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HEAVY WALL PRESSURE VESSELS FOR ENERGY SYSTEMS

D. A. Canonico

Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY*
Oak Ridge, Tennessee 37830

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MASTER

The 1980s must be dedicated to the development of the technology required to assure an adequate supply of economically acceptable energy. Of particular concern is the availability of petroleum during the next decade. It may be in short supply because (1) reserves are depleted or (2) there is an oil embargo. Regardless of the cause, a shortage of petroleum will result in a crisis of major proportions.

In 1978 there were 78.0 quads† of energy consumed in the United States.[1] The energy usage was in three categories, residential/commercial, industrial, and transportation. The percentage of the total energy consumed by each of these categories was 36.5, 37.1, and 26.4%, respectively. The sources of the energy in 1978, as well as for the prior five years, are given in Table 1. It is important to note that oil was the source of nearly 50% of the energy consumed over the six years covered in Table 1 and its usage increased (by nearly 4%) from 1973 through 1978. In 1978 oil supplied 37.8 quads of energy. Transportation accounted for nearly 53% (20 quads) of the petroleum consumed in the U.S. Only 3.9 quads (10.3%) of the oil was consumed by the electric utilities and it was the energy source for 16.6% of the electricity produced. Much of this 16.6% can be supplied

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*Operated by Union Carbide Corporation for the U.S. Department of Energy under Contract W-7405-eng-26.

†1 quad = 1.055×10^{18} J = 10^{15} Btu.

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by nuclear and/or coal. Such is not the case for transportation. This category is nearly totally dependent upon petroleum products. During the next decade we must assure the transportation industry the energy that they require. This may necessitate the increased use of electric vehicles at the current state-of-technology of storage batteries. If such a means of transportation is promoted, the electric energy can be supplied by nuclear or coal facilities. Even with an increase in the use of electric vehicles, the demand for petroleum for transportation will continue.

The availability of crude oil in the next decade is dependent on two factors: (1) recoverable resources and (2) the world political climate. In 1973 it was reported[2] that the U.S. had 8 and 11 years of proven crude oil and natural gas reserves. In 1978 demonstrated recoverable crude oil reserves were reported[3] to be 4.3 years. (Dry natural gas reserves were reported[4] to be 10.7 years.) These figures may be extremely conservative. Proven reserves are economically controlled and higher priced crude oil will no doubt extend the "years of demonstrated reserves." Such a conclusion is based on past experience, fear of "running out of oil," was expressed[5] as early as the 1920s. Although the time period may not be precisely predicted, it is a fact that the U.S. oil and gas reserves are finite. Perhaps of more concern is the fact that most western nations are importers of crude oil. (In 1978 43.7% of the petroleum products consumed[1] in the U.S. were imported!) If this imported oil should become unavailable for any reason, the impact would be serious.

For the above reasons it is necessary that the development of alternate sources of petroleum products be the primary goal of the 1980s. Advanced energy sources such as solar and fusion are technologically challenging but their commercialization is considerably beyond the next decade. It is mandatory that proven energy sources be promoted and where necessary the technology to fully commercialize a system be developed. (Primarily this is the area of coal conversion. Liquefaction and gasification of coal have been proven to be feasible. During the next decade we must emphasize its commercialization.) Commercialization of coal conversion requires large reaction and gasifier pressure vessels. This is an area where engineering skills must be focused to assure that these vessels operated safely and reliably for their design lives. Concurrent with the commercialization of the coal conversion processes, we have the opportunity of advancing the concepts of vessel design, developing improved materials, and improving fabrication procedures. This is a rare opportunity afforded to the metallurgical community and it is a challenge that must be met. This is an opportunity to conduct premortem studies, an approach to safety that, to the best of my knowledge, was first achieved in the Heavy-Section Steel Technology (HSST) Program,[6] a program that is sponsored by the U.S. Nuclear Regulatory Commission and administered by the Oak Ridge National Laboratory.

The HSST Program is an integral part of a comprehensive effort under way in the U.S. to assure the integrity of light-water nuclear reactor pressure vessels throughout their useful life. Nuclear pressure vessels weigh about 454 metric tons (600 tons), approach 6.1 m (20 ft) in diameter, and are over 21.3 m (70 ft) in height. Vessel sizes in recent years have increased to the point where a vessel weighing about 910 metric tons (1000 tons) is not uncommon. Table 2 provides a comparison of typical vessel sizes for boiling and pressurized water reactors. The dimensions of nuclear pressure vessels pale however when compared to those proposed for commercial coal gasification processes. A gasifier vessel for a conceptual two-train, 6.1 MW (500 × 10^9 Btu/day) HYGAS commercial coal conversion plant[7] is nearly 76 m (250 ft) tall, varies in inside diameter from 7.6 to 9.4 m (25 to 31 ft), and weighs nearly three times that of a boiling water reactor (BWR) or a pressurized water reactor (PWR). The nominal operating pressures in the HYGAS process are similar to those for a BWR, but the process temperature is considerably higher, 930 vs 290°C (1700 vs 550°F). A great deal of energy will be contained in an operating pressure vessel the size of that shown in Fig. 1. A cursory calculation based on a nominal design pressure of 9.0 MPa (1300 psi), a temperature of 930°C (1700°F), and a gas composition of 25% H_2, 25% CH_4, 30% H_2O, 10% CO, and 10% CO_2, showed that the energy stored in the conceptual HYGAS gasifier is about 5.9 × 10^{10} J (4.4 × 10^{10} ft-lb), which is equivalent to nearly 13,200 kg (29,000 lb) of TNT. The potential destruction if the vessel were to rupture instantaneously is comparable to 58 conventional 455-kg (1000-lb) bombs. The instantaneous release of this much energy would literally destroy the entire coal conversion facility in which it operated and could hurl fragments of steel hundreds of feet. Needless to say, such an incident is intolerable and owners and manufacturers alike will strive to prevent such an occurrence.

The challenge of the 1980s is to assure that we can build pressure vessels of the sizes that are required for commercialization of coal conversion processes. Perhaps the biggest challenge is to achieve this goal within the limits of current technology.

Working within the confines of current metallurgical technology permits us to:

1. review present rules whereby pressure vessels are designed,
2. utilize melting practices that provide improved ingot quality while increasing ingot yield,
3. develop improved alloys based on current pressure vessel steels, and
4. improve current welding procedures to provide higher deposition rates with improved weld metal and heat-affected zone quality.

