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Assessment of Materials Technology for Gasifier and Reaction Pressure Vessels and Piping for Second Generation Commercial Coal Conversion Systems

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METALS AND CERAMICS DIVISION

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ABSTRACT

The current technology of the materials, fabrication, and inspection of pressure vessels and piping for commercial coal conversion systems is reviewed. Comparison is made between the various codes applicable to these conversion systems. Areas of concern, such as material compatibility and fracture toughness, are cited. Recommendations are made that should increase the reliability of these components, the failure of which would result in a major outage of the plant.

SUMMARY AND RECOMMENDATIONS

Design of Pressure Vessels and Piping for Coal Conversion Systems

Since the prospective coal conversion industry is composed largely of participants currently active in the petrochemical and energy sectors of the economy, one would anticipate that the modus operandi of these industrial sectors would significantly influence the development of coal conversion technology. In this regime of operation, proprietary interests exercise a profound influence on technological interchange. With such competition, few direct forums exist, and, therefore, such paths as trade and professional societies and publications provide the primary channels of communication other than the direct sale by licensing of technological innovations. The most significant path of technological interchange is probably the solicitation of opinion from such professional groups as the ASME and the PVRC. Individual members of such societies indirectly provide the bias for proprietary interests, and a consensus opinion developed from such sharply conflicting interests should provide a reasonable ordering of activities in the national interest.

Historically, this latter type of forum has had the most significant influence on pressure vessel and piping code changes and in the development of technical information to permit these changes. Therefore, we recommend the continuation of this type of technical interaction in the resolution of the controversial issues discussed herein.

The advent of DOE (and such prior government agencies as OCR and ERDA) financing and the Electric Power Research Institute programs presume a common base sharing of technological developments in the national interest. The participation of these organizations in the research and development of materials for coal conversion systems provides the vehicle for the rapid dissemination of information via reports published in the open literature and public information meetings.

We believe that to date most of the current studies of various competing processes have emphasized the capital cost aspects to show potential competition with other energy sources but have not adequately examined the influence of design features on both potential maintenance and disruptive failure costs. It appears, for example, that the choice of vessel size (which is dictated by single vs multiple train process designs) has been examined primarily from the standpoint of capital costs. Maintenance, operation, relative part load capability, and relative probability of failure are unanswered questions.

We believe that, although coal conversion plants are conceived as nominally steady-state operations, fatigue is a valid consideration because of hydrodynamic, chemical reaction kinetics, process control, and thermal interaction effects. Interaction between vessel internals and shells and between refractory linings and vessel shells and piping under fatigue loading conditions can lead to far more serious maintenance costs than are currently assumed. In addition, loss of refractory protection presents a particularly serious question for shells fabricated from quenched and tempered steels for which local hot spots have devastating effects on mechanical properties.

The materials having the most favorable mechanical properties and costs, unfortunately, are sensitive to various embrittling phenomena, as discussed in Chapters 3 and 4. In order to assess the reliability of vessels made from such materials adequately, the principles of fracture mechanics should be employed. However, as discussed in Chapter 4, much of the basic materials fracture toughness data have not yet been determined.

As has been discussed, the framework for implementation of design upgrading, except for the legal status of the ASME Code in most states, is dependent upon industry enlightenment rather than legal mandate. The authors believe that the foregoing recommendations are important considerations and should be incorporated as an objective in DOE-sponsored activities.

Material Compatibility Considerations

Historically, reviews of compatibility experience developed in related industries have been found to be invaluable in identifying potential problems in new industries such as coal conversion. In this vein, Chapter 3 briefly reviews the compatibility problems found in complex industrial systems similar to coal conversion systems. Hydrogen degradation, high-temperature sulfidation, aqueous-phase attack, erosion, and stress-corrosion cracking are identified as potentially significant compatibility problems in the proposed advanced coal conversion systems. In a broad sense, these problems are shown to be solvable; however, this chapter emphasizes that these solutions often result in significant economic penalties. This analysis also identifies several areas where compatibility information previously derived from industrial experience and/or laboratory experiments may not be valid under the anticipated operating conditions of proposed coal conversion systems. As a result, recommendations have been made indicating those areas where additional data are needed.

Since the above observations and recommendations are made primarily as a result of comparative analysis of compatibility problems in similar systems, it must be emphasized that the use of this type of analysis has often failed to identify serious compatibility problems in other complex systems. Therefore, an additional conclusion that can be drawn from this chapter is that efforts to characterize the operating conditions of coal conversion systems must be accelerated.

Several recommendations are made relative to areas where additional engineering and design data are needed. The following is a summary of those recommendations.

1. Alloy selection criteria for materials service in high-pressure, high-temperature hydrogen environments are dependent on the Nelson curves. Experimental evidence suggests that trace-element impurities, applied and residual stresses, and variation in microstructure may alter the response of materials to hydrogen attack. Cursory analysis of coal conversion pressure vessel designs indicates that structural materials will have through-thickness variations in microstructure. Moreover they will be carrying relatively high stresses (as a result of being designed to the requirements of Division 2 of Section VIII of the ASME Pressure Vessel Code) and will be exposed to hydrogen environments containing high

levels of H_2S. In view of these factors, testing is needed to substantiate that the Nelson curves accurately describe the behavior of structural materials in these proposed coal conversion environments.

2. Short-term data are available which show that exposure to high-temperature hydrogen environments alters the stress-rupture, crack growth, fatigue, and impact properties of structural materials. As a result, long-term test data in hydrogen are needed to assess the long-term reliability of these properties for structural materials.

3. Vessel and piping materials used in coal conversion systems will be exposed to moderate-temperature sour gas and sour liquid environments. Current design information describing crack growth rates and fatigue properties of engineering materials in these environments is empirical. The behavior of these candidate materials in sour gas and sour liquid environments requires additional investigation.

4. The petrochemical industry has recently reported catastrophic failures in piping systems used to pump sour liquids. In each case these failures were associated with piping locations subject to high velocities or turbulent conditions. Since previous investigations of these piping materials in static environments maintained at similar temperatures and pressures showed little corrosion response, these failures illustrate the impact of erosion-corrosion interactions. Despite the extensive static testing of candidate coal conversion materials in a variety of aqueous environments, the above observations indicate the urgent need to evaluate erosive-corrosive interactions in these environments.

5. Initial screening tests of candidate materials in sour water environments thought to be representative of gas scrubber and ash quench systems suggest that only stainless steel and highly alloyed materials have acceptable rates of corrosion in these environments. In view of the cost impact of using these materials in commercial-size plants, quantitative studies to identify inhibitors and/or surface coatings that will improve the corrosion resistance of low-alloy steels in gas scrubbers and ash quench environments are urgently needed.

Material Properties

In the course of reviewing the current technology of the materials that are candidates for use in fabricating large thick-walled coal conversion pressure vessels and piping, the authors note the need for additional information. Our primary concern lies in the nonconservative approach taken in the Code toward the toughness requirements for pressure vessels, particularly in view of the size suggested in a number of conceptual designs recommended by architect-engineer firms. The vessel sizes proposed are larger in diameter, height and weight by a factor of 3 to 4 than any that have previously been fabricated. The Section VIII, Divisions 1 and 2, toughness requirements are inadequate for pressure vessels that are as large as those being proposed and that have wall thicknesses that approach 0.3 m (12 in.). A 20-J (15-ft-lb) Charpy V-notch requirement at the lowest operating temperature does not guarantee that thick sections will not fracture in a brittle mode at considerably higher temperatures. Furthermore, the information available concerning the relationship between flaw size, stress, and temperature for many of the candidate materials is minimal. This information, if gathered under the fracture mechanics concepts, would permit a quantitative assessment of the possibility of failure of thick-walled components. This baseline information is required for the large, thick-walled pressure vessel and juxtaposed piping materials that are candidates for the fabrication of commercial coal conversion system components. The authors' specific recommendations are as follows:

1. Develop elastic (K_{Ic}) and elastic-plastic and plastic (K_{Icd}, J_{Ic}) fracture toughness data for the candidate materials for commercial coal conversion systems. Among the types of materials that should be investigated are:

   a. SA 516 Grade 70
   b. SA 387 Grade 22 Class 2

c. A 543 Type B Class 1
d. A 312 (Grades TP 304, 310, 316 and 347)
e. B 407 (Grade 800)
f. A 451 (CPK 20)

These studies should include the determination of the crack arrest (K_{Ia}) and dynamic fracture toughness (K_{Id}) properties of these materials, including the influence of processing history, such as welding and postweld heat treatments. The data for the ferritic materials will complement those previously obtained for SA 533 Grade B Class 1. The SA 516 Grade 70 represents the plain carbon steel class, SA 387 represents a corrosion- and hydrogen-resistant class, and A 543 represents a high-strength steel grade that may be a future pressure vessel steel candidate. Attention must, of course, be paid to the relationship between these higher strength steels and H_2S attack. The A 312, B 407, and A 451 materials represent various high alloys that are candidates for piping components.

2. Determine the separate and synergistic influences of temperature, stress, *and* environment on the sensitivity of these candidate materials and weldments to loss of toughness during service. This investigation will include both the shift in transition temperature and the loss of uppershelf energy, a behavioral pattern that can have considerable influence on the reliable operation of a pressure vessel.
3. Determine the separate and synergistic influences of temperature, stress, and environment on the crack growth rate of candidate base metals and weldments (e.g., hydrogen-assisted crack growth at various temperatures). These data will be used as the basis for making a probability analysis of the reliability of the large thick-walled pressure vessels and piping in a commercial facility.
4. An investigation should be conducted to determine the effect of metallurgically bonding a dissimilar metal to a pressure-retaining component. This investigation would include the effect of the joint on embrittlement and crack growth rate as a consequence of extended service at probable [340°C (~650°F)] operating temperatures. Of particular concern is the sensitivity of the bond (weldment in most instances) to defect formation during fabrication and service and the role of these defects (crack propagation sites) on crack growth and containment reliability.

Fabrication

Large, thick-walled pressure vessels for coal conversion applications will be constructed from carbon or low-alloy steels such as SA 516 Grade 70; SA 387 Grade 22, Class 2; SA 533, Grade B, Class 1; and, perhaps in the future, SA 543, Type B, Class 1. The procurement practices and general forming technology for plates of these materials are described, as are the industral practices for procurement of large forgings of similar composition. Brief descriptions of the principal welding processes for making long seams in the fabrication of vessels are provided, and the welding of nozzles to these vessels is discussed. The factors influencing the general weldability of the steels are noted.

The influence of preheat and postweld heat treatment on heavy-section weld properties is described. The cladding of the steels with corrosion-resistant alloys such as stainless steels is discussed, including such methods as roll-cladding, braze-bond cladding, explosion-cladding, and weld metal overlaying. Field fabrication technology for very large vessels is also described.

Manufacturing procedures for fabricating large pipe (wrought, welded, and cast) are presented, and a discussion of the welding processes, joint designs, and equipment for producing butt welds in this pipe is provided. Conventional procedures for producing dissimilar-metal transition welds in pipe are described.

As a result of this survey, it appears that additional development is needed in several areas of welding technology, notably the following:

1. The need for highly reliable, yet economically viable, large field-fabricated vessels will require the development of improved methods and procedures for welding main seams and nozzles under the adverse conditions to be encountered in field construction.
2. The further adaptation of the high-deposition-rate gas metal-arc welding process (and its narrow-gap modification) for the welding of pressure vessels appears warranted. The potential for out-of-position application makes it attractive for both shop and field usage.
3. The weld cladding of pressure vessel steels with corrosion-resistant alloys, such as Alloy 20, is difficult to deposit without microfissuring, and special cladding techniques will be required.
4. The welding of dissimilar metals is a recurring problem of considerable magnitude, particularly when thermal cycling at elevated temperatures (in the creep range) is encountered. As soon as the specific materials combinations to be utilized are identified, welding development programs aimed at producing high-reliability joints should be initiated.

Nondestructive Testing

An extensive (but not exhaustive) survey has been conducted of the state of the art, problems, and concerns related to nondestructive examinations (NDT) of pressure vessels and piping systems in coal conversion plants. The findings have been divided into the following major sections: (1) flaw detection during manufacturing, (2) major concerns or problems common to both pressure vessels and piping systems, (3) major concerns or problems peculiar to pressure vessels, (4) major concerns or problems peculiar to piping systems, and (5) in-service inspection. Interspersed throughout are comments regarding the pertinent codes and the need for upgrading.

Although NDT has played a valuable role in assuring product integrity, improvements are needed in order to provide the necessary reliability for coal conversion plants and their stringent operating conditions. Recommendations are integrated in the body of the report along with discussions of the problems and concerns. Included among the recommendations are greater implementation of personnel training and certification, upgrading of codes for more definitive procedures and realistic acceptance criteria, and improved inspection technology. Included in the improved inspection technology recommendations are development of more reproducible, quantitative NDT techniques; increased applications of computers in NDT; improved calibration and interpretation techniques; better ultrasonic techniques for thick-section welds; improved NDT techniques and equipment for field-erected vessels; ultrasonic techniques and equipment for high-speed ultrasonic examination of piping welds (including austenitic stainless steels); and development of equipment and techniques that will be applicable in limited-access, high-temperature environments for both continuous and interim monitoring and for in-service inspection to detect loss of integrity due to service.

The authors recognize that through an even more extensive survey additional problems and needs would probably be uncovered. Accordingly, this report should be recognized as a first-effort, interim document with a need for review and continual updating. Attainment of practical solutions of the problems described should afford improvements in the safety, integrity, and reliability of coal conversion systems.

1. INTRODUCTION

1.1 Scope and Basic Considerations*

The pressure vessels and piping have been frequently cited as some of the more important considerations in the successful commercialization of coal gasification and liquefaction processes. The National Academy of Sciences, in their discussion[1] of materials problems, identified "...the severe service conditions upon pressure vessels, pumps, valves, heat exchangers and piping and power conversion components at the combustion interface." They also specifically mentioned "...the unknown long-term reliability of pressure vessel shells...."

J. S. Clarke, of the Esso Research and Engineering Company, put the concern for pressure vessels in the proper perspective in an article[2] in which he discussed the role of the ASME Code in vessel design and fabrication. He mentions that, although Esso has had good experience with pressure vessels and similar equipment, there have been a significant number of actual pressure vessel failures.

The importance of the reliable service of a pressure vessel is evident, particularly when the consequence of its failure is considered. Table 1.1 is a list of components of typical coal conversion systems. Most of the components listed can be replaced with varying degrees of difficulty; the failure of a pressure vessel will, however, cause a major plant outage, as the Federal Energy Administration recognized when they cited[3] a five-year lead time for the acquisition of large pressure vessels.

*This section was prepared by G. C. Robinson and D. A. Canonico.

Table 1.1. Effect of failure of various components on plant availability

Component	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

This assessment of the technology of materials for pressure vessels and piping for coal conversion systems was prepared at the request of the Coal Conversion Division of the U.S. Department of Energy. This document concentrates on the materials, fabrication, and inspection of the gasifier and reactor pressure vessels and juxtaposed pressure-boundary piping that will be required for commercial second-generation coal conversion systems. Design is considered only insofar as it affects the material aspects of pressure-containing vessels and piping. This assessment is especially directed at the extremely large-diameter thick-walled monolithic pressure vessels and associated piping that are proposed in many of the designs suggested by architect-engineering (A-E) firms involved in the commercialization of coal conversion concepts.[4] The conceptual designs for some of the commercial systems require pressure vessels larger than any previously built in the world. The catastrophic failure of one of these components could literally devastate the entire plant. It is hoped that this assessment will, in some part, minimize the probability of the occurrence of such an event.

There are a number[5] of different coal conversion processes under consideration for producing synthetic fuels and gases. Each has a somewhat different combination of temperature and pressure requirements and, in some instances, totally different process environments (see Tables 1.2 and 1.3). Moreover, within any one individual process, there are operations requiring pressure containment components that are widely diverse in their material property requirements. Because of these differences, this document will not address a specific coal conversion system but, rather, will present general discussions regarding the large thick-walled vessels typified by the second generation gasifiers and will concentrate on the requirements of the containment components that are subjected to the extremes of pressure, temperature, and process stream environment.

The authors of this assessment have prepared this document as a critique of technology to serve as a preventive to potential problems. The resulting somewhat negative tone is obviously not intended as an indictment of the petrochemical industry, since we recognize that the petrochemical industry has historically provided leadership in solving many similar problems in developing the technology. We are also aware that the problems we cite are recognized by the foremost petrochemical companies, fabricators, and A-Es and that considerable efforts are under way to provide solutions. However, we believe that the new direction in our nation's energy policy to utilize coal increasingly will inevitably attract firms and personnel into the emerging coal conversion industry who will not have an adequate understanding of these problems. Primarily, then, this document is intended to be tutorial for such firms and individuals, and consequently it may be excessively pedagogic to prominent, informed firms and individuals, whom it may only serve as a summary of the important technological considerations to the extent of the authors' awareness of the pertinent literature and activities. Of course a considerable body of information relating to environmental effects exists only in proprietary form and is therefore unavailable for this assessment.

A document such as this, although directed toward a restricted subject, nevertheless involves a broad spectrum of technology and, consequently, requires some ground rules in its preparation. It is the intention of the authors that this chapter should provide the background for the subsequent chapters.

The first subject to be discussed, economics, is often foremost in the commercialization of any new industry. Indeed, the history of coal conversion dates back to the mid 1800s, although the subsequent availability of cheap oil and gas made conversion economically unattractive in the United States. The economic practicability of coal conversion is an area that will not be considered. However, general economic influences will be discussed.

Table 1.2. Gasification processes for substitute natural gas[a]

Process	Temperature		Pressure	
	°C	°F	MPa	psi
Agglomerating ash				
Combustor	1093–1149	2000–2100	0.7	100
Gasifier	982	1800	0.7	100
ATGAS-PATGAS	1371	2500	0.4	50
BIGAS				
Upper stage	927	1700	6.9–10.3	1000–1500
Lower stage	1482	2700	6.9–10.3	1000–1500
CO_2 Acceptor				
Gasifier	816	1500	1.0–2.1	150–300
Regenerator	1038	1900	1.0–2.1	150–300
Electrofluidic gasification				
Fluidized bed	816	1500	10.3	1500
EXXON gasification				
Gasifier	816–927	1500–1700	0.2–0.3	25–45
Char heater	927	1700	0.2–0.3	25–45
Hydrane				
Hydrogenation	899	1650	6.9	1000
H_2 generator	982–1038	1800–1900	6.9	1000
HYGAS				
Slurry vaporizer	316	600	6.9–10.3	1000–1500
Hydrogasifier	704–982	1300–1800	6.9–10.3	1000–1500
Koppers-Totzek				
Entrained fuel	1816	3300	0.1	15
Liquid-phase methanation				
Catalytic	338	640	3.4	500
Lurgi				
Fixed bed	616–760	1140–1400	2.4–3.1	350–450
Molten-salt				
Catalytic/Na_2CO_3	999	1830	2.9	420
Multiple catalyst	649–704	1200–1300	6.9	1000
Synthane	982	1800	6.9	1000
Wellman-Galusha	649	1200	0.1	15
Winkler				
Fluidized bed	982	1500–1800	0.1	15

[a]Source: J. Howard-Smith and G. J. Werner, *Coal Conversion Technology*, Noyes Data Corp., Park Ridge, N.J., 1976, p. 115.

1.2 Economics

In the broad sense, the question of economics is not an issue in this assessment of the pressure vessel and piping technology. Indeed, the question of whether a coal conversion system, or for that matter, whether the entire technological concept of coal conversion is economically practicable will not be addressed. Economics, however, in areas such as the selection of codes and standards, material selection, plant size and location, and philosophy of operation, will influence decisions that have an impact on pressure vessels and piping that are employed in a coal conversion system. Hence, economics is a multifaceted consideration in the design, fabrication, and operation of a viable coal conversion system. A number of areas are identified in this assessment that are governed primarily

Table 1.3. Processes for liquid-solid and gaseous products[a]

Process	Temperature		Pressure	
	°C	°F	MPa	psi
Clean coke				
Carbonization	649–760	1200–1400	0.7	100
Hydrogenation	482	900	20.1–27.6	3000–4000
Coalcon				
COED				
Fluidized bed	316–816	600–1500	0.04–0.07	5–10
Catalytic fixed bed	390	750	17.2–21.4	2500–3100
COG				
Sol-hydrogenation	454	850	6.9	1000
Gasification section	1649	3000	1.4	200
COGAS				
Fluidized bed	316–816	600–1500	0.04–0.07	5–10
Catalytic fixed bed	399	750	17.2–21.4	2500–3100
Gasifier-combustor	816–927	1500–1700	0–0.2	0–30
Consol synthetic fuel				
Extractions	407	765	1.0	150
Carbonization	496	925	0.07	10
Hydrotreatment	427	800	20.1	3000
Costream				
Stirred extraction	427	800	27.6	4000
EXXON				
Solvent extraction	399	750	2.4	350
Catalytic hydrogenation	427	800	13.8	2000
Fischer-Tropsch synthesis				
Arge fixed-bed	232	450	2.5	360
Kellogg fluidized bed	327	620	2.3	330
Garretts coal pyrolysis				
Pyrolyzer	593	1100	0.1	15
Char heater	649–871	1200–1600	0.1	15
H-Coal				
Catalytic ebullated bed	454	850	15.5–18.6	2250–2700
Lurgi-Rubigas				
Flash-carbonizer	593	1100	0.1	15
Methanol synthesis				
Catalytic	260	500	5.2–31.0	750–4500
Project lignite (SRL)				
Extraction/Hydrogenation	399–449	750–840	10.3	1500
Solvent extraction-U.O.P.				
Solvent extraction	399–449	700–1000	3.4	500
SRC-PAMCO				
Dissolver	435	815	6.9	1000
Synthoil				
Catalytic fixed-bed	454	850	13.8–27.6	2000–4000
Toscoal				
Pyrolyzer	427–538	800–1000	0.1	15

[a]Source: J. Howard-Smith and G. J. Werner, *Coal Conversion Technology*, Noyes Data Corp., Park Ridge, N.J., 1976, p. 105.

by technical consideration but have secondary implications that are controlled economically. These include, assuming that a coal conversion concept has been selected, the choice of code to which the component will be designed and built.

Historically[6] the petrochemical industry has tended to work with Section VIII, Division 1, of the ASME Boiler and Pressure Vessel Code (ASME Code). Some of the proposed commercial coal conversion systems, however, require large pressure vessels, which make Section VIII, Division 2, more attractive. It has been suggested that Division 2 should be used for vessels for servere service that have wall thickness greater than 5.1 cm (2 in).[7] The ability to employ thinner section sizes in Division 2 often offsets the additional quality assurance costs and makes this code economically attractive.

The role of economics continues beyond the code design consideration. For example, once a code has been selected, then a number of materials may be available for use in the fabrication of the pressure vessel and piping. The material choice is dependent upon the allowable stresses at the design temperature *and* upon the experience and expertise of the designer in regard to the behavior of the materials under the conditions and environments of his system. Economics may dictate that a thicker-walled vessel may be more practical, because of cost, availability, and ease of fabrication, than one fabricated from thinner-walled, more environmentally resistant materials. Design, material selection, and the influence of environment on these considerations will be discussed in more detail in subsequent sections of this report.

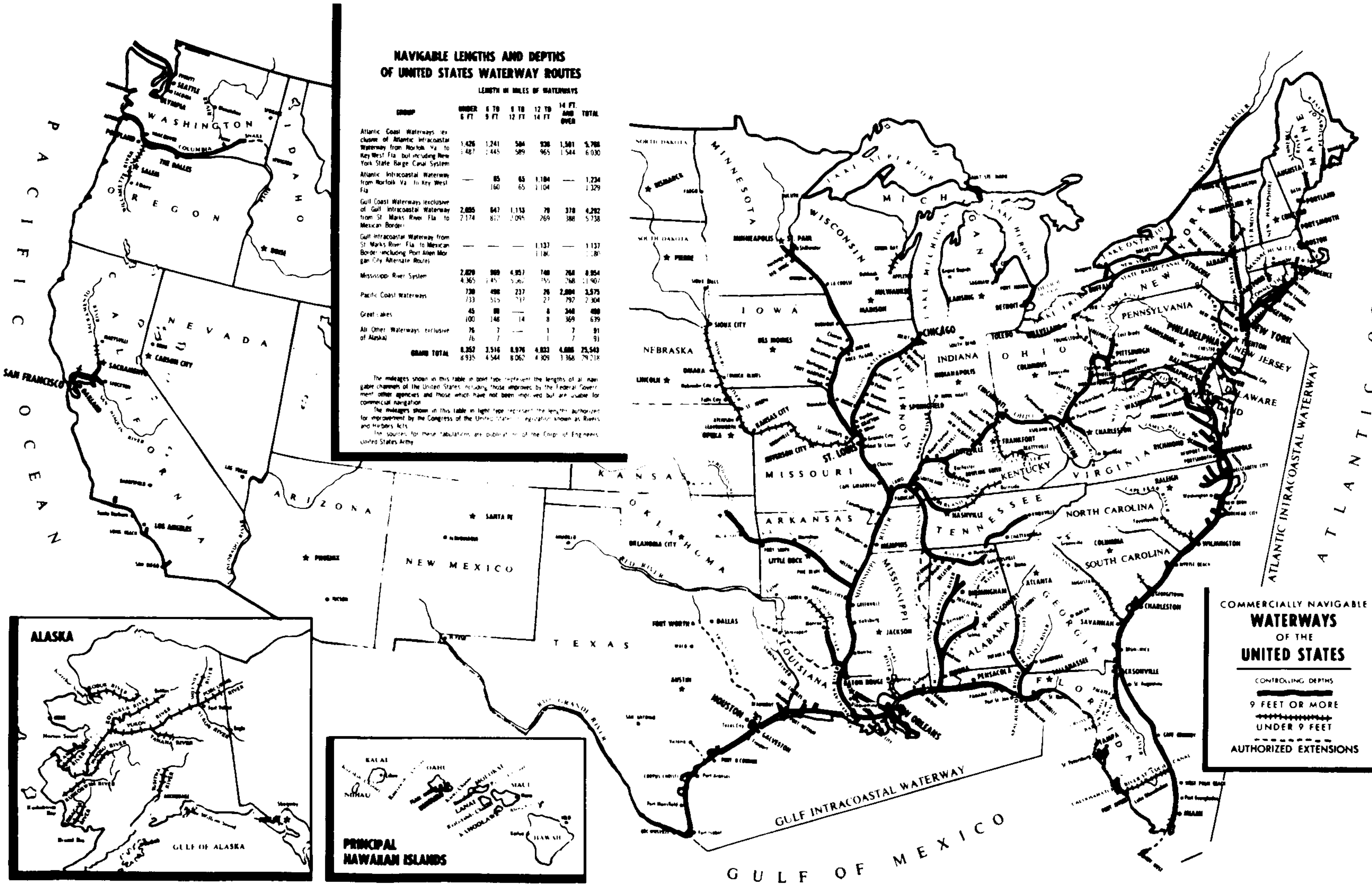
In addition to the primary considerations of design, material selection, and process environment, there are other equally constraining economic considerations. These are related to fabrication procedure and component transportation. The dimensions of pressure vessels that can be transported by railroad are limited[8,9] to 14 ft in diameter and 800 tons in weight. Lengths of about 100 ft have been reported.[7] The shipment of large pressure vessels by barge removes the size and weight constraints imposed by railroad transportation, but 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. Navigable waterways, however, are restricted mainly to the eastern United States. Figure 1.1 shows the waterways of the United States,[10] and it is evident that 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 modes of transportation. In summary, the size of pressure vessel that can be shop fabricated is dictated by the coal conversion plant site. If the site is not accessible to a navigable waterway, then a choice must be made between conversion processes based on a multitrain concept, which would allow the use of pressure vessels of 14 ft in diameter and less, or large field-erected vessels. The advantages and disadvantages of shop vs field fabricated components will be discussed in Chapter 6 of this assessment.

In conclusion, the role of economics must be considered in the design, siting, and fabrication of pressure vessels and piping for coal conversion systems. A number of examples of the necessity for considering economics have been provided, but these are not intended to be inclusive.

1.3 Codes and Standards

1.3.1 General

Much of the technology existent in the petrochemical industry has been utilized in the conceptualization of coal conversion systems. The limited number of A-Es that we contacted assumed in the development of demonstration plant or full-scale plant studies that the standards and



NAVIGABLE LENGTHS AND DEPTHS OF UNITED STATES WATERWAY ROUTES

GROUP	LENGTH IN MILES OF WATERWAYS: 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. but including New York State Barge Canal System	**1,426** 3,487	**1,241** 2,445	**504** 589	**938** 965	**1,501** 1,544	**5,708** 6,030
Atlantic Intracoastal Waterway from Norfolk, Va. to Key West, Fla.	—	**85** 160	**65** 65	**1,104** 1,104	—	**1,234** 1,329
Gulf Coast Waterways (exclusive of Gulf Intracoastal Waterway from St. Marks River, Fla. to Mexican Border)	**2,085** 2,174	**647** 812	**1,113** 2,095	**78** 269	**378** 388	**4,282** 5,738
Gulf Intracoastal Waterway from St. Marks River, Fla. to Mexican Border (including Port Allen-Morgan City Alternate Route)	—	—	—	**1,137** 1,180	—	**1,137** 1,180
Mississippi River System	**2,820** 4,365	**909** [illegible]	**4,957** 5,067	**740** [illegible]	**268** 268	**8,954** 11,907
Pacific Coast Waterways	**730** 733	**498** 515	**237** [illegible]	**26** 27	**2,084** 797	**3,575** 2,304
Great Lakes	**45** 100	**[illegible]** 148	— 14	**8** 8	**348** 369	**480** 639
All Other Waterways (exclusive of Alaska)	**76** 76	**7** 7	—	**1** 1	**7** 7	**91** 91
GRAND TOTAL	**8,352** 8,935	**3,516** 4,544	**8,976** 8,062	**4,033** 4,309	**4,086** 3,368	**25,543** 29,218

The mileages shown in this table in bold type represent the lengths of all navigable channels of the United States including those improved by the Federal Government, other agencies, and those which have not been improved but are usable for commercial navigation.

The mileages shown in this table in light type represent the lengths authorized for improvement by the Congress of the United States in legislation known as Rivers and Harbors Acts.

The sources for these tabulations are publications of the Corps of Engineers, United States Army.

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Fig. 1.1. Waterways of the United States.

codes utilized in the petrochemical industry can be adopted to coal conversion systems. Such transferrence obviously presumes not only that the technical requirements are virtually identical but also that the economic constraints and safety policies would require the same quality of equipment. We support the utilization of existing codes as valid for the emerging coal conversion industry. Where criticisms of the codes are made with respect to application to the coal conversion industry, the authors support the view that practical solutions are best obtained via the forum of industry-codes-standards-government-regulations interactions that have been traditionally employed.

1.3.2 Pressure vessel codes

In recent years the development of the light-water nuclear reactor industry has led to extensive modification of vessel and piping code requirements. Early nuclear reactor vessels were generally based on utilization of the ASME Section I or Section VIII Codes for pressure vessels and the ANSI B31.1 Standard for piping systems. In the intervening years, as technology of nuclear systems matured, ad hoc codes were prepared specifically for nuclear systems by several professional societies. Although these standards were developed primarily to define a quality assurance or degree of reliability acceptable to the nuclear industry, it became evident that some of these new codes, particularly the ASME Nuclear Pressure Vessel Code, Section III, could have application to users other than the nuclear industry, because of the potential cost savings afforded by the higher allowable stresses. An outgrowth of this realization has been the partitioning of the old ASME Section VIII rules such that, at present, petrochemical vessels may be built either according to ASME Section VIII, Division 1, or ASME Section VIII, Division 2.

To some degree the potential cost savings afforded by Division 2, compared with Division 1, by thinner-walled, lighter vessels is offset by the increased cost of more rigorous rules of analysis and inspection. The application of ASME Section VIII, Division 2, has heretofore quite understandably been a matter of considerable debate.[6] Our contacts with some of the A-Es[11–14] involved with studies and designs of coal conversion systems left us with the impression that these A-Es have not subscribed to the view that real differences exist between the reliabilities of Division 1 and Division 2 vessels. This viewpoint seems credible because these A-Es often perform stress and fatigue analyses and impose quality assurance measures on Division 1 vessels that are mandatory for Division 2 vessels. Consequently, when this philosophy is consistently adhered to, life of a vessel or piping system is more a function of environment rather than of whether Division 1 or Division 2 rules are applied. For the A-Es interviewed, because of their considerable imposition of quality standards beyond the minimum required, choice is largely premised on initial capital costs.

An assessment by Cooper and Langer[15] of various reliability studies[16–18] on ASME Code vessels concludes that nuclear vessels designed and constructed in accordance with Section III and operated according to Section XI should experience between 10^{-6} to 10^{-7} disruptive failures per year compared with 10^{-5} for nonnuclear vessels designed and constructed according to Section I or Section VIII, Division 1. Correspondingly, Section VIII, Division 2, vessels (like their counterpart Section III nuclear vessels) should have a more favorable reliability potential if the same degree of relative quality were to be imposed on coal conversion vessels as for the vessels studied by Cooper and Langer.[15] If economic or other factors should lead to a large utilization of vessels meeting the rules of Division 1 and others meeting those of Division 2 as minimum standards, and without imposition of additional quality measures, their study strongly implies that significant differences in reliability will occur between vessels built to Division 1 and those to Division 2 rules.

As noted previously, some A-Es premise their selection of Division 1 or Division 2 of Section VIII of the ASME Code primarily on the basis of initial cost. Some A-Es perform capital cost-scoping studies of vessels, comparing Section VIII, Division 1, against Division 2 at an early stage of conceptual evaluations. In such cases, it is generally found that the break-even point in cost occurs with large, heavy thick-walled vessels or with vessels having complex geometries.[19-24] In addition, systems employing pressures greater than 2.1×10^7 Pa (3000 psig) are excluded from Section VIII, Division 1, usage [U-1(b)] (above 3000 psig, requirements over and above those listed in the Code must be considered) but are permitted under Section VIII, Division 2 (par. A110).

As is well known, in the early 1900s catastrophic pressure vessel failure and consequent loss of life were very common. The major factor in the correction of these wasteful and tragic occurrences was the publication of the first edition of the ASME Boiler Code in 1914. The ASME Code has since undergone a remarkable development utilizing the expertise available from diverse backgrounds (e.g., manufacturers, users, systems designers, A-Es, consultants, insurance underwriters, and regulatory authorities). The Code is intended to provide minimum requirements for safe operation and, in general, components and vessels built to Code rules have been reliable. As a result of this experience, "code" vessels have come to be viewed as the standard of quality. An outgrowth of this confidence has been the adoption of the ASME Boiler and Pressure Vessel Code as a legal requirement in most states of the United States, in many of the large cities, and in many of the provinces of the Dominion of Canada. Table 1.4 provides a current listing of the jurisdictions requiring the application of the ASME Code to boilers and pressure vessels.

Although various jurisdictions have adopted the ASME Code, they have not defined the applicability of Division 1 vs Division 2. This decision rests with owner as delegated to the A-E. Another interesting facet of the information in Table 1.4 is the absence of several states that are leading coal producers in the western region of the United States. In such instances the reliability and safety of plants are obviously dependent upon the integrity and sound engineering judgment of the user, his A-E, his construction contractors, etc., in the application of code rules which are not legally required.

1.3.3 Piping codes

In our contacts with A-Es involved with coal conversion systems, we found a uniform judgment that the American National Standard Code for Pressure Piping, ANSI B31.3, "Petroleum Refinery Piping," should be applied to coal conversion systems. For plant complexes that incorporate electric power generation stations, the Power Piping Code, ANSI B31.1, would be applied. ANSI B31.4, "Liquid Petroleum Transportation Piping Systems," would be used for the transport of refined liquid products from the coal conversion plant site to delivery points; similarly, ANSI B31.8, "Gas Transmission and Distribution Piping Systems," would be used for transmission of gas products from the coal conversion plant site to delivery points. This last standard includes the following precautionary note in the scope paragraph:

> . . .government agencies having jurisdiction may have issued regulations at variance with provisions of this Code. Where such a conflict exists, this Code does not apply.

This note is a reflection upon the fact that gas transmission standards are now covered by federal regulations that may or may not agree with ANSI B31.8.

ANSI standards are developed as voluntary codes by the consensus of the responsible committees. A strong effort is made to incorporate within each committee knowledgeable, experienced, capable people having a diversity of backgrounds with deliberate intent to provide

Table 1.4. National Board Survey of jurisdictions requiring the application of the ASME Code of Boilers and Pressure Vessels[a,b]

	National Board Members[c]		
Alaska	ASME/NB	North Carolina	ASME/NB
Arizona	ASME/NB	North Dakota	ASME/NB
Arkansas	ASME/NB	Ohio	ASME/NB
California	ASME/NB preferred	Oregon	ASME/NB
Colorado	ASME/NB	Pennsylvania	ASME/NB
Delaware	ASME/NB	Rhode Island	ASME/NB
District of Columbia	ASME/NB	Tennessee	ASME/NB
Hawaii	ASME/NB	Texas	ASME/NB
Illinois	ASME/NB (1-1-74)	Utah	ASME/NB
Indiana	ASME (under study)	Virginia	ASME/NB
Iowa	ASME/NB	Washington	ASME
Kansas	ASME/NB	West Virginia	ASME/NB
Kentucky	ASME/NB	Wisconsin	ASME/NB
Louisiana	ASME/NB	Chicago, Ill.	ASME/NB
Maine	ASME/NB	Detroit, Mich.	ASME
Maryland	ASME/NB	Los Angeles, Calif.	ASME/NB preferred
Massachusetts	ASME/NB	Memphis, Tenn.	ASME/NB
Michigan	ASME/NB	Milwaukee, Wisc.	ASME/NB
Minnesota	ASME/NB	Phoenix, Ariz.	ASME/NB
Nebraska	ASME/NB	San Francisco, Calif.	ASME/NB preferred
Nevada	ASME/NB preferred	Seattle, Wash.	ASME
New Jersey	ASME/NB	St. Louis, Mo.	ASME/NB
New York	ASME/NB		
	Canadian Members[d]		
Prov. of Alberta	ASME/NB	Prov. of Nova Scotia	ASME/NB
Prov. of British Columbia	ASME/NB	Prov. of Ontario	ASME/NB
Prov. of Manitoba	ASME/NB	Prov. of Prince Edward Island	ASME/NB
Prov. of New Brunswick	ASME/NB	Prov. of Quebec	ASME/NB
Provs. of Newfoundland and Laborador	ASME/NB	Prov. of Saskatchewan	ASME/NB

[a]Does not cover LPG vessels. Contact jurisdictions for LPG requirements.

[b]The National Board of Boiler and Pressure Vessel Inspectors is an organization charged with the legal enforcement of the ASME Code by the jurisdictions.

[c]ASME/NB or must use State Special procedure to ensure equivalent safety standards.

[d]ASME/NB or must use procedure of the Canadian province to ensure equivalent safety standards.

balance in areas where conflict and controversy are likely to occur. On the other hand, federal regulations are mandatory and have the obvious drawback of the tendency toward bureaucratic tyranny. Pandorf[25] has given a concise review of the relationship of the ANSI committees with other voluntary standards groups as follows:

> B31 is a committee operating under ANSI rules and falling under the surveillance of the ANSI Piping and Process Equipment Standards Management Board. Several people within the B31 activity are members of that ANSI board, so there is continuing liaison.
>
> B31 is administered by ASME, and is one of the Safety Code Committees which report directly to the ASME Policy Board, Codes and Standards. ASME Staff assignments and support for B31 activities fall under the authority of the ASME Managing Director, Research, Codes and Standards, and the Manager, Safety Code Committees.

Through the B31 Standards Committee and elsewhere in the B31 organization, there are effective liaison contacts with all of the major standards goups under ANSI, API, ASME, ASTM, AWS, MSS, NACE, NFPA, and others, all of which are references in the B31 codes.

B31 has developed close and effective liaisons with the Boiler Code in many areas. The most difficult and at the same time the most rewarding has been the coordination of power plant installations wherein the Boiler Code Section I covers the boiler up to the terminal connections, and the Piping Code B31.1 covers the power piping. This has always appeared logical, but was accomplished only after hard work and effective leadership by the committees involved. Other areas of liaison include materials, stresses, NDE, welding, metric conversion, and international activities.

In our contacts with industry, which have been by no means comprehensive, we found a strong, uniform reaction that voluntary standards are safe and economic and that the previously discussed ANSI mode of operation provides an adequate method for correction of deficiencies that come to light.

Styer and Wier[26] underscored the inquiry system used by the ANSI B31 committee in revising B31.3 to keep pace with the considerable technological changes that have occurred in the hydrocarbon processing industry in recent years. The 1973 edition of ANSI B31.3 contains sweeping changes in paragraph 302.3 entitled "Allowable Stresses and Other Stress Limits." Stress limits for ANSI B31.3 were changed to correspond to the then current edtion of ASME Section VIII, Division 2. Since creep range and elevated-temperature mechanical property data are not in Section VIII, Division 2, these data in ANSI B31.3 are, in most instances, based on Section VIII, Division 1. The lower-temperature data for ANSI B31.3-1973 roughly correspond to those set in the now inactive ANSI B31.7-1969 Nuclear Power Piping Code and in the active editions of ASME Section III for piping. Although the stress allowables were brought into conformance with nuclear piping, the analytical requirements do not differ, except in minor detail, from ANSI B31.1 Power Piping Code. This latter code generally follows the philosophy of ASME Section VIII, Division 1, both for stress allowables and for stress analysis.

ANSI B31.3 has been historically a progressive code, setting the pattern for its more conservative relative, ANSI B31.1. The 1973 edition of ANSI B31.3 and the more recent 1976 edition that combines ANSI B31.6, Chemical Plant Piping, with ANSI B31.3 for public review and comment have set higher stress allowables premised on the consensus that the accumulated experience justifies this liberalization. However, the quality measures and stress analysis requirements of the latest addition have not undergone any extensive revision. As noted by Langer,[27] considerable decreases in safety factors have occurred with time by various national codes (e.g., from 5 in the 1914 ASME Code to 2.4 in the 1970 ISO/TC11 Code) that have been based on experience rather than rational analysis of the materials' response to service loading. As further noted by Langer, the accumulated experience for these reductions as with any empirical result has the associated danger that it may be used in a place where it is not applicable. The trend in the ASME nuclear codes has been to offset the greater utilization of a material's mechanical strength and toughness with concurrent increased emphasis on quality assurance with regard to design, analysis, fabrication, and inspection. This philosophy has not been followed by ANSI B31.3, as will be examined in detail in Section 2.3.

ANSI B31.3 provides the petrochemical industry, and more recently the chemical industry, with what should be, on a first cost basis, a more attractive code than B31.1. Assuming the judgment of the committees is justified, no difference in reliability should be evident. To a degree, these speculations ignore the fact that voluntary codes are *minimum* standards and that, to a greater or lesser degree, users must add supplemental requirements. Clarke[28] emphasizes the need for supplemental requirements, as applied to vessels for petroleum service, citing particularly the need to consider corrosion, erosion, thermal transients or shock, environmental (e.g., hydrogen) deterioration, metallurgical aspects of crack initiation and growth, and testing and inspection requirements. Reputable fabricators are cognizant of these needs and often impose requirements beyond those of the codes.[29]

The experience obtained by the Cresap Pilot Plant, commissioned in May 1967 in support of the CONSOL synthetic fuel process, vividly illustrates the need for careful and thorough analysis and for supplemental requirements beyond code rules. During some 900 hr of operation, including 56 production runs, the facility was repeatedly shut down[30–33] as a result of mechanical malfunctions of vessel closures and piping flanges. Analyses by the Foster Wheeler Corporation[34] and by Fluor Engineers and Constructors, Inc.,[35] disclosed that the problems occurred because of inadequate analysis of the mechanical loads applied to the vessel closures and piping flanges and because of excessive temperature rates and gradients resulting from off-normal operation, operator error, equipment malfunction, control inadequacies, etc. As a consequence, Fluor[35] has proposed a comprehensive test program for a variety of these components to determine their capability for a test matrix incorporating pressure, temperature, and imposed mechanical loads.

1.4 Safety and Reliability Considerations

Safety and reliability considerations are inextricably intertwined with those of economics and code selection considered in the previous sections. Safety is the very fountainhead of our code rules for both pressure vessels and piping, and the implementation of these rules has, by long experience, been found to produce increased reliability and, consequently, greater economy. The principle of preventive maintenance, as implemented on vessels and piping systems by periodic in-service nondestructive and visual inspections and by corrosion surveillance programs, has been repeatedly demonstrated to be a prime objective of the operators of petrochemical plants.

On the other hand, economic consideration of the disruptive or catastrophic type of failure is a recent innovation to the petrochemical industry. Economic pressures have led to the design and development of equipment (pressure vessels and piping) of large size, providing increased production per unit capital cost and lowered product costs. This trend in scale-up to benefit from the capacity-cost relationship will, according to Cox,[36] have a cost deterrent due to decreased reliability and maintainability. In addition, the increased inventory of explosible and flammable materials associated with large-capacity production trains has tended to increase the losses associated with disruptive-type failures. Coffee[37] recently reported that the chemical industry has been subjected to radically upward adjusted insurance premiums because of a poor loss record. He further states that insurance companies are promoting the concepts of "Maximum Possible Loss" and "Maximum Probable Loss" and are encouraging the application of "Systems Analysis" or "Hazards Analysis" during the design stage of plants. He further believes that, based on the recent emphasis on social and ecological impact, resulting in the codification by federal regulations of the National Electric Code and the fire codes of the National Fire Protection Association, it will also be mandatory, in the future, to base plant designs on comprehensive hazards evaluation studies.

Several companies in the United States and England are using these types of studies and are reporting very favorable experience.[38–44] Systems analysis,[38–41] also termed "operability studies," "pre-start-up safety reviews," "pre-start-up safety checkouts," and "failure modes and effects analysis," utilizes a study team to make a rigorous, systematic, critical examination of the process, covering all phases of normal operation and abnormal operation and considering such items as chemical toxicities, reactivities, flammabilities, potential fire exposure, instrumentation and controls on critical process variables, design details, design layouts, safety systems, operating procedures, personnel training, etc. Generally, in order to avoid bias, the team members have had no previous association with the project. The primary responsibility of the team is to identify and rank qualitatively design inadequacies and potential safety problems. Hazards analysis, also termed "fault tree," is a quantitative safety assessment based upon the computer programs developed by the missiles and aerospace programs to achieve virtually defect-free hardware. Predicting loss rates by means of the fault tree techniques involves assuming potential failure events, estimating the consequences in terms of dollars or lives lost by the event, identifying precursor events that lead to the failure event, assigning probabilities to the events, performing the solution, and then obtaining reiterative solutions for varying designs or modified probabilities for the chain of events.

Fault tree analysis is relatively expensive,[41] and this disadvantage, coupled with the difficulty of formulating and predicting system behavior and in assessing chemical reactivity for all modes of operation, has discouraged its use in the past. A recent effort to overcome one of these disadvantages has been the development of the CHETAH code by the ASTM E-27 Committee,[45–46] which provides information on relation shock sensitivity of chemicals based only on molecular structural information using the methods of chemical thermodynamics. Other programs[46] based upon equilibrium thermochemistry and an index linking chemical thermodynamics and kinetics[47] are also available to yield predictions of chemical energy hazard potential. Reaction kinetics, reaction mass, specific environment conditions, and other factors are needed to determine the point at which a potential hazard becomes a real one.[46]

Directly related to disruptive failures, noncritical failures and normal plant effluents are the considerations of the industrial hygienist.[48–51] The passage of the Occupational Safety and Health Act of 1970 has obligated all employers in the United States to deal with the toxicity hazards associated with chemicals and with deleterious forms of energy in the work environment. It has been estimated that thousands of new chemicals are produced yearly by the chemical industry, and it is anticipated that the coal conversion industry will markedly add to this category, thereby including many chemicals of significant toxicological impact. A major environmental program[50] complementing the coal conversion development activities has been proposed to deal with the environmental impact problems. These considerations underscore the need for coal conversion systems to have vessels and piping systems of high integrity and noncritical-type failures.

