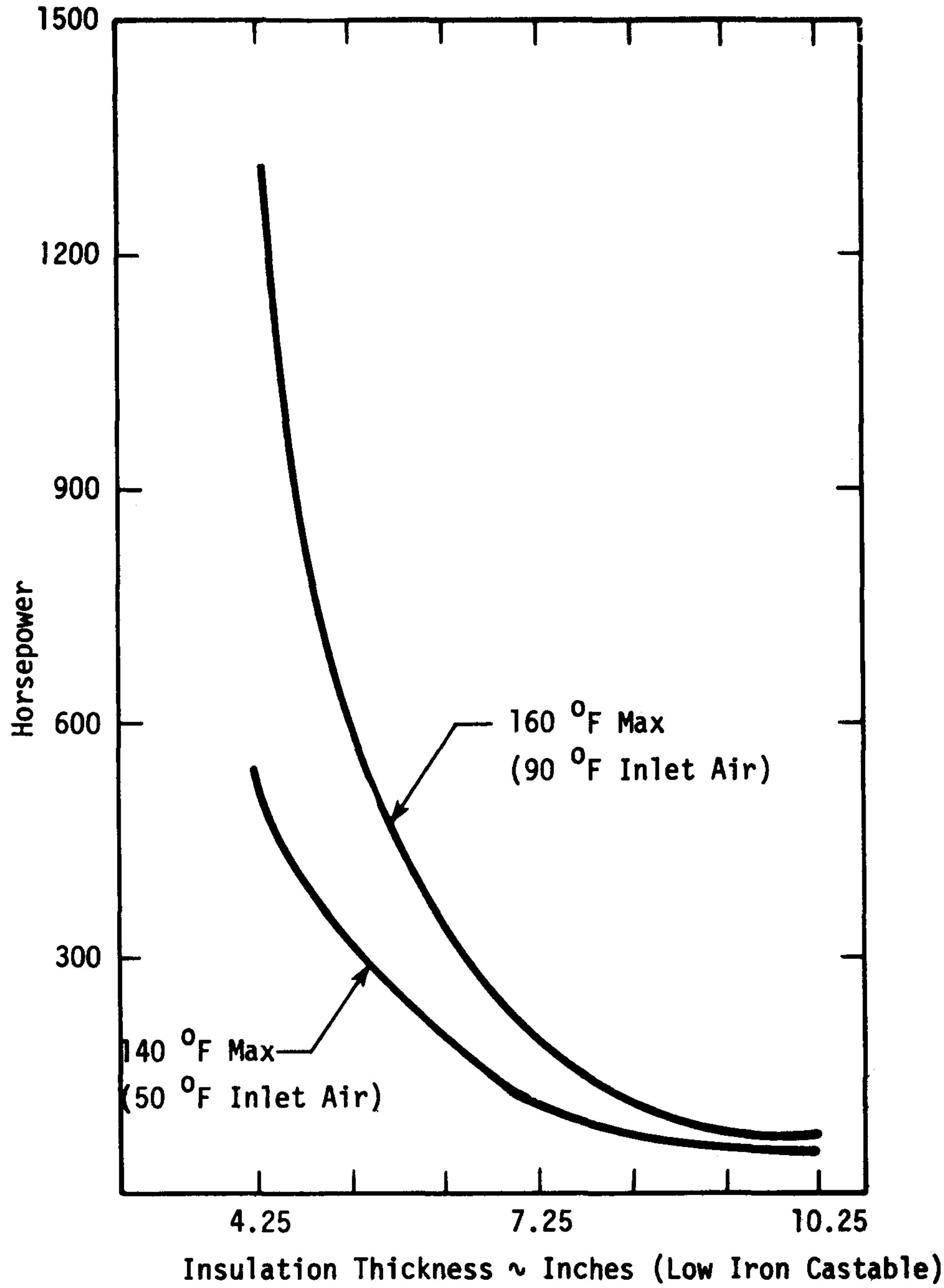


Figure 19 OPTIONAL AIR COOLING USING "SCALLOP" FLOW 80% TO STAGE II, 20% TO LOWER VESSEL