Each of these four areas will be discussed in the following sections.

Vessel Design

Currently large pressure vessels are designed in accordance with the rules of the *ASME Boiler and Pressure Vessel Code* (Code). (The United States and Canadian jurisdictions that require, by law, the application of at least one section of the Code are listed in Table 3.) The basis for establishing maximum allowable stress values or design stress intensity values is related to a number of factors; the most important of which are:

1. design philosophy and criteria,
2. the type of construction permitted,
3. the degree of analysis required, and
4. the amount of nondestructive examination required.

Nuclear pressure vessels are designed and built in accordance with Section III of the Code. Because of the serious nature of a breach of the primary containment, the philosophy of design for class 1 (Subsection NB) nuclear pressure vessels requires a greater degree of design analysis for all construction details. Procedures are given for classifying stresses and evaluating cyclic loading. A factor of three is used on tensile strength when establishing the design stress intensity values.

Currently it appears that pressure vessels for coal conversion processes will be designed in accordance with the rules of Section VIII of the Code. There are two Divisions (1 and 2) in Section VIII. The allowable stresses in Division 1 are lower than those in Division 2. The design philosophy in Section VIII Division 1 is based on the following:

1. The basis for calculating wall thicknesses and allowable pressures is membrane stresses. Secondary bending and stress concentrations are not considered.

2. The formulae used in the design calculations, and the allowable stresses include sufficient margins of conservatism to limit bending or peak stresses to a safe level.

3. A factor of four on tensile strength is used for establishing allowable stresses.

The design philosophy in Section VIII Division 2 is identical to that in Section III Subsection NB. Table 4 provides a comparison of the bases for determining allowable stresses. The differences in the stresses are reflected in the size of the pressure vessel that can be designed and built. Figure 2 allows a comparison between a Division 1 and Division 2 vessel designed to identical pressure and temperature conditions. There is a decided size advantage to a Division 2 design; based on a 305-mm (12-in.) wall thickness, the vessel inside diameters are approximately 2 and 3 m (approximately 7 and 10 ft) for Divisions 1 and 2, respectively. The increase in diameter permitted in Division 2 results in a twofold increase in internal volume. This volumetric increase may result in a cost advantage; however, this advantage may be offset by the increased cost of the more rigorous rules of analysis and inspection required in Division 2. Indeed the analysis and inspection in Section VIII Division 2 are essentially identical to those in Section III Subsection NB. Personnel safety and vessel integrity are of foremost concern, however a breach of a coal conversion pressure vessel is not as serious an event as that of a nuclear vessel. Therefore, requiring identical analysis and inspection, both extremely costly activities, does not seem warranted. There are two areas in Section VIII that require further attention. One area in which the rules of Section VIII are inadequate is toughness. This concern is recognized by reputable fabricators and/or owners and is discussed in refs. 8 and 9. It is entirely possible that a new section of the Code could be developed that recognizes that the stringent requirements mandated by nuclear applications may not be necessary for coal conversion vessels. The development of such a section of the Code will require data that support allowable stresses that are higher than those in Division 1 without the more demanding requirements of Division 2. Liquefied coal will only be acceptable if it can be competitive and any effort to reduce cost will improve its economic position in the world market.

The second area where Section VIII is inadequate is the absence in Division 2 of design stress intensity values for temperatures in the creep range. This void is evident in Table 4. Effort must be put forth to develop a basis for establishing design stress intensity values at temperatures where time-dependent properties become controlling. Currently some coal liquefaction processes that require that the reaction vessels be designed for temperatures near 480°C (900°F) are being based on the design stress intensity values in Code Case N-47. This Code Case[10] was developed for breeder reactor design and contains only five alloys, one of which (2 1/4 Cr-1 Mo) is a candidate for coal conversion reaction and gasifier vessels. Further only the 205-415 MPa (30-60 ksi) strength class is permitted for 2 1/4 Cr-1 Mo in Code Case N-47. Section VIII of the Code should be encouraged to develop criteria for assigning design stress intensity values in the creep range. Further, they should be cognizant that the materials will be used to fabricate coal conversion pressure vessels, the breach of which does not have the same consequences as a breach of a nuclear pressure vessel.

Finally, improved materials that will be discussed later in this paper must be Code approved if they are to be used for Code construction. Usually mechanical property data from three to five commercial heats is desired when setting allowable stresses. This imposes no particular hardship when the alloy has been correctly developed and the required allowable stress values are in the temperature range where tensile properties control. It is considerably more difficult and time consuming to obtain the desired data for setting stresses in the creep range. When setting allowable stresses in the creep range data for time periods of up to 10^4 h are required for three to five heats. Further, at least one heat should be tested to 3×10^4 h, a period of about 3 1/2 years. Assuming that a promising alloy is currently under development, Code approval will not be forthcoming before the middle of this decade. New material requires 4-6 years for Code approval and that assumes that the data are sufficient to satisfy the Code requirements for establishing allowable stresses.

Melting Practice

Recent advancements in melting practices should be employed in the preparation of materials for pressure vessels. The processes of interest are electroslag remelting (ESR), low-sulfur conventional processing (LSC), low-sulfur vacuum carbon deoxidized processing (LSVCD), and central zone remelting (CZR).

The CZR process[11-12] is unique in that it employs the ESR process to improve the quality of the central region of a conventional ingot. Figure 3 contains descriptive illustrations of how the process operates. Briefly the center region (which contains the segregates) of a conventional ingot is trepanned. The central region is then refilled using an electroslag remelting casting procedure. This procedure results in a more uniform higher quality final product. The process lends itself to providing cylindrical forged courses for pressure vessels whose inner wall can be of a chemical composition that will resist the environment in which the vessel must operate. In the case of a coal conversion pressure vessel, this region can be enriched with those elements (chromium and molybdenum) that provide a resistance to hydrogen attack. For nuclear applications the inner core can be of an analysis that is resistant to irradiation embrittlement. For example, the air-melted ingot body can be somewhat higher in Cu, P, and V. The inner core can be cast from an electrode low in those elements thereby providing excellent toughness even at the end of its useful life; the time of operation that is used for determining the probability of a nuclear pressure vessel failure due to thermal shock in the event of a loss-of-coolant accident. The CZR process also is attractive for large tubesheets because of the high quality of its central portion.

