296
9-14-79

1a. 56
ORNL/TM-6969

Structural Integrity of Vessels for Coal Conversion Systems

D. A. Canonico

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $4.50; Microfiche $3.00

ORNL/TM-6969
Distribution Categories
UC-90, -c, -h

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

STRUCTURAL INTEGRITY OF VESSELS FOR COAL CONVERSION SYSTEMS

D. A. Canonico

Date Published - September 1979

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

CONTENTS

STRUCTURAL INTEGRITY OF VESSELS FOR COAL CONVERSION SYSTEMS*

D. A. Canonico

ABSTRACT

The integrity of a coal conversion system need not be compromised by material considerations in design or fabrication. The ASME and ANSI Codes assure the structural integrity of the large pressure vessels and piping when they are placed into service. Imposing additional requirements, such as increased impact toughness, will further assure the reliability and safety of the Code-fabricated vessel. Incorporating in-service surveillance as part of the operational plan will ensure the integrity of the pressure-containing components for the anticipated service life.

INTRODUCTION

Numerous components in coal conversion systems (CCS) will fail as a consequence of service. Failures in some components, such as valves, pumps, filters and some piping lines, are anticipated and can be accommodated through redundancy (during design) or by replacement during scheduled down periods. The cost of extensive downtime (low plant availability) may not be economically acceptable and, ideally, will be "designed out" of a commercial coal conversion system.

The Department of Energy (DOE) has supported a failure analysis data gathering task at the National Bureau of Standards (NBS). A summary of the information was published[1] in 1976. The importance of failure of a component on plant availability is given in Table 1. Evidently, failure of a number of the pressure containing components will not greatly affect plant availability; however, the failure of a pressure vessel and its juxtaposed piping will result in a major plant outage.

A plant failure is often pictured as a catastrophic failure of a major component accompanied by damage to nearby facilities. This is only one failure mode, admittedly the most dramatic. A leak in a primary containment component as well as the detection of rejectable indications by nondestructive techniques are also failures. Any event

Table 1. Effect of Failure of Various Components on Plant Availability

Components	Failure	Result
Valves and valve seats	Corrosion, erosion, cracking	Loss of efficiency, mild upset
Pressure, temperature, and flow controllers	Metering errors, corrosion	Loss of efficiency
Lines	Fouling, plugging, cracking, stress rupture	Major upset
Compressors — reciprocation	Fatigue, erosion, corrosion, explosion	Total shutdown
Pumps — centrifugal	Wear, leakage	Mild upset
Filters	Plugging	Loss of efficiency
Absorption columns	Corrosion	Major shutdown
Steam generators	Boiler-tube failure, plugging	Major shutdown
Catalyst trays	Plugging from entrainment solids	Loss of efficiency
Pressure vessels and piping	Cracking	Major outage
Structural failures	Corrosion, overload, vibration-fatigue, thermal distortions	Major upset

that results in a major outage of a billion dollar coal conversion facility can be considered a failure, whether or not the event is catastrophic.

In view of the consequences of failure in a pressure vessel, we will concentrate on the structural reliability of the gasifier and the reaction pressure vessels that are the heart of the CCS. As pointed out in Table 1, most of the components in a CCS can be replaced with varying degrees of difficulty; however, the failure of a pressure vessel will cause a major plant outage. Vessels in the second generation commercial CCS concepts will require a five-year lead time[2] for acquisition. Hence, loss of such a unit will incapacitate an entire plant for a long time. Several factors affect the structural integrity of a pressure vessel: design, material selection, fabrication, and process environment. We must consider each to assure reliable and safe service.

DESIGN

The design of a CCS is influenced by interrelated scientific and engineering disciplines. Research chemists, thermochemists, kineticists, process chemical engineers, and economists define the required lines, temperatures, catalysts, space envelopes, mass velocities, space velocities, points for entry and exit of process materials, and boundaries between process stages. This information then sets the stage for metallurgists, ceramicists, structural engineers, and mechanical engineers to establish the physical and mechanical property requirements for internal refractories, pressure boundary metals, internal and external structural materials, and external insulation. Layout drafting specialists and/or instrumentation and control specialists cooperate to define the interconnection routing and sizing of the piping, the location of valving and instruments, the mechanical joints, and the internal and external supports. The flow of information from these design actions establishes moments and loads at vessel nozzles, support reactions, and estimates of temperature and pressure perturbations from steady state. Armed with this knowledge and coupled with the selection of design codes and the performance of economic analysis, the vessel and piping designer and stress analysts may finalize the vessel and piping designs.

Other disciplines (e.g., safety, industrial hygiene, insurance, and maintenance) can and should have input into the design of pressure vessels and piping systems. Many of the functions may be combined and performed by a single individual. Conversely, information flow can become rather complex if many individuals employed by several independent companies or entities [e.g., independent or federally owned research laboratories, architect-engineers (A-Es), engineering consultants and/or stress analysts, pressure vessel fabricators, energy or utility companies, insurance companies or insurance pools, etc.] perform these functions.

Consequently, the accomplishment of vessel and piping system function and integrity is a multidisciplinary and frequently a multi-organizational task necessitating the balance of the various requirements. This interaction and cross-checking by multidisciplined technical personnel contributes to the excellent service record of pressure vessels in the U.S.

We will only consider design from a materials viewpoint. In particular, we will refer to the American Society of Mechanical Engineers (ASME) and the American National Standards Institute (ANSI) Codes, which dictate both the material and the design allowable stresses for the construction of pressure vessels and pipes in most states in the U.S. and a number of provinces in Canada. Table 2 provides a list of jurisdictions that mandate the use of the ASME Code. The Codes basically provide the engineering requirements for the safe design and fabrication of pressure vessels and piping. They give *minimum* requirements for construction. Most reputable companies recognize this and impose additional material design criteria, which often go considerably beyond those of the Codes.

The CCS pressure vessels will be designed in accordance with Sect. VIII of the ASME Code, and piping will be designed and fabricated

Table 2. U.S. and Canadian Jurisdictions[a] Requiring the Application of at Least One Section of the *ASME Boiler and Pressure Vessel Code*

U.S. States and Territories		
Alabama	Kentucky	Oklahoma
Alaska	Louisiana	Oregon
Arizona	Maine	Panama Canal Zone
Arkansas	Maryland	Pennsylvania
California	Massachusetts	Puerto Rico
Colorado	Michigan	Rhode Island
Connecticut	Minnesota	South Dakota
Delaware	Mississippi	Tennessee
Dist. of Columbia	Montana	Texas
Georgia	Nebraska	Utah
Guam	Nevada	Vermont
Hawaii	New Hampshire	Virginia
Idaho	New Jersey	Washington
Illinois	New York	West Virginia
Indiana	North Carolina	Wisconsin
Iowa	North Dakota	Wyoming
Kansas	Ohio	
U.S. Cities and Counties		
Albuquerque, N.M.	Miami, FL.	Spokane, WA.
Buffalo, N.Y.	Milwaukee, WI.	Tacoma, WA.
Chicago, IL.	New Orleans, LA.	Tampa, FL.
Dearborn, MI.	New York City, N.Y.	Tucson, AZ.
Denver, CO.	Oklahoma City, OK.	Tulsa, OK.
Des Moines, IA.	Omaha, NB.	University City, MO.
Detroit, MI.	Phoenix, AZ.	White Plains, N.Y.
E. St. Louis, IL.	St. Joseph, MO.	Arlington Co., VA.
Greensboro, N.C.	St. Louis, MO.	Dade Co., VA.
Kansas City, MO.	San Francisco, CA.	Fairfax Co., VA.
Los Angeles, CA.	San Jose, CA.	Jefferson Parish
Memphis, TN.	Seattle, WA.	St. Louis Co., MO.
Provinces in Canada		
Alberta	Newfoundland & Labrador	Prince Edward Is.
British Columbia	Northwest Terr.	Quebec
Manitoba	Nova Scotia	Saskatchewan
New Brunswick	Ontario	Yukon Territory