A recent British study[51] assessed the failure history of some 12,700 vessels built to high standards, involving 100,300 vessel-years, for both disruptive and noncritical-type failures. The calculated failure rate, 1.25×10^{-3} per vessel-year, was based on 132 failures from cracks, primarily at branches and fillet welds, 47 from fatigue and 24 from corrosion. Only seven disruptive failures occurred, four of which resulted from maloperation. Rodabaugh[52] reviewed this survey, as well as other pertinent surveys, in a critical examination of failures of nonintegral nozzle reinforcing, as permitted by the ASME Code Section VIII, Division 1, and by ANSI B31.3. Although it was not possible to differentiate all the effects, it was observed that the toe of the fillet weld 90° from the run is a significant failure location probably due to a variety of reasons (high stress area from geometry, high local stresses, macroscopic cracks, metallurgical effects, etc.), leading to a pronounced sensitivity to fatigue. As noted by Bush,[18] the history of operation of these groups of vessels, having experienced a satisfactorily low failure rate, is strongly keyed to the frequency and adequacy of in-service inspections, the restoration of integrity, and the prevention of disruptive failures.

Doyle's assessment[53] of insurance losses in chemical plants from disruptive failures also emphasizes the need for critical and frequent in-service inspection. He noted that the major factor in the accidents associated with claims paid by the Factory Insurance Association from 1964 to 1968 was inadequate maintenance, followed by poor design or layout of equipment, with incomplete knowledge of the properties of the chemicals being handled. Doyle[53] also confirmed the observation of Cox[36] that some recently constructed large plants that were judged to constitute a large risk were unable to obtain adequate, or any, insurance coverage. Unofficial estimates of recent catastrophic disasters such as Flixborough,[54,55] England, and Pernis, Holland, have been $100,000,000 and $46,000,000 respectively, which is very high and does not include consideration of the loss of life, adverse public reaction, and unfavorable local economic impact.

The lessons that can be derived by the coal conversion industry from the petrochemical industry on safety and reliability are multifold and complex. Some of the principal thoughts that can be advanced are as follows:

1. Safety and reliability are inherently linked to the quality assurance aspects of coal conversion processes and are significantly influenced by factors in each stage of development of the process — conceptualization, process development, design, construction, and operation.
2. A proper balance of economics should include the effects of both noncritical and disruptive types of failures.
3. Codes of design and construction are minimum standards, susceptible to misuse, have varying degrees of quality, are viable in constitution, but tend to lag the needs of technology, and require tempered judgment in application.
4. Quality codes of design and construction are necessary factors but are an inadequate basis, alone, for a proper degree of safety and reliability (e.g., in-service provisions are equally critical issues).

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2. DESIGN OF PRESSURE VESSELS AND PIPING FOR COAL CONVERSION SYSTEMS*

2.1 Basic Design Considerations

An attitude common among technical disciplines is that design should be viewed from the limitations of a particular discipline's expertise. In reality, various features of pressure vessels and piping systems for coal conversion systems are influenced by the interrelated scientific and engineering disciplines, from the bench scale tests to the fabrication and installation of commercial components. 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 model craftsmen, fluid flow specialists, piping flexibility analysts, structural support analysts, and instrumentation and control specialists cooperate to define the interconnection routing and sizing of the piping, location of valving and instruments, mechanical joints, and 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 could become rather complex, because functions could be performed by 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.].

Consequently, the accomplishment of vessel and piping system function and integrity is a multidisciplinary and frequently multiorganizational task and requires balancing of the various, often conflicting, requirements. For example, from the standpoint of safety, major equipment items should be located in a very dispersed array, with possibly intervening fire and missile barriers, and should have redundant isolation schemes in order to limit losses due to catastrophic fires and associated explosions. These criteria could obviously impose, in the extreme, an intolerable capital cost. Resolution of this conflict can be obtained by a reliability study that involves an assessment of the probability of the occurrence of various equipment failures, process malfunctions, and human errors and the assignment of a monetary value to the consequent loss of equipment and lives. Probabilistically derived costs of such losses can then be factored into the overall economic studies or profitability analysis for the plant. For various reasons (previously discussed in Chap. 1) this technique has not been frequently employed by industry in the past but probably will be for more of the complex, high-risk, high-capital-cost installations in the future.

*This section was prepared by G. C. Robinson and D. A. Canonico.

Another multidisciplinary design issue is the interfacing involved with process control. An array of interdependent decisions affecting the design of a prototypic plant proceeds out of the basic information obtained from the precursor developmental efforts. Ideally, the pressure vessel designer receives, at one time, a package of information for each vessel from process design and development specialists and from instrumentation and control specialists that defines the process space configuration and size; the nominal temperature, pressure, and physical characteristics of the process fluid; the normal and upset fluctuations in process conditions that result from normally operating and malfunctioning process controls; the location and configuration of internal components; and the flow criteria for nozzles, including size and orientation. Such an ideal package of information would permit the pressure vessel designer to proceed with his design efforts without the constraint of further interfacing with these specialties.

However, normally, some iterative interfacing is required. For example, if the normal method of control over process temperature and pressure results in appreciable variations in thermal and pressure loading, an investigation should be made of the fatigue resistance of the affected structures. Rather than automatically modifying the structure to resist the imposed fatigue loading, the option to modify the imposing cause (e.g., control technique, awkward nozzle configuration having high stress concentration, poor equipment location, etc.) should be open to investigation. Nevertheless, since engineering costs are appreciable, ranging from 10 to 15% of direct costs for prototypic plants, there is a natural constraint to the amount of iterative interfacing that is usually employed.

We believe the organizational concept described by Pecoraro[1] of the Dow Chemical U.S.A. Engineering and Construction Services (E & CS) to be typical of most discipline-organized architectural-engineering firms and, therefore, to be structured for cost achievement that would minimize iterative optimization of process designs. As described by Pecoraro,[1] the Dow design group receives a comprehensive document, "Plan of Design," including items normally considered as process engineering. This document is disseminated to the various discipline-oriented design groups by means of "control documents" to achieve effective cost control on the project. A target capital rate (i.e., capital dollars per productive hour) is set, and an allocation is made to each discipline. A deliberately low target, based on experience, is set as a tool to improve productivity by the various design groups and individuals. These cost techniques have permitted the Dow E & CS groups to be competitive with competing architectural-engineering organizations and to prevent excessive overruns in completing a project. Effective utilization of this concept is critically dependent on the quality and completeness of the information supplied by the Dow operating groups.

Management functions in DOE construction projects are implemented in a similar manner. Typically, operating contractors prepare the basic design criteria for facilities and may, in some instances, perform the design sequence of conceptual, Title I and II designs. More typically, an architect-engineer is employed to perform Title I and II designs. As indicated by the U.S. Atomic Energy Commission *Manual,*[2]

> The fundamental purposes of conceptual design are: to develop a project scope that will satisfy program needs, to assure project feasibility and attainable performance levels, and to develop reliable cost estimates and realistic schedules. Conceptual design establishes, in particular, the general criteria and design parameters, applicable codes and standards, quality assurance requirements, space allocations for various functions, types of construction, significant features and components, building and facility utility services, energy conservation goals, site work, process equipment requirements, project cost estimates, schedules, methods of performance, security requirements, environmental protection requirements, decontamination and decommissioning requirements, health and safety requirements, related research and development or plant test programs, and any other special requirements for the project.

As may be seen from this expanded statement, the DOE conceptual design serves the same function as the Dow "Plan of Design." In both instances, design concepts become frozen, and interactions into the developmental phase normally cease. Because of the greater administrative controls exercised over federal funds (compared with projects funded from the private sector), design normally proceeds through a two-stage process. The purpose of this expanded design is given by the *AEC Manual* as follows:

> In Title I the design criteria are defined in greater detail and d..wings for the approved project concept are expanded with more detailed information, together with additi.. ..l required drawings. Also further refined descriptive information and more detailed outline specifications are developed that will serve as the firm basis to proceed with definitive design (Title II).
>
> From the more detailed drawings and information developed, more accurate cost estimates and project schedules are developed. This may reveal the need at this stage of design for revisions in scope or project features to keep the project within authorized funds.

The purpose of this discussion of project design management is to emphasize the importance of a thorough definition of mechanical and structural aspects, as well as process, by the groups responsible for process development at the initiation of project conceptual designs. As noted by Ferretti and Kasper,[3] proposed coal conversion plants based on the mature technology of first-generation concepts (e.g., Lurgi, Koppers, and Winkler) have been canceled or delayed because of excessive escalation of capital costs. They state that

> In the space of a year, the capital cost of a standard 250 MM scfd has gone from the $300–500 MM range to the $700–900 MM range. It seems logical, therefore, to ask: What happened??

They suggest that part of the escalation was due (1) to the high current rate of escalation since publication of the cost studies, (2) to the failure to include auxiliary services and site development in costs, and (3) to inadequate assessment of by-product process costs and environmental control costs. These factors have even more significance in the development of second-generation processes because of the relative immaturity, since current efforts are typically at the pilot stage.

Second-generation coal conversion plants, as currently conceived, may use vessels and piping systems that are unparallelled in size in either the petrochemical or utility industries. Fabrication capability in the United States, based upon many personal contacts by the writers, is limited. Since second-generation coal conversion demonstration plants have not been built, an adequate basis does not exist for projected operational conditions. Although materials technology is being vigorously pursued, the relationships of corrosion, stress corrosion, hydrogen embrittlement, and other environmental and metallurgical effects upon noncritical, repairable failures and potential disruptive, catastrophic failures are inadequately assessed.

2.2 Design by Rule and/or Design by Analysis

Harvey[4] in his comprehensive volume on pressure vessel design used the word "design" to mean "(1) the reasoning that established the most likely mode of damage or failure, (2) the method of stress analysis employed and significance of results, and (3) the selection of material type and its environmental behavior." Pressure vessels and piping for coal conversion systems may potentially lose their leak-tight integrity and other functions by means of several failure modes, including (1) excessive elastic deformations resulting in unacceptable distortions for mating parts or in buckling, (2) flaw growth associated with initial fabrication flaw sites, stress concentrations, fatigue, environmental effects, etc., resulting in leakage or catastrophic brittle failure, (3) excessive plastic deformation resulting in plastic collapse or buckling, and (4) excessive creep deformation or creep rupture. A comprehensive assessment must be made to determine which of these potential failure modes is likely. Materials selection can then be made based upon economics and resistance to deleterious environmental effects. Stresses and strains may then be calculated as premised upon a mathematical representation of material behavior and upon an analytical model of the structure being assessed. These values of stress and strain may then be compared against accepted values as published in voluntary standards, such as the ASME Pressure Vessel Codes or the ANSI Piping Codes. Such a procedure can properly be called "Design by Analysis," an aim particularly of the ASME Code, Section VIII, Division 2, and, in part, of the ANSI Codes.

The analytical tools and degree of sophistication required to accomplish the foregoing procedure vary radically, depending upon the choice of codes. The ASME Code, Section VIII, Division 1, assumes that the Rankine theory of failure governs for material behavior below creep limits; that is, the maximum principal stress calculated for a structure may be compared with the stress for a uniaxial test specimen at which yielding or failure has occurred. Rather than depend upon analysis as a primary basis, the philosophy for Division 1, "Design by Rule," is succinctly given in an ASME report:[5]

> The design philosophy of the present Section I (Power Boilers) and Division I of Section VIII (Pressure Vessels) of the ASME Boiler Code may be inferred from a footnote which appears in Division I of Section VIII on page 9 of the 1968 edition. This footnote refers to a sentence Par. UG-23(c) which states, in effect, that the wall thickness of a vessel shall be such that the maximum hoop stress does not exceed the allowable stress. The footnote says: 'It is recognized that high localized and secondary bending stresses may exist in vessels designed and fabricated in accordance with these rules. Insofar as practical, design rules for details have been written to hold such stresses at a safe level consistent with experience.' What this means is that Section I and Division I of Section VIII do not call for a detailed stress analysis but merely set the wall thickness necessary to keep the basic hoop stress below the tabulated allowable stress. They do not require a detailed evaluation of the higher, more localized stresses which are known to exist, but instead allow for these by the safety factor and a set of design rules. An example of such a rule is the minimum allowable knuckle radius for a torispherical head. Thermal stresses are given even less consideration. The only reference to them is Par. UG-22 where "the effect of temperature gradients" is listed among the loadings to be considered. There is no indication of how this consideration is to be given. On the other hand, the Piping Code (USAS-B31.1) does give allowable values for the thermal stresses which are produced by the expansion of piping systems and even varies these allowable stresses with the number of cycles expected in the system.

This ASME report indicates that the procedures of Division 1 of Section VIII have generally been satisfactory for vessels employed in conventional service; however, for vessels requiring a high degree of reliability or for those used in a highly cyclic type of operation, it would be advantageous to design according to Division 2 of Section VIII (i.e., "Design by Analysis"). Division 2 uses the Tresca criterion, maximum shear stress theory, which states that yielding takes place when the maximum shear stress is equal to one-half the yield strength of the material. Limit theory is used by Division 2 to categorize stresses as "primary," "secondary," and "peak," such that (1) the primary stress limits prevent plastic deformation and provide a safe design margin against ductile burst pressure, (2) the primary plus secondary stress limits prevent plastic deformation leading to incremental collapse and validate the application of elastic analyses to fatigue evalution, and (3) the peak stress limit prevents fatigue failure as a result of cyclic loading. Stress limits are also provided by Division 2 to prevent elastic and inelastic instability.

Elevated-temperature design is handled under Division 1 by premising the allowable stresses on creep rate and rupture data, extrapolated to 100,000 hr, that are derived from uniaxial tests.[6] No provisions are given in current Division 2 rules for elevated-temperature design (creep range); however, a series of code cases have been published (Case 1592-7, the current case of interest) that provide a basis for high-temperature design of Section III components. McAfee and Pickel[7] elaborate on the steps required to conform to Code Case 1592 and, thereby, cover the high-temperature regime of "Design by Analysis."

Neither Division 1 nor Division 2 analyzes the potential for low-temperature brittle fracture or the load-carrying capability of flawed structures for any range of temperature service. Material selection and material toughness specification, as particularly determined by the Charpy V test, provide the primary protection against brittle fracture. In the last 20 years, the discipline known as fracture mechanics has been developed to prevent brittle fracture and has experienced a tremendous growth in understanding and application. Although initially limited to assessments of flawed structures loaded under frangible conditions, this discipline now has demonstrated applicability to the elastic-plastic regime. Section XI of the ASME Code now uses this discipline for in-service assessment of flawed nuclear components. Concise descriptions are available for fracture mechanics analytical techniques that have demonstrated utility for analyzing flawed structures for both the elastic and elastic-plastic regimes.[8,9] Further discussions of fracture mechanics are given in Sections 2.5 and 4.4.

Fatigue analysis[10] under Division 2 is premised on the application of strain-controlled experimental fatigue data; on the modified Goodman diagram, to account for the effects of mean stress; and on Miner's hypothesis, to account for fatigue damage under varying loading conditions. In the absence of experimental data or rigorous solutions, peak stresses for fatigue analysis are derived through the application of theoretical stress concentration factors.[11,12] These rules are intended to prevent the initiation of crack-like defects. On the other hand, because of undetected material or fabrication defects (as influenced by environment, heat treatment, or operating conditions), cracks are prevalent in structures. For such cases, the discipline of fracture mechanics (Sections 2.5 and 4.4) provides a basis for assessing the remaining safe usable life of a structure.

The ANSI Petroleum Refinery Piping Code (ANSI B31.3), like Division 1 of the ASME Code, is primarily developed on the concept of "Design by Rule." The minimum wall thickness required for piping is sized by formulas based on the Rankine theory of failure. Wall thicknesses for branches or other configurations that require reinforcement are based on the familiar ASME Code area replacement rules. Elevated-temperature design follows the provisions of Division 1. Fittings in general are required to meet the rules of Division 1, but permission is granted in paragraph 304.7 to substantiate special pressure-containing components by

1. Engineering calculations.
2. Experimental stress analysis. (Such as described in Appendix 6 of Section VIII, Division 2, of the ASME Boiler and Pressure Vessel Code.)
3. Proof test. (The test shall be in accordance with UG-101, of Section VIII, Division 1, of the ASME Boiler and Pressure Vessel Code except it shall be approved by The Inspector.)

The major analytical emphasis of ANSI B31.3 is the prevention of fatigue failure from cyclic expansion stresses. A combination of the torsional and longitudinal bending for every loading stress, according to the Tresca criterion, is compared with the allowable stress range, an empirical combination of the hot and cold (maximum and minimum operating temperatures) tabulated allowable stress values. In order to accommodate variations in expansion stress ranges and cycles, Markl[13] observed that fatigue of a large variety of pipes and components followed the relationship of the form

$$iSN^{0.2} = C$$

where i is the stress-intensification factor, S is the nominal endurance strength, N is the number of stress reversals to failure, and C is a materials constant.

The code uses this relationship by expansion to the formula

$$N = N_E + (S_1/S_E)^5 N_1 + (S_2/S_E)^5 N_2 + (S_3/S_E)^5 N_3 + \dots,$$

where S_E and N_E are the maximum computed expansion stress range and the corresponding actual number of cycles, respectively, and S_1 and N_1, S_2 and N_2, etc., are the expansion stress ranges and cycles of successively lesser amplitude. The current rules for this analysis are largely an updating of stress intensification factors and allowable stresses from the 1955 rules that incorporated the recommendations of the ASA Task Force on Flexibility.[13] Brock[14] presents an extensive summary of the rationale undergirding the flexibility analysis required by the ANSI Piping Codes and of analytical techniques, both computer and manual, available to implement the rules.

A considerable development of the concept of "Design by Analysis" has been applied to nuclear piping. A brief summary of this development, particularly giving the contribution of the ORNL Piping Program to Nuclear Piping Design Codes and Standards, is given by Moore.[15] An earlier review[16] by Rodabaugh and Pickett provides much of the groundwork for the development of the ORNL Piping Program. Because of economic constraints, rather than requiring a mandatory application of ASME Code, Section III, to components on a piece by piece basis, a "stress index" method was introduced to permit design by analysis of piping systems. By using several simplifying nonrigorous (but always conservative) assumptions, the stress index method can be used with conventional flexibility analyses to satisfy the Section III or Section VIII, Division 2, hopper diagram rules for primary, secondary, and peak stress intensities. Because of the lack of application to nuclear piping, stress indices have not been developed for miter joints that will probably be extensively used in the large-diameter piping of coal conversion systems. However, much of the experimental stress analysis needed as input to the development of such stress indices has been performed, and some of the recent effort has been published.[17-22]

A very extensive effort is now under way to permit "Design by Analysis" in the utilization of piping in the high-temperature regime. As discussed by Rodabaugh,[23] this effort is currently an extension of the stress index method applied in Subarticle NB-3600 of the ASME Code for nuclear piping. Two promising methods for such an extension are termed "bounding techniques" and "reference stress methods" (discussed in refs. 24 through 27). Major experimental programs[28,29] are being pursued at ORNL and at Westinghouse in furtherance of this goal; and other extensive experimental efforts[30,31] are under way in England and in Belgium.

2.3 Critical Comparison of ASME Section VIII and ANSI B31.3 Codes

Regardless of which code(s) is employed, the philosophy for their existence is the same—they were established to provide the engineering requirements necessary for the safe design and fabrication of pressure vessels and piping. They provide minimum requirements for construction, and all codes emphasize this point. The ANSI Code B31.3 specifically mentions that "The Code does not do away with the need for the engineer or competent engineering judgment."

The responsibility for the completed component is dependent upon the code according to which it was built. The ANSI B31.3 places the overall responsibility (paragraph 300) for compliance with the code with the owner of the completed piping installation. Division 2 places the responsibility for compliance 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 Division 1 lies with the manufacturer. There is a deviation in the assignment of responsibility even within the ASME Code. The two codes, ANSI B31.3 and Section VIII, are dissimilar in their rigidity. The ANSI Code is more lenient; it permits the use of design stress values based on the criteria employed for Division 2, without imposing the restrictions found in that document. The bases for the allowable stresses for materials other than bolting materials [302.3.2(*b*)] below the creep range are as follows:

$^1/_3$ of the specified minimum tensile strength at room temperature,
$^1/_3$ of the "tensile strength" at temperature,
$^2/_3$ of the specified minimum yield strength at room temperature,
$^2/_3$ of the "yield strength at temperature."

These bases, as well as those employed to obtain stress values for bolting materials, are essentially identical to those employed for establishing the design stress intensity values in Appendix 1, Section VIII, Division 2. The major difference is the provision that permits the use of unlisted materials in the fabrication of a piping system in paragraphs 323.1.2, 323.2.1(*b*), and 323.2.2(*a*)(5) of B31.3. Further, paragraph 323.2.1 permits the use of listed materials at higher design temperatures "... provided the design engineer determines that the material is suitable for the service conditions and no prohibition appears in Appendix A."

The authorization in B31.3 to use, at the discretion of the design engineer, unlisted materials or to employ materials at temperatures above those specifically permitted by the code is a major deviation from the rules of Section VIII of the ASME Code. In both Divisions 1 and 2 the use of materials other than those allowed by the code must be approved by the Boiler and Pressure Vessel Committee [paragraphs UG-5(*c*) and AM-100 respectively]. The data needs and procedure for obtaining permission to use unlisted materials or to extend the limits of use of a permitted material are provided in the appendices to the two Divisions of Section VIII.

The material specifications used in B31.3 are listed in Tables 1 and 2 of Appendix A of the standard. It is evident when reviewing the allowable stresses in these two tables that the ASTM specifications account for nearly 95% of the materials permitted. Other material specifications are provided by the American National Standards Institute (ANSI), the Manufacturers Standardization Society of the Valve and Fittings Industry (MSS), the American Petroleum Institute (API), the American Water Works Association (AWWA), the American Welding Society (AWS), the Association of American Railroads (AAR), and federal specifications. With the exception of ANSI, the role of the other material specifications is minor in B31.3.

The authorization to use a number of specifications is in contrast to the ASME Pressure Vessel Code that has established a section (Sect. II) specifically for materials. Authorization to use materials not specified in Section II requires that data be submitted to the Boiler and Pressure Vessel Committee, and upon their approval a code case is issued. This procedure does not permit the design engineer the freedom "to determine the amount of testing necessary to establish allowable stresses for unlisted materials," a practice that is extremely lenient. "Recommended engineering practice" and a "sound scientific program" are subjective interpretations. Both are permitted in B31.3, paragraphs 323.2.1(*b*) and (*a*) respectively.

The use of materials at elevated temperatures (creep range) is permitted in B31.3 and in Division 1 of Section VIII. The criteria for establishing the stress levels are identical in the two documents; both base the allowable stress on the lowest value of the following:

100% of the average stress for a creep rate of 0.01% per 1000 hr,
67% of the average stress for rupture at the end of 100,000 hr,
80% of the minimum stress for rupture at the end of 100,000 hr.

Criteria for establishing the stress intensity values in the creep range for Division 2 are in preparation. It is interesting to note that, although the basis for establishing the allowable stresses in the creep range for B31.3 and Division 1 are identical, the maximum allowable values are not the same. There are variations, particularly at the higher temperatures. Moreover, in some instances, B31.3 permits the use of a material at a higher temperature than that permitted by Division 1. An example of this is the provision of an allowable stress for piping manufactured from A 515 Grade 70 at 1100° F in Table 1 of Appendix A in B31.3. Table UCS-23 of Division 1 provides allowable stresses for SA 515 Grade 70 to 1000° F.

In summary, a comparison between the allowable stresses in B31.3 and Division 1 shows that higher values are provided in B31.3 at the lower temperatures. Further, B31.3 permits the use of some materials at higher temperatures than those allowed in Division 1.

Both codes emphasize the need to consider the effect of environment on the material of construction. This is done by requiring 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 themselves to this topic. An entire appendix (E) is devoted to this subject in Division 1.

Division 1 of Section VIII also recommends that the user assure himself of the stability of his material selection over the expected life of the component. Mechanical properties are specifically cited (UG-5). Of particular concern is the loss of toughness of a material as a consequence of its extended exposure to various temperatures and environments. Paragraph 323.3 of B31.3 cautions the designer about the use of steel at temperatures in excess of 750° F. This paragraph specifically addresses itself to graphitization and does not consider loss of ductility due to a metallurgical embrittlement.

The codes, B31.3 and Division 1, contain minimal toughness requirements. These requirements, based on Charpy V-notch tests, are cited in 323.2.2 and 323.2.3 of B31.3. Paragraphs UG-84 of Division 1 and AM204 and AM210 of Division 2 cover the same subject. The requirements are quite similar; Divisions 1 and 2 are, however, slightly more restrictive than 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 minimum Charpy V-notch impact values are required. None of the codes requires that upper shelf values be determined. There is no assurance in any of the code rules that the toughness properties are greater than the 15 or 20 ft-lb required.

As noted by Clarke,[32] catastrophic brittle fractures of heavy-walled pressure vessels have occurred in the petroleum industry in spite of the adherence to Charpy toughness requirements exceeding code requirements. In view of the recent advancements in the field of fracture mechanics, the approach to toughness taken both in B31.3 and in Section VIII, Divisions 1 and 2, appears archaic. Testing procedures are currently available that permit a quantitative analysis of a material's toughness. An evaluation of the material's ability to resist initiation of a propagating crack in the presence of a preexisting sharp flaw is possible. This procedure for evaluating toughness should be encouraged for coal conversion systems.

The most obvious differences between B31.3 and Section VIII, Division 2, lie in the fabrication and inspection procedures for manufacturing components. Specifically, the requirements for nondestructive examinations are minimal in B31.3. Random radiography of 5% of the circumferential butt welds is permitted for service above 360° F or for pressures above 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, but it does suggest that for a safe installation (basis for all codes), the most liberal interpretation should be employed. Moreover, Division 1 requires full radiographic examination of specified thicknesses of butt-welded joints of certain P* and group number materials. It is important to note that all thicknesses of $2\frac{1}{4}$

*P numbers provide groupings of base materials that may utilize the same welding procedure qualification; ASME Sect. IX, par. QW 421.

Cr–1 Mo, 3 Cr–1 Mo, 3 Cr–0.9 Mo, 5 Cr–½ Mo, 7 Cr–½ Mo, and 9 Cr–1 Mo steels (P-5 alloys) must be fully radiographed (UCS-57). These alloy steels, because of their excellent resistance to corrosive environments, are frequently candidate materials for the fabrication of pressure vessels and piping for coal conversion systems. This radiographic requirement does not exist in B31.3.

The fabrication rules are more restrictive in Section 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. This is in contrast to 311.1 in B31.1, which permits welded joints in any material for which it is possible to qualify welding procedures. [Table ACS-1 of Division 2 also limits (Note 4) the carbon content of some nominal compositions.] Further, Division 2, in its restrictions, specifically delineates permissible fabrication procedures.

Prior to 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. 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 United States, 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 Section VIII inspector is qualified by a written examination under the rules of any state of the United States 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.

In summary, the codes are formulated to assure the safety of the component being manufactured. The codes ASME Section VIII, Divisions 1 and 2, and ANSI B31.3 provide allowable stress values for pressure vessels and piping, respectively, for a coal conversion system. The ASME Code is considerably more restrictive than B31.3, even when considering essentially identical materials. ANSI B31.3 has allowances that permit the use of unlisted materials. This is not true in the ASME Codes. The allowable stresses in ANSI B31.3 are higher than those in ASME Section VIII, Division 1, and the examination requirements are considerably more lenient. This combination results, by comparison, in a piping installation, built in accordance with B31.3, that is less conservative than a Section VIII, Division 1, vessel. One shortcoming of all the codes lies in the toughness requirements for ferritic materials. This is an area that can and should be expanded to include current technology, based on fracture mechanics.

2.4 Potential Engineering Problems

2.4.1 Oblique nozzles

Lewis[33] discusses several engineering problems that have been encountered in the Synthane process development, some of which are pertinent to this report. Lock-hoppers are used in the Synthane process to introduce coal to the gasification system and to remove solid char. To transfer solids by such a device dependent upon gravity flow requires steeply sloping lines, not deviating perhaps more than 30° from the vertical. Consequently, among more than 40 nozzles in the Synthane pilot plant gasifier were several feed and char nozzles requiring attachment at 30° angles to the vessel. As Lewis notes, conventional nozzle design (nonintegral design as permitted by Division 1) was not amenable to radiographing at the point where stresses are concentrated; therefore, this problem was overcome by the use of special nozzle forgings. Figure 2.1 shows a longitudinal section of the Synthane vessel with the steeply inclined feed and char nozzles. This particular problem is not peculiar to the Synthane design but is a generic one for designs dependent on gravity flow for transfer of solids. Figures 2.2 through 2.5 show similar nozzle configurations for the CO_2 acceptor gasifier, the Battelle-Carbide burner, the Battelle-Carbide gasifier, and the ERDA-MERC stirred bed gasifier.

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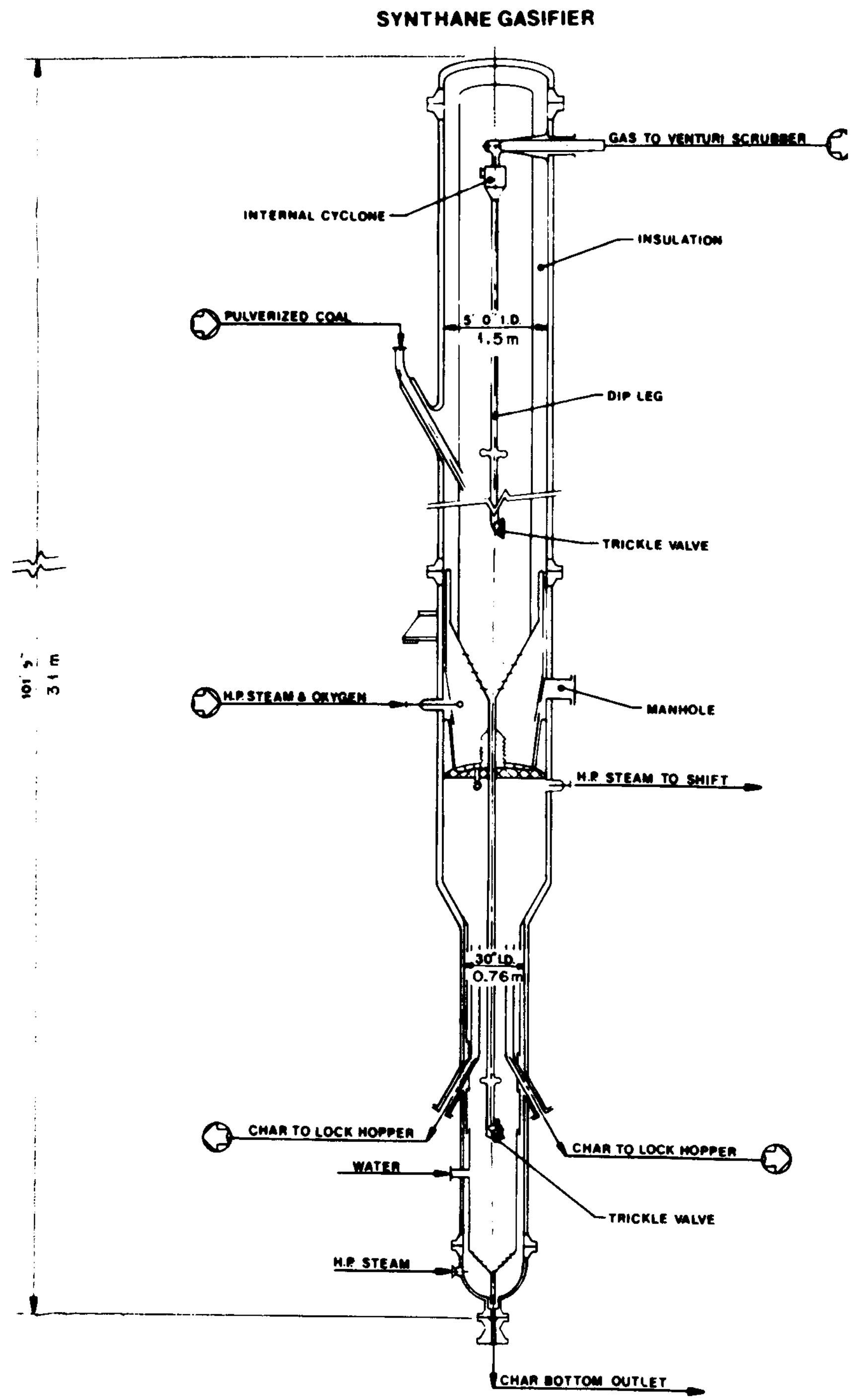

Fig. 2.1. Synthane gasifier. Source: Gravo Corp, *Handbook of Gassifiers and Gas Treatment Systems,* Report FE-1772-11, Pittsburgh, Pa. (February 1976).

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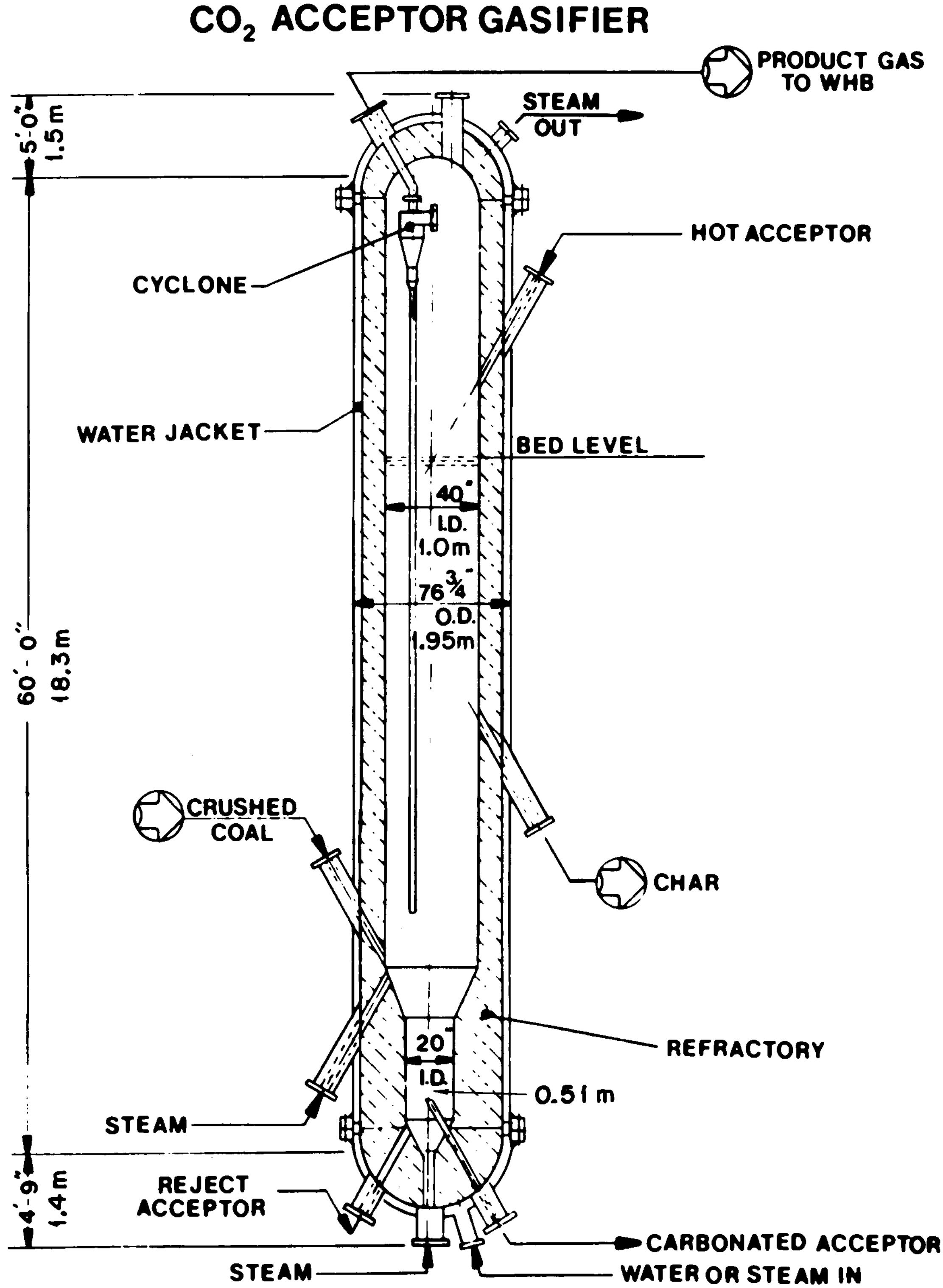

Fig. 2.2. The CO_2 acceptor gasifier. Source: Gravo Corp, *Handbook of Gassifiers and Gas Treatment Systems*, Report FE-1772-11, Pittsburgh, Pa. (February 1976).

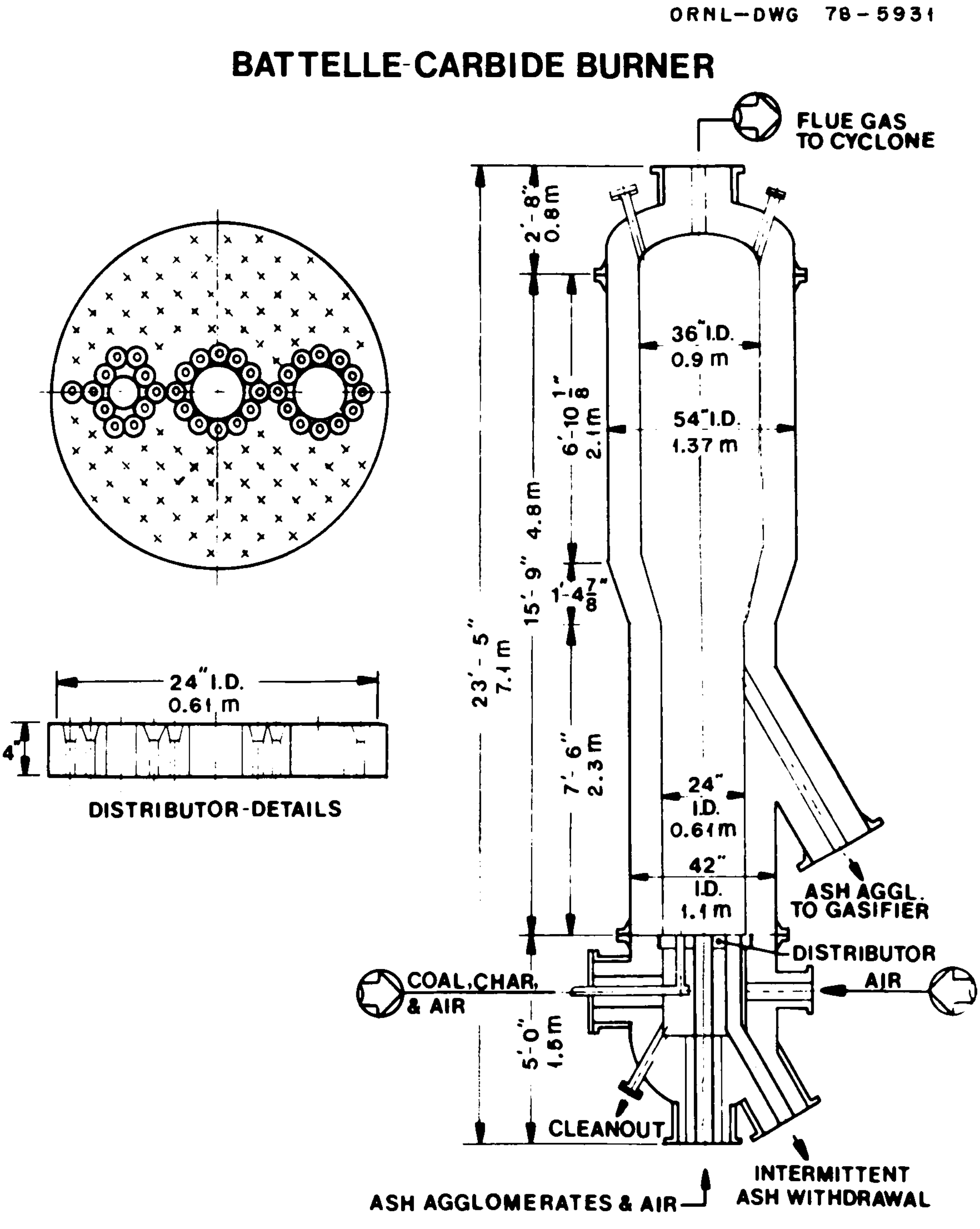

Fig. 2.3. **Battelle-Carbide burner.** Source: Gravo Corp, *Handbook of Gassifiers and Gas Treatment Systems,* Report FE-1772-11, Pittsburgh, Pa. (February 1976).

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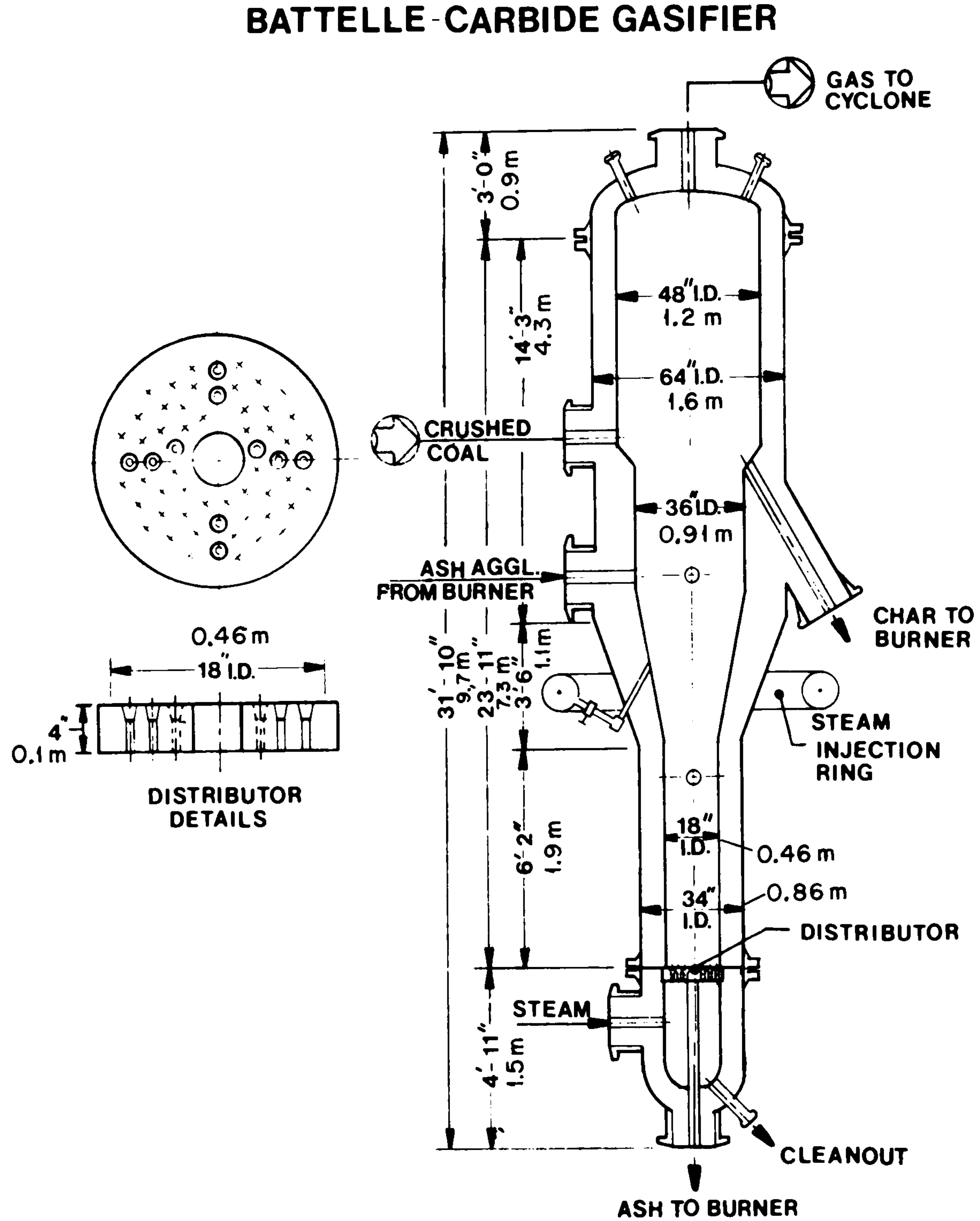

Fig. 2.4. **Battelle-Carbide gasifier.** Source: Gravo Corp, *Handbook of Gassifiers and Gas Treatment Systems,* Report FE-1772-11, Pittsburgh, Pa. (February 1976).

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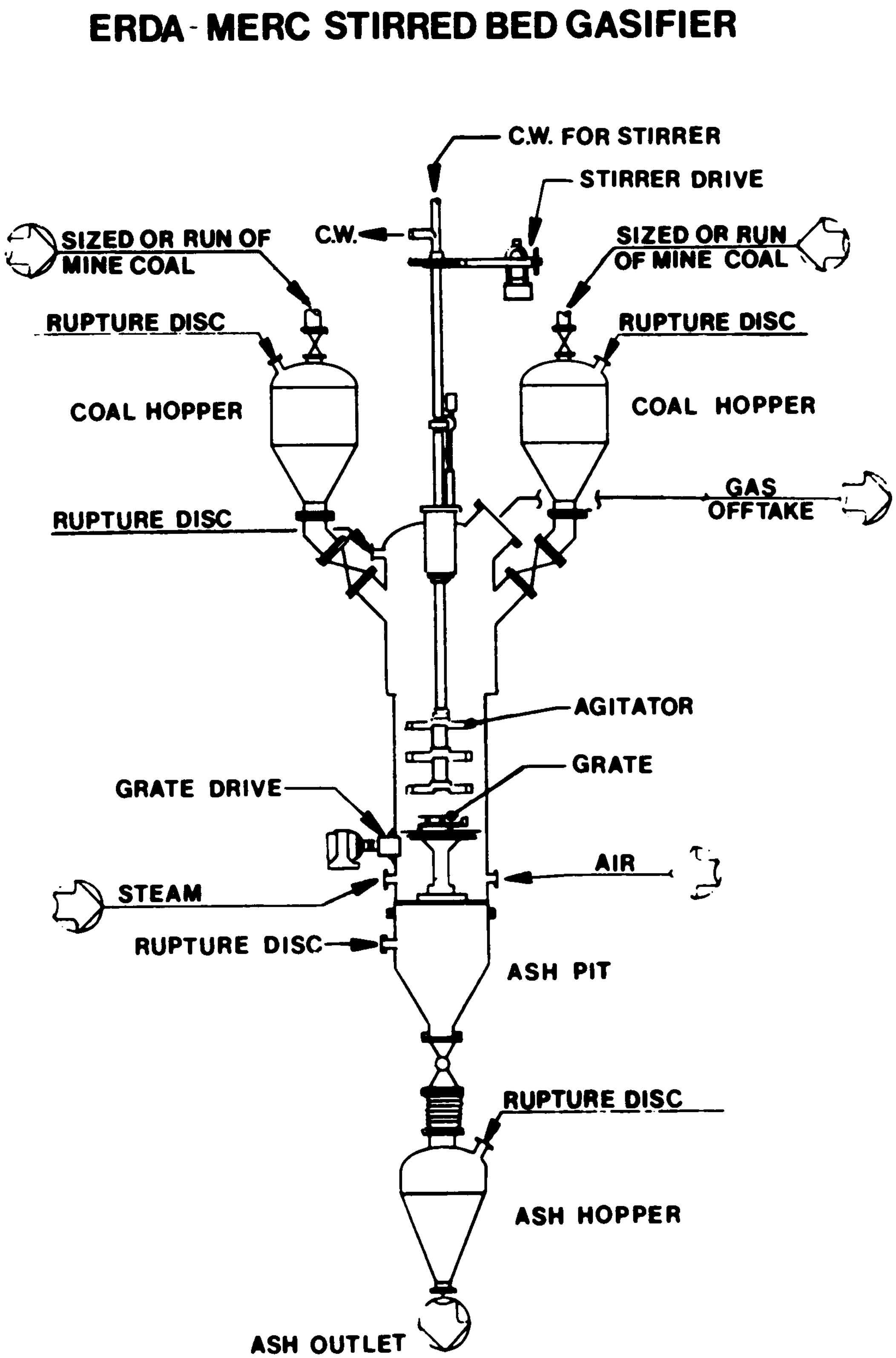

Fig. 2.5. ERDA-MERC stirred-bed gasifier. Source: Gravo Corp, *Handbook of Gassifiers and Gas Treatment Systems,* Report FE-1772-11, Pittsburgh, Pa. (February 1976).