The other three processes (ESR, LSC, and LSVCD) all provide ingots that have extremely low sulfur contents. All three are capable of providing sulfur levels of less than 30 ppm (0.003%) and the LSC reportedly provides levels as low as 7 ppm. The largest ESR ingots are currently available from Rochling-Burbach in the Federal Republic of Germany. They reportedly have cast ESR ingots of greater than 100 tons. Currently such facilities are being developed in the U.S. Bethlehem Steel has a facility capable of producing a 1525-mm-diam (60-in.) ingot. National Forge is installing one of a similar size.

The LSC method of casting ingots was developed by Japan Casting and Forging Corporation. The LSCVD process is a development of Japan Steel Works (JSW). The LSCVD process also provides an ingot with extremely low phosphorus contents (<0.003%) and low silicon (about 0.05%). JSW has opted for the low silicon because they report that low silicon and phosphorus minimize segregation streaks.

All four of these melting processes provide steels that should exhibit superior toughness properties. Sulfur has a deleterious effect on Charpy V-notch upper-shelf impact energy.[13] Obtaining an upper-shelf energy of 68 J (50 ft-lb) or greater is required[14] to establish the RT_{NDT}. Phosphorus was shown by Rineholt[15] to drastically increase the 20-J (15 ft-lb) Charpy V-notch temperature. Decreasing these two elements does not sacrifice a steel's hardenability. Reducing them will improve a steel's resistance to hot cracking and embrittlement during service.

Moreover, the utilization of these advanced melting processes and their higher yields from a given ingot is in itself creditable from an energy conservation viewpoint. Currently the yield from a large conventional air-melted ingot can be as low as 50%. The ESR process and the CZR proceses yields are reportedly 85 to 95%.

New Materials

New materials may be a misnomer. Probably improvements (hopefully) of current materials may be more descriptive. At the present time there are essentially only two alloys used in the manufacture of the primary containment for nuclear reactors. These are the SA 533 grade B class 1 plate and its forging counterpart SA 508 class 3 and SA 508 class 2 forgings. Table 5 contains the chemical compositional ranges permitted in the SA specifications and their counterpart Federal Republic of Germany specifications. These steels satisfy the LWR pressure vessel needs. Unless there is a resurgence in interest for larger LWR facilities, such as there was[16] in the late 1960s and early 1970s, it is doubtful that these steels will be replaced with stronger and/or tougher steels. It is likely however that advantage will be taken of the improved melting practices discussed previously and the quality of the steel from which the LWR vessels are fabricated will be improved. This improvement in quality will be reflected in a lower sensitivity to irradiation. Stabilizing mechanical properties, in particular fracture toughness, will lay to rest the concern that a loss-of-coolant accident accompanied by a thermal shock due to activating the emergency core cooling system may result in the breach of the primary containment.

Such is not the case for steels for coal conversion systems. Currently the top candidate for the fabrication of large gasifiers and reaction vessels is 2 1/4 Cr-1 Mo steel. This steel is of interest because of its resistance to hydrogen attack as predicted from Nelson curves, which are shown in Fig. 4. The range for chromium and molybdenum in most specifications that cover 2 1/4 Cr-1 Mo steel is from 2.0 to 2.5% and 0.90 to 1.10%, respectively. It is possible that a lean heat, one containing near 2.0% Cr and 0.90% Mo, may not have the desired resistance to hydrogen attack if used in a high pressure liquefaction process operating above 425°C (800°F). Further, the hardenability of 2 1/4 Cr-1 Mo steel apears to be too low to provide tensile properties much in excess of 575 MPa (75 ksi) after a nominal postweld heat-treatment (PWHT). Figure 5 illustrates this point. The DATA TRAK, a method for duplicating the cooling rate after austenitizing obtained in thick sections in 12-mm-square (1/2-in.) bars, was used to obtain the results shown in Fig. 5. This procedure is permitted in Paragraph NB 2212 of Section III, and Paragraph AM 202 of Section VIII Division 2. The tensile data in Fig. 5 for 2 1/4 Cr-1 Mo steel cooled from either 927 or 1038°C (1700 or 1900°F) at a rate representing that of the quarter-thickness depth location in water-quenched 305-mm (12-in.) plate indicate that after a 40-h PWHT the steel will barely satisfy the class 2 strength requirements for the SA 387 grade 22 specification. These results suggest that the use of the higher strength classes of 2 1/4 Cr-1 Mo steel (such as SA 542 classes 1 through 4) is not likely.

There is, however, considerable work being done to develop steels that exhibit improved mechanical properties. Most of this work is based on adaptations of current Code-approved specifications and this should aid in their acceptance by the Code if they should prove worthy of being used for the fabrication of large pressure vessels.

Japan Steel Works[17] is modifying 2 1/4 Cr-1 Mo steel by decreasing the Si and adding V, Ti, and B. Deliberate additions of these elements at nominal amounts of 0.30, 0.022, and 0.0023% considerably increased the hardenability of conventional 2 1/4 Cr-1 Mo steel. This modification resulted in increased strength in the creep range; at 480°C (900°F) there is approximately a 50% increase in creep rupture strength for failure in 10^5 h. This improvement was achieved with no apparent loss of fracture toughness. Japan Steel Works have simulated weld heat cycles on the modified base metal and their results indicate that the heat-affected zone properties should be equal to or superior to that of conventional 2 1/4 Cr-1 Mo steel. This work is in its early stages and the results appear promising.

The U.S. Department of Energy is sponsoring the development of improved alloys for coal conversion pressure vessels. Work is under way at the University of California (UC) and at Oak Ridge National Laboratory (ORNL). The UC studies[18,19] have been directed toward the modification of Mn-Mo-Ni steel (A 533 grade B type) and Cr-Mo steel (A 542 type). The modification of the Mn-Mo-Ni steels involves additions of 1% Cr and 0.7% Mn. (The Mn-Mo-Ni specification, SA 533 grade B, currently permits up to 1.5% Mn. This Mn addition is aimed at increasing its level to nearer 2%.) The addition of the Cr and Mn have increased the hardenability of the A 533 grade B steel. The researchers report that the increased hardenability has resulted in improved strength and toughness for specimens heat-treated to represent the quarter-thickness depth location in both 200- and 305-mm-thick (8- and 12-in.) plate.

Zackay and Parker[18,19] are also studying modifications of 2 1/4 Cr-1 Mo steel with 0.5% Mn and 0.5% Ni. They report that these additions retard the transformation of the austenite to proeutectoid ferrite. This results in a more uniform microstructure for thicker sections. This more uniform microstructure is reflected in improved Charpy V-notch toughness properties. Both transition temperature and upper-shelf energy behavior were improved.