[a]Information extracted from: *Tabulation of the Boiler and Pressure Vessel Laws of the United States and Canada,* Data Sheet, Uniform Boiler and Pressure Vessel Laws Society, Inc., Hartford, Conn., June 1979.

in accordance with ANSI Code B31.3. Economics (usually related to the size of the pressure vessel being considered) will be the primary factor dictating whether construction will be to Div. 1 or Div. 2 specifications of Sect. VIII. The general rules of Sect. VIII, Div. 1, limit pressure to 21 MPa (3000 psi), but paragraph U-1(b) does permit higher pressure if additional requirements are imposed. Hence, pressure alone will not be the controlling factor. Each division of Sect. VIII imposes safety factors for permissable design stresses. Table 3 provides criteria for calculating allowable stresses in ANSI B31.3 and the two divisions of Sect. VIII. Note that only Div. 1 and ANSI B31.3 provide allowable stress values for operation in the creep range. The allowable stresses in Div. 1 are lower than those in Div. 2. Table 4 permits a comparison between the Div. 1 and 2 allowable stresses for three grades of steel. We should emphasize that the stresses provided in Table 4 are based on the minimum values obtained for these steels. Usually, the actual strength exhibited by a steel is considerably greater than the minimum required in the specification to which it was purchased and processed. To some degree the potential cost savings afforded by Div. 2 from use of thinner walled, lighter weight vessels is offset by the increased cost of the more rigorous rules of analysis and inspection. Figure 1 is based on SA 387 Grade 22 (2 1/4 Cr-1 Mo) steel heat-treated to Class 2 properties. At temperatures below 455°C (850°F) the design stress intensities allowed in Div. 2 for 2 1/4 Cr-1 Mo steel are about 1.3 times those permitted in Div. 1. Note that at temperatures above 455°C the advantages of Div. 2 quickly disappear. Furthermore, as mentioned previously there are no allowable design stress intensities for temperatures in the creep range.

Figure 2 emphasizes how the difference in Divs. 1 and 2 allowable stresses and intensity limits, respectively, affects the size of a liquefaction pressure vessel. The difference in vessel size can be important when considering the competitiveness of a CCS. By designing with 300-mm-thick (12-in.) plate to the stress intensity limits in Div. 2, a vessel with an internal cross section 2.25 times greater than that possible in Div. 1 can be constructed.

Table 3. Criteria for Calculation of Allowable Stresses (Nonbolting Conditions)

Standard	Fraction of Minimum				
	Ultimate Tensile	Yield Stress	Creep Stress[a]	Rupture Stress[b]	Uniaxial Strain Cycling Fatigue
ASME Sect. VIII, Div. 1	1/4	2/3[c]	100% av	67% av 80% min	
ASME Sect. VIII, Div. 2	1/3	2/3[d]	*e*	*e*	*f*
ANSI B31.3	1/3	2/3[d]	100% av	67% av 80% min	

[a]To give 0.01% strain per 1000 h.

[b]To give rupture in 100,000 h.

[c]Above room temperature these values can be exceeded for some materials when the application involves components where greater deformation is not objectionable, but they cannot exceed 90% of minimum yield stress at temperature.

[d]Above room temperature this value could be 90% of yield stress at temperature for some materials (i.e., austenitic stainless steels and certain nickel-base alloys), but it cannot exceed 2/3 of specified minimum yield stress at room temperature.

[e]Criteria not established.

[f]Fatigue properties are not always required. Need for fatigue analysis is determined by designer in accordance with par. AD-160.2 of ASME Sect. VIII, Div. 2, rules.

Table 4. Comparison of the Sect. VIII Maximum Allowable Stress in Div. 1 and the Design Stress Intensity Values in Div. 2

Temperature		Design Limit, MPa (ksi)[a]					
		SA-516 Grade 55		SA-387 Grade 22 Class 2		A 543 Class 1	
(°C)	(°F)	Division 1	Division 2	Division 1	Division 2	Division 1	Division 2
38	100	94 (13.7)	126 (18.3)	129 (18.7)	172 (25.0)	181 (26.3)	241 (35.0)
204	400	94 (13.7)	119 (17.2)	120 (17.4)	160 (23.2)	179 (26.0)	239 (34.6)
343	650	94 (13.7)	100 (14.5)	119 (17.2)	158 (22.9)	173 (25.1)	231 (33.5)

[a]SA indicates an ASME Code Sect. II, Part A, specification. A indicates an ASTM standard.

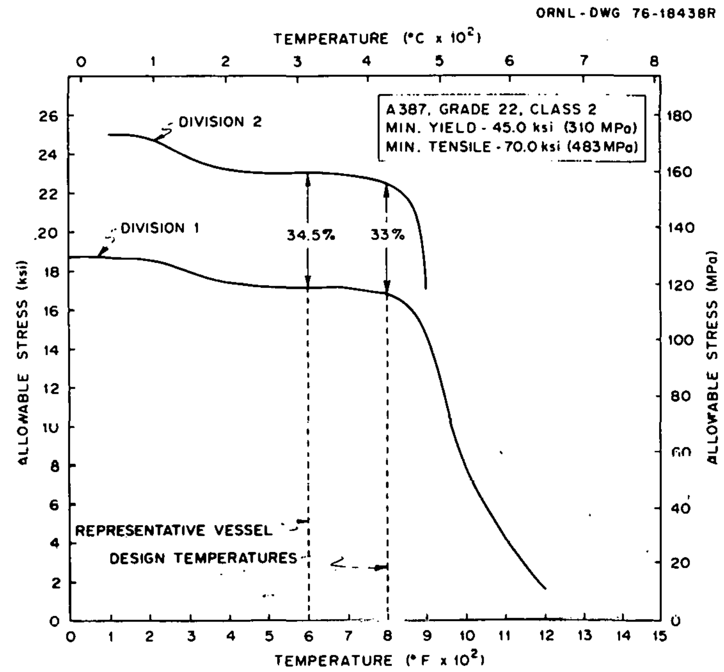


Fig. 1. Comparison of the Allowable Stresses of Sect. VIII, Div. 1, and the Allowable Stress Intensities of Sect. VIII, Div. 2, for SA 387 Grade 22 Class 2 Steel.

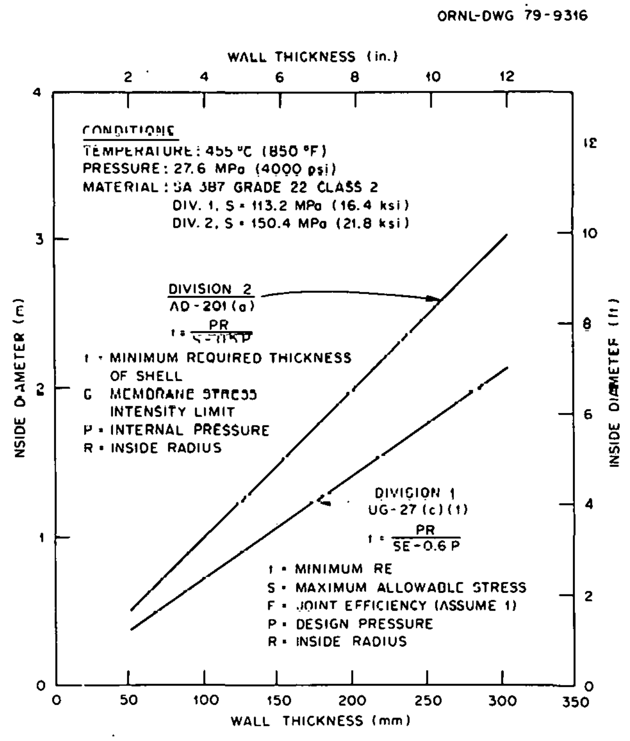


Fig. 2. The Higher Stress Intensity Limits in Div. 2 Permits the Construction of a Larger Diameter Pressure Vessel for a Given Set of Design Parameters.