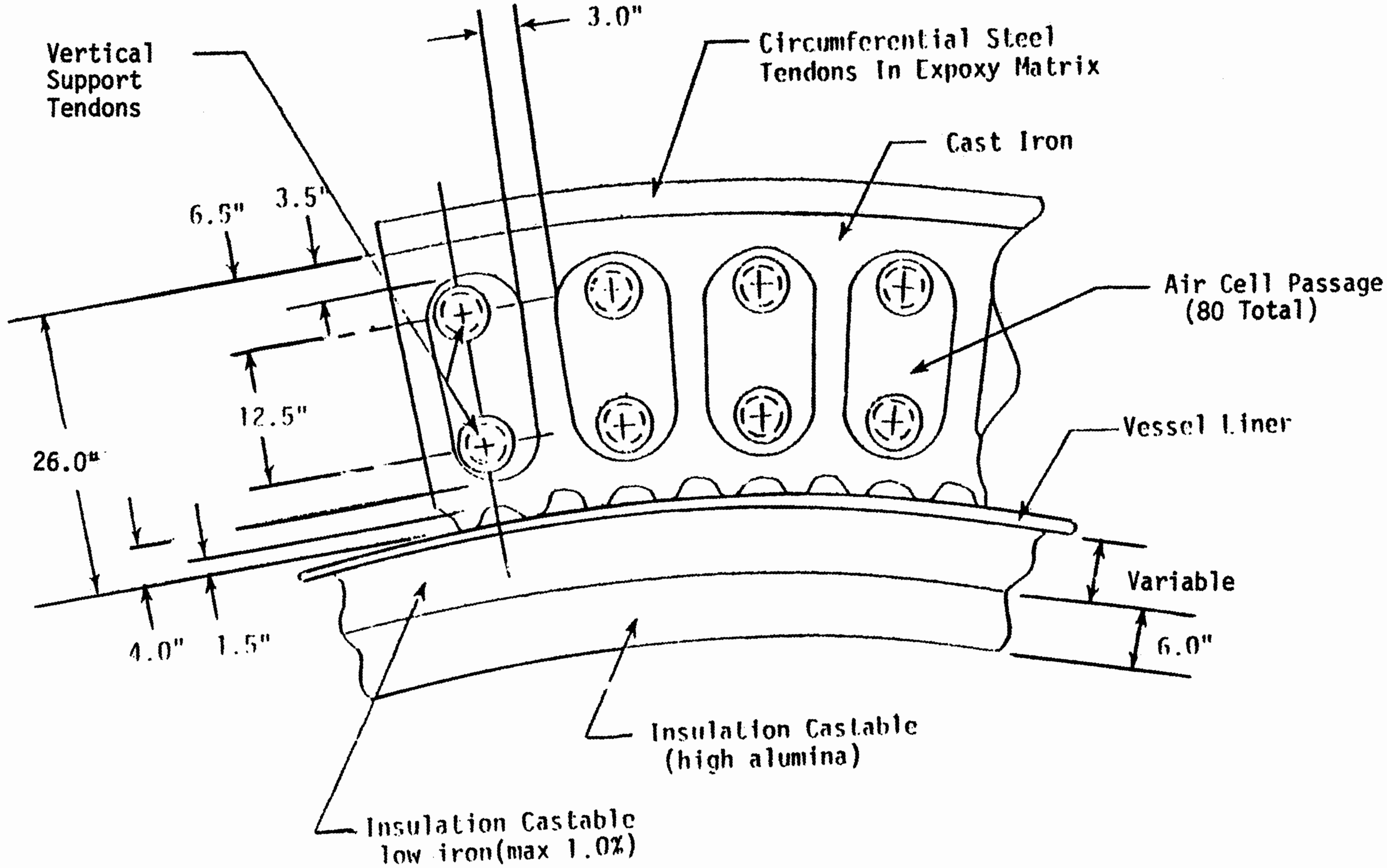


Figure 20 PCIV WALL DESIGN WITH OPTIONAL AIR "CELL" COOLING PASSAGES

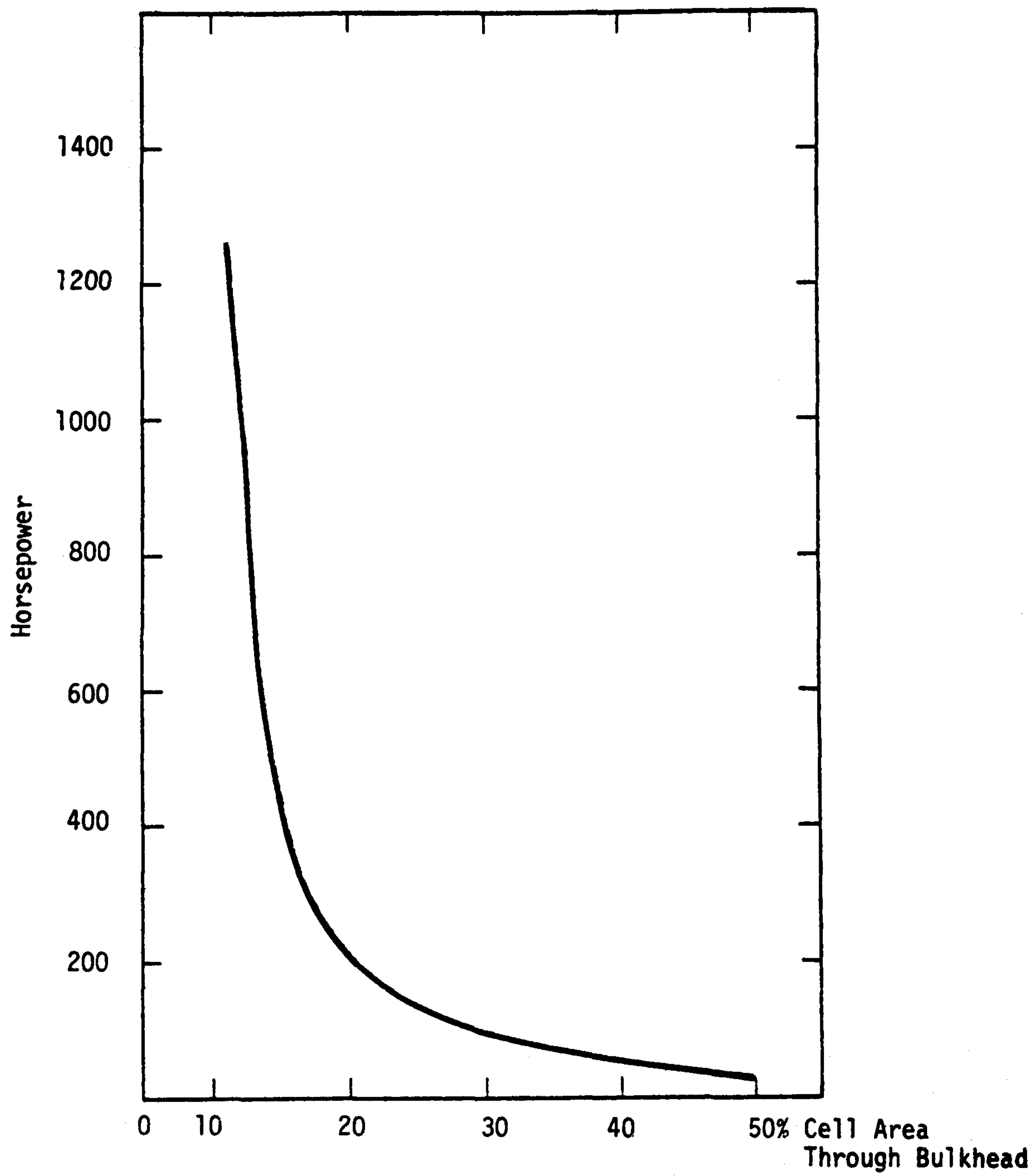


Figure 21 AIR COOLING HORSEPOWER AS A FUNCTION OF PERCENT CELL FLOW AREA THROUGH 80 BULKHEADS 90 °F AIR INLET, 140 °F LIMIT

