NRL Report 6167

Status and Projections of Developments in Hull Structural Materials for Deep Ocean Vehicles and Fixed Bottom Installations

Back-Up Report
Undersea Technology Panel
Project SEABED

Edited by

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U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

PREFACE

Project SEABED, the 1964 Summer Study held at the Naval Postgraduate School, Monterey, California, was organized under the sponsorship of the Special Projects Office. SEABED consisted of four main panels, of which one–Panel III–was concerned with Undersea Technology. This panel, under the chairmanship of Dr. A. H. Keil, Technical Director of the David Taylor Model Basin, was composed of a number of sub-panels, including a Sub-Panel on Materials under the chairmanship of Mr. W. S. Pellini, Superintendent of the Metallurgy Division, U.S. Naval Research Laboratory.

This NRL Report represents the input report to the SEABED study prepared prior to the Monterey Sessions by the Materials Sub-Panel and presents detailed basic and applied information on a wide variety of hull-structural and ancillary materials which can be considered for application in submarines and deep-diving research vehicles. The general aims were to define the present state of technology of these materials, to analyze developments that could be projected to the foreseeable future, and to outline the technical effort required to reach these goals. The report is intended to serve as back-up material for the compendium of other documents emanating from the overall 1964 Summer Study.

This report is, in effect, a compliation of sections covering various topical aspects, prepared by experts in the respective fields. Their contributions are acknowledged by identification of the authorships of the individual sections.

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ABSTRACT

A wide variety of hull structural materials may be expected to compete in the future for applications in both military submarines and deep-diving research vehicles. These include steels, titanium, aluminum, fiber-reinforced plastics, and glass. Additionally, composite construction incorporating different materials may be expected to be competitive. This report comprises a number of separate sections dealing with the state of the art and projections of feasible advances in the related processing and fabrication technologies. Similar dissertations are presented for ancillary materials such as hard sea water piping and buoyancy (syntactic) foams. A unique feature of these sections is represented by the use of "Frame of Reference Charts" which provide a graphical summary of the broad spectrum of strength level and fabrication techniques that may be utilized for the construction of metal structures. This information is applicable also for the construction of fixed bottom installations–of special interest in this respect is a section concerned with the utilization possibilities of concrete.

PROBLEM STATUS

This is the final report of the Sub-Panel on Materials of Panel III, Undersea Technology, of Project SEABED. Other reports resulting from SEABED are being issued by other Navy groups which have participated in this Project.

AUTHORIZATION

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SUMMATION AND INTERPRETATION OF THE MATERIALS SUB-PANEL TOPICAL INPUT REPORTS

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INTRODUCTION

The prelude activities to the Monterey Summer Study provided a unique opportunity for interaction between the various elements of the Navy R&D organization with interests in deep submergence. As prelude activities, the interactions involved a first iteration which provided a basis for the development of input reports which could be expected to serve as source material required by the various panels.

As a summation of the various topical input reports developed by the Materials Panel, this document is aimed at presenting a broad picture of the results of our studies and of their implications. The problems involved in the development of the input material were typical of those faced by any broad front analysis of trends for a dynamic field of development which must be responsive to undesignated sets of future constraints. The first problem was to evolve a suitable course of action for projection of technological developments. One possible course involved assuming certain reasonable sets of possible vehicle constraints with definition of projections for specific materials in these terms. Another possible course involved a "parametric" approach which presents a broad frame of reference of the potential improvements in fabrication capabilities for all materials of interest. This course does not assume constraints dictated by specific future choice of vehicles or specific funding limitations for conducting the R&D effort. The only constraints imposed by such parametric projections involve those of "pure" technical logic with definition of confidence levels. Funding aspects are considered only in terms of rates of effort that do not exceed the capabilities for logical definition of progression of the R&D effort.

The requirement for developing projections which cover the broad scope of deep ocean technology clearly designated the parametric approach as the only practical course of action. The results of this approach are reflected in the various "Frame of Reference Charts" (FRC) of the topical input reports. These charts are intended to communicate the essential elements of the projected capabilities for constructing pressure hull structures for a given class of materials over a wide range of strength levels. A proper interpretation of the significance of the charts requires consideration of the text material which accompanies the individual charts. In utilizing these charts it is essential to recognize that what is represented is feasibility to attain certain technological levels of capability. The actual attainment of such capabilities requires the accomplishing of an adequate level of R&D followed by pilot stage construction trials to serve as a test of the adequacy of the state of knowledge.

It is most important that the full course of R&D activity which leads to confidence in escalation to the construction of specified hull structures be understood. In the absence of such appreciation, the significance of the projections and other matters of vital importance to the purpose of this document will be a source of confusion rather than enlightenment.

ESCALATION PROCESSES IN STRUCTURAL MATERIALS R&D

The final product of R&D in the structural materials area is the structure and its service capabilities to withstand service loading. The strength of a material as measured in a laboratory does not necessarily represent the service strength of the structure. Figure S-1 provides a schematic representation of this fact by illustrating that the base material undergoes a series of degrading processes in translation to its use in a structure. Of this partial listing of degrading processes, it may be surprising to find "environment" and "design" included. This should not be surprising if it is recognized that the structural strength of materials is sensitive to environmental variables and that the allowable stresses which may be imposed on the structure depend on the nature of the environment. Design aspects have a considerable influence by virtue of the introduction of details which cause stress intensification. Such details cause a lowering of the overall (average) effective strength of the structure because failure occurs locally in the region of the detail.

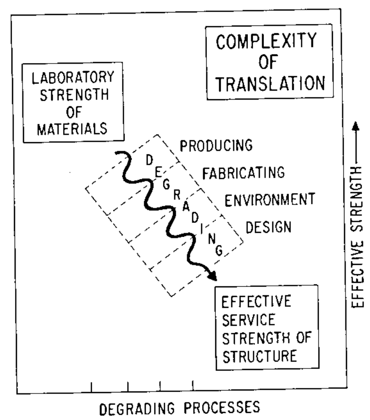

Figure S-1

The attaining of a structure which reflects the basic strength of the material is a problem of alleviating a wide range of strength degrading effects. Accordingly, R&D that is concerned with strength of structures must be concerned not only with maximizing the basic strength of the material, but also with alleviating the causes for degrading of the strength in translation to a structure. All structural materials are subject to an additional adversity – as the strength level is maximized in the direction of the highest levels of laboratory attainability, the sensitivity to degrading processes increases enormously. At some point, the difficulties of preventing degrading become the controlling factor and no advantage can be gained by increasing the basic strength of the material. In great part, the R&D effort on structural materials has to be aimed at developing a balance between improving the basic strength of the material and improving other properties that serve to offset degrading effects. In many cases materials must be improved intentionally in the direction of being less sensitive to specifically serious degrading effects, rather than solely in the direction of increasing strength.

Construction and use of a structure is the final escalation step in the R&D process and as such provides the ultimate test of the effectiveness of the R&D. It is apparent that using the structure as the "final" test specimen is an extremely costly process that has been resorted to only under certain conditions of hardware development for which time limitations were of paramount importance. Rocket case structures have been developed by such procedures of full escalation experimentation. We may define "full" escalation as the "big step forward" in the tryout of the existing R&D knowledge when management "pushes the button" and provides the funds for a full scale-up. While there is time for R&D in successive steps of evolution, the escalation process must be envisaged as a progressive series of stepwise increases in the development of knowledge relating to the effective strength of anticipated structures comprised of the material of interest. The following steps present a logical course of action in the development of capabilities for fabrication of hull structures:

(1) Exploratory research in laboratory properties of materials of higher strength potential.

(2) Tests of "laboratory structures," i.e., configurations such as welded plates, rings of GRP, etc. Additional degradation aspects may be introduced by use of notches, stressing in saline environment, fatigue, etc.

(3) Construction and tests of "structural prototypes," such as small models of different designs. Design degradation aspects are thus combined with production and fabrication degradation aspects.

(4) Scale-up to laboratory tests of thick sections followed by model tests of larger dimensions.

(5) Translation of the fabrication process to a "yard" (non-laboratory activity) to evaluate the practicality of the research laboratory results. This step should involve laboratory teams working with production teams for purposes of education and training.

It should be understood that all of the foregoing steps are conducted with continual iteration with research laboratory elements specialized in three specific areas:

(1) Specialists in the basic properties of materials.

(2) Specialists in the analysis of macroscopic and microscopic modes of failure of materials.

(3) Specialists in failure criteria of structures.

The importance of these iterations is emphasized by the illustration in Fig. S-2. The crucial connecting link between the basic material and the structure is the R&D activity concerned with developing a broad base of knowledge of the failure modes for the specific materials and the significance of these aspects to structural performance. The relationship

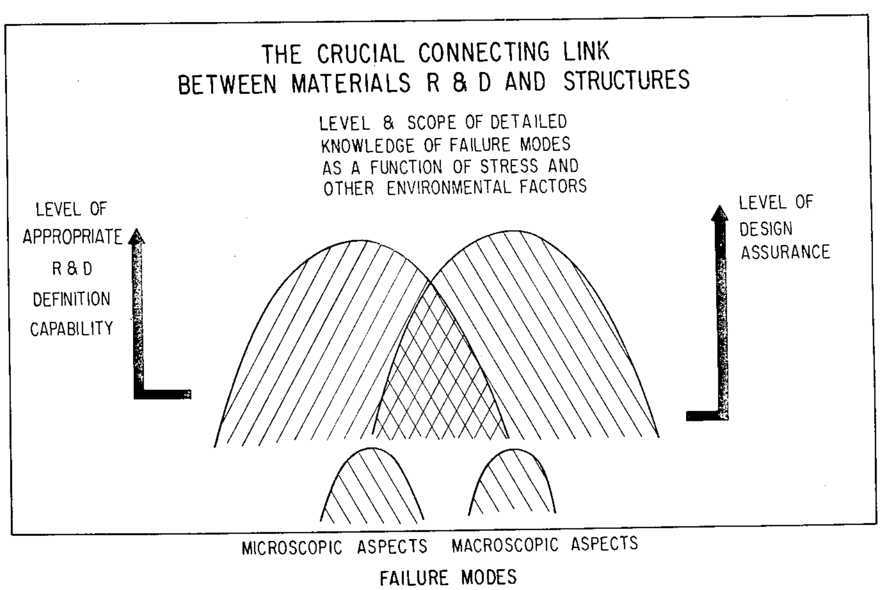

Figure S-2

to design assurance involves the stress level at which the failure modes become operative. The relationship to materials R&D involves the selection of appropriate research activity which contributes to the solution of the basic deficiencies of the materials.

The FRC projections which were evolved by the input studies were based on a logic of anticipating a stepwise escalation of structural testing and materials R&D to a practical point of establishing assurance of the feasibility of the final escalation to fabrication of structures, by the stated time period. This logic does not extend to anticipating achieving all possible end point escalations. The reason for this is that there are a multitude of possible end points each of which would have specific cost (and effort) totalizations. A simpler way of stating the case is that it is impossible to actually attain the end points without decisions "to go" for a specific construction. The costs of the final states of the stepwise escalations are very large and therefore it is to be expected that near-final and final escalations will be made only in response to actual need for fabrication of a structure.

We may now clarify the nature of R&D program that is needed in the materials area. This should be a program which provides for a sufficient number of preliminary escalation steps to prepare for eventual decisions for final escalation to fabrication of structures. The number and scope of R&D escalation steps that are required prior to the final decision for fabrication escalation depend on the size and complexity of the contemplated vehicle. This is another important aspect which must be clearly understood.

Figure S-3 illustrates the experience with HY-80, which followed a decision to construct large, complex hulls with an inadequate backlog of R&D at the time of fabrication escalation. The fabrication escalation costs which resulted must include the consequent costs of yard difficulties with the fabrication of this material and resulting "ship alts" which were required. It is important to recognize that if the fabrication escalation had been made to smaller submarines of simple construction (say research vehicles the resulting fabrication escalation costs would have been minor by comparison. This

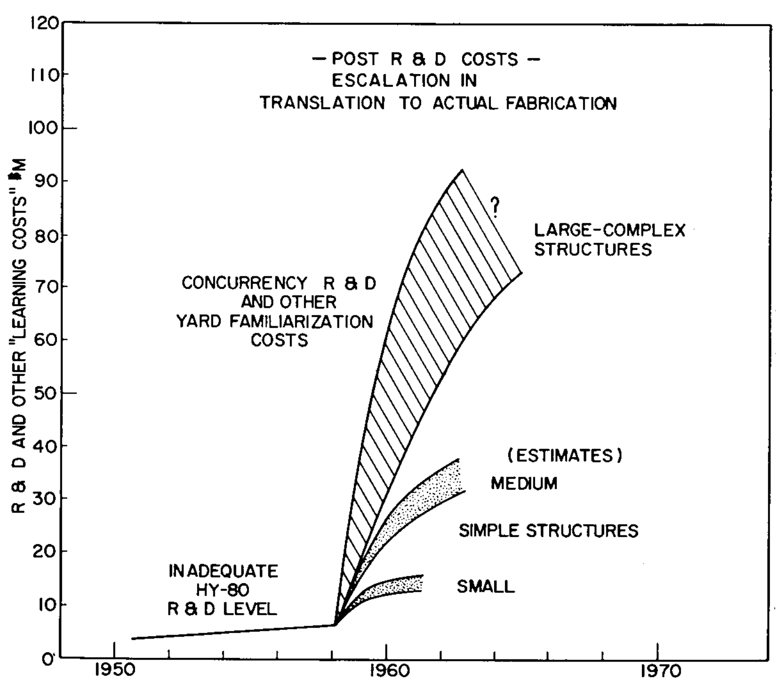

Figure S-3

experience emphasized the fact that an R&D base which is adequate for final escalation to the construction of a simple research vehicle may be totally inadequate for final escalation to a large complex vehicle.

This point is illustrated further by Fig. S-4 which considers other elements of importance to the R&D base required for final escalation to construction. With increasing combination of elements which relate to the size, complexity and load spectrum reliability, it becomes increasingly difficult to use the higher strength level potentials of a given material. In other words, there are practical limits of strength level that can be used with retention of these various structural "premium" items. This situation is represented by the schematic, practical limit curve of the left side of the illustration. For a large structure of high complexity which may be subjected to military attack it may be necessary to restrict the strength level to a low order (point B) as compared to the case of a simple structure which is intended for research submarine use (point A). The R&D base which is required prior to escalation to construction at the point "A" strength (research vehicle) may be of lower level and scope than that which is required for the point "B" (military vehicle) escalation. This is a reversal of what is commonly considered to be the "strength level to fabrication difficulty" relationships. The point of emphasis is that the size, complexity, and spectrum of premium requirements imposed on the structure are of paramount and overriding importance. Unfortunately, this logic is not appreciated generally and as the result inappropriate projections of capabilities for final escalation to fabrication are made for large complex structures, based on evidence of construction capabilities which apply to small structures of simple design.

GENERALIZATIONS RELATING TO THE INTERACTIONS OF MATERIALS AND STRUCTURAL MECHANICS R&D

The previous section emphasized the fact that the level of the R&D base required for escalation to the construction of a specific hull structure is a function of the size and functional spectrum of the structure. It follows (from this thesis) that the attained R&D status of the various materials may be described in terms of the fabrication escalation potential for hull structures of graded size and graded functional spectrum. The "depth" capability of materials at any given time becomes meaningful only if a specific combination of hull structural requirements are defined. For purposes of preliminary discussion we shall consider a schematic relationship, such as illustrated in Fig. S-5. At any given time in the course of developing a broad family of materials having a range of potential S/D ratios, we shall be confronted by restrictions in the escalation possibilities that will be characteristically related to the principal function of the hull structure. As a "broad brush" separation, these have been defined as characteristic hull structures for:

(1) Versatile military vehicles
(2) Specialized military vehicles and versatile research vehicles
(3) Research vehicles
(4) Civil engineering structures

Increasing the totality of requirements that is imposed on the hull structure will generally tend to restrict depth capabilities, as illustrated by the figure. These relationships relate to the full spectrum of S/D ratios that are represented by the various materials under consideration. By definition of specific primary and secondary trade-off elements, a zone of functional aim is defined, as illustrated by the "circled" region of the figure. Within the constraints of these requirements, it is then possible to define the material which best fits the aim of escalating to construction. A specific material may be eliminated from consideration because the R&D base is not adequate for the desired scale-up or for other practical reasons. The point to be made is that by "moving" the "circled" region, different materials may emerge as the best choice for the intended purpose. The choice may be expected to be time-dependent because advances in R&D will affect the

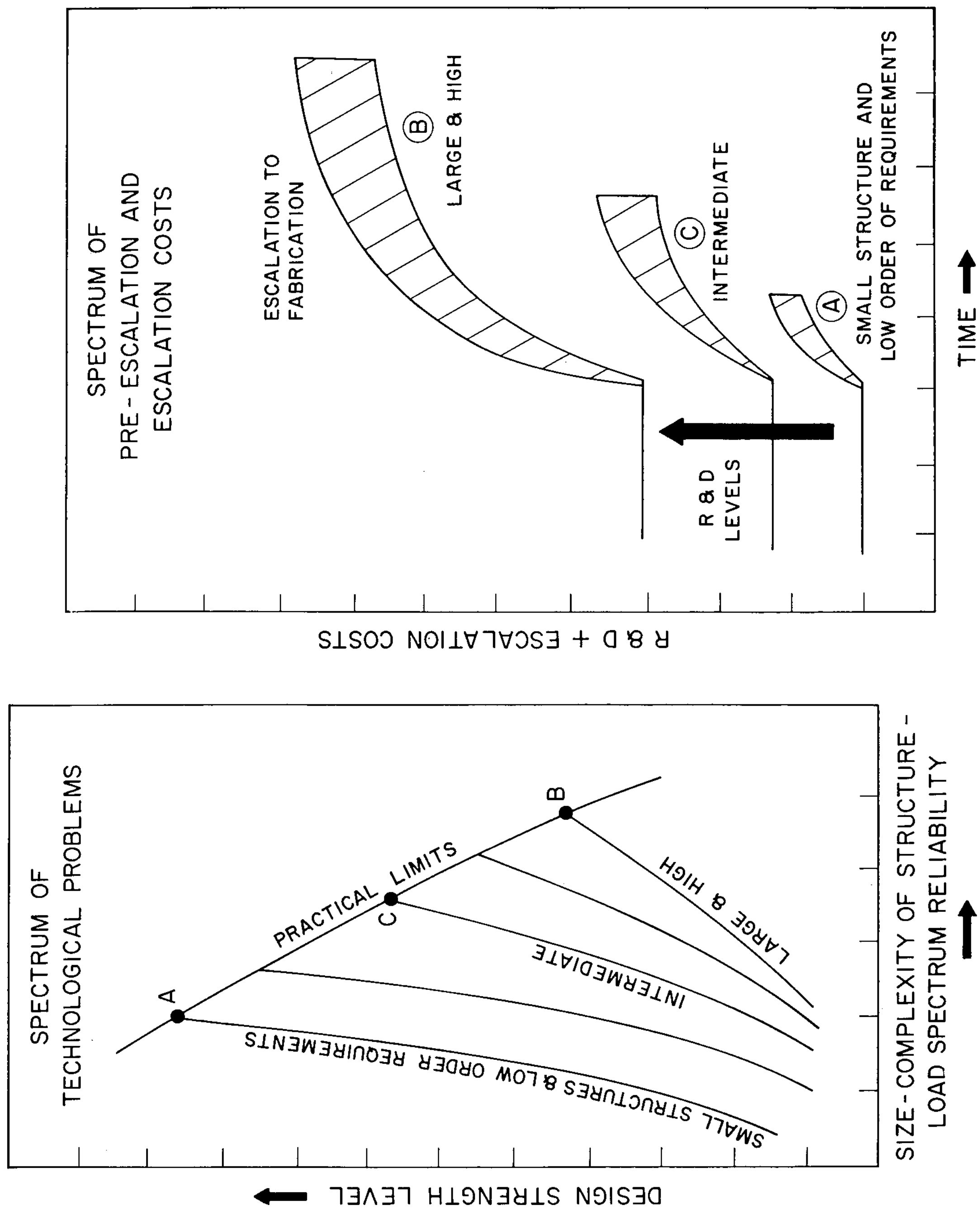
SPECTRUM OF
PRE-ESCALATION AND
ESCALATION COSTS
ESCALATION TO
FABRICATION
B
LARGE & HIGH
C
INTERMEDIATE
A
SMALL STRUCTURE AND
LOW ORDER OF REQUIREMENTS
R & D
LEVELS
TIME
R & D + ESCALATION COSTS
SPECTRUM OF
TECHNOLOGICAL PROBLEMS
PRACTICAL LIMITS
A
C
B
LARGE & HIGH
INTERMEDIATE
SMALL STRUCTURES & LOW ORDER REQUIREMENTS
SIZE-COMPLEXITY OF STRUCTURE-
LOAD SPECTRUM RELIABILITY
DESIGN STRENGTH LEVEL

Figure S-4

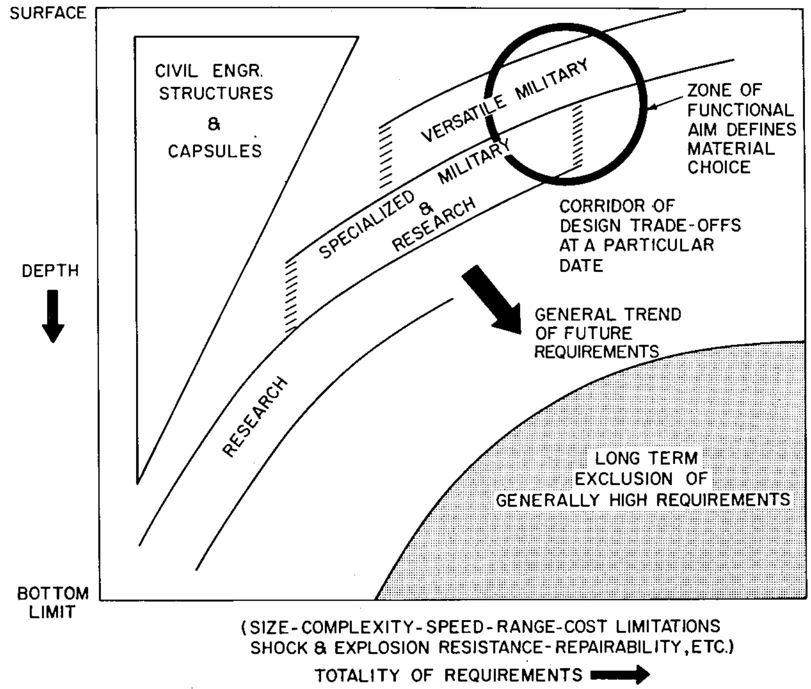

Figure S-5

fabrication scale-up status of materials. As the result, the general trend will be for increases in depth capabilities for a specified set of requirements, as the materials R&D base is increased on a broad front.

From this point of view we may now consider the present state of projections for fabrication use of the various primary materials for hull construction, in terms of the principal elements which relate to the potential for fabrication use, as illustrated in Fig. S-6. These include:

(1) State of design knowledge for the material.
(2) State of fabrication technology for the material.
(3) The basic strength to density ratio capability of the material.

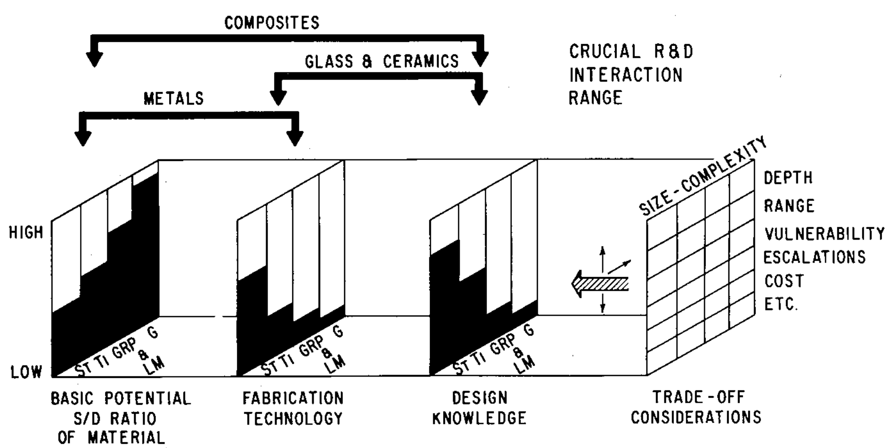

Fig. S-6 - Generalized frames of reference. (Levels depend on size and complexity of structure.)

The present R&D status in these respects is broadly generalized by the respective frame of reference levels for steels, titanium, metal layered construction, FRP, and glass. The composite generalization that may be deduced from these charts is that the near-term status of fabrication technology and design knowledge is inversely proportional to the basic strength of density (S/D) ratio potential of the materials. This generalization holds both across materials and for increasing strength levels of a given material. The R&D problems that must be solved prior to fabrication escalation for high strength steel and titanium are noted (Fig. S-6) to involve primarily the basic metal and fabrication technology. The R&D problems related to layered metal structures and FRP cover the span of basic materials, fabrication technology and design knowledge. The R&D problems related to glass and other brittle materials center in the areas of fabrication technology and design knowledge.

The significance of these generalizations is that the element of design knowledge presents a particularly difficult area of R&D because of the extensive and expensive intermediate structural prototype scale-up steps that must be taken to provide design assurance prior to fabrication of structures. By inclusion of design aspects, the totality of the R&D program that must be performed prior to a major escalation in construction is increased greatly. Unfortunately, all materials that offer the greatest promise for high S/D ratios are in this category. It is illusory to expect attainment of fabrication escalation R&D status for such materials in the reasonably near future, in the absence of decisions for major expenditures in the area of "spin-off" prototype construction. In the absence of such planning and programming, these materials will remain in the category of low level R&D status in that confidence for a major escalation will be absent by virtue of absence of design knowledge capabilities which satisfy the designers requirements for assurance as to structural reliability. The greater the totality of functional requirements that are imposed in the structure the less likely will be the near-term choice of such materials for actual construction, irrespective of the laboratory level (materials) R&D promise shown by such materials. The logical course is to plan for use of such advanced materials first in research vehicles of limited functional requirements. Based on this experience, design confidence for additional scale-up escalations in concurrence with additional R&D would follow.

The state of the art with respect to fabrication capabilities for pressure resistant structures is in its infancy. It may be described as approximately three times the strength level of the steel which was used for construction of the first U. S. Navy submarine, the HOLLAND, in 1898. However, a rapid change could be developed during the period of the next ten to twenty years. How much of a change will actually be attained is a question that involves many considerations. The "envelope of research opportunity" is illustrated in Fig. S-7. The time scale beyond 1970 is purposely not defined. The only assumption involved in this plot is that the higher the level of potential structural efficiency, the greater the difficulty of attainment of design assurance in the reliability of the structure, particularly if of large size. On this basis, the time scale is slanted to indicate a later time of potential attainment with increasing structural efficiency of the material. A dividing line has been placed at the limits of monolithic construction based on macroscopically isotropic materials. This dividing line emphasizes that the time of application attainment of fabrication capabilities for macroscopically orthotropic materials depends not only on the solution of materials R&D problems but also on the solution of classical problems in structural mechanics.

We should be keenly aware that the application of orthotropic composites and highly rigid brittle materials for deep submergence vehicles is without precedent. Although offering future break-through possibilities we must open a virgin field of research and engineering involving design optimization on a full scale basis. The basic elements which provide the S/D advantages simultaneously provide complexities in developing classical equations describing the collapse or other failure modes of structures comprised of these new materials. This is not an argument against consideration of such materials, but

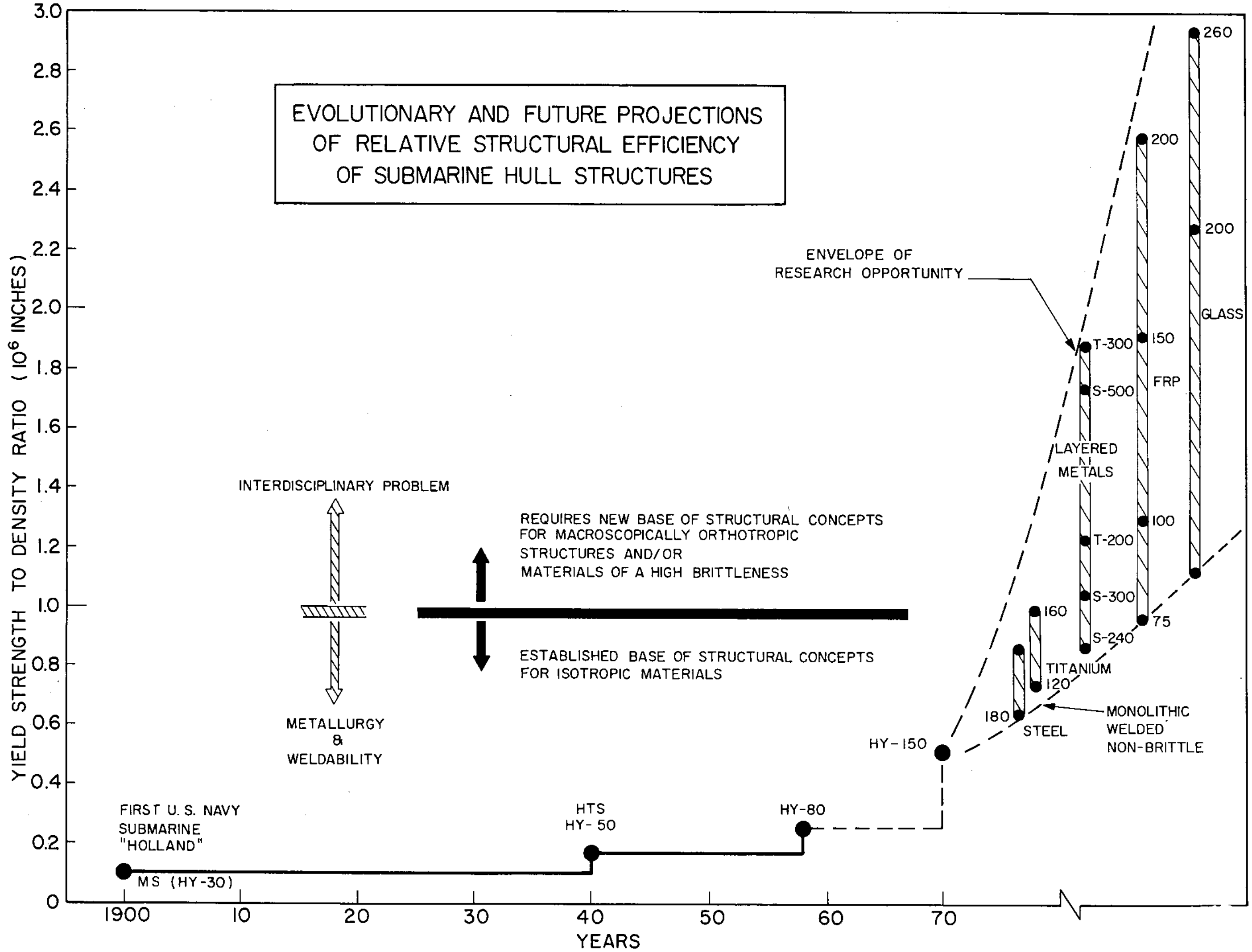

Fig. S-7 - Evolutionary and future projections of relative structural efficiency of submarine hull structures simply an expression of a potential delay element beyond the control of the materials field. It argues that the potentialities of monolithic construction with fracture tough metals must not be neglected because of the future promise of composite construction. At the same time, the intrinsic S/D limitations of monolithic construction with fracture tough metals argue for aggressive research into the possibilities for composite metal construction and composite non-metal construction as well as construction with highly brittle materials. Improvements will be needed for the near-term, for the mid-term and for the far-term period.

