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Analysis of Welded Structures

Residual Stresses, Distortion, and their Consequences

by

KOICHI MASUBUCHI

Professor of Ocean Engineering and Materials Science
Massachusetts Institute of Technology, U.S.A.

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Preface

FROM December 1974 through November 1977, a research program entitled "Development of Analytical and Empirical Systems of Design and Fabrication of Welded Structures" was conducted at the Department of Ocean Engineering of the Massachusetts Institute of Technology for the Office of Naval Research, U.S. Navy under Contract No. N000 14–75–C–0469 NR031–773 (MIT OSP # 82558). The objective of the research program was to develop analytical and empirical systems to assist designers, metallurgists and welding engineers in selecting optimum parameters in the design and fabrication of welded structures. The program included the following tasks:

Task 1: The development of a monograph about the prediction of stress, strain and other effects produced by welding.
Task 2: The development of methods of predicting and controlling distortion in welded aluminum structures.

Efforts under Task 1 have resulted in a monograph entitled "Analysis of Design and Fabrication of Welded Structures". This book has been prepared from the monograph. This book covers various subjects related to design and fabrication of welded structures, especially residual stresses and distortion, and their consequences. How and whom this book is intended to help is written in Chapter 1 (Section 1.1.3).

Results of Task 2 are incorporated in Chapter 7. The final report of this research project is included as Reference (720).

Financial assistance also was given, especially in preparing the final draft of this book from the original monograph prepared under Task 1, by a group of Japanese companies including:

Hitachi Shipbuilding and Engineering Co.
Ishikawajima Harima Heavy Industries
Kawasaki Heavy Industries
Kobe Steel
Mitsubishi Heavy Industries
Mitsui Engineering and Shipbuilding Co.
Nippon Kokan Kaisha
Nippon Steel Corporation
Sasebo Heavy Industries
Sumitomo Heavy Industries

The author wishes to acknowledge financial assistance provided by the Office of Naval Research and the above Japanese companies.

The author also acknowledges a group of individuals who provided guidance, encouragement, and assistance. A number of people in the U.S. Navy, especially Dr. B. A. MacDonald and Dr. F. S. Gardner of the Office of Naval Research, reviewed

the monograph and provided numerous valuable comments. Professor W. S. Owen, Head of the Department of Materials Science and Engineering of M.I.T., provided various suggestions. Dr. K. Itoga of Kawasaki Heavy Industries, Ltd., Kobe, Japan, who was a research associate at M.I.T. from April 1975 through April 1978, assisted the author in preparing Chapters 9 to 10. Mr. V. J. Papazoglou assisted the author in preparing Chapter 13. Mrs. J. E. McLean, Mrs. M. B. Morey, and Miss M. M. Alfieri helped the author in typing.

In order to write this book, while working as professor at M.I.T., the author spent numerous hours during nights and weekends. The author sincerely thanks his wife Fumiko for her encouragement and understanding during these days.

KOICHI MASUBUCHI

Units

CURRENTLY changes are being made, slowly but steadily, in the United States in the use of units from the English system to the metric system, or more precisely the SI system (le Système international d'Unités). However, many articles referred to in this book use the English system and many readers of this book are still accustomed to the English system. To cope with this changing situation, the book has been prepared in the following manner.

(a) All values given in the text are shown in both English and the SI units—the unit used in the original document first followed by a conversion. For example, when the plate thickness used was 1 inch it is shown as 1 in. (25.4 mm or 25 mm). On the other hand, when the original experiment was done with a 20-mm-thick plate, it is shown as 20 mm (0.8 in.). In the case of stresses, values are written in psi (or ksi), kg/mm^2, and newton/m^2 (or meganewton/m^2).

(b) Most figures and tables are shown as they appear in the original document, although in some cases both the English and the SI units are used.

The author hopes that the way in which this book is written provides a compromise rather than a confusion, thus making the book easy to read by people in various countries.

Below is a conversion table for units frequently used in this book.

To convert from	*to*	*multiply by*
inch (in.)	meter (m)	2.54×10^{-2}
inch	mm	2.54
foot (ft)	meter	3.048×10^{-1}
lbm/foot^3	kilogram/meter^3	1.601×10
Btu	joule (J)	1.055×10^3
calorie	joule	4.19
lbf (pound force)	newton (N)	4.448
kilogram force (kgf)	newton	9.806
pound mass (lbm)	kilogram (kg)	4.535×10^{-1}
lbf/inch^2 (psi)	newton/meter^2 (N/m^2)	6.894×10^3
ksi	MN/m^{2}*[a]	6.894
kgf/meter^2	newton/meter^2	9.806
Fahrenheit (t_F)	Celcius (t_C)	$t_C = (5/9)(t_F - 32)$

[a] MN (meganewton) = 10^6 N (newton).