Several different coal conversion processes are being considered for producing synthetic fuels and gases. Of current primary interest are processes that will provide high Btu gas or liquid. We can generally define the environments in which each process operates as low temperature [500°C (900°F)], high pressure [14–28 MPa (2000–4000 psi)] for liquefaction and high temperature [1000°C (1800°F)], low pressure [10 MPa (1500 psi)] for gasification. In general, we will consider these two conditions in our discussion.

The conditions described above essentially establish the pressure vessel sizes that can be contemplated for liquefaction or gasification. The liquefaction vessels will be about 3 to 5 m (10 to 15 feet) in diameter, while the gasification pressure vessels can range up to 10 to 12 m (30 to 36 ft) in diameter. Figure 3 provides a relative comparison

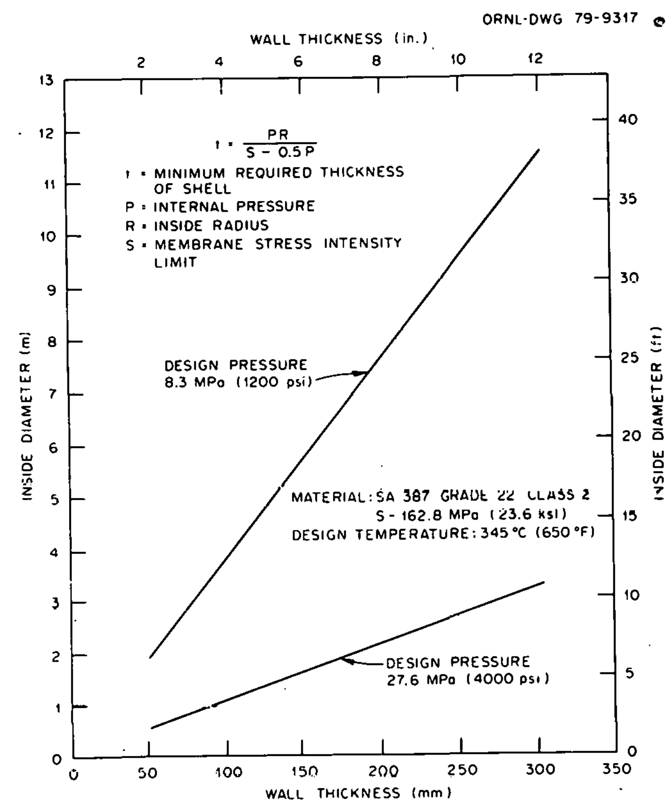
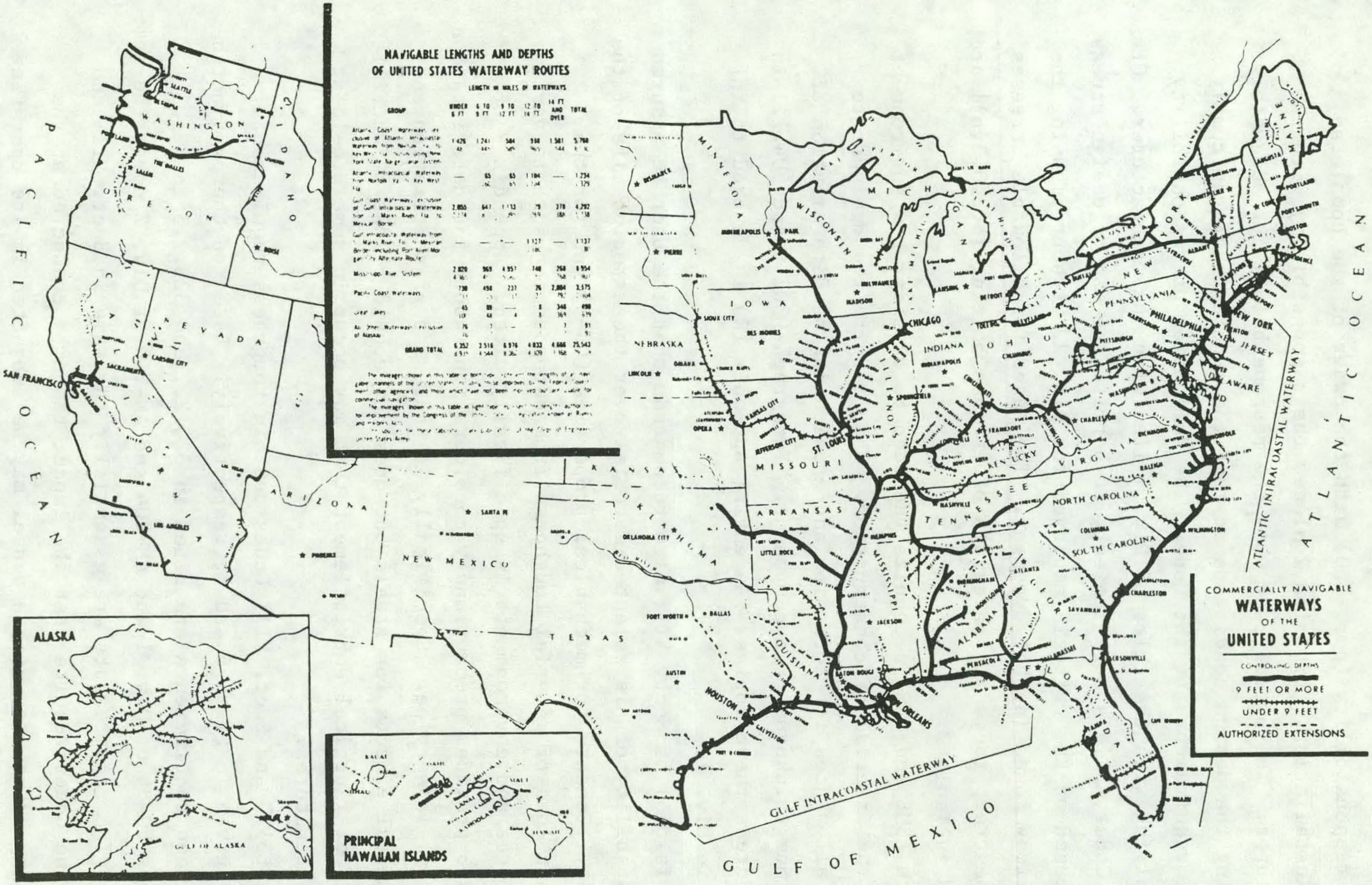


Fig. 3. The Lower Pressures Required for Gasification Processes Permit the Fabrication of Extremely Large Diameter Pressure Vessels Within the Current Technology Limits for Plate and Forging Thicknesses.

of pressure vessel diameters that can be considered for the two major CCSs. This figure is based on the 345°C (650°F) stress intensity limits in Sect. VIII, Div. 2, of the ASME Code for SA 387 Grade 22 Class 2 steel (2 1/4 Cr-1 Mo). Evidently, the high pressures [163 MPa (4000 psi) in the example in Fig. 3] in the liquefaction processes will limit the pressure vessel size to about 3 m (10 ft).