Several factors are significant considerations in the design and fabrication of oblique nozzles having a very acute angle with respect to the shell. It has been suggested that Division 2 rather than Division 1 should be used for the design of vessels subjected to significant cyclic loading.[5] Nonetheless, if Division 1 is the applicable code and if the vessel contains a lethal substance, par. UW-2(a) requires all butt-welded joints to be fully radiographed, and par. UW-2(b)-(4) requires that Category D welds (nozzle-shell welds) be the full penetration type. If Division 1 is the applicable code and if heat treatment is used to enhance the properties of the material, paragraphs UHT-17 and UHT-18, Figs. UHT-18.1 and UHT-18.2, require full penetration welds, and par. UHT-57(*b*) requires full radiographic examination for nozzles above 2 in. in inside diameter and magnetic particle or liquid penetrant examination below this diameter.

A lethal substance, as defined by the Code (Division 1 or Division 2), is limited to toxic effects and has no bearing on flammability, explosibility, or the potential hazards of asphyxiation. Division 2 defines a lethal substance as follows:

> By 'lethal substances' are meant poisonous gases or liquids of such a nature that a very small amount of the gas or of the vapor of the liquid mixed or unmixed with air is dangerous to life when inhaled. For purposes of the Code this class includes substances of this nature which are stored under pressure or may generate a pressure if stored in a closed vessel. Some such substances are hydrocyanic acid, carbonyl chloride, cyanogen, mustard gas, and xylyl bromide. For design purposes under this Code, chlorine, ammonia, natural or manufactured gas, any liquefield petroleum gas (such as propane, butane, butadiene), and vapors of any other petroleum products are not classified as lethal substances.

According to a report of Greenfield, Attaway, and Tyler, coal conversion systems would be classified as containing lethal substances.[34] Although users have not traditionally designated coal conversion vessels as containing lethal substances, if the opinion of the report were considered valid, the rules of UW-2 requiring radiography would apply.[34]

In addition, according to Rodabaugh's review,[35] nonintegrally reinforced nozzles were indicated to have drastically shortened fatigue life, as compared with the unperforated shell, and to be particularly sensitive to failure during hydrostatic testing because of the prevalence of undetected macroscopic cracks in the toe of the fillet weld 90° from the run position. These considerations fortify the decision to utilize integral nozzle reinforcing in the Synthane gasifier reported by Lewis.[33]

If Division 2 is chosen by the A-E as the proper code for gasifiers, depending on the determination of par. AD-160.2, fatigue analysis may be required. We know of no current projections of anticipated cyclic loading conditions for commercial units that would permit an immediate evaluation of the sensitivity of such vessels to fatigue. Pilot plants are intentionally operated in a more fatigue-susceptible mode (i.e., frequent cyclic loading) than anticipated for prototype commercial units; and, therefore, such experience is not necessarily directly transferrable.

Nevertheless, the failures, leaks, fires, and explosions experienced with the CRESAP facility convinced Fluor[36] that a major investigation of mechanical connections and closures subjected to cyclic loading should be made.

Division 2 requires impact testing for lethal service, per par. AM-204 and Table AD-155.1, and postweld heat treatment, per par. AF 402 and Table AF 402.1. Either integral or nonintegal (pad-type) reinforced nozzles per paragraphs AD-414 and AD-601, Figs. AD-610.1, AD-612.1, and AD-613.1, and Table AF-241.1 are permitted. For nozzles subject to external loading, full-penetration welds, butt, corner, or fillet (per par. AD-414), are permitted; examination may be full radiography, magnetic particle, or liquid penetrant per Table AF-241.1. If cyclic loading is sufficiently severe, as determined by par. AD-160, fatigue analysis is required by Appendix 4, par. 4-135, and Appendix 5; and, if opted for by the designer, stress indices for nozzles are provided in Article 4-6, par. 4-610. The formula given for lateral connections in cylinders is

$$K_2 = K_1[1 + (\tan \phi)^{4/3}] ,$$

where

K_1 = normal stress component stress index given in par. 4-612 for a radial nozzle,
K_2 = estimated normal stress component stress index for the nonradial connection,
ϕ = angle between the axis of the nozzle and the normal to the vessel.

A discussion[37] of the experimental data supporting this formula is given by Mershon; Fig. 2.6 (Fig. 16 of ref. 37) presents a plot of the above code formula and the supporting experimental data. No experimental data substantiate the code stress index formula for skew angles greater than 60°, which is likely to be the area of application for coal conversion vessels similar to the Synthane gasifier. Figure 2.6 also presents an alternative, more conservative, stress index formula recommended by Marshon.

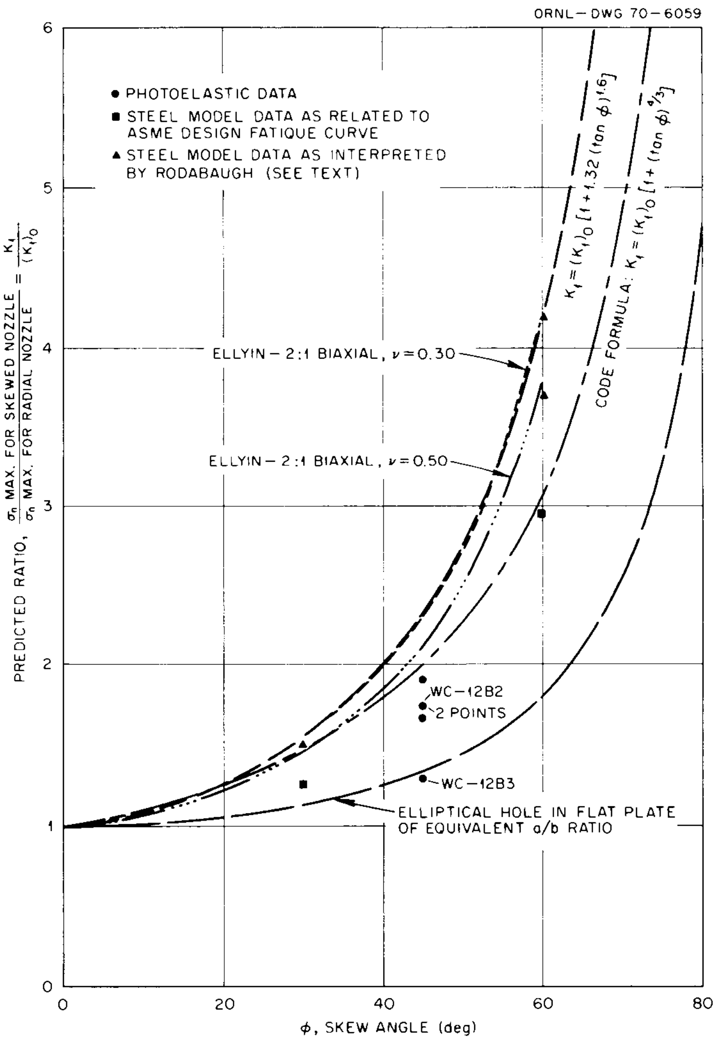

Fig. 2.6. Comparison of experimental data with maximum stresses predicted by various formulas for lateral connections in cylindrical shells.

2.4.2 Refractory linings

In discussions with prominent A-Es (Ref. 11–14 in Chap. 1), we found that they favor the application of internal refractories to large-diameter thick-walled pressure vessels in order to maintain wall temperatures at about 650°F for coal conversion service. Very extensive experience in the application of refractories has been accumulated in the petroleum, chemical, and metals industries. McDowell et al.[38] report that utilization of internal refractories exposed to internal environments similar to those in the petrochemical industry was begun in World War II in German coal hydrogenation plants. Evidently the first use of castable refractories in hydrocrackers was based on the experience[38] derived from a series of specimens subjected to the H-Oil reactor at the Lake Charles, Louisiana, Cities Service Refinery. Bakker[39] has reviewed refractory technology and has given an excellent summary of many of the potential problems as applied to the emerging coal conversion industry. Lewis[33] reports on the misapplication of a refractory concept for the Synthane pilot plant gasifier which was avoided by the report of a failure of a similar application elsewhere. In a review[23] of high-temperature piping applications, Rodabaugh reported on ten-year service of refractory-lined steam reformer furnaces and piping. Although reported experience is rather limited, contact with the A-Es indicates that refractories for coal conversion systems vessels and piping will probably require repair in five years and potential replacement in ten years.

Although refractories in coal conversion systems are anticipated to provide reasonably good service, they are expected to be a significant operating (maintenance) expense. Generally, it appears that, with respect to vessels, the refractory is designed mechanically as a separate entity by proprietary, in-house, refractory manufacturer's rules. Pierce and Bressi[40] reported on the development of a computer program for the engineering involving gunited and brick refractory linings. Motivation for this computer development was the achievement of increased refractory reliability and reduced maintenance costs.

Several A-Es indicated experience with the design of low-pressure refractory-lined ducts, 6 to 10 ft in diameter, for which interaction between the steel duct and the refractory lining was considered. The piping designers considered the effect of the refractory on the flexibility of the composite duct and lining and the consequent stresses on the refractory as a result of thermal loadings. In addition, the degree of ovalization of miter bends caused by piping expansion was calculated and limited to prevent excessive loading of the refractory. Reportedly, the experience with these ducts has been good, indicating that the piping designers used good judgment in estimating the mechanical properties of the refractory linings. Even though published high-temperature mechanical property data of refractories are limited, there are two recent significant papers.[41,42]

The experience with refractory linings is primarily proprietary; and, although refractory usage is known to be a significant cost factor in the metals industry, similar information is not readily available from the petrochemical industry. We believe the economics favorable to the more rational analysis of refractory linings in conjunction with the analysis of the associated vessels and piping (i.e., analysis similar to that of Pierce and Bressi[40]).

2.5 Fracture Mechanics

Brittle catastrophic failure has been the impetus for recurring investigations involving various industries, throughout this century. Armament, railroad, shipbuilding, automobile, aerospace, and other manufacturers have directed extensive studies and investigations to combat such failures. Until recent years the solutions centered around the specification of some toughness parameter for the materials involved, the prevention of defects during fabrication, and the avoidance of crack growth during service. These approaches continue to be the mainstay afforded the designer by the ASME Pressure Vessel Codes and by the ANSI Piping Codes.

Development of rational analytical approaches to prevent catastrophic failure due to flawed structures received particular impetus from the numerous Liberty Ship failures of World War II and by the applications of high-strength materials to the structures of the aerospace industry. The resulting Griffith-Orowan-Irwin linear elastic theory on flawed structure behavior, known as fracture mechanics, has enjoyed an extensive development incorporating a vast literature. Developments known as J-integral, Equivalent Energy, Normalized COD, and others have extended the application of fracture mechanics into the elastic-plastic, and fully-plastic toughness regions.

One of the admirable goals of professional engineers and societies (e.g., ASME and ANIS) is the increased utilization of materials capability for sustaining loads. Advances in this direction over the years have been accomplished by the accumulation of a vast experience in service, by developments of the technology of nondestructive testing, and by increased theoretical knowledge of structural and material behavior. With this advancement has come a fuller realization of the prevalence of flaws and their characteristics in all manmade structures and that some such flaws, depending upon shape, size and character, and associated material properties, have a profound influence on the ability of structures to resist catastrophic failure, whether it be at the initial hydro test of the structure or at some future in-service period following considerable cyclic loading. These influences have prompted the aerospace industry to use the principles of fracture mechanics for both design and in-service assessments of structures. In-service assessment of nuclear vessels via fracture mechanics has also been implemented because of the virtual impossibility of removing all defects that may have significance and because of the degradation that nuclear vessels experience in their environment.

Time- and temperature-influenced metallurgical embrittlement, associated with corrosion, stress corrosion, crevice corrosion, hydrogen attack, etc., is sufficiently severe that a serious consideration should be given to the application of fracture mechanics principles to the assessment of sensitive structures. The petroleum industry has already begun such an application; however, the in-service assessments of these efforts have been greatly impeded by the lack of fracture toughness, properties of the base materials, and weldments of the structures. It was necessary, in these instances, to resort to correlations[43] between Charpy V impact values and fracture toughness for the class of materials used. We believe that a rational implementation of fracture mechanics to coal conversion vessels and piping should incorporate actual materials fracture mechanics testing of the structures sensitive to these needs.

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3. MATERIALS COMPATIBILITY CONSIDERATIONS*

3.1 General Considerations

This section will address corrosion and erosion mechanisms that potentially could affect the performance of pressure vessel and piping materials. In addition, we will attempt to identify those areas where further data are needed to ensure that components will safely and reliably operate for the design lifetime of these proposed systems.

To gain a better perspective of the corrosion-resistant properties required of these candidate materials, one must review the operating environments of typical coal conversion systems. A number of processes have been proposed to convert coal into clean fuels and organic feedstocks, with each of the systems having unique operating parameters. Tables 1.2 and 1.3 in Chapter 1 list several representative gasification and liquefaction systems and summarize the nominal operating conditions for these systems.

Pressure vessel and piping materials will be exposed to a broad spectrum of temperature and pressure conditions. As a result, the composition of process environments varies widely among the systems. A secondary factor influencing the product gas is the composition of the coal. Table 3.1 illustrates this by comparing the composition of three U.S. coals fed into a Kopper-Totzek system.

*This section was prepared by R. H. Cooper.

Table 3.1. Kopper-Totzek gasifier data for U.S. coals[a]

	Western coal	Illinois coal	Eastern coal
Gasifier feed			
[Dried coal to gasifier analysis, vol % operating at 3300° F (1650° C) and a pressure of 1 atm]			
C	56.76	61.94	69.88
H_2	4.24	4.36	4.90
N_2	1.01	0.97	1.37
S	0.67	4.88	1.08
O_2	13.18	6.73	7.05
Ash	22.14	19.12	13.72
Moisture	2.00	2.00	2.00
Raw gas			
[Analysis (dry basis), vol %]			
CO	58.68	55.38	55.90
CO_2	7.04	7.04	7.18
H_2	32.86	34.62	35.39
N_2	1.12	1.01	1.14
H_2S	0.28	1.83	0.35
COS	0.02	0.12	0.04
	100.00	100.00	100.00

[a]The author recognizes that the Kopper-Totzek system is not entirely representative of advanced high-pressure, high-Btu gasifiers; however, the obvious relation illustrated in this table between the sulfur content of the input coal to the H_2S and COS content of the raw gas is expected in advanced gasifier systems.

Note that the differences in sulfur concentration in these coals have a substantial effect on the H_2S level in the product gas.

Similar variations are observed in liquid-phase products in liquefaction systems. Products from a typical liquefaction reactor vessel have a broad range of molecular weights, which are separated for subsequent refining to specific products. Table 3.2 summarizes the compositions of various distilled product fractions produced by the H-coal process. This table illustrates that these various fractions contain a wide spectrum of compounds that have different potentials for corrosion. Furthermore, with process refinement, these compounds may be further altered by changes in operating temperature and pressure or by variations in the composition of the coal input.

Table 3.2. Analysis of various distilled products produced from the H-Coal process

Compounds	Composition of the less than 200°C (400°F) fraction (%)	Composition of 200–340°C (400–650°F) fraction (%)	Composition of 340–490°C (650–920°F) fraction (%)
Saturated Compounds	11.99		
C_4 thru C_{12}			
Saturated Naphthenes			
Paraffins		6.5	1.4
Monocycloparaffins	42.64	14.0	3.1
Dicycloparaffins	8.5	7.9	.6
Tricycloparaffins	.19	2.6	.7
Tetracycloparaffins			.4
Pentacycloparaffins			.2
Mexacycloparaffins			.1
Unsaturated Naphthenes			
Monocycloparaffins		4.3	.5
Dicycloparaffins			.3
Tricycloparaffins			.2
Tetracycloparaffins			.2
Pentacycloparaffins			.1
Mexacycloparaffins			.1
Aromatic Compounds			
Alkyl Benzenes	17.55	12.6	3.0
C_6 thru C_{12}			
Indans and Tetralins	6.44	30.8	.5
Indenes		5.7	
Naphthalene		3.7	
Acenaphthenes		6.2	
Tricyclics		.4	
Unidentified Aromatics			72.8
Miscellaneous			
Phenols	7.93	2.0	1.5
Unidentified Hydrocarbons	.59	3.10	13.8
Phenyls			.5
	100	100	100

Source: Office of Coal Research, *Project H-Coal Report on Process Development* R & D Report No. 26, U.S. Government Printing Office, Washington, D.C., 1967.

The major point is that environments associated with coal conversion systems are dynamic and may effect a range of responses. Experience from other industries allows some predictability of interactions for selected combinations of structural materials and environmental conditions, and these anticipated interactions will be the principal subject of this chapter. However, a point of great concern is the potential for corrosive interactions that cannot be anticipated based on the limited previous experience with coal conversion systems. Such corrosion problems are expected to be the greatest barrier in the realization of commercially reliable coal conversion systems.

The following discussion classifies corrosion problems into two groups—high temperature and low temperature. The arbitrary delineation for these groups was chosen to be about 200°C (400°F).

3.2 High-Temperature Degradation

Although the environmental conditions vary widely among the numerous coal conversion schemes, two high-temperature processes can be expected to have the greatest influence on the life and reliability of the systems. These principal mechanisms are: high-temperature hydrogen degradation and sulfidation.

3.2.1 High-temperature hydrogen degradation

Hydrogen attack occurs in plain carbon and low-alloy steels on long-term exposure to high-pressure, high-temperature hydrogen environments. The primary reaction associated with hydrogen attack is the reaction of hydrogen with the carbon in the steel to form methane. If the reaction occurs at the steel surface, carbon diffusion to the surface results in decarburization, with an attendant loss in strength. However, if hydrogen diffuses into the steel, the reaction may occur internally, resulting in both decarburization and the formation of methane bubbles, the result of which is a loss in both strength and ductility. Hydrogen attack can be prevented or minimized by using alloy steels containing strong carbide formers. The Nelson curves,[1] which are discussed later, describe the limits of temperature and hydrogen partial pressure for safe operation of selected carbon and alloy steels.

In carbon and low-alloy steels, the kinetics of hydrogen attack can be separated into two steps or stages: (1) an incubation period followed by (2) rapid attack. Vitovec[2] has suggested that, during the incubation step, hydrogen is continuously diffusing into the material to form methane, and that methane pressure builds up in submicroscopic voids. Initially, this pressure is balanced by surface tension, and the growth of the voids is slow. The effects of this step are not permanent, and a decrease in hydrogen partial pressure will result in no change in mechanical properties. However, when a void reaches a critical size, it grows rapidly. This rapid increase in growth rate marks the end of the incubation stage. Continued growth of the void during this second stage of attack is controlled by creep. As voids grow to microscopic size, significant reductions in mechanical properties are observed.

The length of the incubation period is a function of temperature, hydrogen pressure, and alloy content. The typical influence of temperature and hydrogen pressure on the length of the incubation period for a 1020 steel is illustrated in Fig. 3.1. The selection of 1020 steel is meant to afford an interesting example, not to imply its suitability as a pressure vessel or piping material. The effect of alloy content on the resistance of steels to attack by hydrogen is illustrated in Fig. 3.2. This figure shows the combination of alloy content and temperature which yield an incubation period of 100 hr. This figure indicates that molybdynum is the most potent alloy addition for retarding hydrogen attack, followed by tungsten and chromium.

Although temperature, pressure, and alloy content are known to be major factors influencing the kinetics of hydrogen attack, secondary factors, such as residual strain, heat treatment, and composition of the environment, may also influence the hydrogen-attack response of a material. For example, Allen et al.[3] have shown that increasing percentages of cold work in a material will

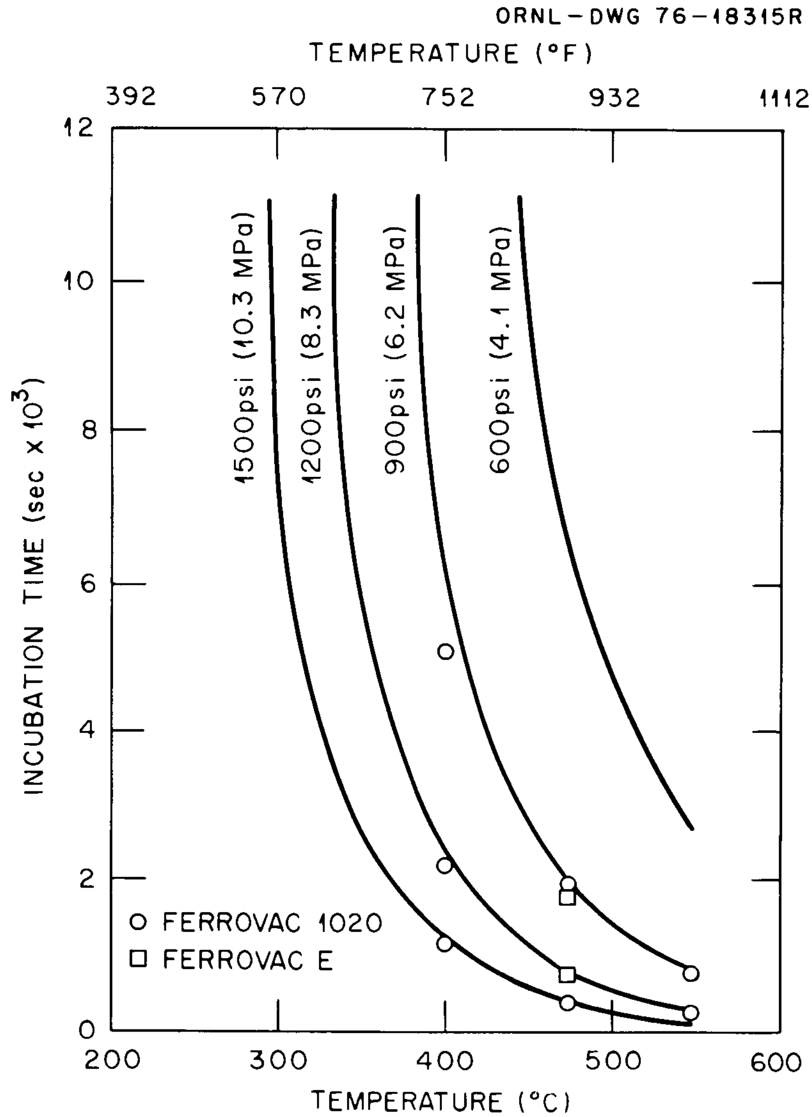

Fig. 3.1. Incubation time at various exposure conditions. Source: D. A. Westphal and F. J. Worzala, "Hydrogen Attack of Steel," Fig. 1, in M. Smialowsky, ed., *Hydrogen in Metals*, Pergamon, Oxford, 1962. Reprinted by permission.

decrease the incubation time for hydrogen attack. These data emphasize the need for effective stress-relief procedures in weld pressure vessels and piping components.

With regard to heat treatment, Schuzten[4] noted, as a result of a survey of synthetic ammonia plant experience, that fine pearlite or bainitic structures are more resistant to hydrogen attack than are coarse pearlite structures. In addition, Worzala and Aclum[5] have recently suggested that quenched and tempered materials appear more resistant to attack than does normalized material. The significance of these observations is that variations in microstructure at heat-affected zones and through large-section thicknesses may alter the anticipated hydrogen resistance of a candidate material. This effect could become quite significant for field-fabricated thick-walled pressure vessels such as those being considered in this report. (See the discussions in Sects. 4.3.2 and 5.2.5.2).

The presence of H_2S in the coal conversion environment may also increase the susceptibility of materials to attack. Palczewska and Ralajczykowa[6] in 1966 showed that the presence of H_2S

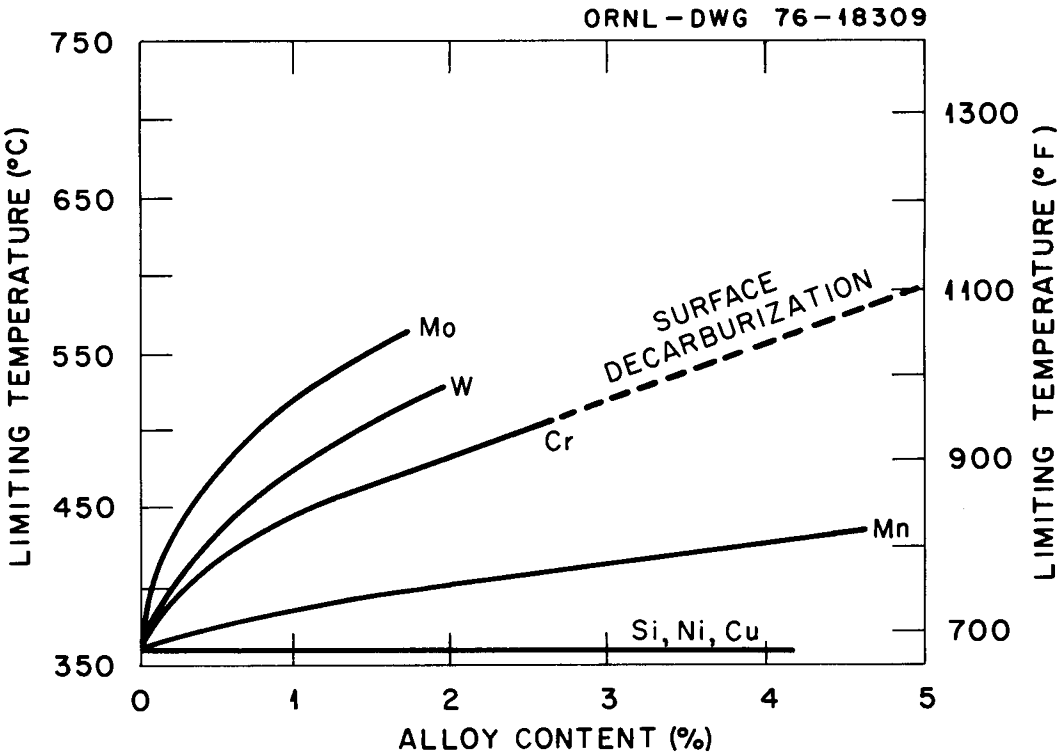

Fig. 3.2. Effect of alloying elements on the resistance of steels to attack by hydrogen. Source: E. H. Fletcher and A. P. Elsea, *The Effects of High-Pressure, High-Temperature Hydrogen on Steel,* DMIC Report 202, Battelle Memorial Institute, Columbus, Ohio (1964), Fig. 15. Reprinted by permission.

significantly increases the uptake of hydrogen in iron and iron alloys. As a result, one would expect a shortening of the incubation time for hydrogen attack.

The primary standard for the selection of materials for operation in high-temperature, high-pressure hydrogen is the Nelson curves, Fig. 3.3, which were developed by the petroleum industry. These curves reflect over 25 years of petrochemical experience and depict the operating limits for carbon, carbon-molybdenum, and chromium-molybdenum steels in contact with hydrogen-containing environments. The solid curves on this figure represent tendencies for steels to decarburize internally due to methane formation. The addition of carbide stabilizers such as chromium, molybdenum, tungsten, vanadium, titanium, and niobium tends to tie up the carbon and reduce the tendency to form methane; this allows materials to be safely used at higher temperature-pressure combinations.

The dotted lines on this chart represent conditions for which steels are subject to surface or external decarburization. Current theories[7,8] describing surface decarburization suggest that carbon migrates to the surface to form CH_4 or CO, resulting in a portion of the steel being depleted in carbon. As indicated above, steps to increase the stability of carbides can reduce the decarburization potential of a steel. Generally, alloy steels containing 2% Cr and/or $^1/_2$ to 1% Mo may not be subject to internal attack at a given temperature and pressure but may be subject to external decarburization.

A designer should be aware that the Nelson curves have some significant limitations. In particular, these curves are empirical and are based solely on the accumulated experience that has been drawn from the ammonia- and petroleum-refining industry. The hydrogen environments associated with these systems are not pure, and results from these systems reflect the interaction of materials with a mixed environment.

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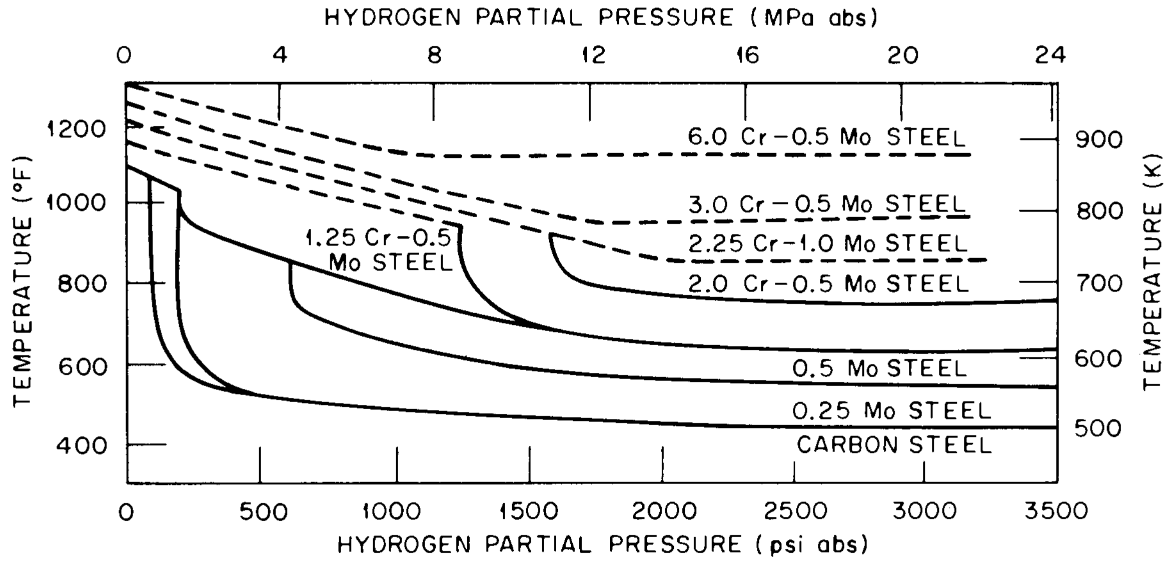

Fig. 3.3. Operating limits for steels in hydrogen service — the Nelson curves.

As a result, these curves may not have sufficient flexibility to describe the response of structural materials in coal conversion design applications. To illustrate this point, designers should recognize that the Nelson curves were derived from structures built primarily in accordance with Section VIII, Division 1, of the ASME Code. Therefore, the reliability of the Nelson curves in predicting the onset of hydrogen attack could be altered for structural materials operating at the higher stresses allowed with Division 2 of the code.

In designing pressure vessels for coal conversion systems, one should note that the ASME Code clearly indicates that it is the designer's responsibility to assess the deterioration of mechanical properties of a structural material due to environmental effects (see Sect. 2.3). Therefore, attention should also be directed toward the loss of load-carrying capability observed in materials exposed to high-pressure and high-temperature hydrogen environments. Changes in mechanical properties of carbon and low-alloy steels resulting from hydrogen exposure were extensively studied during the early 1960s by Vitovec et al.[2,9–11] These studies indicated that the progressive degradation in the mechanical properties of a material could be divided into three stages (Fig. 3.4) that were closely related to the development of fissures in the material. Typically, an analysis employing light microscopy indicated that stage 1 occurs before any evidence of hydrogen attack has appeared (incubation period). The second stage was characterized by a rapid decrease of the rupture strength, associated with the formation of fissures and with decarburization. Microscopic evaluation of third-stage samples indicates that hydrogen attack and decarburization are essentially complete when fracture occurs in this time interval. As would be expected, increases in hydrogen pressure and/or temperature tended to accelerate the onset of the rapid decrease in rupture strength associated with the second stage.

In comparing the stress-rupture properties of 1020 steel with those of various low-alloy steels, Vitovec found an immediate improvement with alloying; however, full strength was not retained for the duration of a 500-hr test until a steel containing 2¼ Cr–1 Mo was used. However, data from an API investigation[12] show that the rupture strength of a 2¼ Cr–1 Mo steel after a 5000-hr test in hydrogen is as much as 20% lower when compared to a similar test in argon.

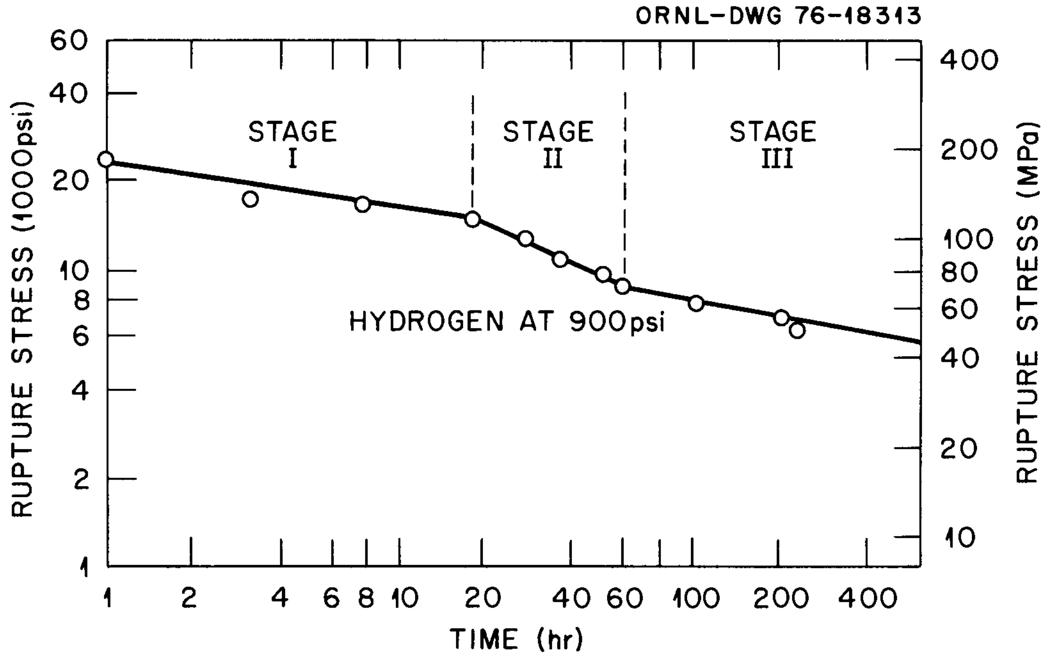

Fig. 3.4. Stress-rupture curves for SAF 1020 steel at 1000° F in hydrogen atmosphere at 900 psi pressure. Source: R. E. Allen, P. C. Rosenthal, and F. H. Vitovec, "Creep Rupture Behavior of Mild Steel under Conditions of Hydrogen Attack," *Proc. Am. Pet. Inst., Sec. 3,* 42(3), 464 471 (1962), Fig. 3. Reprinted by permission.

Additional work by Vitovec et al.[11,13] indicates that the ductility of a carbon steel can vary significantly with variations in hydrogen pressure and temperatures, even in the range of specimen life where the effect on rupture stress is small. Figure 3.5 from Combs and Vitovec[13] illustrates the effect at 1000°F (538°C) and 400 psi and 900 psig (2.8 and 6.2 MPa) hydrogen on the reduction in area at fracture of a 1020 steel. These data suggest that ductility decreases as the hydrogen pressure is increased; however, a recovery of ductility does occur when decarburization due to hydrogen attack is complete (900-psig coupon). In studying the effect of hydrogen on low-alloy steels, Vitovec also observed significant fluctuations in the ductility of $^1/_2$% Mo and 1% Cr–$^1/_2$% Mo alloy steels during 1000-hr tests (Fig. 3.6).

Additional work by Vitovec[14] has shown increased creep rates for ferritic steels in high-temperature, high-pressure hydrogen. More recently, increased creep rates and fatigue crack growth rates have also been reported for austenitic and nickel-based alloys, neither of which are susceptible to hydrogen attack.[15-17]

Three important points can be resolved from the previous discussion of high-temperature hydrogen degradation. Although resistance to hydrogen attack can be realized through the use of materials having increasingly higher levels of Cr and Mo, this solution may be economically prohibitive in view of the quantity of structural materials required in some proposed designs. Cursory data suggest that second-order factors, such as trace elements in the hydrogen environment (H_2S), phase of the environment (aqueous or gaseous), and metallurgical factors (heat-affected zone, heat treatment, etc., see Sect. 4.3.2), may alter the resistance of materials to such an extent that previous alloy selection criteria may not be effective in choosing hydrogen-resistant materials. Cursory short-term tests have shown that a high-temperature hydrogen environment can lead to failure under conditions considered safe by the Nelson curves.[5] Adequate long-term tests of both austenitic and ferritic materials under these conditions are not available. This information must be obtained in order to complete an accurate assessment of the long-term reliability of candidate materials in coal conversion applications.

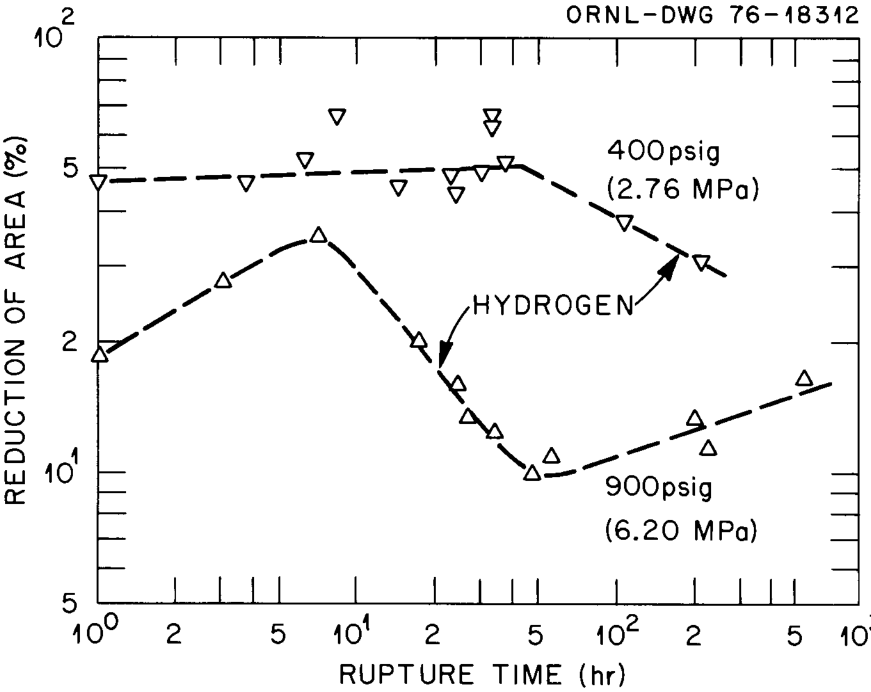

Fig. 3.5. Stress-rupture curves and reduction of area as a function of rupture time for SAE 1020 steel in argon and in hydrogen at 538°C (1000°F) and different pressures. Source: J. W. Combs, R. E. Allen, and F. H. Vitovec, "Creep and Rupture Behavior of Low Alloy Steels in High Pressure Hydrogen Environment," *J. Basic Eng., Trans. ASME* 87, 313–318 (1965), Fig. 3. Reprinted by permission.

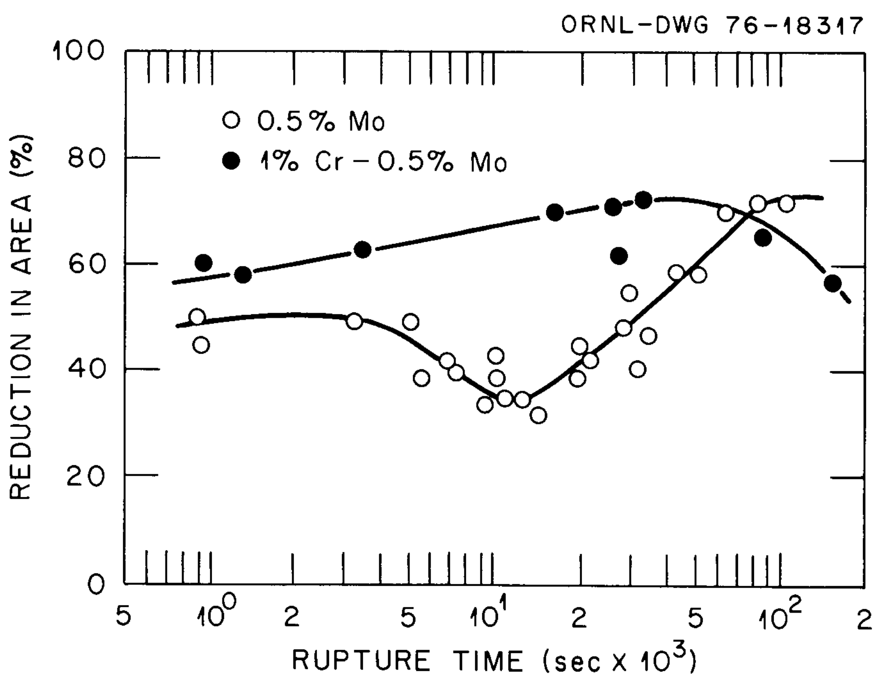

Fig. 3.6. Reduction in area as a function of rupture time for 1% Cr-½% Mo and 0.5% Mo steel in hydrogen at 540°C (1000°F) and 6.2 MPa (900 psig). Source: J. W. Combs, R. E. Allen, and F. H. Vitovic, "Creep and Rupture Behavior of Low Alloy Steels in High Pressure Hydrogen Environments," *J. Basic Eng., Trans. ASME* 87, 313–318 (1965), Fig. 4. Reprinted by permission.

3.2.2 High-temperature sulfidation

The effect of the H_2S on structural materials correlates strongly with the concentration of H_2 in the same environment. With H_2 present, low-chromium alloys are no more corrosion resistant than carbon-steel. As a result, most published corrosion rates for this environment do not distinguish between carbon steels and steels containing up to 5% Cr. In contrast, increasing additions of chromium significantly alter the corrosion resistance of steels in hydrogen-free environments.[18-20] Since coal conversion systems will operate with a relatively high partial pressure of hydrogen, primary attention will be given to sulfidation in H_2-H_2S environments.

High temperature sulfidation is characterized by the wastage of a material surface, and the rate of this wastage is principally influenced by time, temperature, pressure, and alloy content. Figure 3.7 characterizes the effect of time and temperature on the weight change of a 9 Cr–1 Mo steel exposed to an H_2-H_2S environment. This figure suggests that the initial rate of weight change is parabolic; however, after 300 to 400 hr, the rate of weight loss follows a linear relation with time. In view of this observation, it is not surprising to find that the corrosion product on a material surface exposed to a high-temperature H_2-H_2S environment is made up of two distinct scales. The outer scale is a porous layer, and spalling of this layer generally accounts for the weight loss observed. The inner scale is a tenacious, higher-density layer which forms to some equilibrium thickness and is thought to be an iron-chromium spinel ($FeCr_2S_4$).[21,22] It is believed that H_2S can rapidly penetrate through the porous scale, and subsequent growth of the porous layer is controlled by the outward diffusion of metal ions and electrons across the inner scale. Loss of this protective inner scale as a result of erosive wear could lead to catastrophic corrosion rates.[23] Based on the limited available data, designers should avoid exposures of unlined low-alloy surfaces to high-velocity, high-temperature environments containing entrained solid particles and levels of H_2S above 1 mole %. Erosion should not be a factor for the walls of gasifier vessels; during normal operation these vessels will have an internal ceramic lining. Such conditions could however be met in unlined transfer piping, unlined liquefaction reaction vessels, and gas scrubber systems.

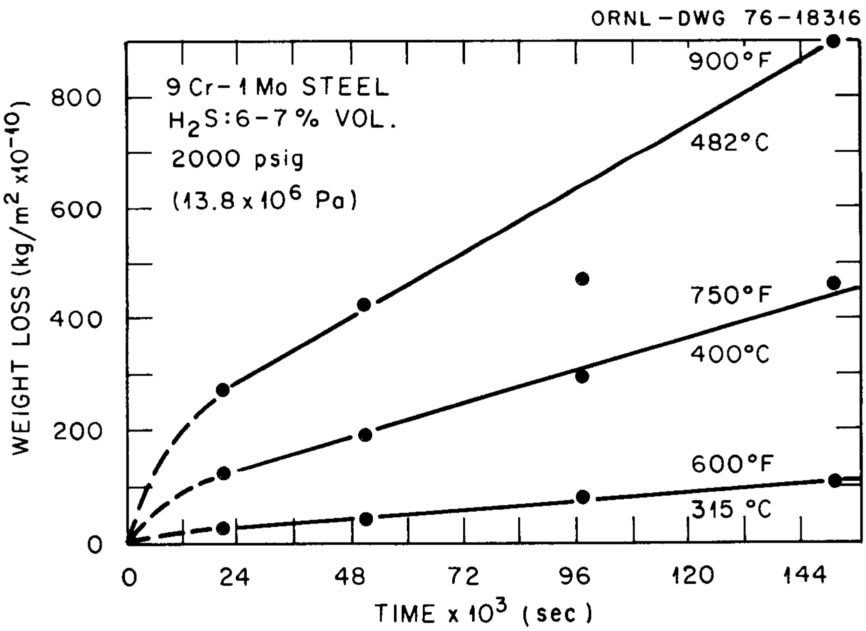

Fig. 3.7. Effect of time and temperature on corrosion of 9 Cr–1 Mo Steel. Source: J. D. McCoy and F. B. Hamel, "New Corrosion Data for Hydrodesulfurizers," *Hydrocarbon Process.* 49(6), 116–120 (June 1970), Fig. 2. Reprinted by permission.

Based on the kinetic factors described above, increases in H_2S concentration would not be expected to produce proportional increases in corrosion rates as higher levels of H_2S are reached. The work of McCoy[24] and Sharp[19] tends to support this observation for a variety of low Cr-Mo alloys. Figure 3.8 from McCoy[24] shows the effect of variations in the partial pressure of H_2S in an H_2-H_2S mixture on the weight loss of a 9 Cr—1 Mo alloy. This figure reveals that a maximum weight loss occurs at approximately 4×10^4 Pa (6 psi) partial pressure of H_2S. Other corrosion evaluations[19] of low Cr-Mo alloys at temperatures ranging from 320 to 480°C (600 to 900°F) in varying H_2S concentrations also showed no noticeable increase in the corrosion rate for H_2S concentrations above 1.0 mole %.

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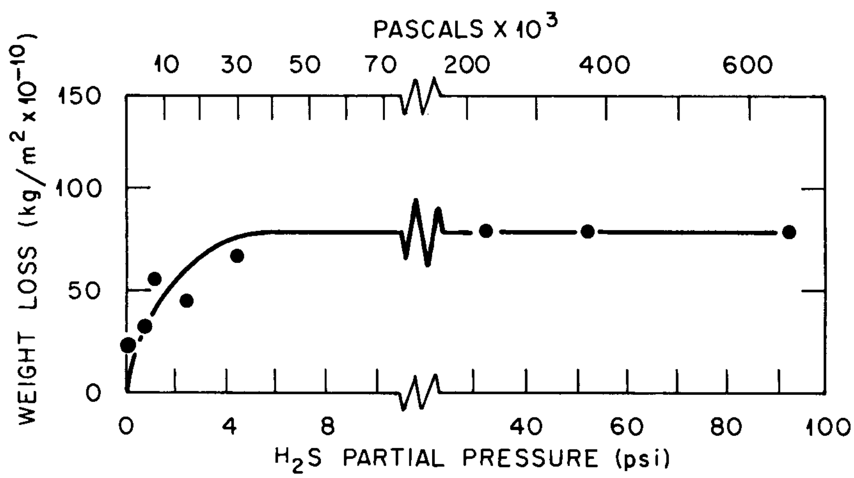

Fig. 3.8. Effect of H_2S pressure on corrosion of 9 Cr-1 Mo alloy steel. Test conditions were 515 psia (3.45 MPa), 700°F (371°C), 336 hr. Source: J. D. McCoy, "Corrosion Rates for H_2S at Elevated Temperatures in Refinery Hydrodesulfurization Processes," *Mater. Perform.* 13(5), 19–75 (1974), Fig. 8. Reprinted by permission.

The effect of alloy compositions becomes increasingly important above 600°F (316°C) in H_2S concentrations greater than 1%. This is illustrated in Fig. 3.9 (from the work of McCoy[24]), which suggests that materials exposed to high-temperature H_2S environments should, to maintain a corrosion rate of less than 5 mpy, contain at least 17 to 18% Cr; however, alloys with higher chromium content show little improvement in corrosion resistance.[25]

With regard to pressure vessels and piping in coal conversion systems, the above data suggest that low-alloy structural steels such as 2¼ Cr—1 Mo will be subject to significant H_2-H_2S attack at the required vessel wall temperature; however, the use of higher-alloy liners and/or claddings appears to be a practical solution to this problem. Further analysis of this information indicates that there are little or no data available that describe the responses of engineering materials to H_2-H_2S environments at temperatures above approximately 480°C (900°F). This has been recognized within the design of gasifier internals such as cyclones and fluidized-bed grates and is the subject of a DOE-funded investigation at the Illinois Institute of Technology Research Institute (IITRI).[23] A related problem arises due to the support (attachment) of the gasifier internals to the pressure vessel wall. Depending on the design details, localized heating of the pressure vessel material may occur, leading to increased sulfidation of the vessel material at these locations.