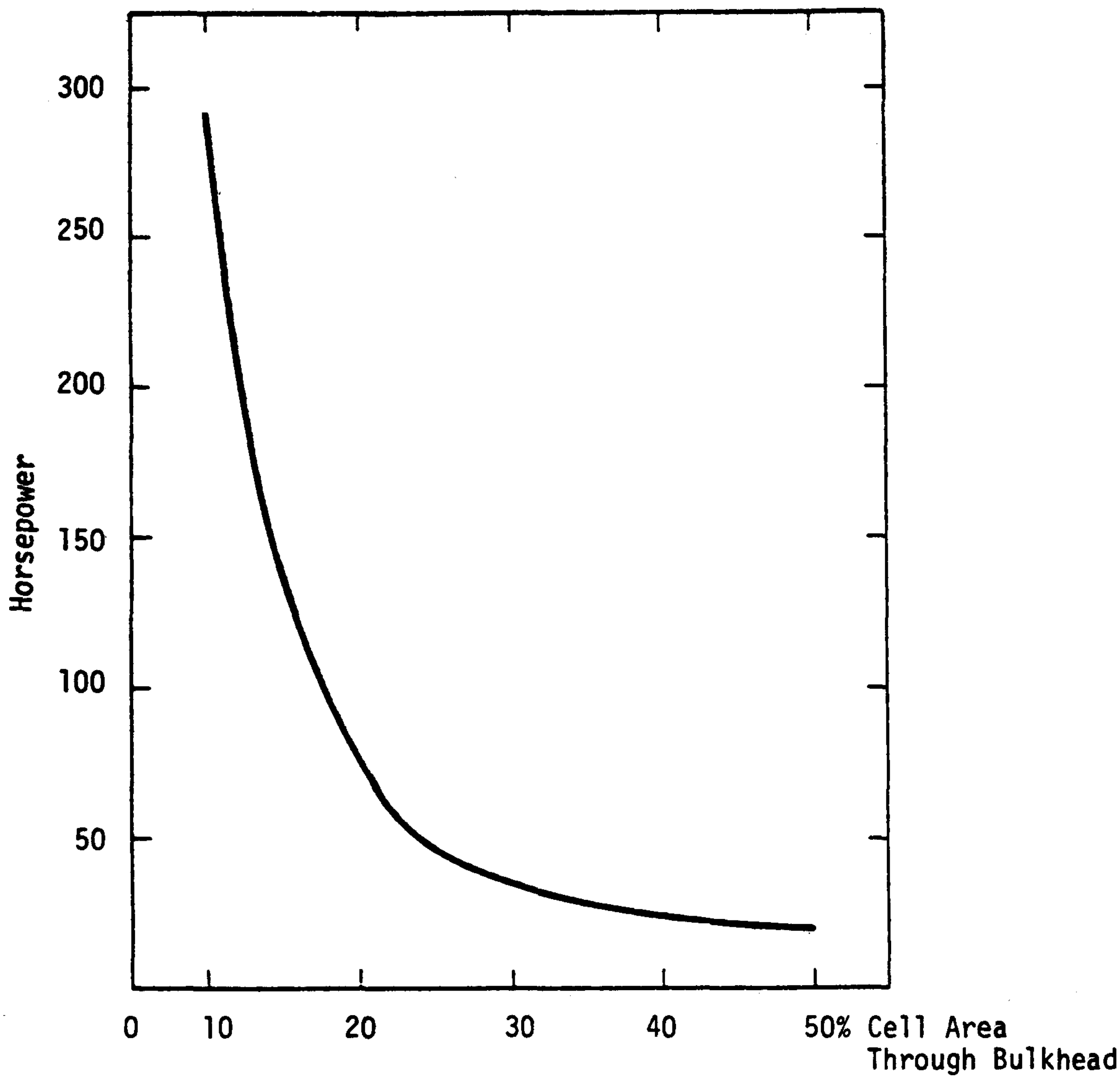


Figure 22 AIR COOLING HORSEPOWER AS A FUNCTION OF PERCENT CELL FLOW AREA THROUGH 20 BULKHEADS 90 °F AIR INLET, 140 °F LIMIT