Figure 3 establishes the vessel sizes that can be considered for the two CCS concepts. In addition to the basic considerations of design, material selection, and process environment, there are other equally constraining factors. These are related to fabrication procedure, which is dictated by component transportation. The pressure vessels that can be transported by railroad are limited[3,4] to about 4.2 m (14 ft) in diameter and 730 t (800 tons) in weight. Lengths of about 31 m (100 ft) have been reported.[3] Though the shipment of large pressure vessels by barge removes the size and weight constraints imposed by railroad transportation, it does require that the coal conversion plants be sited near navigable waterways. Such siting will tend to eliminate any size constraint other than the ability of the general contractor to handle the components during erection. However, navigable waterways are restricted mainly to the eastern U.S. Figure 4 shows the waterways of the U.S.,[2] and evidently, navigable routes do not extend much further west than eastern Oklahoma. Therefore, the northern Great Plains and the Rocky Mountains coal regions can be serviced only by land. In summary, the size of pressure vessel that can be shop fabricated is dictated by: (1) the coal conversion plant site and/or (2) the lifting capacity of the fabrication shop. If the site is not accessible to a navigable waterway, then a choice must be made between the use of conversion processes based on a multitrain concept, which would allow the use of pressure vessels no more than 4.2 m in diameter, or of large field-erected vessels.

As was mentioned, ASME Sect. VIII, Div. 1 or 2, will be used to design CCS pressure vessels, and ANSI B31.3 will be used for the piping. Responsibility for compliance of the completed component with Code specifications is stated in each Code. The ANSI B31.3 places the



NAVIGABLE LENGTHS AND DEPTHS OF UNITED STATES WATERWAY ROUTES

LENGTH IN MILES OF WATERWAYS

GROUP	UNDER 6 FT	6 TO 9 FT	9 TO 12 FT	12 TO 14 FT	14 FT AND OVER	TOTAL
Atlantic Coast Waterways exclusive of Atlantic Intracoastal Waterway from Norfolk, Va. to Key West, Fla. (including New York State Barge Canal System)	1,426	1,241	584	958	1,581	5,788
	42	445	585	965	544	[illegible]
Atlantic Intracoastal Waterway from Norfolk, Va. to Key West, Fla.	—	65	65	1,104	—	1,234
		66	65	[illegible]		1,329
Gulf Coast Waterways, exclusive of Gulf Intracoastal Waterway from St. Marks River, Fla. to Mexican Border	2,055	647	1,133	79	378	4,292
	[illegible]	[illegible]	[illegible]	369	188	[illegible]
Gulf Intracoastal Waterway from St. Marks River, Fla. to Mexican Border including Port Allen-Morgan City Alternate Route	—	—	—	1,137	—	1,137
				[illegible]		[illegible]
Mississippi River System	2,020	969	4,957	740	268	8,954
	[illegible]	[illegible]	[illegible]	[illegible]	268	[illegible]
Pacific Coast Waterways	730	498	237	76	2,004	3,575
	[illegible]	[illegible]	[illegible]	[illegible]	792	[illegible]
Great Lakes	45	89	—	8	348	490
	101	48	4	8	369	539
All Other Waterways (exclusive of Alaska)	76	[illegible]	—	1	[illegible]	91
	76	[illegible]		[illegible]	[illegible]	[illegible]
GRAND TOTAL	6,252	3,516	6,976	4,833	4,666	25,543
	[illegible]	4,544	[illegible]	4,109	[illegible]	[illegible]

Reprinted with permission of American Waterways Operators, Inc.

Fig. 4. Waterways of the U.S. Source: Federal Energy Administration, *Project Independence Report*, Stock No. 4118-00029, U.S. Government Printing Office, Washington, D.C., November 1974, p. 69.

overall responsibility (par. 300) with the owner of the completed piping installation. Division 2 places the responsibility with the manufacturer. The owner (user) has the responsibility for adequately specifying the design conditions so that the manufacturer can comply with the requirements of the Code. The delegation of responsibility for complying with the rules of Div. 1 lies with the manufacturer. Of the two Codes ANSI is more lenient; it permits the use of design stress values based on the criteria employed for Div. 2, without imposing the restrictions found in that document. The bases for allowable stresses below the creep range for materials other than bolting [302.3.2(b)] are provided in Table 3.

Both ASME and ANSI recognize the need to consider how environment affects the material of construction. They require the designer to include allowances for corrosion and erosion in the determination of the minimum thickness of a component. Paragraphs 302.4 and 304.1.1 in B31.3 address these topics. An entire Appendix (E) is devoted to this subject in Div. 1.

Division 1 of Sect. VIII also recommends that the user be assured of the stability of his selected material over the expected life of the component. Concern for mechanical properties (UG-5) and for the consequent loss of material toughness from extended exposure to various temperatures and environments is specifically cited. Appendix F of B31.3-1976 provides precautionary considerations about the deterioration of material in service. Specifically it addresses graphitization and environmental effects for steels but does not consider loss of ductility from the metallurgical embrittlement that may occur in some steels at these temperatures.

The B31.3 and Sect. VIII Codes contain toughness requirements; they are given in Figs. 5 and 6, respectively. Based on Charpy V-notch tests, these requirements are cited in 323.2.2 and 323.2.3 in B31.3. Paragraphs UG-84 of Div. 1 and AM-204 and AM-210 of Div. 2 cover the same subject. The requirements are essentially the same in Sect. VIII and B31.3. The Codes require that the impact tests be conducted at the lowest temperature to which a vessel may be subjected in its operating cycle and that the minimum required Charpy V-notch impact values must be attained at these temperatures. The Codes do not require determination of Charpy V-notch upper shelf energy values. Furthermore, the Code rules do not assure that the toughness properties are greater than the 20 to 25 J (15 to 20 ft-lb) required. The toughness requirements in the Codes are minimal for thick sections. This fact is recognized by reputable A-Es, owners, and fabricators.

The most obvious differences between B31.3 and Sect. VIII, Div. 2, lie in the fabrication and inspection procedures for manufacturing components. Specifically, the requirements for nondestructive examinations

Table 323.3.7 Minimum Required Charpy V-Notch Impact Values

		Energy, ft-lbf[1]	
Specified Minimum Tensile Strength	No. of Specimens[2]	Fully Deoxidized Steels	Other Than Fully Deoxidized Steels
A. Carbon and Low Alloy Steels			
65 ksi (448 MPa) and less	Average for 3 specimens	13	10
	Minimum for 1 specimen	10	7
Over 65 to 75 ksi (to 517 MPa)	Average for 3 specimens	15	13
	Minimum for 1 specimen	12	10
Over 75 but not including 95 ksi	Average for 3 specimens	20[3]	–
(656 MPa)	Minimum for 1 specimen	15[3]	–
		Lateral Expansion[4]	
95 ksi and over[5]	Minimum for 3 specimens	0.015 in(0.38 mm)	
B. Steels in P-Numbers 6, 7, and 8	Minimum for 3 specimens	0.015 in(0.38 mm)	

[1] Energy values in this table are for standard-size specimens. For subsize specimens, these values shall be multiplied by the ratio of the actual specimen width of a full-size specimen, 10 mm (0.394 in). To convert ft-lbf values to values in joules (*J*), multiply by 1.356.

[2] See 323.3.7(d) for permissible retests.

[3] In addition to the energy values, the values of lateral expansion opposite the notch, and percent shear in the fracture surface, shall be recorded. These recorded values shall be shown on the certified reports for information only.

[4] When the lateral expansion criterion is applicable, in addition to a record of lateral expansion values, the values of absorbed energy in foot pounds and of the percent shear in the fracture surface shall be recorded on the certified report for information only.