Notations

EFFORTS were made to use the same notation symbols, as much as possible, to express various quantities throughout the entire book. For example, I and V are used to express welding current and arc voltage, respectively. However, the author has found that it is almost impossible to use a single, unified system of notation throughout the entire book because:

1. the book covers many different subjects,
2. the book refers to works done by many investigators who used different notations.

Efforts were made to provide sufficient explanations whenever symbols are used.

References

REFERENCES are numbered by the number of the chapter in which the document is referred to first and the sequence in that chapter. For example, (103) is the third reference in Chapter 1, and (809) is the 9th reference in Chapter 8. At the end of each chapter, references which are used in that chapter for the first time are listed. For example, references (901), (902), ..., are listed at the end of Chapter 9.

When a reference is used repeatedly in later chapters, the original reference number is used throughout this book. For example, if reference (101) is used in a later chapter, it is still referred to as (101).

CHAPTER 1

Introduction

THIS chapter provides the necessary background information on structural materials and welding processes to enable those readers whose knowledge in these areas is limited to understand the remainder of this book.

1.1 Advantages and Disadvantages of Welded Structures and Major Objective of this Textbook

Since this book discusses at length the problems associated with the design and fabrication of welded structures, it risks creating the impression that welded structures are impractical due to their many special problems and their tendency to fracture. On the contrary, welded structures are superior in many respects to riveted structures, castings, and forgings. It is for this reason that welding is widely used in the fabrication of buildings, bridges, ships, oil-drilling rigs, pipelines, spaceships, nuclear reactors, and pressure vessels.

Before World War II, most ships and other structures were riveted; today, almost all of them are fabricated by welding. In fact, many of the structures presently being built—space rockets, deep-diving submersibles, and very heavy containment vessels for nuclear reactors—could not have been constructed without the proper application of welding technology.

1.1.1 *Advantages of Welded structures over riveted structures*

(A) *High joint efficiency.* The joint efficiency is defined as:

$$\frac{\text{Fracture strength of a joint}}{\text{Fracture strength of the base plate}} \times 100(\%)$$

Values of joint efficiency of welded joints are higher than those of most riveted joints. For example, the joint efficiency of a normal, sound butt weld can be as high as 100%. The joint efficiency of riveted joints vary, depending on the rivet diameter, the spacing, etc., and it is never possible to obtain 100% joint efficiency.

(B) *Water and air tightness.* It is very difficult to maintain complete water and air tightness in a riveted structure during service, but a welded structure is ideal for structures which require water and air tightness such as submarine hulls and storage tanks.

(C) *Weight saving.* The weight of a hull structure can be reduced as much as 10 and 20% if welding is used.

(D) *No limit on thickness.* It is very difficult to rivet plates that are more than 2 inches thick. In welded structures there is virtually no limit to the thickness that may be employed.

(E) *Simple structural design.* Joint designs in welded structures can be much simpler than those in riveted structures. In welded structures, members can be simply butted together or fillet welded. In riveted structures, complex joints are required.

(F) *Reduction in fabrication time and cost.* By utilizing module construction techniques in which many subassemblies are prefabricated in a plant and are assembled later on site, a welded structure can be fabricated in a short period of time. In a modern shipyard, a 200,000-ton (dead weight) welded tanker can be launched in less than 3 months. If the same ship were fabricated with rivets, more than a year would be needed.

1.1.2 *Problems with welded structures*

Welded structures are by no means free from problems. Some of the major difficulties with welded structures are as follows:

(A) *Difficult-to-arrest fracture.* Once a crack starts to propagate in a welded structure, it is very difficult to arrest it, therefore, the study of fracture in welded structures is very important. If a crack occurs in a riveted structure, the crack will propagate to the end of the plate and stop; and, though a new crack may be initiated in the second plate, the fracture has been at least temporarily arrested. It is for this reason that riveted joints are often used as crack arresters in welded structures.

(B) *Possibility of defects.* Welds are often plagued with various types of defects including porosity, cracks, slag inclusion, etc.

(C) *Sensitive to materials.* Some materials are more difficult to weld than others. For example, steels with higher strength are generally more difficult to weld without cracking and are more sensitive to even small defects. Aluminum alloys are prone to porosity in the weld metal.

(D) *Lack of reliable NDT techniques.* Although many non-destructive testing methods have been developed and are in use today, none are completely satisfactory in terms of cost and reliability.