These considerations of materials development time-framing and design capability time-framing have a major bearing on the realities of the "logic" extrapolations presented in the FRC charts. While it may be technically "logical" for the materials specialist to present the subject projections of fabrication capabilities, it may not be equally logical to expect that these will become design feasible within the same time frame. The most reasonable view is to consider the materials FRC projections as technically possible in the same sense that a parametric analysis may project that a particular weapon system may be technically possible by a specified time period. The reality of attainment hinges on decisions to expend the required materials and structural mechanics technical effort as an integrated interdisciplinary program. A low level R&D effort which results in developing laboratory capabilities to fabricate and test of small model structures does not provide for escalation capabilities for building of military service hull structures.

SUMMARY OF FRC PROJECTIONS AND OF R&D REQUIREMENTS FOR THE ATTAINMENT OF POTENTIALS

The previous sections have defined the major variables that influence the attaining of capabilities for fabrication of hull structures of specified structural efficiencies. We shall now summarize the technical projection "logic" and the R&D tasks that must be accomplished to attain the state of art expressed by the projections. The coverage will be restricted to points of major issue.

Q&T Steels — The development of fabrication capabilities for constructions of fracture tough military hulls of quenched and tempered steels is paced by development of welding technology. The 1970 projections indicate high confidence T.L. (technical logic) for the attainment of 140-150 ksi* levels by evolutionary improvements in present methods of welding and fabrication. The BuShips R&D program provides R.L. (realization logic) that the laboratory phase of this aim should be completed by 1966. It is necessary that additional funding be expended to translate the laboratory results to practice by a (presently undefined) program of prototype fabrication and yard training. This follow-through is essential for high confidence R.L. for 1970 fabrication of military vehicles.

In the absence of such a follow-through, fabrication escalation feasibilities will be restricted to simple structures for research applications and to civil engineering structures.

Possibilities for realization of fracture tough, welded fabrication of higher strength steels resulting from the development of improved welding procedures are rated as having a reasonable T.L. confidence level. It is unlikely that the laboratory R&D phase will be completed in time for realization of fabrication escalation capabilities for large military structures by 1970. For the 1980-85 period the projections for 200 to 240 ksi fabrication are a reasonable possibility on both T.L. and R.L. bases. Construction at 200 to 240 ksi strength levels, for small research submarine by the 1970 period has a reasonable

*Note: Strength levels are cited in terms of yield strengths for metals and ultimate fracture strengths for non-metals.

possibility on both T.L. and R.L. bases. The R&D requirements for attainment of R.L. confidence primarily involve prototype fabrication and yard training similar to that which has been defined for the 140-150 ksi level.

Fabrication based on brittle steels to strength levels as high as 260 ksi (large structures) and 300 ksi (small structures) has a relatively high T.L. feasibility. However, the R.L. feasibilities must be rated as low for 1970 period and possibly for the 1980-1985 period for the case of military vehicles. The structural mechanics R&D effort required to attain design confidence is relatively large in comparison to the expected pay-off if equivalent effort is applied.

Maraging Steels — The primary potential advantage of these steels (or cross-breed variations of Q&T steels) lies in the possibilities that are provided for fracture tough, 180-200 ksi fabrication based on evolutionary extension of present welding procedures and yard practices. A reasonable T.L. possibility exists for this attainment by 1970. However, considerations of R.L. suggest that fabrication escalation by 1970 would, at best, be limited to small structures of simple design. This conclusion derives from the insufficiency of time for first evolving laboratory R&D solutions and then following through with a prototype and yard training phase. Because of the uncertainties involved with the basic R&D phase of these materials, it is not feasible to extrapolate to the 1980-85 period.

Fabrication capabilities based on ultra-high strength, brittle maraging steels may be summarized in the same terms as cited previously for the Q&T steels.

Titanium Alloys — The promise of large structure fabrication fracture tough titanium alloys of 110-125 ksi strength level for the 1970 to 1980 period should be compared with that of steels of the 180-220 ksi strength range. Such comparisons indicate a markedly higher T.L. confidence of attainment for the titanium alloys. Discussions of R.L. factors are unavoidably concerned with cost aspects related both to R&D costs and fabrication costs of the structure. The R&D cost aspects have been considered in considerable details and with considerable debate. The best assessment that can be made is that the R&D costs may be roughly 1-1/2 to 2 times those of the high strength steels. However, offsetting this extrapolation is the higher T.L. confidence (as projected presently) in the attainment for titanium as compared to the high strength steels. Considerations related to costs of the structure will resolve strictly to the importance of attaining specific depths in comparison to other functional aspects. Beyond a certain depth, limitations in what may be "traded off" for a military vehicle may exceed the capabilities of 150 ksi steel. At this point, the increased cost of titanium construction must be accepted if the related depth is required. We must conclude that the R.L. confidence for titanium construction of large military submarines by 1970, 1975, or 1980 hinges entirely on the date of the decision to attain specific depths. Following such a decision it will then be necessary to plan for prototype and yard familiarization programs. In the absence of such a decision to proceed toward a fabrication escalation R&D point, the R.L. potentialities of titanium construction will be restricted to small research submarines.

Within the next two or three years it should be possible to make a firm decision on the potentials of 180-220 ksi fabrication for steels. Such a decision is not possible at this time. During this interval there should be an aggressive accelerated program for exploitation of the fabrication potentials of titanium alloys. There is a danger that a delay in acceleration of this program because of concern on the ultimate cost of the titanium structure will result in a delay in attainment of potentially required depth capabilities for military vehicles in the middle or late 70's.

Fabrication based on brittle titanium alloys presents the same relatively high T.L. confidence and low R.L. confidence as expressed for the steels. The structures could be fabricated; however, design confidence in such structures cannot be developed in the absence of a major program of related structural mechanics, R&D and prototype fabrication. It is unlikely that this effort will be justified in view of other possible routes of materials development for large military submarines.

Aluminum Alloys — Projections for welded fabrication of large diameter hull structures clearly indicate limited S/D capabilities in comparison to high strength steels and titanium alloys. The major problem involves a relatively low S/D ration for materials that can be welded in massive sections. By considering strong alloys of 60-70 ksi yield strength which require bolting or cementing construction, attractive capabilities are indicated for small diameter hull structures. The problems involved in such construction relate to design assurance that the base strength of the material will not be degraded to low levels by the structural details.

The T.L. aspects of the FRC projections are largely reduced to low level R.L. confidence because of the relatively major R&D effort required to attain a relatively low pay-off potential.

Metal Layered Metal Construction — The S/D potentialities of steel and titanium layered construction clearly exceed those of the thick-section, brittle materials of the same metals. The fracture toughness of thin plate material, as well as producibility and fabricability clearly outmatch those of the heavy sections. The problems involved in the use of such structures are typical of composite materials — a new base of design knowledge is required. The principal problem involves the analysis of the mechanical behavior of such structures in regions subjected to shear loads. A high T.L. confidence for projection of fabrication capabilities of such structures of large size may be based on the considerable experience in industrial fabrication for internally pressurized vessels. In visualizing such construction it is not necessary to consider the same metal or the same yield strength for each concentric shell. In fact, orthotropic properties in the thickness directions may serve as a means for optimizing the structural performance, particularly with respect to fracture toughness.

Because of the time element involved in developing design experience and criteria for the utilization of such structures, a low R.L. confidence is expected for the near-term future. Active research and development should provide for fabrication capabilities in the late 70's and in the 80's. For the near-future, it is essential to explore these possibilities on a laboratory scale. As for all cases involving the establishment of a new design base, it will be necessary to expand this research activity to large structural prototypes before escalating to large scale fabrication. Thus, the attainability of the T.L. projections become highly dependent on decisions to enlarge such a program with the aim of specific escalations.

Fiber Reinforced Plastics -- The S/D advantage of glass reinforced plastics (GRP) provides for attractive T.L. projections of attainments in the fabrication of hull structures. These projections indicate that large, thick-walled structures could be fabricated. Active laboratory research in this area indicates that new combinations of fibers and plastic matrices offer additional future advantage. At the same time, tests of small models indicate that new design concepts must be developed to achieve structural efficiencies which are not grossly degraded in comparison to the laboratory test values. The shear failure modes through the matrix of these materials are unique and new experience must be evolved in developing composite materials which are customized to alleviating the degrading effects of the characteristic shear failure mode. In general, the development of shear failure through the matrix material occurs at points of shear stress concentration. The usefulness of such structures are greatly dependent on the development of new structural concepts and on the evolution of a related R&D base in structural mechanics. The final structure is generally conceived to represent sections of GRP bonded together with or without the use of metal inserts. Ports and openings are generally conceived to involve the use of metal inserts. Thus, the structure as a whole is represented as a macroscopic aggregate of materials having widely different mechanical properties such as strength level, modulus, ductility, etc. The rudimentary design knowledge which suffices for present construction of monolithic structures composed of fracture resistant metals is totally inadequate for design of such mechanically complex structures.

It is crucial to the development of confidence in the escalation to fabrication of such structures that an extensive program of structural prototype testing be placed into effect. In the absence of such a program, the laboratory R&D promise of FRP materials will remain as a continuing tantalizing source of interest and projections of structural capabilities which do not have R.L. substance. It is not conceivable that sufficient interdisciplinary R&D of such scope can be accomplished to justify escalation to large hull structure construction by 1970..

Escalation to construction of specialized research vehicles of structural designs which are optimum for GRP construction is a major requirement for advancement in the utilization of these materials. The structural efficiency that is attainable for GRP will be determined by such trial escalations. The major missing elements in all present evaluations is the degree of degradation from the laboratory measured strength levels that must be accepted in translating to structural use. Other important questions to be resolved are the spectrum of loads that will be acceptable by such structures and the long term reliability of the material in the service environment.

Monolithic Glasses — The construction feasibilities for such structures involve questions of fabrication and design concepts that will assure the absence of tensile stresses, at depth and at the surface. R&D for the base material appears to be of minor importance in this context because of the laboratory measured compressive strength to density ratios are reported as extremely high. In fact, the theoretical levels have not been achieved in the laboratory because of difficulties in "idealizing" the test conditions. In the absence of laboratory structural test studies of the performance of other than simple spheres, it is not possible to estimate the R.L. potentials of these materials for the construction of practical hull structures. Because of the great promise, it is essential that such studies be conducted as guidance for the future course of R&D action. These materials are definitely in the first stages of laboratory evaluation and should not be subject of serious extrapolation as to fabrication capabilities in the near-term future.

Proposed R&D Program — Definition of a five-year, materials R&D program which best serves the interest of developing a broadly based deep ocean technology (DOT) was a principal requirement of the prelude activities to the Monterey Summer Study. Such a program should provide for the development of a technological base from which reasonable escalations to fabrication of various types of hull structures could be made. In other words, it should provide for a systematic evolution of a reasonable base for designers "choice" in the future. With reference to the foregoing discussion it is apparent that the attainment of escalation capabilities at the end of the five-year period will be limited by the level of R&D that has been expended fruitfully during this period. By virtue of the present state of development it should be expected that some materials may be developed to escalation possibilities involving relatively large structures for military use while others may be fruitfully developed only to the point of escalation possibilities for small structures of simple design, intended for research use. For each class of materials the relative strength level should be considered as a projection variable in these respects.

The evolution of such a program should proceed following a deliberate plan which may be modified by perturbations arising from specific systems and vehicle projections, only as these increase the effort in specific areas without simultaneously reducing the general exploratory effort commensurately to low levels. If such perturbations are permitted to dislocate the proposed plan, the broad objectives of the DOT program will not be achieved.

It is assumed that the logical time for perturbation increase of specific rates of effort should be the point at which the then developed R&D base indicates that the attainment of anticipated major escalations is feasible. It is also assumed that none of the materials of major interest will be carried past the point of escalation potential for the construction of small structures of simple design without the application of such an accelerating perturbation in the R&D effort. The basis for this assumption is that the final drive for the attainment of "yard" fabrication capabilities for a large structure is sufficiently expensive to preclude such attention on a broad front. In general, the distribution of the broad base R&D effort in DOT should be in preparation for future escalation decisions in proportion to the promise of positive results from such an action.

A totalization of the R&D funding estimates provided in the topical input reports indicates a five-year total somewhat in excess of $150M.* This total does not include the cost of large scale prototype construction or "spin-offs" which (to various degrees) are essential items preceding escalation to fabrication of large structures. The $150M figure may appear to be high but this is because so little has been spent in the past for purposes of developing a broadly based DOT. It should be noted that it costs approximately $150M to develop a new jet engine, and we are faced with far greater difficulties.

The next five years should be recognized as the coming to an end of an era of evolutionary development of materials for deep submergence structures. This point will be reached with the attainment of the objectives of the BuShips HY-150 steel program. The cost of the laboratory R&D program for this development are in the order of $5 to $6M. The additional costs for prototype evaluation and yard training could increase this figure to approximately $12 - $15M. For the new materials the R&D costs for attaining a similar end point are estimated conservatively as in the order of $25 to $35M. These figures do not include the costs of major structural "spin-offs" or of capital investment required for new shipyard facilities.

A reasonable plan was developed (in consultation with G. Sorkin and E. Bukzin of BuShips) which entails considering all of the promising new materials in a "laboratory phase" of R&D during the first three years. A decision to increase the effort in preparation for major escalations to follow, would be made at the end of the third year based on the R&D promise of the materials. For example, it could be decided that two materials should be placed in advanced development status and the remainder continued in laboratory research status in proportion to their respective promise. The elements of this plan are illustrated in Fig. S-8.† The "pay-off" of this program at the end of the five-year period will be that two materials could be considered ready for the last stages of escalation for large structural applications and the remainder would have various levels of escalation potentials for research vehicle applications. In comparison to the present level of expenditure ($6 - $7M), the proposed plan involves an increase ranging from two to three times the present rate.

The principal element of this plan is the application of level funding with distribution of effort in the interest of proceeding with the development of a broad spectrum of DOT capabilities. The plan includes all major elements of importance to the development of the pressure resistant portions of the hull structure. Decisions to achieve specific objectives within the specified time period would require an increase in effort from separate funding. Depending on the stage of evolution of the basic plan, it may be necessary to

*As originally submitted (prior to the Monterey SEABED Sessions) this document included detailed estimates of R&D funding requirements for the various elements of the program. These were reviewed and adjusted during the course of the SEABED deliberations and have been made part of the official PANEL III REPORT. Accordingly, on final editing of this document, the preliminary estimates of R&D funding requirements were deleted by the chairman.

†Details of plan deleted on final editing.

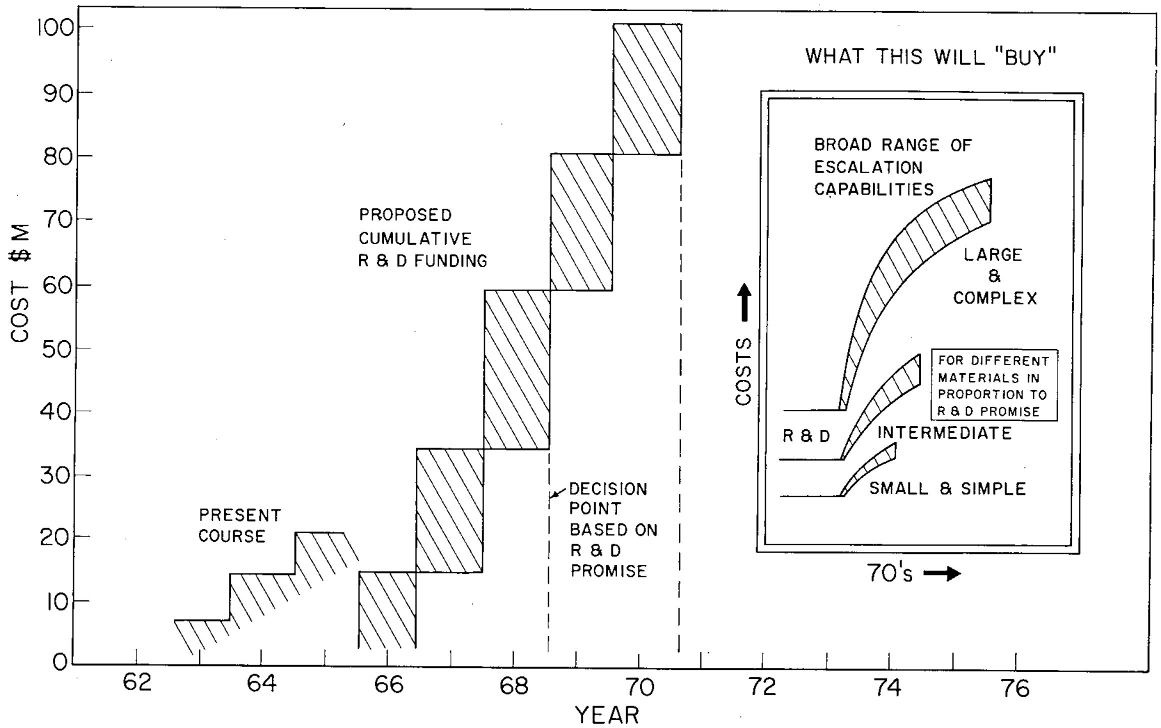

Fig. S-8 - [redacted]

conduct concurrent accelerations for more than one material, if the R&D status indicates that these are closely competitive for the specified objective. As the basic plan matures, such concurrency will become less likely — in fact, this is one of the most important aspects of instituting a broad base R&D effort.

HIGH STRENGTH STEELS

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(A) QUENCHED AND TEMPERED STEELS

Metallurgy

Quenched and tempered (Q&T) steels have been produced in large tonnage quantitie for military applications as plate and forgings; these have included WW2 armor plate ranging from 3-16" thickness and submarine hull steels (HY-80) of 2" to 3" thickness. In addition, a wide variety of industrial plate (of lower alloy contents than HY-80) has been produced since the middle 50's for welded fabrication at strength levels of 100 to 115 ksi.* High strength forgings (such as aircraft landing gears) have been produced in large quantities in the past 20 years at strength levels in the 180 to 230 ksi range and more recently in the 230-260 ksi range.

Plates and heavy forgings are generally heat treated by heating to "austenitizing" temperatures in the 1550-1650°F range and then quenching in water. Quenching is required for the purpose of preventing transformation of the high temperature austenite phase to undesirable microstructural constituents (pearlites and upper bainites) which are the no[illegible]transformation on "slow" cooling through the 1100° to 800°F range. These products have a relatively coarse microstructure and as such have inferior strength and relatively poor fracture toughness. Transformation to constituents which evolve on cooling through the 800 to 500°F range (lower bainites and martensites) is desirable because of their very fine microstructures. These products which are generally referenced as "martensites," are hard and brittle as-quenched and require tempering to develop desirable combinations of strength and ductility. Tempering involves reheating to temperatures in the range of 400 to 1250°F for periods which may range from a fraction of an hour to several hours. The highest tempering temperatures result in the lowest strength and maximum fracture toughness and conversely the lowest tempering temperatures result in the highest strength with lowest fracture toughness, as a first approximation.

The carbon content of the as-quenched martensites determines the strength level which is attained for a specified tempering temperature — the higher the carbon content the higher the strength level. The following tabulation illustrates the general effects of carbon content and tempering temperature on yield strength.

Tempering Temperature

Carbon Content (%)	400°F	800°F	1100°F	1200°F
.20	210*	160	120	90
.40	240	180	130	110
.50	260	200	140	120

*Approximate yield strength - ksi.

*All references to strength level in this section relate to yield strength.

The specific effects of alloy elements such as Cr, Ni, Mo, and Mn on the level of tempered strength are relatively secondary compared to the effects of carbon content. The major importance of the alloy elements is to control the hardenability of the steel, i.e., the section thickness that can be quenched "through" to martensite with avoidance of partial transformation to the undesirable pearlite and upper bainite products. An example involving HY-80 steel illustrates this point:

Approximate Alloy Content Required for "Quench Through"

Plate Thickness (in.)	% Mo	% Cr	% Ni
1	.25	1.0	2.2
3 to 4	.50	1.6	3.0

Processing of plates of 3-in. to 4-in. thickness with the 1-in. plate alloy element composition results in a steel of closely the same yield strength as that of the 1-in. plate but with greatly inferior fracture toughness — in fact, the plates would be classed as "brittle."

For Q&T steels that are intended for welding fabrication and for use in the as-welded state, it is generally necessary to restrict the carbon content to levels in the order of .10 - .20%. This requirement results from the fact that the hardness and relative brittleness of as-quenched martensites increases rapidly with increasing carbon content. The weld HAZ (heat affected zone) which transforms to martensite as the result of rapid cooling from high temperatures tends to develop cracks if its hardness exceeds specific levels which depend on the strength level of the steel and the degree of weld restraint. For this reason steels of approximately 80-100 ksi strength level which are intended for welding of complex structures, normally feature carbon contents in the range of .12 to .18%. For steels of 140 to 160 ksi strength level it is advisable to lower the carbon content further to the range of .10 to .14%. The limitations on carbon content imposed by the weldability aspect requires the use of lower tempering temperatures to develop a specified level of strength (say 150 ksi) than would be the case for a steel of .30 to .40% C. The use of lower tempering temperature tends to decrease fracture toughness, this effect may be countered by the addition of a strong carbide forming element, such as vanadium, for purposes of promoting retention of strength when tempering at a somewhat higher temperature than is normal for a vanadium-free steel of low carbon content.

The 5 Ni-Cr-Mo-V steel which is being developed by the U.S. Steel Corporation for HY-150 submarine hull applications illustrates the practical applications of these principles — a possible composition (exact composition not defined at this time) for 3" thick plates is as follows:

% C	% Mn	% Ni	% Cr	% Mo	% V
.12	.50	5.0	.60	.60	.07

The tempering temperature for developing of 150 ksi strength level is approximately 1050°F. In comparison to HY-80, the HY-150 steel features — slightly lower Cr, higher Ni, the addition of V, lower carbon and tempering at 1050°F rather than at 1225°F.

The development of a steel which is customized to have the optimum combination of strength and fracture toughness for a specific thickness is a relatively direct process based on well established metallurgical principles. However, the determination of optimum welding conditions is a much more complicated problem requiring consideration of weld cooling rates and degree of structural restraint (geometric complexity). As the alloy content (hardenability) and strength levels are increased the optimization of welding conditions becomes more difficult and the utilization of such steels depends on establishing closely controlled limits on welding procedures.

Steels that are not intended for welding feature a gradually increasing carbon content and gradually decreasing tempering temperature (in optimum combination to maximize fracture toughness) with increase in strength level. For the 180 to 220 ksi strength level the typical carbon contents are in the .30 to .45% range. The attainment of yield strength levels in excess of 260-280 ksi is difficult because the high carbon contents required (.50 - .60%) results in the formation of massive carbides. In effect the carbon and alloy elements segregate and therefore, are not effective in increasing strength further. Thermo-mechanical treatments involving hot working in the transformation or the tempering range coupled with the application of cold work may be used to raise the strength level of Q&T steels to 300 - 500 ksi. The need for penetration through the section thickness for the metal working treatments, limits the thickness that may be strengthened by these means. Such treatments are subjects of intensive investigation and the full potential of the processes have not been fully explored.

Section Size Effects

Increasing of section thickness results in a decrease of cooling rates that may be attained on water quenching. These effects may be minimized by increasing the quench efficiency (rate of heat transfer from the plate surface) — for example, spray quenching with high pressure water. However, even for optimum quench conditions, it is unavoidable that the gradual decrease in cooling rates due to increased section, will result in the inability to develop fully martensitic structures within reasonable limits of alloy additions. With proper alloy balance, the effects of increased thickness is that of a gradual decrease in strength level and toughness. The maximizing of strength level and toughness for a specific thickness is also a matter of careful adjustments in melt purity (S, P, O_2, N_2, etc.) and of improvements in rolling and forging practices. These various factors are broadly defined as alloy and process variables — improvements of this type involve the careful application of established knowledge rather than research or invention.

The frame of reference chart (FRC*) predictions, Figs. 1 and 2, illustrate the general effects of section size on the strength levels which correspond to the change from T to B (tough to brittle) properties of Q&T steels. The projections for 1970 are placed at the OMTL (optimum material trend line limit) shown in Fig. A5 of Appendix A. The 1980-85 predictions reflect an additional increment of 20 ksi which is considered a reasonable expectation. In both projections, the material is referenced to high quality processing involving high degree of cross rolling, i.e., closely similar properties in the longitudinal and transverse directions.

Forgings and castings will be required of section thickness approximately two times that of the plate thickness, for purposes of inserts at ports and openings. For forgings, advantage may be taken of directional properties (anisotropy) by processing so that the fiber direction is 90° to the direction of maximum stress. Thus, the direction of highest fracture toughness could be oriented to maximize resistance to fracture of the structure. It is possible that such forgings could be produced with properties superior to those of the matching thinner plates because of the added benefit which derives from the fact the basic geometries tend to be bar-shaped rather than plate-shaped. The faster cooling rates that are developed for bar-shapes would result in improved microstructures and therefore improved fracture properties compared to the same thickness of plates — or similar properties for structurally matching plates of one-half the forging thickness.

For designs of relative simplicity, forgings are generally preferable to castings — the converse is true for complex designs because of the difficulty of forging complex shapes. Castings of high strength steels do not feature the advantage of fiber orientation

*See general explanation of frame of reference charts in Appendix B and fracture toughness discussion in Appendix A.

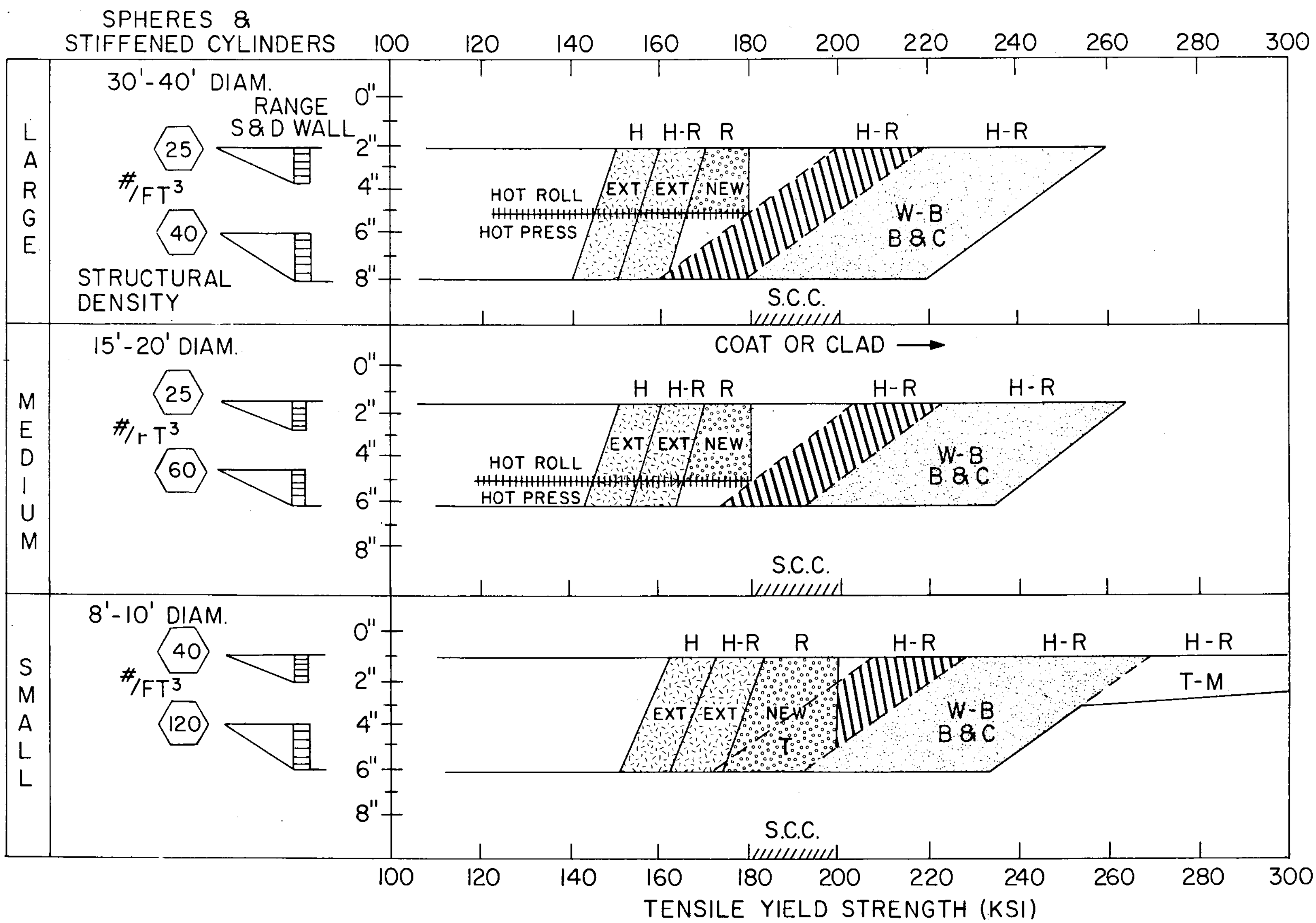

Fig. 1 - Frame of reference chart. Q&T steels -- 1970 forecast.