[5] For bolting of this strength level in sizes 2″ and under, the impact requirements of ASTM A320 may be applied. For bolting over 2″, requirements of this table shall apply.

Fig. 5. Impact Requirements for ANSI B31.3 – 1976. Reproduced from: *ANSI Code for Pressure Piping, Chemical Plant and Petroleum Refinery Piping*, American Society of Mechanical Engineers, N.Y., 1977, p. 53.

are minimal in B31.3. Random radiography of 5% of the circumferential butt welds is permitted for service above 180°C (360°F) or for pressures above 1.03 MPa gage (150 psig) [336.5.1(b)]. No consideration is given to environment. Division 1 requires that all butt-welded joints in a vessel that is to contain a lethal substance shall be fully radiographed. The definition of a lethal substance is open to interpretation. For a safe installation (basis for all codes) the most liberal interpretation should be employed. Moreover, Div. 1 requires full radiographic examination of specified thicknesses of butt-welded joints of certain P* and group number materials. Note that all thicknesses of 2 1/4 Cr-1 Mo,

---

*P numbers provide groupings of base materials that may use the same welding process qualification (ASME Sect. IX, par. QW 421).

TABLE UG-84.1
MINIMUM CHARPY V-NOTCH IMPACT TESTS REQUIREMENTS
FOR CARBON AND LOW-ALLOY STEELS LISTED IN TABLE UCS-23

Specified Minimum Tensile Strength		Charpy V-Notch Impact Energy, ft lb: Fully Deoxidized Steel	Charpy V-Notch Impact Energy, ft lb: Other Than Fully Deoxidized
65,000 psi and less	Average for 3 specimens	13	10
	Minimum for 1 specimen	10	7
Over 65,000 to 75,000 psi inclusive	Average for 3 specimens	15	13
	Minimum for 1 specimen	12	10
Over 75,000 to but not including 95,000 psi	Average for 3 specimens	20	
	Minimum for 1 specimen	15	. . .
95,000 psi and over(1)	Minimum for 3 specimens	Lateral expansion 0.015 in. (15 mils)	

NOTE:
(1) For bolting of this strength level, in diameters of 2 in. and under, the impact requirements of SA-320 may be applied. For diameters above 2 in., the requirements of this Table shall apply.

TABLE AM-211.1
MINIMUM CHARPY V-NOTCH IMPACT TEST REQUIREMENTS
FOR CARBON AND LOW-ALLOY STEELS

Specified Minimum Tensile Strength		Charpy V Notch Impact Values Energy, ft-lb: Fully Deoxidized Steels	Charpy V Notch Impact Values Energy, ft-lb: Other Than Fully Deoxidized Steels
65,000 psi and less	Average for 3 specimens	13	10
	Minimum for 1 specimen	10	7
Over 65,000 to 75,000 psi inclusive	Average for 3 specimens	15	13
	Minimum for 1 specimen	12	10
Over 75,000 psi but not including 95,000 psi	Average for 3 specimens	20	. . .
	Minimum for 1 specimen	15	. . .
95,000 psi and over	Minimum 3 specimens (Note 1)	Lateral Expansion Values 0.015 in.	

NOTE:
(1) See AM-211.6(b) for permissible retests.

Fig. 6. Impact Test Requirements for Sect. VIII, Div. 1 (Table UG-84.1 and Div. 2 (Table AM-211.1). Reproduced from: *ASME Boiler and Pressure Vessel Code,* American Society of Mechanical Engineers, N.Y., 1977, p. 51 (Div. 1) and p. 27 (Div. 2).

3 Cr-1 Mo, 3 Cr-0.9 Mo, 5 Cr-1/2 Mo, 7 Cr-1/2 Mo, and 9 Cr-1 Mo steels (P-5 alloys) must be fully radiographed (UCS-57). Because of their excellent resistance to coal conversion environments and hydrogen attack, these alloy steels are candidate materials for the fabrication of pressure vessels and piping for coal conversion systems. The above radiographic requirement does not exist in B31.3.

The fabrication rules are more restrictive in Sect. VIII than in B31.3. Division 1 [UCS-5(b)] restricts welding on carbon and low-alloy steels to those that contain less than 0.35% carbon. In contrast, 311.1 in B31.1 permits welded joints in any material for which it is possible to qualify welding procedures. [Table ACS-1 of Div. 2 also limits (Note 4) the carbon content of some nominal compositions.] Furthermore, Div. 2 specifically delineates permissible fabrication procedures in its restrictions.

Before final acceptance of a system, an authorized inspector must be satisfied that the pressure vessel or piping installation meets the requirements of the Code to which the component was manufactured. Code B31.3 states that the authorized inspector is a representative of the owner. Section VIII states that the inspector can be an employee of a state or municipality of the U.S., a Canadian Province, an insurance company authorized to underwrite boiler and pressure vessel insurance, or the owner (when the owner has purchased the pressure vessel for his own use).

A Sect. VIII inspector is qualified by a written examination under the rules of any state of the U.S. or province of Canada. This is in contrast to B31.3, which requires that the authorized inspector have a minimum of ten years experience in the design, fabrication, or inspection of industrial pressure piping.

Finally, the hydrostatic test required in both divisions of Sect. VIII and in ANSI B31.3 provides the best assurance that the vessel and/or piping is functionally sound. Section VIII requires that the hydrostatic test be conducted at 1.25 times the design pressure. The ANSI B31.3 Code requires that the piping be proof tested at 1.5 times the design pressure.

In summary, the Codes are formulated to assure the safety of the manufactured component. The ASME Sect. VIII, Divs. 1 and 2, and

ANSI B31.3 Codes provide allowable stress values for pressure vessels and piping, respectively. The ASME Code is considerably more restrictive than B31.3, even when considering essentially identical materials. The ANSI B31.3 Code permits the use of unlisted materials. This is not true in the ASME Code. The allowable stresses in ANSI B31.3 are higher than those in ASME Sect. VIII, Div. 1, and the examination requirements are considerably more lenient. As a result of the above differences in requirements, a B31.3 piping installation is correctly less conservative than a Sect. VIII, Div. 1, vessel. The hydrostatic test that the Codes require before a vessel (or piping) is placed in service assures that the quality required by the designer has indeed been achieved in the fabricated component.

MATERIAL SELECTION

Section VIII permits selection of only those materials that are listed in Sect. II of the Code. Section II, Part A, provides specifications for plate and forging steels that are candidates for the fabrication of CCS pressure vessels. By mandating that steels be obtained in accordance with the requirements of the specifications in Sect. II, the materials will exhibit a level of quality commensurate with their intended use. Steels that are permitted in the Code have exhibited acceptable properties either through laboratory tests or through years of successful use in operating systems.

The ASME and ASTM specifications do not have specific requirements for qualifying materials for elevated-temperature and associated process environmental conditions. However, the material must satisfy both the mechanical property requirements at room temperature and the other requirements of the specification. However, elevated-temperature allowable stresses are provided for each Code-approved material, and these values are based on tests of heats of that grade and experience.

Basic to the selection of the materials is consideration of the operating conditions. Although the CCS environments are somewhat more hostile than those encountered in refining petroleum,[5,6] the petroleum experience, particularly concerning hydrogen attack, provides an excellent base for considering in-service deterioration. The Nelson curves provide the experience necessary for the initial environmental consideration when selecting pressure vessel and piping materials. These curves, shown in Fig. 7, represent over 25 years of experience and are periodically reviewed and updated. This background minimizes the potential for in-service problems from hydrogen attack. This experience is a major factor when considering vessel reliability, particularly for the high-pressure liquefaction reactor vessels and piping.