(E) *Residual stress and distortion.* Due to local heating during welding, complex thermal stresses occur during welding; and residual stress and distortion result after welding. Thermal stress, residual stress, and distortion cause cracking and mismatching; high tensile residual stresses in areas near the weld may cause fractures under certain conditions; distortion and compressive residual stress in the base plate may reduce buckling strength of structural members.

Consequently, in order to design and fabricate a soundly welded structure, it is essential to have: (1) adequate design; (2) proper selection of materials; (3) adequate equipment and proper welding procedures; (4) good workmanship; and (5) strict quality control.

1.1.3 *Major objective of this book*

Figure 1.1 shows the importance of residual stresses and distortion in the design and fabrication of welded structures.

When a practicing engineer is concerned with residual stresses and distortion, he is

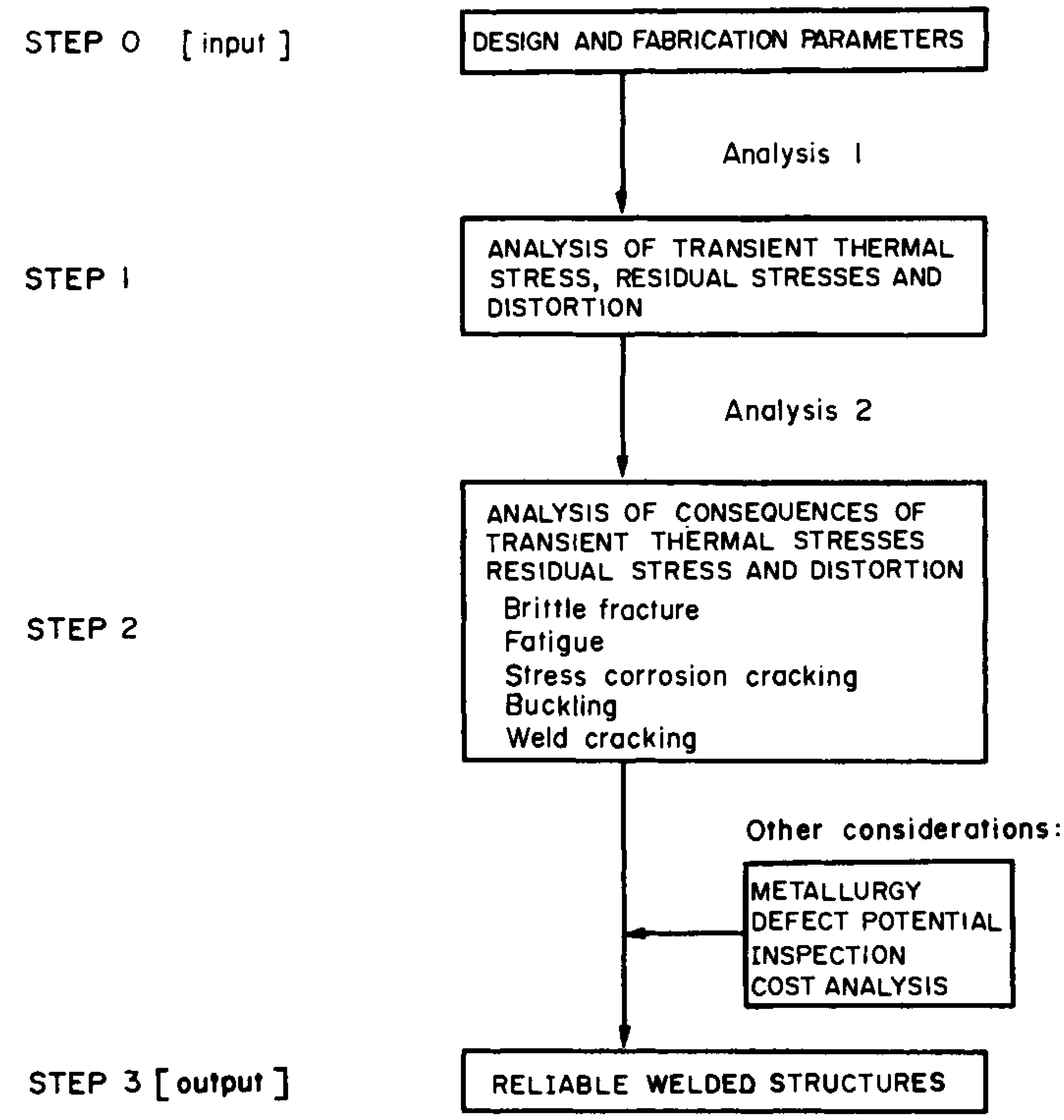


FIG. 1.1. Importance of residual stresses and distortion in the design and fabrication of welded structures.

also likely to be concerned with their adverse effects on the service performance of the structure which he is designing or fabricating. High tensile residual stresses in regions near the weld may promote brittle fracture, fatigue, or stress corrosion cracking. Compressive residual stresses and initial distortion may reduce buckling strength. What complicates the matter is that the extent of the effects of residual stresses is not only governed by residual stresses but also brittleness of the material. When the material is brittle, residual stresses may reduce the fracture strength of the weldment significantly. When the material is ductile, on the other hand, the effects of residual stresses are practically zero.