Until recently, material selection for applications in hot, gaseous H_2-H_2S environments was based on iso-corrosion curves generated by Bakensto et al.[18] This work was based on laboratory and pilot-plant testing of relatively short duration and led to results that were too conservative. Recently,

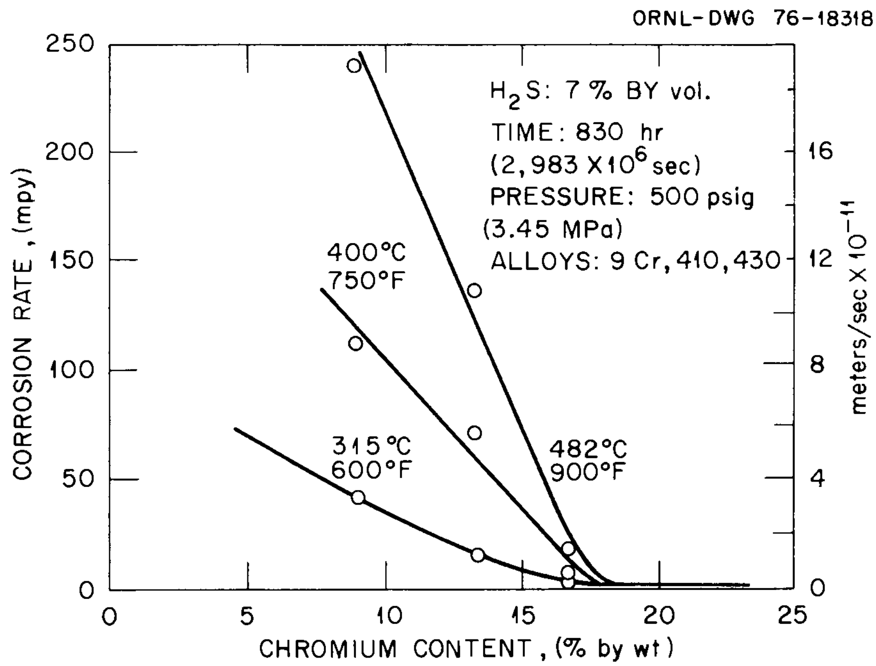

Fig. 3.9. Effect of chromium content on corrosion rate. Source: J. D. McCoy and F. B. Hamel, "New Corrosion Data for Hydrodesulfurizers," *Hydrocarbon Process.* 49(6), 116–170 (June 1970), Fig. 4. Reprinted by permission.

Couper and Gorman[20] used tests of 500 hr or more duration in commercial petrochemical units to develop revised iso-corrosion curves for selected alloys. Unfortunately, these iso-corrosion curves were derived from H_2-H_2S environments containing hydrocarbon diluents. One must question whether the response of materials to H_2-H_2S environments with petroleum distillates is similar to the response of these materials in coal conversion environments.

In passing, it should be noted that aluminide coatings represent an additional method of protecting low-alloy steel from corrosion in some high-temperature H_2-H_2S environments. Although application of aluminide coatings on an entire reactor vessel wall appears impractical, these coatings could see use in unlined transfer piping, piping flanges, and elbows, where flexure may lead to failure of ceramic insulation, and in anticipated hot spots of the vessel wall (i.e., areas where the vessel wall will support gasifier internals such as cyclones and grates). To illustrate the advantage of using an aluminide coating, McCoy[24] compared the corrosion rates of a 9 Cr–1 Mo alloy both with and without an aluminized coating. The results from exposures to H_2-H_2S mixtures at 370 and 480°C (700 and 900°F) are summarized as follows:

Temperature		Corrosion rate			
		Plain		Coated	
°C	°F	mm/year	mils/year	mm/year	mils/year
370	700	2.6	103.1	0.074	2.9
480	900	8.5	335.8	0.053	2.1

Despite these encouraging results from corrosion testing, application of aluminum diffusion coatings has several limitations. First, it is doubtful that reliable and corrosion-resistant welds can be made between two "aluminized" steels, since trace quantities of aluminum in steel promote hot cracking of welds. Second, only components that can be placed in a high-temperature retort can be aluminized; therefore, large and irregular-shaped components cannot be aluminized. Third, the aluminized coating is brittle, and only a minimum of bending at room temperature can be tolerated without cracking and exposing the base metal to subsequent attack. Fourth, the effect of localized "holidays" in the cladding on the corrosion rates of a low-alloy base metal could be catastrophic and should be evaluated. Such limitations illustrate the need for examination methods that will determine the uniformity and integrity of surface coatings (see Sect. 6.2.3).

The above analysis of high-temperature sulfidation leads to two important conclusions. First, low-alloy structural shell materials typically used in cold-wall pressure vessel and piping components may be required to withstand H_2-H_2S environments at temperatures ranging from 260 to 430°C (500 to 800°F), which will probably require the use of cladding or liner materials containing 17 to 18% Cr to protect the structural material from excessive sulfidation. Second, the limited data available indicates that structural materials containing high levels of chromium appear to have marginal resistance to H_2-H_2S environments at temperatures ranging from 820 to 980°C (1500 to 1800°F). Although these temperatures are above the normal operating range for piping and vessels, local areas could be exposed to such levels if there is a breakdown in the insulating refractories and/or at points where the hot internal components (i.e., cyclones and grates) are attached to the vessel wall for support.

3.3 Low-Temperature Compatibility Considerations

One important source of low-temperature compatibility data is the experience accumulated by the petroleum industry in catalytic crackers and hydrodesulfurizers. However, in many cases these data are not directly relevant to coal conversion processes because of basic differences in operating temperatures and pressures and in the types of organic compounds handled. Obviously, more data and experience are needed before an accurate assessment of low-temperature compatability problems in coal conversion systems can be made.

Among the important low-temperature problem areas in coal conversion systems that can be identified and that will be discussed in this section are (1) low-temperature hydrogen degradation, (2) erosion-corrosion, (3) aqueous corrosion, and (4) stress-corrosion cracking (SCC).

3.3.1 Low-temperature hydrogen degradation

Discussions of hydrogen degradation phenomena are hampered by a lack of universally accepted terminology. Therefore, the classifications of hydrogen damage suggested by Hirth and Johnson[26] have been adopted here for the principal forms of low-temperature hydrogen embrittlement: blistering, hydrogen environmental embrittlement, delayed cracking or hydrogen-assisted cracking, and loss of tensile ductility. A more definitive description of these classifications follows.

Deterioration due to hydrogen blistering begins with atomic hydrogen entering the surface, diffusing through the steel, and subsequently depositing as molecular hydrogen at a defect such as a lamination or nonmetallic inclusion. As more atomic hydrogen is made available to the material, the pressures of molecular hydrogen build at these defect sites, forming blisters. Defects of this type are generally associated with ductile materials such as carbon steel and have been observed in numerous refinery applications. Use of clean steels with a minimum of inclusions and laminar defects reduces the potential for failure.

All steels—ferritic, martensitic, and austenitic—containing hydrogen in solution exhibit some loss in tensile ductility. This loss of ductility is often characterized by a reduction in fracture strength, while the yield strength remains unchanged. The reduction in fracture strength is dependent on dissolved hydrogen content, as is illustrated in Fig. 3.10. Loss of tensile ductility is also sensitive to strain rate and temperature, as is illustrated in Fig. 3.11. Although this phenomenon can be minimized by alloying, some loss of tensile ductility is observed even in austenitic steels.

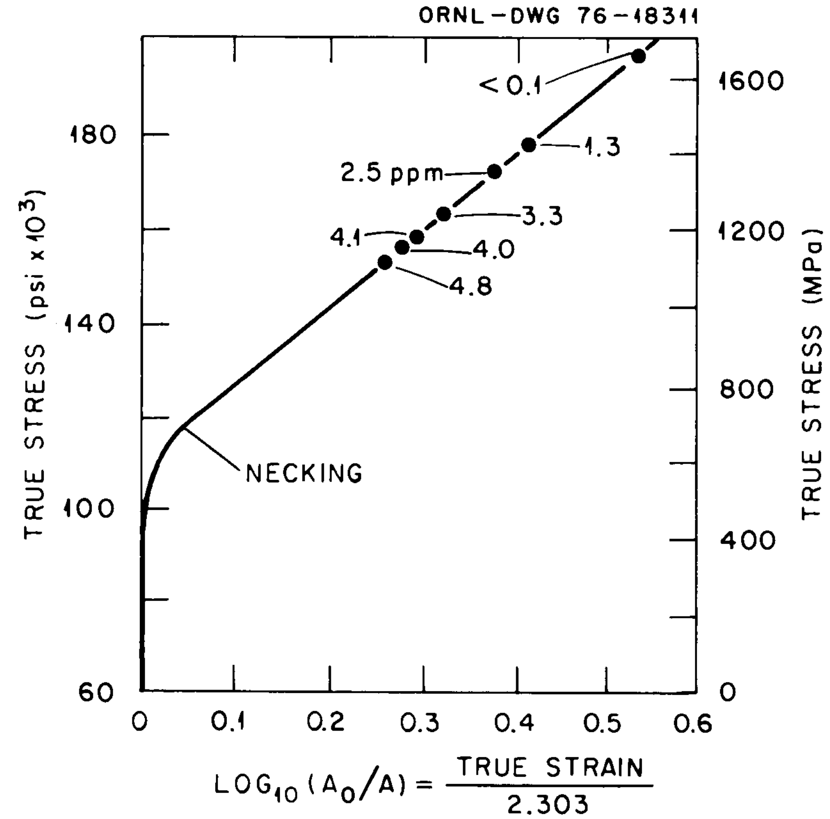

Fig. 3.10. True stress-strain curve for a hydrogen-impregnated 3 Cr–Mo steel. Source: C. G. Interrante, "Interpretive Report on Effects of Hydrogen in Pressure Vessels, Section I – Basic and Research Aspects," *Weld. Res. Counc. Bull.* No. 145, pp. 1–32 (1969), Fig. 7. Reprinted by permission.

In summary, the principal characteristics of these various forms of hydrogen embrittlement are presented in Table 3.3. With regard to coal conversion systems, those areas that appear to be potentially vulnerable to low-temperature hydrogen degradation are the structural shell materials in high-temperature reaction pressure vessels, the product-gas quenching systems, and the sour-water piping system. Focusing on the pressure vessel, one finds that structural materials in this system will be exposed to a high partial pressure of hydrogen while at a high temperature. Under these conditions, these materials can be expected to dissolve large quantities of hydrogen. Rapid cooldown of these systems may not allow sufficient time for the evolution of this hydrogen. As a result, high-stressed components and/or sharply notched components, such as threads and nozzles, will be vulnerable to delayed cracking.

Piping materials will be exposed to sour waters, sour gases, or a two-phase combination of both. The potential for sulfide cracking in either environment is well documented. In recognition of this problem, a National Association of Corrosion Engineers (NACE) standard practice report[31] suggests that sulfide cracking can be avoided by not exposing steels with yield strengths above 620 MPa (90 ksi) to sour environments. Because more recent data[32] suggests that this criterion may not be sufficient for the handling of the new high-sulfur crude oils, designers should question whether

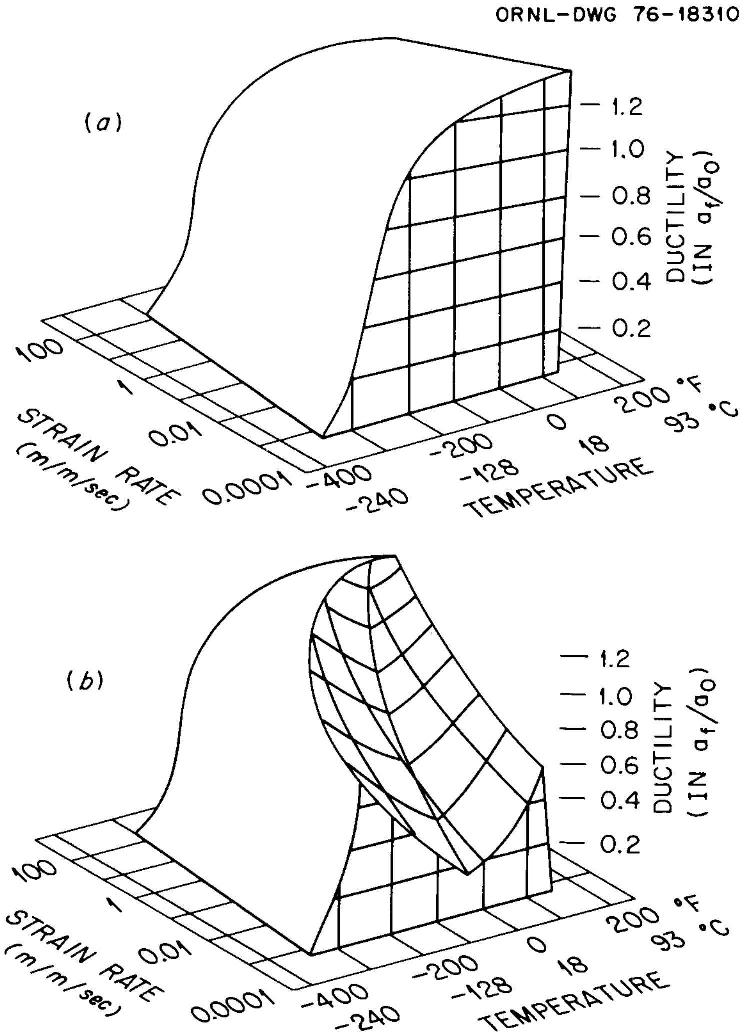

Fig. 3.11. Ductility of an SAE 1020 steel as a function of strain rate and temperature. (*a*) As annealed at 1250° F (677° C) 168 hr; (*b*) hydrogen-charged sample. Source: C. G. Interrante, "Interpretive Report on Effects of Hydrogen in Pressure Vessels, Section 1 – Basic and Research Aspects," *Weld. Res. Counc. Bull.* No. 145, pp. 1 32 (1969), Fig. 9. Reprinted by permission.

this criterion will be adequate for the materials handling the sour waters and gases produced from the conversion of high-sulfur coals.

The above discussion has pointed out several design alternatives or criteria that are used to avoid hydrogen embrittlement in practice. In practically all cases, these criteria are based on empirical observations from the refinery industry. Therefore, these engineering data may not reflect the long-term reliability of candidate materials in coal conversion environments. As a result, additional engineering data are needed. Specifically, quantitative determinations of cracking susceptibility, crack growth rates, and fatigue properties of engineering materials are needed in the low-temperature sour gases and liquid environments expected in coal conversion systems. Furthermore, information relating the effect of residual stresses, heat-affected zones, and microstructure to the propensity for hydrogen embrittlement will be valuable.

Another area requiring additional study is the effect of impure H_2 environments on hydrogen embrittlement. Preliminary data in this area suggest that oxygen may greatly reduce the adsorption of hydrogen on a metallic surface[33] and in turn reduce the potential for embrittlement. Additional studies indicate that CO_2 and SO_2 additions may also be beneficial.[26] The destructive influence of

Table 3.3. Summary of phenomenological classification of processes of hydrogen degradation of metals

	Hydrogen environment embrittlement	Hydrogen stress cracking	Loss in tensile ductility	Blistering
Typical materials	Steels, Ni-base alloys, metastable stainless steel, titanium alloys	Carbon and low-alloy steels	Steels, Ni-base alloys, Be-Cu bronze	Steels
Usual source of hydrogen (not exclusive)	Gaseous H_2	Thermal processing, electrolysis, corrosion	Gaseous hydrogen; internal hydrogen from electrochemical charging	Hydrogen sulfide corrosion; electrolytic charging
Typical conditions	10^{-6} to 10^{8} N/m² gas pressure (~10^{-10} to 10^{4} psi)	0.1 to 10 ppm total hydrogen content	0.1 to 10 ppm total hydrogen content; range of gas pressure exposure	Hydrogen activity equivalent to 3000 to 15,000 psi (0.2 to 1 × 10^{8} N/m²)
	Observed −100 to 700°C; most severe near 20°C	Observed −100 to 100°C; most severe near 20°C	Observed −100 to 700°C	0 to 150°C (30 to 300°F)
	Strain rate important; embrittlement more severe at low strain rate; generally more severe in notched or precracked specimens	Strain rate important; embrittlement more severe at low strain rate; always more severe in notched or precracked specimens	Occurs in absence of effect on yield stress; strain rate important	
Failure initiation	Surface or internal initiation; incubation period not observed	Internal crack initiation; incubation periods observed	Surface and/or internal effect	Internal defect
Mechanisms	Surface or sub-surface processes	Internal diffusion to stress concentration	Surface or sub-surfaces processes	Hydrogen diffusion, nucleation and growth of bubble

H_2S in refinery environments is well documented; however, the magnitude of this interaction at the possible concentration levels associated with the conversion of high-sulfur coal is not known. Studies relating to the influence of impurities on the hydrogen embrittlement of candidate materials could be valuable in identifying problem areas and could possibly indicate additions that could act as inhibitors.

3.3.2 Erosion and erosion-corrosion

Erosion refers to the mechanical damage to a metal surface produced by an abrasive and/or high-velocity environment. When the environment is also corrosive, the mechanisms of erosion and corrosion can combine to produce accelerated failures. Numerous potentially erosive environments are known to exist in both gasification and liquefaction systems, and failure of components due to erosion has been documented for both systems.[34]

In coal conversion systems, erosive wear can result from interactions between a surface and a rapidly flowing fluid environment or from the impingement of a surface with solid particles entrained in either a gaseous or fluid environment. The potential for significant metal loss from either environment is high. Models describing metal loss as a result of erosion from solid particles usually correlate attrition rates with the toughness characteristics of the material; therefore, materials can be categorized as being in either a "ductile" or "brittle" regime.[35] With regard to the ductile regime, Finnie[36] feels that metal loss is due to the cutting or abrasive action of the impinging particles, which is analogous to the cutting action of a machine tool. Mamoun[37] suggests that, in the brittle regime, the repeated impact of particles produces localized and highly stressed areas on the surface of a brittle material. Continued energy transfer to the surface of the brittle material will result in stresses in excess of the critical fracture stress, and fracture of the surface will follow. Subsequent detachment of this fractured volume from the solid produces a measurable wear rate.

As would be expected from the above discussion, experimental work has shown that the highest surface removal rate occurs when entrained particles impinge on a ductile surface at a relatively low angle. Since the largest quantity of energy can be transferred between impacting particles and a flat surface at impingement angles approaching 90°, the greatest wear rate for a brittle surface is observed at these high angles of impingement. Numerous other factors have been identified that may influence erosion rates. Some of these factors are particle size, particle shape, and surface properties.[35]

Since the majority of proposed reaction-vessel designs for coal conversion systems call for the use of internal ceramic insulations, structural shell materials should not be exposed to significant erosion attack. However, it is anticipated that the ceramic insulating material will be exposed to an aggressive and erosive environment. The resistance of these ceramic materials to this environment has not been well characterized (see Sect. 2.4.2).

Designers are also aware that internal pressure vessel components may be exposed to high-velocity char and ash particles entrained in high-temperature gas environments. Although the subject is not in the scope of this report, it should be noted in passing that this area is the subject of extensive experimental studies. Analysis of data from these tests indicates that this environment can be quite aggressive for many of the candidate alloys being considered for gasifier internals.[23]

However, more appropriate to this report is the potential erosive attack of materials exposed to liquid-solid mixtures, as in the coal solvent refining and the coal liquefaction processes. Pressure vessels and primary piping for these processing schemes could be designed to operate without internal ceramic insulation, and any erosion problems will be manifested at the pressure vessel wall. In view of the higher velocities of process liquids at nozzles, let-down valves, and process piping, these components could be vulnerable to the most severe erosion attack. At present, no screening tests are under way to evaluate the resistance of candidate pressure vessel and piping materials to erosive attack of solids entrained in synthetic crude oil or sour water environments.

Rapidly flowing fluids free of solid particles may constitute another potentially erosive environment in coal conversion systems. Only limited experimental data are available describing erosion wear in this type of environment. Principal factors influencing this potential wear phenomenon are the corrosive aggressiveness of the fluid in static conditions and the velocity of the fluid. Fluid velocity will affect the transfer rate of oxidizing species to the metal wall as well as the transfer rate of corrosion products from the wall. As a result, materials that exhibit an acceptable corrosion rate on static tests may fail catastrophically in a rapidly flowing environment. An example of this type of attack was reported in a recent survey of failures in petrochemical plants by Piehl,[38] who reported numerous catastrophic failures of sour-water piping systems within the temperature range of 38 to 200°C (100 to 400°F) which have occurred despite the use of NH_3 for pH control. The attack occurred only at piping locations subject to high velocities or turbulence conditions, such as elbows and U-bends. Although extensive static testing of candidate materials in a variety of aqueous environments is being carried out in the Metals Properties Council (MPC) testing conducted at IITRI,[23] Piehl's observations point out the need to also evaluate possible erosive-corrosive interactions in this type of screening test.

3.3.3 Stress-corrosion cracking

The fracture of a normally ductile metal when simultaneously exposed to an applied or residual tensile stress and to certain corroding chemical environments is called stress-corrosion cracking (SCC). Although considerable information has appeared in the literature regarding SCC of both ferritic and austenitic steels, theories and mechanisms describing these cracking processes are the subject of extensive discussions in the corrosion literature.

Because of the high corrosion resistance of austenitic stainless steels, large quantities are likely to be used in coal conversion systems. However, experience from both the refinery and the nuclear reactor industries has shown that under certain conditions stainless steels are highly susceptible to failure due to SCC. Although this type of failure can occur in a variety of environments, refinery experience tends to associate these failures to exposures to halide ions or polythionic acid. Since halide-induced SCC is well documented, the immediately following discussion will identify potentially dangerous areas in proposed coal conversion systems and then will briefly describe the source of polythionic acid and its influence on the cracking of austenitic stainless steels.

In a typical gasification system, raw coal is fed into the gasifier through a lock-hopper system. This coal, in the form of a slurry, is heated to 120°C (250°F) at 6.9 MPa (1000 psi). In this environment, chlorides are leached from the coal, and the slurry is slightly acidic (pH of 5 to 7).[39] Under these conditions, chloride cracking of austenitic steels could be a problem.

As indicated earlier (see Sect. 3.2.2), in order to avoid rapid sulfidation of low-alloy pressure vessel materials, designers will probably specify weld overlays of austenitic stainless on the interior contour of the gasifier vessel. Condensates containing chlorine could, however, form between the overlay and the refractory insulation, causing stress corrosion of the stainless steel overlay. Such failures have been observed in refinery systems; fortunately, propagation of these cracks is usually arrested at the base metal–overlay interface.[40] In view of this situation, however, designers should assure themselves that the internal surfaces of pressure vessel materials have sufficient toughness to stop crack propagation. In addition, the presence of condensate behind the vessel insulation could also lead to SCC of the austenitic stainless steel anchors.

An additional cracking agent for austenitic stainless steels is polythionic acid, $H_2S_xO_6$, where x usually is 3, 4 or 5. This acid is expected to form during the shutdown of a pressure vessel and is produced by oxidation of H_2S and/or sulfide corrosion scales. Contact between stressed and sensitized austenitic stainless steels and polythionic acid often results in intergranular corrosion and stress cracking.[41,42]

Samans[41,42] investigated polythionic stress cracking and found that regular grades of stainless steel (types 304 and 316) cracked in only a few hours in polythionic acids if the steel had been sensitized. He also found that the stabilized grades of stainless steel (types 321 and 347) were much more resistant to polythionic stress cracking and were essentially immune to cracking after a stabilizing anneal [900°C (1650°F)] for 4 hr.

Although the major point of this section has been to illustrate the susceptibility of austenitic steels to SCC, one should note that there is evidence that carbon steels may also be vulnerable to SCC. One potential means of cracking is sulfide embrittlement, which has been discussed previously; however, in work done for the British Gas Council, Parkins[43] discovered that the carbon steels are prone to cracking in solutions containing NH_3, H_2S, CO_2, and HCN. Although Parkin's work is incomplete, he does suggest that cracking tends to occur only with specific ratios of NH_3 and acid gases. Such cracking conditions could possibly be met in both the process piping and the gas quench systems.

One of the primary ways of reducing stress-corrosion cracking is to modify the environment by elimination of the active corrodent, changing the pH of the effluents, or adding inhibitors. In the petroleum industry, these modifications are accomplished by adding NH_3 to maintain the pH of the aqueous solution at values between 7 and 9, and by adding inhibitors such as filming amines.[44] However, even with these controls, SCC failures continue to be observed.

Another solution to the problem of stress-corrosion cracking of stainless steels is to use alternative materials. In an effort to reduce the number of failures by cracking, many petroleum systems designers specify low-alloy steels and nickel-based alloys in place of austenitic stainless steels. These substitutions are made in spite of the higher cost of nickel-based alloys and the higher corrosion rates expected from carbon steels.

As can be seen from the above discussion, SCC of austenitic steels and, possibly, of carbon steels in coal conversion systems should be anticipated. In many instances, there are no obvious design alternatives to this problem that appear practical from an economic and design standpoint.

This section has attempted to review the compatibility experience developed in related industries as a means to identify potential problem areas in coal conversion systems. As would be expected, numerous potential compatibility problems were identified that to a large extent, apparently could be solved by use of more highly alloyed materials and/or special surface coatings. Collectively, however, these solutions tend towards significant economic penalties when the overall coal conversion system is considered.

Furthermore comparative analysis of compatibility problems in complex systems quite often fails to identify some serious compatibility problems. Therefore, the DOE/industry efforts to characterize the operating conditions of coal conversion systems must be accelerated if we are to meet the energy needs of the 1980s.

Hydrogen stress cracking (or delayed cracking) results in brittle fractures of nominally ductile ferritic steels under sustained loads at tensile stresses below the yield strength. Troiano[27] has suggested that hydrogen stress cracking normally involves three events: incubation, crack initiation, and crack propagation. This series of events is depicted in Fig. 3.12, which shows two stress-time curves, one for crack initiation and one for fracture. The two curves in this figure are bounded by two stress levels, an upper critical stress (UCS) and a lower critical stress (LCS). Applied stresses above the UCS result in failure without time delay, while stresses below LCS result in no failure. At intermediate stress levels, failure is inevitable. In addition, an increase in hydrogen content and/or strength level tends to decrease both the upper and lower critical stresses and the delay time for failure.

A possible adjunct to delayed cracking is hydrogen sulfide stress cracking. Despite the magnitude of this problem in both the petroleum and natural-gas industries, the mechanisms associated with this failure mode are not well understood. In general,[28] it is thought that H_2S reacts with metal surfaces to form metal sulfides and nascent hydrogen, which readily dissolves in the material. Subsequent cracking of a material could be explained on the basis of hydrogen delayed cracking.[28,29] Increases in H_2S concentration and temperature decrease the critical stress required to cause cracking.[28-30] On the other hand, high-pH solutions generally reduce susceptibility to cracking.[29,30] The primary material factor influencing the susceptibility to sulfide cracking is strength; therefore, the petroleum industry reduces the potential of sulfide cracking by not exposing steels or weldments with yield strength greater than 621 MPa (90 ksi) or R_C 22 to sour environments.[31]

Hydrogen environmental embrittlement[26] results in degradation in mechanical properties of ferritic steels, nickel-based alloys, and metastable austenitic steels when these materials are

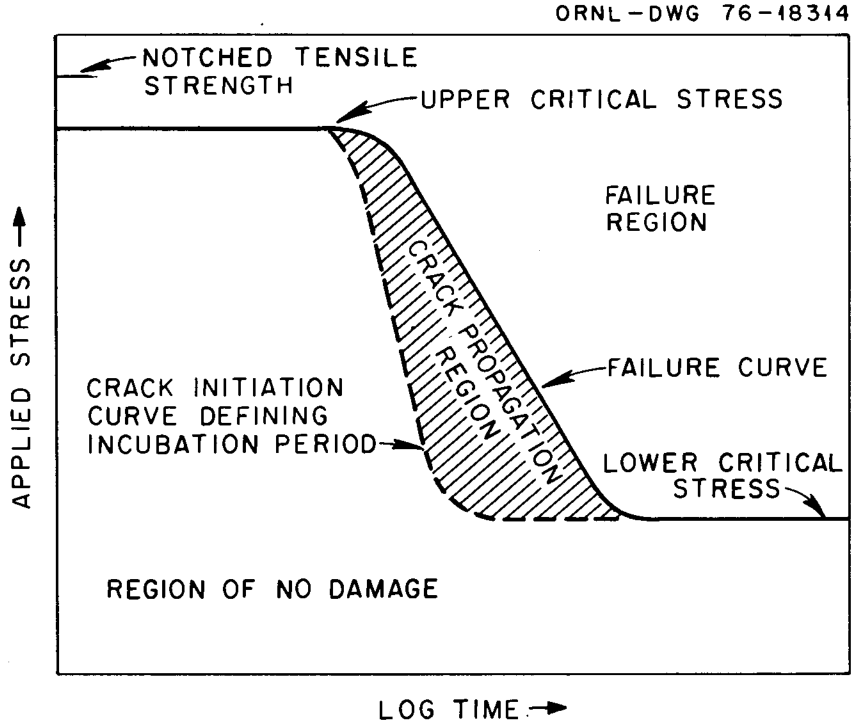

Fig. 3.12. Schematic drawing of characteristic failure behavior of notched tension specimens containing hydrogen. Source: C. G. Interrante, "Interpretive Report on Effects of Hydrogen in Pressure Vessels, Section 1 – Basic and Research Aspects," *Weld. Res. Counc. Bull.*, No. 145, pp. 1 32 (1969), Fig. 12. Reprinted by permission.

plastically deformed in contact with gaseous hydrogen. Hydrogen environmental embrittlement is not limited to materials with an ultimate tensile strength above a certain minimum; however, the effect is more pronounced at higher strength levels. Principal factors influencing hydrogen environmental embrittlement are hydrogen pressure, strain rate, and temperature. With regard to temperature effects, nickel-based alloys have been found to be susceptible to this form of embrittlement at 700°C (1292°F); however, low-alloy pressure vessel materials are not expected to be influenced by this phenomenon at their respective operating temperatures. On the other hand, this form of degradation could be a serious problem for piping materials handling moderate-temperature, low-Btu gas.

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4. MATERIAL PROPERTIES*

4.1 General Considerations

Once a process has been optimized for commercial applications, one of the most influential factors in the efficient (and safe) operation of a coal conversion system is material reliability. The significance of material reliability in conversion processes is particularly evident in the experience[1] to date with process development units (PDU) and pilot plants (PP) that are operating under the sole sponsorship of DOE or in cooperative DOE-industry programs. The ERDA survey[1] has identified a number of components that have failed; however, as shown in Table 1.1, very few of these components have a major influence on the continued operation of the coal conversion system. Table 1.1 identifies the components that result in an extended plant outage as the piping and pressure vessels. This section is concerned with the properties of materials for pressure containment applications and those metallurgy-related factors that will affect their performance.

Assurance of reliable service of one of these difficult-to-replace, long-lead-time pressure vessels is impaired by the severe operating conditions under which these components must function. The process stream temperatures in gasification systems are as high as 1480°C (2700°F), and the pressures are near 8.3 MPA (1200 psi). The liquefaction systems operate at lower temperatures and higher pressures. Tables 1.2 and 1.3, respectively, provide the temperature and pressure requirements for a number of gasification and liquefaction processes. The vessel sizes suggested by a number of conceptual designs to accommodate these process systems are larger than any that have been previously built[2,3] and, as such, tax the limits of our processing technology for plates, forgings, and piping.

Although refractory liners are not within the scope of this document, the need to protect the vessel from the environment (process stream and temperature) requires that some consideration be given to the effect of the liner materials on the pressure-containment component. These liner materials include the thick refractories required to protect the pressure vessel and piping from the high-process temperature, as well as the wear-resistant coatings that may be applied to minimize erosion and wear. Further, the internals, which are not part of this report, should be considered during design and operation because the need to support them will require attachments that may affect the properties of the vessel. Refractory liner materials were briefly discussed in Section 2.4.2.

Consideration of all possible materials for pressure vessels and piping for coal conversion systems would be prohibitive in cost. However, the conceptual designs that have been completed by some engineering firms do suggest a number of likely materials. This chapter will direct its attention (not, however, to the exclusion of all other materials) primarily to those materials which have been identified by the A-Es as candidates for construction.

Material requirements will be discussed relative to specifications in codes and standards. These standards usually include chemical composition, minimum mechanical property requirements, fabrication methods, size limitations, and heat treatment. It is the intent of this chapter to point out those areas within the scope of current technology that will improve the reliability of the coal conversion systems. The chapter discusses metallurgical considerations in order to amplify the importance of such factors as chemical composition, processing history, microstructure, size, and joining, which determine a material's behavior in a given application. This chapter also includes an examination of the effects of the operating conditions, specifically temperature and process stream environment, on those long-term mechanical properties that determine whether a specific material is the correct choice for the lifetime (20 to 30 years) of a commercial plant.

*This section was prepared by R. K. Nanstad and D. A. Canonico.

4.2 Material Specifications

4.2.1 General

The ASME Code, Section II, Part A, provides specifications for plate and forging steels that can be considered for thick-walled vessels for coal conversion systems. Tables 4.1 and 4.2 provide a number of these specifications for candidate steels that have been limited to those cited because the economics of fabricating the extremely large pressure vessels proposed for some coal conversion systems will dictate their use. High-alloy steels (such as the stainless steels and high-nickel alloys) will probably be too costly for consideration as basic strength members (although necessary as liners to resist corrosion). The tables cite a number of alloys, but it is most likely that the fabrication of the larger pressure vessels will be limited to Code approved steels, such as SA 387 Grade 22 Class 2, and SA 533 Grade B Class 1.

Tables 4.1 and 4.2 show that there are a number of specifications that are indeed candidate materials; however, each has a limitation that minimizes its selection. For example, the plain carbon steels, because of their poor hardenability, are normally available in section sizes that are limited to about 200 mm (8 in.). The SA 516 Grade 70, a prime candidate, is not available in section sizes above 8 in. Only the Grade 55 of SA 516 is normally available in section sizes up to 300 mm (12 in.). Specification SA 515 is nearly identical to SA 516; however, SA 515 is designed for intermediate- and elevated-temperature service. It is likely that these coal conversion vessels will operate warm [about 320°C (600°F)] and may, during their lifetime, be subjected to a thermal excursion above their nominal design temperature. This thermal excursion, however, will be of short duration, and the need for elevated-temperature properties will probably not govern the material choice. There is a stronger likelihood that a rapid cooldown could occur, and the superior notch toughness exhibited by the SA 516 alloy will make it more attractive for coal conversion applications.

Another candidate material is $2^1/_4$ Cr–1 Mo steel (SA 387 Grade 22, SA 336 F22), a steel which has been frequently employed in the fabrication of pressure vessels. It is often used because of its superior resistance to environmental attack and its higher strength at elevated temperatures. Grade 21 (3 Cr–1 Mo) of SA 387, because of its increased resistance to hydrogen attack, may offer an attractive alternate to $2^1/_4$ Cr–1 Mo. The SA 387 Grade 22 specification is usually employed for steel plate that is to be normalized and tempered (N&T) (Class 2) or annealed (Class 1). There is a specification for quenched and tempered (Q&T) $2^1/_4$ Cr–1 Mo steel (SA 542), but it probably will not be employed for coal conversion pressure vessels[3] [SA 387 allows accelerated cooling (par. 5 of the specification) when permitted by the purchaser. It is necessary to quench and temper thick sections of $2^1/_4$ Cr–1 Mo steel in order to satisfy the mechanical property requirements of SA 387 Grade 22 Class 2 steel].

Frequently interest is shown in higher-strength steels, but, in most cases these are not currently ASME Code approved. Tables 4.1 and 4.2 contain examples of plate and forging specifications for steels that have ultimate tensile strengths in excess of 687 MPa (100,000 psi). (These steels are commercial adaptations of the submarine hull steels commonly referred to as HY 80 and HY 100.) The A 543 (ASTM specification) analysis and the A 508 Classes 4 and 5 are permitted for use in specific pressure-containing applications through ASME Code cases.

Selection of piping materials will generally be limited to carbon steel, low-alloy steels (up to 9% Cr and 1% Mo), the austenitic and ferritic stainless steels, and some special materials, such as Incoloy 800.

Tables 4.1 and 4.2 provide the minimum room-temperature mechanical property requirements and (when applicable) the size limitations provided in the various specifications. It is evident that many specifications do not limit the thickness. They do, however, require that the minimum room-temperature mechanical properties be satisfied. The suggested maximum available plate thickness given

Table 4.1. Candidate plate steels for pressure vessels with wall-thickness requirements of greater than 4 in.

Steel identification[a]	Grade (class)	Chemical requirements (wt %) C[b]	Mn	P	S	Si	Mo	Ni	Cr	V	Maximum available plate thickness in. (mm)	Tensile requirements UTS ksi (MPa)	Yield Point ksi (MPa)	Elongation in 2 in. (5.1 cm) (%)	Reduction in area (%)
SA 203	A	0.23	0.80	0.035	0.040	0.13/0.32		2.03–2.57			6 (150)[c,d]	65–85 (450–585)	37 (255)	23	
	B	0.25	0.80	0.035	0.040	0.13/0.32		2.03–2.57			6 (150)[c,d]	70–90 (485–620)	40 (275)	21	
SA 204	A	0.25	0.90	0.035	0.040	0.13/0.32	.41/.64				6 (150)[c,d]	65–85 (450–585)	37 (255)	23	
	B	0.27	0.90	0.035	0.040	0.13/0.32	.41/.64				6 (150)[c,d]	70–90 (485–620)	40 (275)	21	
SA 299		0.30	0.86/1.55	0.035	0.040	0.13/0.33					8 (203)[c,d]	75–95 (515–655)	40 (275)	19	
SA 302	A	0.25	0.90/1.35	0.035	0.040	0.13/0.32	.41/.64				d	75–95 (515–655)	45 (310)	19	
	B	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64				d	80–100(550–690)	50 (345)	18	
	C	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64	.37/.73			d	80–100(550–690)	50 (345)	20	
	D	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64	.67/1.03			d	80–100(550–690)	50 (345)	20	
SA 387	2(1)	0.21	0.51/.84	0.035	0.040	0.13/0.32	.40/.65		.46/.85		d	55–80 (380–550)	33 (230)	22	
	(2)										d	70–90 (485–620)	45 (310)	22	
	12(1)	0.17	0.36/.69	0.035	0.040	0.13/0.32	.40/.65		.74/1.21		d	55–80 (390–550)	33 (230)	22	
	(2)										d	65–85 (450–585)	40 (275)	22	
	11(1)	0.17	0.36/.69	0.035	0.040	0.44/0.86	.40/.70		.94/1.56		d	60–85 (415–585)	35 (240)	22	
	(2)										d	75–100(515–690)	45 (310)	22	
	5(1)	0.15	0.27/.63	0.040	0.030	0.55	.40/.70		4.00/6.00		d	60–85 (415–585)	30 (205)	18	45
	(2)										d	75–100(515–690)	45 (310)	18	45
	21(1)	0.17	0.27/.63	0.035	0.035	0.50	.85/1.15		2.63/3.37		d	60–85 (415–585)	30 (205)	18	45
	(2)										d	75–100(515–690)	45 (310)	18	45
	22(1)	0.17	0.27/.63	0.035	0.035	0.50	.85/1.15		1.88/2.62		d	60–85 (415–585)	30 (205)	18	45
	(2)										d	75–100(515–690)	45 (310)	18	45
SA 515	55	0.28	0.90	0.035	0.04	0.13/0.33					12 (305)[c,d]	55–75 (380–515)	30 (207)	27	
	60	0.31	0.90	0.035	0.04	0.13/0.33					8 (203)[c,d]	60–80 (415–550)	32 (220)	25	
	65	0.33	0.90	0.035	0.04	0.13/0.33					8 (203)[c,d]	65–85 (450–585)	35 (240)	23	
	70	0.35	0.90	0.035	0.04	0.13/0.33					8 (203)[c,d]	70–90 (485–620)	38 (260)	21	
A 516	55	0.26	0.56/1.25	0.035	0.04	0.13/0.33					12 (305)[c,d]	55–75 (380–515)	30 (205)	27	
	60	0.27	0.80/1.25	0.035	0.04	0.13/0.33					8 (203)[c,d]	60–80 (415–550)	32 (220)	25	
	65	0.29	0.80/1.25	0.035	0.04	0.13/0.33					8 (203)[c,d]	65–85 (450–585)	35 (240)	23	
	70	0.31	0.80/1.25	0.035	0.04	0.13/0.33					8 (203)[c,d]	70–90 (485–620)	38 (260)	21	
SA 533	A(1)	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64				12 (305)[c,d]	80–100(550–690)	50 (345)	18	
	(2)										12 (305)[c,d]	90–115(620–795)	70 (485)	16	
	B(1)	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64	.37/.73			12 (305)[c,d]	80–100(550–690)	50 (345)	18	
	(2)										12 (305)[c,d]	90–115(620–795)	70 (485)	16	
	C(1)	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64	.67/1.03			12 (305)[c,d]	80–100(550–690)	50 (345)	18	
	(2)										12 (305)[c,d]	90–115(620–795)	70 (485)	16	
	D(1)	0.25	1.10/1.55	0.035	0.040	0.13/0.32	.41/.64	.17/.43			12 (305)[c,d]	80–100(550–690)	50 (345)	18	
	(2)										12 (305)[c,d]	90–115(210–795)	70 (485)	16	
SA 542	(1)	0.15	0.27/.63	0.035	0.035	0.13/0.32	.85/1.15		1.88/2.62		d	105–125(725–860)	85 (585)	14	
	(2)										d	115–135(790–930)	100 (690)	13	
A 543	B[e](1)	0.23	0.40	0.020	0.020	0.18/0.37	.41/.64	2.93/4.07	1.44/2.06	.03	d	105–125(725–862)	85 (585)	14	
	(2)											115–135(795–930)	100(690)	14	
	(3)											90–115(620–795)	70 (485)	16	

[a]Specifications designated SA have been taken from the *ASME Boiler and Pressure Vessel Code, Section II, Part A* (1977 ed.). Those designated A have been taken from the *1976 Annual Book of ASTM Standards, Part 5.*

[b]Maximum carbon content based on requirements for thickest plates.

[c]Current practice normally limits the specification to this thickness.

[d]Maximum thickness is limited only by the capacity of the chemical composition to meet specified minimum mechanical properties.

[e]Only type B has been listed; however, a type A can also be specified, with the only difference being higher allowable phosphorous (0.035 max) and sulfur (0.040 max).

Table 4.2. Candidate forging steels for pressure vessels and components

Steel iden-tifi-cation[a]	Grade (class)	Chemical requirements (wt %)[b,c]									Maximum available thickness[d]	Tensile Requirements[e]			
		C	Mn	P	S	Si	Mo	Ni	Cr	V	in. (mm)	UTS ksi (MPa)	Yield pt. ksi (MPa)	Elong. in 2 in., %	Reduction in area, %
SA 266	(1)	0.35	0.40/0.90	0.040	0.040	0.15/0.35						60–85 (415–585)	30 (205)	23	38
	(2)	0.35	0.40/0.90	0.040	0.040	0.15/0.35						70–95 (485–655)	35 (240)	20	33
	(3)	0.50	0.50/0.90	0.040	0.040	0.35						75–100(515–690)	37.5(260)	19	30
SA 336	(F1)	.20/.30	0.60/0.80	0.040	0.040	0.20/0.35	0.40/0.60					70–95 (485–655)	40 (275)	20	30
	(F12)	.10/.20	0.30/0.80	0.040	0.040	0.10/0.60	0.45/0.65		0.80/1.10			70–95 (485–655)	40 (275)	18	25
	(F5)	0.15	0.30/0.60	0.030	0.030	0.50	0.45/0.65	0.50	4.0/6.0			60–85 (415–585)	36 (250)	19	35
	(F5a)	0.25	0.60	0.040	0.030	0.50	0.45/0.65	0.50	4.0/6.0			80–105(550–725)	50 (345)	19	35
	(F21)	0.15	0.30/0.60	0.030	0.030	0.50	0.80/1.06		2.65/3.25			75–100(515–690)	45 (310)	18	35
	(F21a)	0.15	0.30/0.60	0.030	0.030	0.50	0.80/1.06		2.65/3.25			60–85 (415–585)	30 (205)	20	35
	(F22)	0.15	0.30/0.60	0.030	0.030	0.50	0.90/1.10		2.00/2.50			75–100(515–690)	45 (310)	18	25
	(F22a)	0.15	0.30/0.60	0.030	0.030	0.50	0.90/1.10		2.00/2.50			60–85 (415–585)	30 (205)	20	35
	(F30)	0.45	0.50/0.90	0.040	0.040	0.15/0.45	0.30/0.60			.10/.25		80–105(550–725)	50 (345)	21	35
	(F31)	0.35	0.50/0.90	0.040	0.040	0.10/0.40	0.20/0.50	2.25/3.00		.15		95–120(655–825)	70 (485)	18	35
	(F32)	0.35	0.50/0.90	0.040	0.040	0.15/0.45	0.30/0.50	0.50/1.00	3.00/3.60	.05/.15		100–125(690–860)	60 (415)	18	35
A 508	(1)	0.35	0.40/0.90	0.025	0.025	0.15/0.35	0.10	0.40	0.25	.05		70–95 (485–655)	35 (240)	20	38
	(2)	0.27	0.50/0.90	0.025	0.025	0.15/0.35	0.55/0.70	0.50/1.00	.25/.45	.05		80–105(550–725)	50 (345)	18	38
	(2a)	0.27	0.50/0.90	0.025	0.025	0.15/0.35	0.55/0.70	0.50/1.00	.25/.45	.05		90–115(620–795)	65 (450)	16	35
	(3)	15/.25	1.20/1.50	0.025	0.025	0.15/0.35	0.45/0.60	0.40/1.00	0.25	.05		80–105(550–725)	50 (345)	18	38
	(4)	0.23	0.20/0.40	0.020	0.020	0.30	0.40/0.60	2.75/3.90	1.50/2.00	.03		105–130(725–895)	85 (585)	18	45
	(4a)	0.23	0.20/0.40	0.020	0.020	0.30	0.40/0.60	2.75/3.90	1.50/2.00	.03		115–140(795–965)	100 (690)	16	45
	(4b)	0.23	0.20/0.40	0.020	0.020	0.30	0.40/0.60	2.75/3.90	1.50/2.00	.03		90–115(620–795)	70 (485)	20	48
	(5)	0.23	0.20/0.40	0.020	0.020	0.30	0.40/0.60	2.75/3.90	1.50/2.00			105–130(725–895)	85 (585)	18	45
	(5a)	0.23	0.20/0.40	0.020	0.020	0.30	0.40/0.60	2.75/3.90	1.50/2.00			115–140(795–965)	100 (690)	16	45
SA 541	(1)	0.35	0.40/0.90	0.050	0.050	0.15/0.35				.05	3 (76.2)	70–95 (485–655)	35 (240)	20	38
	(2)	0.27	0.50/0.80	0.035	0.040	0.15/0.35	0.55/0.70	0.50/0.90	.25/.45	.05	8 (203)	80–105(550–720)	50 (345)	18	38
	(3)	.15/.25	1.20/1.50	0.035	0.040	0.15/0.35	0.45/0.60	0.40/0.80		.05	8 (203)	80–105(550–720)	50 (345)	18	38
SA 592 (identi-cal with SA 517) A,E,F	A[f]	.15/.21	0.80/1.10	0.035	0.040	0.40/0.80	0.18/0.28		.50/.80		1.5 (38.1)	115–135(795–930)	100 (690)	18	45
	E[g,h]	.12/.20	0.40/0.70	0.035	0.040	0.20/0.35	0.40/0.60		1.40/2.00		3.75(95.2)	105–135(725–930)	90 (620)	17	40
	F[g,i]	.10/.20	0.60/1.00	0.035	0.040	0.15/0.35	0.40/0.60	0.70/1.00	0.40/0.65	.03/.08	3.75(95.2)	105–135(725–930)	90 (620)	17	40

[a]Specifications designated SA have been taken from the *ASME Boiler and Pressure Vessel Code, Section II, Part A* (1974 ed., with Addenda through Winter 1975). Those designated have been taken from the *1976 Annual Book of ASTM Standards, Part 4.*

[b]Where single values are given, they represent the maximum content allowed.