ORNL-DWG 77-3541R

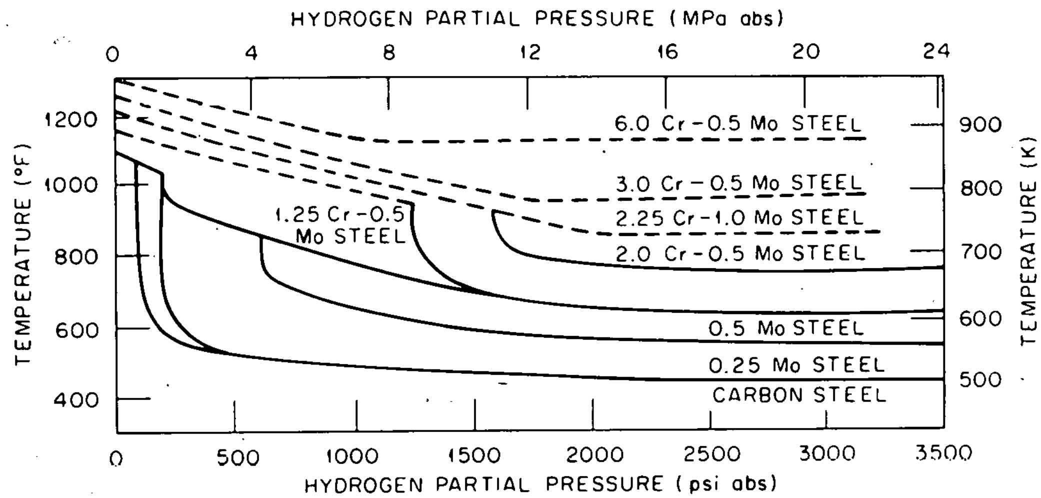


Fig. 7. The Nelson Curves Show Operating Limits for Steels in Hydrogen Service.

METALLURGICAL CONSIDERATIONS

The choice of material for fabrication of a component depends on the volume (this will determine the vessel's diameter and height) and chemical characteristics (corrosivity) of the process stream, the required temperature and pressure, and the acceptability of the material under the Code. These criteria will dictate whether the component will operate in the warm mode [about 340°C (650°F)] or hot mode (above the temperature at which creep must be considered).

Because of their high process temperatures, the pressure vessels used in gasification systems will likely be designed to operate below the creep range and above the dew point of the process stream. The limitations are selected because at the temperatures for which time-dependent properties must be considered, the Code allowable stresses decrease rapidly for small increases in design temperature. This loss of strength at temperatures of about 500°C (900°F) is evident in Fig. 1 and is particularly true for the ferrous materials. The high-alloy materials (austenitic stainless steels and high-nickel alloys) maintain their strengths to higher temperatures, but generally their allowable stress levels are low, and their cost per fabricated pound is comparatively high. Hence, economics will probably dictate that gasification pressure vessels will be fabricated from carbon or low-alloy steels, protected from the high process temperatures by refractory insulation, and perhaps overlaid (or clad) to protect them from the process stream. Liquefaction pressure vessels may possibly be designed to operate near their process temperature [about 500°C (930°F)]. If so, a refractory lining may not be required.

Low-alloy steels will be employed in the fabrication of the CCS pressure vessels. These steels, in the thick sections required for large vessels, will be quenched and tempered to satisfy the requirements of the Sect. II specifications. The Code requires that the tensile and toughness requirements be satisfied at the quarter thickness depth in the plate (or forging).

Quenching and tempering of carbon and low-alloy steels results in a variation in properties through the plate thickness.[7] Such a variation caused by quenching is illustrated in Fig. 8. As mentioned above, the Codes require that the minimum requirements of the specification be satisfied at the quarter thickness depth. Consequently, quite often the properties are not determined at other depths. Note that the minimum room temperature yield and ultimate strength for steel in Fig. 8 are 345 and 550 MPa (50 and 80 ksi), respectively. The heat of steel used to develop the data in Fig. 8 actually exhibited yield and tensile strengths of 480 and 640 MPa (70 and 92 ksi), respectively. These

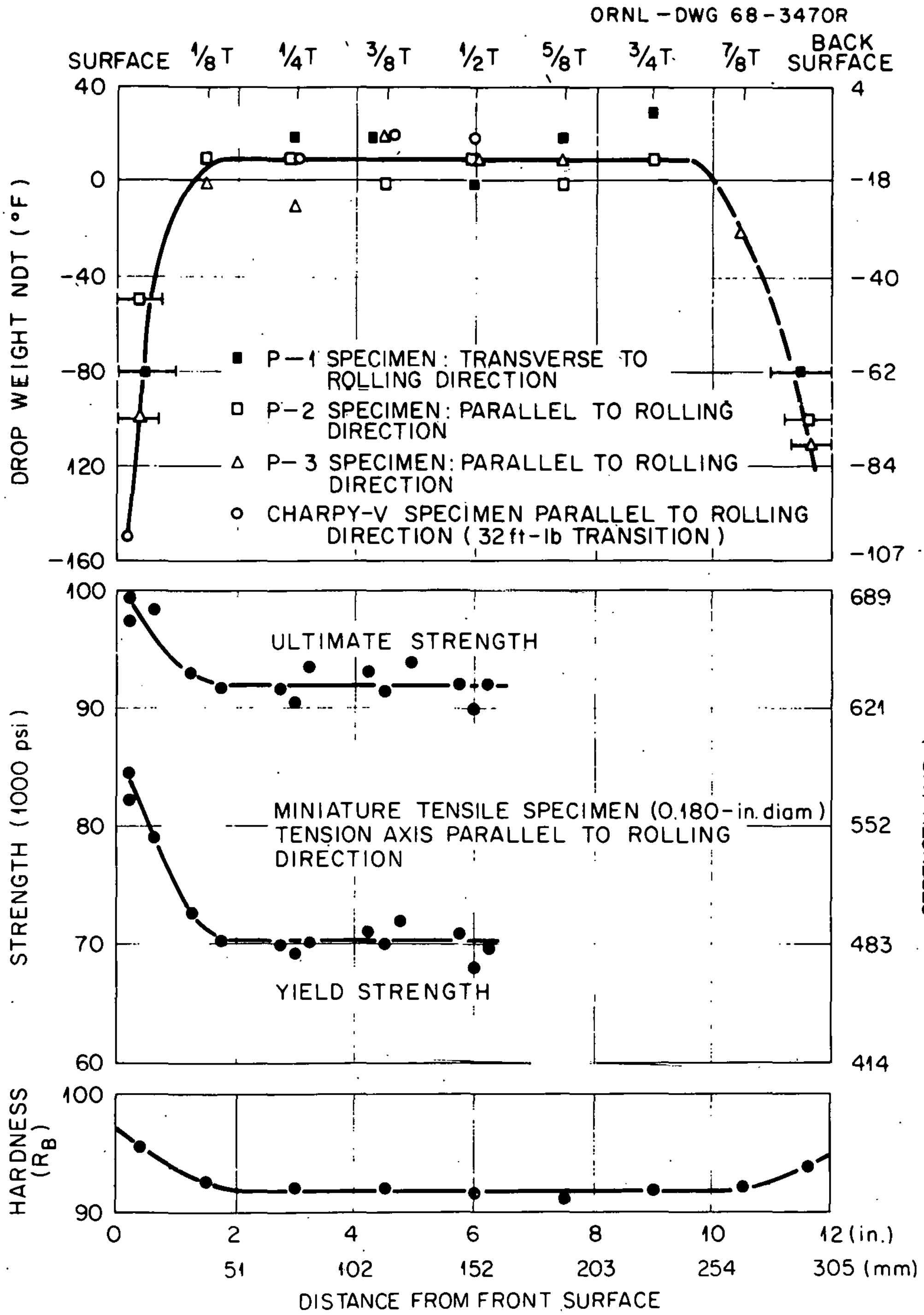


Fig. 8. Variation with Depth in Plate of Representative Mechanical Properties for Central Region of a 3.05-m by 6.10-m by 305-mm (10-ft by 20-ft by 12-in.) Plate of ASTM A 533 Grade B Class 1 Steel.