In fact what the practicing engineer wishes to do is to change design and fabrication parameters, such as plate thickness, joint design, welding conditions, welding sequence, etc., so that the adverse effects of residual stresses and distortion can be reduced to acceptable levels. It is much better to achieve this goal during an early stage of design and fabrication rather than confronting the problem at later stages of fabrication.

In order to accomplish this task, the engineer needs at least two kinds of analysis:

1. An analysis of transient thermal stresses, residual stresses, and distortion (Analysis 1 between Steps 0 and 1 in Fig. 1.1).
2. An analysis of the effects of thermal stresses, residual stresses and distortion on the service behavior of welded structures (Analysis 2 between Steps 1 and 2).

The major objective of this book is to cover the present knowledge of these two analyses.

Chapters 2 through 7 cover Analysis 1, while Chapters 8 through 14 cover Analysis 2.

The engineer also must consider many subjects other than residual stresses and distortion, and their consequences. These subjects include metallurgy, weld defect potential, inspection, fabrication cost, etc. The welding conditions that would give the minimum amount of distortion may not be usable because of the poor metallurgical properties or excessively high fabrication cost, for example. Therefore, what the engineer really needs is an integrated system which can analyze all the relevant subjects required. However, such an integrated system, yet to be developed, would be too extensive to be covered in a single book.

This book primarily covers subjects related to residual stresses and distortion, and their consequences. Attempts have been made to minimize duplications with other existing books. For example, a number of books have been written on brittle fracture, fatigue, stress corrosion cracking, buckling etc. Discussions in this textbook emphasize those subjects characteristic of welded structures, especially those related to residual stresses and distortion.

In preparing this book, discussions on welding processes, materials, and welding metallurgy have been kept to a minimum. The author plans to cover these subjects in subsequent books with the desire that the entire system will one day be fully integrated.†

1.2 Historical Overview and Future Trends[(101)]

When one thinks about what may happen in the future, it is often worthwhile to first examine what has happened in the past and what is happening now, because the future can be regarded as an extension of the past and present (although abrupt changes often take place). Figure 1.2 illustrates some major events in recent world history, the use of materials for ships and other large structures, and the development of joining methods and their applications.

1.2.1 *Materials for large structures*

From wood to steel. Until around 1850 wood was the principal material for building ships, bridges, and other structures. Around the middle of the nineteenth century, iron was introduced as a construction material. By the early 1900s, however, iron also became obsolete; since then steels, alloys of iron and carbon, and other elements have become the principal materials for ships and various other structures. Although other construction materials have been developed, steel still remains the most widely used material for the construction of ships and other large structures. Low carbon steels are used for most applications. However, high-strength steels are experiencing an increased use.

Figure 1.3 shows how the yield strength of materials used for U.S. Navy submarines and submersibles has increased.[(101,102)] Prior to the early 1940s, combat submarines were fabricated largely from low-carbon steel, a material with a tensile yield strength of about 32,000 psi (22.4 kg/mm^2 or 220 MN/m^2). Between 1940 and 1958 high-tensile-strength steel (HTS) with a 50,000 psi (35.2 kg/mm^2 or 344.7 MN/m^2) yield strength was used in most submarine structures. In 1958 HY-80 steel, a quenched-and-tempered

† The following three books are under preparation: (1) *Welding Engineering*, (2) *Fractures of Welded Structures*, (3) *Materials for Ocean Engineering* [revision of Reference (102)].