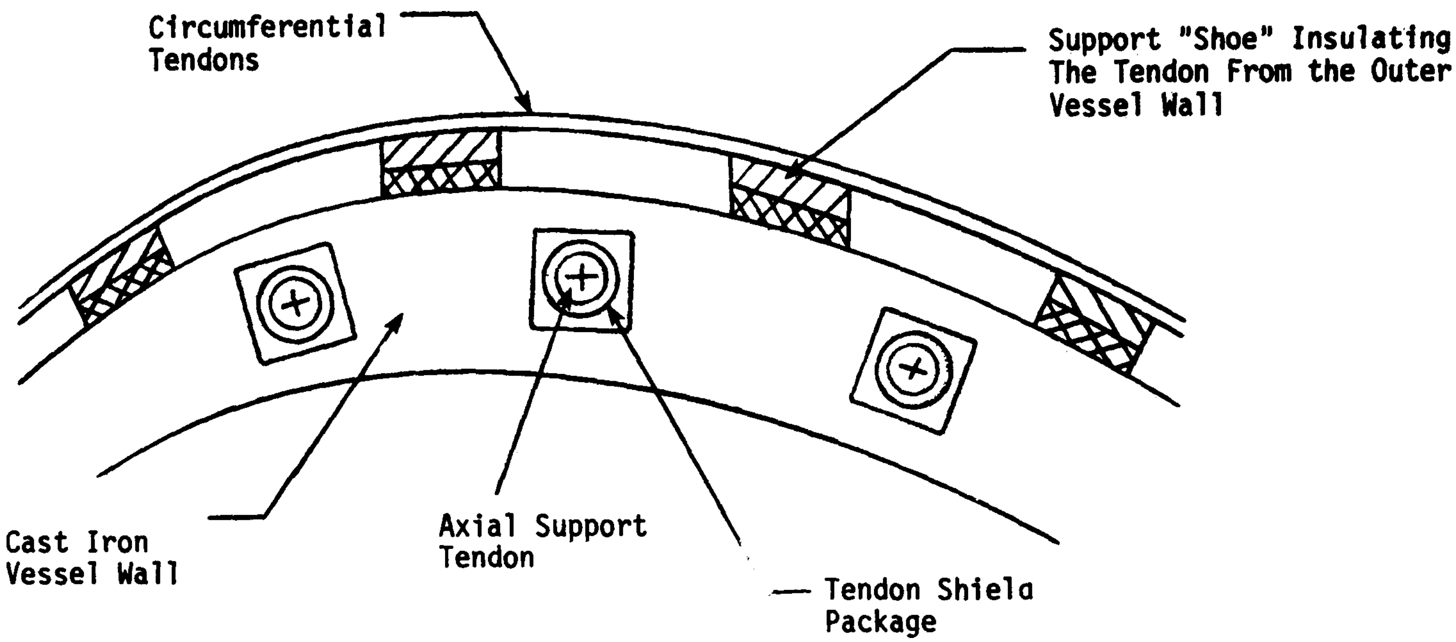


Figure 23 CIRCUMFERENTIAL TENDON WRAPPING ON INSULATED "SHOES" AXIAL TENDONS WITH RADIATION SHIELD

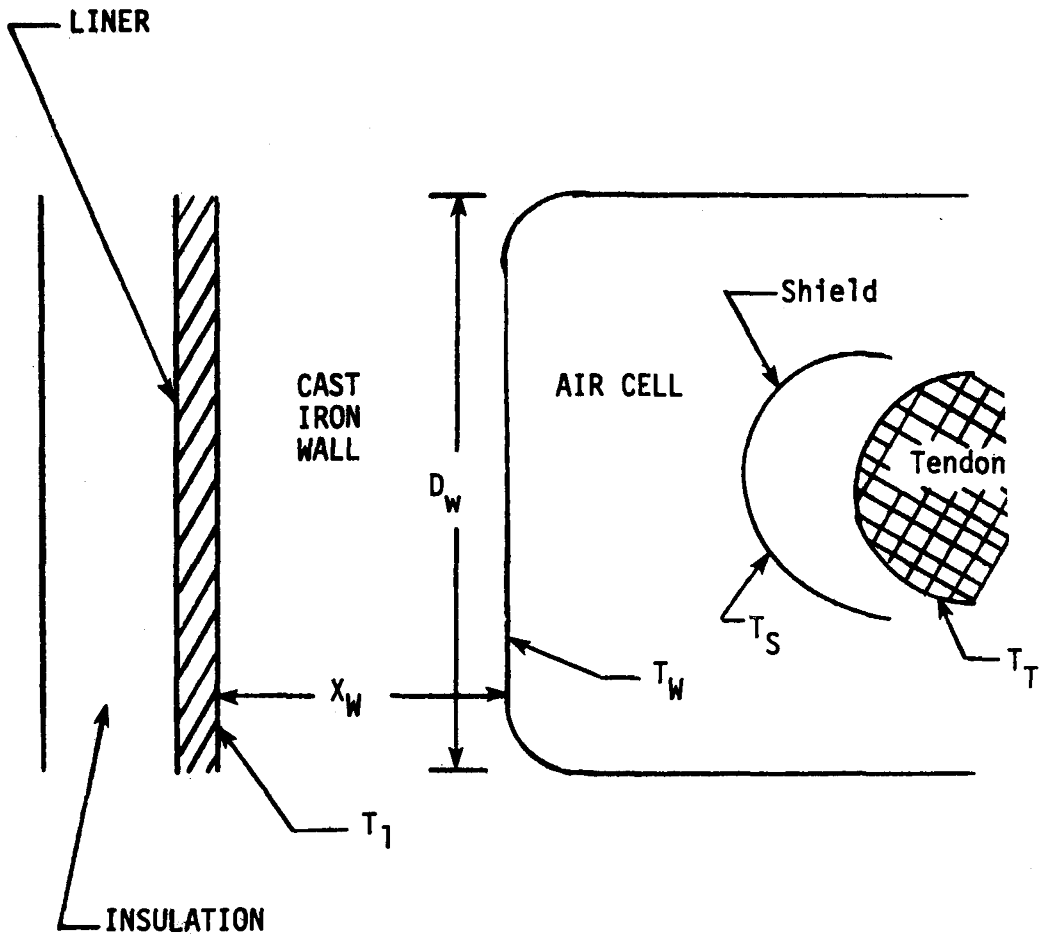