enhanced properties are not considered when reviewing the integrity of a pressure vessel. The surface properties are superior to those at the quarter thickness depth because of the faster cooling rate there. The higher strength *and* improved toughness provide a degree of conservativeness that is not considered in the safety analysis of the pressure vessel. For certain applications this increase in strength is beneficial. In the case of a CCS, the increase in strength at the surface could be detrimental if excessive. A National Association of Corrosion Engineers (NACE) Committee reported[8] that carbon and low-alloy steel candidates for the fabrication of vessels for coal conversion systems are susceptible to sulfide stress cracking when their hardness is about R_C22 or greater. For most of the candidate CCS pressure vessel steels the R_C22 hardness will not be exceeded. However, the owner should be alerted to the fact that these steels may have higher surface strengths than reported in a mill certification test.

From the above discussions the required tensile properties can evidently be achieved, even in the extremely thick sections, by quenching and tempering. Notch toughness, particularly under the requirements of ANSI B31.1 and Sect. VIII, Divs. 1 and 2, of the ASME Code, can be met by the candidate alloys being proposed; however, the adequacy of these requirements for thick sections is questionable. Most disruptive pressure vessel failures reported in the open literature have occurred as a result of poor initial toughness[9] or because of loss of toughness from service.[10] The Thompson vessel, which failed in 1966 during hydrostatic testing, exhibited near 20-J (15-ft-lb) impact energy at the failure temperature [40°C (104°F)]. Experienced fabricators[11] and/or owners[12] avoid this problem by requiring 54- to 68-J (40- to 50-ft-lb) Charpy V-notch impact energies as part of their internal procurement specifications. Imposing such impact toughness requirements assures that the fracture toughness of the containment steels is high enough to minimize the probability of catastrophic failure. High quality steels and their weldments will exhibit toughness properties considerably greater than these values. These superior toughness properties are not considered in the review of the integrity of a vessel. Figure 9 illustrates this point with Charpy V-notch and compact specimen data from A 533 Grade B Class 1 steel. The linear elastic fracture toughness (K_{Ic}) value for this steel at the 20-J (15-ft-lb) temperature [about −20°C (−40°F)] is about 66 MPa $\sqrt{m}$ (60 ksi $\sqrt{in.}$); whereas, the value is near 220 MPa $\sqrt{m}$ (200 ksi $\sqrt{in.}$) at the 68-J (50-ft-lb) temperature [about 35°C (95°F)]. The degree of improvement can also be expressed through the Rolfe-Novak correlation:[13]

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 5\left(\frac{CVN}{\sigma_{ys}} - 0.05\right) ,$$

where

CVN = Charpy V-notch impact toughness in ft-lbs,

σ_{ys} = 0.2% offset values yield strength.

By assuming a minimum yield strength of 345 MPa (50 ksi) and toughness values of 20 and 50 J, the correlation provides K_{Ic} values of about 60 and 120 MPa $\sqrt{m}$ (55 and 109 ksi $\sqrt{in.}$), respectively, for the two impact energy values. A K_{Ic} value of 120 MPa $\sqrt{m}$ (109 ksi $\sqrt{in.}$) will provide reasonable assurance that leak before break is probable, even for thick sectioned (near 150 mm) CCS pressure vessels. This assumes no degradation of toughness from operation. Degradation can be determined through an in-service surveillance program.

The CCS vessels and piping are given a mandatory hydrostatic test either before shipment for shop fabricated components or before acceptance for field fabricated components. The ASME Codes require that these tests be conducted at a pressure that is 1.25 times design pressure. The piping Code requires that this pressure be 1.5 times the operating pressure. The hydrostatic test temperature is usually near room temperature, a temperature considerably below that of operation. By satisfactorily passing this final test, the vessel being placed into service has quality with guaranteed integrity. As was mentioned earlier, ORNL-DWG 78-1773

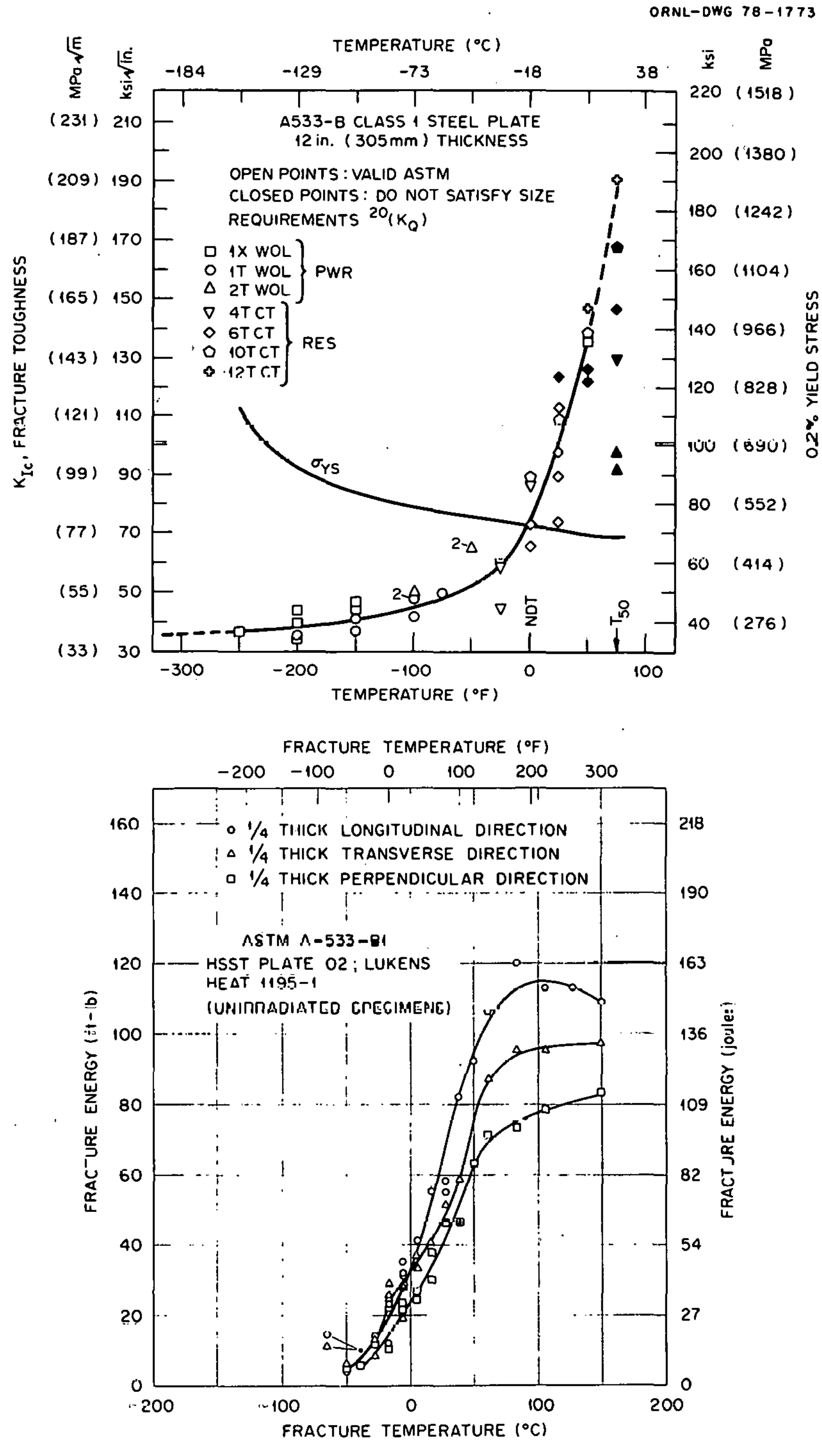


Fig. 9. Relationship Between Valid K_{Ic} Fracture Toughness (a) and Charpy V-Notch Toughness (b) from the Same 305-mm-Thick (12-in.) Plate of A 533 Grade B Class 1 Steel.