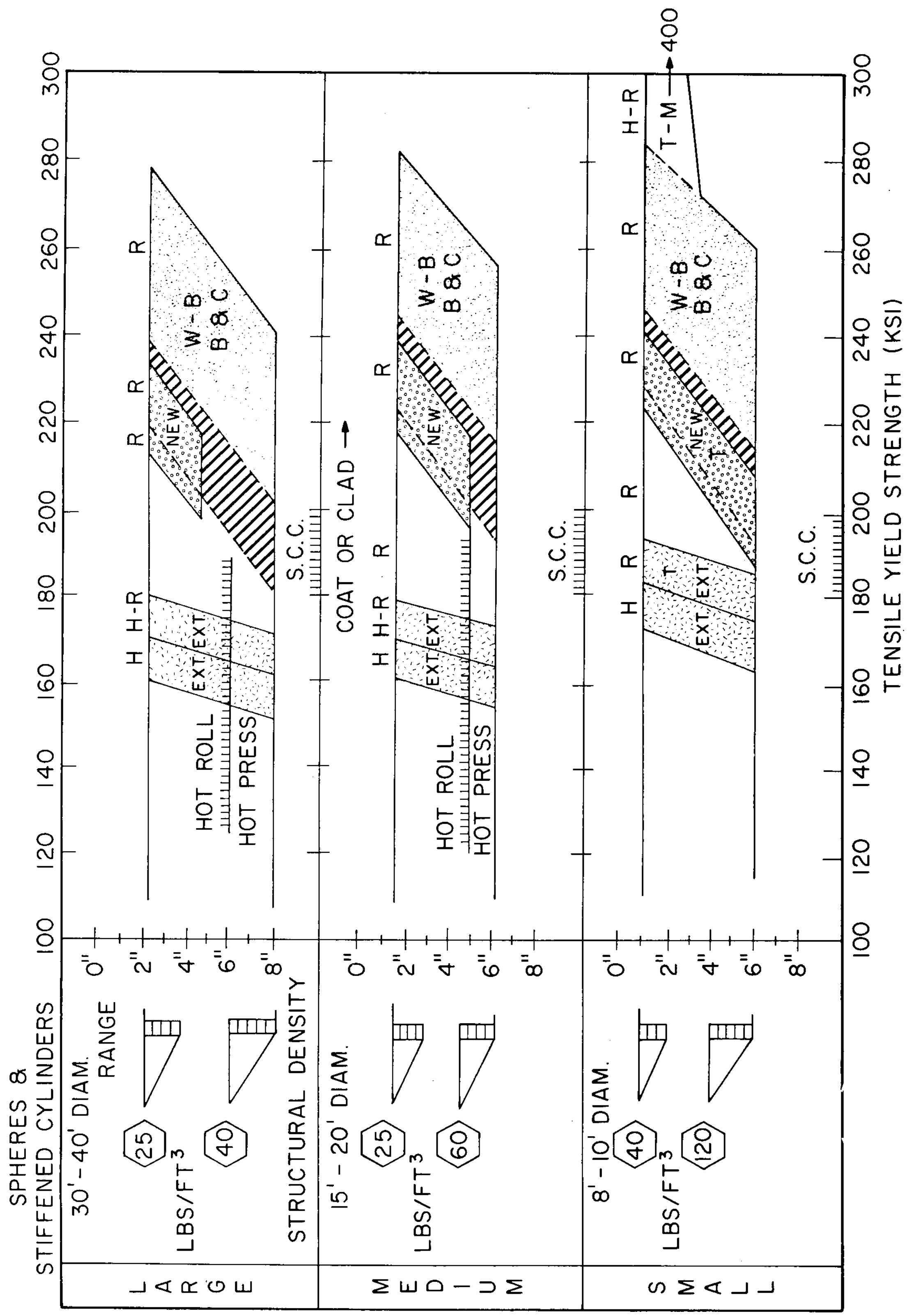

Fig. 2 - Frame of reference chart. Q&T steels -- 1980-85 forecast.

described for forgings. Thus, the possibility of matching or exceeding plate properties with respect to fracture toughness depends entirely on the effectiveness of the geometric quench rate effects. It is likely that with increasing strength level the properties of thick castings would degenerate to levels which are sufficiently inferior to forgings to preclude their use.

Fabricability

The fabricability limits of Q&T steel construction, as defined by the FRC projections, do not imply design acceptability. These limits singly define "what can be constructed" and the fracture toughness characteristics of the construction. For example, the acceptability of a brittle steel welded with a brittle weld or the same steel bolted or cemented is a matter of design decision based on service requirements.

The T-B (fracture tough to brittle) band defines strength levels above which the base steel is brittle — welding of such steel is possible; however, the result is a similarly brittle weld. Forged sections of brittle steel may be bolted or cemented in preference to welding. Such preference may be exercised if welding of specific steels is expected to result in fabrication cracking. Any use of the metal above the "B" line represents the acceptability of a fracture risk, or a decision that the geometric features, stress levels, etc., preclude this risk — this is a design decision.

The bands which define weld fabrication capabilities relate to the fracture toughness properties of the weld metal and heat affected zone and have the same significance as those of the steel, i.e., the band relates to the T-B range of the weld joint. Two types of weld joint are considered, those which represent an evolutionary extension, "EXT," of the welding technology (stick-Mig and Tig techniques) and those which represent new, "NEW," or advanced methods of welding (narrow gap, plasma arc, electron beam, etc.). Consideration is also given to the use of tempering, "T," post heat-treatment for welds which are made by processes which do provide for tempering effects — for example, electron beam welding.

The present state of the art for the welded fabrication of large structures that must be used in as-welded condition is in the 80-110 ksi range, depending on the level of toughness that is required. Recent steel and electrode developments suggest a 1970 capability in the order of 150 - 170 ksi for extension of present welding technology. The utilization of new technology, principally of the narrow gap type suggests 170 - 180 ksi capability by 1970. The 1970 cut-off of the new technology at 5" thickness reflects lack of knowledge as to the applicability of narrow gap welding to heavy sections and not a known lack of capability.

The small diameter structures are given slightly higher limits because it is considered that these could be constructed of hemispherical and ring forgings and that highly precise welding controls could be used. Also, welding could be performed from two sides, thus increasing the section thickness limits. These structures could be welded by electron beam techniques, followed by tempering to soften the narrow martensitic HAZ resulting from such welding.

The 1980 projections reflect an increase in the T-B zone for the base material resulting from improvement in metal processing. This shift provides additional strength range for exploitation primarily by the use of the new welding techniques. Difficulties are expected in raising the limits for the conventional methods by more than 10 to 20 ksi.

It is indicated that the upper limits of weld fabrication are paced both by improvements in base steel quality and by improvements in welding methods. The new welding technology offers the potential of attaining 220 - 240 ksi fabrication limits by 1980-85 period.

The use of shear spinning, ausforming and other thermo-mechanical treatments provides for increase in the strength range of forgings above that provided by simple Q&T treatments. The 1970 projections indicate a 300 ksi potential for sections of 1" - 2" thickness. The potential strength levels of such fabrication may approach 400 ksi by 1980-85 for sections of 1" - 3" thickness.

It should be noted that the 180 - 200 ksi range is defined as the transition zone from relative insensitivity to stress corrosion cracking (SCC) to a condition of high sensitivity. Present information indicated that in the 180 - 200 ksi range the degree of sensitivity depends on the alloy content of steel. Projections of weld fabrication capabilities for 1970 indicate an approach to the limits established by (SCC). However, the 1980-85 projections indicate that welded fabrication capability should extend to and past the SCC range depending on the size of the structure. Thus, the full utilization of fabrication capabilities may require the application of positive protection, which may be attained by roll-cladding a thin layer of SCC insensitive steel having 140 - 150 ksi strength when heat treated with the underlying base metal. The weld regions may then be weld-clad with a weld metal of similar properties.

(B) MARAGING STEELS

Metallurgy

The maraging steels represent a new family of steels that have little similarity to the Q&T steels. The strengthening mechanism involves a precipitation of microscopic particles throughout the matrix as the result of heat treatments commonly known as "aging." In this respect, there is a similarity to the heat treatment of age hardenable aluminum alloys and the precipitation hardenable stainless steels. The "mar" part of the name derives from the transformation to an almost carbon-free, soft and ductile martensite, on cooling from austenitizing temperatures in the range of 1500 to 1900°F. There is no tendency to form undesirable high temperature transformation products (such as the pearlites and upper bainites of Q&T steels) therefore, the cooling rate from the austenitizing temperature is not an important factor. The soft martensite is strengthened (hardened) by aging treatments in the 850-950°F range for periods which may range from 15 minutes to several hours. As is common for precipitation hardening reactions, the resulting combination of strength and ductility is a function of the time-temperature combination used for the aging treatment. High aging temperatures and long aging times promote coarse dispersions of the precipitate particles with resulting lower levels of strength and higher levels of fracture toughness. Low aging temperatures and long aging times generally promote fine dispersions of the precipitates resulting in higher levels of strengths and lower levels of fracture toughness. Various alloy elements may be added for purposes of inducing the age hardening reactions. For example, the addition of titanium to Ni-Co-Mo steels results in the formation of complex Co-Mo-Ti compounds on aging.

The maraging steels are a relatively recent development and the compositions of various grades are subject to modification as new research information is obtained. Representative compositions are listed in the following tabulation:

Developed	% C	% Ni	% Cr	% Co	% Mo	% Ti	% AL	% Cb
25% Ni 1959	.03 max.	25				1.5	.25	.40
20% Ni 1959	.03 max.	20				1.5	.25	.40
18% Ni 1959	.03 max.	18		8	4.5	.4	.10	-
12% Ni 1962	.03 max.	12	5		3	.12	.15	-

The 25% and 20% Ni alloys transform to martensite at temperatures below room temperature; for example, the 25% Ni grade requires refrigeration at -100°F to ensure complete transformation. Interest in these grades primarily relates to applications requiring very high strength with acceptability of relatively low fracture toughness. The 18% and 12% Ni grades completely transform to martensite at temperatures above room temperature and therefore do not require refrigeration treatments. Depending on the alloy balance, the 18% Ni and 12% Ni grades may be heat treated to strength levels in the range of 150 to 250 ksi. By increasing titanium content, the 18% Ni grade may be heat treated to strength levels approximately those of the 25% Ni grade.

For all compositions, fracture toughness generally decreases with increasing strength level. The development of maximum fracture toughness for a specific strength level requires optimizing of the composition and of heat treatment conditions. The optimum fracture toughness for the 150 to 190 ksi strength range appears to be developed by the 12% Ni grade. The 18% Ni grade appears to be optimum for the 200 to 240 ksi strength range. The 20% Ni and 25% Ni grades are designed to develop strength levels in the range of 240 to 320 ksi and have correspondingly lower fracture toughness.

The weld joining advantage that has been claimed for these steels is that the weld and the heat affected zone (HAZ) is "soft" as welded and therefore should not result in cracking. The disadvantage is that the required strength level must be attained by heating the weld region to aging temperatures in the range of 850 to 950°F. For small structures which can be placed in a furnace this is not a problem; however, for large structures it would be necessary to use localized flame or electrical strip heaters. Alternatively, the structure as a whole may be heated by internal application of heat. Recent welding experience with the 18% Ni grade has shown tendencies for the development of subsurface cracks in regions contiguous to the HAZ, due to the presence of macroscopic, sheet-like inclusions which probably reflect the presence of aggregations of complex titanium compounds. These cracks are parallel to the plate surface and apparently become more pronounced with increase in plate thickness. Another problem is the tendency to develop somewhat lower strength properties in the HAZ due to incomplete transformation of the austenite to martensite (austenite stabilization). These effects are reported to be less pronounced for the 12% Ni grade.

The discussions to follow are based on extrapolations of the present types of 12% and 18% Ni maraging steels. It should be noted that intensive studies are underway to develop new families of maraging steels and new types of "cross-breed" steels having alloy features intermediate between the maraging and Q&T steels. The results of these studies cannot be projected at this time.

Section Size Effects

The maraging steels are insensitive to section size with respect to strength properties, but apparently highly sensitive with respect to fracture toughness properties. The basic problem appears to be the growth of large grains which occurs at the high rolling temperatures required for processing thick plates. These steels are much "stiffer" at rolling temperatures than Q&T steels and therefore it is more difficult to "work" the center regions of thick plates at normal rolling temperatures. A possible solution to this problem appears to be the use of press-forging which is more effective than rolling for developing "working" of the metal in thick sections. It is claimed that press forging would permit the use of lower process temperatures and thereby prevent grain coarsening.

The sensitivity to the degree of hot work and to the hot work temperature of these steels indicates that property uniformity in large forgings, and particularly in flat plate forgings, may be difficult to attain. The properties of thick castings have not been established to date; however, section size sensitivity should be expected.

The FRC projections for 1970, Fig. 3, designate reasonable confidence for matching the Q&T steel T-B band to the 5" thickness limits established by hot roll-forming capabilities. The 5" thickness limit also defines the maximum thickness which is expected to be produced by mill rolling of the plates. Thicknesses above this limit are considered to require press forging. The T-B band for materials of this thickness is estimated to be an extension of rolled plate band by virtue of the improvements expected for press forging operations.

The maximum strength level for the 12% and 18% Ni steels of low titanium content, processed as mill heat treated forgings are expected to be similar to those projected for Q&T steels. The 18% Ni grades of high titanium content may be expected to develop a maximum of 300 ksi by conventional heat treatment and possibly 400 ksi by the application of thermo-mechanical treatments. In all cases, strength levels above the T-B band indicate that the forgings may be "produced" and do not necessarily imply acceptability of bolting, cementing or "brittle weld" joining of these for fabrication of a structure.

Fabricability

Comments relating to fabricability should be assessed with the understanding that the 18% Ni grade was committed (by design choice) to large diameter fabrication of experimental solid propellant rocket boosters of 3/4" - 1" wall thickness and port sections of 2" - 4" thickness, approximately 3 years following initial laboratory development. There is no public record of extensive welding experience of prototype variety which preceded this commitment. The 12% Ni grade was developed in 1963 and attempts to produce this material as plates of 2" - 3" thickness for weld fabrication trials of 8' diameter spheres were made in late 1963 and continued into 1964. Prototype model welding of this grade is expected to be initiated in 1964.

The compositions which have been described as the 18% Ni and 12% Ni grades are the result of the first cursory investigation of a potentially large family of alloys. The subject steels are strengthened, in part, by the addition of .1 to .4% titanium which has a strong affinity for C, O_2, N_2 and S. As the result, significant amounts of inclusions involving carbides, nitrides, sulfides and oxides of titanium have been present in these steels. Moreover, all large heats have been air-melted with practices that may be subject to major revision as experience is obtained. These non-metallic inclusions can significantly embrittle the steel and increase its susceptibility to weld and HAZ cracking. Additions of aluminum also are believed to contribute to embrittlement. Recent experience has shown that improved control of melting and processing practices is effective in reducing the amount and deleterious nature of the distribution of these non-metallics.

Welding experience with the large size, air melted heats of plate and forgings has been disappointing, but understandable in view of the above comments. The non-metallic inclusions have caused small cracks (1/2" to 1") in and near the weld HAZ. These cracks are generally parallel to the plate surface and tend to be located in the center of the thickness. The frequency of cracking increases with plate thickness and it is relatively insensitive to the application of pre-heat. All of these signs point to the presence of undesirable colonies of sheet-like, non-metallic inclusions rather than a basic metallurgical (phase transformation) crack origin. Weld cracking of transverse type has been experienced for the 18% Ni grade with indications that this is the result of fissures representing grain boundary segregation of non-metallic films. It may be summarized that the expected attainment of crackless welding by virtue of the "weld-soft" aspect of the maraging steel has been prevented to date by the nature and distribution of non-metallic constituents.

Projections to the state of the art in 1970 must be based on the possibilities for reducing or eliminating the effects of non-metallic constituents. The development directions apparently involve substitution or reduction of Ti and Al additions, improvement in

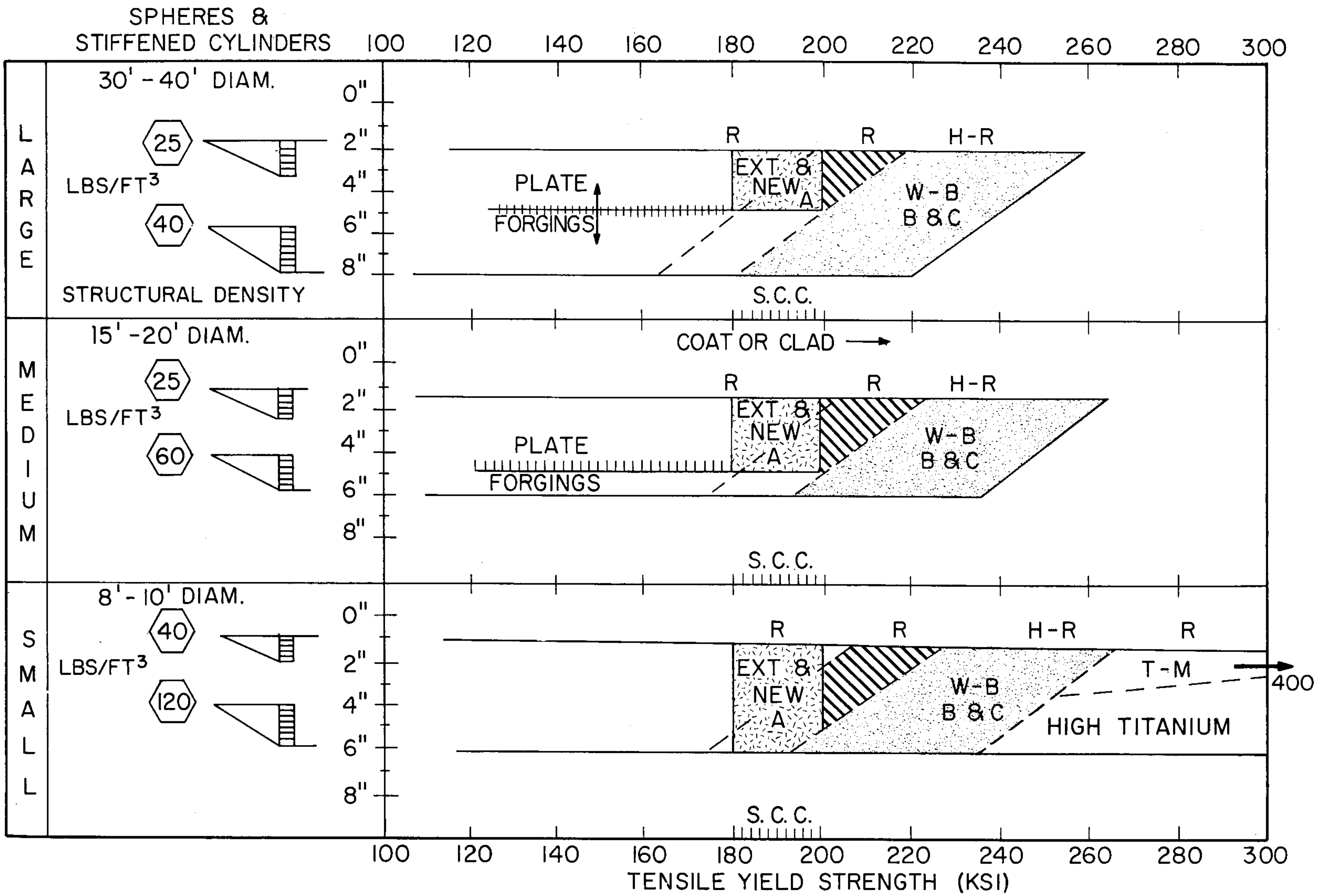

Fig. 3 - Frame of reference chart. MA steels -- 1970 forecast.

melt quality with respect to impurities, and improvement in ingot to plate or forging processing methods. These improvements are most needed for welding procedures based on evolutionary improvements of present methods. The new welding methods may be expected to decrease the dependence on metal improvement. A reasonable projection for 1970 is that metal improvements will provide for acceptable weldability in the 180 to 200 ksi strength range based on the use of improved versions of the present welding techniques (MIG) or of the new welding methods and the application of post weld aging treatments. The thickness limitations for weld fabrication of the large structures have been based on plate producibility limitations rather than on weldability limitations. These projections are rated as involving only reasonable, "R," confidence because of the assumptions for improvement of the base steel as well as on the basis of weldability.

No extrapolations are presented for the 1980-85 period for the described family of maraging steels. Such projections should be based on the expected new families of steels which are expected to emerge, if feasible, during the 1966 to 1970 period. To be interesting, these new types require the attainment of fracture tough weld fabrication capabilities in the 220 - 240 ksi strength range. There is a reasonable possibility that this aim may be attained by the 1980-85 period.

It should be noted that the maraging steels become sensitive to stress corrosion cracking in the same 180 to 200 ksi strength range that was defined for the Q&T steels. The utilization of weld fabrication at this level of strength may require the application of positive protection, which may be attained by roll-cladding a thin layer of SCC insensitiv maraging steel having 140-150 ksi strength when aged with the underlying base metal. The weld regions may then be weld clad with a weld metal of similar properties.

The approximate values of mechanical and physical properties of steels of various levels of strength are summarized in Table 1. These include Q&T, maraging and high purity types of Q&T steels. A more exact definition was not attempted because of the dependence of the ductility properties on orientation with respect to rolling or forging directions. The general trends of fracture toughness with increasing strength level are defined in Appendix A.

Table 1
Approximate Mechanical and Physical Properties of Steels

Type	TUS (ksi)	TYS (ksi)	% EL (2 in.)	% RA	CYS (ksi)
HY-80	103	88	22	65	98
HY-100	118	105	22	65	115
HY-150	165	150	18	60	165
MA-180	190	180	17	58	200
MA-250	255	250	12	50	280
MA-300	305	300	10	50	340
HP-150	162	150	18	60	168
HP-9-4-25	210	200	14	40	225
HP-9-4-45	280	250	8	35	280
4335	230	220	10	40	245
4340	262	250	8	30	280

Density - .283 to .285 lbs/in.^{3} (.287-.292 lbs/in.^{3} for maraging)
Modulus - 29 to 30 x 10^6 psi (28 to 29 x 10^6 psi for maraging)
Poisson Ratio - .33 (.32 for maraging)

(C) FABRICATION COSTS – STEELS

The cost of the base steel may be a major or minor component of the cost of the fabricated structure because fabrication costs are highly sensitive to the design complexity and dimensional tolerance requirements. A comparison of HY-80 costs is indicative of these relationships.

Cost per Pound

Steel Plate	Weldment as Small Cylinder	Weldment as a Test Model	Weldment as SSN or SSBN Structure
\$.28 - \$.30	\$.90	\$3.50 - \$4.00	\$3.00 (average)

With reasonable simplification of the present designs and the use of narrow gap MIG welding (more automatic welding and a decreased volume of weld metal) the hull costs for large submarines could be reduced to approximately \$2.00 to \$2.50 per lb. of weldment. These figures illustrate that it is not possible to discuss costs of construction without defining the design features of the structure and the welding processes – this statement applies to any material.

The cost of Q&T 150 ksi steel has been quoted as approximately \$.50 per lb. Based on design refinements that could be applied to a new class of submarines and the use of narrow gap welding, the cost of fabrication is estimated to be \$2.50 to \$3.00 per lb. The cost of Q&T 180 - 240 ksi steel is expected to be in the order of \$1.00 per lb. The costs for weldments of refined designs which would be required for this material is expected to be in the \$3.50 to \$4.50 range, depending on the strength level.

The cost of maraging steel is in the order of \$1.40 per lb. over the range of 150 to 250 ksi. Projections on the basis of refined designs indicate cost of weldments in the range of \$3.50 to \$5.00 per lb., depending on the strength level.

A major reason for the high present costs of HY-80 welding is the problem of "living with" complex fabrication due to adverse design details. These can be completed only with the application of high artisan skills, high inspection and high rework costs. The worst of these details have been redesigned for other reasons, principally that of fatigue and of delayed weld cracking. If such design details and hand welding methods were perpetuated, the costs of fabrication with high strength steels would be of academic interest – the structures simply could not be built. The improved welding methods and design details that must be relied upon to make the use of high strength materials possible, also must make the costs of such construction reasonable. In other words, high fabrication costs are an index of fabrication difficulty – the fact that design complexity can "skyrocket" costs simply means that it can "skyrocket" difficulties of fabrication. The elements which enter into developing fabrication feasibilities of reasonable scope also enter in developing of reasonable cost levels. If one is not attained, the other is likewise not attained. This does not mean that there should not be a gradual increase in costs for fabrication of structures of higher performance, but that these increases should be within reason if the design characteristics are kept within reason.

(D) R&D REQUIREMENTS – STEELS

The production of steels of the strength levels or thicknesses indicated in the FRC projections does not require the development of a new industry. Industry capabilities for production exist and may be applied interchangeably to the new product or to old products. This statement applies also to forgings and castings. Another significant aspect is that a major effort of upgrading melting and processing practices has been underway in the steel industry. These trends are accelerating under the pressure of economic competition that does not involve deep ocean technology. Thus, the elements of upgrading that are envisaged as necessary for deep ocean technology are already in progress and do not require funding stimulation. One example of these trends is the vacuum carbon deoxidation process by which a ladle of steel is poured into another ladle in a vacuum chamber.

The projections on which the funding requirements should be based are illustrated in Fig. 4. One of the pacing items is noted as the increase in strength level at which brittle characteristics are reached for plates of 2" - 4" thickness (as a point of reference). This level is projected from the present 200 ksi to a future of approximately 240 ksi. This is a conservative projection of the benefits expected from the improvements in melting practices and processing. No funding requirements are assumed for this development.

The present U.S. Steel Corporation contract to BuShips for development of HY-150 is assumed to culminate in 1966 with the establishment of a "LAB" capability for 140 to 160 ksi fabrication, depending on the fracture toughness requirements. A summation of R&D costs for this attainment (including in-house studies of fracture toughness, weldability checks, etc.) indicates a total of approximately $3M. The attainment of "YARD" production capabilities may require several more years of development effort which includes fabrication trials to familiarize yards, large scale prototype construction for fatigue models, explosion tests, etc. At an absolute minimum this phase of "assurance seeking" would require additional costs in the order of $4 to $6M. The minimum grand total thus would be in the order of $7 to $9M. The HY-150 development was based on considerable amount of available information and the chemical analysis modifications of the steel compared to HY-80 are of degree rather than kind. The success of this development will in large measure be creditable to development of improved weld metal — again the modifications in weld metal characteristics represent degree rather than kind. This process of extension of present welding technology for Q&T steels may be considered to come to an end with the attainment of 140 - 160 ksi fabrication capabilities. The most optimistic projections of continued extensions of present welding technology beyond this point represent marginal gains and as such are <u>not</u> projected.

The next level of potential attainment (for 2" - 4" wall thickness) is that of the 210 - 230 ksi range. This attainment may follow one of several possible routes, including:

(1) Application of new welding technology to Q&T steels.

(2) Application of new welding technology to new types of maraging steels or crossbreeds between the maraging and Q&T types.

(3) Extension of present welding technology to the new steels.

Because of the multiple paths available the possibilities of attaining this level of strength are reasonably good. The funding requirements for the FY 66-70 period are considered to involve explorations of these various avenues with a narrowing to a single, most promising avenue by the late 60's.

The potentialities of layered construction are particularly noteworthy. If this method of fabrication is structurally acceptable, customized fracture toughness could be provided by the layering of brittle and fracture tough steels. Such combinations could conceivably provide for a jump to 300 ksi and eventually to 500 ksi. Layered construction would capitalize on the developments of new welding technology and ultra high strength, thin plates required for first stage rocket booster applications. If conducted in parallel with the exploration of new steels and new welding technology for monolithic fabrication, the layered metal program could be advanced by modest expenditures for a period of three years.