Figure 24 AXIAL TENDON WITH RADIATION SHIELD AIR COOLING IN THE SHIELD ANNULUS

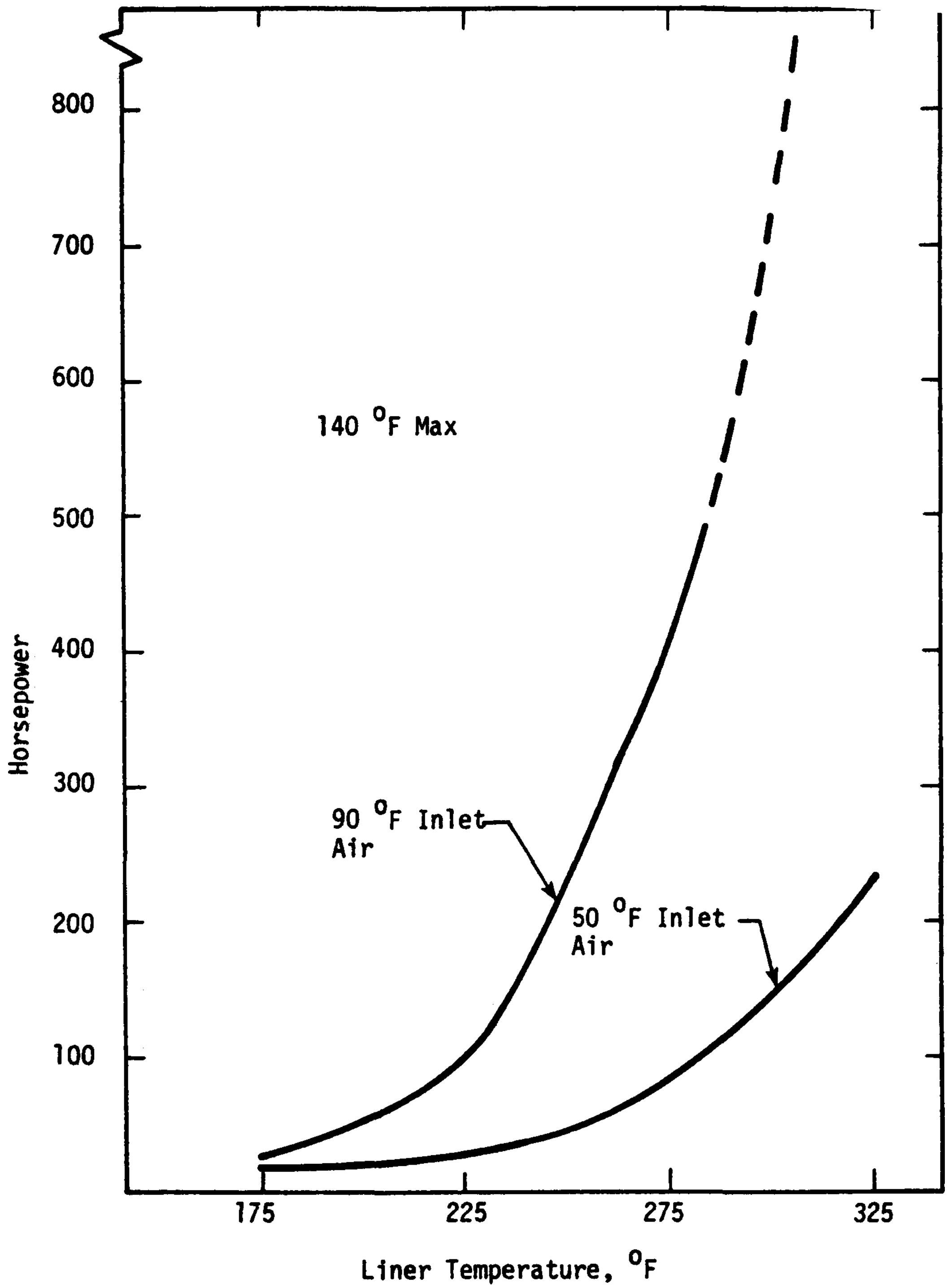


Figure 25 AXIAL TENDON COOLING WITH RADIATION SHIELD 140 °F MAX CONDITION: 