This work at the University of California, although in its early stages, does show considerable promise. The modifications to the A 533 grade B analysis should improve that steel's resistance to hydrogen attack but whether it is improved sufficiently to permit its use at typical liquefaction temperatures must be established. The results for the modifications for the two steels reported in refs. 18 and 19 are based on tempering times of 4 h. This time period is too short when considering the extended PWHT times that are encountered during the fabrication of large pressure vessels. These time periods often exceed 40 h and can be as long as 100 h.

The ORNL, in cooperation with Combustion Engineering Inc., is involved[12] in the development of an improved high temperature alloy based on the 9 Cr-1 Mo analysis. The modification in this case consists of the addition of Nb and V at levels of near 0.1 and 0.2% respectively. The conventional 9 Cr-1 Mo steel has considerably greater hardenability[20] than 2 1/4 Cr-1 Mo. This hardenability is not affected by the Nb and V modifications. This is evident in the Jominy End Quench results obtained by Climax Molybdenum[21] for modified 9 Cr-1 Mo and conventional 2 1/4 Cr-1 Mo steels. These results are shown in Fig. 6. The 9 Cr-1 Mo is an air-hardenable steel and as such will transform to martensite even at section sizes greater than 200 mm (8 in.). Further, there is no evidence that proeutectoid ferrite will be present in thick sections and therefore the microstructure should be uniform even in section sizes greater than 200 mm. This conclusion is based on studies[22] conducted at Lehigh University that correlated the cooling rates at various Jominy End Quench distances with those obtained experimentally in thick water-quenched plate. The ORNL researchers report that the creep strength of the modified 9 Cr-1 Mo alloy is similar to that of type 304 stainless steel up to about 625°C (1150°F).

Weldability studies[23] are being conducted on the modified 9 Cr-1 Mo alloy. Early results indicate that hot cracking will not be a problem. Also, Gleeble studies involving simulated weld thermal cycles show that the heat-affected zone toughness is independent of cooling rate over the range of 14 to 55°C/s (25 to 100°F/s).

The alloys discussed above all are modifications of existing specifications already approved for Code construction. This fact will expedite their acceptance into the Code. Of course, this assumes that all the development data are substantiated through testing programs that provide the needed confirmatory results required for the commercialization of these alloys.

The development of improved alloys should be commended. There is also much that can be achieved with current alloys. The fact that through modern melting methods sulfur and phosphorus can decrease to near 30 ppm in large commercial heats is noteworthy. Even in ingots poured from air-melted heats, the S and P levels can be limited to 0.01% (100 ppm) and lower. In view of this capability it is ludicrous to tolerate ASTM and ASME pressure vessel steel specifications that permit S and P levels of 0.035 to 0.045%. A review and update of these specifications should be undertaken.

Fabrication

All large pressure vessels are fabricated by welding. Economics dictate this method of fabrication. The entire chemical, petroleum, and energy producing industries are dependent on high quality weldments. A large pressure vessel of the size suggested in Fig. 1 will contain over 305 m (1000 ft) of weld. Welding and its related activities (joint preparation, inspection and examination, and postweld heat-treating, etc.), are responsible for over 50% of the fabrication cost of a large pressure vessel. Currently, a 910-metric ton (1000-ton) vessel is the largest that can be shop fabricated. This size is attainable in only three or four shops in the U.S. and this limit is set by their crane capacities. Vessels heavier than 910 metric tons (1000 tons) must be field fabricated. The size of shop-fabricated vessels is further restrained by the ability to deliver them. The dimensions of pressure vessels that can be transported on land are limited to about 4.3 m (14 ft) in diameter and 725 metric tons (800 tons) in weight. Lengths of up to 30 m (100 ft) have been transported. The shipment of large shop-fabricated vessels such as those listed in Table 2 is done by barge; however, this requires navigable waterways. Because of the lack of navigable waterways in the western part of the U.S., this mode of transportation is generally limited to the eastern half of the U.S.

All joining is done by fusion welding processes. Currently two welding processes are employed for most vessel fabrication; these are the submerged-arc (SA) and shielded metal-arc (SMA) processes. The SA process employs a granular flux covering over the weld arc and until recently has only been used in the 1G (flat position) welding position. Because of this limitation, the SA process has been primarily used for shop fabrication. Field fabrication because of the need for welding in all positions [flat (1G), horizontal (2G), vertical (3G), and overhead (4G)] is accomplished primarily with the SMA process.

These generalizations are being challenged by recent improvements and advancements in joining procedures. Submerged-arc welding procedures that permit the use of this process in positions besides the 1G are being developed[24] by Chicago Bridge and Iron Company. They have procedures that permit the containment of the flux even in the overhead (4G) position. This development will greatly increase the field fabrication deposition rate, thereby decreasing costs.

A considerable amount of effort is being directed to adapting the electron-beam (EB) process for joining thick sections. This process is normally confined to use in vacuum chambers and is considered an "exotic" joining procedure more commonly encountered in applications for the aerospace and electronic industries. It is being developed for out-of-chamber welding of thick sections and has shown promise. The goal is to produce a high quality joint typical of an EB weld without the need for a full heat-treatment such as is necessary for electroslag welds. This development work is being done independently by Babcock and Wilcox Company[25] (B&W) and Sciaky Brothers, Inc.[26] The B&W program is sponsored by the Department of Energy. They have achieved sound welds in 200-mm-thick (8-in.) plate of 2 1/4 Cr-1 Mo steel using simulated field fabrication procedures. Their procedure requires welding from both sides. Sciaky Brothers have successfully welded 135-mm-thick (5 3/16-in.) A 533 grade B steel rings.

The adaptation of the EB welding procedure for thick walled pressure vessel steels appears promising. Additional metallurgical studies must be conducted to assure that the properties, in particular toughness, are adequate for the vessel's intended use after PWHT.

Conclusions

The challenge of the 1980s will be to assure that the western world has an *adequate supply of needed energy*. Conservation is commendable and perhaps can be made to work but in recent years the only time that the U.S. underwent a sustained reduction in energy growth was during the 1930s, a period of a severe depression in not only the U.S. but the entire world. This behavior is clearly seen in Fig. 7. More recently, the U.S. decreased its energy growth and that was, as can be seen in Table 1, during 1974 and 1975, two years in which the U.S. had a somewhat severe recession. Further, even if the western world can curtail its energy consumption, the world needs will grow. The standard of living in most third-world countries will increase in the years ahead and this growth will require energy.