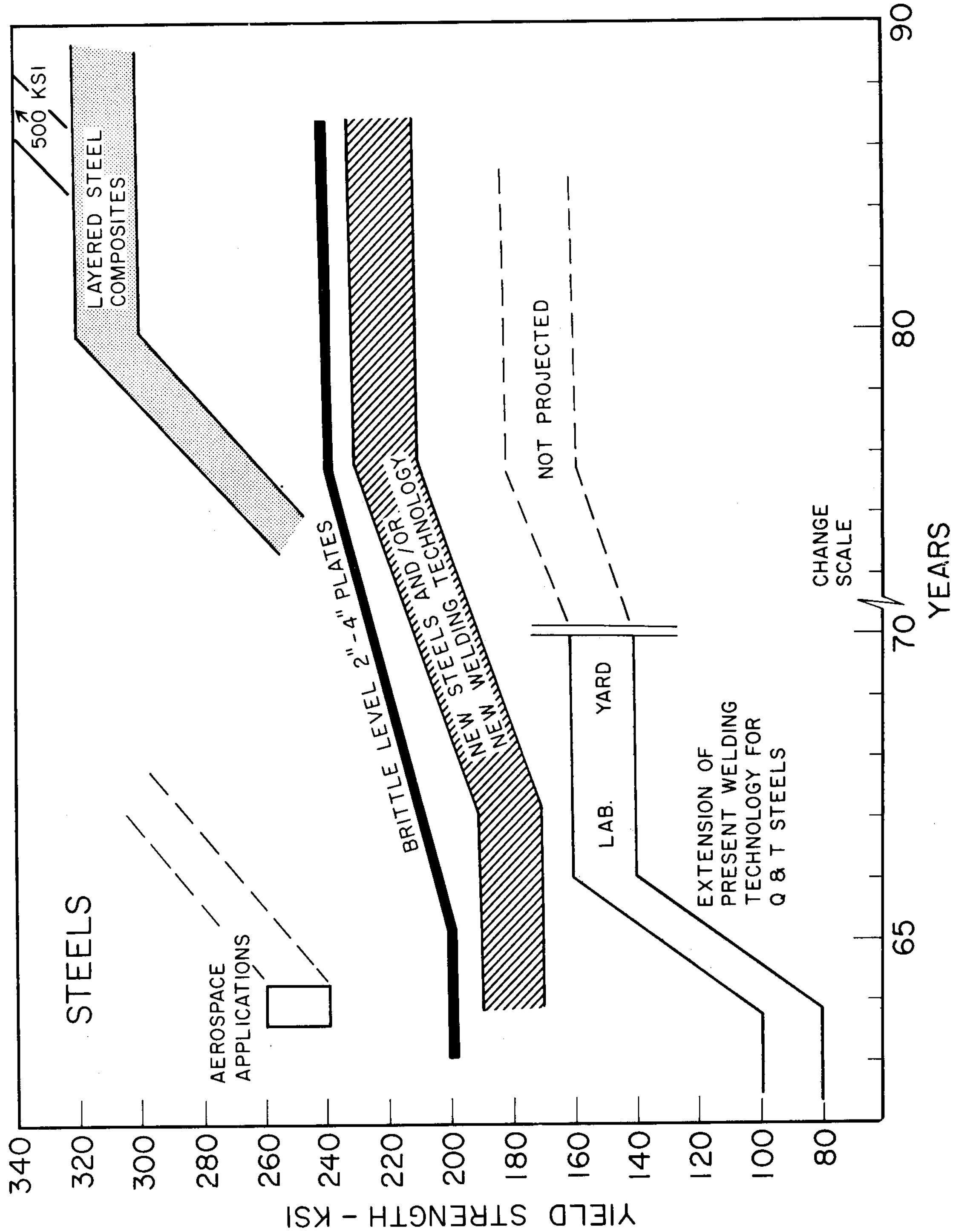
STEELS
AEROSPACE APPLICATIONS
BRITTLE LEVEL 2"-4" PLATES
NEW STEELS AND/OR NEW WELDING TECHNOLOGY
LAYERED STEEL COMPOSITES
500 KSI
NOT PROJECTED
LAB.
YARD
EXTENSION OF PRESENT WELDING TECHNOLOGY FOR Q & T STEELS
CHANGE SCALE
YIELD STRENGTH - KSI
340
320
300
280
260
240
220
200
180
160
140
120
100
80
YEARS
65
70
80
90

Fig. 4 - Steels

The last two years of the five year R&D program for steels should reflect a choice between the 210 - 230 ksi aim for monolithic construction and the 300 ksi (plus) LAYERED steel approach, with a consolidation of effort for the approach most likely to succeed by elimination of the competing effort.

TITANIUM ALLOYS

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TITANIUM FORECAST FOR 1970

METALLURGY

Titanium and its alloys can be produced as sheets, plates, bars, forgings, tubes and castings. These offer great potential for use in deep-ocean structures, machinery and other equipment. Major points of advantage include high strength-to-weight ratio, non-magnetic characteristics, high resistance to fatigue and corrosion-fatigue, and practically complete immunity to all forms of marine corrosion.

Unalloyed titanium exists in the alpha (hexagonal close packed) form up to 1620 F. Above this temperature it exists in the beta (body centered cubic) form. Alloying elements can be added to strengthen the alpha structure or to modify the room temperature structure to an all-beta or mixed alpha-beta structure.

The type of structure existing at room temperature determines whether the titanium alloy will respond to heat treatment, and whether it is sensitive to thermal embrittlement which interferes with weldability. The all-alpha alloys are generally insensitive to heat treatment and are considered to be weldable. Alloys containing over approximately 12 atomic percent aluminum plus tin in combination with the interstitial elements oxygen and nitrogen are exceptions. Such alpha alloys are susceptible to thermal embrittlement due to formation of an ordered structure. The action can be minimized by a prior high-temperature homogenization anneal of the base metal. However, because the strengthening effect of these alpha stabilizers is negligible above 12 atomic percent, they can be held at a low level where their effect is innocuous. The beta-stabilizing elements have a limited solubility in alpha titanium and can be added in amounts up to the solubility limit to act as strengtheners without stabilizing the beta phase.

Aluminum and tin are the only metallic alpha-stabilizing elements of major importance. The interstitial elements (carbon, oxygen and nitrogen) are also alpha-stabilizing elements. Although the interstitials are potent strengtheners of alpha titanium, their presence tends to increase notch and strain-rate sensitivity and to lower toughness and room-temperature creep resistance.

Both the beta and alpha-beta structures result from the addition of beta-stabilizing elements. The amount of beta phase present at room temperature is a function of the type and amount of stabilizer and the rate of cooling below the beta transus temperature. The beta and alpha-beta alloys are considered heat-treatable when the beta structure exists in a metastable condition. The alloys are water-quenched from a temperature near the transus and subsequently aged at a lower temperature to achieve strengthening through precipitation of an equilibrium or near-equilibrium phase.

The beta and alpha-beta alloys are generally classified as nonweldable or of borderline weldability. The degree of weldability is considered dependent on the amount and form of the beta phase. However, this concept is based on experience with alpha-beta alloys of relatively high interstitial content, and there is reason to believe that the physical metallurgy of the alpha-beta alloys should be reinvestigated with alloys of low interstitial content to determine their potential for naval applications.

At the present time there is one commercially-available all-beta titanium alloy. This alloy is heat treatable to very high-strength levels by precipitation of an eutectoid compound in the beta matrix. The alloy is brittle at the high-strength levels. Work is in progress aimed at developing compound-free all-beta alloys of better ductility. These show some promise, but it is doubtful that useful alloys of high-strength levels can be developed for major structural applications.

DESIGN PROPERTIES

The tensile yield strength now available in commercial titanium plate of 1 in. nominal thickness ranges from about 25,000 psi for unalloyed high-purity material to about 160,000 psi for a heat-treated alpha-beta alloy such as Ti-6Al-6V-2Sn. On the basis of present knowledge, low-toughness, low-ductility titanium alloys, not now produced commercially, could be made as 1 in. plate with a heat-treated yield strength of about 200,000 psi.

Tough, weldable, unalloyed wrought titanium products, with yield strengths ranging from 40,000 to 90,000 psi, offer no particular problems, and prototype structures and equipment (such as piping systems, condensers, etc.) could be built today.

Cast components (such as valves and pumps) are also feasible now. Present casting sizes are limited (about 500 pounds finished) by the capacity of the vacuum arc-melting shell furnaces used for this purpose, but larger equipment could be built if there were a demand for larger castings. Work to date indicates that toughness should not be a problem with cast titanium, but the yield strength would be lower than in wrought material. Alloys cast with an extra-low oxygen content have produced Charpy V-notch values of 54 ft-lbs at 30 F (41 ft-lbs at -80 F). Considerable effort should be made to obtain more information on the mechanical properties of castings.

Recent Navy R&D effort has been concentrated on higher-strength wrought alloys for welded, heavy-section structures such as submarine pressure hulls. All-alpha alloys have received first emphasis for reasons of weldability. A major effort concerns modifications of a basic alloy containing 7-8% Al, 2% Cb and 1% Ta. To date, 30 ft-lbs minimum Charpy V-notch at 30 F (21 ft-lbs at -80 F) can be guaranteed in 1 in. plate at strengths up to 105,000 psi tensile yield and 115,000 psi compressive yield. An investigation of mill-processing variables is now under way which should, by mid-1964, raise these guaranteed yield strengths to 115,000 psi tension and 125,000 psi compression without loss in toughness.

Special laboratory heats of the Ti-7Al-2Cb-1Ta alloy have been made with extra-low oxygen content (0.03 - 0.04%). These heats have produced impact values up to 70 ft-lbs at -80 F (no data at 30 F), although the lower interstitial level resulted in a yield strength of only 100,000 psi.

The tensile ductility of Ti-8Al-2Cb-1Ta alloy is approximately 12% elongation and 18% reduction in area. This alloy (as well as all other alloys under consideration) requires a low interstitial content to develop good toughness. As a result, the strain-rate sensitivity is low. Tests of Ti-8Al-2Cb-1Ta alloy indicate an increase of approximately 2,000 psi in tensile yield by increasing the strain rate from 0.001 to 0.020 in./in./min. The compressive yield strength increases about 5,000 psi over the same strain rate increase. Compressive and tensile room-temperature creep at a stress level of 80% of the yield strength is negligible. The notch tensile strength ratio is approximately 1.5.

The outlook for obtaining at least 115,000 psi tensile yield in the Ti-7Al-2Cb-1Ta alloy during 1964 is very favorable. Welds made in this alloy, where there has been no interstitial pickup, have shown both higher tensile strength and better Charpy V-notch impact strength than the base metal. Effort is being made to duplicate the thermal cycle of the weld as a heat treatment for the base plate. For example, a yield strength of 119,000 psi and a Charpy V-notch value of 26 ft-lbs at -80 F has been developed in plate having initial properties of only 104,000 psi and 23 ft-lbs (no data at 30 F).

A promising alpha-beta composition, 6 - 7% Al - 2% Mo, is under investigation. In the solution-annealed condition, this alloy has a yield strength of 117,000 psi and a Charpy V-notch value of 55 ft-lbs at 30 F (35 ft-lbs at -80 F). A quantity of this alloy has been ordered for comprehensive evaluation.

Higher-strength alpha-beta alloys appear promising. These are compositional variations of the commercial Ti-6Al-6V-2Sn alloy. One alloy has a yield strength of 145,000 psi and a Charpy value of 30 ft-lbs at 30°F (26 ft-lbs at -80°F) in the quenched and aged condition.

All of the foregoing are materials of good toughness designed for applications where resistance to catastrophic failure is critical. For applications where toughness is less important, higher strength levels can be obtained by interstitial alloying both of the alpha alloys and the alpha-beta alloys. The higher interstitial alpha alloys would be considered weldable, whereas most of the alpha-beta alloys would have nil or borderline weldability.

The density of all commercially available titanium alloys ranges from 0.158 to 0.162 pounds per cubic inch. The Ti-7Al-2Cb-1Ta alloy has a density of 0.160 pounds per cubic inch. The elastic modulus of titanium alloys ranges from 15 to 18 x 10^6 psi. The modulus of Ti-7Al-2Cb-1Ta is 17.7 x 10^6 psi.

Studies have been made of the tensile stress-strain curves for Ti-7Al-2Cb-1Ta alloy specimens with an average yield strength of 105,000 psi. The proportional limit averaged approximately 90,000 psi. At the 0.2% yield-strength point, the tangent modulus averaged 2.5 x 10^6 psi, and the secant modulus averaged 13.3 x 10^6 psi. The yield strength-tensile strength ratio of the alloy was about 0.83. This should be fairly typical of the alloys at this strength range. In general, the yield-strength to tensile-strength ratio is high for titanium alloys, and this ratio tends to increase with increasing strength.

SECTION SIZE EFFECTS

The effects of increased section size on design properties can only be postulated from knowledge of the physical metallurgy of present alloys.

The alpha alloys are considered first. Increasing the thickness of plate means that the finished product will be subjected to less working from ingot to plate than occurs in 1-in. plate with which there has been the most experience to date. Increased thickness will probably result in slightly lower tensile strength but no detrimental effect on toughness. Work on cast Ti-7Al-2Cb-1Ta alloy has shown that the toughness of the large, equiaxed-grain material is equivalent to that of the wrought material. Titanium producers generally believe that plates up to 4-in. thick can be given the equivalent amount of working now given to 1-in. plate in the rolling operation by simply starting to roll with a thicker slab. An investigation of the effects of rolling processes on the properties of Ti-7Al-2Cb-1Ta alloy plate is now in progress, and results will be known within the next few months.

The potential use of alpha-beta alloys may be limited by thermal cycling problems when produced in the form of thick plate. This problem is associated with the low thermal conductivity of titanium. In the production of heavy plates, slow cooling due to low heat loss may lead to loss of toughness through aging of the beta phase. Likewise, in the welding of thick-plate alpha-beta alloys, the weld metal and adjacent heat-affected zone will be at elevated temperature for a relatively long period of time due to the low thermal conductivity; this may also cause loss of toughness by aging of the beta. In the event that heat-treatable, high-strength, alpha-beta or beta alloys find application as thick sections, quenching of the alloy prior to aging may also be a problem.

In brief, it can be said that thick sections of the all-alpha titanium alloys in the form of plate, forgings or castings are not expected to deviate greatly in design properties from those in thinner sections; thus, the transition from thin-section to thick-section applications should not present too great a problem. However, the use of thick-section alpha-beta or beta alloys may be difficult, and this warrants exploratory investigation to determine limiting conditions.

The effect of thickness or "mass effect" relative to susceptibility to catastrophic failure in the presence of notches and flaws is an important consideration. So far, this has been given only cursory examination in plate up to 2-in. thick. The all-alpha Ti-8Al-2Cb-1Ta alloy, heat treated for optimum toughness, behaves satisfactorily through thicknesses of 2 inches. Further investigation of the influence of thickness on toughness is to be undertaken.

FABRICABILITY

The limitation on size of the end product (plate, forging or casting) is set by the capacity of melting facilities. Wrought products can be worked from ingots on the same equipment as used for steel.

The largest ingot produced at the present time is about 10,000 pounds. Assuming 60% yield from ingot to plate, this would produce about 30 sq. ft. of 2-in. plate or 60 sq ft of 1-in. plate. The production of larger plates in this thickness range, or of large plates above 2-in. thickness, would require new melting facilities to make larger ingots. One titanium producer has indicated plans for building facilities within the next year to enable production of 40,000-pound ingots. Ingots beyond this size are feasible, but equipment for production would require a year to build.

The development of optimum properties in thick titanium plates through proper processing techniques has not been investigated by the industry. This has been due to lack of demand for heavy plates. The major producers are aware that this problem exists. The variation in properties of 1-in. and 2-in. plates produced so far has emphasized the need for more knowledge of optimum processing schedules.

A program is now in progress to develop processing techniques for the all-alpha Ti-7Al-2Cb-1Ta alloy. Much of this information should be applicable to titanium plates of other alpha compositions. However, optimum processing techniques may vary among the classes of alloys (alpha, alpha-beta and beta).

Facilities for forming steel can be used for forming titanium. Because of the lower elastic modulus of titanium, about three times as much energy is required to form titanium at the 120,000 psi yield-strength level than HY-80 steel. Heating titanium to between 400-600°F makes possible a reduction in the energy requirements to the level necessary for HY-80 steel.

As mentioned earlier, the tensile and impact properties of welds in 1-in. alpha titanium plates are equal to or exceed the properties of the base metal when the weld is free of contamination. Whether this holds true for thicknesses greater than 1 in. has not yet been proved. However, from knowledge of the properties of cast titanium (weld metal is essentially cast metal) it is expected that welds in thick titanium will have toughness equal to that of the base metal.

The tensile strength of cast titanium has been found to be less than that of the wrought material. The reason for occasional instances of superior tensile properties in welded 1-in. thick Ti-7Al-2Cb-1Ta alloy is still not understood. However, there are indications that it is associated with the fast cooling rate (semi-quenching) which causes some strengthening and toughening phase to be held in solution. If this be the case, there is a strong possibility that welds in thicker titanium plates will have the high tensile strength characteristics of the welds in 1-in. plates.

The weldability of thick-plate alpha-beta alloys of low interstitial content has not yet been demonstrated. An investigation is now under way to determine if toughness properties can be retained subsequent to welding in several selected alpha-beta compositions.

The preparation of thick-walled vessels by multi-layer construction may offer metallurgical and fabrication advantages. This should be investigated for both alpha and alpha-beta titanium alloys.

Because of the deleterious effect of interstitial contaminants on toughness, it is imperative that pickup of these contaminants during welding be prevented. One way to accomplish this is to perform welding operations inside an enclosure in which the atmosphere is a contaminant-free gas. The feasibility of such a system is inversely proportional to the size of structure to be welded. Enclosures of this type could be provided for small research-type submarines and submersible structures, but would not appear feasible for large military-type submarines.

An alternate method, which is receiving the most attention at present, is provision of a shield of inert gas around the welding torch and a trailing shield for protection of the hot metal after welding. Excellent progress has been made in open-air shielded welding of titanium plate up to 2-in. thick. The method used is the consumable electrode (MIG) process in which the electrode is wire of similar composition to the material being welded. Although this method appears very promising, it will require the development of a high degree of artisan skill.

Present practice requires that the joint in the plate to be welded have a rather large included angle to permit the torch and associated shields to reach the root of the joint for the initial pass. There are two disadvantages to this. First, the large angle requires a great amount of wire to be used in filling the joint, and wire costs three to four times as much as the base metal. Second, the deposit of a large volume of molten metal introduces complications with regard to the width of the weld zone and heat-affected zone. This probably will not be of concern in the all-alpha alloys, but may be an important consideration for alloys containing beta. It seems reasonable that narrow gap MIG welding can be developed by 1970, and that other problems concerned with open-air shielded welding can be solved in the same period.

Electron beam welding shows promise for future development possibly in the 1970's. There are many problems associated with adapting this method for construction of submarines, but the small size of the weld deposit and the relatively small heat affected zone make it appear attractive for future use. It also appears feasible to construct small submersibles in a vacuum chamber using electron beam welding. It has been proposed that existing environmental chambers for testing space vehicles could be adapted for this purpose.

Work is under way to adapt electron beam welding to out-of-chamber, open-air welding. There are many problems associated with this which may take several years to solve.

Therefore, it is predicted that open-air, electron-beam welding for thick plates will not be feasible until about 1980.

The deleterious effects of interstitial contamination during welding of titanium is of considerable concern, and a nondestructive method for detection of contaminants in the finished structure is highly desirable. Efforts to develop nondestructive test procedures have been initiated, and there are indications that something can be developed by 1970. An alternative, but less desirable approach, would be to monitor the welding process to the extent that noncontamination could be guaranteed. This could be accomplished by welding in an enclosure, or a partial enclosure for large structures.

OTHER SPECIAL CONSIDERATIONS

Aside from its conventional properties, there are other characteristics of titanium that make its use very attractive for submersible structures.

Titanium and its alloys are non-magnetic. No other structural material shows such remarkable resistance to all forms of sea water corrosion. The fatigue properties of unnotched titanium specimens in sea water are essentially the same as for the material in air, and the high-cycle corrosion-fatigue resistance in sea water exceeds that of all other known materials. It is expected that these properties will be realized in all new titanium-base alloys that may be developed in the future.

Titanium acts as a noble metal in sea water, so that less noble metals coupled to it would tend to suffer accelerated corrosion by galvanic action. Thus, if titanium hulls are to be used, it would be desirable to use noble metals for equipment such as internal sea-connected lines. This should offer no great difficulty, as titanium has already shown excellent performance in simulated piping and condenser tests.

The importance of maintaining a low interstitial content in titanium alloys has been emphasized in this report. The present specified and maintained limit on oxygen is 0.08%. There are indications that it would be desirable to maintain the oxygen level even lower. In such a case, it would be necessary to upgrade the sponge quality and tighten the vacuum of the melting furnaces. Interstitial pickup in processing from ingot to plate is negligible.

The titanium producers do not have sufficient incentive at the present time to try to upgrade their product by reducing oxygen content. The demands of the aircraft industry (the principal user to date) are for materials in which a higher interstitial content is allowed and desired for its strengthening effect. However, if the demand for higher-purity material were to materialize, titanium alloys could be made with a maximum oxygen content of 0.04% or less.

The recycling of scrap is an important economic consideration. This practice would not be feasible at the present time for production of submarine materials. It is possible that an economical electrolytic method could be developed for reclaiming scrap to produce high-purity material. If not, the scrap from Navy applications could be recycled for aircraft and missile materials.

The present cost of titanium alloys is about $5 per pound for 2-in. plate and $6.25 per pound for 1-in. plate. One producer has predicted that if the Navy becomes an important tonnage user of titanium plate, the price would be lowered to about $3.50 per pound in three years. A projection of $3 per pound by 1970 seems reasonable.

It is difficult to estimate the cost of fabricating a structure of heavy-section titanium, as there has been practically no shop experience to date. Contracts are now in effect for production of titanium models by private industry. One contract is for construction of two models simulating conventional ring-reinforced shell construction. The contract will produce 4,130 pounds of finished structures at an average of $32 per pound. Another contract involves sandwich-type construction of a 1,268-pound structure at an average of $65 per pound. It should be recognized that these contractors have priced their work to include risk factors, engineering costs, development of techniques, etc. Experience indicates that these costs are actually competitive with the cost of constructing similar models from more conventional materials.

When procedures have been worked out and experience has been gained, it has been estimated that heavy-section titanium structures will cost roughly two to three times the cost of the base material. Thus, the cost within three years for heavy titanium structures should be between $10 and $15 per pound. Assuming fabrication costs will also diminish with material costs, the predicted 1970 structure costs should be $8 to $10 per pound.

R&D EFFORT

Experience to date in the thick-plate hull program has served to emphasize the lack of knowledge concerning the physical metallurgy of titanium. Past applications have been for the aircraft industry in which wrought forms were in thin section sizes, and the alloys were designed for elevated temperature strength and creep resistance. Toughness was of less concern in these applications, and the presence of impurities (principally the interstitials) was not detrimental to design properties and in some cases was a distinct advantage.

The first evaluation of titanium as a hull material indicated that high purity was a necessity if the material were to have the required toughness. This has been further confirmed by later work.

The production of plate is a new experience for the titanium producers. They all now realize that there are problems they did not anticipate. The optimum working procedures are still unknown. The industry's work on alloy development has been confused. The influence of microstructure on properties is still not definitely delineated. There are several instances in which the mechanical properties of finished plate has approached or exceeded goals, but these results have been inconsistent for reasons yet unknown.

It is therefore obvious that, with the lack of basic knowledge concerning the physical metallurgy of titanium (relative to applications in thick, massive forms), too much involvement in new alloy development at this time is rather meaningless. This has become apparent in the investigation of all-alpha alloys. As the program expands to include the alpha-beta compositions, the situation will become more complicated because the physical metallurgy of these alloys is more complex.

It is believed that more long-range benefits will result if efforts in the next two to three years are concentrated on a physical metallurgy study of titanium relative to massive forms. Relatively little effort should be expended toward alloy development per se, but rather a small amount in correlation with the physical metallurgy study. The remaining time to 1970 should be concentrated on alloy developments to scale up to large heats possessing target properties.

Those properties not associated with strength and toughness can still be evaluated in increasingly thicker sizes of plate. This includes the effects of flaws and flaw size (thickness influence on toughness).

Problems related to fabricability should also be investigated on increasingly thicker sections. This includes welding, forming and non-destructive testing. Processing procedures to achieve optimum properties in thick plate should be coordinated with the physical metallurgy programs.

The present "cook book" approach to alloy development is no doubt necessary for a "crash program." However, it appears rather wasteful and inefficient, since some of the present work may have to be repeated as more knowledge of the physical metallurgy of titanium is gained.

Other areas to be considered are sponge production and scrap reclamation. Research should be conducted in these areas in an effort to obtain a more pure product.

TITANIUM FORECAST FOR 1980-85

DEVELOPMENT OF NEW ALLOYS

It is anticipated that by 1980 much will have been learned concerning the micromechanisms of metal strengthening and fracture toughness. This should enable the development of new titanium alloys of much higher strength with good toughness, as well as refinements in design procedures to safely utilize high-strength alloys of marginal toughness as judged by present-day standards.

Titanium alloy research up to the present time can only be considered to have "scratched the surface." In particular, much more can be done to investigate alloy systems using high-purity raw materials. The majority of work in the past has been done with titanium sponge of relatively high interstitial content, and the interstitials have played a major part in the strengthening and embrittling mechanisms of these alloys.

There is a major lack of knowledge concerning the physical metallurgy of titanium. A better understanding of this field should lead to improved alloys and processing practices.

NEW MECHANICAL PROPERTIES

It appears reasonable to predict that titanium alloys can be developed by 1980-1985 with useful toughness and weldability at yield strength levels up to about 180,000 psi. Alloys considerably stronger than this, but with marginal toughness, probably can be developed, but joining will probably be restricted to cementing or mechanical fastening unless there is a major break-through in welding technology. Thinner sections suitable for built-up structures (honeycombs, etc.) probably will be weldable or brazable up to the 180,000 psi level.

CHANGE IN THICKNESS RESTRICTIONS

As section thicknesses increase, it is anticipated that yield strengths and toughness will drop off slightly.

Developments in equipment and melting procedures will be necessary if ingots are to be produced large enough to yield large-area plates in excess of about 4-in. thickness. It is predicted that this could be accomplished within 5 to 8 years, provided the industry has a marketable outlet for such products.

FABRICABILITY

The procedures are expected to make great progress by the early 1980's in setting up new and larger facilities for the production of titanium plates. The producers now admit that the present practice of using steel-mill facilities for conversion of titanium

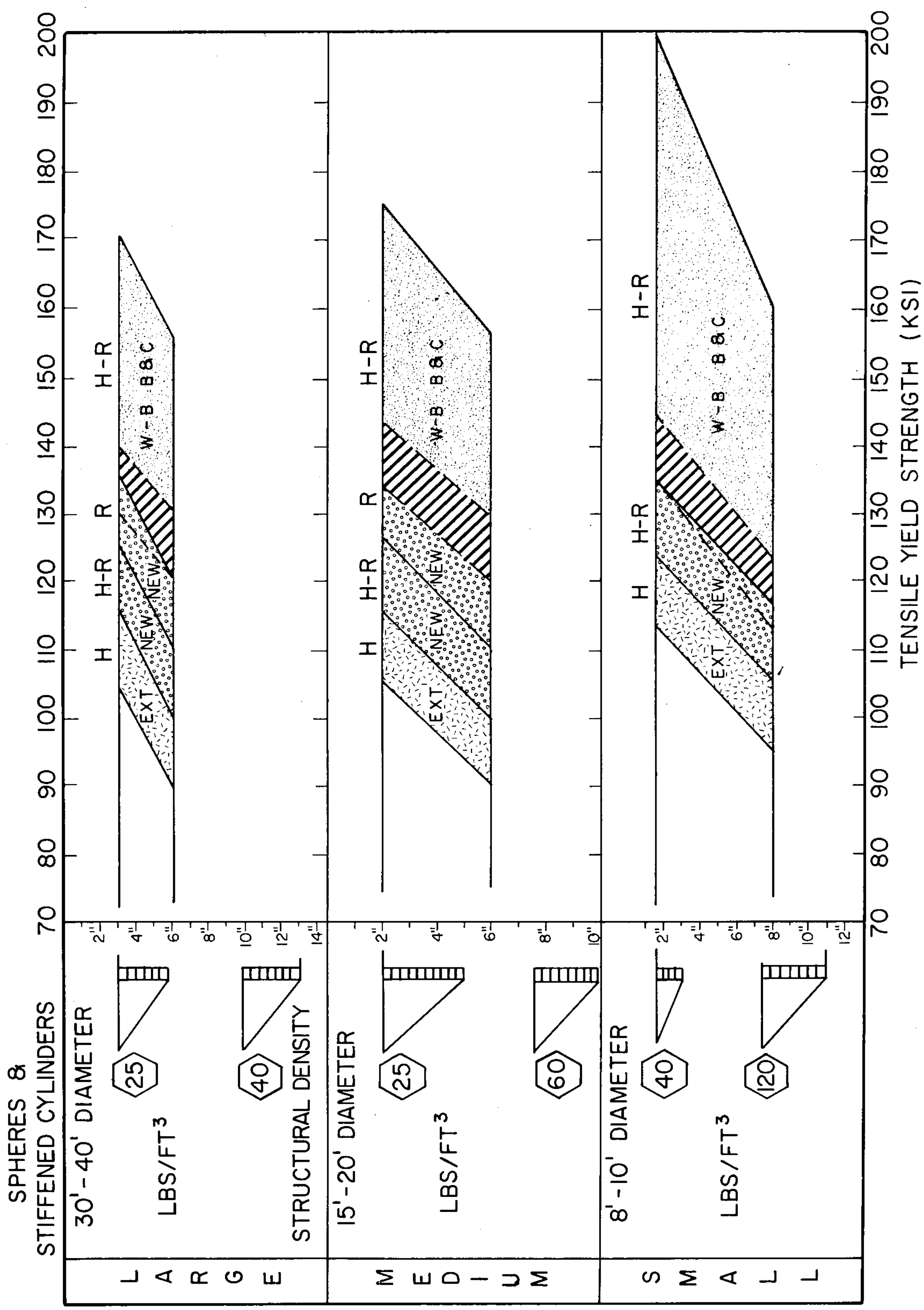

Fig. 1 - Frame of reference chart. Titanium alloys -- 1970 forecast.