in-service degradation of material properties can occur. This possibility must be dealt with by maintaining in-service surveillance, which will be extremely important during the early years of a demonstration facility. During this period the industry is gaining much needed experience with the commerial second generation CCS. Stability of mechanical properties, particularly toughness, must be emphasized when discussing the long-time integrity of the pressure containment in a CCS.

CONCLUSIONS

We can expect that large, thick-walled coal conversion pressure vessels will exhibit structural integrity if they comply with the following considerations:

1. They are built in accordance with the requirements of the ASME and/or ANSI Codes.

2. The multidisciplined approach to design, material selection, and fabrication is adhered to, and communication between these groups is maintained.

3. The fracture toughness requirements imposed by experienced and reputable companies, *which are considerably beyond those required by the Code*, become the standard for the industry.

4. The sharing of technological developments is continued and, indeed, is increased.

5. The role of materials in the success of any conversion system is emphasized and assumes its rightful place in the development of coal conversion technology. *There will be no industry if process and material development are not wed in pilot plant as well as demonstration plant facilities.*

6. In-service surveillance programs are included in the operational plans for coal conversion systems.

7. The effect of the process environments on the mechanical properties of the pressure containment components is adequately established.

ACKNOWLEDGMENTS

The author wishes to acknowledge the following personnel for their contributions to this report. The report was reviewed by R. W. Swindeman and R. K. Nanstad, edited by B. G. Ashdown, and prepared for final publication by D. E. Campbell.

REFERENCES

1. *ERDA Newsl. Mater. Components Fossil Energ. Appl.* 4: 1–3 (April 1, 1976).
2. Federal Energy Administration, *Project Independence Report,* Stock No. 4118-00029, U.S. Government Printing Office, Washington, D.C., November 1974, p. 69.
3. R. G. Dunn, G. F. Whiteley, and W. Fairhurst, "Album of Modern Pressure Vessels," *Molybdenum's Place in the Pressure-Vessel Field,* Climax Molybdenum Co., Greenwich, Conn., 1969, p. 163.
4. S. J. Keating, Jr., "The Transport of Nuclear Power Plant Components," paper presented at the Lighter Than Air Workshop, Monterey, Calif., Sept. 8–13, 1974.
5. A. M. Hall, "Potential Material Problems in Coal Gasification Systems," p. 183 in *Prevention of Failure in Coal Conversion Systems,* Proc. 24th Meeting of Mechanical Failures Prevention Group (Columbus, Ohio, April 21–23, 1976), NBS Spec. Publ. 468 (April 1977).
6. D. A. Canonico et al., *Assessment of Materials Technology for Gasifier and Reaction Pressure Vessels and Piping for Second Generation Coal Conversion Systems,* ORNL-5238 (August 1978).
7. D. A. Canonico and R. G. Berggren, "Tensile and Impact Properties of Thick-Section Plate and Weldments," *Nucl. Eng. Des.* 17(1): 4 (1971).
8. NACE Unit Committee T-1F, "Sulfide Cracking Resistant Metallic Materials for Valves for Production and Pipeline Service," *Mater. Prot.* 5(9): 81–2 (Sept. 1966).

9. R. Weck, "Brittle Fracture of a Thick Walled Pressure Vessel," *Br. Weld. Res. Assoc. Bull.* 7(6): 149–78 (June 1966).

10. J. Watanabe et al., *Investigation in a Failure of a Direct Desulfurization Reactor During its Field Repair Work,* Japan Steel Works report PV76-3-41 (March 1976).

11. Chicago Bridge and Iron Co., *Cost Study, Shop Assembly vs Field Assembly of Heavy Wall Coal Gasifier Reactor Vessels, Final Report,* FE-2009-13 (December 1976).

12. Private Communication, G. Sorrel, Exxon Corporation, Florham Park, N. J., November 21, 1978.

13. S. T. Rolfe and J. M. Barsom, *Fracture and Fatigue Control in Structures,* Prentice-Hall, Englewood Cliffs, N. J., 1977.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

ORNL/TM-6969
Distribution Categories
UC-90, -c, -h

INTERNAL DISTRIBUTION

1–2. Central Research Library
3. Document Reference Section
4–5. Laboratory Records Department
6. Laboratory Records, ORNL R.C.
7. ORNL Patent Section
8. V. B. Baylor
9. R. J. Beaver
10. M. Bender
11. R. G. Berggren
12. R. A. Bradley
13. C. R. Brinkman
14–38. D. A. Canonico
39. G. M. Caton
40. H. D. Cochran
41. R. H. Cooper, Jr.
42. J. E. Cunningham
43. S. A. David
44. J. H. DeVan
45. D. P. Edmonds
46. M. S. Edwards
47. W. H. Fleischman
48. E. L. Fuller
49. T. G. Godfrey
50. G. M. Goodwin
51. J. C. Griess
52–53. M. R. Hill
54. R. S. Holcomb
55. J. M. Holmes
56. J. R. Horton
57. J. K. Huffstetler
58. R. R. Judkins
59. J. R. Keiser
60. J. F. King
61. J. J. Kurtz
62. S. Y. Lee
63. C. J. Long
64. R. E. McDonald
65. J. W. McEnerney
66. R. W. McClung
67. L. E. McNeese
68. R. K. Nanstad
69. T. W. Pickel
70. W. R. Reed
71. H. E. Reesor
72. J. E. Selle
73. S.P.N. Singh
74. G. M. Slaughter
75. J. H. Smith
76. W. J. Stelzman
77. J. O. Stiegler
78. R. W. Swindeman
79. V. J. Tennery
80. O. W. Thomas, Jr.
81. B. T. Thompson
82. T. N. Tiegs
83. W. C. Ulrich
84. P. J. Walsh
85. F. W. Wiffen
86. W. R. Williams
87. R. W. Balluffi (Consultant)
88. A. L. Bement, Jr. (Consultant)
89. W. R. Hibbard, Jr. (Consultant)
90. E. H. Kottcamp, Jr. (Consultant)
91. M. J. Mayfield (Consultant)
92. J. T. Stringer (Consultant)

EXTERNAL DISTRIBUTION

93–95. DOE OFFICE OF FOSSIL ENERGY, 20 Massachusetts Avenue, N.W., Washington, D.C. 20545

W. T. Bakker
S. J. Dapkunas
John Fairbanks

96. DOE OAK RIDGE OPERATIONS OFFICE, P.O. Box E, Oak Ridge, Tennessee 37830

Assistant Manager, Research and Development

97–393. DOE TECHNICAL INFORMATION CENTER, OFFICE OF INFORMATION SERVICES, P.O. Box 62, Oak Ridge, Tennessee 37830

For distribution as shown in TID-4500 Distribution Category, UC-90 (Coal Conversion and Utilization); UC-90c (Coal Gasification); and UC-90h (Materials and Components).