In the U.S. transportation places the greatest demand on petroleum products. These demands can be met through the liquefaction of coal. Commercializing the coal conversion processes will impose an unprecendented demand for large pressure vessels. This demand can be met through modernization of the Code to meet the needs of an evolving industry. This was accomplished for nuclear pressure vessels; it can be done for coal conversion vessels. Advantage should be taken of modern melting practices. The steels produced by these processes should be of higher quality, exhibit improved fracture toughness, and be less susceptible to in-service degradation. Modifications of steels currently accepted in the Code appear to provide improved mechanical properties. These steels may permit the fabrication of larger diameter vessels with thinner section sizes and improved reliability and integrity. Adapting current specifications should expedite Code approval. Finally the challenge of improving welding procedures and adapting processes for field applications will result in higher quality weldments.

The challenge of the 1980s lies in assuring that the world has adequate energy. This can only be achieved through the assurance that when the industry requires large pressure containment systems that the technology exists to satisfy that need - immediately.

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23. D. P. Edmonds and P. L. Sturgill, *Weldability of Modified 9 Cr-1 Mo Steels*, ORNL/TM-6890 (August 1979).

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25. C. M. Weber, "Development of Automated Welding Processes for Field Fabrication of Thick-Walled Pressure Vessels - Electron Beam Method," p. III-45 in *Third. Ann. Conf. Materials for Coal Conversion and Utilization*, Gaithersburg, Maryland, October 10-19 1978.

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Table 1. The Major Sources of the Energy Consumed in the United States[a] for the Years 1973-1978

Year	Total Consumption (quads)[b]	Percent of Total				
		Coal	Gas	Oil	Hydro	Nuclear
1973	74.61	17.8	30.2	46.7	4.0	1.2
1974	72.35	17.8	30.0	45.7	4.6	1.8
1975	70.71	18.1	28.2	46.3	4.6	2.7
1976	74.16	18.5	27.4	47.0	4.1	2.9
1977	76.66	18.4	26.0	48.5	3.4	3.5
1978	78.01	18.1	25.4	48.4	4.1	3.8

[a] U.S. Department of Energy, Information Administration, Annual Report to Congress, 1978, DOE/EIA-0173/2 (April 1979).

[b] 1 quad = 1.055×10^{18} J = 10^{15} Btu.

Table 2. Comparison of Sizes of Pressure Vessels for Comparable Plants

Reactor Type	BWR	PWR
Identification	Hartsville-1	Palo Verde-1
Net Electrical Output, MW	1205	1235
Coolant Pressure, MPa (psi)	7.2 (1040)	15.3 (2250)
Cylinder Wall Thickness, mm (in.)	145 (5.7)	231 (9.1)
Inside Diameter, m (in.)	6.045 (238)	4.623 (182)
Height, m (ft)	∿22 (∿73)	∿15 (∿48)

Table 3. U.S. and Canadian Jurisdictions[a] Requiring the Application of at Least One Section of the *ASME Boiler and Pressure Vessel Code*

U.S. States and Territories

Alabama
Alaska
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Dist. of Columbia
Georgia
Guam
Hawaii
Idaho
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New York
North Carolina
North Dakota
Ohio
Oklahoma
Oregon
Panama Canal Zone
Pennsylvania
Puerto Rico
Rhode Island
South Dakota
Tennessee
Texas
Utah
Vermont
Virginia
Washington
West Virginia
Wisconsin
Wyoming

U.S. Cities and Counties

Albuquerque, NM
Buffalo, NY
Chicago, IL
Dearborn, MI
Denver, CO
Des Moines, IA
Detroit, MI
E. St. Louis, MO
Greensboro, NC
Kansas City, MO
Los Angeles, CA
Memphis, TN
Miami, FL
Milwaukee, WI
New Orleans, LA
New York, NY
Oaklahoma City, OK
Omaha, NB
Phoenix, AZ
St. Joseph, MO
St. Louis, MO
San Francisco, CA
San Jose, CA
Seattle, WA
Spokane, WA
Tacoma, WA
Tampa, FL
Tucson, AZ
Tulsa, OK
University City, MO
White Plains, NY
Arlington Co., VA
Dade Co., VA
Fairfax Co., FA
Jefferson Parish
St. Louis Co., MO

Provinces in Canada

Alberta
British Columbia
Manitoba
New Brunswick
Newfoundland and Labrador
Northwest Territory
Nova Scotia
Ontario
Prince Edward Island
Quebec
Saskatchewan
Yukon Territory

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

Table 4. Criteria for Calculation of Allowable Stresses (Nonbolting Conditions)

Standard	Fraction of Minimum				
	Ultimate Tensile	Yield Stress	Creep Stress[a]	Rupture Stress[b]	Uniaxial Strain Cycling Fatigue
ASME Section VIII Division 1	1/4	2/3[c]	100% av	67% av 80% min	
ASME Section VIII Division 2	1/3	2/3[d]	[e]	[e]	[f]

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

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

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

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

[e] Criteria not established.

[f] Fatigue properties are not always required. Need for fatigue analysis is determined by designer in accordance with para. AD-160 of ASME Section VIII Division 2 rules.

Table 5. Compositional[a,b] Ranges of Nuclear Pressure Vessel Steels

Specification	Composition, wt %									
	C	Mn	P	S	Si	Mo	Ni	Cu	Cr	V
					Plate					
SA 533 Grade B Class 1	0.25 -	1.15- 1.50	0.035 (0.012)[c]	0.040 (0.015)[c]	0.15- 0.30	0.45- 0.60	0.40- 0.70	- (0.010)[c]	- -	- (0.05)[c]
20 Mn-Mo-Ni 55	0.25 -	1.15- 1.50	0.035 -	0.040 -	0.15 0.30	0.45 0.60	0.40 0.70	- -	- -	- -
					Forging					
SA 508 Class 3	0.15- 0.25	1.20 1.50	0.025 (0.012)[c]	0.025 (0.015)[c]	0.15 0.40	0.45 0.60	0.40 1.00	- (0.10)[c]	0.25 -	0.50 -
SA 508 Class 2	0.27 -	0.5- 1.00	0.025 (0.012)[c]	0.025 (0.015)[c]	0.15 0.40	0.55 0.70	0.50- 1.00	- (0.10)[c]	0.25 0.45	0.050 -
22 Ni-Cr-Mo 37	0.17- 0.23	0.50- 1.00	0.02 -	0.02 -	0.35 -	0.50- 0.80	0.60- 1.20	- -	0.30- 0.50	0.05 -

[a] Single values are maximum limits.