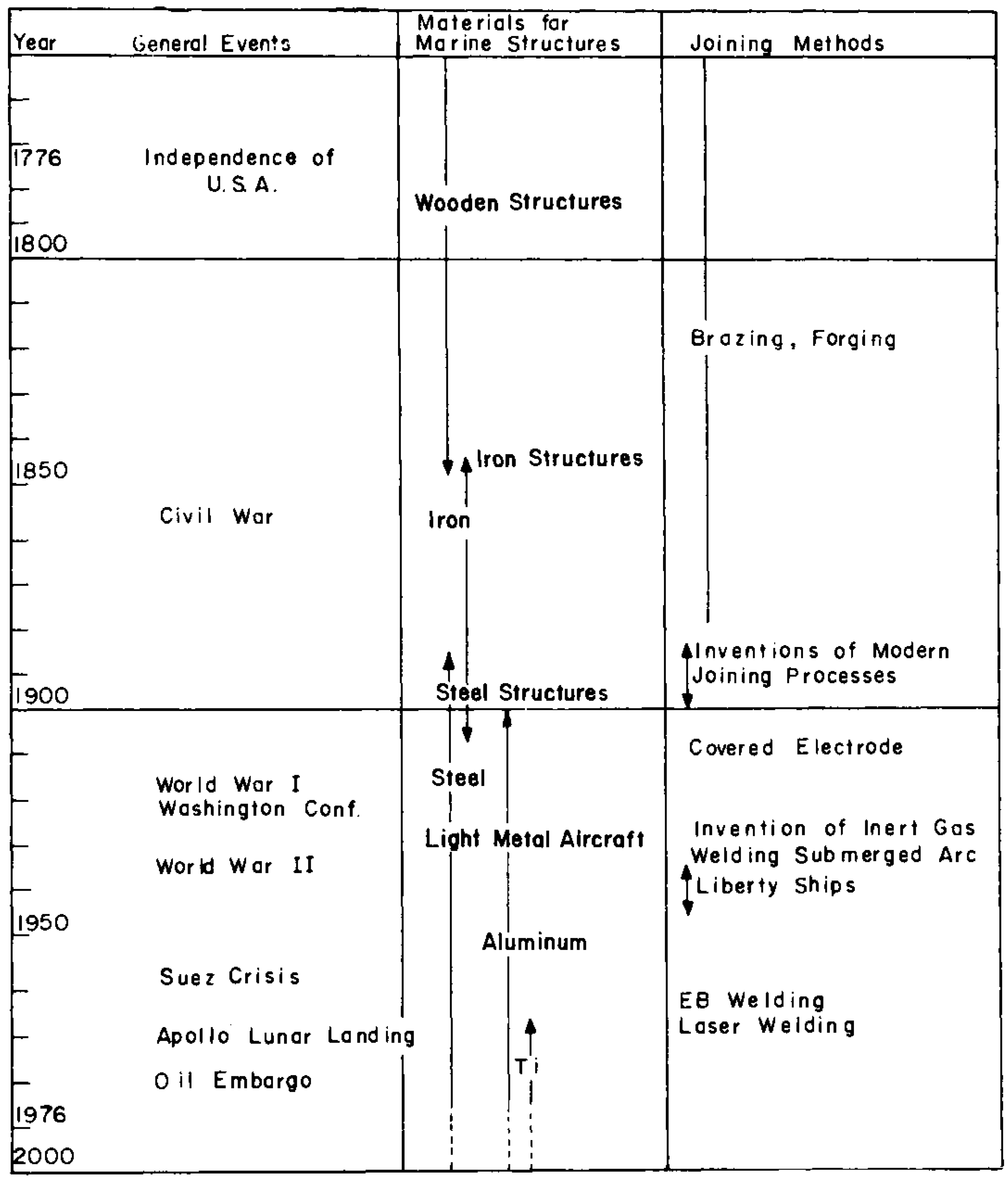


FIG. 1.2. Some major events.