[c]Values provided are ladle analysis requirements. Permissible variations in check analyses for each element are provided in each specification.

[d]Where thickness limits are not given, the thickness is limited only by the capacity of the composition to meet the specified mechanical properties.

[e]Minimum Charpy V-notch impact requirements are specified for some materials in the appropriate specification.

[f]Includes requirement for Zr, 0.05/0.15; B, 0.0025 max.

[g]Mechanical properties listed for Grades E and F of SA 592 are based on thicknesses over 2.5 to 4.0 in. (63.5 to 101.6 mm). For thicknesses of 2.5 in. (63.5 mm) and less, the mechanical properties are the same as given for Grade A.

[h]Includes requirements for Cu, 0.20/0.40; B, 0.0015/0.005; Ti, 0.04/0.10 (V may be substituted on a one-to-one basis).

[i]Includes requirements for Cu, 0.15/0.50; B, 0.002/0.006.

in Table 4.1 is 305 mm (12 in.). This value is near the maximum thickness that current technology can provide; the upper limit is reported[2,4] to be about 356 mm (14 in.). Usually, the plate specifications are employed for wall thicknesses up to about 203 to 254 mm (8 to 10 in.). Forging grades are used for the heavier-wall thicknesses. The procurement practices and processing of plates, forgings, and pipes are discussed in Chapter 5.

None of the specifications in the ASME or ANSI Codes or ASTM standards have requirements for qualifying the materials at elevated temperatures or in associated process environmental conditions. The ASME Code requires only that the designer consider environmental effects. All that is demanded of a material is that it satisfy the minimum mechanical property requirements at room temperature. Allowable stress values are provided over a range of temperatures for each material in the tables of the ASME and ANSI Codes. However, these stress values are based on trend curves which are derived from experience with individual alloy grades, and no elevated-temperature tests are required on heats of steel to assure that they satisfy the minimum values upon which the allowable stresses are based. In the case of most coal conversion systems, the knowledge of specific process conditions is limited. Most of the experience upon which a judgment of environmental effect is based is obtained in PDU and PP operations. However, the much greater size of commercial plants [perhaps up to 9.75 m (32 ft) in diameter] may introduce inconsistencies in the process, and these effects cannot be measured in small experimental vessels. The large size of the vessels cited in many of the conceptual designs will require that the materials employed be near the limits of current steel-making technology. Further, as is discussed in Chapter 5, size will tax current field fabrication, field heat treating, and field examination technologies.[3]

The long-term reliability and safety of pressure-containing components are dependent on the ability of a material to resist crack initiation and growth. Among the Codes considered by coal conversion system designers, only the ASME Code, Section VIII, Division 2, provides an assessment (through fatigue analysis) of crack initiation resistance. None of the codes considers a material's resistance to crack growth. Indeed, the fracture toughness requirements in the various Codes is minimal. The ASME Code only requires that the material from which the pressure vessel is fabricated exhibit 20 to 27 joules (15 to 20 ft-lbs) Charpy V-notch (C_V) toughness at the lowest service temperature. The Code does not consider section size: the requirements are the same for 25.4-mm-thick (1 in.) plate as they are for 305-mm-thick (12 in.) plate. Fracture toughness, because it controls the behavior of structures under fatigue loading and under flawed conditions, is one of the more important considerations in the analysis of the adequacy of a pressure-containment component to achieve its intended service life satisfactorily. The phenomenon of crack growth resulting from fatigue or environmental effects can lead to flaws that may grow to critical size and result in rupture. In view of the minimal fracture toughness requirements in Section VIII of the Code, this aspect of reliable service rests solely with the designer. Reputable A-Es and fabricators require that the materials used in the fabrication of large pressure vessels exhibit C_V toughness values considerably in excess of those required by the Code. For example, Chicago Bridge and Iron,[5] in their cost comparison between field-fabricated and shop-fabricated pressure vessels for a second generation coal gasification system, required in their Users Design Specification 52 joules (40 ft-lbs) at 10°C (50°F). This requirement serves two purposes: (1) it provides a C_V energy considerably above the minimal Code values, and (2) it assures an upper shelf energy of at least 52 joules.

The basis for most material specifications is tensile properties. In some instances, toughness may be required; however, as was mentioned above, the requirements, particularly for thick sections, are minimal. The codes provide allowable stresses for design based on tensile properties or creep and stress-rupture properties, depending on the temperatures of interest. The allowable stresses in the code are considered conservative. The basis for establishing stress values is provided in Appendix P and

Appendix 1 of Section VIII, Divisions 1 and 2, respectively, and in par. 302.3 of ANSI B31.3-1976. The effect of environment, per se, is not addressed in the Code. The Code recognizes that environment may have an effect on the reliability of a component; however, it is the user's responsibility to consider this problem [e.g., see par. A 301.1(b) of Section VIII, Division 2]. The choice of material involves a number of factors other than mechanical properties. The selection is indeed one of continual integration between a material's fabricability, availability, and cost, as well as its design-allowable stresses and its behavior under operational conditions. The choice of materials for pressure-containment applications is logically limited to those alloys permitted by the codes, since these incorporate the principal fabricator experience. Generally, the materials will fall into two categories—carbon and low-alloy steels and high alloys. A brief discussion of each category follows.

4.2.2 Carbon and low-alloy steels

This category contains the leading candidate materials for large pressure-containing components. These materials are candidates because of availability, cost, fabricability, and, in particular, acceptable design stresses in the temperature range up to about 480°C (900°F), the upper limit being dependent on the specific alloy. The vessel (and piping) size will, for the most part, dictate the material choice. A multitrain conversion process will permit the use of small vessels built of plain carbon (lower strength) steels, but a single-train (or a minimal-train) operation will require large vessels. The choice of design lies with both the architect-engineer (A-E) and the process developer. From the standpoint of initial capital costs for plant construction, large vessels are desirable.[3] As was pointed out in Chapter 1, these large vessels and their associated piping are the components that are specifically addressed in this document.

As suggested in Sect. 1.3.2, the extremely large pressure vessels will be designed in accordance with Section VIII, Division 1 or 2. Any vessels that operate at temperatures where time-dependent properties control material behavior (i.e., creep and stress rupture) will be designed in accordance with Division 1. There are no high-temperature design stress values in Division 2. However, it is improbable that the extremely large thick-walled second generation coal conversion system pressure vessels will operate at temperatures where creep occurs. Figure 4.1 illustrates the differences between the allowable stress values of Division 1 and the allowable stress intensities of Division 2 for SA 516 Grade 70 steel. There is only a small difference in the numerical values at the temperature [320°C (600°F)] at which an SA 516 coal conversion vessel would most likely be designed. However, the allowable stresses for SA 516 drop rapidly at temperatures above 370°C (700°F). Figure 4.2 compares the stress intensity values for SA 387 Grade 22 Class 2. A significant difference (≥33%) exists between the two divisions of the code for this steel specification, up to about (430°C (800°F). Both steels undergo a rapid drop in allowable stresses at the temperature where time-dependent (creep) properties are controlling. The advantages of Division 2 over Division 1 are evident for SA 387 Grade 22 Class 2. There is, however, essentially no difference in the allowable stress values for SA 516 Grade 70 at 320°C (600°F) and, therefore, little advantage in employing the rules of Division 2 for this steel for design at this temperature. Although an argument can be made for designing at lower temperatures, as discussed in Section 3.3 of this report, that compromise could result in other problems, such as condensate deposition and resultant corrosion.

To this point, the SA 516 and SA 387 specifications have been used as examples. Other higher-strength alloys are available, and these would permit the use of higher allowable stress values. For example, ASTM specification A 543 (or the forging equivalent, SA 508 Class 4) is one such popular alloy. Although this alloy is not approved for use in Section VIII, Divisions 1 and 2, a Code Case permitting its use has been proposed.[6] Table 4.3 provides a comparison of the allowable stresses of

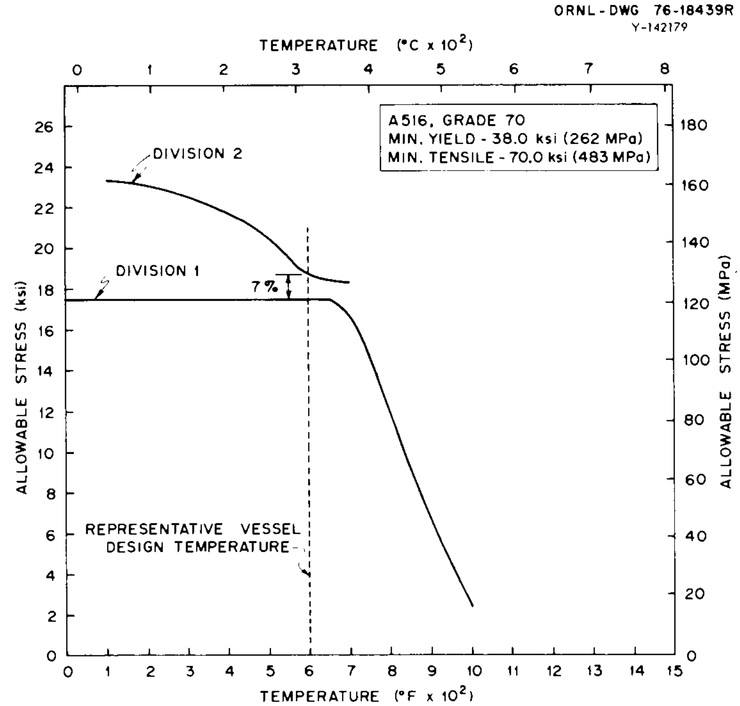

Fig. 4.1. Comparison of the allowable stresses of Section VIII, Division 1, and the allowable stress intensities of Section VIII, Division 2, for SA 516 Grade 70 steel.

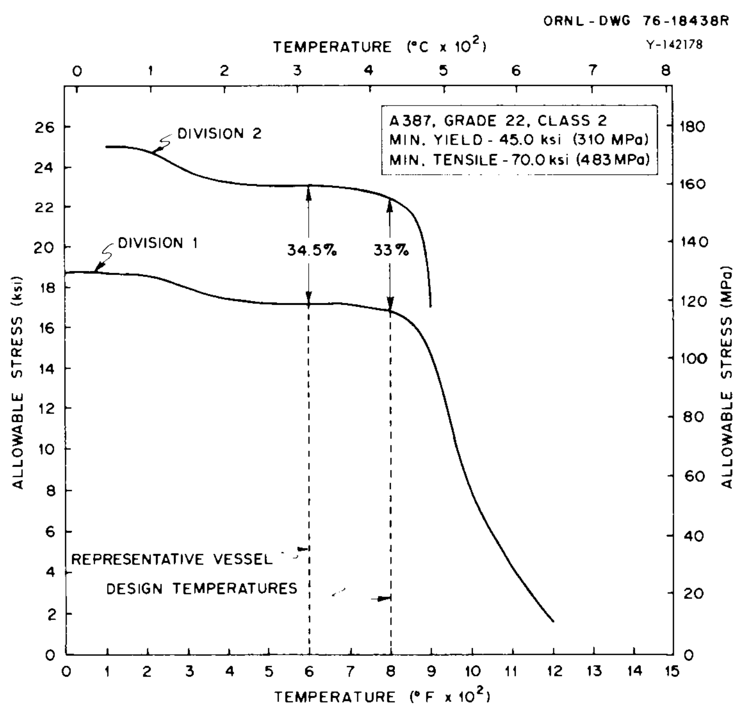

Fig. 4.2. Comparison of the allowable stresses of Section VIII, Division 1, and the allowable stress intensities of Section VIII, Division 2, for SA 387 Grade 22 Class 2 steel.

Table 4.3. Comparison of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 allowable stresses and Division 2 stress intensity values

Temperature		Allowable stresses, Section VIII, Division 1						Stress intensity values, Section VIII, Division 2					
		SA 516 Grade 70		SA 387 Grade 22 Class 2		A 543[a] Class 1		SA 516 Grade 70		SA 387 Grade 22 Class 2		A 543[a] Class 1	
°F	(°C)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)
100	(38)	17.5	(120.6)	18.7	(128.9)	26.3	(181.2)	23.3	(160.5)	25.0	(172.2)	35.0	(241.2)
200	(93)	17.5	(120.6)	18.6	(128.9)	26.3	(181.2)	23.1	(159.2)	24.8	(170.9)	35.0	(241.2)
300	(149)	17.5	(120.6)	17.9	(123.3)	26.3	(181.2)	22.5	(155.0)	23.8	(164.0)	35.0	(241.2)
400	(204)	17.5	(120.6)	17.4	(119.9)	26.0	(179.1)	21.7	(149.5)	23.2	(159.9)	34.6	(238.4)
500	(260)	17.5	(120.6)	17.2	(118.5)	25.8	(177.8)	20.5	(141.2)	23.0	(158.5)	34.4	(237.0)
600	(316)	17.5	(120.6)	17.2	(118.5)	25.4	(175.0)	18.7	(128.8)	23.0	(158.5)	33.9	(233.6)
650	(343)	17.5	(120.6)	17.2	(118.5)	25.1	(172.9)	18.4	(126.8)	22.9	(157.8)	33.5	(230.8)
700	(371)	16.6	(114.4)	17.1	(117.8)			18.3	(126.1)	22.8	(157.1)		

[a]Proposed Code Case for Section VIII, Item BC-74-149, June 11, 1976.

Division 1 with the allowable stress intensity values of Division 2 for SA 516 Grade 70, SA 387 Grade 22 Class 2, and A 543 Class 1. Even though the advantage of the higher-strength alloy is evident, the selection of a material based on strength alone is not done. Other factors, such as economics, weldability, and sensitivity to embrittlement, must be considered. In addition, the sensitivity of these higher-strength materials to sulfidation attack may prove an insurmountable problem. Sulfidation attack is discussed in Section 3.3 of Chapter 3 and Section 4.3.1 of this chapter.

4.2.3 High-alloy materials

The high-alloy materials are attractive because of their excellent resistance to most process environments and good high-temperature strength. However, even these materials are not immune to environmental degradation, and Chapter 3 presents detailed discussions of the compatibility problems. Other attractive features of many high-alloy materials are that they can be fabricated easily and, for many grades, need no post-weld heat treatment. Economic considerations will probably dictate that the large, thick-walled coal conversion vessels be operated at temperatures below the creep range and be built from clad carbon or low-alloy steels with erosion and temperature control maintained through the use of refractory linings. High-alloy materials may well be used for transfer line pipe and fittings as well as for internal members of reaction vessels. However, because this document is concerned primarily with the pressure-boundary piping in operational juxtaposition with the gasifiers and reactor pressure vessels, the discussion does not include the many relatively small diameter transfer lines which will exist in a coal conversion plant and may well be constructed of various high-alloy materials. Within this context then, the large-diameter pressure-boundary piping will be exposed to high temperatures and high pressure, the degree of each being dependent on the specific system (see Section 1.1).

Because of the penalties in allowable stresses and resultant increases in wall thicknesses, it is likely that the large-diameter pipes will be refractory lined in order to lower their wall temperatures. In some systems, it may be advantageous to fabricate these pipes from carbon or low-alloy steels which would be metal clad or weld overlaid for corrosion protection. A discussion of cladding procedures is provided in Chapter 5. The properties of carbon and low-alloy steels discussed in Section 4.2.2 should apply to that generic class of materials whether they are used for large, thick-walled pipes or vessels.

Table 4.4 identifies a number of candidate seamless piping alloys, and Table 4.5 provides the allowable stresses for those materials at various temperatures. The allowable stessses were obtained from Appendix A, Table 1 of ANSI B31.3-1976, *Chemical Plant and Petroleum Refinery Piping.* ANSI B31.3 provides allowable stresses for seamless pipe, welded pipe (welded by various processes) and centrifugally cast pipe. Tables 4.4 and 4.5 contain seamless pipe only to allow ease in comparison. Depending on the type of material, thickness, diameter, environment, economics, etc., the method of fabrication will vary. Section 5.3 discusses pipe fabrication in greater detail. In addition to high-alloy materials, Tables 4.4 and 4.5 include a carbon steel (A 106, Grade C) and a low-alloy steel [$2^1/_4$ Cr–Mo (A 335, Grade P22)] for comparison. Only the annealed grade [210 MPa yield strength; 410 MPa ultimate tensile strength (30 and 60 ksi)] of $2^1/_4$ Cr–1 Mo steel seamless piping is given in ANSI B31.3. From Table 4.5 it is evident that Alloy 800 (B407, cold drawn-annealed) and type 347 H stainless steel are superior to the alloys listed in that they have the highest allowable stresses in the temperature range of 430–470°C (800–1100°F). Although the allowable stresses for type 347 H stainless steel are slightly higher than those of Alloy 800 over part of that temperature range, the type 347 H weldability[7] is not as good. Hence, a choice based on a factor other than strength may govern the material selection process. A judicious balance of these various factors must be considered constantly during the material selection procedure. At elevated temperatures, 590°C (1100°F) and above, types 316 and 347 stainless steel have nearly the same allowable stress as does Alloy 800. A cast stainless steel pipe, CPK-20, is also listed in Tables 4.4 and 4.5. The allowable stress values are lower because an efficiency factor of 0.9 is employed for cast materials. ANSI B31.3 does, however, allow the use of higher stress values for cast materials if special inspection procedures are employed (see Section 302.3.3 of ANSI B31.3). Even with the maximum values permitted under this provision, the CPK20 centrifugally cast alloy would have lower allowable stresses than the type 310 stainless steel (both are, basically, 25 Cr–20 Ni compositions) up to about 510°C (950°F). Cast pipes are often attractive because they permit the fabrication of larger seamless pipes at a lower cost (see Section 5.3.1.3).

The high alloys will be attractive in those areas where advantage can be taken of their elevated-temperature properties.[8] At these temperatures, creep and rupture strength are key material properties that control the allowable stress limits. Figure 4.3 is a compilation of stress-rupture data for a number of materials including carbon and low alloy steels. The high-alloy properties in Fig. 4.3 are from ref. 8, and the carbon and low alloy properties were compiled from stress-rupture values given in the *Metals Handbook, Volume 1* (8th Edition). It is obvious that the high-temperature [>650°C (>1200°F)] allowable stresses are low; this fact alone may inhibit their use for large-diameter piping for high pressures. For many applications, it may be necessary to design the piping system to operate at low temperatures [360°C (600°F)] and employ refractory-lined carbon and low-alloy steel piping.

The alloy systems suggested in Fig. 4.3 are also candidates for the internal support members of the pressure vessels. These materials have physical properties that differ from those of the carbon and low-alloy steels that are candidates for the pressure vessel. Frequently, welds made between these dissimilar materials tend to contain defects that can serve as initiation sites for subsequent service-related crack extensions (see Section 5.3.3). This sensitivity to defects and the impact of such defects on the safe and reliable operation of the containment vessel must be considered in the design, material selection, and fabrication of internals.

Table 4.4. Candidate materials for seamless piping

Steel identification[b]	Grade (Class)	Chemical requirements (wt %)[a]												Tensile requirements			
		C[a]	Mn	P	S	Si	Ni	Cr	Mo	Ti	Cb + Ta	Cu	Al	UTS ksi (MPa)	Yield point ksi (MPa)	Elongation in 2 in. (5.1 cm) (%) Longitudinal	Transverse
A 312	TP304 H	0.04–0.10	2.00	0.040	0.030	0.75	8.00–11.0	18.0–20.0						75 (517)	30 (207)	35	25
	TP310	0.15	2.00	0.040	0.030	0.75	19.0–22.0	24.0–26.0						75 (517)	30 (207)	35	25
	TP316 H	0.04–0.10	2.00	0.040	0.030	0.75	11.0–14.0	16.0–18.0	2.00–3.00					75 (517)	30 (207)	35	25
	TP347 H	0.04–0.10	2.00	0.040	0.030	0.75	9.00–13.0	17.0–20.0			*c*			75 (517)	30 (207)	35	25
B 407	800 (cold drawn annealed)	0.10	1.5		0.015	1.0	35.0–30.0	23.0–19.0		0.60 0.15		0.75	0.60 0.15	75 (517)	30 (207)	30	
A 106	C	0.35	1.06–0.29	0.048	0.058	0.10 min								70 (483)	40 (276)	30	16.5
A 335	P22	0.15	0.60–0.30	0.030	0.030	0.50		2.60–1.90	1.13–0.87					60 (414)	30 (207)	30	20
A 451	CPK20	0.20	1.50	0.040	0.040	1.00	22.0–19.0	27.0–23.0						65 (448)	28 (193)	30	

[a]Single values indicate maximum allowed, except where noted.

[b]From *American Society for Testing and Materials,* ASTM Standards, Parts 1 and 8.

[c]The columbium plus tantalum content shall be not less than eight times the carbon content and not more than 1.0 %.

Table 4.5. Allowable stresses in tension for candidate piping materials[a]

Specification	Grade	Min. temp. to 100 (38)	200 (93)	300 (149)	400 (204)	500 (260)	600 (316)	650 (343)	700 (371)	750 (399)	800 (427)	850 (454)	900 (482)	950 (510)	1000 (538)	1050 (566)	1100 (593)	1150 (621)	1200 (649)	1250 (677)	1300 (704)	1350 (732)	1400 (760)	1450 (788)	1500 (816)
ASTM 312	TP 304 H	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	18,700 (128.9)	17,450 (120.3)	16,400 (113.1)	16,150 (111.4)	15,950 (110.0)	15,550 (107.2)	15,150 (104.5)	14,900 (102.7)	14,650 (101.0)	14,350 (98.9)	13,750 (94.8)	12,150 (83.8)	9,750 (67.2)	7,700 (53.1)	6,050 (41.7)	4,700 (32.4)	3,700 (25.5)	2,900 (20.0)	2,300 (15.9)	1,800 (12.4)	1,400 (9.7)
ASTM 312	TP 310	20,000[c,d] (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	19,200 (132.4)	18,800 (129.6)	18,300 (126.2)	18,000 (124.1)	17,500 (120.7)	14,600 (100.7)	13,850 (95.5)	12,500 (86.2)	11,000[b] (75.8)	9,750 (67.2)	8,500 (58.6)	7,250 (50.0)	6,000 (41.4)	4,750 (32.8)	3,500 (24.1)	2,350 (16.2)	1,600 (11.0)	1,100 (7.6)	750 (5.2)
ASTM 312	TP 316 H	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	19,250 (132.7)	17,950 (123.8)	17,000 (117.2)	16,650 (114.8)	16,300 (112.4)	16,050 (110.7)	15,850 (109.3)	15,700 (108.2)	15,550 (107.2)	15,400 (106.2)	15,300 (105.5)	14,500 (100.0)	12,400 (85.5)	9,800 (67.6)	7,400 (51.0)	5,450 (37.6)	4,100 (28.3)	3,050 (21.0)	2,250 (15.5)	1,700 (11.7)	1,250 (8.6)
ASTM 312	TB 347 H	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	19,900 (137.2)	19,300 (133.1)	18.950 (130.7)	18,600 (128.2)	18,450 (127.2)	18,300 (126.2)	18,200 (125.5)	18,150 (125.1)	18,100 (124.8)	18,050 (124.4)	17,100 (117.9)	14,250 (98.2)	10,500 (72.4)	7,900 (54.5)	5,900 (40.7)	4,350 (30.0)	3,200 (22.1)	2,450 (16.9)	1,800 (12.4)	1,300 (9.0)
ASTM B407	800 (cold drawn annealed)[e]	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	20,000 (137.9)	18,300 (126.2)	18,200 (125.5)	17,900 (123.4)	17,600 (121.3)	17,000 (117.2)	13,000 (89.6)	9,800 (67.6)	6,800 (46.9)	4,200 (29.0)	2,000 (13.8)	1,600 (11.0)	1,100 (7.6)	1,000 (6.9)	800 (5.5)
ASTM A106	C	23,300 (160.6)	23,300 (160.6)	23,300 (160.6)	22,900 (157.9)	21,600 (148.9)	19,700 (135.8)	19,400 (133.8)	19,200 (132.4)	14,750[b] (101.7)	12,000 (82.7)														
ASTM A335	P22	20,000 (137.9)	18,700 (128.9)	18,000 (124.1)	17,500 (120.7)	17,200 (118.6)	16,700 (115.1)	16,200 (111.7)	15,600 (107.6)	15,200 (104.8)	15,000 (103.4)	14,500 (100.0)	12,800 (88.3)	11,000 (75.8)	7,800 (53.8)	5,800 (40.0)	4,200 (29.0)	3,000 (20.7)	2,000 (13.8)						
ASTM A451	CPK20[f,g]	16,800 (115.8)	16,800 (115.8)	16,800 (115.8)	16,800 (115.8)	16,800 (115.8)	16,200 (111.7)	15,750 (108.6)	15,400 (106.2)	15,100 (104.1)	14,700 (101.4)	11,500 (79.3)	11,250 (77.6)	10,700 (73.8)	9,900[b] (68.3)	8,800 (60.7)	7,650 (52.7)	6,550 (45.2)	5,400 (37.2)	4,300 (29.6)	3,150 (21.7)	2,150 (14.8)	1,450 (10.0)	1,000 (6.9)	700 (4.8)

[a]From *American National Standard Code for Pressure Piping*, ANSI B31.3-1976, Petroleum Refinery Piping Code. Temperature given in °F(°C), stress values given in psi (MPa).
[b]A single bar in the stress tables indicates that there are conditions other than stress which affect usage above or below the temperature.
[c]At 1050°F and above, these stress values apply only if the steel has a predominant grain size not finer than No. 6 per ASTM E112. Otherwise, lower values given in Table 1 of ANSI B31.3 apply.
[d]At temperatures over 1000°F, these stress values apply only when the C content is 0.04 percent or higher.
[e]Annealed at approximately 1800°F.
[f]Above 100°F these stress values apply only when the carbon content is 0.04 percent or higher.
[g]Stress values shown include the casting quality faster of 0.90. Higher stress values can be used if special inspection is accomplished (see 302.3.3 of ANSI B31.3).

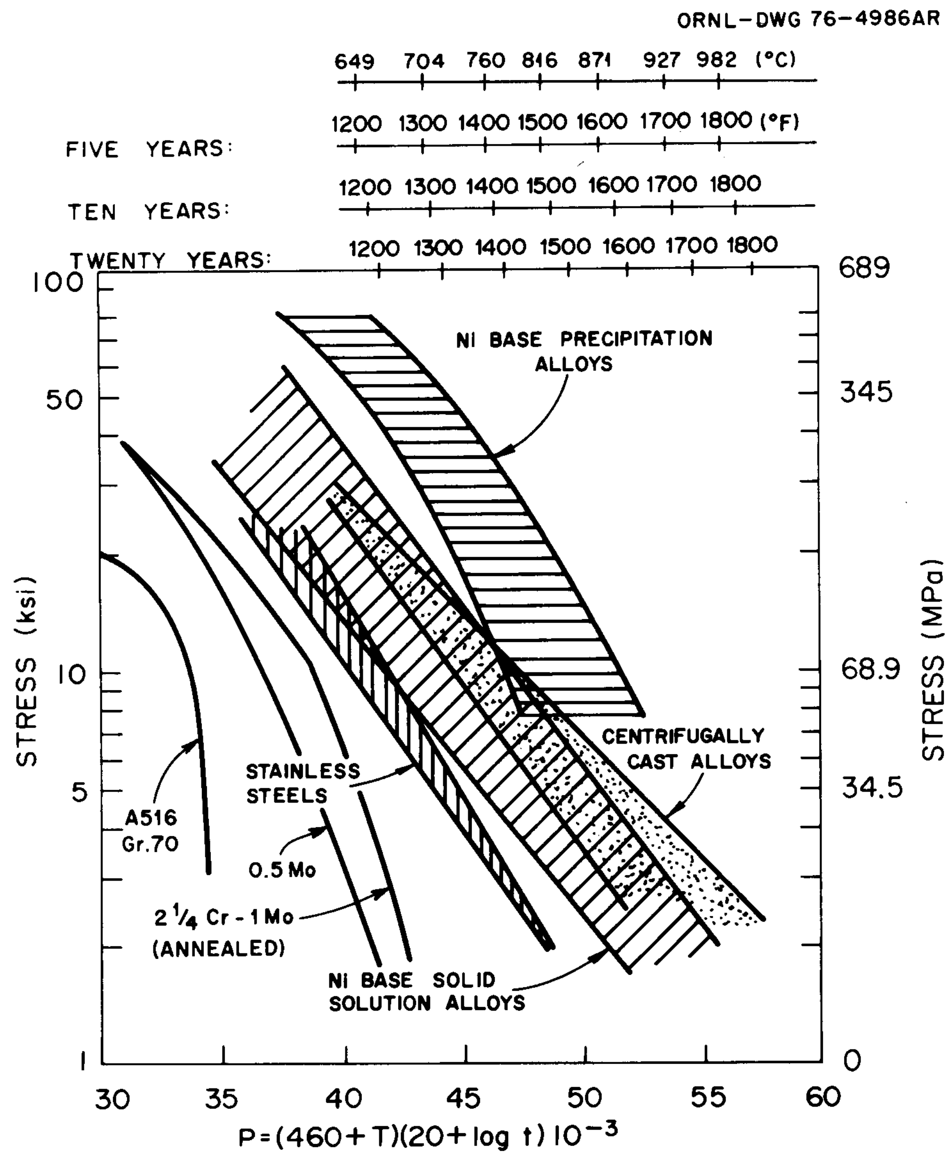

Fig. 4.3. Comparison of the stress-rupture properties as a function of time and temperature for candidate construction materials for coal conversion systems. Source: *Report of the American Iron and Steel Institute Nuclear Steel Making Task Group* (May 1975).

4.3 Metallurgical Considerations

4.3.1 Processing and heat treatment

The choice of the materials for the fabrication of the pressure vessel and its associated piping is dependent primarily on the process conditions which it must contain. Of foremost consideration is the design temperature and pressure at which the vessel must operate. Of nearly equal importance are the chemical characteristics of the process environment. The design temperature will dictate whether the vessel will operate in the cold mode [~340°C (~650°F) and below] or the hot mode (near or above the onset of creep). The pressure vessels used in the second generation coal conversion systems considered in this document will probably operate below the creep range and above the dew point of the process stream. These temperature limitations are selected because, at temperatures where time-dependent properties must be considered, the code-allowable stresses decrease at a rapid rate for small increases in design temperature (see Figs. 4.1 and 4.2), particularly for the ferritic materials. The nonferritic materials (austenitic stainless steels and high-nickel alloys) maintain their strength to higher temperatures, but, generally their cost per fabricated pound is relatively high. Hence, the large pressure vessels most likely will be fabricated from carbon or low-alloy steels and will be protected from the high process temperatures by refractory insulation and, perhaps, will be overlaid (or clad) to protect them from the process stream environment. Furthermore, the desirability of minimizing capital costs of coal conversion systems will lead to a maximization of vessel sizes and a minimum number of trains employed in a large commercial system.[5] These criteria—temperature, pressure, and environment—therefore set the stage for the vessel design, and it appears likely that the gasifiers and reactor vessels for commercial coal conversion systems will be thick-walled.

Thick section sizes require that plates (and forging courses) be processed from ingot sizes that permit only minimal working during slabbing and rolling. For thick sections[9] [~300 mm (~12 in.)] the amount of reduction from ingot to final product form is about 3.3 : 1 and the cross-rolling ratio is about 1.7 : 1. After processing, it is necessary to austenitize, quench and temper these massive sections to achieve the tensile properties that are required by the SA specifications. These specifications require that the minimum tensile properties for quenched and tempered steels be achieved at a location in the plate (or forging) that is at least $^1/_4$ of the thickness below the surface and one thickness away from an end. This test location is required for materials that are cooled in a medium that provides a cooling rate faster than that of still air. For example, thick sections of SA 336 Class F22 steel (see Table 5.2) are usually[10,11] quenched and tempered in order to achieve the minimum tensile properties required in the specification. Quenching and tempering allow the minimum tensile requirements of the specifications to be achieved even in the maximum plate thicknesses (see Section 5.2.1). The low cross-rolling ratio cited above will result in some anisotropy, which is most easily recognized when toughness properties are compared. Figure 4.4. contains the results[12] of Charpy V-notch (C_V) tests on a 300-mm-thick (12-in.) plate of A 533 Grade B Class 1 steel. There is little effect of specimen orientation on the toughness in the transition temperature region; the effect of the cross rolling is, however, reflected in the upper shelf energy values.

As mentioned above, the codes require that the minimum properties of the specification be satisfied at the $^1/_4$-thickness location, and consequently, quite often, no attention is paid to the properties at the other through-the-thickness locations. After quenching and tempering, however, a surface-to-surface variation in mechanical properties exists in thick steel sections. Figures 4.5 and 4.6 contain the results[12] of tensile and toughness tests on a 300-mm-thick (12-in.) steel plate. Note that the surface properties are superior to those at the $^1/_4$-thickness location. The ultimate tensile strength is about 10% higher [~690 MPa vs 630 MPa) (100 ksi vs 92 ksi)] than what would be nominally reported for this heat of steel. For certain applications, this increase in strength *and* the improved notch toughness properties are beneficial. In the case of a coal conversion system, the increased strength on the surface could prove to be a detriment in hostile environments. A National Association of Corrosion Engineers (NACE) committee reported[13] that carbon and low-alloy steels, candidates for the fabrication of vessels for coal conversion systems, are susceptible to sulfidation attack when their hardness is about R_C 22 or greater. Interrante[14] has also reported a correlation between strength and susceptibility to hydrogen embrittlement. This area is discussed in considerably more detail in Section 3.3 of this document.

It is probable that the process stream environment will dictate that a steel resistant to hydrogen attack be employed. The $2^1/_4$ Cr–1 Mo steel analysis (specification SA 387 Grade 22 and SA 336 F-22) may be selected, based on its greater resistance as indicated by the Nelson curves (see Fig. 3.3 and the discussion in Section 3.2.1).

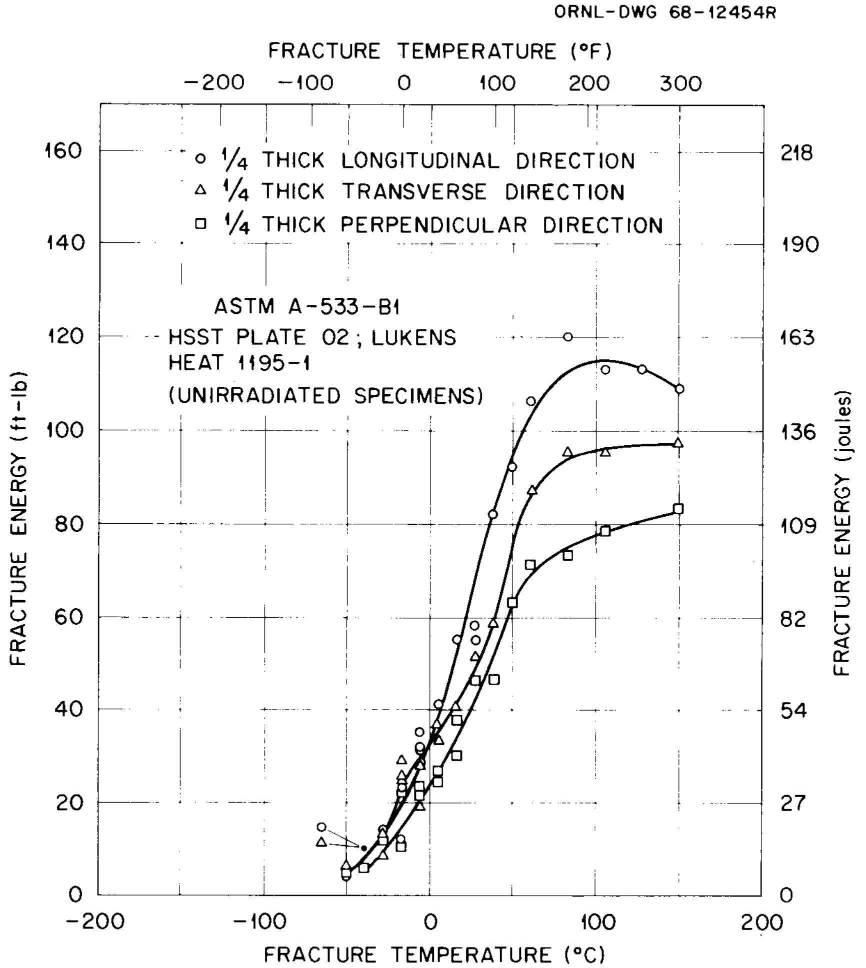

Fig. 4.4. Charpy V-notch impact test results for three specimen orientations at 1/4 T level in a 12-in.-thick (305-mm) plate of A 533 Grade B Class 1 steel.

4.3.2 Fabrication

The above discussions indicate that the code-required tensile properties can be achieved, even in extremely thick sections, by accelerated cooling. Notch toughness, per se, particularly the requirements of Section VIII, Division 1 and 2 (see Fig. 4.7) of the ASME Code, can also be met by the ferritic materials being considered for coal conversion applications, especially the quenched and tempered steels. Figures 4.4, 4.5 and 4.6 substantiate the ability of the low-alloy steels to meet the requirements. Toughness, however, is of utmost concern. Many disruptive failures reported in the open literature occur as a consequence of poor initial toughness or because of a loss of toughness due to service. Figure 4.8 is a photograph of a pressure vessel that failed[15] during hydrostatic testing because of an improper postweld heat treatment (PWHT). Figure 4.9 contains the Charpy V-notch properties of the weld metal in the as-fabricated condition (including an improper PWHT) and after a correct PWHT at 650°C (1218°F) for 6 hr. The improvement is obvious.

Frequently, a failure will initiate from an existing crack in the heat-affected zone (HAZ) of a weldment. Such a flaw was responsible for the catastrophic failure during hydrostatic testing of an ammonia tank[16] in England in 1966. The initiation site in the ammonia tank failure was similar to that shown in Fig. 4.10. The crack was located in a region of the HAZ that had a hardness of 380 to 400 DPH.

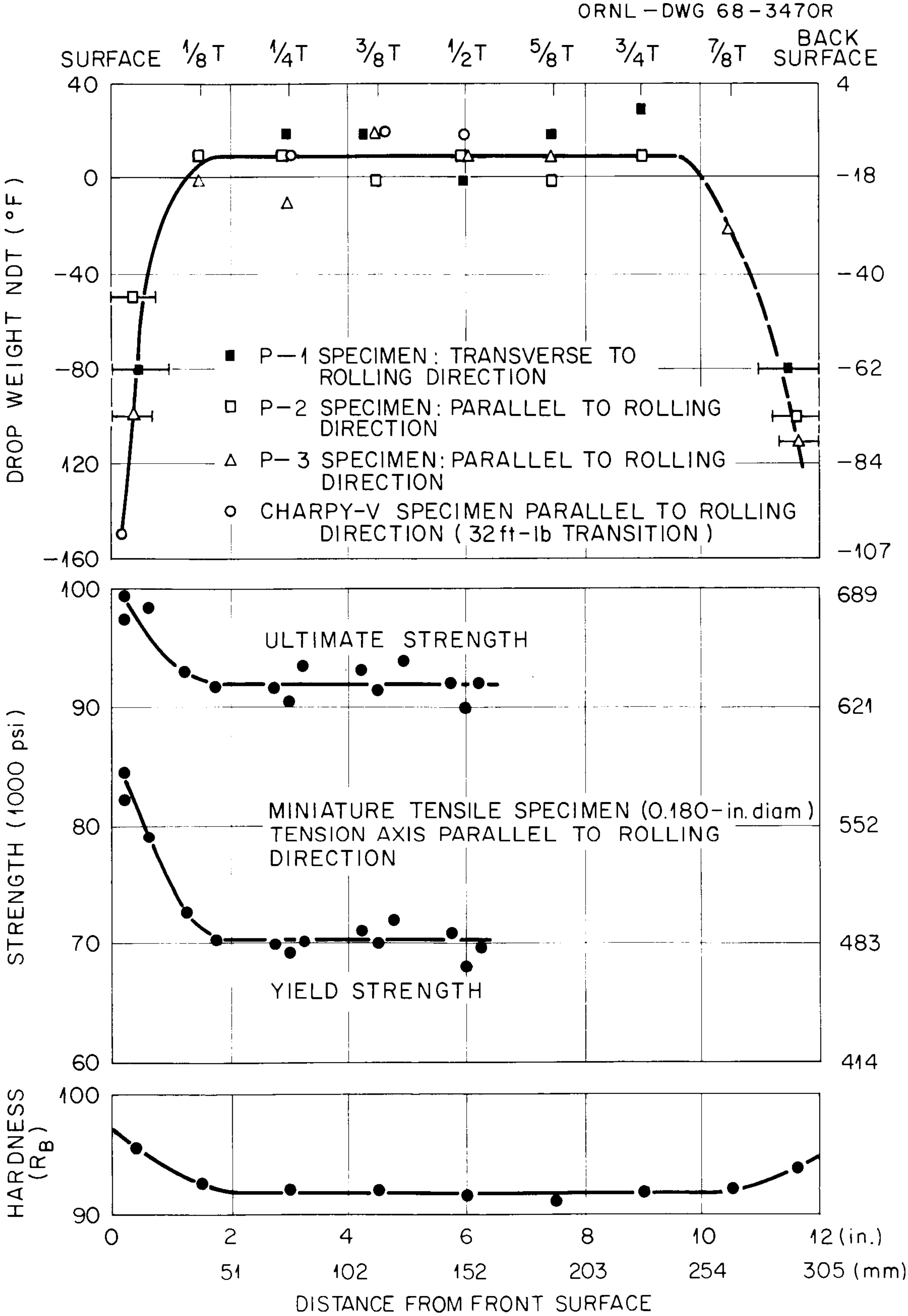

Fig. 4.5. Variation with depth in plate of representative mechanical properties for central region of a 10 ft × 20 ft × 12 in. (3.05 m × 6.10 m × 305 mm) plate of ASTM A 533 Grade B Class 1 steel.

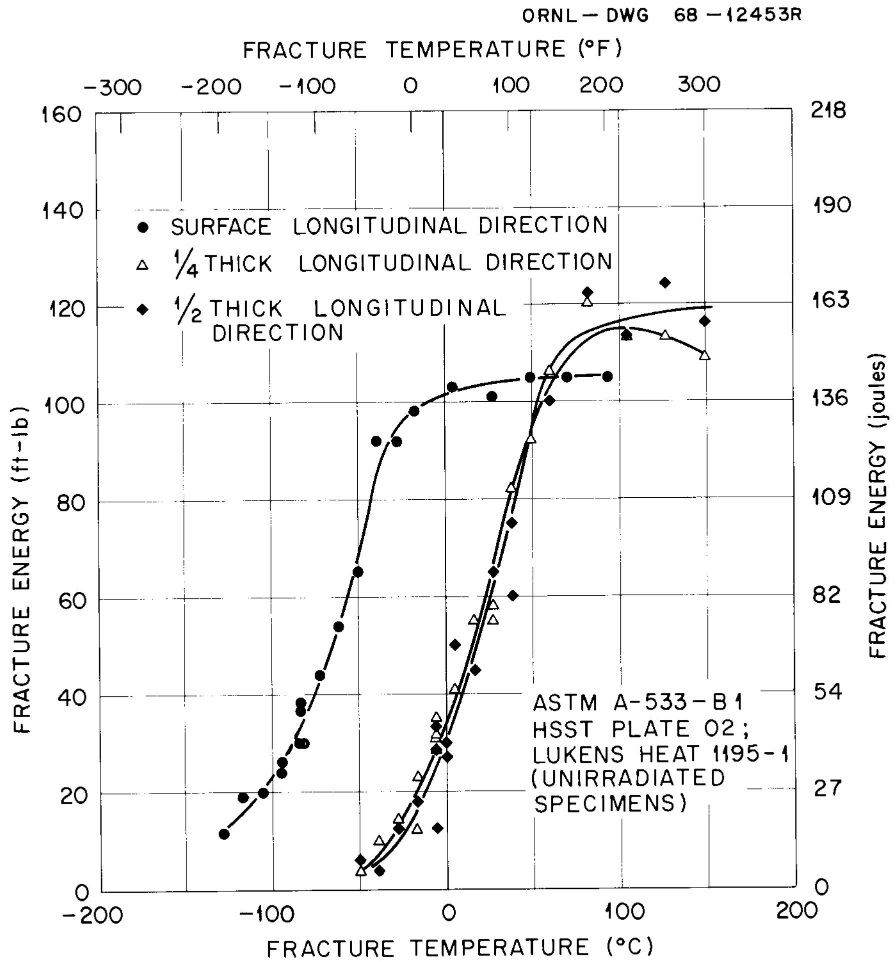

Fig. 4.6. Charpy V-notch impact test results for specimens from three depth levels in a 12-in.-thick (305-mm) plate of A 533 Grade B Class 1 steel.

These two failures are testimonial that inadequate toughness, per se, can be a costly problem. Even though the two vessels cited[15,16] were not fabricated from materials that are considered as candidates for pressure-containing components for coal converison systems, they do illustrate the relationship between heat treatment and fracture-toughness properties. Chromium-molybdenum steels are temperature sensitive, and an incorrect tempering temperature may result in very poor impact properties.

Sterne[17] has presented data for 2¹/₄ Cr–1 Mo steel plate that shows the influence of tempering temperature on C_V toughness. Sterne's work showed a decrease in the C_V toughness at −12° C (+10° F) from 66 J (50 ft-lb) to 15 J (11 ft-lb) when the tempering temperature was decreased from 620° C (1150° F) to 593° C (1100° F). A study[18] at Lehigh University investigated the effect of section size on the toughness of A 542 (quenched and tempered 2¹/₄ Cr–1 Mo steel) and found considerable scatter in the data obtained in the transition temperature region. Similar scatter in toughness behavior was noted in some drop-weight data presented[19] by Babcock and Wilcox for 51-mm-thick (2-in.) A 387 Grade D steel. These data, relative to the toughness behavior of quenched and tempered 2¹/₄ Cr–1 Mo steel, are disconcerting and suggest that the toughness of thick sections of these candidate materials be further investigated. The sensitivity of the steels to heat treatment is responsible, to a great measure, for the results. The thick sections of SA 387 Grade 22, a prime candidate for thick-walled gasifiers and reactors, will be quenched and tempered in order to satisfy the Class 2 property requirements. Therefore, the problem just noted[17–19] may also prevail for coal conversion vessels fabricated from 2¹/₄ Cr–1 Mo steel.

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 lbs: Fully Deoxidized Steel	Charpy V-Notch Impact Energy ft lbs: 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[1]	Average for 3 specimens	20	–
	Minimum for 1 specimen	15	–
95,000 psi and over[2]	Minimum for 3 specimens	Lateral expansion 0.015 in. (15 mils)	

[1] The values of lateral expansion opposite the notch and fracture appearance in percentage of shear shall be recorded for information and these shall be retained for a period of two years.
[2] For bolting of this strength level, in diameters of 2 inches and under, the impact requirements of SA-320 may be applied. For diameters above 2 inches, 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-lbs: Fully Deoxidized Steels	Charpy V-Notch Impact Values Energy, ft-lbs: 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 (Note 1)	Average for 3 specimens	20	...
	Minimum for 1 specimen	15	...
95,000 psi and over	Minimum 3 specimens (Note 2)	Lateral Expansion Values 0.015 in.	

Note 1: The values of lateral expansion opposite the notch shall be recorded (see AM-211.2).
Note 2: See AM-211.6(b) for permissible retests.

Fig. 4.7. Impact test requirements for Section VIII, Division 1 (Table UG-84.1), and Division 2 (Table AM-211.1).