[b] Compositional limits are for heat analysis; the limits for product analysis are more broad.

[c] Restricted values for heats used at the beltline.

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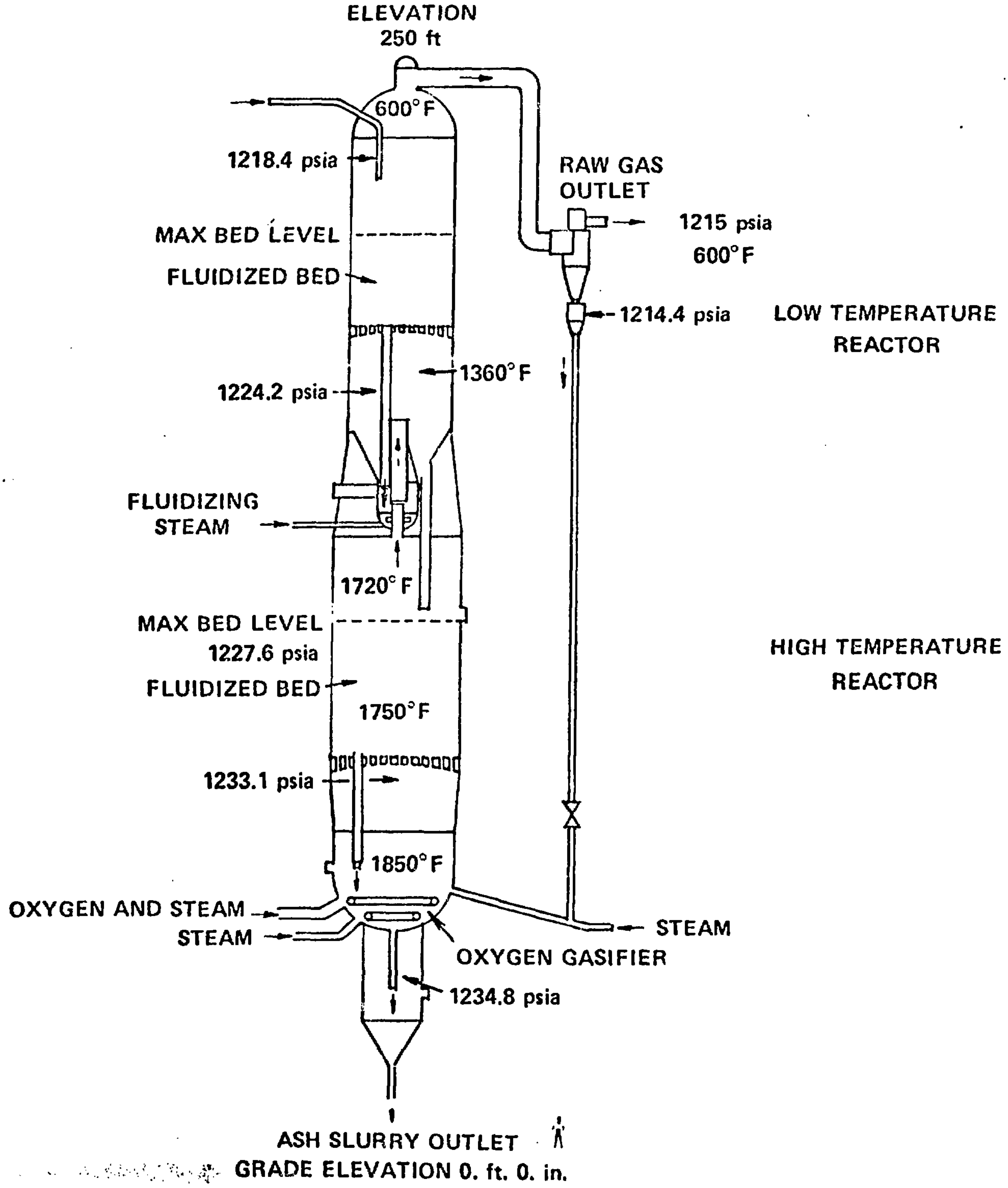