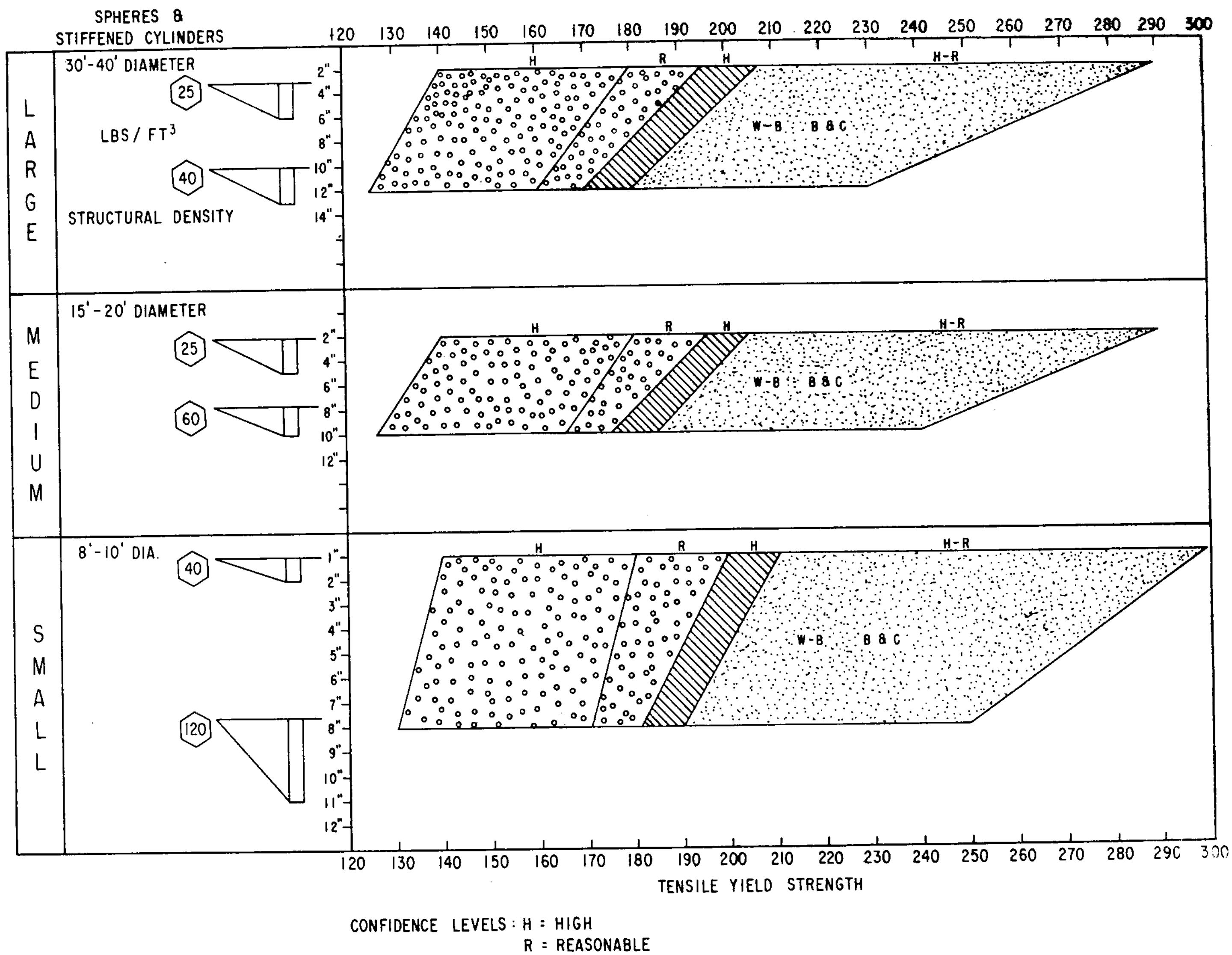

Fig. 2 - Frame of reference chart. Titanium alloys -- 1980-85 forecast.

ingots to plates leaves something to be desired. The use of automation and specially-designed facilities would allow closer control of furnace, forging and rolling temperatures, plus closer control of drafts-per-pass in rolling and cross-rolling. All of these factors are believed to influence the properties of the finished product. Melting facilities can be enlarged to produce thick plates in large sizes.

Narrow-gap welding should be feasible by MIG and possibly open-air electron beam welding. The weld properties should closely match the base metal properties. The problem of nondestructive inspection for interstitials should be resolved. Casting practices for titanium should be completely developed by this time, and the capacity for producing large castings should be realized. Mechanical properties of massive castings should be predictable with accuracy.

Extrusion facilities can and should be developed for making large T-section stiffeners required for larger submarines.

SPECIAL CONSIDERATIONS

The good corrosion characteristics of titanium should not change in the future.

Sponge of high purity should be available, and a method for utilizing scrap should be developed. Melting furnaces should be up-graded, and present arc-melting may be replaced by electron beam or laser melting.

Titanium ores are abundant, and the market for titanium and the development of more efficient processing techniques should enable the price of titanium plate to be reduced to $2 to $2.50 per pound. This is in line with the prediction that eventually the price will be stabilized at approximately twice the cost of stainless steel. At this cost titanium would be directly competitive with stainless steels for structural applications because of the higher strength-weight ratio of titanium.

R&D BEYOND F.Y. 1970

The R&D effort in the 1970's should emphasize micromechanisms of metal strengthening, fracture characteristics, new alloy developments based on theoretical rather than empirical knowledge, dispersion strengthening, and laser and electron-beam welding. This decade also should see the practical demonstration of the use of titanium in large structures, the success of which will require the laboratories to assist in the revolutionary changes which must be met by shipyards and other fabricators.

ALUMINUM ALLOYS

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METALLURGY

The candidate wrought alloys for deep submersibles fall in the 5000 and 7000 series.* Magnesium is the major additive in the 5000 series; magnesium, zinc or magnesium, zinc, and copper are the main alloying elements for two classes of the 7000 series alloys. Strain hardening and artificial aging (or precipitation hardening) are two methods used to increase the mechanical properties of an alloy beyond those obtained by solid solution. Insofar as is possible with a particular alloy, final tempers are selected to furnish some desired combination of strength, resistance to corrosion, workability, and toughness.

The 5000 series have been used for ten years in marine applications requiring a high degree of resistance to corrosion; in addition, they have been used as armor plate for military vehicles.

The 7000 series, such as 7075, 7178, and 7079, have been widely used in airframe construction. Recent modifications of these alloys, i.e., 7002, 7005, 7106, 7039, and 7139, are being evaluated for use in hydrofoils, missile tankage, and armored vehicles. In addition, the mechanical properties of heavy forgings and thick plates are being determined.

When supplied in strain-hardened tempers, the 5000 series are usually given a low-temperature, thermal-stabilizing treatment to insure stability of properties which may cause a slight reduction in strength; for example, the full hard unstabilized 5086 alloy may lose 2000-3000 psi in tensile strength.

The 5000 series can be used in the annealed condition; this is usually done by annealing between 650 and 800 F and then cooling in still air. The industry will usually strain the annealed material to obtain various strength levels and then thermally stabilize. These stabilizing treatments vary with the type of alloy. In general, however, the producer recommends hot forming at 425 F to avoid adverse effects of cold work and residual stresses. The hot forming reduces the strength level of the base material. Production welding of the 5000 series does show that the tensile strength of the weldment exceeds 80 percent of the base material. For example, 5083-H112 and 5454-H34 have base metal tensile strengths of 44,000 psi, whereas the weldments of these alloys are reported to have 40,000 and 31,000 psi minimum tensile strengths, respectively. However, regardless of the base metal temper, the weld yield strength will approach that of annealed yield strength of the base material, 21,000 psi. If the base material is in the strain-hardened condition and thermal stress relieving is required after welding, the

*Wrought aluminum alloys are identified commercially by a four-digit system established by the Aluminum Association. The first digit indicates the major alloying constituents, the second, the modification, and the last two, the alloy. When used in the 2xxx through 8xxx alloy groups, the last two digits have no special significance but serve only to identify the different aluminum alloys in the group. When new alloys become available, the last two digits are assigned consecutively beginning with xx01. Identification of cast aluminum alloys is not as systematized as it is for wrought alloys although numbers are used almost universally.

strength levels of the base material and weldment will be equivalent to the material in the annealed condition.

The 7000 series can be supplied in many conditions. Usually these alloys are solution heat treated at 850 F, with a soaking time consistent with the thickness of the material, and then given an immediate cold-water quench. The applicable aging treatments for the modified 7000 series alloy are specific to the alloy. Some of the alloys do exhibit material aging tendencies at room temperature. Thermal treatments are usually given to obtain the optimum combination of mechanical properties.

The 7000 series are considered weldable on a broad sense; metal inert arc (MIG) studies are being pursued to improve the welded strength. The filler metals used to weld sheets of these 7000 series alloys are of the 5000 series chemistries.

Current research in welding by the aluminum industry is concerned with the development of stronger filler metal alloys for the new 7000 series base metals. Welding procedures are being optimized for thick plate, and the precise effect of welding variables, including repairs, will be determined. Improved post-weld aging treatments are to be investigated. The characteristics of welds between 5000 and 7000 series alloys will be surveyed.

It is interesting to note that the present available filler weld metal has a material aging tendency when used to weld some of the 7000 series. After 3 months of natural aging, yield strengths of 30,000 psi and tensile strength of 42,000 psi minimum are obtained. However, if the alloy is artificially aged, yield and tensile strengths of 40,000 and 50,000 psi, respectively, can be obtained.

The toughness of heavy weldments is an unknown factor for the modified 7000 series alloys since no data have been made available on the notch toughness of the weld deposits; however, these alloys behaved in a ductile manner when sheet specimen weldments were hydraulic bulge tested by the aluminum industry. The toughness of the sheet metal welds is attributed to its lower strength. If the toughness of thick plate parent metal is acceptable and the lower strength of the weld deposit can be tolerated, there is little likelihood that the toughness of the welds will be a problem in joining heavy sections.

Electron beam welding is being studied as a possible means of welding thick aluminum sections; however, it has been reported that the volatilization of zinc and magnesium shorts out the electron beam. Experience with "low voltage" equipment shows that volatilized magnesium in 5456 aids penetration.

Although the chemistries given by the Aluminum Association and by military specifications contain a breakdown of major constituents and a maximum for trace elements, the producers consider that the beneficial or detrimental effect a trace element may have on a given property is proprietary information. The effects of trace elements on mechanical and corrosion properties will have to be known in order to write a specification adequate to obtain from any producer material suitable for deep-submergence application.

DESIGN CONSIDERATIONS

Tensile and compression specimens are taken by standard test methods applicable for evaluating a specified aluminum alloy. Plates of the 5000 series are tested in the longitudinal direction whereas the heat-treatable alloys such as the 7000 series are tested in the transverse direction. For material less than 1.5 in. thick, the test specimens are taken from the central plane of the plate. Test specimens are taken from the quarter thickness for plates greater than 1.5 in. thick.

The mechanical properties developed in 1-in. plate for the aluminum alloys which may have applicability to submarine hull structures are given in Table 1. The properties given in Table 1 for the 5000 series can be considered as minimum, whereas the mechanical properties given for the 7000 series can only be considered as tentative nominal values. None of the 7000 series has been produced in enough quantity to set exact minimums. The mechanical properties given are not dependent upon loading rate since aluminum alloys are rather insensitive to rates of loading.

Table 1
Mechanical Properties of Aluminum Alloys
Considered for Deep Submergence
(1-in. Plate)

Alloy Designation and Temper.	TUS (L) (ksi)	TYS (L) (ksi)	Percent El. in 2-in. (L)	CYS (L) (ksi)	TUS (LT) (ksi)	TYS (LT) (ksi)	Percent El. in 2-in. (Lt)	CYS (LT) (ksi)
5083-0	40	18	16	18	40	18	--	18
5083-H112	40	18	12	19	32	19	--	19
5083-H113	44	31	12	26	44	28	--	29
5086-H34	44	34	10	32	44	33	--	34
5086-H112	35	16	10	16	35	16	--	16
5454-H32	36	26	12	24	36	24	--	26
5454-H34	39	29	10	27	39	28	--	29
5454-H112	31	12	11	12	31	12	--	12
5456-H321	46	33	12	27	45	29	--	31
X7002-T6	61	50	9	53	61	50	9	--
X7005-T6	45	36	7	36	45	36	--	38
X7106-T6	55	50	--	50	55	50	6	52
X7106-T63	56	50	9	50	54	47	5	47
X7039-T6	65	55	13	58	65	55	13	60
X7039-T61	62	51	14	--	62	51	14	--
X7139-T63	63	55	13	--	--	--	--	--
X7005-T63	47	38	7	38	47	38	--	40

The physical properties given in Table 2 show that the differences in chemical compositions of the various series of alloys are not reflected in the values of the modulus of elasticity and of Poisson's ratio. These values do not vary with product, size, or temper.

The aluminum industry does not use Charpy V-notch impact tests as a measure of notch toughness. The fracture characteristics of aluminum alloys are generally measured in terms of a number of fracture mechanics factors such as (a) the stress-intensity factor "K" or strain-energy release rate "G" from fracture-toughness tests, (b) unit propagation energy from tear tests, and (c) notch toughness from the relationship of the strengths of notched tensile specimens to the tensile properties of the material.

Unfortunately, the fracture-mechanics approach which is applicable to brittle and semi-brittle material is not well suited for determining the fracture characteristics of tough aluminum alloys which are required for deep-diving submarines. However, a comparison of the available strengths of notch tensile specimens with the tensile properties of the various aluminum alloys may provide a useful measure of notch toughness.

One of the major aluminum producers believes that the most significant information on notch toughness can be obtained by comparing the notch yield ratio — the ratio of the notch strength of the tensile specimen to the tensile yield strength of the various aluminum

Table 2
Physical Properties of Aluminum Alloys
Considered for Deep Submergence

Alloy Designation	Density 16/in.³	Modulus: Tension in 10^6 psi	Modulus: Compression in 10^6 psi	Modulus: Rigidity in 10^6 psi	Poisson's Ratio	Coef. of Exp. 10^{-6} in./in. F (68-212)	Melting Range
5083	0.096	10.2	10.4	3.85	0.33	13.2	1075-1185
5086	0.096	10.2	10.4	3.85	0.33	13.2	1084-1184
5454	0.097	10.2	10.4	3.85	0.33	13.2	1115-1195
5456	0.096	10.2	10.4	3.85	0.33	13.2	1060-1180
7002	0.099	10.3	--	3.90	0.33	--	1065-
7005	0.101	10.3	10.5	3.90	0.33	13.2	1125-1195
7106	0.099	10.3	10.5	3.90	0.33	13.3	1090-1195
7039	0.0988						

alloys being considered for use in deep-diving submarines. Exceptionally sharply-notched specimens with theoretical stress concentration factors equal to or greater than 12 were used for evaluating the notch toughness of their aluminum alloys.

Unfortunately, only limited data are available concerning the notch-toughness properties of the alloys of interest here. Table 3 contains the data available on the transverse notch toughness of aluminum alloys in general. It is interesting to note from Table 3 that the modified 7000 series alloy, 7106, has a notch tensile to tensile yield strength ratio for sheet and plate of approximately 1.10 and 1.59, respectively. These ratios compare favorably with the 5456 and 6061 aluminum alloys. Drop-weight tear-test data obtained

Table 3
Transverse Notch Toughness Properties of Aluminum
Alloys Considered for Deep Submergence

Product (in.)	Alloy Designation and Temp.	TUS (psi)	TYS (psi)	NTS/TUS	NTS/TYS
Sheet:					
.063	5456-H321	--	--	--	1.12
.063	6061-T6	55,700	51,200	--	1.15
.063	7178-T6	88,500	78,500	--	0.66
.063	7075-T6	82,200	73,000	--	0.88
.063	7106-T6	64,300	58,800	0.99	1.09
.063	7106-T63	61,000	55,000	1.24	1.13
Plate:					
1 - 1-1/2	5456-H321	--	--	--	1.75
1 - 1-1/2	6061-T6	--	--	--	1.60
1 - 1-1/2	7178-T6	--	--	--	0.97
1 - 1-1/2	7075-T6	--	--	--	1.25
1 - 1-1/2	7106-T6	64,600	57,900	1.42	1.59
3	7106-T6	63,400	57,100	1.40	1.55
1/2	7106-T6351	62,200	54,400	1.46	1.67

by the U.S. Naval Research Laboratory indicate that the 5456 and 6061 have greater energy absorption than the 7075-T6 or 2024-T6 alloys; 5456 and 6061 alloys absorbed 1750 ft-lb whereas 7075 and 2024 absorbed 150 to 800 ft-lb, respectively. Although NRL did not perform any notched tensile tests when exploring the possibility of correlating the drop-weight tear test and the explosion tear test on a limited number of aluminum alloys, there appears to be a correlation between the various tests. From the limited drop-weight and explosion tear-test data, 6061 and 5456 alloys can be considered as somewhat tough. The notched tensile toughness data obtained to date from one of the modified 7000 series indicate that the behavior of this higher strength alloy and probably others of this series will be similar to that of the 6061-T6 alloy in the NRL tear tests. The toughness data depicted in Fig. 1 are based upon extrapolation of these limited data.

SECTION SIZE EFFECTS

Aluminum alloys of the 5000 series are considered applicable for deep-submergence purposes and can be used in plate thickness up to 5 in.; however, the tensile properties will approach the yield strength for annealed materials. It should be noted that there are no minimum values for annealed materials; the mechanical properties generally quoted for annealed materials are maximums.

The aluminum industry claims it can supply the 7000 series of alloys in plate thickness up to 6 in. with no loss in properties. In fact, one producer states that if the need arises, he can supply a particular alloy (7106) in plates up to 18 in. thick, 140 in. wide, weighing 17,000 lb and having the following guaranteed properties:

Alloy X7106-T63

Properties	Thickness		
	Up to 8-in.	8 to 12-in.	12 to 18-in.
TUS (L) (ksi)	56	56	55
TYS (L) (ksi)	50	49	48
Percent El. in 2-in. (L)	9	9	8
TUS (LT) (ksi)	54	54	53
TYS (LT) (ksi)	47	46	45
Percent El. in 2-in. (LT)	5	5	5
TUS (ST) (ksi)	53	53	52
TYS (ST) (ksi)	45	44	43
Percent El. in 2-in. (ST)	3	3	3

It should be understood that the properties given above for the various thicknesses will be from specimens taken from quarter thickness in accordance with ASTM Standard B-209. The properties at the center will depend upon the amount of work that can be given to the ingot. Preforging of ingots into billet shape is a recent development of the aluminum industry. There appears to be no data to indicate that the center of a plate 4 in. or more thick will be worked sufficiently to break down the as-cast structure. However, if the need arises, the aluminum industry feels confident that it can put a sufficient amount of work into the ingot to obtain optimum properties; in other words, the industry will insure that the center properties are acceptable and better than as-cast.

At present, the largest ingots that can be made by the aluminum industry are 60-in. in diameter by 180-in. long, or 26 x 72 x 200 in. These ingots weigh 28,000 and 37,000 lb, respectively. The resultant mechanical properties will depend on the amount of directional work that can be given to the ingot. If the ingot is worked all in one direction,

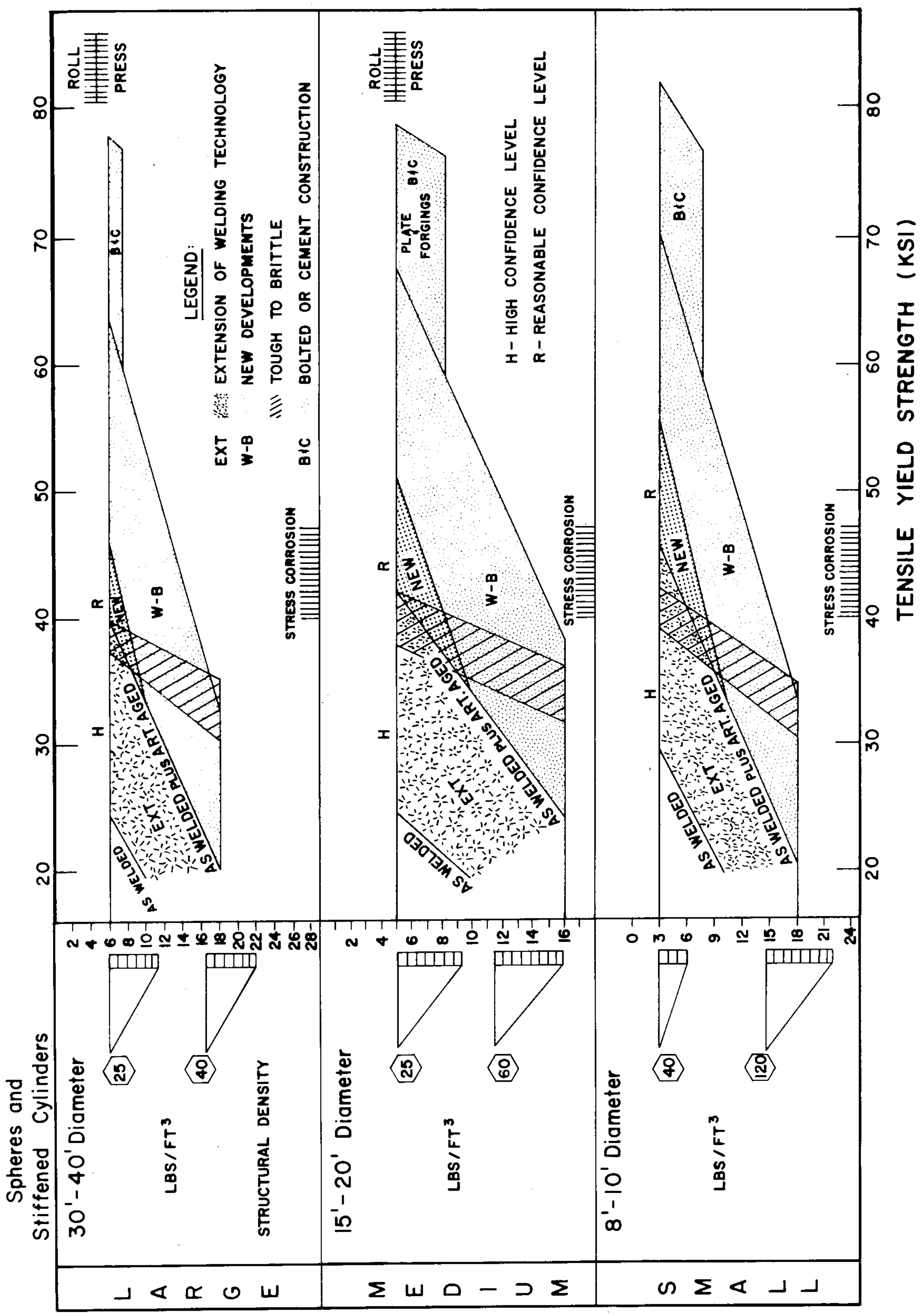

Fig. 1 - Frame of reference chart for aluminum alloys -- 1970 forecast

marked anisotropic properties can be expected. It should be understood that the anisotropy resulting from directional work is not limited to aluminum alloys. The industry has a 50,000-ton press available to minimize the anisotropic effect. The major limitation to this press is that the amount of workable daylight space available is approximately 13 ft; an ingot 13 ft long can be upset to obtain the maximum amount of work in the short transverse direction.

At present, intricate forgings 12-in. x 3-1/2 ft x 16 ft can be produced with a minimum yield strength of 48,000 psi. Extrusions of pipes, tees, and shapes can be made up to 23 in. in diameter; the length will depend upon the cross-sectional area of the item and the weight of the ingot.

It appears from available information that plates up to 4-in. thick can be rolled into cylinders 15 ft or more in diameter. Smaller diameters will have to be pressed or ring forged as shown in Fig. 1.

The effects of section thickness on toughness will have to be investigated for the modified 7000 series of aluminum alloys. The Marine Engineering Laboratory has shown that when tested by the slow notched bend test, the 7079-T6 alloy demonstrated sudden and extensive failure with very little deformation when the cross-sectional area of the bend specimen approached 4 sq in. When the 5000 and 6000 series alloys were tested under the same conditions, they showed no tendency toward sudden failure with increasing cross section up to the limit of the test (9 sq in.). If the notch tensile results can be used as a toughness indicator, it is expected that the modified 7000 series will behave in a ductile manner when tested by the slow notched bend test.

The aluminum industry is capable of producing hollow casting of the 7000 series alloys up to 41-in. in diameter, 4-1/2 in. thick and 9 ft long. The aluminum castings industry can produce bulk castings of commercially available alloys with wall thicknesses up to 2 in. and still retain the minimum yield strength properties of 22,000 psi. Using standard foundry practice, achievement of proper chill in heavy sections represents a major problem and results have been fairly negative on sections above 2-in. However, some foundry men believe that with proper chilling and gating, they can cast sections with wall thicknesses up to 6 in. without loss in mechanical properties.

FABRICABILITY

The aluminum industry uses continuous casting procedures for making ingots, thereby producing ingots of extremely high quality and fine metallurgical structures. Various shapes, such as rounds, squares, rectangles, or hollows, may be produced with thickness limitations yet to be determined. Length is dependent on casting pit depth, but other handling or working limitations may dictate maximum size. Melting and metal-handling procedures are controlled in order to minimize hydrogen (an undesirable gas), sodium, and nonmetallic inclusions. Filtering devices have been developed which have made major quality improvements.

Metal is poured from a melting furnace into a holding furnace for holding and refining. It is then transferred to the ingot casting unit using troughs and baffles that minimize turbulence. A short aluminum water-cooled mold is used to contain the metal. A bottom plate is lowered from the mold, withdrawing an ingot at a controlled rate and exposing the hot surface of the ingot to a water spray. This direct chill gives a very rapid solidification rate. The surface of the ingot generally shows liquation; this is removed by subsequent scalping.

The direct chilled ingots produced are sound and free of shrinkage and nonmetallic inclusions. Thermal stresses from the direct water chill can cause ingot splitting which presents problems on some alloys and sizes. Minor segregation of alloying elements does occur, but this segregation is much less than is obtained by other casting methods, or which is prevalent in other metals. The largest sizes produced to date are 60 in. in diameter, and a rectangular ingot of 26 x 72 in. These sizes do not represent the maximum size possible. Larger sizes will be produced when needed.

Chemistry of alloys is rigidly controlled. Ingots are fabricated after homogenizing, a high-temperature treatment to improve workability, on some of the largest and most intricate hot-working equipment in the country. Exact practices for a given product are regarded as proprietary, but rigid control and inspection procedures are exercised at each operation. A typical fabricating sequence might be: (1) homogenize, (2) hot roll, (3) solution heat treat, (4) stretch, (5) age, (6) saw to size.

As thickness of pieces increase, attainment of maximum properties and desirable structures becomes more difficult in most alloys. In the heat-treatable alloys, the maximum quench rate with water quenching is limited by the ability of heat to flow out of the piece. If minimum cooling rates are not attained, loss of mechanical properties and poor structures will result. The modified 7000 series of alloys are relatively insensitive to this section-thickness effect. Calculations indicate that satisfactory properties should be obtained in section thicknesses as great as 20 in. This should be of major importance in the deep-submergence program. It should be understood that the aluminum industry will have to determine quantitatively the effects of cooling rates on the mechanical properties of thick aluminum plates. If the modified 7000 series have the exceptionally low quench sensitivity claimed by the aluminum industry, then optimum mechanical properties can be obtained in heavy structural sections regardless of the fabrication processes used to form or join structural sections.

Representatives of the aluminum industry generally believe that in fabricating an aluminum section, e.g., in forming a hull from an aluminum plate, the section should be formed by the industry and given the proprietary heat treatment which will insure optimum toughness.

Ultrasonic procedures established by the Aluminum Association are used to inspect the quality of plates, extrusions, and forgings. The ultrasonic quality is based upon class "A" or "B" standards. These standards are related to a dimensional discontinuity, but the type or nature of the discontinuity is not defined.

OTHER SPECIAL CONSIDERATIONS

Fundamental factors which affect the life of a structure are the corrosion and fatigue resistance of the material used in the construction of the structural components. Of these two factors, corrosion is probably the one more difficult to take into account. This is because the specific conditions of the service often greatly affect corrosion rates; and these specific conditions are frequently not known or their importance is not appreciated in advance.

It is well known that aluminum alloys in a sea water environment may be subjected to corrosion, corrosion fatigue, and stress corrosion. The aluminum industry has produced alloys of the 5000 series having a large number of tempers. These were developed to resist a wide variety of environments and have permitted successful use in many marine applications.

The high-strength, heat-treatable alloys of the modified 7000 series do not have as high a resistance to corrosion as the 5000 series. However, improvement in fabrication, particularly thermal treatments and the development of suitable methods of protection (such as alcladding, protective coatings, or the application of cathodic protection) can prevent or minimize the detrimental effects of a corrosive environment.