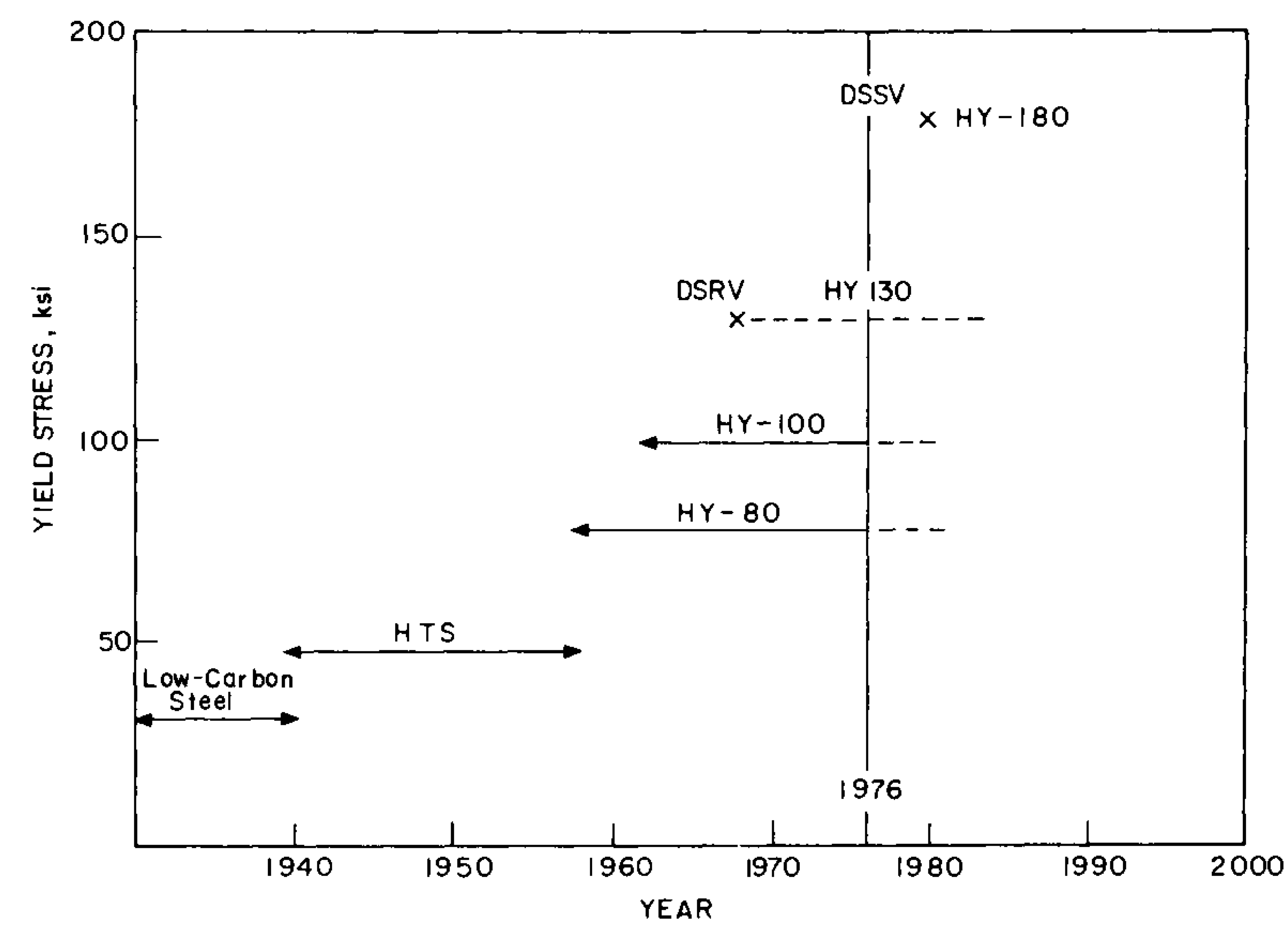


FIG. 1.3. Use of high-strength steels for U.S. Navy submarines and submersibles.