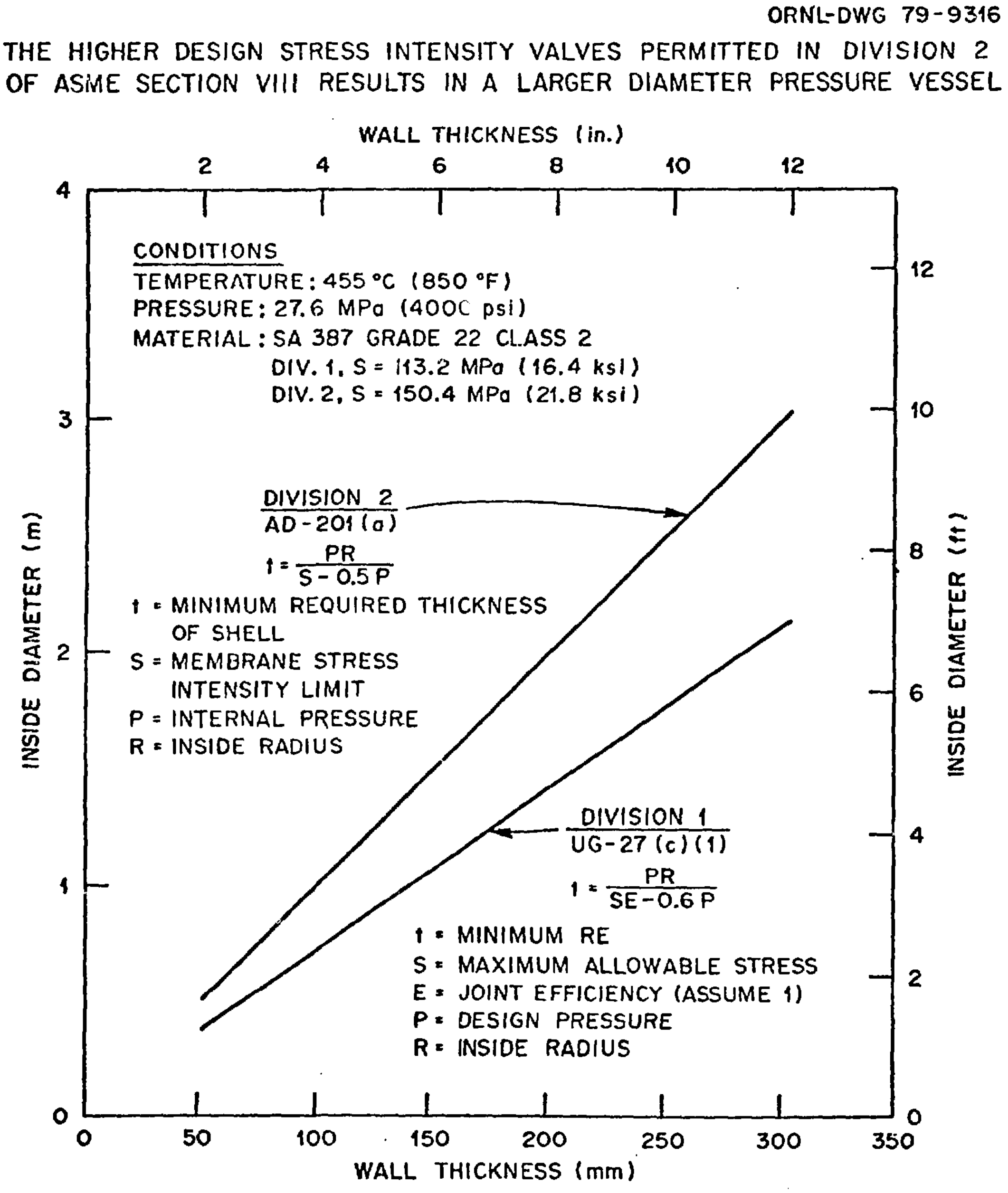

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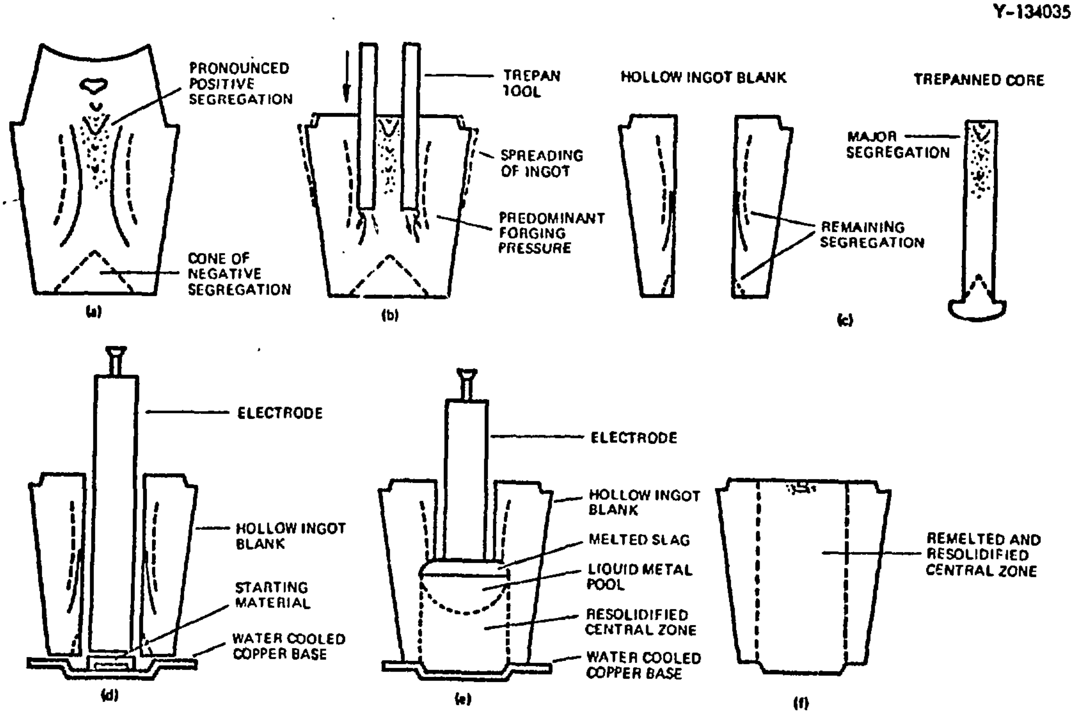

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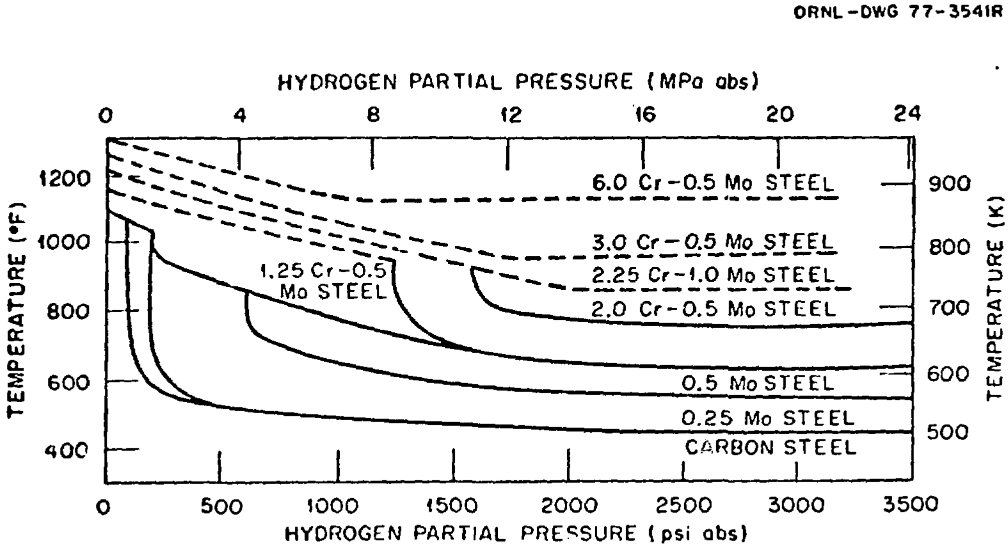