It is reported that stress corrosion of the modified 7000 series can be reduced by proprietary aging treatments; for example, the stress required for short transverse stress corrosion level can be increased from 10,000 to 25,000 psi. Stress corrosion evaluation of a limited number of as-welded specimens indicates that they have good resistance to stress corrosion cracking; however, it is felt that a still lower resistance can be expected after artificial aging of the as-welded structure. Good resistance to stress corrosion cracking is restored to the welded structure by post-weld solution heat treatment and artificial aging; however, post-treatment may not be possible in large structures.

The problem of general and exfoliation corrosion becomes of prime importance since the aluminum alloy will be in contact with sea water environment and probably simultaneously with more cathodic metals. Protection by insulation, anodic materials, and the application of counter EMF will have to be studied. In addition, the effects of inadvertent grounding of the electrical systems and stray electrical currents will have to be considered in the corrosion studies. Stray currents follow paths other than the intended circuit corrosion will occur when currents flow between a metal structure and an adjacent electrolyte. Corrosion deterioration due to stray currents may be quite rapid when the aluminum hull of a submersible is tied up to a steel tender ship or is lying on the bottom of the ocean.

Rotating beam data obtained in air indicate that the 7000 series has a better fatigue stress life than the 5000 series; that is, the fatigue stress level to produce 100,000 cycles is approximately 38,000 psi for the 7000 series and 28,000 psi for the 5000 series. However, the corrosion fatigue stress level for these two series of alloys at 100,000 cycles will probably be around 21,000 psi.

A number of studies have showed that mercury or its amalgams which wet the surface of the aluminum can cause catastrophic stress corrosion failure. However, no data are available as to the effects of mercury on the stress corrosion life of the modified 7000 series of alloys.

RESEARCH AND DEVELOPMENT EFFORT

The aluminum industry does not foresee any major breakthrough in the development of high-strength systems in the next five years other than those depicted in Fig. 1. It is reasonable to expect that intensified effort will uncover variations in composition, thermal treatment, or mechanical processing that can provide substantial gains in the mechanical properties of aluminum alloys. Prediction of the nature or the extent of the gains to be expected in the next 5 years is of course hazardous. However, with the current rate of research, it seems reasonable to expect that base metal strength levels of weldable alloys in the 7000 series can be increased in the next 5 years by perhaps 20 percent with no significant loss in toughness or resistance to corrosion. If the research effort were doubled, an additional 15 percent increase might be possible in the same time period. The prediction for extending (EXT) the present weldable alloy systems by 1970 is depicted in the dotted areas of Fig. 1.

Although no entirely new basic alloy types are presently known that offer prospects for developing high strength, several alloying elements and combinations that have not been used previously in commercial alloys are being investigated, on a limited basis by the aluminum industry. Furthermore, the intricate interactions of different elements in complex alloys offer a multitude of possibilities for variation and change in characteristics. The current alloy development programs of the aluminum industry are applying information accumulated from various basic research programs and are being greatly assisted by use of relatively new investigative tools, e.g., electron microscopy and diffraction, fractographic techniques, and electron microprobe analyses. Cataloging of the fine structures formed in the different alloy systems and interpretation of alloying and heat-treating effects on deformation mechanisms may provide guideposts to improve existing alloy types. It is expected that a new system of alloys may be developed by 1970. The expected advances for new alloys are shown in Fig. 1 in the area marked NEW. With technical breakthroughs (W-B) it is expected that weldable alloys can be developed having the strengths and thicknesses shown in the single hatched area of Fig. 1.

The white areas at the right of Fig. 1 indicate the extension of strength and thickness of present-day alloys that can be joined by bolting or adhesives.

It may be possible to solve problems of stress corrosion, corrosion fatigue, and fracture toughness as a specific need arises. It is recognized that the problems of corrosion and notch toughness are not limited solely to aluminum but are also found in most other alloying systems. It has to be admitted that the stress corrosion, corrosion fatigue, and notch toughness characteristics of the high-strength aluminums required for submersibles will have to be studied in detail.

In design, there may be areas which are susceptible to stress corrosion cracking, such as the short transverse direction of the material when inadvertently exposed to the environment. If this is so, the effects of biaxial and triaxial stress on the exposed area will have to be known. This type of study is necessary since the amount of stress corrosion or simple corrosion data available on aluminum alloys were obtained under unstressed or uniaxially stressed conditions.

If mercury or its amalgams are to be used in conjunction with an aluminum hull or inadvertently come in contact with the structure, the effects that mercury and its compounds have on the fracture strength and dissolution of aluminum alloys will have to be studied.

As shown in Fig. 1, the section sizes for aluminum alloys required for deep-diving submersibles are quite thick. In order to obtain a homogenous wrought structure throughout the thickness, the ability of large ingots to respond to working will have to be studied.

Like other materials, aluminum alloys have anisotropic properties and the magnitudes of the directional effect depend on the amount of working given when going from the ingot to the final product stage; detailed studies will have to be undertaken to determine the optimum amount of work necessary to produce the minimum properties required for marine applications.

It is anticipated that the notch toughness of thick sections of aluminum alloys will be of acceptable level as shown in the cross-hatched area of Fig. 1. The projection on notch toughness can be considered as an educated guess based upon a very limited amount of data. Since the Navy has not developed criteria to date for evaluating this property for aluminum alloys, it may be that the cross-hatched area may be greater than, or less than, that indicated in Fig. 1.

The aluminum industry is conducting research on treatments which will increase the corrosion and notch toughness resistance of aluminum alloys. It will have to be determined whether these proprietary treatments are effective on thin plates which may be used in lamellar structures as well as on thick sections which may be used in monolithic structures. Studies should be undertaken to determine the effects that variations in proprietary treatments can have on the overall properties. These studies should examine the effects of removing surface layers, machining or burning of penetrations, welding, corrosion pitting, and the magnitude and type of residual stresses.

Since certain thermal treatments put the outer surface into compression and the area below the surface into tension, low-cycle fatigue properties would have to be investigaged.

Although the loading is compressive over major regions for submersibles going to deep depth, a cyclic load will be experienced in the mid-thickness of the material; that is, when the compressive loading stresses produced by submergence are combined with these residual tensile stresses, the material in the center will experience an alternating fatigue cycle. In the presence of a properly oriented defect, a fatigue crack may originate at the center and work its way out to the surface. Both structural model and material specimen fatigue studies will have to be undertaken on a suitable scale in order to obtain data for predicting the fatigue life of a full-scale submersible.

In the welding of aluminum alloy, surface preparation is important, especially in thick wall sections. Weldability studies that have been performed indicate that prior to welding, it is necessary to pre-weld, clean the base material, weld wire (by use of chemicals, surface wire brushing, etc.), and to protect the filler wire from the atmosphere. The effects of these preparations prior to welding will have to be determined in order to prepare quality-control standards for welding.

Developmental research work has to be pursued to increase the strength of weld deposit to match or exceed the strength of the base material. This is a necessary requirement since the design operating depth of a submersible is based on the minimum yield strengths throughout the thickness of the pressure bearing material. If the strength of weldments has approached its peak and is still below the strength of the base material, consideration can be given to increasing the section thickness where weldments are required in members carrying heavy loads.

Ultrasonic and X-ray inspection standards will have to be developed for detecting defects in thick aluminum sections. This work should be correlated with notch-toughness studies for determining tolerable defect sizes in the various thicknesses of plate and weldments.

Bolted construction will require studies of compatible materials, i.e., the material should be capable of polarizing under corrosive conditions in order to minimize corrosion deterioration. In addition, studies will have to be undertaken to insure that the bolts will remain fixed upon removal of compressive stresses from the hull material. If in submerging, the hull material compresses to a greater extent than the bolting material which is in tension, the bolt may become loose when the submarine surfaces.

At present there is no glue or cement which will not deteriorate after a 2-year exposure to sea-water environment. If adhesives are seriously considered for attachments which will be exposed to sea water, a concentrated effort will have to be undertaken to develop a suitable adhesive.

Foundry techniques and alloy systems for obtaining high strength in heavy section sizes will have to be studied. This is necessary to minimize the amount of dissimilar metals in a deep-diving submergence unit.

PREDICTIONS FOR 1980-1985

The aluminum industry does not foresee any radically new alloys. They feel some progress may be made by adding noble metals such as silver or rare metals not investigated to date. A breakthrough may come in the dispersion-hardening area or by the use of elements which will control the surface reactivity and the quench sensitivity. However, it is not believed that a marked improvement can be made beyond what is shown in Fig. 1 by modifying present alloy systems, or any alloy systems by 1970.

One of the aluminum producers has a contract with the Army for the development of aluminum base alloys. The approach is to study by powder metallurgy, a combination of age hardening and dispersion hardening and in Al-Zn-Mg-Cu alloy systems to which insoluble alloying elements are added. Extrusions were made up to 2 in. in diameter and with yield strengths averaging 120,000 psi. However, the ductility of this system as measured by percent elongation is negligible.

Another producer under in-house funds is developing means of continuous production of aluminum sheet from finely divided particles. This powder-rolling process permits a wide range of alloy composition which can be fabricated into sheet; that is, the atomizing or casting operation produces finely divided aluminum alloys that ordinarily could not be cast into ingot or even strips without segregation or cracking. No mechanical properties are reported for sheets made using this process.

Although both the powder metallurgy and the direct production of sheet from finely divided particles have a potential for marine structural applications, it is not possible to make predictions of future fabricability for marine structural applications.

FIBERGLASS REINFORCED PLASTICS AND OTHER FILAMENTOUS COMPOSITES

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INTRODUCTION

A composite material has been defined as a material which is composed of dissimilar materials which are bonded together by some means so that the component materials can act together in response to external conditions. The components are combined to achieve characteristics possessed by neither component alone. Fiber reinforced composites are being used in many structural applications because of their high strengths and strength-to-density ratios. Filament-wound glass-fiber reinforced epoxy composite is being used for Polaris and Minuteman rocket chambers. The strength-to-density ratio of this material in tension is far greater than that of any metal currently available. The properties of this material in compression are also outstanding and these are compared to other materials in Tables 1, 2 and 3. Glass reinforced plastic (G.R.P.) compares quite favorably with other materials on a specific strength or specific modulus basis. It is very appropriate therefore that this and similar composites be examined thoroughly for possible use as primary structural units in deep submergence vehicles.

In this section, the components comprising the composite are discussed first and forecasts are presented for improvements in their properties. The properties of the composites are then discussed along with projections of improvements. Emphasis is placed on glass-fiber reinforced epoxy resin composites through 1970 since this is the most likely material to be used in this period. Somewhere in the period 1970-1985, the glass-fiber reinforcement and the epoxy resin matrix will probably be replaced by superior materials now under development.

MATERIALS FOR FILAMENTOUS COMPOSITES

REINFORCEMENTS

Glass Filaments

1. Present strengths — It is assumed at the outset that high tensile strengths in glass fibers are indicative of relative freedom from damage and inherent flaws. Direct compressive strength data for the single glass filaments now in use for structures do not

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Table 1
Specific Strength of G.R.P. and Metals

Material	Design Stress ($lb/in.^2$)	Density ($lb/in.^3$)	Stress/Density (10^6 in.)
Epoxy-Fiberglass	100,000	0.075	1.3
	150,000		2.0
	200,000		2.7
Steel	80,000	0.28	0.3
	100,000		0.35
	150,000		0.5
	200,000		0.7
Aluminum	25,000	0.099	0.25
	50,000		0.5
	100,000		1.0
Titanium	100,000	0.17	0.6
	125,000		0.75
	150,000		0.9

Table 2
Buckling Strength and Stiffness of G.R.P. and Metals

Material	Compressive Modulus (E) (10^6 $lb/in.^2$)	Density (D) ($lb/in.^3$)	$E/D^{2.5}$ $\left(10^9 \dfrac{lb/in.^2}{(lb/in.^3)^{2.5}}\right)$	$E^{1/3}/D$ $\left(10^2 \dfrac{(lb/in.^2)^{1/3}}{lb/in.^3}\right)$
Epoxy-Fiberglass				
(1964)	5.6	0.075	3.7	23.6
(1970)	8	0.075	5.3	26.7
Fiber Reinforced Composite (1980)	40	0.075	26.6	45.6
Steel	30	0.282	0.7	11.1
Aluminum	10	0.099	3.2	21.7
Titanium	15.5	0.17	1.3	14.6

Table 3
Stress Required for Equal Stress/Density Ratios
for G.R.P. and Metals

Stress/Density (10^6 in.)	Required Stress ($lb/in.^2$)			
	G.R.P.	Steel	Aluminum	Titanium
0.5	37,500	141,000	49,500	85,000
1.0	75,000	282,000	99,000	170,000
1.5	112,500	423,000	148,500	255,000
2.0	150,000	564,000	198,000	340,000

exist. Filaments now commercially available have diameters near 0.00038 inch. These have zero compressive buckling strength in any useful length unless continuous lateral support is provided by the matrix, usually an epoxy resin for high strength filament windings. Nevertheless good lateral support is obtainable in composites. Since alignment, parallelism, and equal loading among fibers are never perfectly achieved in a structure, the strength of the composite cannot equal the sum of the strengths of all of its "parallel" elements. Likewise because of the statistical distribution of flaws in glass no matter how carefully made, some fractured filaments are always present in the structure.

The most common types of commercial high strength filaments available today are E glass and S or S994 glass, both sold with the "HTS" surface finish applied at the factory. This finish provides a considerable protection from mechanical damage which is always severe especially if a clean bare glass surface touches another similar surface.

The strength of the filaments can only be expressed in statistical terms and since the probability of a surface flaw occurring is proportional to the surface area there is an effect of specimen length on strength. In Fig. 1 is shown strength data for E glass freshly drawn and not touched except by the surrounding air. The average strength obtained from about 100 tests at each length approaches a maximum of 550,000 psi for short lengths. In Fig. 2, S glass (Owens-Corning) exhibits a maximum average strength of about 650,000 psi. It seems reasonable to suppose that with perfect alignment and lateral support the compressive strengths would not be less. In forecasting strengths obtainable in the future, we are guided by the predictions of the major glass manufacturers and by recent progress reported in the literature. Estimates of future obtainable properties of glass fibers are given in Fig. 3.

2. Effects of Moisture on Glass Strength -- Otto and others have shown that E and S glass fiber strengths are not appreciably affected by exposure to water or humid air for several months if no stress is imposed during exposure. On the other hand the presence of moisture even during a usual short time tensile test (10 to 30 sec) causes a drastic reduction in strength. This means that practically all of the data that we have on the

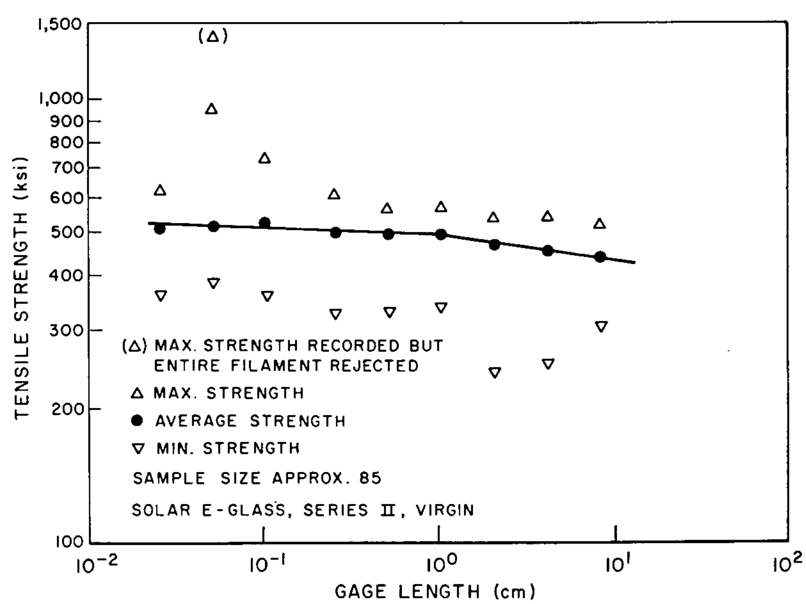

Fig. 1 - Strength-length relation of virgin E-glass

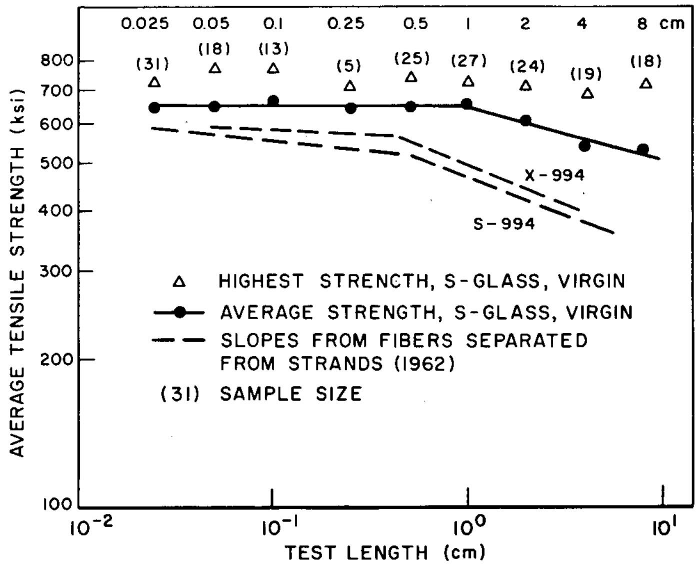

Fig. 2 - Strength-length relation of OCF S-glass

strength of glass filaments includes a large reduction caused by stress corrosion. Tests have demonstrated that at liquid nitrogen temperatures, with dry nitrogen surrounding the specimen, the strength of composites and of filaments increases by identical amounts, i.e., about 60 percent. This also means that present glass finishes and resins do not exclude moisture and that there is always a very deleterious amount present. It is anticipated that glasses will be compounded which will be somewhat superior to S and E glasses in this respect. In addition improved surface finishes will also be developed for better protection against moisture.

The density of glass filaments is not expected to change to a major degree.

Figure 3 gives summaries of forecasts for 1970 for glass filaments only. These were prepared after consultation with engineers at various glass companies. The cost projection shown would apply to any glass fiber with the properties indicated, as long as there is a market of the order of a million pounds, which would be required for a deep submergence vehicle. Modulus of elasticity "E" for glass filaments is not likely to ever become great enough to permit plastic composites to match titanium or steel. This objective probably can be reached by developing boron, boron carbides, beryllium or Al_2O_3 filaments.

3. 20-Year Forecast — The maximum properties will be reached in approximately 5 years. Other forms of glass and nonglass filaments will probably replace glass after 20 years.

Hollow glass fibers have been lightly considered here because a very wide variety of cross sectional shapes and ratios of ID/OD is possible and the direction of amount of R and D justifiable for such shapes is not clear. The use of hollow glass fibers instead of solid glass fibers would result in a thicker wall for the same weight and greater resistance to buckling. However, the hollow fibers could provide channels for moisture. The effect that this would have on the strength of the composite has not yet been determined. Also, by providing a jacket of metal or an outside layer of solid glass fibers, it may be possible to keep water away from the hollow fibers. This entire problem requires further investigation.

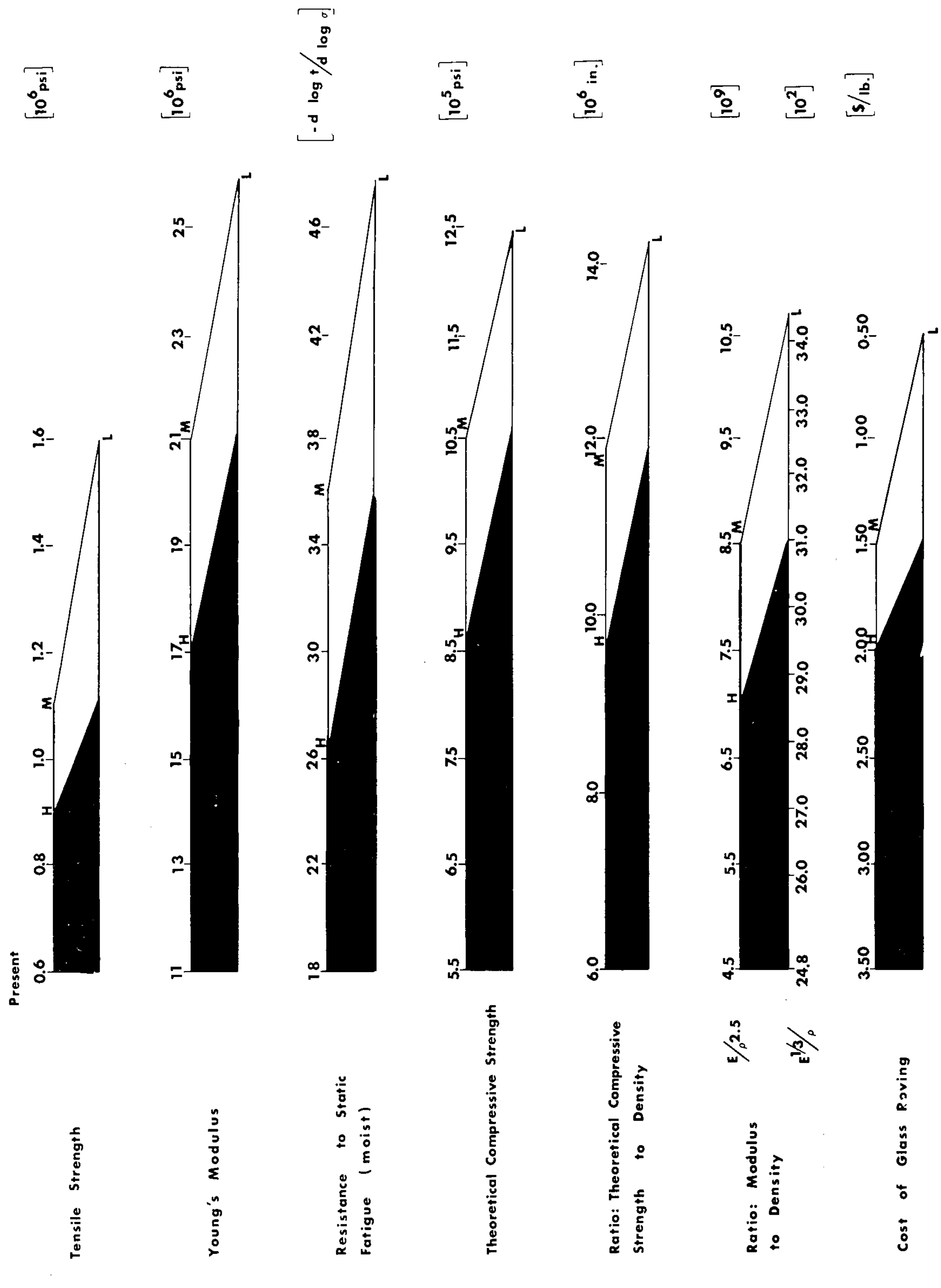

Fig. 3 - Commercial non-beryllium glass, single filament, 1970 forecast

Metals and Other Filaments, Whiskers

Metal wire has been evaluated as reinforcement in filament wound structures in the Polaris program. The results were disappointing. As shown in Table 4, the tensile strength to density ratio for glass filaments is far superior to that of any of the continuous metal filaments now available. However, continuous filaments mentioned here other than ordinary solid glass offer the promise of high modulus. Since modulus and density are pretty well known and subject to only minor changes with future development, the data are presented in tabular form. The objective of future R and D would be to reduce the price, make the materials more readily available, and determine the properties of composites incorporating them. Table 5 lists Young's Modulus, density and $E^{1/3}/D$.

Table 4
Properties of Reinforcements

Material	Tensile Strength (lb/in.^{2})	Density (lb/in.^{3})	Strength/ Density (10^6 in.)	Modulus of Elasticity (10^6 lb/in.^{2})
S-glass (Single filament)	650,000	0.091	7.1	12.5
S-glass roving (Strand test)	450,000	0.091	4.9	12.5
Beryllium	180,000	0.066	2.7	44
Boron	500,000	0.094	5.3	55
Steel (Music wire)	600,000	0.282	2.1	30
Titanium	250,000	0.17	1.5	15
Tungsten	400,000	0.695	0.6	50

Table 5
Some Properties of Continuous Filament Other than E Glass
and S Glass Solid Filaments

Filament	Not Subject to Change Except*				
	Density D (lb/in.^{3})	E (lb/in.^{2})	$E^{1/3}/D$	Theoretical† σ_{comp}/D	$E/D^{2.5}$
E glass, Hollow	0.06	6.7×10^6	33.0×10^2	5.6×10^6	7.59×10^9
SiO_2	0.083	11.0×10^6	38.3×10^2	6.6×10^6	5.56×10^9
Asbestos	0.072	25.0×10^6	43.0×10^2	17.4×10^6	18.0×10^9
Be	0.066	44.0×10^6	53.5×10^2	33.3×10^6	39.3×10^9
89% ZrO_2 11% SiO_2	0.148	50.0×10^6	24.9×10^2	16.9×10^6	5.96×10^9
B	0.083	$50.0^{*} \times 10^6$	49.7×10^2	15.0×10^6	25.2×10^9

*E expected to increase to 60×10^6 psi with R and D in 5 years.
†Theoretical strength = E/20.

Whiskers or single crystals in short staple fiber form are all extremely expensive now so that a revolutionary change in production methods would be required to make them useful for hull structures. However, they offer as a class the possibility of higher strengths. Table 6 lists some properties and these with a minor exception are not expected to change with R and D. The idea of using such short staple fibers for reinforcement has a precedent in nature. Wood is essentially lignin reinforced with cellulose fibers generally less than one millimeter in length.

Metal whiskers are not listed in Table 6 because they offer no advantages over those listed. The strengths and moduli are, in general, not higher and the densities are generally significantly higher.

The tensile strengths of whiskers are not listed in Table 6. They are often quoted as being approximately 2 million psi. However, these quoted values are for very short gage lengths and are generally maximum values. Whiskers offer no higher tensile strengths than glass fibers for equal gage lengths and diameters.

Table 6
Properties of Whiskers

Whisker	D (lb/in.^{3})	E (lb/in.^{2})	$E^{1/3}/D$	Theoretical† σ_{comp}/D	$E/D^{2.5}$
Be_2C	0.088	45 x 10^6	40.5 x 10^2	25.6 x 10^6	19.6 x 10^9
BeO	0.103	55 x 10^6	37.0 x 10^2	26.7 x 10^6	16.2 x 10^9
Al_2O_3	0.143	60* x 10^6	30.1 x 10^2	20.9 x 10^6	7.86 x 10^9
SiC	0.115	70 x 10^6	35.8 x 10^2	30.4 x 10^6	15.7 x 10^9
C	0.081	144 x 10^6	64.7 x 10^2	88.9 x 10^6	77.2 x 10^9

*E expected to increase to 70 x 10^6 in 5 years.
†Theoretical compressive strength = E/20.

MATRICES

Epoxy resins are used exclusively at the present as the matrix or binder in military filament-wound vessels. They are used in preference to other candidate materials such as polyester resins because of superior strength properties and resistance to water, and decreased shrinkage on curing. Glass-fiber reinforced epoxy composites are being used in such applications as the Polaris and Minuteman chambers and the Mark 57 mine case. The resins that are being used in these laminates are essentially the same as those available ten years ago, since there have been no major advances in the field of epoxy resins during this time period. This is no major drawback in the case of a rocket chamber, since in this application the resin probably plays a relatively minor role except at port openings involving cut filaments. This is because in internally loaded vessels, the glass reinforcement can act almost with no matrix. In addition, the time of loading is quite short, further reducing the importance of the resin. Thus the epoxy resins presently available have served satisfactorily in rocket chambers and it is probable that improved resins would yield only marginal improvements in internally loaded vessels.

In deep-submergence vehicles, however, the resin plays a much more important role. Its function, to oversimplify, is to provide lateral support to the fibers for resistance to buckling, to resist interlaminar shear fracture, to transfer stresses around discontinuities in the glass fibers, and to exclude water from the fibers. In addition to serving a role of increased importance, the resin must serve under more difficult conditions. Firstly, the period of load application is infinitely greater, so that creep effects become important. In addition, the environment, water, exerts a much greater degradative effect in the case of a deep-submergence vehicle than does moist air in the case of a rocket chamber. Therefore, much greater attention must be given to the resin.

There is every indication that with government support, major advances will be forthcoming in the field of resins for composite structures for deep-submergence vehicles. These advances are projected in Fig. 4. Government support will be required because of the very limited commercial requirement for this premium type of resin at the present. However, with some funded support, epoxy resins have improved in just two years to the extent that tensile strength has increased from 12,000 psi to 19,000 psi, compressive strength from 19,000 psi to 29,000 psi, and Young's Modulus has increased from 4.5×10^5 psi to 7.0×10^5 psi. These improved resins have been produced in pilot plant quantities and can be produced commercially with no problem when they are optimized. Further improvements of similar magnitude can be fully expected in the next few years. In addition, self-extinguishing epoxy resins could be developed in the same time period, having properties similar to those projected in Fig. 4.

Polyester resins have recently been developed having a modulus of 7×10^5 psi. It may be possible with sponsored research to improve other properties of this type of resin to overcome some of its shortcomings.

Another possible development in resins is the use of thermoplastic resins as the matrix in filament wound structures. This type of resin offers the general advantages of greater toughness and higher elongation than thermosetting resins. In addition, lower processing temperatures would probably be required, tending to reduce residual stresses. However, thermoplastic resins as a class tend to creep more readily than thermosetting resins, such as epoxies and polyesters. This tendency has not been studied as yet, though, for thermoplastic resins with glass fiber reinforcement loaded in compression. As progress is made in this field, a complete evaluation of these materials for deep submergence vehicles should be made. Some preliminary work on the use of phenoxy resins for filament winding has been conducted with very encouraging results, indicating the desirability of further study.