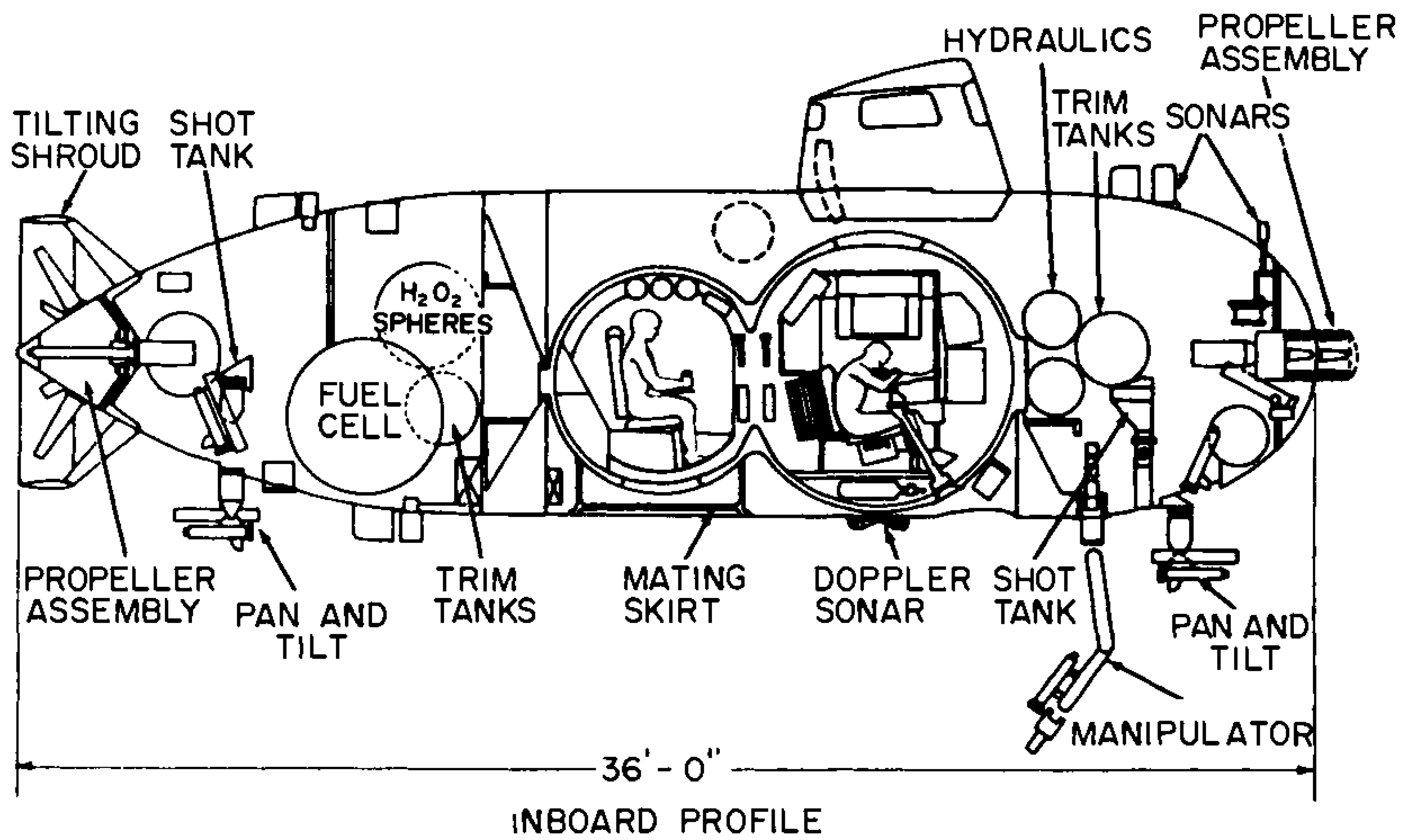


FIG. 1.4. General schematic of 20,000 ft (6100 m) DSSV. This figure is taken from Reference (103). Some design changes may have been made.

steel with a minimum yield strength of 80,000 psi (56.2 kg/mm^2 or 552 MN/m^2) was first introduced to submarine hulls. Some years later HY-100, a steel with 100,000 psi (70.3 kg/mm^2 or 689 MN/m^2) minimum yield strength and very similar to HY-80, was introduced. Today, HY-80 and HY-100 are the basic fabrication steels for submarine hulls.

The next steel in line is HY-130. This steel was first called HY-140; however, it was discovered later that only 130,000 psi (91.4 kg/mm^2 or 896 MN/m^2) yield strength can be guaranteed in the welds. In 1969 the first Deep Submergence Rescue Vehicle (DSRV) was fabricated by Lockhead Missile and Space Company using HY-130. DSRV is capable of diving to a depth of 6000 ft (1830 m). The U.S. Navy plans to use HY-130 for submarines in the next decade. The U.S. Navy also has a plan to build Deep Submergence Search Vehicle (DSSV) with a depth capability of 20,000 ft (6100 m). The material being considered is HY-180.

Figure 1.4 is a general scheme of the DSSV which is designed to operate at the maximum depth of 20,000 ft (6100 m).[103]

Applications of high-strength steels to commercial structures, including ships, bridges, and pressure vessels, occurred several years later; and most applications have been limited to steels up to 120,000 psi (84.4 kg/mm^2 or 827 MN/m^2) yield strength. Besides the Navy's HY-80 and HY-100, there are a number of commercial quenched and tempered steels such as ASTM A514/517. These steels have excellent fracture toughness at low temperatures and they have been extensively used for various structures.

So far, attention has been placed on development of high-strength steels. Another important development involves materials with excellent fracture toughness at cryogenic temperatures primarily for tanks for liquefied natural gas (LNG) carriers. Table 1.1 list several tank systems developed to date.[101] The most important feature from the viewpoint of materials and welding technology is the cryogenic tank. Ferrous alloys which have been used include:

9% and $5\frac{1}{2}$% nickel steel,
Austenetic stainless steel,
36% nickel steel (Invar).

TABLE 1.1. Tank systems for LNG Carrier.