1.85" ANNULUS GAP, 3.3" TENDON DIAMETER

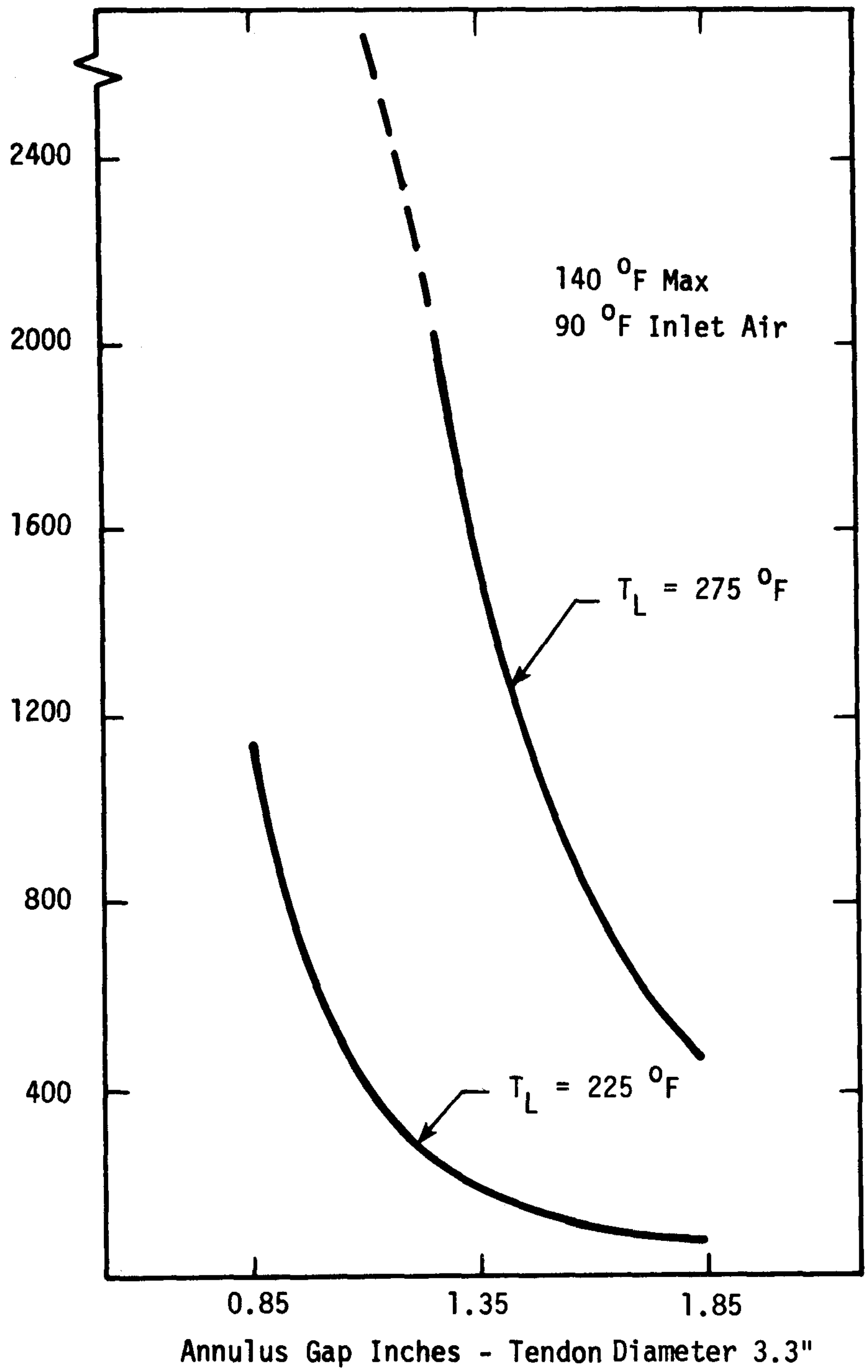


Figure 26 AXIAL TENDON COOLING WITH RADIATION SHIELD, EFFECT OF ANNULUS GAP; TENDON DIAMETER = 3.3"