As was shown in Fig. 4.10, the HAZ of the candidate structural materials is of utmost concern. Figure 4.11 shows the macrostructure and hardness across a submerged-arc weldment in a 300-mm-thick (12-in.) A 533 Grade B Class 1 steel plate. Note that the two hardness peaks occur in the HAZ regions. The HAZ hardness of about 230 DPH compares to the base metal hardness of about 190 and 175 DPH in the weld metal. Using standard conversion tables,[20] those values correlate with tensile strengths of 730, 606, and 565 MPa (106, 88, and 82 ksi) respectively. This is representative of a low-alloy steel after an extensive [40 hrs at 620°C (1150°F)] PWHT. Prior to the PWHT, there are even greater differences between the hardness (strength) of the HAZ, base metal and weld metal. Figure 4.12 illustrates the effects of a PWHT. The upper photomacrograph is of a weldment in the as-welded

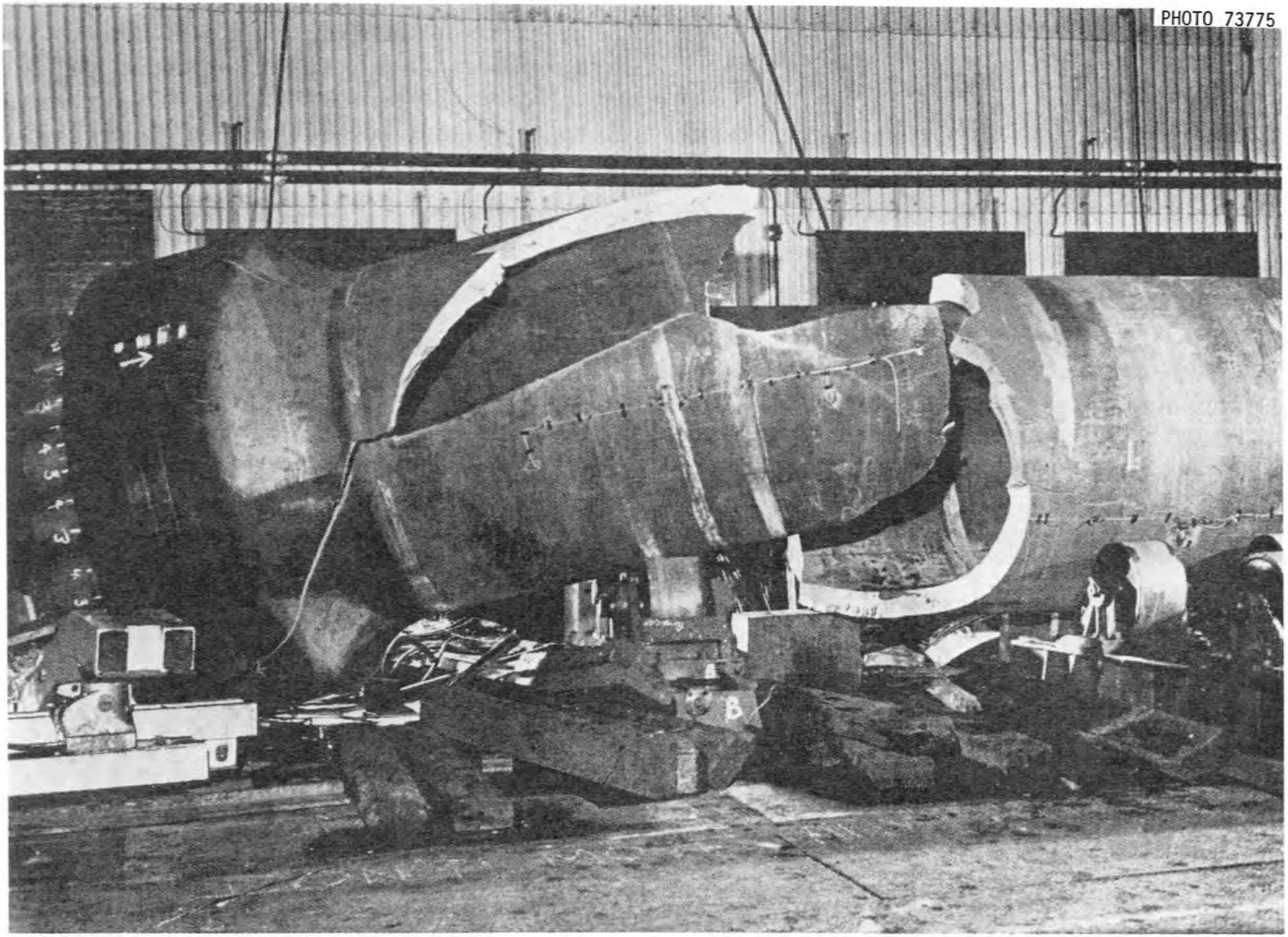

Fig. 4.8. Vessel that failed during hydrostatic testing. Source: R. Weck, "Brittle Fracture of a Thick-Walled Pressure Vessel," *Br. Weld. Res. Assoc. Bull* 7(6) (June 1966), Fig. 12. Reprinted by permission.

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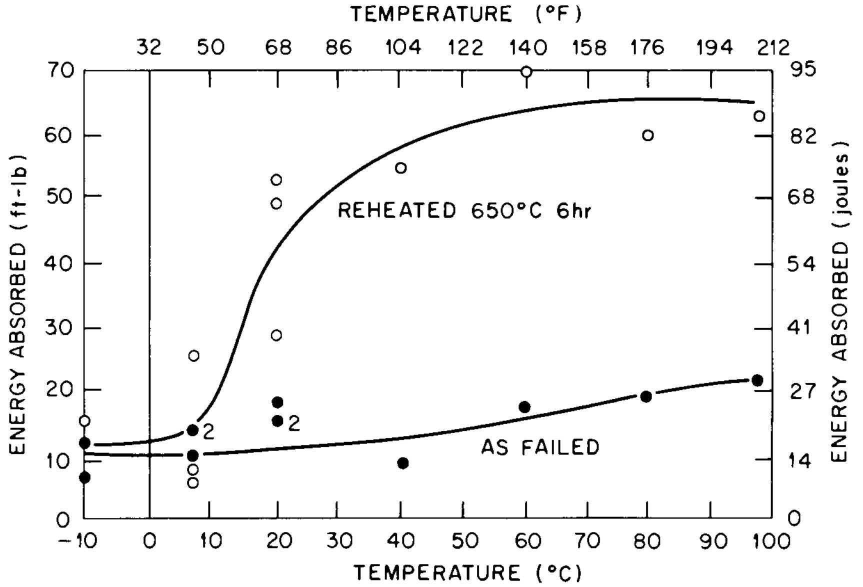

Fig. 4.9. Charpy V-notch toughness of an unproperly postwelded heat-treated low-alloy steel (as-failed). The upper curve represents the toughness properties of the same material correctly heat treated. Source: R. Weck, "Brittle Fracture of a Thick-Walled Pressure Vessel," *Br. Weld. Res. Assoc. Bull.* 7(6) (1976), Fig. 44. Reprinted by permission.

condition; the HAZ hardness is as high as 364 DPH. After a proper PWHT of 700°C (1300°F) for 1 hr, the hardness is similar to that shown in Fig. 4.11. The effect of these high hardnesses on the susceptibility of the steels to sulfidation attack[13] should be considered. Sections 3.3 and 4.3.1 address themselves to the relationship between hardness and sensitivity to attack.

The effects of PWHT parameters[21] on the toughness of pressure vessel steels are shown in Fig. 4.13 and 4.14. Figure 4.13 shows the effect of varying stress relief temperatures on the C_V impact energy for A 533 Grade B Class 1 steel. Figure 4.14 shows the effects of varying hold times for stress relieving of the same material. The transition temperature is increased, and the upper shelf energy is decreased both with higher temperature and with longer times. This response should be determined for all pressure vessel steels that receive stress relief treatments. It is especially important during field fabrication procedures where conditions in the field may not be optimum and examination following fabrication is more difficult. Since many coal conversion vessels will be field fabricated, attention must be given to the response of candidate pressure boundary materials to PWHT.

4.3.3 Service effects

There are many variables throughout the lifetime of a structural component that can affect its ability to satisfy the intended performance. Frequently, there are changes in the mechanical properties of the material from which the component is fabricated. Often, these changes are reflected as a loss of strength (at high temperatures) or as a loss of toughness at lower temperatures. This loss of toughness, usually referred to as embrittlement, is observed for many steels operating within the intended coal conversion pressure vessel and piping design temperature ranges [290 to 500°C (550 to 900°F)]. A typical example of the changes that can occur in 2¼ Cr–1 Mo steel was reported[22] by Watanabe et al. Another paper on the same subject discussed the results of a study of the steel from a Direct Sulfurization Reactor that failed[23] in Japan during field repairing. Watanabe showed that the failure of the vessel initiated from cracks that had extended through the stainless steel overlay into the 2¼ Cr–1

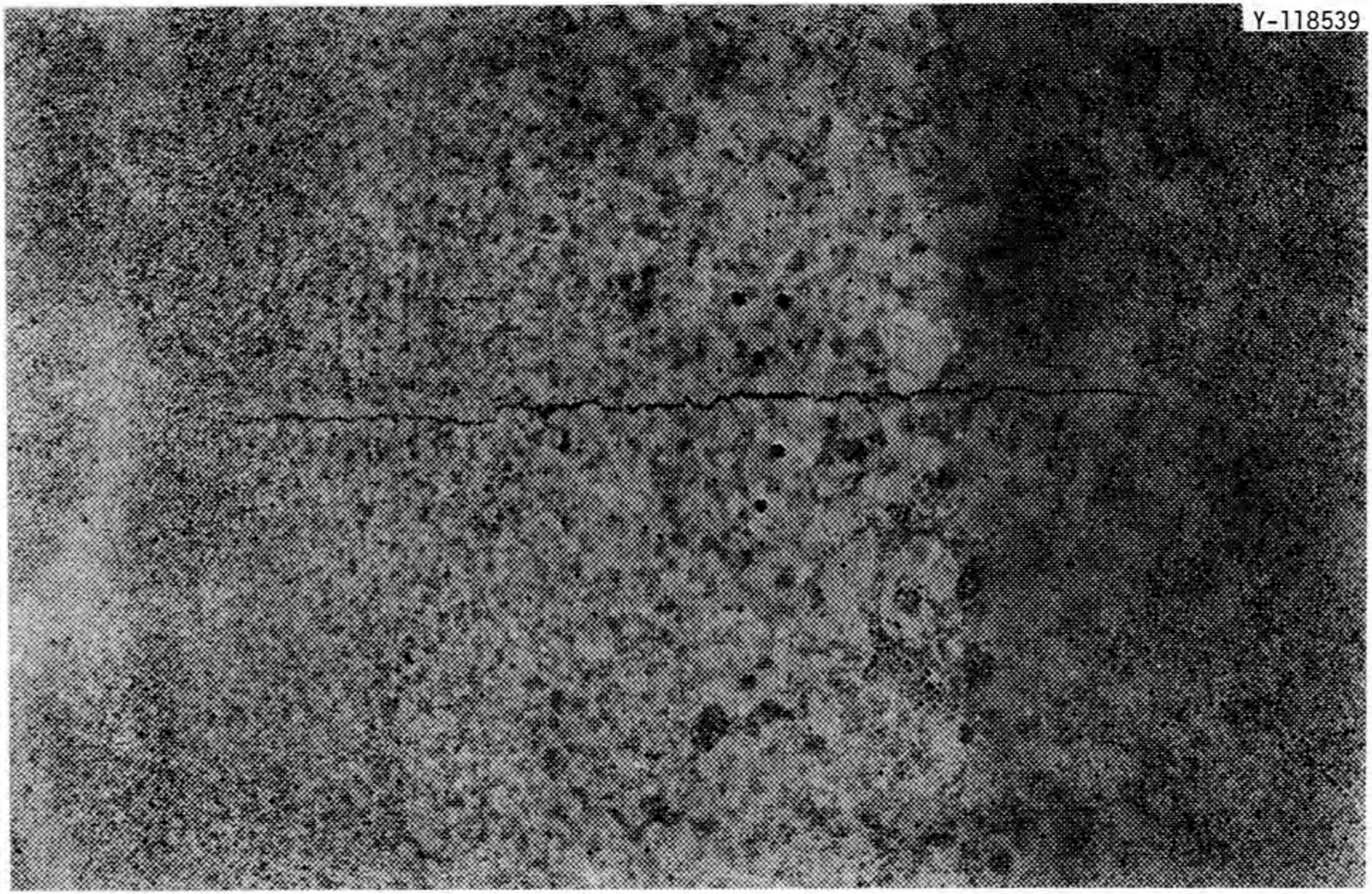

Fig. 4.10. A preexisting welding crack in a hard spot (380–400 DPH) of a heat-affected zone in a low-alloy weldment. Source: R. Weck, "Brittle Fracture of a Thick-Walled Pressure Vessel," *Br. Weld. Res. Assoc. Bull.* 7(6) (1966), Fig. 38. Reprinted by permission.

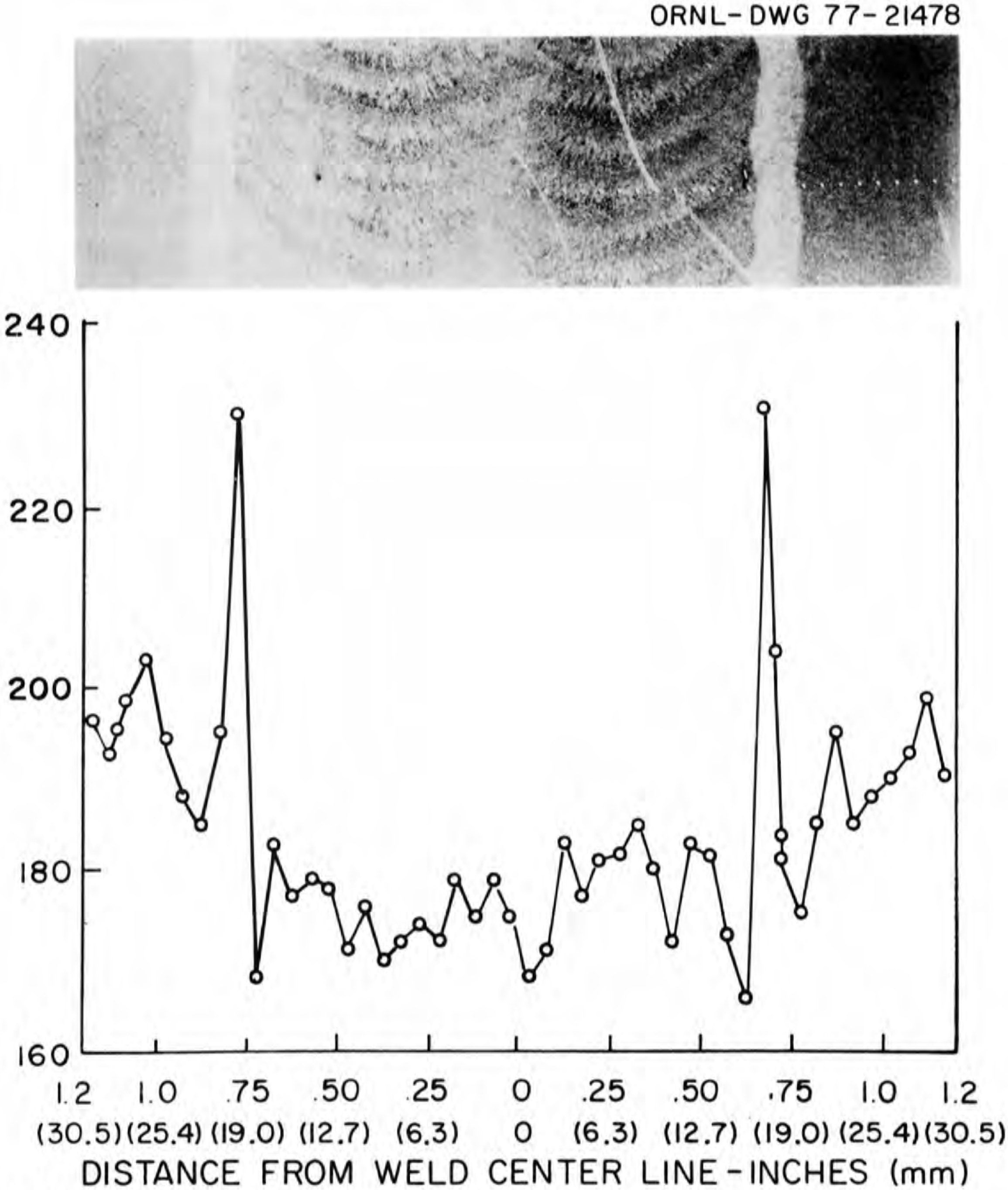

Fig. 4.11. Hardness traverse across the heat-affected zone of a submerged-arc weldment in a 12-in.-thick (305-mm) A 533 Grade B Class 1 steel plate.

Mo steel vessel. Figure 4.15 (ref. 22) shows an approximate 80°C (175°F) shift in the 54-J (40-ft-lb) temperature on the inner surface of the pressure vessel. The loss of toughness and the subsequent failure were attributed to temper embrittlement. Temper embrittlement of 2¼ Cr–1 Mo steel is of great importance in the petrochemical industry and warrants a more extensive discussion. For example, little is reported concerning the behavior of the SA 387 Grade 22 Class 1 (annealed) steel (most studies were conducted for higher-strength materials in pressure vessels). There is information that shows that as-annealed steel has poorer C_V toughness than embrittled N&T and Q&T steels. Swift and Gulya[24]

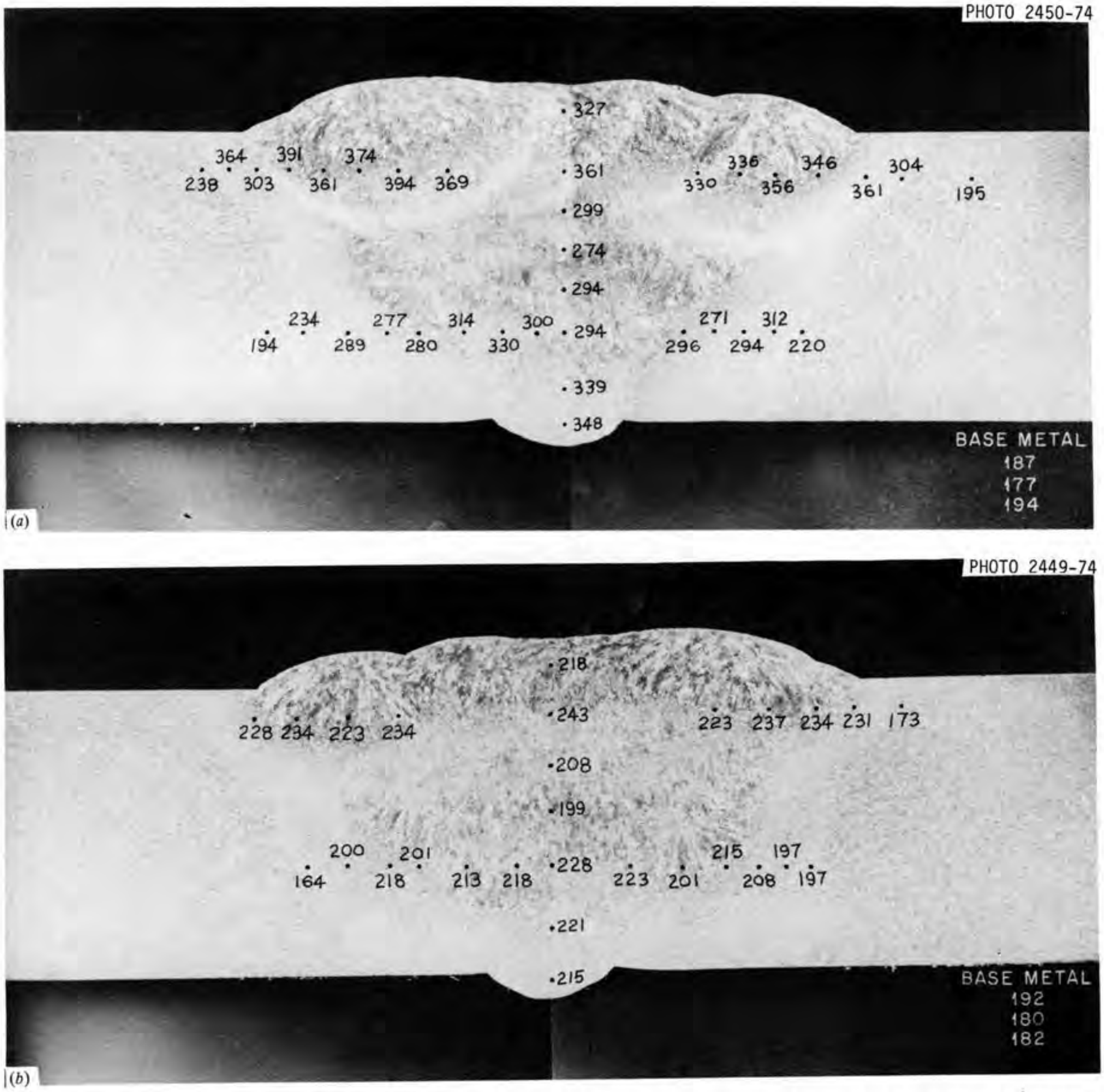

Fig. 4.12. Macrograph of high-carbon (0.11% C) 2¼ Cr–1 Mo steel multipass weld, showing hardness (DPH) variations. (*a*) As welded, (*b*) welded and tempered 1 hr at 1300°F (704°C). The base metal is ½-in.-thick (13-mm) A 387 Grade 22.

simulated quenched heavy sections of 2¼ Cr–1 Mo steel by furnace cooling [950 to 720°C (1750 to 1325°F), followed by air cooling] 1-in.-thick (25-mm) plate. Their tests show the furnace-cooled (annealed) plate to have a higher fracture appearance transition temperature (FATT), 24°C (75°F), than nearly all their embrittled Q&T plates. Canonico[25] reported 41-J (30-ft-lb) C_V energy at −4°C (+25°F) for two different annealing treatments on one heat of steel. These data are in contrast to a 41-J (30-ft-lb) energy value at −34°C (−30°F) for 2¼ Cr–1 Mo steel Q&T to 590 MPa (85,000 psi) reported by Ripling and Crossley.[26]

In view of the evidence (admittedly sparse) available in the literature, it is probable that truly annealed 2¼ Cr–1 Mo steel will not undergo a shift in its toughness behavior as a consequence of operating within the 370 to 593°C (700 to 1100°F) temperature regime. The slow cool during the anneal heat treatment results in a stable microstructure that does not embrittle as a consequence of exposure to elevated temperatures for long periods of time.

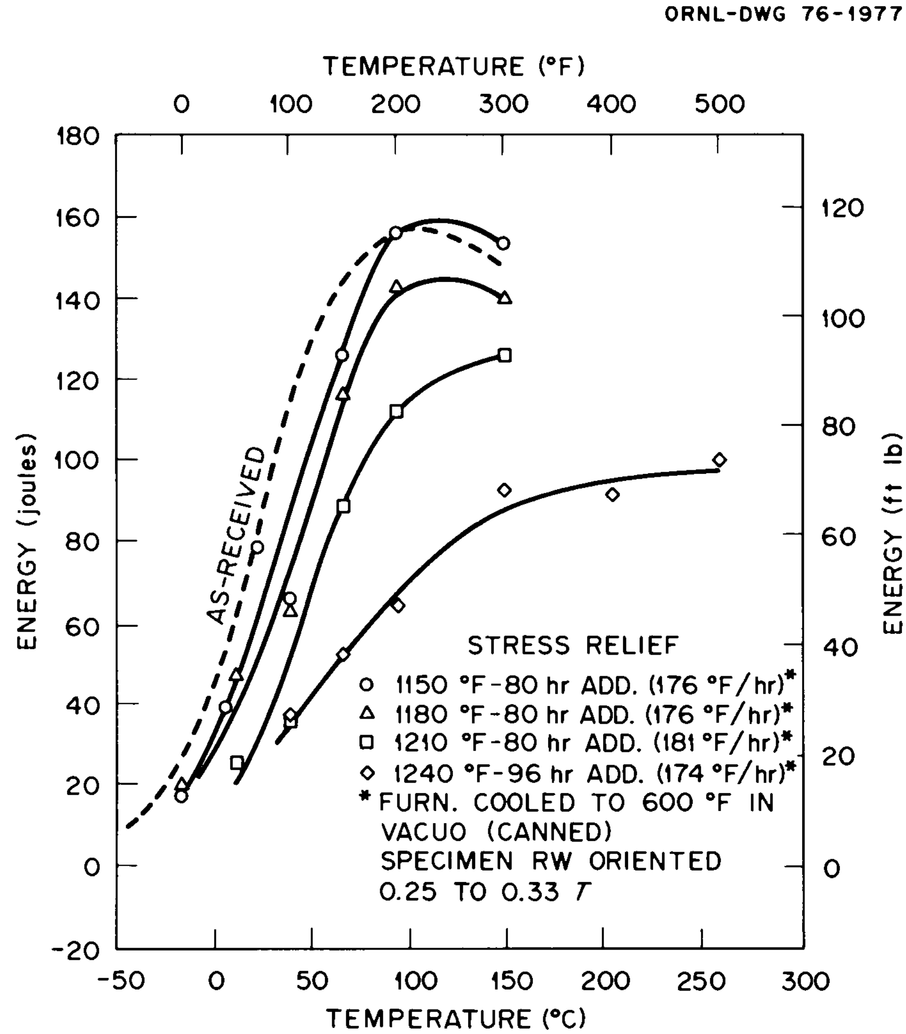

Fig. 4.13. Effect of postweld heat treatment temperature on Charpy V-notch toughness of A 533, Grade B, Class 1 steel.

The situation as previously mentioned for Q&T or N&T materials is quite different. A study[27] performed by Clauser et al. on a number of heats of thick -section A 542 (quenched and tempered $2\frac{1}{4}$ Cr–1 Mo) steel and also on normalized and tempered material clearly showed that, in the tensile strength range from 483 to 728 MPa (70 to 120 ksi), a decrease in strength resulted in an increased susceptibility to step-cool embrittlement for Q&T and N&T (both stress relieved) $2\frac{1}{4}$ Cr–1 Mo plate. The authors concluded that all commercial heats of A 542 may be expected to undergo an increase in transition temperature as a result of temper embrittlement of from 10°C (50°F) to about 54°C (130°F) after isothermal aging at 482°C (900°F) for 500 hr. Figure 4.16 shows the change in the 84-J (60-ft-lb) transition temperature with time at 480°C (900°F) for 25-mm (1-in.) and simulated 150-mm (6-in.) Q&T plate [95 ksi (655 MPa) tensile strength]. The transition for the 150-mm (6-in.) plate increased from −37°C (−35°F) to 20°C (68°F), an increase of 57°C (103°F), after 3160 hr ($4\frac{1}{2}$ months) of exposure.

A different heat of material increased its transition from −8 to 64°C (18 to 147°C, a change of 72°C (129°F), after 5000 hr (7 months) at 480° (900°F). Clauser et al. employed scanning electron fractographs of pre- and post-aged specimens in their examination. The brittle intergranular failure was evident in the fracture surface after temper embrittlement. Another important observation was that the heat-affected zone of heavy section plate (simulated) remained superior to the base material in toughness when subjected to temper embrittlement.

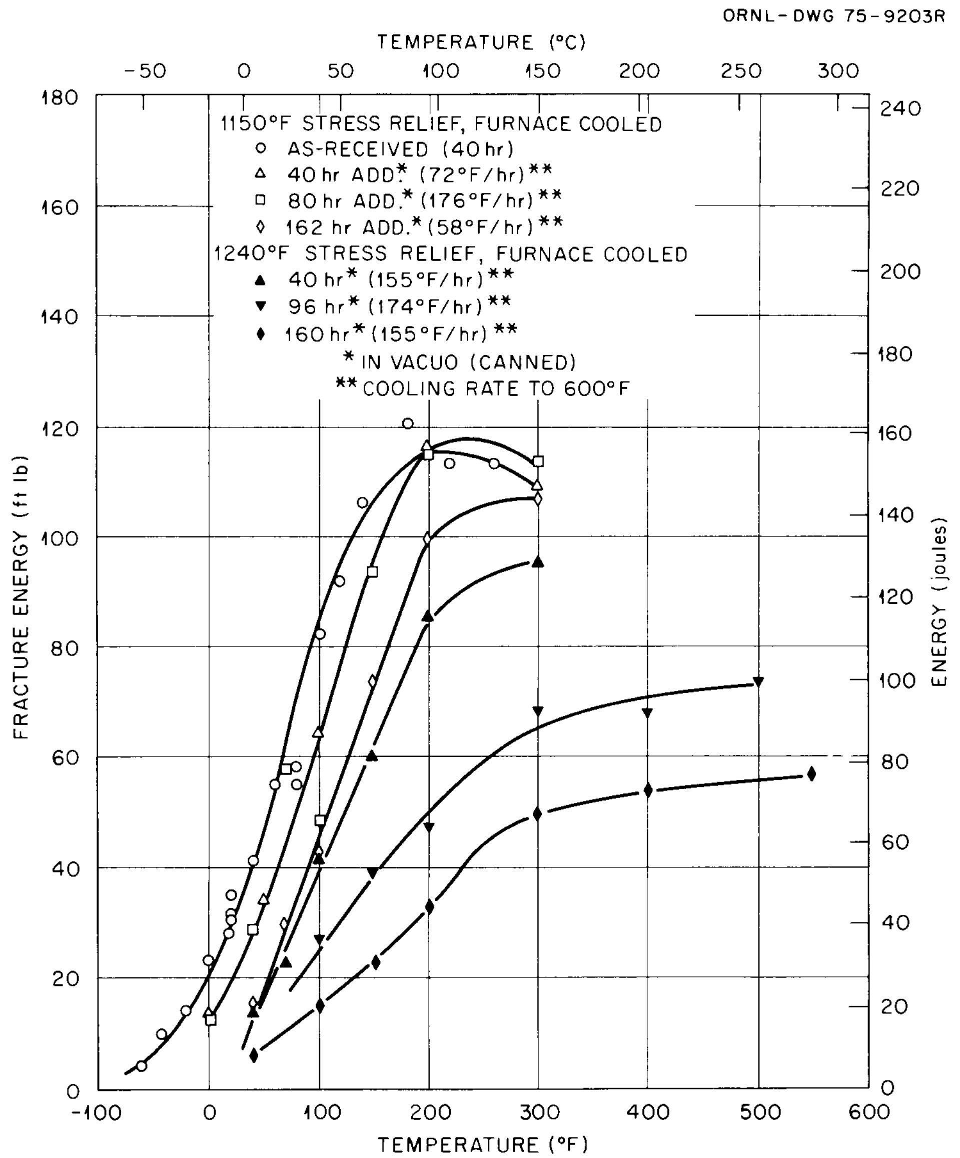

Fig. 4.14. Effect of postweld heat treatment time on Charpy V-notch toughness of A 533, Grade B, Class 1 steel.

Clauser et al. recommended modifications in service and operating conditions to ensure that high stresses are not applied when the material is below about 90° C (200° F). After temper embrittlement has occurred, the ductile-to-brittle transition may have increased significantly above room temperature, and proper startup and shutdown procedures will be critical to ensure against catastrophic brittle fracture of the vessel. This indeed was the case for the failure reported by Watanabe.[23]

Evidently, quenched and tempered steels are more susceptible to temper embrittlement than normalized and tempered or annealed steels. This susceptibility is particularly relevant in the case of the heavy section steels that must be employed in the commercial coal conversion pressure vessels. As was pointed out earlier, it is necessary to quench and temper section sizes of about 8 in. (200 mm) and greater to obtain the tensile properties required in the SA specifications. The surfaces of these steels may be more sensitive to temper embrittlement because of their superior tensile properties (see Fig. 4.5). Moreover, these surfaces, because of their higher strength (hardness), may be more sensitive to sulfidation attack (see Sections 3.3 and 4.3.1).

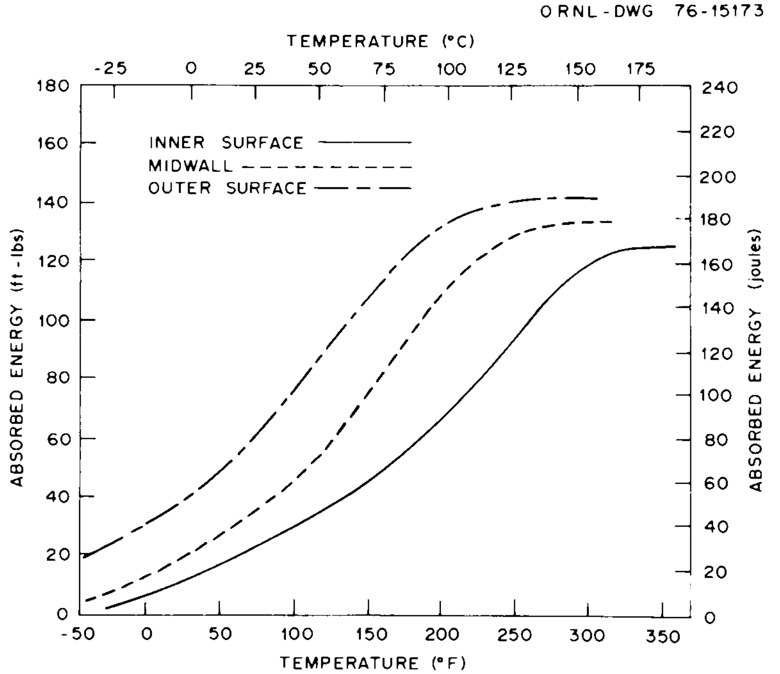

Fig. 4.15. Charpy impact transition curves of $2^1/_4$ Cr-1 Mo steel after 30,000 hr of service. Source: J. Watanabe et al., "A Fracture-Safe Analysis of Pressure Vessels Made of $2^1/_4$ Cr 1 Mo Steel," Paper No. 126, *Corrosion/76, The International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials, March 22–26,* 1976, Houston, Texas, Fig. 1.

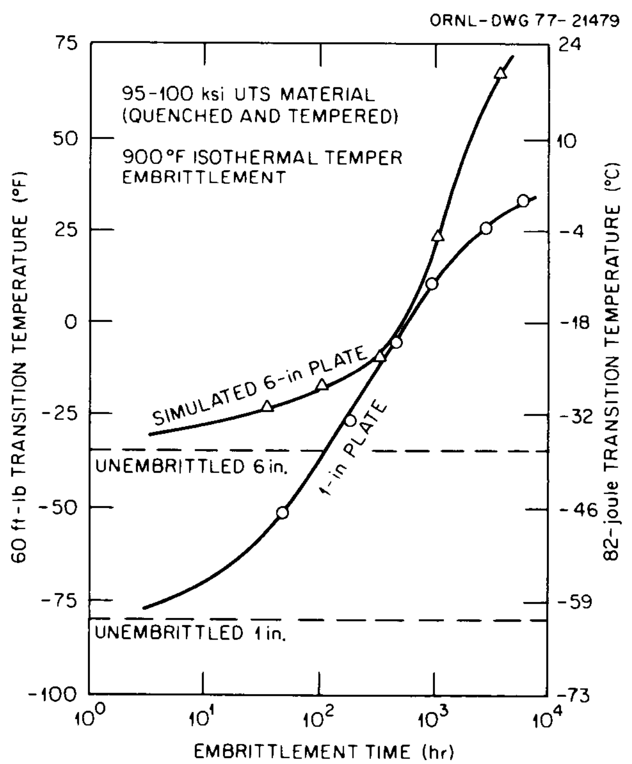

Fig. 4.16. Kinetics of embrittlement for 1- and 6-in. A 542 steel plate. Source: C. D. Clauser et al., "A Phenomenological Study of the Susceptibility to Temper Embrittlement of 2.25% Cr 1% Mo," *Proc. Div. Refin., Am. Pet. Inst.*, 52, 790–815 (1972), Fig. 9.

Other forms of embrittlement occur in the materials that are candidates for the fabrication of coal conversion components. All of these phenomena reflect themselves as a decrease in the ability of a material to plastically deform. Usually, a loss in toughness (often C_V impact values) is employed to measure the degree of embrittlement. The embrittlement manifests itself in many different modes, depending on the chemical composition, heat treatment fabrication procedures, and environment (including temperature, pressure, and process stream).

4.4 Fracture Toughness

Until recently, discussions of material acceptability centered about "classical" mechanical properties, in particular, strength and toughness (as measured by the Charpy V-notch impact test). Recent innovations in the measurement of toughness permit a quantitative assessment of the ability of a structure to resist fracture. This analytical tool is the result of the extension of the field of fracture mechanics to include the assessment of the behavior of lower-strength [<690-MPa (<100-ksi)] steels.

Fracture toughness is a material property that describes a material's ability to resist brittle fracture in the presence of a flaw. The parameter of interest is called the stress intensity factor; it is not to be confused with the stress concentration factor. The stress intensity factor, K, is a function of component geometry, state of stress, applied load, and the size and orientation of a crack. In a relatively thin section, a biaxial stress state will exist, and, under loading, plastic deformation can occur and fracture will be relatively slow and stable (plane stress). As component thickness increases, however, the material is constrained by its surrounding material, and a triaxial stress state results (plane strain). In this second case, strain is not relaxed by deformation and can build up to a critical level, whereupon a slight increase in stress will cause sudden, rapid fracture. The presence of a crack has the same effect as thickness on constraint. Thus the combination of a crack *and* a thick section results in considerable mechanical constraint and tends to reduce substantially the ability of the metal to flow plastically. This relationship between stress, flaw size, and configuration has been expressed mathematically, and the value of plane strain fracture toughness is expressed as K_{Ic}. This mathematical relationship is $K_{Ic} = \sigma c\sqrt{\pi a}$, where σ = applied stress, a = flaw size, and c is a geometrical factor. If the fracture toughness of the material and the loads are known, then the critical crack size (that size which, under the cited stress and temperature conditions, will initiate a propagating crack) can be calculated for a complex structure, such as a pressure vessel or pipe. If a crack reaches its critical size (depth into the component), it can be expected that a sudden, catastrophic fracture could occur. Fracture mechanics is also used to characterize the fracture toughness of a material under stress-corrosion cracking conditions, and the parameter, K_{Iscc}, is often seen; K_{Iscc} is defined as the threshold stress intensity below which crack growth is not detected in an environment that promotes stress-corrosion cracking. Fracture mechanics procedures have been extended to permit the determination of the rate of crack extension under operating conditions. The growth rate, da/dN (crack extension, da, per load cycle, dN), is related to the cyclic stress intensity factor ΔK. This application of fracture mechanics theory permits the prediction of the reliability of a component, based on the time required to reach a critical flaw size. Of course, the most desirable situation is to use a material that has high fracture toughness under design conditions and, preferably, one whose critical crack size will be greater than the thickness of the component. In that case, a pressure-containing component would experience "leak before break," and a catastrophic failure will be avoided.

Fracture toughness data are available for many materials. However, fracture toughness is a material property that is affected by temperature, strain rate, heat treatment, etc. Thus, to present data obtained under environmental "standard" conditions and to compare them for various materials would not be very meaningful. The most characterized material, applicable to this report, regarding fracture toughness is A 533 Grade B Class 1 steel. The Heavy Section Steel Technology (HSST) program, which is administered at ORNL, tested compact specimens up to 300 mm (12 in.) in thickness, in order to obtain plane strain fracture toughness data for that material. The valid K_{Ic} values[28] for A 533 Grade B Class 1 steel are provided in Fig. 4.17 as temperature increases. The curve provides the information that, at a certain temperature, a section thickness less than that indicated for that temperature will experience some plastic deformation (i.e., plane stress behavior) prior to fracture.

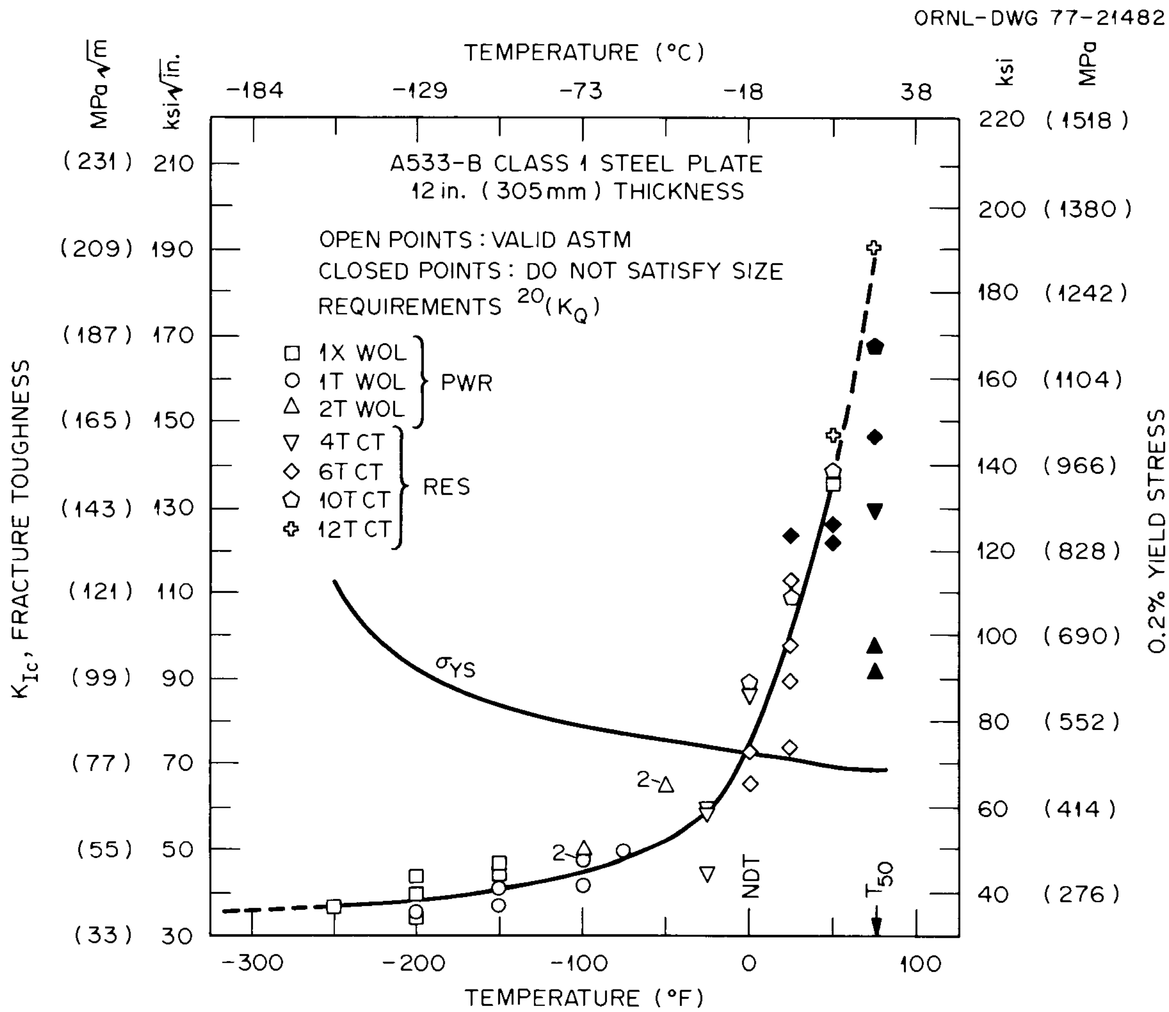

Fig. 4.17. Valid K_{Ic} fracture toughness data for 12-in.-thick (305-mm) A 533, Grade B, Class 1 steel plate.

The results of this study showed that plane strain fractures can occur at temperatures above those at which Section VIII Divisions 1 and 2 require 20 J (15 ft-lb) of impact energy in a C_V test. For example, heats of A 533 Grade Class 1 steel that have been thoroughly characterized in the ORNL HSST program absorb 20 J (15 ft-lb) at about −23°C (−10°F). This steel exhibits a "flat" fracture at 16°C (60°F), which is 39°C (70°F) above the temperature at which the minimum Section VIII toughness requirements were satisfied. Similar comparisons at various temperatures are facilitated by Fig. 4.18, a composite of Figs. 4.4 and 4.17. That 20-J (15-ft-lb) C_V Code criterion is not adequate for the section sizes being considered for large coal conversion vessels is recognized by experienced fabricators[5] who impose C_V requirements higher than those of the Code. This subject is discussed in Section 4.2.1.

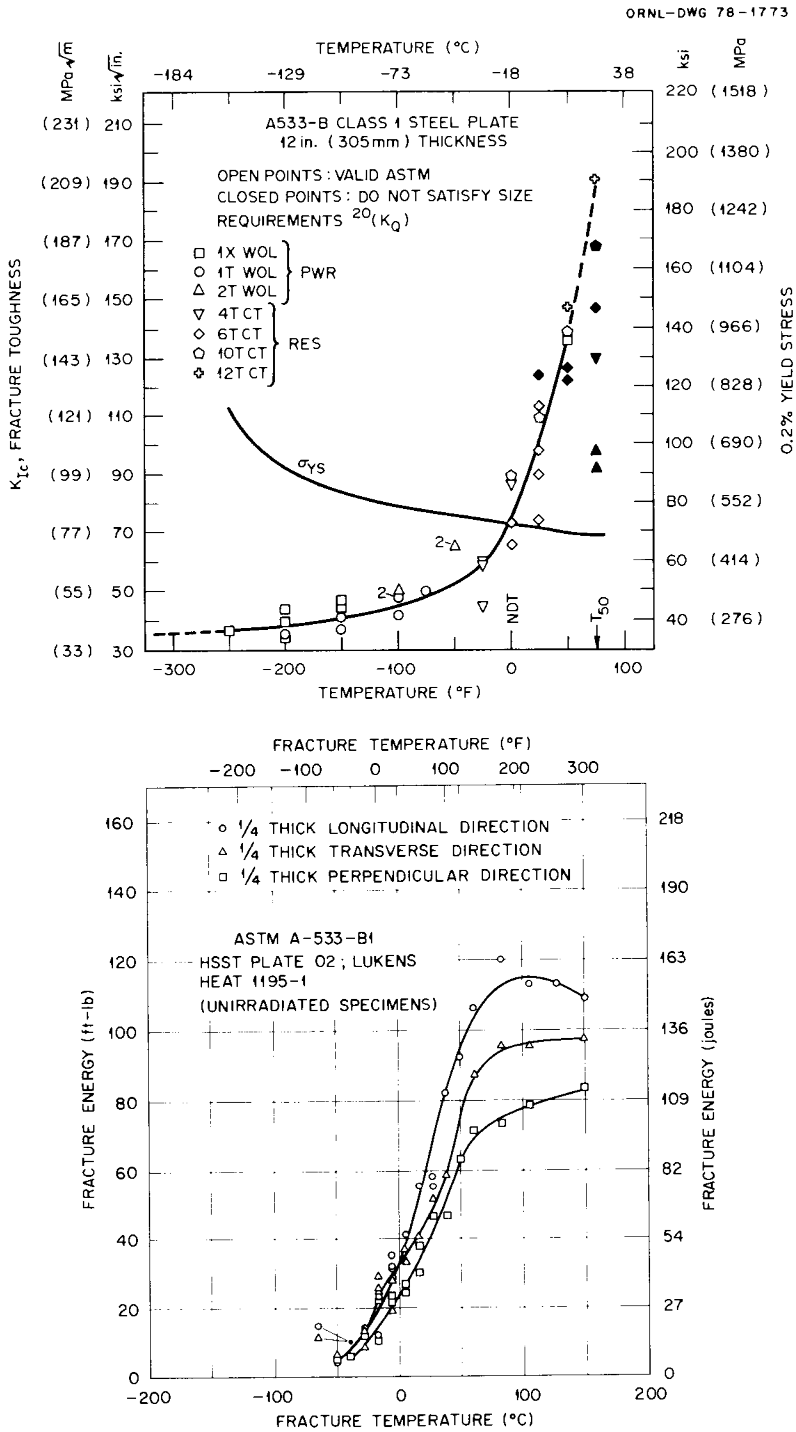

Fig. 4.18. Relationship between valid K_{Ic} fracture toughness (*a*) and Charpy V-notch toughness (*b*) from the same 12-in.-thick (305-mm) plate of A 533, Grade B, Class 1 steel.

The results of the Intermediate Test Vessels (ITV) program conducted by the HSST program at ORNL support the suggestion that a 20-J (15-ft-lb) energy criterion is inadequate. The HSST program has tested eight vessels to date. These vessels are 1 m in diameter (39 in.) and have 150-mm (6-in.) wall thickness. The most significant test, insofar as this discussion is concerned, is ITV-2. This vessel was tested at 0° C (32° F), a temperature where the base metal had exhibited C_V toughness values greater than

90 J (60 ft-lb) and K_{Icd} (equivalent energy) toughness values greater than 220 MPa $\sqrt{m}$ (200 ksi $\sqrt{in.}$) with 4T compact specimens.[29] The results[30] of the ITV-2 test are shown in Fig. 4.19. The vessel failed in a catastrophic manner and fragmented; it was literally in two pieces after the test had been completed.