Considerable work is being done on developing new heat-resistant polymers, mainly for space applications. These include inorganic polymers, polybenzimidizoles and polyimides. The inorganic polymers show a possibility of having high strengths, low water permeability, and coefficient of thermal expansion more nearly that of glass. The polybenzimidizoles show promise of being tough and having good adhesive properties. However, they all require very high processing temperatures, which would involve changes in the present fabricating techniques. As these materials reach a more advanced stage of development, a more thorough evaluation of their properties will be required. At the present, they can only be considered as developmental materials to be considered for the future. They are indicative of the wide horizons available for new matrix materials.

In support of work on improved matrix materials, studies should also be conducted of the exact role of the matrix in a composite. This would help to establish more clearly the specific resin properties that should be improved for improved composites.

In discussing resin matrices, it is appropriate to discuss curing agents. The dimensions of a deep-submergence vehicle would make it desirable that the fabricated structure be cured at room temperature. Although room temperature curing hardeners are available for epoxy resins, the properties of resins cured with these agents are not as high as those cured with elevated temperature curing agents. Some work should be directed toward the improvement of room temperature curing hardeners.

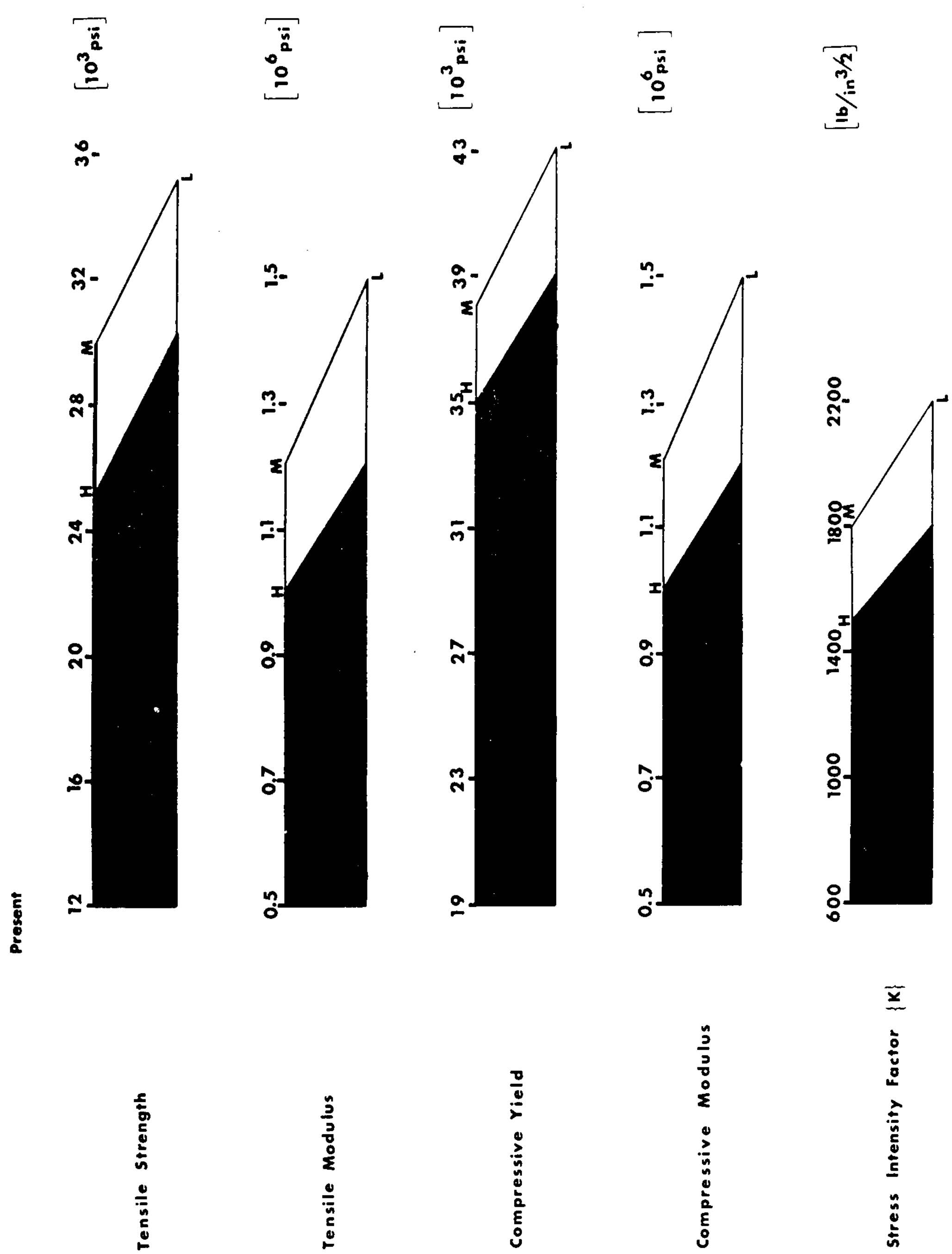

Fig. 4 - Commercial epoxy resins, 1970 forecast

Finally, some thought is being given to a composite consisting of a ceramic matrix reinforced with metal or ceramic fibers. This would yield a high strength, high modulus material. A high modulus reinforcement and a low modulus matrix should be used. Possible ceramic matrix materials are the oxides, glasses and chemical cements. There are many potential high modulus fibers that might be suitable for the reinforcement. The main problems in fiber reinforced ceramics are in fabrication. It is conceivable that this type of composite could achieve a tensile strength of 150,000 psi, a compressive strength of 300,000 psi and a modulus of elasticity of 30×10^6 psi. This is a field in which some work should be started now so that it could reach the stage of practicality in the 1970-1985 period.

Research Program

The matrix program should be directed mainly toward the improvement of epoxy resins. In addition, some effort might be devoted to the improvement of other resin systems appropriate for the filament winding process, such as polyesters. The possible use of thermoplastic resins as matrices should be explored. A program for the improvement of room temperature curing agents should be initiated. An analytical and experimental program to elucidate the role of the resin in a composite loaded in compression should also be initiated. Preliminary work should be started on ceramic matrices.

The field of polymers, which are used primarily as the matrix in structural composites, and the field of composites are changing so rapidly at the present that it is difficult to project a matrix research program beyond 1970. It will depend on the state of development of reinforcements and polymers at that time, and will be guided by fundamental information on the theory of composites now being derived in research programs. Therefore, no specific recommendations are included for a matrix research program beyond 1970.

SURFACE FINISHES

Surface finishes are chemicals applied in solution to fibers as they emerge from the drawing bushing. They are used to protect the fibers from abrasion against one another and to improve the wet strength retention and fatigue life of composites made with these fibers. The exact mechanism by which finishes provide this protection has not yet been defined. An explanation of this action is needed to guide research for further improvement in finishes which will reduce the loss of strength of composites as a result of fatigue loading or exposure to water.

A fundamental program is required to accomplish these aims. Such a program should include:

1. Studies of the reactions of the glass surface with typical finish functional groups.

   a. Investigate the nature of the interaction with glass.

   b. Determine how different chemical groups affect water sorption at the glass surface.

2. Studies of wetting at the glass surface -- how it is affected by various chemical groups on the surface.

3. Investigation of the effects of various groups on the glass surface on resin interaction.

   a. Effects on the type of bonding between the resin and the surface.

b. Effects on wetting of the surface by the resin.

4. Studies of the effect of water on the strength of glass fibers.

a. Effects of various types of finish functional groups applied to the glass surface.

b. Effects of resins forming different types of bonds with the glass surface.

Beyond this, it is necessary to develop simple test methods for evaluating finishes. This would be directed toward predicting long term effects of different environments on composites as a function of the finish used.

A significant effort directed toward the fundamental approach outlined above has been initiated within the Navy in the past twelve months. It is quite reasonable to expect significant advances in the fields of finishes in the next five years which will be reflected in major improvements in wet strength and fatigue life of glass-reinforced composites.

AUXILIARY MATERIALS

Coatings*

1. Status of Research — Progress in coatings research closely parallels the development of new polymers. Some idea of the versatility of polymers can be gained from many examples of polymers of the same general class finding application in the fields of coatings, plastics, adhesives, and sometimes elastomers. The field of coatings is the oldest and best developed of these technologies, and major furtherance of the state of the art is not foreseen in the near term, i.e., period ending 1970. There is very little likelihood that the water permeability of organic polymers will be appreciably reduced below the rates now provided by coatings such as Saran F-120† (0.15 grams H_2O/100 sq. in. of 1 mil film/24 hrs. at 100°F and 90% R.H. - differential); Hypalon - 30‡ (approx. 0.5 gm H_2O/100 sq. in. of 1 mil film/24 hrs. at 100°F. and 100% R.H. differential); and the copolymers of vinyl and vinylidene chloride (approx. 0.20 gms. H_2O/100 sq. in. of 1 mil film/24 hrs. at 100°F. and 90% R.H. differential). However, there is a good opportunity to reduce, through chemistry, the water permeability of some of the coatings that are relatively poor in this respect — the polyesters, polyurethanes, alkyds, epoxies, and some others. Rendering the coatings more dense through halogen substitution at various points in the polymer is a reasonable approach to this end. Copolymerizations to include highly water-impermeable types is another approach, and unquestionably, there exist other avenues of research to greater water impermeability of the polymers themselves.

It is likely that much more productive avenues for developing maximum water resistance are via formulation studies of leafing pigments, and "engineering" techniques for the production and application of very thick coatings — perhaps inches thick. Actually, the latter method would be more analogous to the application of a plastic skin, probably of a thermoplastic polymer that could be fabricated in sections, and heat-fused to adjacent sections.

There has been, and continues to be, a need for anechoic coatings. It is not too difficult to formulate such coatings that are specific to a narrow spectrum of sonar energy,

*The potential for using massive metallic "skins" is considered self-evident, and therefore is not a part of this study. However, in the event that metal skins are used, it is likely that they in turn may require protective finishes to prevent corrosion and fouling, and for the provision of anechoism.

†Trade name product of the Dow Chemical Company.

‡Trade name product of E. I. duPont de Nemours and Co.

but broad spectrum anechoic coatings have not yet been developed. Theory predicts great difficulty in the development of coatings having broad spectrum anechoism over great ranges of pressure (depth) because the required coatings would have to manifest the properties of a variety of components having vastly different mechanisms of energy absorption. This is a highly important area of research for military applications, and, therefore, deserves continued effort by the most highly qualified researchers. However, a slow rate of progress is foreseen.

Epoxy coatings and sealants that will polymerize under water are in an advanced stage of development. Some types, approaching the properties of mastics in application, already are in use. This class of materials could be very valuable as sealants, and should be fully developed prior to 1970.

The foregoing remarks pertain to exterior coating systems for deep ocean structures. The Navy's current sea based deterrents have revealed a need for internal coatings having special qualities. There is a need for coatings that evolve no toxics in application. These coatings also should be fire retardent. Good progress toward these ends has been made in recent years, and both problems should be solved through research prior to 1970.

The technology of antifouling coatings and anticorrosive coating is in good order, and no problem is foreseen in adapting existing types to deep ocean applications. There is, in fact, evidence to indicate that fouling in the deep ocean is not a serious problem.

Existing types of antifouling and anticorrosive coatings are expected to fully meet the requirements of deep ocean applications. The antifouling coatings will provide two or more years of excellent protection in almost any environment. There could be some difficulty in attaining satisfactory adhesion to some substrates, particularly titanium, aluminum, and the very high strength steels. However, it is believed that this problem can be overcome by resort to special types of surface pretreatments; this has been a long standing practice when adhesion is difficult to obtain.

Adhesives

Improvements in adhesive bond strength in composite structures will probably originate primarily from improved joint design. Much work along this line was done in the Polaris program and resulted in marked structural improvements. A great deal of this information can probably be utilized in an externally loaded vessel but additional studies will be required.

There will also undoubtedly be improvements in the strengths of adhesives themselves. Epoxy resin adhesives are being used primarily in Polaris chambers. One can predict that the increase in adhesive strength will parallel the increase in strength of epoxy matrix resins, previously discussed.

In addition, studies are being made of the application of fracture mechanics to adhesive joints. This may yield information which could guide the design of joints and the selection of suitable adhesives.

PROPERTIES OF FILAMENTOUS COMPOSITES

INTRODUCTION

The following text is an amplification in considerable detail of current and forecast properties. These are graphically presented in considerably streamlined form in Fig. 5.

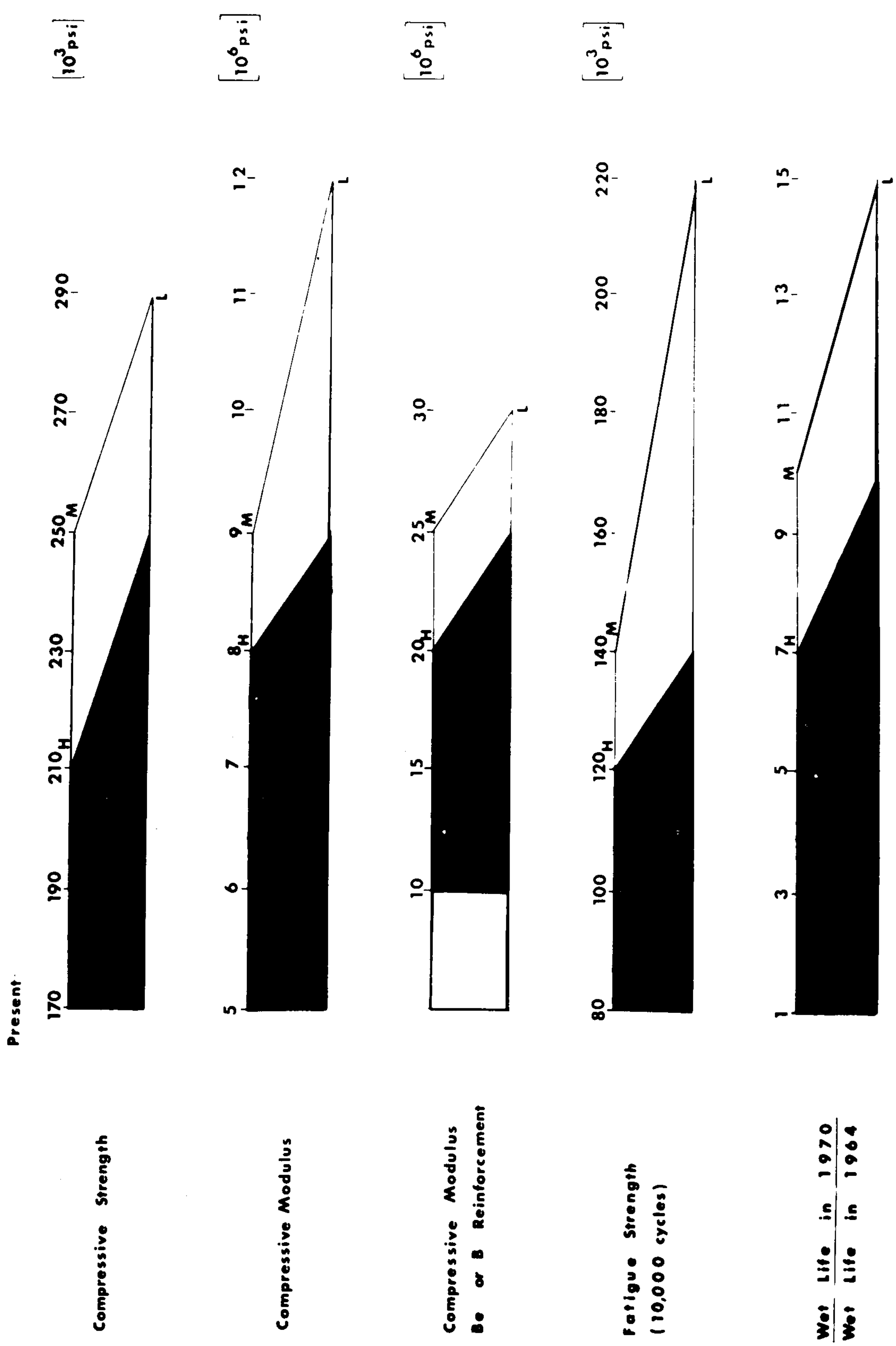

Fig. 5 - Filament-wound glass reinforced plastics. 6-inch diameter test cylinders. 1970 forecast.

Composites or multiphase materials are highly anisotropic and gain their properties through the combined action of their component materials. Their mechanical characteristics can be therefore designed into a complex structure in any desired direction giving them an advantage over isotropic materials. Structural reinforced plastics are unique in many other ways as listed in Table 7.

Table 7
Advantages and Disadvantages of Filament Wound Glass Reinforced Plastics for Deep Submergence Hulls

I. ADVANTAGES

Filament-wound plastics have gained recognition as potential structural materials for deep-submergence hulls, primarily because of high strength: weight characteristics.

Other advantages are that reinforced plastics are:

a. Non-corrosive
b. Non-magnetic
c. Non-critical (readily available supply)
d. Thermal insulative
e. Sound and vibration attenuative (in plane of lamination)
f. Dielectric
g. Easy to fabricate; F.W.P. process is automated, hence it is amenable to quality control; there are no foreseeable limitations to size; anticipated improvements in materials do not necessarily create new fabrication problems; no specialized labor requirements.
h. Amenable to high speed production and show a consistent trend of decreasing raw material prices point to potential finished product costs of $2/lb.
i. Capable of being used in F.W.P. — metal composite construction and sectionalized for ease of modification and repair.
j. Tough (Izod impact is in the neighborhood of 35-60 ft. lbs per inch of notch; toughness and strength increase with decreasing temperature).
k. Proven in that models have been tested which meet arbitrarily established performance standards.

II. DISADVANTAGES RECOGNIZED

a. Non-metallic (Non-ductile)
b. Cannot be fabricated using conventional metal-working techniques (welding, bending and forming).
c. Absorb water and lose a fraction of "dry" strength if no jackets or other external protective means are employed.
d. A new family of materials (date back ten years with regard to mine case applications and three years for deep-submergence applications — 12-year submarine use in fairings; 20 years entire history for glass reinforced plastics).
e. Need to develop background and basic knowledge with regard to materials, long-term performance, fabrication and design to raise acceptance and confidence level.
f. New design concepts, approaches and attitudes are required.
g. Abrasion resistance and cavitation erosion resistance may be problem areas.

In assessing the properties of composites, care must be taken when interpreting test results. Methods devised for isotropic materials are not ideally suited to composites and are not completely meaningful in themselves. Therefore, one must eventually indulge in model and prototype testing just as with metallic structures.

In view of the above, a knowledge of and the ability to interpret property data in terms of applications becomes important for deep submergence. New test methods, increased data collection, and test method standardization are each needed for direction and coherence on the use of composites.

STATE-OF-THE-ART

The properties of composites are determined using several test methods on specimens of varying complexity. Simplest of these are specimens cut from flat laminate panels. (These, in concept, are really quite sophisticated structures.) Next, NOL rings and plain right circular cylinder forms are used. Of final complexity are the models and prototypes relating closely to the final application. A wide variety of tests as inferred above is necessary since one is measuring the properties of an anisotropic structure in which fabrication is a variable. These are not simple isotropic materials characteristics.

For the purpose of this report, however, data is being presented only for the cylindrical models and prototype specimens, since these represent most nearly the form in which the material will be used. It has been pointed out previously that the results one obtains in testing composites depends on the form in which they are tested.

Models and Prototypes

Several models and prototype testing programs have established a body of data on the underwater performance composite structures. These are summarized below for cylinders with a 2 circumferential: 1 longitudinal glass fiber orientation.

1. Unstiffened Cylinders

a. Short-term hydrostatic biaxial tests: Hoop compressive strengths of over 170,000 psi have been developed. It has been shown that actual performance of these cylinders will closely follow theoretical predictions. These data demonstrate a superiority of reinforced plastics over other materials for underwater pressure resistance.

b. Hydrostatic biaxial fatigue tests: Tests demonstrate that cylinders will withstand approximately 10,000 cycles at 80,000 psi hoop compressive stress levels (Fig. 6). Improved cylinders should yield higher results. These results were obtained in numerous fatigue tests in which the specimens were cycled up to the stress indicated until failure occurred. The rate varied from 30 to 500 cycles per hour (CPH). In the tests conducted at 30 CPH, the specimens were maintained at the maximum load for 1 minute during each cycle. These changes in cycling rate did not appear to affect the fatigue behavior.

c. Hydrostatic biaxial static fatigue (creep):

(1) Specimen stressed to 42,000 psi (hoop compression) - 1-1/2 years - still going on.

(2) Specimen stressed to 86,000 psi - 6 months - still going on - longitudinal creep strain 100 micro inch/inch; circumferential creep strain 500 micro inch/inch. Since total strain at rupture is on the order of 25,000 micro inch/inch, it has been concluded that creep will not be a significant factor in the deep-submergence application.

2. Ring-Stiffened Cylinders

a. A ring-stiffened cylinder with weight displacement ratio of 0.54 has been designed using the following material characteristics:

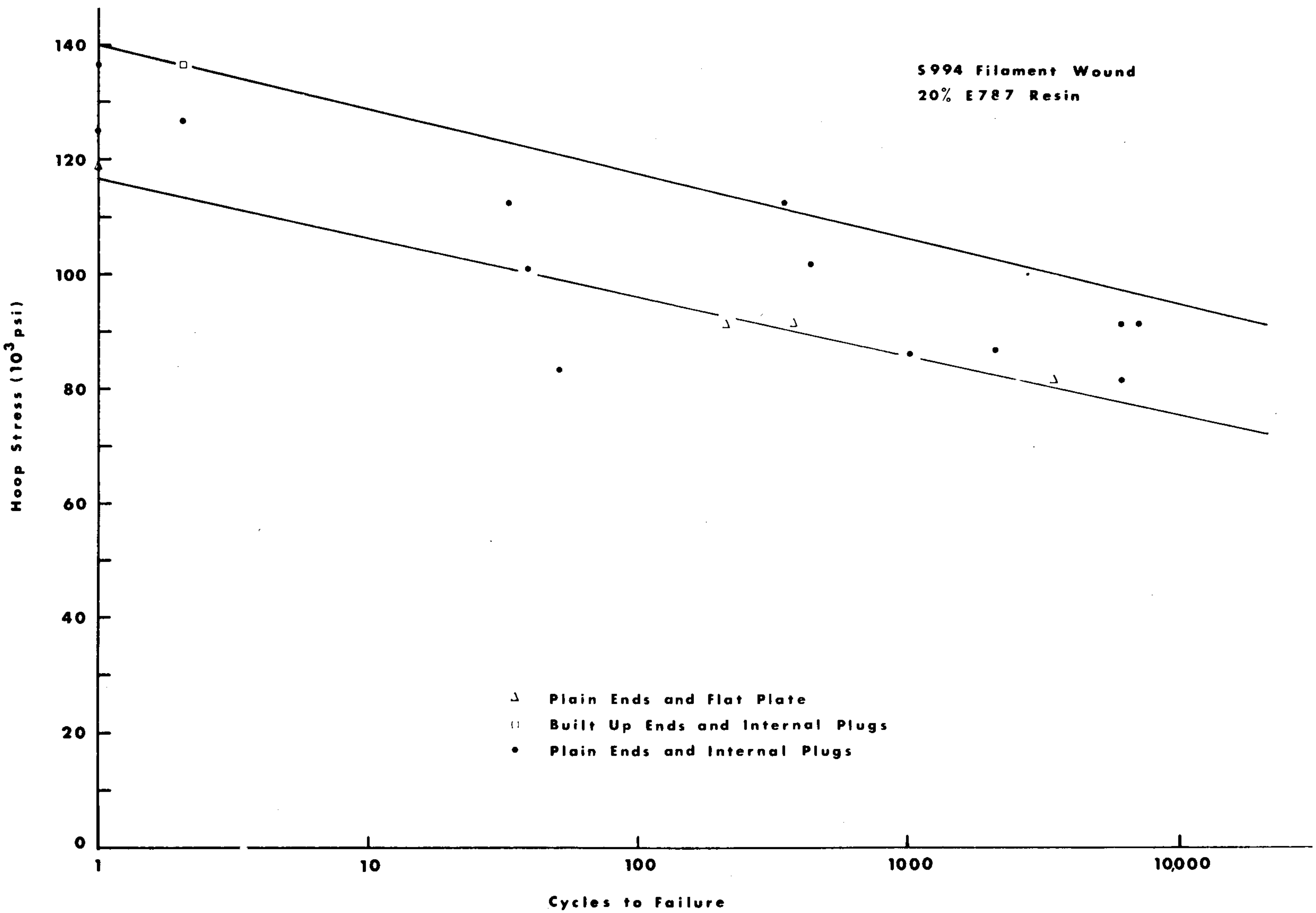

Fig. 6 - Biaxial fatigue data filament-wound cylinders under external hydrostatic loading

Ultimate Compressive Strength (circumferential) 100,000 psi

E (circumferential) = 6×10^6 psi E (frames) = 7.25×10^6 psi

E (longitudinal) = 4×10^6 psi Poisson's ratio = 0.15

(1) Short-term biaxial, hydrostatic tests indicate such models meet the design collapse depth of 30,000 feet (13,330 psi).

(2) Cyclic fatigue tests between 0-15,000 feet pressure (6700 psi) for 10,000 cycles — no apparent damage when ends properly sealed — very little apparent reduction in strength when static tested after subjecting to fatigue testing. A series of cylinders (5) made as identically as possible except for variation in method of attaching ring stiffeners, exhibited a coefficient of variation of 8%.

b. Ring-stiffened cylinders with end-closures, through-hull penetrations in cylindrical hull and in end closure. Assembly Weight: Displacement Ratio = 0.64 - meet the short-term and cyclic fatigue performance requirements above.

Use History

Two applications of filament wound glass reinforced plastics provide experience apropos to the deep submergence problem. These are radome masts and the Mine Case Mk 57.

Radome masts without any protective coatings have been in use on POLARIS and fleet-type submarines for over two years. One is the BRA-9, which is a streamlined radome, 7-3/4" x 12-3/4" x 234 long. Another is a cylindrical radome, 6-5/8" o.d. x 194" long. Radome masts are proof tested at 950 psi external pressure and see the same service extremes as the submarine.

EXPECTED STATE-OF-THE-ART IMPROVEMENTS — 1970

Models and Prototypes

Higher strengths will be realized in models and prototypes through the use of improved reinforcements and matrix materials and improved design. In addition, better test methods should yield more definitive data. There are indications that many of the results obtained to date on test models represent the limitations of the model and not the inherent property of the material itself. It is expected in five years that models, based upon 210,000 psi hoop compressive strengths and moduli of 8×10^6 psi, with hull weight displacement ratios of 0.45 can be built. These will be able to operate at a 15,000 ft. depth with a factor of safety of 2. It is also projected that the fatigue strength at 10,000 cycles will be 120,000 psi and that the wet life will be increased seven to ten times over the present. In addition, it should be possible by 1970 to wind 6-inch cylinders using a high modulus fibrous reinforcement such as boron or beryllium, which would result in a composite with a modulus of 20×10^6 psi. These projections are shown in Fig. 5. In 20 years, compressive strength should be up to 300 to 400,000 psi with moduli of 30 - 60 x 10^6 psi. Then a hull weight/displacement ratio of 0.2 may be enjoyed with operation at a 30,000-foot depth.

Test Method Improvements

As potential composite properties are realized, problems may be anticipated in development of valid test methods.

1. It is expected that current methods for determining the following properties will be applicable with little or no development work: compressive and tensile modulus, interlaminar shear strength, Poisson's ratio, and environmental effects on properties and permanence.

2. Determination of the following properties may require development of new methods or extensive modification of existing methods: compressive, tensile, shock and impact strengths; creep, fatigue and stress rupture characteristics. Fracture mechanics will also require new techniques as will the measurement of built-in stresses in the structure. Problems in all these areas will increase as wall thickness increased. In all instances work will be required on method standardization, including round-robin testing. Other tests should be made to better understand the performance of materials under bulk compression.

Data Accumulation

Considerable effort will be required to accumulate data on materials properties to assist in development of engineering design characteristics and to establish confidence levels.

R AND D PROGRAM

Objectives

New test methods will be developed to further knowledge and confidence in reinforced plastics. Data accumulation on standard and newly developed materials will be carried out using flats, rings, and models. These data will be correlated and related to end-item application. Test methods will be standardized.

Approaches

Several test methods for all types of specimens are available in Navy laboratories and in contractors plants. These will be standardized and used on a continuing basis. New methods will be developed in the areas of shock loading, creep, fatigue, fracture mechanics, measurement of built-in stress, properties of thick-walled sections, and moisture vapor transmission.

APPLICATIONS CONCEPTS

INTRODUCTION

Nonmetallic materials are not simply substitutes for metals or to be used in structures designed to be constructed of metals, at least in the tradition of relying heavily on ductility as defined in terms of elongation, reduction of area, and Charpy transition temperature. It is feasible to use the nonmetallics in special structural concepts.

Massive glass has almost zero strength in tension except for the compressive surface layer produced by tempering or chemical treatment. Glass fiber reinforced plastics, although very strong in tension, are porous, at least under biaxial tension. Under hydrostatic compression, g.r.p. is not porous and is highly resistant to water penetration. For such materials a structural design should provide for them to be always in compression and this is more likely to be difficult for operations near the surface than for deep submergence.