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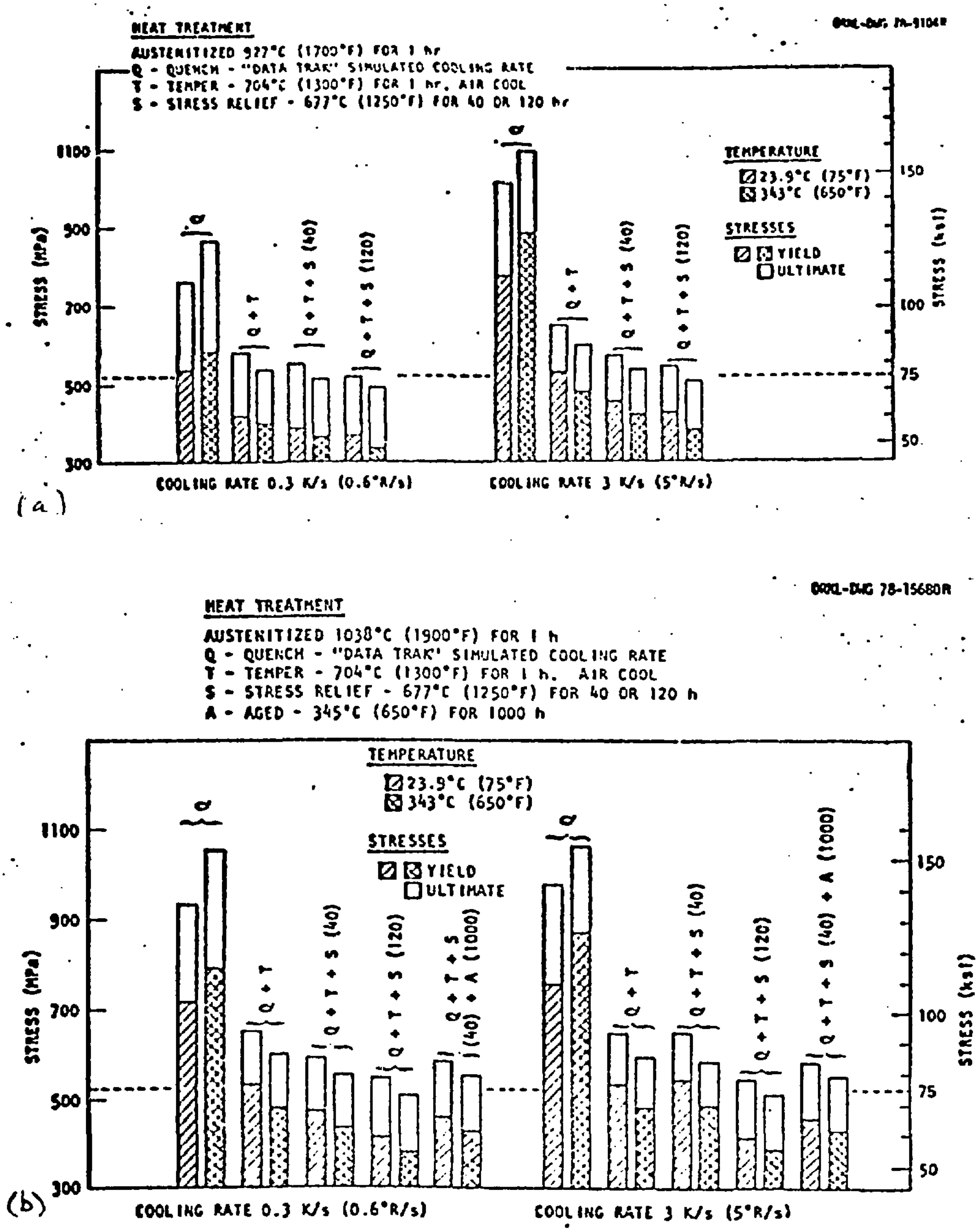

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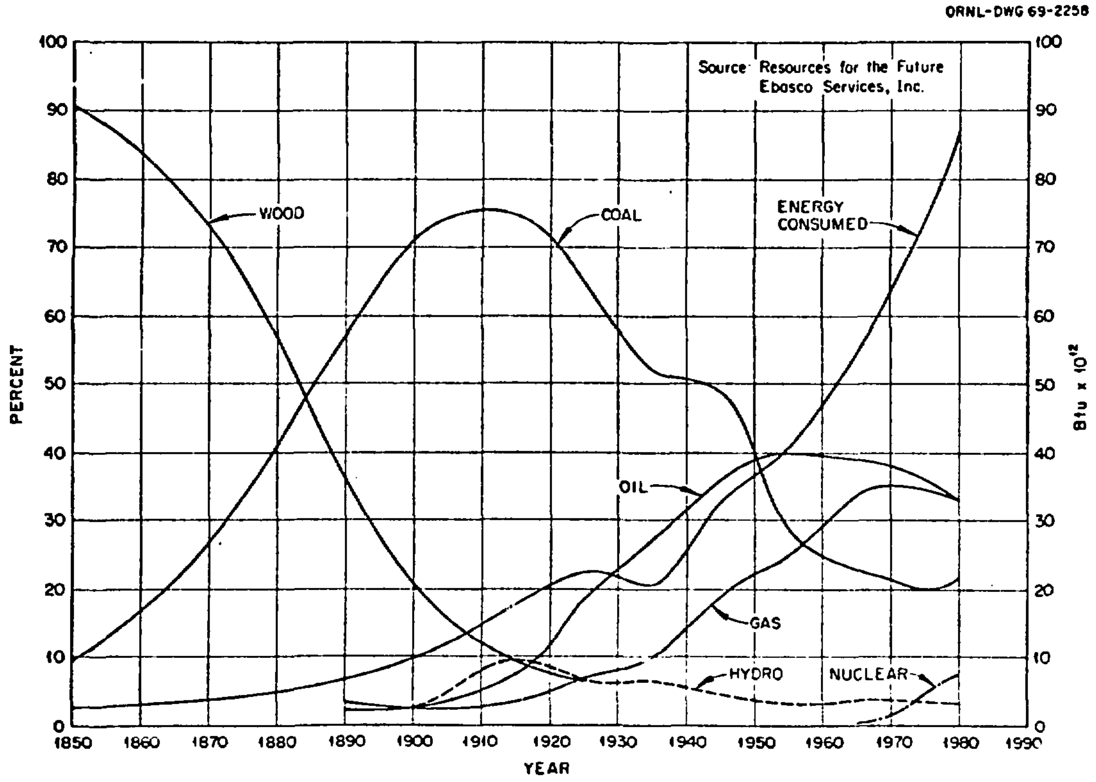

Source: Resources for the Future
Ebasco Services, Inc.

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