Furthermore, the Section VIII toughness criteria do not impose any minimum upper-shelf energy value that must be satisfied by the candidate steels. Satisfying the Section VIII C_V criterion does not guarantee that the upper-shelf energy value is adequate. That a material's ability to simply achieve 20-J (15-ft-lb) energy does not assure an acceptable margin of safety for thick sections of pressure vessel steels is evident in the C_V results shown in Fig. 4.9. The steel represented in that study exhibited approximately 20-J (15-ft-lb) at the failure temperature. These vessels will normally operate at temperatures above the onset of upper-shelf energy, and this lack of assurance of adequate toughness is unacceptable. It is likely that the operating conditions (temperature and process stream environment) of coal conversion vessels and piping will be such that a shift upward in transition temperature and a loss of upper-shelf energy may simultaneously occur in service, as was pointed out in Section 4.3.3. The magnitude of the energy stored in the large gasifier vessels proposed in a number of conceptual designs is such that safety, as well as reliability, may be an issue and, if so, the toughness of the vessel materials at operating temperature must be proven adequate.

Reference has been made to the application of fracture toughness criteria in design and operation in Sections III and XI of the ASME Code. An Electric Power Research Institute study[31] of representative nuclear pressure vessel base materials, weldments, and HAZ showed that the K_{IR} (Section III, Appendix G) and K_{Ic} (Section XI) curves, arrest and crack initiation requirements, respectively, are conservative. The K_{IR} approach to safety is based on an arrest criterion. This basis for assuring safety may be too conservative for coal conversion pressure vessels; however, the requirements in Section VIII appear inadequate and should be reviewed.

Fracture toughness data for $2\frac{1}{4}$ Cr–1 Mo steel are more scarce than for the A 533 Grade B Class 1 steel. The Japanese[22] determined the K_{Ic} values (these were converted from J_{Ic} data) for temper-embrittled steels. Their data, presented in Fig. 4.20, show the difference in K_{Ic} at the same temperature for the two different heats of $2\frac{1}{4}$ Cr–1 Mo steel. These results reflect the heat-to-heat differences that can be expected in the response of $2\frac{1}{4}$ Cr–1 Mo steel to temper embrittlement. The effect of through-the-thickness location in postembrittlement fracture toughness is shown in Fig. 4.21. This is the same material whose C_V properties are provided in Fig. 4.15. There is a factor of 2 between different locations in the K_{Ic} value at a given temperature. For example, the inner surface and outer surfaces have K_{Ic} toughness values of about 82 and 165 MPa $\sqrt{m}$, (75 and 150 ksi $\sqrt{in.}$), respectively, at 16°C (60°).

The fracture analysis conducted by Watanabe et al. on the steel from the desulfurization vessel failure[22,23] indicated a critical flaw size of 580 mm (23 in.) at 54°C (130°F) for a steel with a C_V upper-shelf value of 169 J (125 ft-lb). The loss of upper-shelf energy, as a consequence of any of a number of reasons (embrittlement, stress relief, environmental affects, etc.), could result in a decrease in the critical flaw size to a value that is below the threshold of detection by nondestructive examination procedures.

It has been mentioned previously that crack growth rates in service are of extreme importance. The probability that a crack of a critical size exists prior to service is essentially zero. The nondestructive examination procedures required, especially in Section VIII, Division 2, *and* the requirement for a hydrostatic test usually assure that they do not exist. These NDE procedures are discussed in Chapter 6. In service, however, a crack can grow (it is reasonable to assume that a flaw is present, and, for that reason, crack incubation and initiation are not required), at a rate of growth dependent on temperature, frequency, environment, and stress intensity range. Figure 4.22 shows the crack growth rate for $2\frac{1}{4}$ Cr–1 Mo steel in air,[32] particularly the influence of temperature on the rate of crack growth. This effect of temperature is observed even though the strength of $2\frac{1}{4}$ Cr–1 Mo steel is quite stable in this temperature

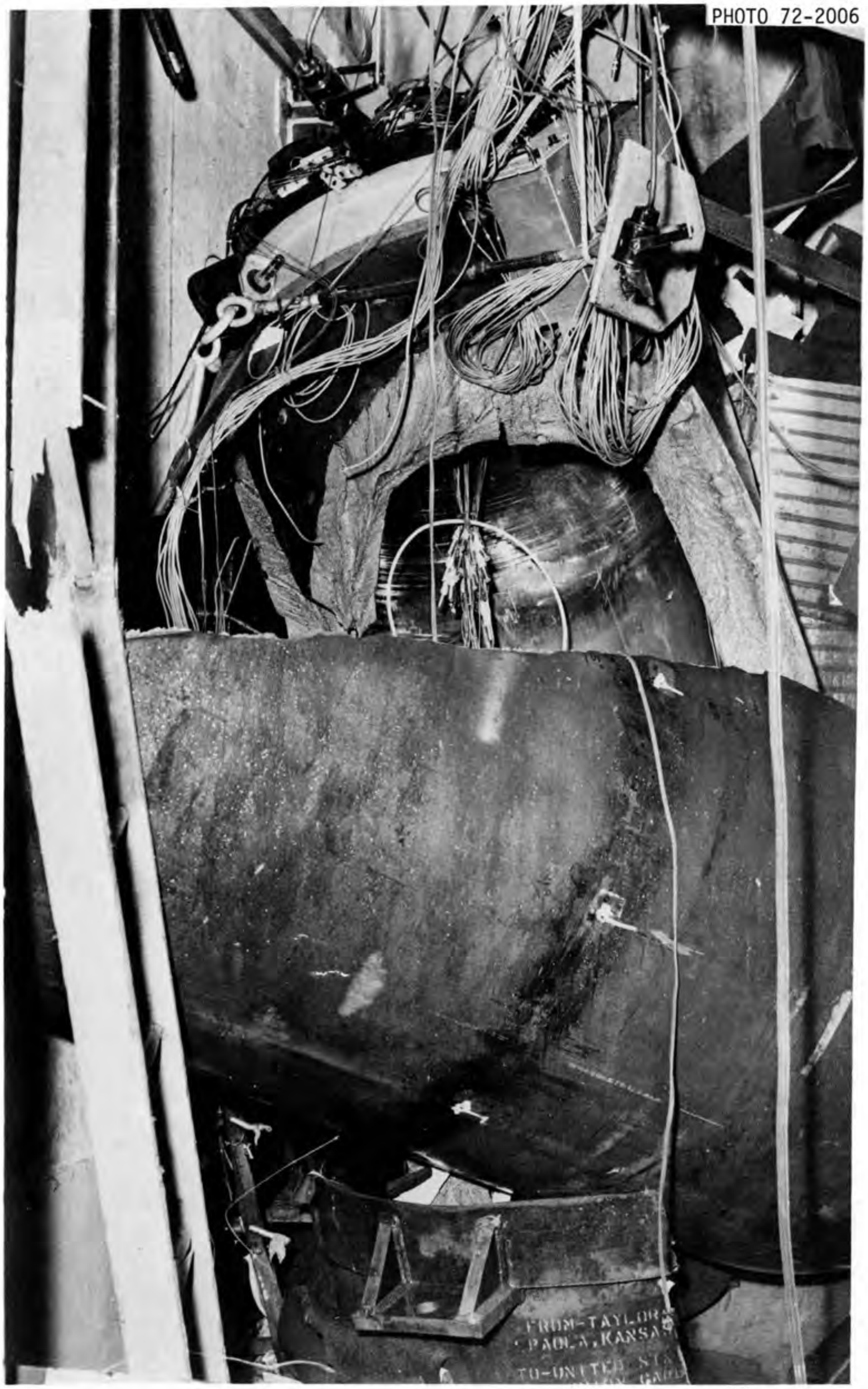

Fig. 4.19. Vessel V-2 (A 508, Class 2) in test pit immediately after testing to failure at 0° C (32° F). The portion of the vessel shown in the foreground fragmented as a consequence of the test conditions.

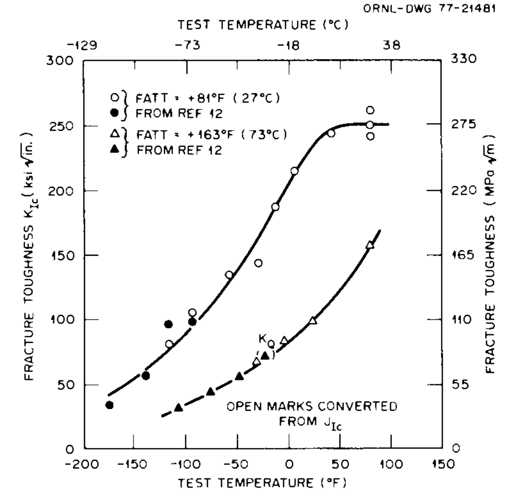

Fig. 4.20. Temperature dependence of fracture toughness of two temper-embrittled 2¼ Cr–1 Mo steel forgings. Source: J. Watanabe et al., "A Fracture Safe Analysis of Pressure Vessels M of 2¼ Cr–1 Mo Steel," Paper No. 126, *Corrosion/76, The International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials*, March 22–26, 1976, Houston, Texas, Fig. 5.

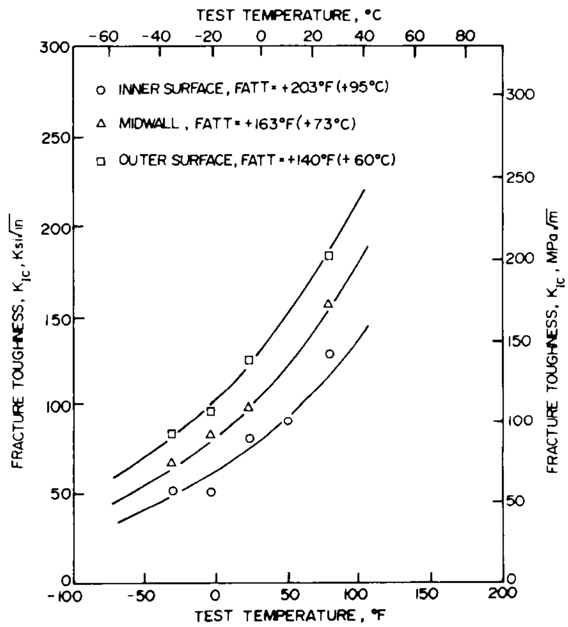

Fig. 4.21. Temperature dependence of fracture toughness of 2¼ Cr–1 Mo steel after 30,000 hr of service. Source: J. Watanabe et al., "A Fracture Safe Analysis of Pressure Vessels Made of 2¼ Cr–1 Mo Steel," Paper No. 126, *Corrosion/76, The International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials*, March 22–26, 1976, Houston, Texas, Fig. 4.

range. Pense and Stout showed that temperature and stress intensity range have a major effect on the crack growth rate of A 212 Grade B steel (A 212 Grade B is similar to A 516 Grade 70) and that increasing the stress intensity factor, ΔK, from 55 to 88 MPa $\sqrt{m}$(50 to 80 ksi $\sqrt{in.}$) resulted in a tenfold increase in crack growth rate.[33] Cycle frequency has an even more dramatic effect. Figure 4.23 contains data[34] showing the effect of 60-, 1-, and 0.5-cpm frequencies on the crack growth rate of A 533 Grade B Class 1 steel. These results do not consider the influence of environment, which, even in a comparatively benign environment such as that in a pressurized water reactor, has a dramatic effect[34] on the crack growth rate of A 533 Grade B Class 1 steel.

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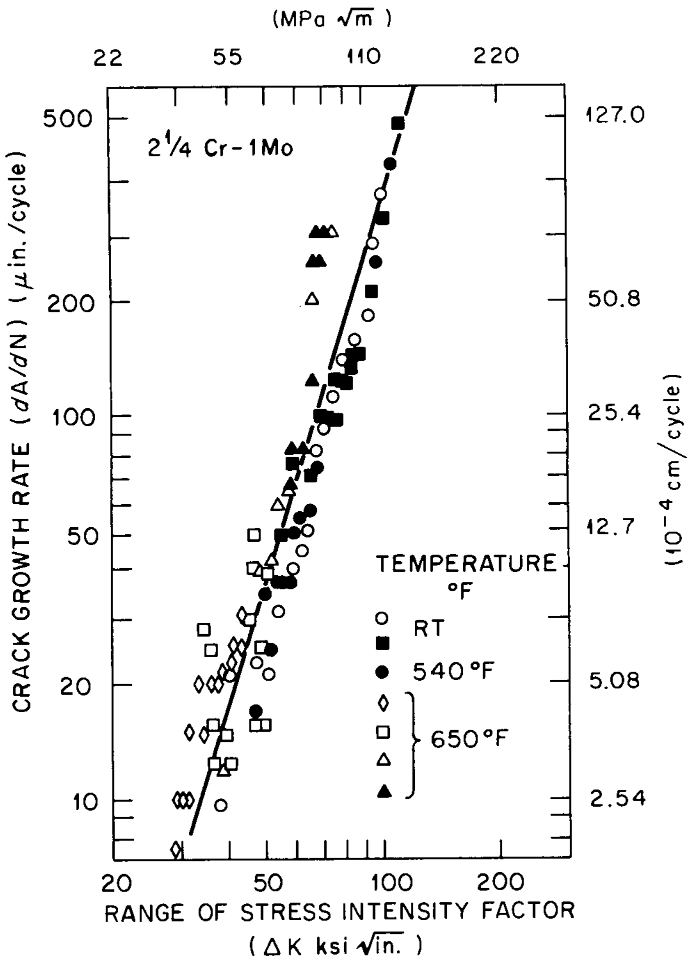

Fig. 4.22. Effect of test temperature on the crack growth correlation for 2¼ Cr-1 Mo steel.

4.5 Operational Considerations

The discussions presented so far in this chapter have been intentionally general and without regard to application within an operational context. Pressure vessels, such as the primary reaction vessels in commercial gasification and liquefaction plants, will be large, thick-walled, welded components. Some of the vessels proposed for coal conversion applications are larger than any ever previously fabricated. Further, they will be required to operate under environmental conditions that are severe by any standard of measurement. Process operating conditions have been established for the individual coal conversion system, but the degree of process control has not been established and, indeed, may be affected by the component size. Factors such as the temperature fluctuations, especially in localized areas of large vessels, are unknown and may give rise to cyclic thermal stresses. These could affect crack growth, and the designer must anticipate this type of occurrence and at least provide a cursory consideration of this behavior in the selection of materials. Most reaction vessels will be lined with refractory to protect against erosion and to reduce metal wall temperatures. Further, the thick vessel walls will be lined with metal cladding or weld overlay for protection against the corrosive environment. This requirement for protection will also be necessary for low-alloy piping. Experience with refractory linings of vessels and piping has shown that they will crack, spall, and allow penetration of corrosives to the wall. Cracks can

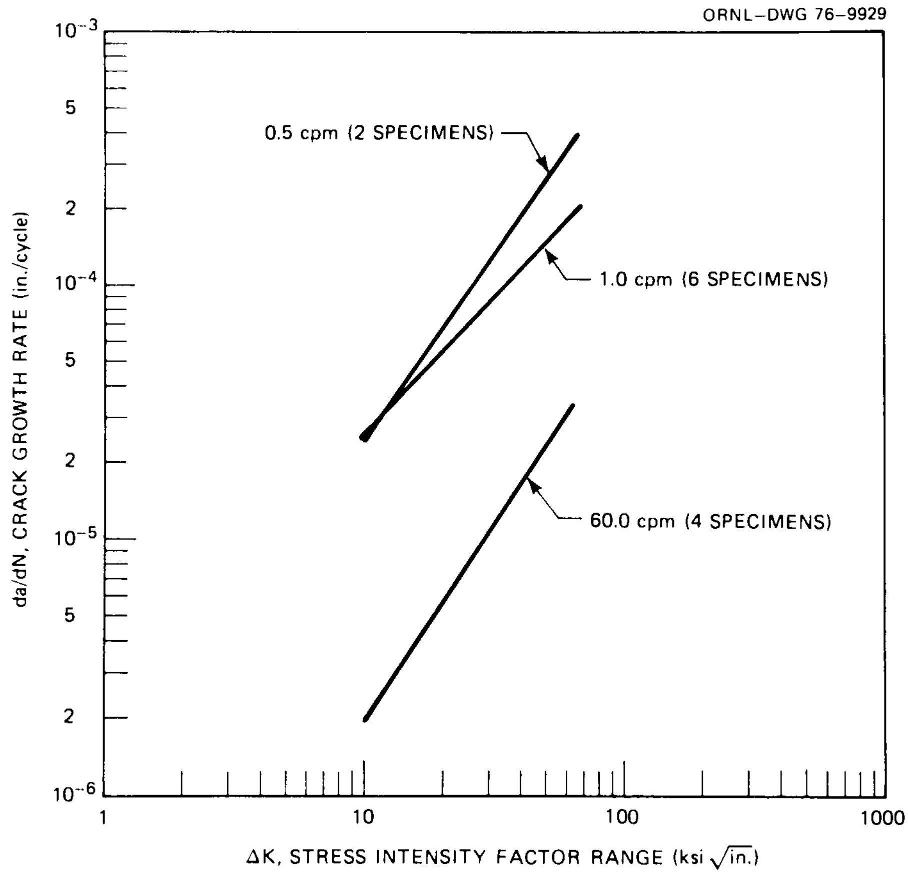

Fig. 4.23. Effect of cyclic frequency on crack growth for A 533 B and A 508 steel tested in a PWR environment preliminary result (tests conducted prior to Feb. 15, 1976). 1 in. = 25.4 mm; 1 ksi $\sqrt{\text{in.}}$ = 1.0988 $MN \cdot m^{-3}$.

also develop in the cladding or overlay and expose the base material. If this should occur, the pressure-retaining component may be exposed on both thermal and process stream environments that were not anticipated in its original design. In the case of hydrogen, cracks in the cladding are not necessary for base-metal attack. The hydrogen will diffuse through the corrosion-resistant high alloys, such as the austenitic stainless steels. Therefore, the base material must be chosen to resist the hydrogen conditions in the system.[35] The presence of hydrogen adds a measure of importance to the cladding operation. Whether roll clad, explosive bonded, or overlayed by weld deposit, the operation must ensure good contact with the base material. Any small gaps between the two materials will act as collection locations for diffusing hydrogen atoms, which will combine into molecular hydrogen. (Cladding procedures and their examination by NDE methods are discussed in Chapters 5 and 6, respectively).

Molecules of hydrogen are too large to diffuse into the metal, so that a buildup of pressure can occur in the gap upon cooldown. When the clad material cannot resist the pressure, it will spall resulting in the exposure of the base material.

The many attachments that are necessary to support the internals will either be welded directly to the wall or attached to supports that have been welded to the wall. In either case, the welding process will affect the base material. Since the attachment welding will probably be accomplished in the field, postweld heat treatment must be achieved under less than optimum conditions. It is probable that the attachments will be subject to thermal and stress fatigue because of the difference between their physical properties and those of the containment material. It is possible that cracks will be initiated in the attachment welds and, subsequently, will grow into the base metal. Thus it is not unreasonable to suggest that the thick-walled vessel or pipe materials will be presented with a crack and/or exposed to the process stream environment.

Shutdown conditions can become particularly critical because of the possibility of the formation of acidic condensates. If the material has been embrittled, pressurization at low temperatures could result in an unstable crack propagation. Even at high temperatures, subcritical crack growth can occur due to small cyclic loads or stress-corrosion mechanisms, and, if the toughness of the material has been severely reduced, failure could occur.

In ductile steels, such as those which would be selected for pressure vessels, the effect of hydrogen is to assist slow, stable crack growth through void growth and coalescence.[14] If undetected, slow growth will continue until instability, at which point fracture occurs (1) because of ductile failure due to plastic overload of remaining ligament or (2) because the crack reaches critical size and unstable fracture occurs.[36]

In the design of pressure-retaining components, such as pressure vessels and pipes, all aspects of material properties must be considered. The magnitude and depth of consideration are dependent on knowledge of the operating conditions and service experience with various materials. Design codes provide guidelines for design methods, analyses, and material properties. When selecting a material for a given application, the designer initially refers to material specifications that give room temperature, mechanical properties, chemical composition, and other basic requirements that the material must meet. For operation at elevated temperatures, tables are provided in the code that give the maximum allowable design stresses at various temperatures. These limits are straightforward and can be used in appropriate equations for calculating thickness requirements, based on design pressure and temperature. The tables are based on elastic loading of an integral section of material; that is, they do not account for flaws in the material. Once a flaw or crack is introduced in the component, the loading conditions are changed and the material will react differently. Therein lies the motivation for considering fracture toughness characterization of materials.

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5. FABRICATION*

5.1 Introduction

The thick-walled pressure vessels included in the conceptual designs (discussed in Chapters 1 and 4) for coal conversion processes will be fabricated from either thick plate or forgings. The product form used is dependent upon the facilities and equipment of the individual fabricators. Often, because it will minimize the amount of longitudinal seam welding, large-diameter thick-walled vessels are fabricated from ring-rolled (or ring-forged) forgings. Figure 5.1 is a schematic presentation of the various vessel parts joined together to produce a large complicated vessel.

The product form used (plate or forging) dictates the fabrication procedures employed in the fabrication of the individual shell courses. For example, Fig. 5.1 depicts shell courses fabricated from plate material. Note the longitudinal seams in the shell courses. This step in the sequence of fabrication is not required when forgings are employed.

5.2 Pressure Vessels

5.2.1 Plate

5.2.1.1 Procurement practices and inspection. The shell courses, head domes, and tori of large pressure vessels will undoubtedly be constructed primarily from carbon or low-alloy steels such as SA 516, SA 387, and SA 533.[1] Another steel, A 543, appears attractive for advanced applications and should be evaluated further as a material of construction for coal conversion applications. A list of plate specifications and properties is provided in Table 4.1. The plates are purchased to the SA specification and applicable supplements, as provided in SA 20 of Section II, Part A, of the ASME Code. Often, in addition to the code requirements, the individual fabricator will impose supplementary requirements that are unique to his organization. In those cases where the fabricator will do his own heat treating, he may require that the supplier provide the results of tests conducted on samples that have received simulated heat treatments. In other cases the fabricator may place additional restrictions on the normal specification; these may include a requirement for vacuum degassing of the ingot and limitations on certain elements that have been determined to be detrimental because of processing or service conditions. Additionally, some users are currently specifying that the steel plate be manufactured to fine grain practice: greater toughness is realized with some loss of creep strength. Some users also specify composition limits which are more stringent than the ASME Code to produce material with desired hardenability and to preclude, for some steels, temper embrittlement.

The heaviest plate-weight that is produced in the USA today is about 100,000 lbs (45,000 kg).[2] Larger plates can be fabricated at Japan Steel Works, with maximum weights of 160,000 lbs (73,000 kg).[3] Maximum plate widths are limited by rolling mill widths and approach 5 m (200 in.). Plate thicknesses up to 350 mm (14 in.) are produced by Japan Steel Works; similar thickness can be produced in the USA. Maximum plate lengths are dependent on the plate weight for a given thickness and plate width.

In addition to mill inspection of plates, it is common practice to inspect the edges and surfaces of all plates carefully in the shop before starting fabrication. Edge inspection during burning, machining, and welding operations can reveal harmful laminations. A detailed discussion of inspection practices is presented in Chapter 6.

5.2.1.2 Forming. Two main techniques are employed for forming pressure vessel plates for shell fabrication: bending in offset rolls or pinch rolls in a unidirectional manner and press forming with dies.

*This section was prepared by G. M. Slaughter, D. P. Edmonds and J. W. McEnerney.

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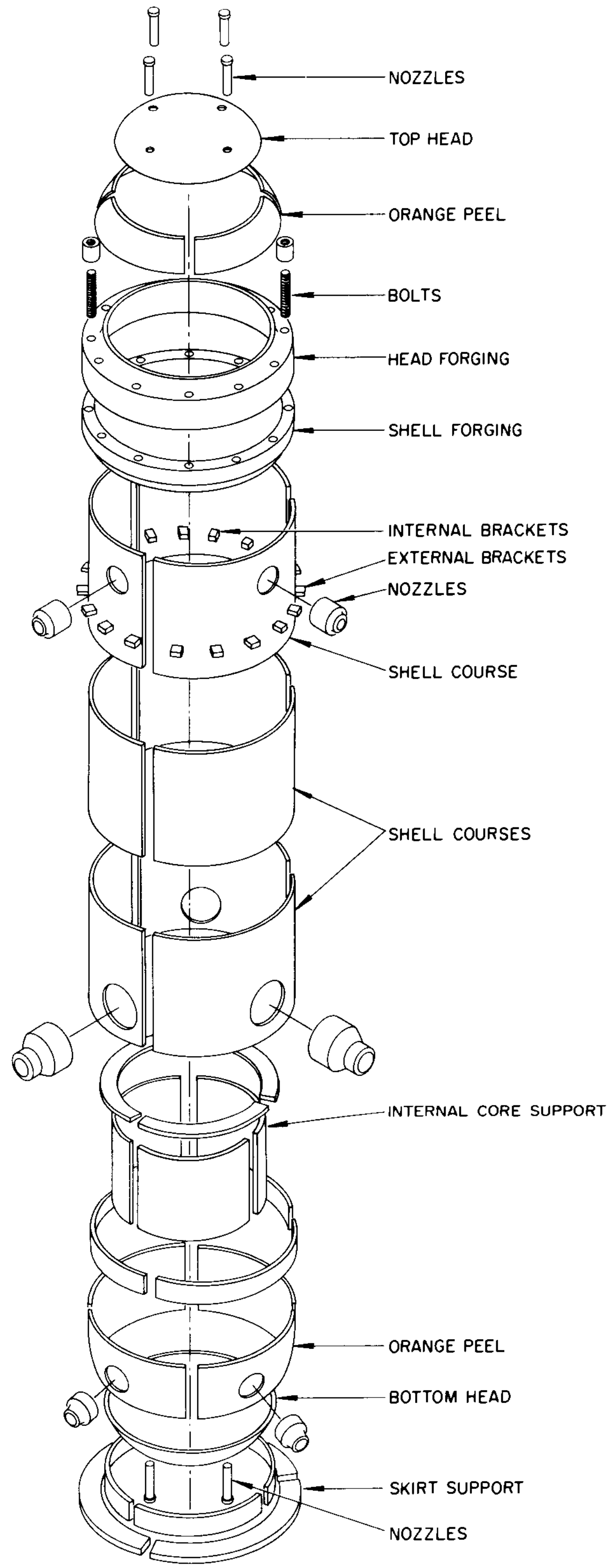

Fig. 5.1. Exploded schematic view of a typical large pressure vessel.

These operations may be performed cold, in the case of thin sections, but hot forming is more common in press-forming operations involving thick plates.

Heads are also fabricated from formed parts, either full sections (Top Head in Fig. 5.1) or in segments (Orange Peel in Fig. 5.1). This is done by press-forming plates between a set of dies of the desired configuration and contours. Forming can be done cold or hot; however final sizing is usually done cold, after the plate has been heat treated. After forming, excess plate is burned or cut away and weld joints are prepared on the plate edges.

The limits for cold forming are set by plate thickness, strength of the steel, and amount of forming involved. Cold forming, which is carried out on fully heat-treated plates, may be carried out at 150 to 200°C (300 to 400°F) to minimize the possibility of cracking during the processing operation. Cold-forming operations are commonly based on producing a maximum outer-fiber stretch of 3%. If more stretch is needed, cold forming is done in two or more stages with an intermediate stress relief at about 650°C (1200°F). Special techniques are utilized for forming the heads of pressure vessels.

Studies have been conducted on a number of pressure vessel steels to determine the effects of cold straining. All the steels are affected by straining and, perhaps even more important, by a subsequent aging. For example, an ASTM A 302 Grade B steel studied[4,5] at Lehigh University had an increase of approximately 33°C (60°F) in its 0.38 mm (15-mil) lateral expansion temperature as a consequence of aging at 260 to 370°C (500 to 700°F) after being strained 5% at room temperature. Although stress relieving will normally relieve this embrittlement, excessive exposure to elevated temperatures can degrade the toughness of pressure vessel steels.[5]

Hot forming can roughly double the plate thickness that can be formed in a specific press and is carried out on plate purchased in the hot-rolled condition. Hot forming of ferritic steels can start out at about 1180°C (2150°F) and will usually continue until the temperature approaches 930°C (1700°F). Plate is generally formed in one continuous operation without intermediate reheating. Spinning and its various modifications are sometimes used to form heads. The hot-formed parts must be cold sized after heat treatment to meet required tolerances. After forming, the parts are generally fully heat treated prior to further fabrication.

5.2.2 Forgings

5.2.2.1 Procurement practices. Flange rings, closure flanges, and nozzles for pressure vessels are generally forgings. Additionally, some companies prefer to fabricate their large pressure vessels with shell-course ring forgings. They are produced essentially by two techniques—mandrel forging and ring rolling. The mandrel forging operation is a process whereby the blank is elongated or enlarged in a steplike manner. The forging blank is incrementally upset between the top head and the mandrel. There is an appreciable time lapse between increments of upset for adjacent positions around the forging blank. In contrast, the ring rolling operation is a continuous process quite like rolling. The time during one revolution of the forging blank is normally negligible.

Nozzles may be produced by either the open or the tight mandrel processes, depending on their sizes. The forgings, regardless of how they were manufactured, are contour machined essentially to finished dimensions, austenitized, quenched and tempered, and then finish-machined prior to shipment to the fabricator. Therefore, it is the forger's responsibility to assure that the required mechanical properties are met.

Forgings often differ in composition from plate (see Tables 4.1 and 4.2). Some fabricating companies order forgings to company specifications that satisfy the requirements of the ASME Code. Additional requirements concerning determination of mechanical properties after simulated postweld heat treatment and determination of a Charpy V-notch impact transition curve are usually imposed. The supplier must also conduct ultrasonic and magnetic-particle inspections of the forgings.

Differences do exist among the various manufacturing processes employed to produce forgings.[6] However, the end products (e.g., from ring rolling vs those from open-mandrel forging) having undergone comparable degrees of working, are usually quite similar.

Low hydrogen levels in the forgings are guaranteed by the use of vacuum treatment procedures, which are standard practice throughout the world with suppliers of large forgings. The vacuum treatment often provides an added degree of homogeneity to the composition of the forging.

Other differences in processing result from the practices of various manufacturers, mostly in the area of heat treatment. Austenitizing and tempering temperatures, cooling rates, and holding times can differ greatly. However, the fabricator considers the results of the final mechanical tests as a guarantee that satisfactory procedures have been followed.

5.2.3 Preparation for welding

Edge preparations for welding differ because of plate thickness, welding process employed, position of welding, and individual shop preferences. Whenever possible, edges are prepared in the flat position on side planers, gantry machine-cutting equipment, or other similar devices. To avoid exceeding the specified diameter tolerances in thick ring sections, the weld grooves normally are prepared after forming.

Single-U, double-U, and single-V grooves are probably the most commonly used welding joint designs. Typical dimensions for single-U and double-U grooves consist of a $^1/_8$-in. (3.175-mm) root face, a $^1/_4$- to $^5/_{16}$-in. (6.4- to 7.9-mm) radius, and an included angle of about 15°. The single-V groove has straight sloping sides and a root opening. This joint design has the advantage of being easily made by oxygen cutting techniques when machining equipment is not available. This is also true of the double-V groove, which finds extensive use in field welding operations.

Single-U and single-V grooves lend themselves to automatic submerged-arc welding from one side, as well as manual welding. For relatively small-diameter vessels, where preheat for welding is required, the best practice is to plan the fabrication so that welding is accomplished from the outside.

In the assembly of cylindrical vessel courses, the mating edges are brought together and held together with lugs and bars and are frequently tack welded on the weld root side. The abutting beveled edges may be either touching or gapped to a predetermined distance for improved weld metal penetration. In heavy-wall construction, tack welding is insufficient, and "strongbacks" are used to hold the cylinders in position for handling and welding. The ASME Code notes that tack welds may be used in pressure vessels for fit-up (subject to the restrictions stated with respect to removal), preparation, and examination.

In heavy-plate fabrication, correction of out-of-roundness is generally obtained by means of bevel selection, struts, and jacks. A tolerance of 1% of the vessel diameter is frequently allowed. It is highly desirable to try to prevent this distortion in heavy plate during forming by opening the chord distance of each element and during assembly and welding by placing supporting struts in the cylinder. The use of double-bevel joints instead of single bevel will further minimize distortion.

5.2.4 Welding

5.2.4.1 **Processes for long seams.** Selection of processes for specific applications is influenced by several factors; these include position, joint configuration, quality requirements, heat input, and subsequent heat treatment. Welding processes most likely to be utilized in the fabrication of carbon and low-alloy steel vessels for coal conversion applications are manual shielded metal arc, submerged arc, and electroslag. A process that should be considered for future applications is gas metal-arc welding. In all the processes, the choice of filler metal and/or flux is predicated upon providing adequate mechanical properties and corrosion resistance for the particular service encountered.

Submerged arc. The widespread use of submerged-arc welding stems from its ability to produce high-quality welds at high rates of deposition. In this method, single or multiple electrodes (usually two) are automatically fed through a powdered flux covering the molten puddle. In the multiple-wire system, the electrodes are sometimes inclined slightly toward each other in the same plane so that both operate in the same pool of molten metal. With independent control of welding current and voltage for each electrode, a wide variety of parameters is available for controlling bead width and shape. In the case of single-electrode operation, a narrower range of conditions exists before poor bead shape, cracking, or porosity is encountered. One of the disadvantages of the process results from the operator's inability to view the deposition of the filler metal directly. An accurate guidance system for the electrode is mandatory.

In the case of low-alloy steels, the introduction of alloying elements may be made (1) through the filler metal or (2) through the use of enriched fluxes containing alloying elements. In the first case, variations in welding conditions (such as current, voltage, and travel speed) have minimal effects upon the composition of the deposited metal. In the second case, the final composition is dependent upon the volume of the flux melted. Therefore, depending upon the welding conditions employed, considerable variations in composition can be produced. For this reason, it is extremely important that, once welding procedures have been established, they are maintained throughout the fabrication of the vessel.

Shielded metal-arc welding. This manual welding process is still used extensively in shop fabrication of pressure vessels and is the primary process used in field erection. Depending upon the type of joint and fit-up, electrodes as large as 7.9 mm ($^5/_{16}$ in.) in diameter may be employed. Smaller electrodes are used at the root of the groove, and larger electrodes are employed as the thickness of the deposit increases.

Heavy-section welds are built up in relatively thin layers, approximately 2 to 4 layers per centimeter (6 to 10 per in.) of thickness. The beads may be deposited either in a linear mode (stringer passes), or the electrode may be oscillated from side to side to cover the full width of the welding groove (weaved). The relatively thin layers or beads of weld metal permit a partial progressive grain refinement of preceding layers of ferritic weld metal and heat-affected zone to minimize the columnar structure characteristics of single beads of weld metal as deposited and improve the ductility and impact resistance of both the weld and the heat-affected zone.

Electroslag/Electrogas. This process is being used increasingly because of its high deposition rates and economic advantages. Base-metal dilution tends to be very high (often 50 to 60% of the total fused zone), and, therefore, the base-metal composition will have a strong influence on the resultant weld-metal composition and properties.

The as-welded microstructure is generally considered to be unacceptable, and electroslag/electrogas welds must be reaustenitized and cooled (accelerated cooling is required for thick sections). Furthermore, the extremely high heat input necessary to produce the welds results in a heat-affected zone that extends for an appreciable distance into the base metal. The filler metals used for electroslag welds are selected with response to the austenitizing and quenching heat treatment as an important criterion. The welds produced by this process normally possess a degree of cleanliness and soundness not found in other processes.

Gas metal-arc. Currently, this process has not gained wide acceptance for the manufacture of large pressure vessels of carbon steels and low-alloy steels. It permits a relatively high deposition rate of submerged arc and has the added advantages of a visible arc and the potential for out-of-position welding. Electrodes in coils of many types, diameters, and chemical compositions are readily available.

The version of the process called narrow-gap welding may have future application to thick-walled vessels. The weld groove is machined with the minimum groove angle consistent with attaining satisfactory tie-in with the groove faces.

Hot-wire gas tungsten-arc. This process has recently been developed and is quickly gaining popularity. Already it has found limited use in the production of pressure-boundary welds in large pressure vessels. Deposition rates comparable to single-wire submerged-arc welding can be obtained with this process. These welds are also cleaner because of gas shielding and require less manpower to perform than comparable submerged-arc welds. Since a heavy slag is not present, there is less chance of trapping slag in the deposit.

5.2.4.2 Welding of nozzles. Nozzles and other external and internal connections to pressure vessels may be welded by manual or semiautomatic methods. The submerged-arc, shielded metal-arc, and gas metal-arc processes seem to be the most common because of geometrical limitations. All connections must be made before postweld heat treatment of the vessels. The specific joint designs used in nozzle attachment can vary widely and are usually delineated in the specifications. However, because socket weld connections have exhibited severe erosion in some coal conversion pilot plant applications, for nozzles and other connections to pressure vessels, full penetration welds should probably be used.

5.2.4.3 Weldability of pressure vessel steels. The weldability of steels is much too complex to discuss in detail in this section, and the reader is referred to such treatises as *Weldability of Steels* by Stout and Doty,[7] and *Welding Metallurgy* by Linnert.[8] However, a short discussion of two important considerations—cold-cracking and hot-cracking—is merited.

Cold-cracking, associated with the heat-affected zone of the base metal, occurs only when martensite is formed and when hydrogen is present. Cracks that run roughly parallel to the fusion line are referred to as underbead cracks; those that initiate close to the toe of the weld and propagate away from the weld because of the stress system are called toe cracks. Since cracking caused by hydrogen may occur hours or even days after welding, it is also known as delayed cracking. All of these types of cracking originate by the same mechanism. There are three factors, however, that act simultaneously in the generation of cold cracks: dissolved hydrogen (from the shielding gas, flux, or surface contamination), tensile stresses, and a low-ductility microstructure such as martensite.

Elimination of hydrogen by vacuum treatment of the billet from which welding filler metals are prepared and the base metal will assure that these are not sources. Another source (and probably the most important) is the slag or flux covering that protects a weld deposit during solidification. The coating on a shielded metal-arc electrode may be comprised of hydrogen-containing compounds. The proper use of low-hydrogen electrodes eliminates this possibility of weld contamination. If the welding procedure specifies that only thoroughly dried electrodes and submerged-arc fluxes can be used, the possibility of hydrogen pickup from extraneous moisture is also minimized.

As a further assurance that cold-cracking will not occur, a preheat of usually greater than 120°C (250°F) for low-alloy high-strength steels is used. Proper preheat minimizes the possibility that the transformation product in the heat-affected zone of the weldment will be martensite. The upper limit for the preheat is usually about 260 to 320°C (500 to 600°F) because, if the steel should transform above this temperature, the required properties may not be met.

Several other factors that influence the susceptibility of a low-alloy steel weldment for hydrogen cracking include:

- "*Carbon-equivalent*" *composition of the base metal.* A formula is available which can be used to provide a rough guide to cracking sensitivity.[9]
- *Segregation and nonuniformities in composition.* Cracking sensitivity will be locally enhanced by higher levels of carbon and alloying elements.
- *Microstructure of base metal.* Some localized microstructures may be more crack-sensitive than others.
- *Joint restraint.* Increased restraint increases susceptibility to cracking.
- *Cooling rate.* The cooling rates characteristic of arc-welded thicknesses over 12.7 mm ($^1/_2$ in.) are capable of producing some martensite in any but the mildest of carbon steels. The tendency for cracking is usually increased as the cooling rate increases.

Hot-cracking (cracking of the base metal and/or weld metal at temperatures near the melting point of the steel) is also an important consideration. Hot-cracking is attributed to the segregation of low melting point constituents to the grain boundaries of the heat-affected zone and the interdendritic regions of the weld metal. The melting point of the segregated region is below that of the bulk alloy, and any strain placed across it can result in cracking. Both hot cracks and cold cracks are often microscopic and can go undetected.

Filler-metal selection is a very important criterion in the fabrication of reliable pressure vessels. The filler metal composition depends not only on strength requirements but also on whether it is expected to respond to an austenitizing and/or stress relief treatment. If the weldment is to be re-heat treated (as is necessary in most cases for electroslag welds), the composition must be selected to respond to the heat treatment in the same way as the parent metal. Generally a closely matching composition is chosen.

Usually, however, filler metal is selected so that, when it is deposited by a multipass technique, a complete re-heat treatment is unnecessary. There is seldom any trouble in meeting the strength requirements, but notch-toughness properties will be poor unless a suitable composition is used with good welding practices. Mechanical properties of deposits generally improve with increasing number of passes and with weld refinement.

The carbon content of the weld metal is usually lower than is normally found in the parent metal, for example, 0.10% in the deposit vs 0.20% in the parent metal. Molybdenum is usually present in the range of 0.15 to 0.75% as a strengthening agent. Nickel is often higher than in the parent metal, while chromium, which is a less effective strengthener than molybdenum, is usually kept under 1%, except in weld metals where higher amounts are needed for corrosion resistance. Up to 2% manganese is present as a strengthener, but silicon is kept low because it tends to decrease toughness. Vanadium is generally considered undersirable if the weldment is to be postweld heat treated.

5.2.5 Heat treatment

5.2.5.1 Preheating. As was mentioned previously, heating before and during the welding of relatively heavy shell plates may prevent the formation of cold cracks in the welded joints. The preheat temperature required depends on the mass and rigidity of the joint and the type of plate metal used.

The ASME Code, in its various sections, gives some mandatory and nonmandatory requirements for preheating. The Appendix of *Weldability of Steels,* by Stout and Doty,[7] also provides some very useful guideline information.

5.2.5.2 Postweld heat treatment. The ASME Boiler and Pressure Vessel code[1] requires that the residual-stress condition caused by the welding operations be minimized by subjecting the welded vessel to a heat treatment at elevated temperatures. The postweld heat treatment for carbon and low-alloy steels usually consists in heating the welded vessel at a uniform rate to a temperature of 590 to 700°C (1100 to 1300°F), holding at that temperature for a period of 1 hr per inch of thickness, and then cooling uniformly. Although most codes permit local heat treatment of girth and nozzle joints by circumferentially heating the entire part, the general practice on pressure vessels is to heat the vessel as a unit. Clearly this may not be possible on the larger field-erected vessels, and techniques for localized heating need to be considered.

The usual postweld heat treatments do not produce any appreciable changes in the microstructure of either the plate or the weld metal. Some slight spheroidization can occur in the base metal, which will result in a slight reduction in yield and tensile strengths and in a slight increase in ductility. Postweld heat treatment also results in softening and increased ductility of the weld metal and heat-affected zones. However, the extended postweld heat treatments common for extremely thick section vessels can result in significant decreases in strength and toughness for materials with properties enhanced by quenching. A discussion of the effects of welding and heat treatment on properties is given in Section 4.3.

The major purpose of the heat treatment, however, involves removal of residual stresses, removal of cold work, imparting of dimensional stability, and control of toughness in the weld metal, base metal, and heat-affected zones. Recommended postweld heat treatments are provided in the Appendix of Pense, Stout, or Kottcamp.[5]

5.2.6 Cladding

5.2.6.1 Introduction. Various methods and materials are used in industry to provide a corrosion-resistant layer to internal surfaces of pressure vessels.[10] In the petrochemical and paper industry, wide usage is made of strip or sheet-metal liners individually attached by welding to the internal surface of vessels. However, where severe cyclic conditions of temperature and pressure are encountered, a continuously bonded cladding is more desirable. The conventional methods for applying continuously bonded clads to the interiors of pressure vessels are hot rolling (roll cladding), brazing, explosion bonding, and weld metal overlaying (surfacing). The welding of clad vessels is covered in Section 5.2.6.5.

5.2.6.2 Roll-clad plate. Integrally clad plate is manufactured in steel mills by rolling an assembly of carbon- or alloy-steel slabs and stainless steel (or other corrosion-resistant metal) plates. A variety of cladding materials are available, including copper, copper-nickel, Inconel, nickel, Monel, and a variety of 300 and 400 series stainless steels. A continuous forge weld is made between the two metals, and the resultant clad-plate is heat treated, cut, and formed as an integral plate. Roll clad plates in thicknesses up to 100 mm are common in the United States. Maximum thicknesses of 250 mm have been reported at Phoenix-Rheinrahr.[11]

5.2.6.3 Braze-bonded cladding. Large internally clad plates are manufactured by a proprietary vacuum-brazing process.[12] Brazing of the evacuated sealed assembly occurs when it is heated to a temperature high enough to relax the metal. Intimate contact occurs, and a braze bond approaching 100% takes place.

5.2.6.4 Explosion-bonded cladding. Explosion bonding (explosive welding) is a process for applying corrosion-resistant cladding.[13] The plates making up the assembly are carefully positioned at a specified distance from each other 2.4 to 6.4 mm ($^3/_{32}$ to $^1/_4$ in.), and the explosive charge is placed on top of the cladding plate and detonated. The plates are progressively brought together as the explosion radiates from the point of initiation. Surface contamination is squeezed out of the interface as the clad plate is progressively welded to the base plate under the advancing shock wave.

The process is capable of producing clad plate of consistently uniform composition and thickness. Shell and head sections of pressure vessels can be clad with this process prior to hot-forming and welding.

5.2.6.5 Weld metal overlays. Probably the most commonly used method for obtaining sound, continuously bonded claddings for pressure vessels is by weld metal overlays. This method provides the fabricator with a means of cladding shapes and sizes not possible by other processes. Component sizes and thicknesses that can be weld-overlay clad vary from very small to very large. The upper limit depends on fabrication and handling capabilities. For example, large pressure vessel shell courses are generally weld clad by holding the welding assembly stationary (with respect to the shell surface) and rotating the shell on large rolls. The lower limit of sizes that can be clad is dependent on the minimum size of the weld torch assembly. Generally, the smallest piping or nozzles that can be overlayed are 8 cm in (3.15 in.) in internal diameter. This is done by using the gas tungsten-arc or gas metal-arc welding processes. (These small diameter pipes, as stated in Chapter 1, are not within the scope of this assessment).

In cladding steels with weld overlays, overlapping beads of weld metal of the desired stainless steel composition are deposited by the submerged-arc, gas metal-arc, plasma-arc or shielded metal-arc processes. Welding procedures must be controlled carefully to minimize dilution from the carbon or low-alloy steel in order to ensure that the resultant transition microstructures are not crack sensitive.

A variety of submerged-arc processes involving strip electrodes, series-arc, and multiple wires (up to six) are being used successfully. The degree of oscillation of the electrode and the type of flux are, of course, important variables. The gas metal-arc and plasma-arc processes—both automatic and manual—are also used for certain applications and alloys. The choice of process is a function of accessibility, position of welding, size of components, and other similar factors. Generally, for most applications a 4.8- to 6.4-mm ($^3/_{16}$- to $^1/_4$-in.) minimum thickness of overlay is required with the submerged-arc, plasma-arc, and gas metal-arc processes. The shielded metal-arc and gas metal-arc processes are used in places of limited access, irregular geometry (such as nozzle inlets), and where repairs are needed.

It is essential to emphasize that the successful deposition of an adequate corrosion-resistant and high-integrity cladding on a carbon or low-alloy steel vessel requires a thorough understanding of the metallurgy of the two materials. The cladding operation involves a dissimilar-metal weld between the ferritic base metal and the first layer of cladding, and more or less homogeneous welds between that layer and any succeeding layers of cladding.

The same metallurgical considerations that govern the soundness of dissimilar metal welds are important in cladding. Delta-ferrite content, minor element pickup, and carbon diffusion are important subjects that must be addressed in the deposition of high-integrity claddings. Of course, the various filler metals used to clad steels are governed by different criteria. It is urgent that adequate programs be carried out to develop reliable cladding procedures for the various clads and base metals proposed for use in coal conversion applications. Although stainless steel and Inconel cladding operations on steels are relatively routine, the overlaying of other corrosion-resistant materials is not.

5.2.6.6 Welding of clad steels. In developing welding procedures and joint designs for welding clad plate, it is a general rule that steel filler metals not be permitted to fuse with the clad. The steel weld metals have little tolerance for dilution with most clads, and hard brittle deposits often result. On the other hand, the commercial stainless steel and high-nickel-alloy filler metals are more tolerant of dilution by steel.