B2.3 NOMENCLATURE

A	=	Area, ft^2 (m^2)
A_p	=	Passage surface area, ft^2 (m^2)
C_p	=	Specific heat, $\frac{Btu}{lb_m\ ^oF}$ $(\frac{J}{kg\ ^oC})$
D	=	Equivalent passage diameter, ft, (m)
D_i	=	Equivalent passage diameter, in (cm)
e	=	Total energy, $\frac{Btu}{lb_m}$ $(\frac{J}{kg})$
F	=	Radiation shape factor
f	=	Friction factor
G	=	Mass velocity, $\frac{lb_m}{hr\ ft^2}$ $(\frac{Kg}{sm^2})$
g	=	Gravitational constant
h	=	Convective heat transfer coefficient, $\frac{Btu}{hr\ ft^2\ ^oF}$ $(\frac{W}{m^2\ ^oC})$
h_n	=	Natural convection coefficient, $\frac{Btu}{hr\ ft^2\ ^oF}$ $(\frac{W}{m^2\ ^oC})$
h_r	=	Equivalent radiative coefficient, $\frac{Btu}{hr\ ft^2\ ^oF}$ $(\frac{W}{m^2\ ^oC})$
H_L	=	Head loss, ft (m)
K	=	Thermal conductivity, $\frac{Btu}{hr\ ft\ ^oF}$ $(\frac{W}{m\ ^oC})$
L	=	Passage length, ft (m)
m	=	Mass flow rate, $\frac{lb_m}{hr}$ $(\frac{kg}{s})$
P	=	Pressure, psi (Pa)
Q	=	Volumetric flow rate, $\frac{ft^3}{min}$ $(\frac{m^3}{s})$
q	=	Heat flux, $\frac{Btu}{hr\ ft^2}$ $(\frac{W}{m^2})$

$\dot{q}$ = Heat flow, $\frac{Btu}{hr}$ (W)

S = Surface area, ft^2 (m^2)

T = Temperature, ^oF, ^oR (^oC, K)

U = Internal energy, $\frac{Btu}{lb_m \, ^oF}$ $(\frac{J}{kg})$

V = Velocity, $\frac{ft}{s}$ $(\frac{m}{s})$

$\forall$ = Volume, ft^3 (m^3)

W = Work, rate $\frac{Btu}{hr}$ (W)

Z = Height reference, ft (m)

η = Efficiency

ρ = Density, $\frac{lb_m}{ft^3}$ $(\frac{g}{cm^3})$

σ = Stephen Boltzman Constant 0.171×10^{-8} $\frac{Btu}{hr \, ft^2 \, ^oR^4}$

SUBSCRIPTS

$(\ )_a$ = air

$(\ )_l$ = liner

$(\ )_s$ = shield

$(\ )_t$ = tendon

$(\ )_w$ = wall

$(\ )_{ws}$ = wall to shield

$(\ )_{st}$ = shield to tendon

B2.4 REFERENCES

1. Pierce, B. L., et. al. "Tap-A, A Program for Computing Transient or Steady State Temperature Distributions,: WANL-TME-1872, December 1969.

2. Baumeister, T., Marks, L. S., et al., Mechanical Engineers Handbook, 6th ed.

3. Van Wylen, G. J. and Sonntag, R. E., Fundamentals of Classical Thermodymanics, 2nd ed., Wiley.

4. Giles, R. V., Fluid Mechanics and Hydraulics, 2nd ed., McGraw Hill.

5. Chicago Bridge and Iron Co., "Cost Study, Shop Assembly vs. Field Assembly of Heavy Wall Coal Gasifier Reactor Vessels, FE 2009-13, December 1976.

6. Krieth, F., Principles of Heat Transfer, 2nd ed., International Textbook Company

7. Lampe, R. F., Design Data Letter MD:RL:78-98, PCIV Layout 102E201, December 18, 1978.

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