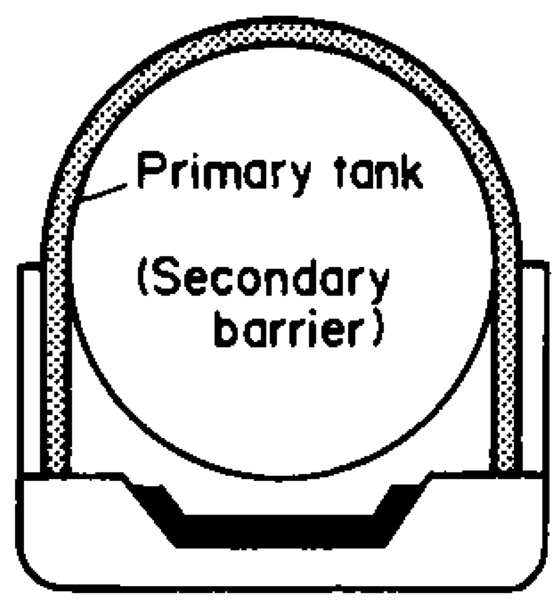
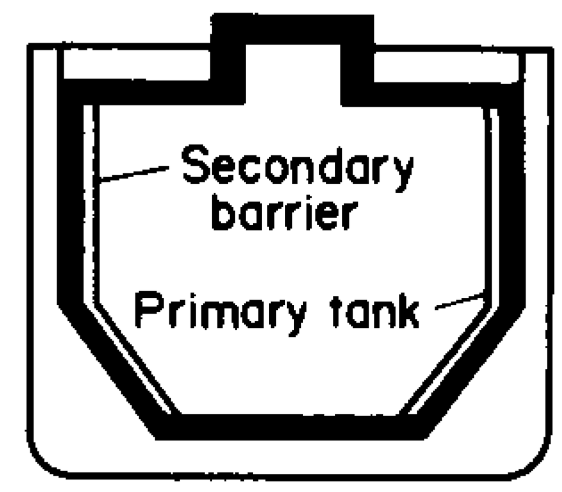
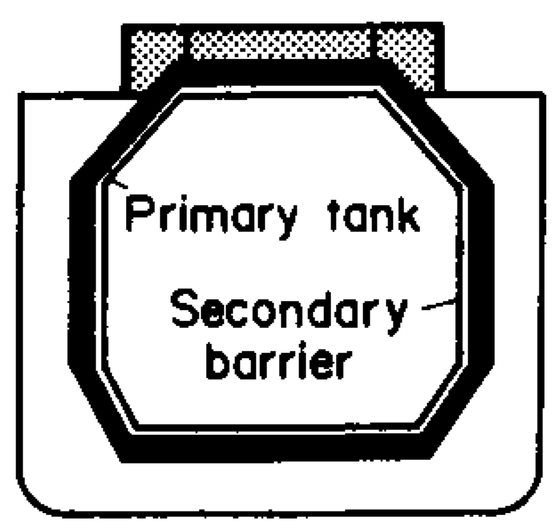
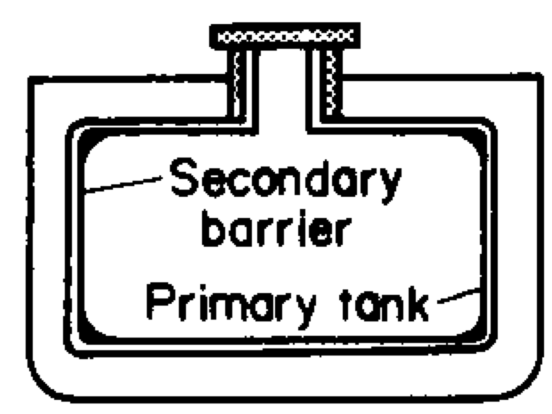
Tank system	Independent tank					
	Spherical type			Square type		
Midship section						
Licensee	Moss-Kvaener	Techni-Gaz	Gaz-Transport	Conch	ESSO (single tank)	ESSO Conch (double tank)
Tank material	9% Ni steel and aluminum	9% Ni steel	9% Ni steel	Aluminum	9% Ni steel	Aluminum
Midship section						
Licensee	Techni-Gaz	Gaz-Transport		Bridgestone Liq. Gas	Ishikawajima-Harima	
Tank material	Stainless steel	36% Ni steel (invar)		9% Ni steel and aluminum	Aluminum	

FIG. 1.5. Surface effect ship-SES 100.[101]. This photograph shows SES 100, a 100-ton surface effect ship completed in 1975 by the Bell Aerospace for the U.S. Navy. This ship cruises at a speed of over 80 knots. The U.S. Navy plans to build surface effect ships as large as 2000 tons with a crusing speed of 100 knots.