Where the clad steel joint is to be a composite weld—carbon steel or low-alloy filler metal plus high-alloy filler metal—the backing steel is usually welded first, and the joint and procedure are designed so that the first pass of steel filler metal will not penetrate into the cladding. This may be done by (1) ensuring that a sufficient portion of the root face is backing steel or (2) beveling or stripping back the cladding. An alternative method is to weld the entire joint with the high-alloy filler. This latter method simplifies edge preparation and back-gouging operations at the expense of increased consumption of high-alloy weld metal.

As was previously mentioned, specifications for joining clad steel often require that the cladding be stripped back before welding to allow the entire thickness of the base plate to be welded with filler metal of similar analysis. In this case the clad weld is restored, where possible, by making a weld overlay, using the same techniques and processes employed in the original cladding operation. If the same techniques and processes cannot be employed, special techniques must be utilized.

Defective areas in the clad materials are often found by NDE techniques, as discussed in Section 6.1.3, either on receipt of clad plate or later during fabrication. Examples of these defects are porosity, lack-of-fusion, trapped slag or other inclusions in weld overlays, and areas of lack-of-bond in roll-clad or explosive bond plate. If defects are on the surface and can be ground out without exceeding the minimum required clad thickness, weld repair is not necessary. However, for deeper indications, the defective clad material is chipped or ground away and repair welding is performed. Welding filler metal of nominally the same composition as the original clad metal must be used.

5.2.7 Field fabrication

Coal conversion vessels too large, or heavy, for complete shop fabrication and/or shipping will have to be field erected. Field erection is more complicated than shop construction, and efficiency and quality can suffer unless adequate procedures are utilized and care is taken to accommodate the special conditions involved.

Some of the conditions handicapping field operation are as follows:[10]

1. Welding must be performed in difficult positions and at elevated locations. This limits the use of automated operations, and loss of welding efficiency is probable. A significant need exists for the development of high-deposition-rate automated welding processes and procedures for specific application to field erection.
2. Weather conditions present special problems to schedules, procedures, and quality.
3. Local work forces usually must be employed. These workers are generally less effective than those in a shop facility accustomed to working as a team, even though their welding ability may be equal or even superior.
4. Forming equipment to correct poorly fitting parts is not usually available.
5. Field work requires special versatile equipment, careful planning of material requirements, and delivery coordination. For example, fit-up, positioning, and temporary support of components in elevated positions can present significant problems.

Overhead, vertical, and other out-of-position welding is minimized in shops through the extensive use of welding positioners. To the fullest extent possible, field crews should also be equipped with positioners and automated welding equipment to allow a maximum use of high-deposition-rate automatic welding methods. Most field fabrication today is done using manual shielded metal-arc welding. Gas metal-arc welding has also been used for field fabrication of such components as nuclear reactor containment vessels. However, welding speeds could be greatly increased if such processes as narrow-gap gas metal-arc, narrow-gap gas tungsten-arc and hot-wire gas tungsten-arc were adapted to field welding applications. Significant problems exist for adapting these processes, because fit-up (which is difficult) is very critical. Electroslag/electrogas processes cannot be used for field fabrication since an austenitize, quench, and temper heat-treatment is required after welding to refine the grain structure and improve mechanical properties.

Edge preparations for field welding differ mainly in the methods of application and the positions in which welding is to occur. Plates for main joints generally are scarfed to single-V or double-V grooves, but occasionally U-grooves or combination grooves are used. The use of automatic field-girth welding equipment has led to special joint designs to accommodate radiography and to minimize lack of fusion and other problems.

Preheating is more critical in the field because of the possibility of fabrication under adverse environmental conditions. Requirements for preheating in cold weather differ, depending on material classification and the various codes by which vessels are constructed. Normally the base metals should be preheated in accordance with the guidelines discussed in Section 5.2.5.1. Common methods of preheating include resistance-strip heaters and gas torches.

Postweld heat treatment in the field presents unusual problems. The vessel may be enclosed in a temporary furnace or covered externally with an insulation. Heat may be internally or externally applied, depending on the geometry of the vessel. Electric heaters are frequently used. For internal heating, gas or oil burners are sometimes fired through openings in the insulated vessel or hot air is blown into the vessel openings from an external furnace. One precaution that must be observed is that the vessel must be self-supporting at the selected temperature.

5.2.8 Multilayer (multiwall) vessels

Recent reports[14,15] in *Welding Design and Fabrication* discuss multilayer fabrication procedures that permit the construction of pressure vessels of sizes that are of interest in this assessment. Pechacek[14] states that vessels over 4500 metric tons (5000 tons) with wall thicknesses greater than 510 mm (20 in.) can be built by multilayer techniques. Further, he suggests that these vessels can be field as well as shop fabricated. Although this document specifically addresses monolithic pressure vessels, the availability of such large units may create an interest in multilayer fabrication methods. Furthermore, there is activity within the ASME Code to obtain approval for vessels constructed by multilayer methods. Because of the significance of these activities, a short discussion on multilayered vessels is presented here.

Multilayer (multiwall) vessels are intended for use at high pressures and are generally built to users' or manufacturers' specifications. There are several methods for producing multilayer and multiwall vessels. These procedures are generally used where the size and weight of the vessel rule out monolithic units because of the inability to develop the desired strength in available materials.[10,16] The selection of steels for these vessels is a function of service conditions; often the inner layer differs in composition from the outer layers.

The Multilayer design (Multilayer is a trademark of the Chicago Bridge and Iron Company) involves wrapping relatively thin plate layers [~6.4 mm (~$^1/_4$-in.) thick] and tensioning them around a core shell. Longitudinal welds then increase the tension as the wall thickness is built up. These vessels have an inherent advantage for field assembly, since they do not need stress relieving.

The Multiwall design (Multiwall is a trademark of the Struthers Wells Corporation) involves accurately sized cylinders typically 32 to 51 mm (1¼ to 2 in.) thick, which are made slightly smaller in internal diameter than the external diameter of the previous wrap. These cylinders are then heated and shrunk onto the assembly. Unlike the previous design, the longitudinal welds in the wrapping plates are stress relieved.

Another method, the Schierenbeck process, utilizes specially formed strip, which is heated above the critical temperature and wound spirally on an inner core shell. The core shell is grooved so the strip locks into these grooves. The strip is quenched immediately after winding.

Mitsubishi's Coilayer vessels are made with an inner cylinder, about 12.7 mm (½ in.) thick, around which is continuously wound a 3- to 4-mm-thick (0.12- to 0.16-in.) steel hoop until the required thickness is reached. An outer cylinder is then fitted over the winding. No longitudinal welds are present except on the inner and outer cylinders. To make long pressure vessels, such unit cylinders are connected by girth welding until the necessary length is produced, and the ends are completed by welding on a forged steel flange or cover plate. By using a hydrostatic pressure higher than the working pressure, the vessels are given a mechanical stress relief and, when desired, autofrettage.

Somewhat in the category of Multilayer vessels is the Foster Wheeler two-layer method involving a half-thickness shell with loose outer wrapping covering the cylindrical part only. The inner shell is expanded by hydraulic pressure to give a snug fit in the outer cylinder and cause a stress condition much like that created by autofrettage.

5.3 Piping

5.3.1 Manufacture of pipe

Several different processes can be used to manufacture pipe for coal conversion applications. These processes can be grouped into three general classifications: wrought seamless pipe, welded pipe, and cast pipe. A combination of different processes is often used in manufacture; for example, hot pierced pipe may be cold drawn to improve mechanical properties and dimensional control. A brief discussion of the most common primary processing operations and some of the important secondary operations follows. The reader is referred to other texts such as the *Metals Handbook*,[17] *Piping Handbook*,[18] and the *Making, Shaping, and Treating of Steel*[19] for further details on these processes.

5.3.1.1 **Wrought seamless pipe.** *Hot rotary piercing* using the Mannesmann-type process is a common method for manufacturing pipe of ferrous alloys. It involves piercing a heated round in either one or two piercing mills, which consist of a pair of cylindrical rolls rotating in the same direction with their axes inclined to each other. The pipe, reheated if necessary, is finally passed through two or more sets of sizing rolls to produce uniform size and roundness throughout the length of the pipe. This process typically produces pipe from 5.1 to 66 cm (2 to 26-in.) O.D. with lengths up to 12 m (40-ft) and wall thicknesses as light as 6.4 mm (¼-in.).[19]

The *hot extrusion* process can be either horizontal or vertical. In the vertical process, for example, a descaled steel billet, heated to approximately 2300°F (1260°C), is formed into a blocker by rounding and piercing. The blocker is extruded through the annular gap, between the extrusion die and the piercing mandrel to produce a pipe or tube. This process typically[20,21] produces pipe from 20 to 120 cm (8 to 48-in.) O.D. and wall thickness from 19 to 150 mm (¾ to 6 in.) with lengths up to 14 m (45 ft.) depending upon diameter and wall thickness.

The *forging process* is primarily used for pipe sizes of large diameters and heavier wall thicknesses, where other seamless grades are not readily available because of costs or equipment limitation.

Forged and bored pipe starts with a steel billet, which is heated to approximately 2300° F (1260° C) and is then elongated by forging in heavy presses or under forging hammers to a diameter approximately 2.5 cm (1 in.) greater than the diameter desired for the finished pipe. The billet is then machined in a lathe to the actual outside diameter required; following this, the inside is bored out with a special tool to the specified inside diameter.

Hollow-forged pipe is produced directly from steel ingots melted in an electric arc furnace. The ingots are hot pierced and transferred to a draw bench, where they are worked through a series of ring dies to produce the desired size.

Rotary point extrusion is a cold-forming process wherein rollers apply pressure internally or externally to a cylindrical pipe blank, gradually increasing the length and reducing the thickness. Typically several cold reduction sequences are used with intermediate anneals. This process is capable of providing very tight dimensional control. The pipe size capability is typically from 2.5 to 130 cm (1 to 50-in.) O.D. with lengths up to 7.6 m (25 ft) and wall thicknesses down to 1.6 mm ($^1/_{16}$-in.).[22]

5.3.1.2 Welded pipe. The *continuous butt-weld* process consists of forming strip or plate into a circular shape, heating it to forging temperature, and pressing the edges together. This process is used to manufacture small diameter pipe, typically 1.3 to 10 cm ($^1/_2$ to 4-in.) O.D. with wall thicknesses up to 9.5 mm ($^3/_8$ in.) and lengths limited only by available plate or strip.[19]

The *electric resistance welding* process uses the resistance of the material being joined to generate heat. Four methods of resistance welding are extensively used to produce pipe. In every process, the strip or plate is initially formed by rolling or ring forming into a circular shape. Flash welding, low-frequency resistance welding, and high-frequency resistance welding are applied to the manufacture of pipe in the largest sizes. High-frequency induction welding is used primarily for the production of small sizes of pipe. This process typically produces pipe from 2.5 to 51 cm (1 to 20 in.) O.D. with wall thicknesses up to 13 mm ($^1/_2$ in.) and lengths limited only by available plate or strip.[19]

In the *electric arc welding* process, pipe is made from strip or plate that has been rolled, pressed, or bent into a cylinder with a continuous straight or helical seam running the length of the pipe. Electric arc-welded pipe is produced by three primary methods: submerged-arc, gas tungsten-arc, and gas metal-arc. Some manufacturers utilize twin welding heads (e.g., submerged-arc), where the second arc follows about 2.5 cm (1 in.) behind the first. One bead is deposited inside the pipe and one bead on the outside. The electric arc welding process is normally used to fabricate large diameter pipe which is beyond the practical limits of the seamless processes. The size of the pipe which can be fabricated by this process is usually only limited by the available strip or plate. However, the typical pipe sizes range from 25 to 130 cm (10 to 50-in.) O.D. with wall thicknesses up to 130 mm (5 in.) and lengths to 12 m (40 ft).[23,24] Because of its adaptability to the production of large diameter thick-walled pipe, this process will probably be the one employed for the manufacture of the piping discussed in Chapter 1.

5.3.1.3 Cast pipe. Cast pipe is generally made in the United States either by the *static casting* or *centrifugal casting* processes. Static pipe castings generally are limited to relatively short lengths. Centrifugally cast pipes are produced by introducing molten steel made in electric arc or induction furnaces into a horizontally or vertically spinning mold and allowing the metal to solidify under the pressure of the centrifugal force. Molds containing rammed sand with binders, molds with ceramic surfaces, or permanent metal molds are used. Centrifugally cast pipe has been produced in outside diameters from about 10 to 140 cm (4 to 54 in.) and in lengths up to about 9 m (30 ft.)[24]

Weld forming of pipe is a continuous casting type process.[25] The weld forming process is a recent development of Japanese fabricators in which piping is made directly by electroslag deposition. Several different deposition techniques can be used to form the pipe. Normally, electrodes are spaced around the circumference of a water-cooled mold, with the finished pipe being vertically withdrawn from the bottom of the mold. This process has produced pipe in sizes from 2.5 to 38 cm (1 to 15-in.) O.D. with wall thicknesses from 6.4 to 64 mm (0.25 to 2.5-in.) and lengths only limited by handling capability.[25]

5.3.1.4 **Secondary** operations. Some of the primary processes which were described above are shown in Fig. 5.2, together with major secondary forming operations. Some of the additional operations, such as repair, inspection, annealing, sizing, and straightening, are required to meet existing specifications for piping such as are found in ASME Section II.

5.3.2 Pipe fabrication

5.3.2.1 **General.** Pipe fabrication involves the various forming, shaping, machining, welding, cleaning, and heat treatment operations necessary to convert initially straight pipe sections, valves, and fittings into a finished piping system or into components that may become integral parts of piping systems.

As much prefabrication as is feasible should be performed in fabricating plants where specialized equipment is available for the production of piping components under carefully controlled supervision. The only field fabrication processes are then the on-site assembly and welding of the prefabricated components. The advantages of shop fabrication become particularly pronounced with increasing diameter and wall thickness of the piping components. Assemblies that require precision fit-up and that have complex configurations are best prefabricated in well-equipped shops where suitable bending, swaging, automatic welding, and heat treatment equipment is available.

5.3.2.2 **Welding** processes. Although increasing use is being made of semiautomatic and automatic welding processes, the process still extensively used in pipe shop welding, and particularly in field welding, is manual shielded metal-arc welding.[9] The equipment required for its application is comparatively simple and compact, readily portable, safe to use, and generally requires little maintenance. For welding low-carbon and low-alloy steel pipe in the rolled or horizontal position, the number of weld layers is approximately one per 3.2 mm ($^1/_8$ in.) of the pipe thickness, although the number of passes varies, of course, with the wall thickness of the pipe, the welding position, the size of the electrode used, and the welding currents employed. When the pipe is in the vertical fixed position, weaving is not usually effective, and the metal is deposited in the form of a series of small overlapping stringer beads.

The gas tungsten-arc process is becoming increasingly popular for the welding of ferrous pipe, particularly with regard to the root passes, and development of automated equipment has progressed rapidly during the last few years. For pipe wall thicknesses over 6.4 to 9.5 mm ($^1/_4$ to $^3/_8$ in.), it is generally more economical to complete the pipe weld with other processes such as gas metal-arc, submerged-arc, or shielded metal-arc. Accurate end preparation and good fit-up are particularly important considerations. Consumable insert rings are frequently used to assist in the welding of the root pass (see the next subsection, "Welding Joint Design").

In recent years, variations of the gas metal-arc welding process have become popular for pipe welding, particularly those using small-diameter wires. Gas shielding for carbon and low-alloy steels is primarily done with carbon dioxide, or with argon – carbon dioxide mixtures. Welding is done on open pipe joints with a root spacing of approximately 2.4 ± 0.8 mm ($^3/_{32} \pm {}^1/_{32}$ in.).

The submerged-arc process is used extensively in the shop welding of ferrous piping. The process can be automatically or semiautomatically employed and is applicable for pipes 20 cm (8 in.) or larger in diameter, where the pipes can be rolled under the weld arc.

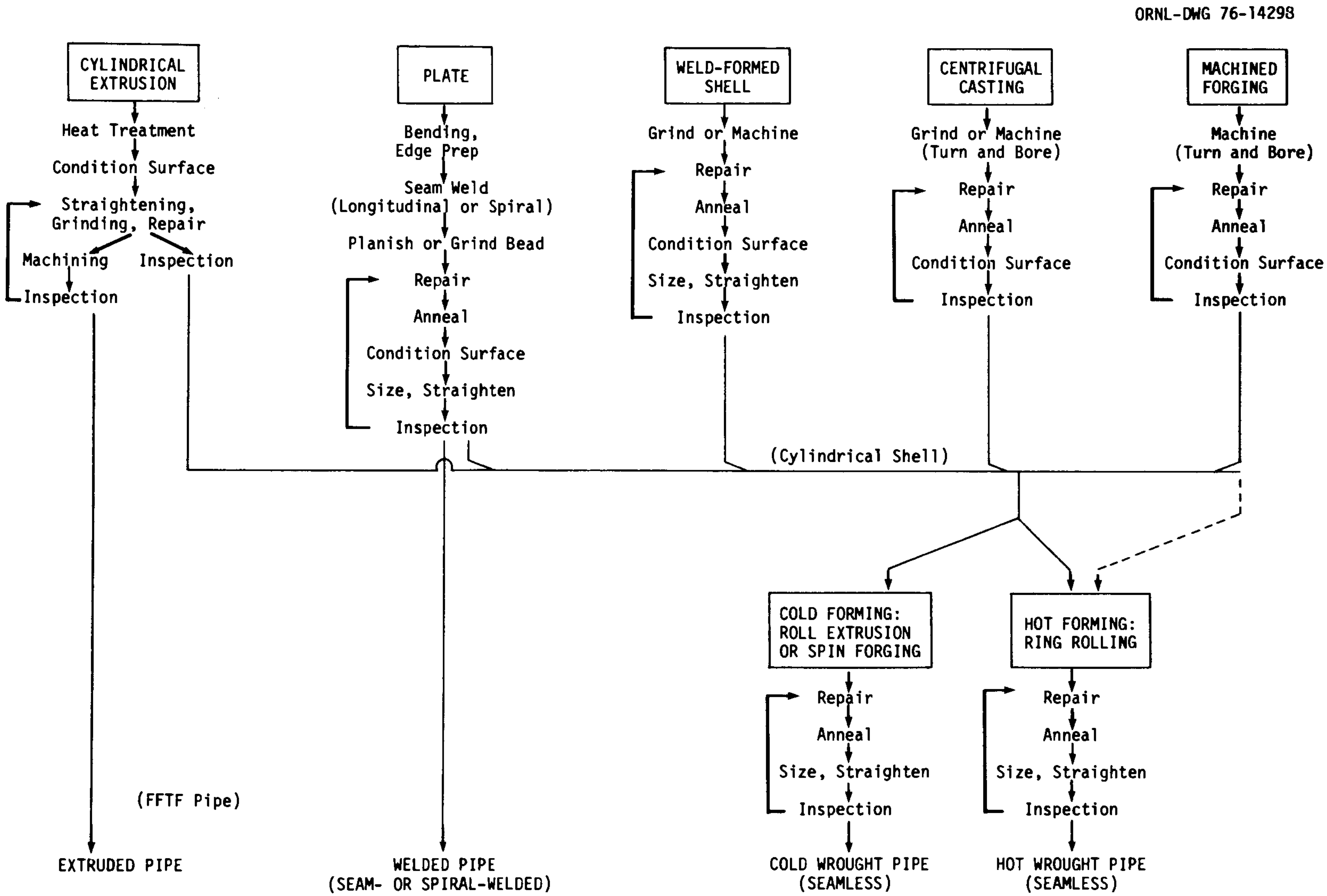

Fig. 5.2. Typical primary and secondary pipe fabrication operations.

5.3.2.3 **Welding joint design.** The most common type of joint employed in the fabrication of welded pipe systems is the circumferential butt joint. Its general field of application is pipe to pipe, pipe to flange, pipe to valve, and pipe to fitting joints. When the root passes of steel pipe joints are made by the shielded metal-arc process, backing rings are frequently used, particularly in such applications as steam power plants. Backing rings are rarely used in chemical refinery piping.

One excellent technique for producing root passes of the highest quality is to employ consumable insert rings of proper composition and dimensions in conjunction with the gas tungsten-arc process. The bevel geometries considered adequate for shielded metal-arc welding often pose a problem when the gas tungsten-arc process is used. Extended "U" or "flat-land" bevel preparations are generally considered to be much more suitable. When used with a suitable joint geometry, a consumable insert ring can function towards three very important ends: to provide the best welding conditions, for minimizing the effects of undesirable welding variables caused by the human element; to provide the most favorable weld contour for resisting cracking resulting from weld metal shrinkage and for eliminating notches at the weld root; and to provide the best possible weld metal composition for desired strength, ductility, and toughness properties.

5.2.2.4 **Welding** equipment. Welding power supplies for the shielded metal-arc process are fairly well standardized. However, a trend toward the use of constant current controls exists. This type of control maintains constant current during welding in order to eliminate current fluctuations produced by line voltage variation and by temperature variations of the welding power supply, power supply cables, and welding current cables.

The trend in pipe welding of ferrous materials is toward the use of automated systems. In addition to precision control of the welding parameters, the incorporation of an automatic arc-voltage control head, torch oscillator, and wire feeder is becoming relatively routine for gas tungsten-arc systems. Sophisticated automated equipment for gas metal-arc pipe welding applications is also available. Benefits that come with the use of higher-precision equipment are reduced costs per weld by less rework and less time to make a weld.

5.3.3 Dissimilar-metal transition joints

5.3.3.1 **General.** Because various portions of a coal conversion system operate under different service conditions, different structural metals and, hence, dissimilar-metal joints may be needed in specific sections. Many factors must be considered when welding dissimilar metal joints, and the development and qualification of adequate procedures for the various metals and sizes of interest in a coal conversion plant must be undertaken. The problem of cracking in dissimilar-metal welds, principally between ferritic steels and austenitic stainless steels, is a recurring problem in the petrochemical industry and in electric utility generating plants. Cracking has been repeatedly observed in heat-affected zones of the ferritic portions of dissimilar-metal welds, particularly those which have been subjected to a large number of thermal cycles at elevated temperatures around 570° C (1050° F). The possibility of such cracking is vitally important in the coal conversion industry, since repair maintenance and nonproductive downtime are costly.

The principal factors that can be responsible for cracking in dissimilar metal welds are (a) general alloying problems (brittle phase formation, limited mutual solubility of the two metals, widely differing melting points, etc.), (b) differences in coefficients of thermal expansion, (c) differences in thermal conductivity, (d) carbon depletion, and (e) oxide notches in the ferritic side of ferritic-to-austenitic welds.[26]

5.3.3.2 **Welding procedures.** A welding procedure commonly employed in industry for ferritic steel-to-austenitic stainless steel joints involves "buttering," or over-laying, the edge of the ferritic steel with stainless steel weld metal before welding it to the mating stainless steel component. A thick overlay [13 mm ($^1/_2$ in.) or greater] of a highly austenitic weld metal, such as type 309 stainless steel, can be deposited on carbon or low-alloy steel nozzles so that stainless steel–to–stainless steel welds can be made subsequently in the field. This technique has limited reliability for high-temperature cyclic service and has not been used extensively for materials combinations other than ferritic steels and stainless steels.

Austenitic stainless steel weld metals are employed extensively in industry for making stainless steel–to–ferritic steel welds directly. Again, the joint has limited reliability for elevated-temperature cyclic service. High-nickel filler metals, such as MIL-EN82 (Inconel 82) and MIL-8N12 (Inconel 182) are useful for applications where cyclic temperature is encountered. The coefficients of thermal expansion of Inconel alloys approximate those of ferritic steels, and, during cyclic temperature service, the major differential expansion stresses are located primarily at the tough stainless steel–weld metal interface. Another advantage of a nickel-base weld metal is that it markedly reduces carbon migration from the ferritic steels to the weld metal. Extensive carbon migration into stainless steel weld metal weakens the heat-affected zone of the ferritic steel. Recent studies have indicated that addition of a pipe segment of an alloy having an intermediate expansion coefficient between the ferritic steel and stainless steel is useful in prolonging service life.

5.3.3.3 Joint design. Dissimilar metal joints are often made with groove geometries similar to those used in conventional similar-metal welds and are left in the unmachined condition. It is recognized, however, that there are advantages to removal of the weld root to eliminate defects inherent in the root of the joint and notches and crevices associated with backing rings. Removing the weld root also improves nondestructive tests (radiography, liquid penetrant, and ultrasonic). Provision can also be made for removing the exterior reinforcement to eliminate stress concentrations associated with undercutting and with the change in section thickness across the as-welded joint. Again, inspection capabilities are improved.

An industrial means has also been developed for joining selected materials with widely different metallurgical characteristics. It consists of a metallurgically bonded, tubular transition joint between the two metals; a feature of this joint is a long, thin [0.005 mm (0.0002 in.)] diffusion layer that withstands severe thermal and mechanical forces. Industrial capabilities are currently limited to sizes of approximately 5.1 cm (2 in.), and, if larger sizes are needed, capabilities would have to be developed. Explosive welding and brazing provide alternate methods for joining of widely different metals, but specific procedures would have to be developed and qualified for the particular sets of base metals involved.

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6. NONDESTRUCTIVE TESTING*

6.1 General

The current nondestructive testing (NDT) requirements for pressure vessels and piping for coal conversion plants are found in the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2 and in the ANSI Pressure Piping Code B31.3, Chapter VI. In general, the Codes provide excellent procedural and acceptance requirements to meet specific safety criteria. However, there are areas, discussed in Section 6.2.2.2, Codes and Procedures, where improvements are needed.

Some of the quality assurance steps in pressure vessel fabrication provided by the ASME Code, Section VIII, are intended to provide the minimum requirements to establish the safety of a fabricated vessel. Others (including industry-based specifications) are process-control steps intended to minimize or to prevent the generation of rejectable defects during fabrication. The examination and testing performed at intermediate steps of fabrication are intended to detect defects and to assure their elimination through repair, when possible, early in the manufacturing sequence, rather than incur delays, additional costs, rejects, and extensive repairs by waiting until a later, or even final, code-required inspection.

The ANSI Code, B31.3, for pressure piping sets engineering requirements that are deemed necessary for safe design and construction of piping systems. The code is under the direction of the American National Standards Committee B31 and is under the administrative sponsorship of ASME. Chapter VI (Inspection and Test) of the code details requirements for testing and inspecting components before assembly or erection and for the completed system after erection.

The principal concern of the codes is safety, and they require examinations and tests intended to find and reject (or require repair of) defects at some stage of the construction and to verify the adequacy of the completed construction. They try to avoid redundancy by minimizing code-required intermediate examinations which are primarily a matter of economy and convenience to the fabricator. The fabricator is then responsible for determining when and to what extent such intermediate examinations should be used. There is, of course, some contribution to safety from the earlier detection and elimination, by repair, of defects, and this consideration prompts some code-required in-process examination. Other specifications call for material samples and tests in order to develop a body of materials-properties data for guidance in design and specifications for subsequent vessels. These tests serve in determining the acceptability of the vessel actually being fabricated.

Many of the process control and inspection requirements cited here relate to actual code requirements. These will not be repeated or discussed in detail except where further clarification may be required. In the ASME Code the term "inspection" is used to cover those tasks which are performed by the "qualified inspector," an individual who holds certificates from a state jurisdiction and from the National Board of Boiler and Pressure Vessel Inspectors and who is employed by a state, a municipality, or an insurance company; "examination" includes those operations of nondestructive testing (e.g., radiography, dye penetrant, magnetic particle, ultrasonic, eddy current, and visual observation) that are done by someone other than the inspector (such as a nondestructive-test specialist employed in the quality control department of the supplier or fabricator). However, no particular effort will be made to maintain this distinction in the discussion that follows. As was stated in the introductory chapter (Section 1.1) the discussions regarding nondestructive testing will be limited to thick-wall vessels and their adjacent large diameter piping systems. It should be noted that the inspections and techniques discussed herein are not peculiar to coal conversion units.

*This section was prepared by B. E. Foster and R. W. McClung.

6.2 Flaw Detection During Manufacturing (Preservice)

The minimum requirements for nondestructive examination of pressure vessels materials for the detection of flaws are incorporated in Inspection and Tests in Section VIII, Division 1, of the ASME Code. The materials discussed are plates, forgings, bars, castings, pipes, fittings, bolts, and bolting materials. Additional requirements for inspection and tests, pertaining to methods of fabrication and classes of materials, are fully referenced. More restrictive requirements, limited materials, and higher pressures are incorporated in Section VIII, Division 2, of the ASME Code.

6.2.1 Examination procedures

Detailed procedures are provided in the code for radiographic examination of welded joints, ultrasonic examination of plate, magnetic-particle examination, and liquid-penetrant examination. In addition, frequent reference to visual inspection is made without detailed procedures. Occasional reference is made to various ASTM documents for materials or performance of nondestructive examinations.

The radiographic examination procedure is referenced to Article 2, Section V, of the code. The procedure covers surface preparation, film processing, film selection, and radiographic quality, with particular emphasis on penetrameters (image quality indicators).

The purpose of the penetrameter is to assure the attainment of at least a minimum acceptable level of radiographic quality (on the film) in a reproducible manner. The penetrameter is not intended to be used as a reference standard for comparison of flaws. A primary requirement of this procedure is the designation of the appropriate penetrameter for the thickness of material. The thickness of the penetrameter is 2% of the material thicknesses from 6.4 to 38 mm ($^1/_4$ to $1^1/_2$ in.). From 38 to 150 mm ($1^1/_2$ to 6 in.) the percentage thickness of the penetrameter decreases stepwise from 2% to 1%. This value of 1% is then maintained to the maximum designated thickness of 510 mm (20 in.) The penetrameter contains three holes with diameters normally 1, 2, and 4 times the penetrameter thickness. The minimum hole size is 0.25 mm (0.010 in.). The penetrameter specification is referenced to ASTM-E-142. Part 11, of the Annual Book of ASTM Standards.

The approved magnetic-particle examination procedure is described in Appendix VI, Section VIII, Division 1 of the code. The procedure allows the use of wet or dry particles; direct or rectified magnetizing current; and prods, coils, or magnetic yokes (suggested for discontinuities open to the surface) to produce the magnetic field. The magnetic yoke procedure is the one recommended for locating discontinuities open to the subject. The detailed magnetic-particle examination procedure is referenced to Article 7, Section V, of the ASME Code.

The liquid-penetrant examination is described in Appendix VIII, and the detailed procedure is referenced to Article 6 of Section V. The procedure allows the use of both color-contrast and fluorescent penetrants. In each case, there are three acceptable types: (1) water washable, (2) post-emulsifying, and (3) solvent removable. The procedure cautions against the use of a blasting technique with shot or dull sand for surface conditioning. This may peen material across discontinuities at the surface, closing cracks, pinholes, etc., thereby preventing their detection.

Ultrasonic examination is required for plates and forgings and is referenced, respectively, to SA-435 and SA-388 (ASME Code, Section II, Materials Specification). Procedures are detailed for both the straight beam and angle beam technique, with restrictions relative to the use of the angle beam technique (limited to rings, flanges, or hollow forgings). One or more discontinuities that produce indications accompanied by a complete loss of back reflection not associated with the geometric configuration are the cause for the component to be unacceptable.

The Code for Pressure Piping Inspection and Test (ANSI B31.1, Chapter VI) details or references the examination procedures for piping installations, in order to assure compliance with the design, material, fabrication, and assembly requirements, with safety as the basic consideration.

Detailed limitations on defects are defined in the codes for the methods of inspection (magnetic particle, liquid penetrant, ultrasonics, and radiography).

The codes specify that each of the methods of inspection shall be in accordance with the appropriate article of Section V of the ASME Code (i.e., magnetic particle, Article 7; liquid penetrant, Article 6; ultrasonics, Article 5; and radiography, Article 3). The code further cites that the visual inspection shall be in accordance with Article 9.

6.2.2 Major concerns or inspection problems common to both pressure vessels and piping systems

It must be recognized that NDT has played a major, beneficial role in assuring the integrity and lowering the costs of materials, components, and assemblies. Significant flaws have been detected, safety has been improved, and many other gains have been attained through the appropriate application of NDT. However, it must also be recognized that even greater benefits can be accrued through selective improvements in NDT technology. With advanced industrial technology and more stringent service requirements on materials and components, improvements in NDT methodology are mandatory. This and the following sections are intended to address those areas where work is needed to further improve NDT.

Several NDT specialists* representing different manufacturing interests were surveyed for their opinions and comments on areas of inspection technology that are inadequate. This was not an exhaustive survey but represents a good cross section of the industry. The following sections include the results of the discussions as well as the opinions of the authors, based on their experience and expertise in NDT. The problems that were cited as needing resolution included personnel qualification and certification, procedural requirements, and inspection technology.

6.2.2.1 Personnel. There are several aspects of the "people problem" that must be recognized. Satisfactory performance of the varied methods of NDT requires adequate training and experience for the operators. With expanding demands for NDT throughout all industry and with limited educational opportunities for development of new personnel, it is becoming a greater problem to assure that inspection organizations have the necessary qualified people. This can, of course, affect reliability of the NDT being performed. The anticipated construction of many coal conversion plants will greatly multiply the needs for increasing numbers of well-trained personnel. The historic experience of large personnel turnover on construction projects emphasizes the problem. Among the several solutions are increased educational opportunities and training to provide upgrading and a greater supply of competent personnel and development of improved equipment, techniques, and technology, to reduce the reliance on the skill and subjective reasoning of the operator.

The guidelines for qualifications and certification of NDT personnel established by the American Society for Nondestructive Testing (ASNT), in their document SNT-TC-1A,[1] have done much to establish standard ground rules for training and for measuring the capability of personnel. The document has been used to improve the educational opportunities by encouraging more, well-qualified courses in the various methods of NDT and has been adopted, in varying degrees, by code bodies such as ASME. However, continued improvements are needed to achieve optimum inspection results and to

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*Many of the comments and recognized needs for improvements in nondestructive testing came from extensive interviews with knowledgeable personnel of fabricators, architect-engineering firms, and others involved in coal conversion plants. To assure free information exchange and candid remarks, personal anonymity was promised. However, beneficial assistance was provided by personnel from Bechtel, C. F. Braun, Chicago Bridge and Iron Company, ERDA, Fluor, Parsons, and others.

keep costs down. For example, the cited SNT-TC-1A does not include criteria for certification of visual examiners. ASNT is now certifying the Level III (the highest level) examiner[2] in all of the basic NDT methods. The ASME Code, Section VIII, requires the certification of personnel for ultrasonics and radiography (in accordance with SNT-TC-1A) but does not require certification for the performers of liquid-penetrant, magnetic-particle, or visual examinations. The code for piping (ANSI B31.1) requires qualification and certification for all methods except visual. These discrepancies should be corrected in order to ensure uniformity in certification requirements between the two Codes and to assure that only competent, qualified, and certified personnel perform the examinations. Furthermore, to help to ensure that only valid examination procedures are used, close coordination should be maintained between the personnel preparing procedures and those who are responsible for using them.

6.2.2.2 **Codes and procedures.** Although the several codes are considered to be excellent for establishing the minimum legal requirements to set safety criteria, they are considered inadequate in several respects and are frequently exceeded in various procedures by manufacturing concerns or by industry standards that supplement the codes to establish more stringent requirements. Of course, these latter enhancements of code requirements are generally voluntary, subject to change, and cannot be assured. The following discussion covers several areas of needed code improvement. (Needed improvements in specifying personnel qualification have already been noted.) For example, visual examination is widely recognized and accepted throughout industry as necessary for both economic and quality reasons. However, for the most part, improvements are needed in the code requirements for visual examination, and more positive guidelines should be provided. In welds the examinations should be geared toward looking for undercut, lack of penetration, burn through, surface porosity, and the conventional surface roughness. Inadequate visual examination can permit poor manufacturing quality to be accepted and can create problems for performance of NDT, such as penetrant examination, or for interpretation of penetrant, radiographic, ultrasonic, or other NDT examinations.

The procedural requirements and acceptance criteria in the codes can and should be improved. In the case of ultrasonic examination, it has been shown that different teams examining with the same procedures do not attain the same results.[3] One phase of correction is to be more definitive in the procedures; another is to improve the equipment and technology. The latter will be discussed further in Sections 6.2.2.3. Recent relaxations in the quality requirements for radiography (as measured by the penetrameter) have unnecessarily degraded the benefits to be obtained by this most widely used examination method. Many of the acceptance criteria are applied to all components within a given class of configuration (e.g., ring forgings, plate, etc.), which could result in an over- or under-stringent requirement. Giving more consideration to the actual service requirements of components and to the establishment of realistic reference standards and acceptance criteria, based on the significance of the examination to component performance could lead to greater inspection confidence and, in some cases, decreased costs. At times, acceptance criteria can differ between examination methods (or between codes) for the same component. Correction of these anomalies is needed. Although ultrasonic methods for examination of welds have been available for years (and have been used extensively in Europe), code utilization has been limited and slow in coming. Because of recognized limitations in many of the NDT methods for detection or characterization of certain types of flaws, complementary NDT techniques should, at times, be required—either for full inspection or to provide additional insight into detected flaws. Accelerated applications, for example, should be made to obtain the benefits provided by ultrasonics for the detection of cracks and lack of fusion (planar flaws that are difficult to detect with radiography but are probably more detrimental than the porosity that is readily discernible in radiographs).

6.2.2.3 **Inspection technology.** A problem frequently encountered is the lack of reproducibility[4] of inspection data between organizations (e.g., buyer and seller) or even within the same organization when the inspections are done at different times. This variability creates confusion, debate, commercial problems, and questions about the safety or reliablity of the components (or the reliability of the inspection method). The previously cited needs for improvements in personnel qualification and procedural (code) requirements are necessary steps toward reproducibility. A third important need is for improved understanding of the many variables in both techniques and equipment so that appropriate corrective action can be taken through improved procedures, optimized techniques, advanced instrumentation, and better utilization and processing of the complex data that is available (and has only limited use now). An associated need in inspection technology is for more quantitative data from NDT. Historically, the methodology has been primarily a tool for the detection and location of flaws, with only qualitative consideration given to their sizes. The capability for quantitative analysis has been limited. The shortcomings of current methods have become increasingly evident with the advent of fracture mechanics and the need to characterize discontinuities quantitatively for size, orientation, and type. The application of fracture mechanics to determine the integrity of a pressure-containing component quantitatively is limited by the ability of the nondestructive examination to determine the size and location of a flaw accurately. The detection of the flaws shown detrimental by fracture mechanics is not normally considered to be a problem; however, quantifying those flaws as to type and size is a severe problem requiring technical improvements to meet the challenge for higher reliability, reproducibility, and quantitativeness. More discussion of fracture mechanics is found in Chapter 2, Section 2.5 and Chapter 4, Section 4.4. The specific sizes or types of flaws that need quantifying will have to be determined by design and operating details of individual units and cannot be dealt with in a general fashion.

Another problem with broad-based application to many NDT methods is that for increased need of computers or other advanced instrumentation for processing and analyzing data. The many requirements and benefits of advanced NDT computer technology include improved capability for improved inspection methods (allowing rapid utilization of more portions of the available inspection data and possible correlation between complementary examinations), feedback of inspection data for process control of manufacturing, and storage of voluminous data for later comparison with results from in-service inspections.

In addition to the general comments noted that are broadly applicable to most of the NDT methodology, a few specific suggestions can be cited for individual methods that would improve their reliability, reproducibility, quantitativeness, or overall confidence and capability. For example, improvements in the usefulness of radiography may be possible through enhancement techniques [to aid the interpreter (or ultimately to allow automatic interpretation)] and though improved penetrameters. (Are the European or American-style penetrameters superior for controlling radiographic quality? Or are there better alternatives?) Improvements in ultrasonic testing can be achieved through better calibration techniques, better transducers, utilization of more of the data in the signals (e.g., frequency, spectra, and phase contain much inspection information that is, at present, poorly understood and largely ignored), and further investigation into ultrasonic imaging. Eddy-current techniques should find much greater application for quantitative surface and near-surface examinations with improvements in instrumentation and developed capability for performance on ferromagnetic materials. Liquid-penetrant and magnetic-particle examination techniques both need improved capability for calibration and improved techniques for checking performance and sensitivity. Improved high-temperature penetrant materials are needed for examination of welds without the need to lower the preheat temperature and for in-service inspection at operating temperatures.

Special problems can occur in field erection of coal conversion plants that are related to both environment and equipment. For example, there may be variables in the water supply, temperature, and electrical power. If unrecognized or uncompensated, these can result in poorly processed radiographs, improper penetrant examination, improper lighting for film viewing or visual examination, or erratic instrumentation. Fixes on these conditions could include correcting the environmental conditions or development and application of more tolerant inspection equipment and procedures (without sacrificing needed sensitivity or precision).

6.2.3 Major concerns or inspection problems peculiar to pressure vessels

There is lack of reproducibility and consistency in examination of welds in thick sections with ultrasonics. Some of these problems are traceable to inadequate calibration techniques that include transducers, electronic circuitry, reference standards, and the assembled system. Improved calibration techniques are needed. Successful control on the size, shape, and direction of the ultrasound beam would increase confidence in flaw location and resolution. Major effort should be directed toward gaining a better understanding of the role of frequency and phase in ultrasonic testing, with the attendant improvement in reliablity and confidence. Improved quantitative capability is needed to allow measurement of the through-the-thickness dimension of discontinuities as well as to determine the orientation and type of flaw.

A common examination technique for thick multipass welds is to use liquid penetrants at various stages during welding. There is concern that the residual penetrant material could contribute to faulty welds in subsequent passes. This concern needs investigation in order to ascertain its validity, and, if it is true, supplementary development should be done to allow performance of a noninterfering examination after any weld pass.

A protective coating (typically weld-overlay cladding) is frequently used on the inner surface for protection against corrosion and erosion. The thickness of this overlay needs to be measured (probably with eddy currents or ultrasonics), but development is required. Other important problems include the evaluation of the bond between the wear cladding and the base material in order to detect lack of bonding and to obtain a correlation between bond strength and test indications and to detect pre- and post-operation cladding defects.

Jacketing or other external/internal protrusions minimize accessibility, and thus limit or prevent the use of conventional NDT methods, so that fabrication inspections may have to be performed prior to the installation of the jackets or protrusions or alternate inspection methods will be required. However, the selection or details of these alternate methods will have to be determined by the particular type of restriction. In-service inspection must be performed in the assembled condition and other alternate methods will be required. Additional information is contained in Section 6.3 on in-service inspection.

The inherently large size of the pressure vessels creates problems and requirements for improved technology to perform volumetric examinations. Residual stresses can be an important factor to the vessel, but the current inspection technology is inadequate to detect and measure these stresses. In addition, certain areas of these vessels may need examination with extremely fine detail. Screening techniques should be developed to assure that the proper localized areas are identified.

Inspection requirements and sensitivity will be more stringent in the nozzle areas because of higher stress levels. The increased demand is complicated because of inspection difficulties due to the configuration of the joints and accessible surfaces. Development studies are needed to overcome those problems. In addition, close coordination will be necessary between design and inspection to ensure inspectability of the critical areas. Further discussion of this problem is in Chapter 2.

When thick-walled pressure vessels are fabricated in a shop, high-energy x-ray equipment is usually available for high-quality radiographic examination. However, for field assembly, such equipment is not generally available. Mobile linear accelerators, which have been developed in recent years, should be required for this examination. However, the inherent limitations of the best radiography for detection of planar flaws should necessitate the complementary use of advanced ultrasonic techniques.

6.2.4 Major concerns or inspection problems peculiar to piping systems

There is a major trend toward automated pipe welding; therefore, developments should be accomplished to permit automated mechanisms for high-confidence nondestructive examination of the joint, using ultrasonic and eddy-current techniques shortly after the welding process. Otherwise, the testing phase can severely lag that of fabrication, thus potentially causing schedule delays and economic problems.

Another widely recognized problem is the volumetric examination of coarse-grained stainless steels, particularly welds or centrifugally cast stainless steel pipe in piping systems. This problem should be considered for design and material selection.

The primary reason for the problem is the difficulty in applying ultrasonic techniques because of the large, variable attenuation and the high level of noise encountered during an examination. The widespread use of these materials and the limited capacity for radiography in crack detection make this an important problem for investigation. Dissimilar metal welds or transition joints between different materials are commonly used, and many of the same problems are present.

Multiparameter eddy-current techniques should also be studied for application to base metal and welds to detect and measure near-surface flaws, ferrite content, and heat treatment conditions.

It is generally recognized that the code for piping inspection (ANSI B31.3, Chapter VI) is less restrictive in many instances than that for pressure vessels (ASME Section VIII, Divisions 1 and 2). For instance, the piping code permits the use of fluorescent screens in radiography, whereas the pressure vessel code does not. The use of fluorescent screens can reduce image sharpness and resolution detail. In addition, the film density is required to be only 1.3 density units in the piping code. Such a low density permits ambient light viewing but certainly reduces image contrast, thus creating the potential for not detecting some flaws. Also, a higher-speed, coarser-grained x-ray film is permitted for piping inspection, which further reduces image quality and defect detectability.

6.3 In-Service and Postoperation Examination

For both economic and safety reasons, it will be necessary to perform periodic examinations (or continuous monitoring) of the pressure vessel and piping to assure that the original required integrity has been maintained. Such examinations should allow correction of undesirable conditions during periods of scheduled maintenance rather than at unexpected shutdowns due to component failure. Operating under such controlled conditions should make significant contributions to the overall plant reliability, availability, and operational efficiency and economy.

The previously discussed problems for manufacturing inspection apply equally to this section on in-service inspection, with the additional restrictions of limited access and higher temperatures as well as necessitated field application. The most common approach to interim examination after operation places emphasis on visual techniques. This may include optical aids such as replication, borescopes, periscopes, or television where direct viewing is not possible. An adjunct to visual examination includes the use of liquid penetrants to enhance the ability to see surface cracking. External hot spots (indicating present or incipient failure of the component or internal structure) can be detected with contact sensors (including paints) and infrared detection and imaging systems. Applications development should be accomplished to assure the availability of all these visual-related examinations.

As noted earlier, many of the manufacturing inspection techniques (and attendant problems) should be applicable to in-service inspection. Applied development should be accomplished to permit field application on completely assembled plants despite the operating environment. These advances will be simple extensions if the units were field-erected and inspected.

Consideration needs to be given to internal or external examination during the design of vessel. If the vessel is jacketed, preventing external access, then flanges should be provided such that the inside is accessible during routine shutdown periods. If the vessel is refractory lined, then welded joints could be considered and inspections would be external. The inner surface could be inspected by scheduling examination during the period of refractory replacement. In either event, several NDT techniques will need to be developed or modified for these inspections.

Acoustic emission[5] is a promising method for in-service inspection. Acoustic emission might be used for continuous monitoring, but, if the background noise is excessive it could preclude detection of flaws. There has been a tremendous upsurge of interest and application of acoustic emission to monitor deformation and crack propagation as well as other stress-wave-emitting phenomena in a variety of materials and configurations. A better understanding of the significance of the emission and improved quantitative interpretation of the signals, in terms of flaw growth or deformation, is definitely needed. Extensive experimental application of acoustic emission on coal conversion components should be made to improve the quantitative and qualitative aspects and to gain a better appreciation of the limitations and impediments to the method. ASTM and ASME are preparing written procedures for applications of this nature.

Other continuous monitoring techniques, such as acoustical signature analysis and ultrasonic wall thickness measurements, should be applied. This will require the development of high-temperature transducers and coupling techniques that can function for extended periods.

Because of limited access, innovative mechanical devices will be required for examinations in hard-to-reach locations.

The ultimate choice of types of interim inspection or continuous monitoring techniques will be determined in part by the selective capability of the respective examinations and the duty cycle of the operating unit (i.e. how frequently, and for how long is the unit shut down).

In addition to the more classical applications of NDT for the detection of discrete flaws or wall thinning, there is a need for NDT technology for the measurement of degradation of material properties. Included in conditions contributing to degradation of properties are embrittlement, sensitization, corrosion, deformation, creep, onset of third-stage creep, carburization, decarburization, and stress corrosion cracking. Each of these undesirable conditions need to be detected (and measured) to assure that premature or unexpected failure does not occur. NDT techniques need to be developed to assist in-service detection and measurement of these conditions (or conditions such as residual stress that can contribute to such degradation).

The performance of periodic examination (or continuous monitoring), with voluminous data, and the need to compare with previous results to detect flaw growth or other progressing incipient failure will demand the development of computer storage techniques for NDT data as well as techniques, instrumentation, and mechanical scanning equipment compatible with computer technology.

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