H. Perry has submitted a separate report on glass and other so called Bridgmanites and E. Bukzin is dealing separately with buoyancy materials. Therefore this report is primarily concerned with filament reinforced plastics and their combination with metals.

RECENT R AND D IN SMALL MODELS OF G.R.P.

A considerable and successful R and D program in materials and model design and testing has already been accomplished in the Bureau of Ships program, and a review of this is submitted herewith as a separate report by K. Hom et al. Strength values both computed and measured for a few specific models are given therein. These together with the section by R. Barget et al., submitted as part of this report on strength properties of small scale pressure vessels, form the basis for making the forecasts shown in chart form in this report. The data include many pressure tests of cylinders, both stiffened and smooth and with one cycle and with fatigue cycling from 1 to more than 10,000 cycles.

The 1970 forecast for design capability of filament wound glass reinforced plastics is shown in Fig. 7. This forecast is based on the tests previously referred to and the materials projections, as shown in Figs. 3, 4, and 5. It is considered conservative and starts from 1964 as one-half the compressive strength achieved in short-time tests. The design stress includes a minimum factor of safety of 30 percent for all conditions of loading. As in metal structures, fatigue can be a problem in g.r.p. if designs do not avoid unwarranted notches and sudden changes in stiffness. Even considering the low level of sophistication in design and fabrication achieved thus far, we expect to retain more than 90 percent of the initial short time strength after cycling for as many as 10,000 cycles at the strength levels shown in the charts. This is expected to improve greatly but this is largely up to the designer and outside the area of this report.

JOINTS AND OPENINGS

Some work has been done on 6-inch diameter models to evaluate joints and openings in cylindrical composites. The test results have been quite satisfactory. The openings were reinforced with a metal ring. Joints were lap joints. Also, molded end closures attached to cylinders have performed satisfactorily. There will undoubtedly be some problems encountered in this field, in scaling up to large diameter vessels, and R and D work is required. However, it is not anticipated that the problems will be insurmountable. Many of the problems posed by joints and openings can be greatly reduced by proper design.

Since the joint and opening problem is primarily a design problem, it is expected the panel on structures will deal with this.

FUTURE STRUCTURAL CONCEPTS

This topic is necessary in forecasting the capability of the nonmetallics for reasons already stated. Examples of future design concepts in which F.R.P. and other nonmetallics will appear to advantage in the future are as follows:

1. <u>Prestressed Composite Construction with a Metal Outer Shell such as Titanium Alloy or Steel</u> — The emphasis on prestressed construction is deserved because only by precompression maintained by tensile stresses in an outer shell can we achieve the following:

a. Adequate load acceptance in the relatively low stiffness g.r.p. when metal must strain compatibly with the g.r.p.

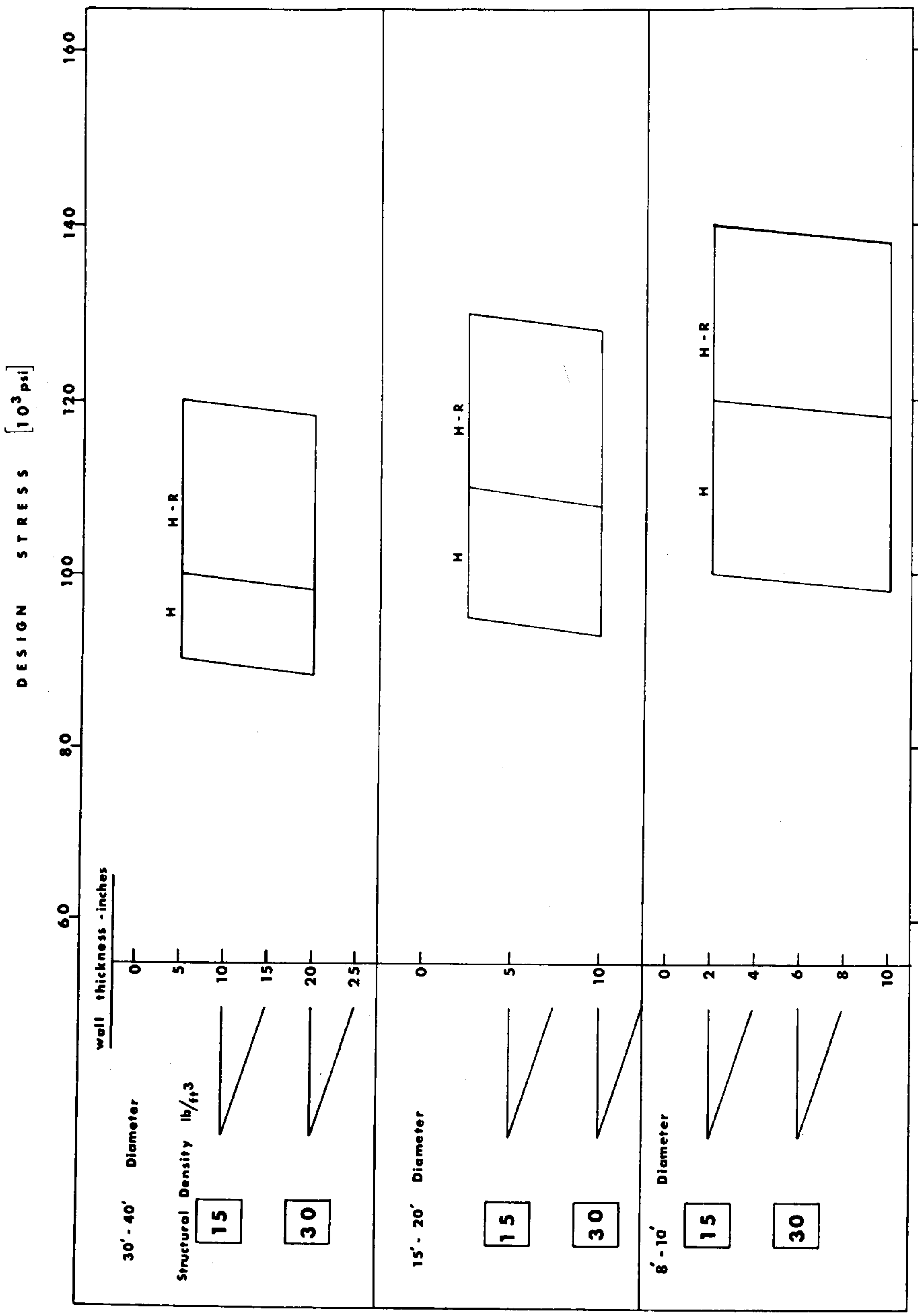

Fig. 7 - Filament-wound glass reinforced plastics. Spheres and cylinders. 1970 forecast.

b. At maximum depth or pressure the metal must not approach compressive yielding stresses or strains; otherwise low cycle fatigue will damage the metal. Adequate prestressing can keep the metal in a safe fatigue range.

2. Metal - f.r.p. Combinations — In paragraph (1) preceding, we have suggested a metal outer shell for f.r.p. merely for considerations of effective loading in a safe range. There are other advantages to be gained by future design, materials, and structural studies including f.r.p. and metals. These are to list a few:

a. Maximum leak resistance.

b. Abrasion and mechanical damage resistance.

c. Simple joint requirements for segmented structures.

d. Protection of f.r.p. from possible water degradation not yet fully explored and predicted.

e. Laminar construction stops cracks attempting to travel through the thickness.

f. The outer metal shell can be ribbon or otherwise wrapped for multilayer construction.

3. Special Shapes

a. F.R.P. should probably never be used to make spheres if those spheres must provide large access ports. Cut filaments at ports require heavy reinforcement. This would involve a heavy weight penalty at an equatorial joint between hemispheres.

b. Toroidal shapes in two or more segments joined by metal flange fittings offer a natural advantage in ease of fabrication and minimum problems of access. Segments would be replaceable and thus facilitate damage repair. Theoretical and experimental work on this shape have scarcely started.

c. Ellipsoids permit natural geodesic isocompressoid windings if only one port opening is needed or two opposite and equal ports are desired. Theoretical and experimental work for internal pressure vessels has been highly developed on missile programs. It is recommended that similar studies be conducted for external pressurization. There would be not cut filaments. The windings would go around metal port reinforcements and the hatch covers would be a separate part, perhaps metal.

RELIABILITY DEMONSTRATION AND ELIMINATION OF STRUCTURAL SENSITIVITY

It is essential to the achievement of the 1970 forecast that a generous R and D and testing program be conducted using fair sized models, say up to 9 ft in diameter with components especially placed to produce and then eliminate structural sensitivity to fatigue and premature failure from unnecessary stress concentration. Such a program has not as yet been started. There is a question as to whether the planning and funding should be under materials or under structures research. It is important to combine the two in this area. We have not included this as yet in our budget request in the belief that it will be covered by the structures panel under Dr. Liebowitz.

1980 FORECAST

In the f.r.p. materials we do not visualize a slow steady growth of performance beyond 1970 by small increments. It is instead predicted that drastic improvements will occur as breakthroughs when such things as boron filaments become available, which offer large sudden improvements over the upper limit of properties in glass filaments. The forecast of capability for 1985, shown in Fig. 8, is based on such reinforcements.

R AND D PROGRAM

The R and D program to advance this field should consist of the following studies:

1. Improved design of cylindrical hull structures.

2. Development of core materials for sandwich structures.

3. Investigation of hull shapes other than cylinders.

4. Studies of failure mechanisms of laminated orthotropic structures.

5. Studies of design limitations of filament wound structures.

6. Investigate composite hull structures other than glass-reinforced plastics.

7. Determine the structural response to dynamic loads of hulls fabricated from composite materials.

8. Determine structural response of reinforced plastic pressure hulls subjected to a deep-sea environment.

9. Investigate improvement of joints and openings.

10. Study methods for installation of equipment and mounting heavy machinery to non-weldable hulls.

FABRICATION OF FILAMENT-WOUND VESSELS

TECHNIQUES

There is no inherent reason why the present general method of filament winding could not be used for winding a large deep-submergence vehicle. The process is readily amenable to scaling up, with only engineering problems to be solved, largely by design and development studies. In the period of less than a decade, the filament winding process has been improved from little more than a laboratory curiosity to one having the control and reproducibility required for major structural components for missiles. The size of military production items has increased to over 4 ft in diameter and over 12 ft long. Last year, the Hercules Powder Company wound a chamber 13 ft in diameter and 25 ft long, merely to show that it can be done and done simply. Aerojet-General Corp. has a contract to fabricate a chamber 260 in. in diameter and 65 ft long. No unanticipated problems have developed in this program. It has merely required a modification of existing techniques. There is no reason why the advance could not be extended further to 25 ft and 35 ft diameters with greater lengths and wall thicknesses than are now being fabricated.

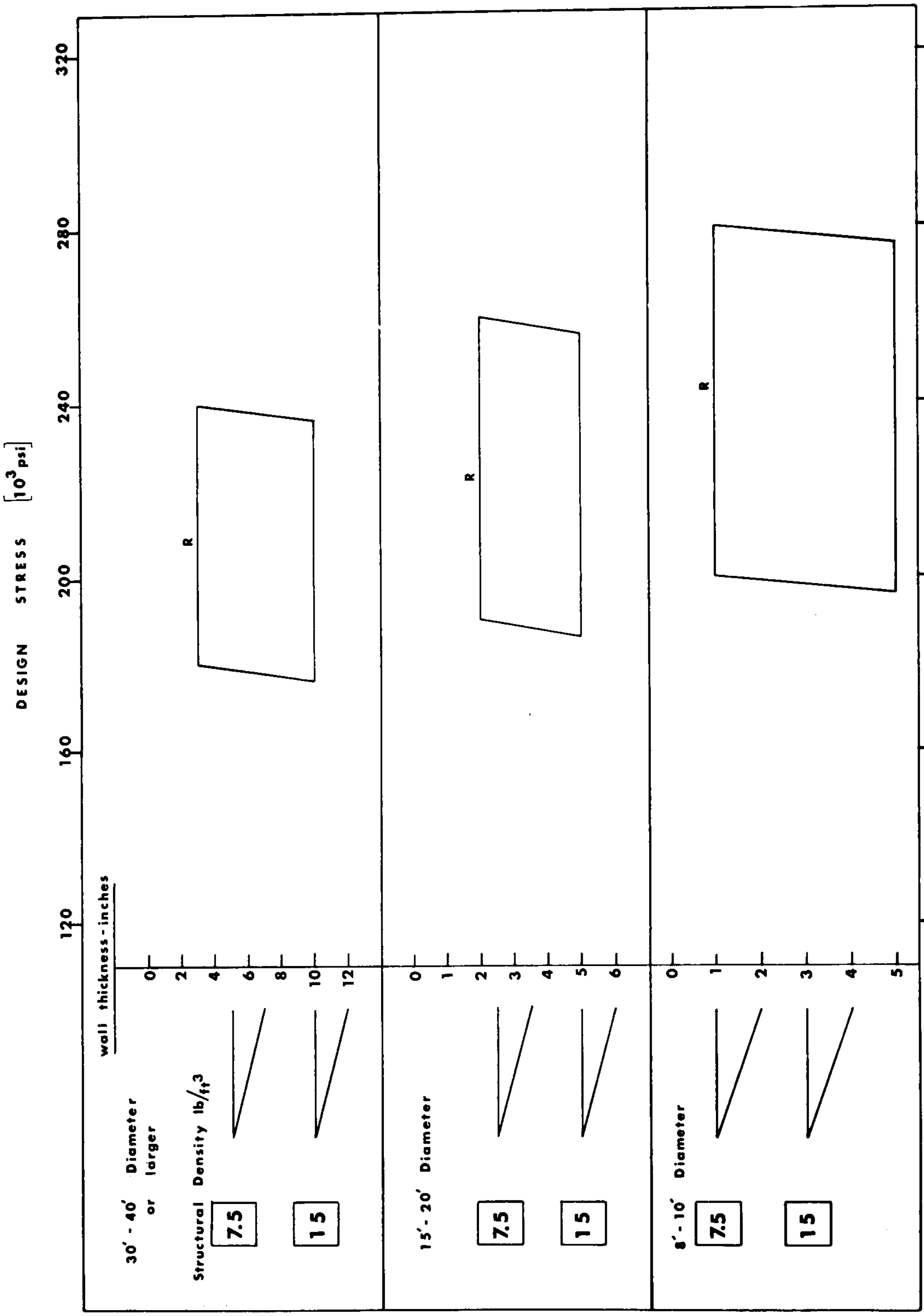

Fig. 8 - Fiber reinforced composites, 1985 forecast

Consideration is already being given by fabricators to the solution of some of the obvious engineering problems that will be encountered in scaling up to a 30-ft diameter structure. These include the winding machine and winding pattern, winding speed, type of mandrel, type of raw material, compaction, and cure. There is no indication of any insurmountable problem among these. Some of the solutions proposed are considered proprietary at the present time. Nevertheless, it can be stated that two types of winding machines are considered feasible — a horizontal machine and a vertical machine. Both would be capable of winding the circumferential and the longitudinal windings. The winding speed, or the rate at which the material is applied to the mandrel, can be varied greatly, merely by adding more spools of fiberglass to the creel. It is anticipated that a vessel 30 ft in diameter and 120 ft long weighing 4,000,000 pounds could be wound in two months — or less if necessary. A room-temperature curing "prepreg" or preimpregnated fiberglass roving would be used. The mandrel would probably be a composite, with a very high modulus core material and a steel sheathing on which the glass would be wound. The longitudinal wrappings would be compacted by the circumferential windings and curing would take place at room temperature.

The above discussion is based on existing techniques. New concepts in filament winding might well be developed with encouragement and support.

FACILITIES

Special facilities would be needed for winding a vessel 30 ft in diameter and 120 ft long. Several of the large filament winders have talked in terms of associating with a shipyard for such a venture. Aerojet-General Corp. is in fact using the facilities of the Todd Shipyard on their 260-in. program. Handling equipment and experience are available there for structures of this size. The winding facility would have to be constructed.

Costs for such a facility are not considered to be excessive. A filament winding machine for a 30-ft diameter structure might well be constructed for one-half to three quarters of a million dollars. A reusable mandrel could be constructed for approximately the same price. However, both would be used for many such vessels, so that the cost per vessel is nominal. Facilities costs and availability are probably one of the strongest points in favor of glass fiber filament wound composites.

COSTS

As stated previously, a filament winding machine to wind a cylindrical structure approximately 30 ft in diameter and 120 ft long could be constructed for approximately one-half to three-quarters of a million dollars. A reusable mandrel could be constructed for the same price.

Any type glass filaments, purchased in lots of several million pounds as required for a large vehicle, could be obtained for one to two dollars per pound. The cost of impregnating the glass with resin to make a prepreg would be approximately another dollar per pound. The cost of fabrication is estimated at about 25 percent of the materials cost. The cost of the fabricated hull would therefore be three to four dollars per pound.

RESEARCH PROBLEMS

As stated previously, development work would be required to scale-up the filament winding process for the fabrication of a structure 30 ft in diameter and 120 ft or more long. Subjects to be examined would include development and evaluation of large mandrels, modification of winding machines, improvement of prepreg materials for large scale winding operations, further studies of fabrication controls for large scale winding and the fabrication and testing of scale models.

NONDESTRUCTIVE TESTING

Table 8 lists NDT methods in current application or showing potential usefulness for inspection aspects of glass reinforced and epoxy glass filament wound materials. Important limitations and areas of application of the methods are indicated along with estimates of current and future applicability. Future utility is given in 5-year and 20-year projections for which adequate development support is assumed. These projections are qualified by symbols indicating the degree of confidence of the prediction.

Table 8
Nondestructive Test Methods for Quality Control and Inspection of Glass Reinforced Plastics

NDT Code	Method	Comment on Applicability	Applicability Rating		
			Present	5 yrs. hence	20 yrs. hence
V-Visual					
V-1	Liquid Penetrants	For surface cracks and porosity	B	B(H)	B(M)
V-2	Microscopy	Coupon study-indirect application to end item	B	B(M)	C(M)
V-3	Optical Candling	For thin sections - possible future use of Lasers	B	C(M)	C(M)
V-4	Stress Coatings	To locate stress distribution	B	B(H)	B(M)
T-Thermal					
T-1	Infra-red	Thermal methods unsuited due to insulating property of materials	C	C(M)	---
R-Radiographic					
R-1	Radio Penetrants	For moisture penetration study	B	B(H)	C(M)
R-2	X-ray, fluoscopic or photographic	For defect detection	C	B(M)	C(M)
R-3	X-ray, TV display	Permits continuous scanning, improves defect detection	B	B(M)	B(L)
R-4	X-ray transmission	Possible quality indicator	E	B(L)	B(L)
R-5	Gamma Rays	Similar to X-ray	E	B(M)	B(M)

(Table continues)

Table 8 (Cont.)
Nondestructive Test Methods for Quality Control and Inspection of Glass Reinforced Plastics

NDT Code	Method	Comment on Applicability	Applicability Rating		
			Present	5 yrs. hence	20 yrs. hence
R-Radiographic (Cont.)					
R-6	Beta or Gamma Ray Backscatter	Thickness gaging. Possibly resin-glass ratio during winding.	E	C(M)	C(L)
R-7	Neutron absorption	Measure glass content	E	C(M)	---
E-Electrical					
E-1	Dielectric	Measures variation in dielectric constant and resistivity. Not able to differentiate types of flaws, short depth of penetration with single probe. Sensitivity decreases rapidly with thickness for electrodes on both sides.	C	C(H)	C(H)
E-2	Microwave	Limited value when tried in Aerojet Polaris A-3. Highly experimental. Potential good for measuring thickness, moisture and resin content.	E	B(M)	B(L)
E-3	Eddy Current	Thickness gaging only when using conductive backing. Thickness limit 0-5 inches.	C	C(M)	---
E-4	Corona	Detection of small voids near surface. Oil immersion needed.	E	C(M)	---
E-5	Resistivity	For measuring water absorption	B	C(M)	C(L)
E-6	Spark test	For pin holes in thin material	B	B(H)	B(M)
E-7	Strain gage	Measure deformations and stress	B	B(H	B(L)

(Table continues)

Table 8 (Cont.)
Nondestructive Test Methods for Quality Control
and Inspection of Glass Reinforced Plastics

NDT Code	Method	Comment on Applicability	Applicability Rating		
			Present	5 yrs. hence	20 yrs. hence
U-Ultrasonic					
U-1	Pulse echo	Detect defects and Q.C. Manual or automated scanning and recording capabilities. Current 5" thickness limitation.	B	A(M)	B(M)
U-2	Thru-transmission	Current 10" thickness limit. Good Q.C. potential. Poor defect discrimination.	B	A(M)	B(M)
U-3	Resonance	Thickness gaging. Moderate Q.C. capability.	B	B(M)	B(L)
U-4	Image System	A form of thru-transmission	E	B(L)	---
U-5	Frequency Modulated	Defect detection	E	B(L)	B(L)
U-6	Sonic monitoring	Fibers breaking under stress	E	B(M)	---
D-Dynamic					
D-1	Vibrational	Measures physical properties as E, G, u. Requires special samples. Offers little advantage over destructive tests.	C	C(M)	C(L)
D-2	Damping	Measures internal friction which may be related to quality and types of defects	C	C(M)	C(L)
O-Others					
O-1	Nuclear Magnetic Resonance	Detection of excessive stress conditions.	E	C(L)	C(L)
O-2	Photocells	Alarm system potential. Bandwidth control during winding.			

NOTES: (1) Ratings for current and future utility of NDT methods are coded as follows: A - High, B - Moderate, C - Low, E - Experimental or applicability inadequately determined. (2) Confidence levels for future applicability of NDT methods, assuming adequate development support, are coded as follows: H - High, M - Moderate, L - Low. (3) NDT methods are coded as indicated in Table 5.

REFERENCES: McGonnagle, W.J.: Nondestructive Testing, McGraw Hill, New York. McMasters et al., Nondestructive Testing Handbook, Ronald Press, New York. Hogarth and Blitz, Techniques of Nondestructive Testing, Butterworth and Company, London.

Table 9 lists the important defects occurring in these materials and indicates by code referring to the NDT methods of Table 8 which procedures are applicable to detecting and evaluating a particular defect.

A study of Tables 8 and 9 indicate the following:

1. Few of the methods have been developed sufficiently to exploit their full potential.

2. Some methods are expected to decrease in applicability as other methods are improved and displace less discriminating tests.

3. There are several methods of currently experimental nature which are exceptionally good prospects if further developed. These warrant further study and support. The outstanding example of this is microwaves.

4. Methods of greatest current promise and activity are ultrasonics and certain forms of radiography.

5. Some methods, such as eddy currents and corona have marginal application and do not warrant substantial support from the point of view of reinforced plastics.

Table 9
Specific Methods Applicable to Quality Control and
Defect Detection in Glass Reinforced Plastics

Defect	Applicable NDT Method (see Table 5)
Delamination	U-1, 2, 3, 5; R-2, 3, 5; V-3
Voids	U-1, 2, 3; R-4, 5; E-1, 2; V-3
Porosity	Same as voids. If at surface V-1, R-1, E-1
Improper Resin Content	
(a) Prepreg	E-1, 2; R-6
(b) Wet Roving	E-1, 2; R-6
(c) End item	U-1, 2; E-2
Improper Glass Content	
(a) Roving	R-6, 7
(b) End item	U-1, 2; E-2
Thickness Variation	U-1, 2, 3; E-2; R-6
Bandwidth	
(a) In winding	O-2
(b) In end item	none currently
Broken Fibers	
(a) During winding	R-7
(b) In end item	U-6
Cracks and Crazing	V-1, 3; R-2, 3, 5; U-1, 2
Improper Cure	E-1, 2
Foreign Inclusions	U-1, 2; R-2, 3, 4, 5; E-2

6. Methods of high future promise, such as ultrasonics, are in some cases the same as those of greatest current utility. In these, predictions are based on the rate of past improvement and estimates of what can be done in the future.

The history of NDT indicates the introduction of essentially new and useful concepts at a significant rate. Consequently, over a five-year period and surely over a twenty-year period, a number of entirely novel concepts and systems should be conceived. These may supplement or surplant current techniques.

FEASIBILITY

Many questions, some misleading, have been raised regarding the feasibility of using a glass-reinforced epoxy composite for the hull of a deep submergence vehicle. A reply to these questions involves a discussion of materials properties and since that is the general field to be covered in this section, some attention is given here to this subject.

It should be borne in mind that g.r.p. like all other materials has advantages and disadvantages. These have already been mentioned in this section. The design engineer and materials engineer have a choice of trying to utilize the advantages and circumvent the disadvantages or of ignoring the advantages and utilizing the disadvantages as an excuse for not using this material.

Some of the questions regarding feasibility involve the topics mentioned below.

Fire Resistance

This question must be examined closely for a deep submergence vehicle, especially in considering a combat vehicle. Epoxy resins will support combustion if heated to several hundred degrees for a finite period of time. Fire-retardant epoxies have not yet been developed but probably will be in the next five years. It should not prove to be a very difficult task. However, even with the present resins there is serious doubt as to the danger posed by this material. First of all, there would have to be an intense source of heat for a finite period of time before the g.r.p. will start to burn. During this time, steps would undoubtedly be taken to eliminate the source. Secondly, g.r.p. is an excellent thermal insulator and this would tend to localize any burning. The danger of an entire thick wall of g.r.p. being heated to the point where its structural integrity is threatened is rather remote. This danger is much greater for metals, where the hull walls would be much thinner and the heat would be conducted throughout the entire wall in a much shorter period of time. Given an intense source of heat for a finite period of time, it would appear that the danger to the structural integrity of a hull may be greater for metals than for g.r.p. This principle is being utilized in the use of g.r.p. for rocket nozzles and nose cones. With regard to the danger of toxic fumes being generated by g.r.p., the evaluation of carbon monoxide and carbon dioxide and the loss of oxygen would probably be so serious due to the source of the heat that the effects of the surface burning of g.r.p. would be rather slight in comparison. The toxicity problems would be quite critical before the g.r.p. has started to burn.

This rather brief and incomplete discussion would indicate that the question of danger due to fire aboard a vehicle constructed of g.r.p. is not very serious when considered logically and calmly. It is a question that would merit further consideration and study but should not cause doubt as to the feasibility of this material for primary structural use in a deep submergence vehicle.

Repairability

Studies are underway at the present time to establish accept-reject criteria for Polaris g.r.p. cases with external damage. Tests would indicate that the prospects for repairing external damage are quite promising. In the case of a submergence vehicle, damage to the external surface would be far less critical than in the case of an internally loaded structure. This problem requires study and evaluation, and is listed in the proposed program. It does not appear to be a serious or insurmountable problem.

Chemical Resistance

The epoxy resins, like most thermosetting resins, have excellent chemical stability. Glass reinforced epoxy pipe is being used in many chemical plants to replace stainless steel and other metals in chemically corrosive environments. This is not a problem, but an advantage.

Attachments

Much has been said about the "problem" of attachments aboard a vehicle with a g.r.p. hull. Actually, in the section on fabrication of metal, it is pointed out that nonprimary attachments aboard a metal vehicle would involve the use of adhesives. It is not desirable to weld to a heat-treated metal hull nor to drill holes in the hull. Adhesives could also be used for attachments to a g.r.p. hull. Primary attachments would require proper attention to design, and with the versatility of the filament winding process, this should offer no problem.

Habitability

There is no data or information that there would be any unique problems of habitability caused by the use of a g.r.p. hull.

APPLICATIONS CONCEPTS FOR F. R. P.

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Filament-wound plastics and cloth laminated reinforced plastics cannot be characterized in the same manner as a homogeneous material. As a matter of fact, FRP does not behave as a composite material until the structure element has actually been fabricated. It is thus difficult to divorce discussion of structural response of FRP from performance characteristics of the material. This is particularly evident in the case of test specimens used for determining the material properties and behavior of FRP under compressive loading. A great quantity of data related to the material properties of glass-reinforced plastics have been generated by subjecting thick-walled, unstiffened cylinders to hydrostatic pressure loading. These unstiffened cylinders, in a sense, are unsophisticated hull structures that can be used as external pressure vessels if weight were not a problem.

In the past, the major effort has dealt with the investigation of composite material properties and fabrication techniques. It has only been recently that efforts have been devoted specifically to the problems of submarine hull design. A "state-of-the-art" review of this latter effort would give an insight as to possible trends in technology and development of FRP materials, and identification of R & D needs.

Glass-reinforced plastics (GRP), a special case in the generic classification of fiber-reinforced plastics (FRP), have been of dominant interest in the investigation of composite materials for pressure hull application; this is due primarily to its high strength-to-weight ratio. The "state-of-the-art" review will be focused on test results obtained from models fabricated of GRP. It is tacitly assumed that application concepts developed for GRP materials would, in general, also apply to other fiber-reinforced plastics.

GENERAL CONSIDERATIONS

One can consider submarine design to be bounded by two structural modes of failure, that is, instability of the hull or crushing of the wall. By incorporating a stiffening system into the pressure envelope one can circumvent the instability mode of failure; in addition, as depth increases, the hull design tends to be governed by membrane compression rather than by instability. Thus, one can use as an index, an "upper bound" collapse pressure based on stress failure to determine the degree of efficient utilization of composite materials in cylindrical pressure hulls. This "upper bound" pressure can be based on consideration of an equivalent unstiffened cylinder. Applying the maximum principal stress theory of Rankine to a state of stress determined from the Lamé solution for a thick-walled, unstiffened cylinder one can arrive at an "upper bound" collapse pressure p_c of

$$p_c = \frac{\delta_W}{\delta_{FRP}} \times \frac{\sigma_f}{2} \times \frac{W}{D} \qquad (1)$$

where δ_W = density of sea water,
δ_{FRP} = density of the material,
σ_f = fracture strength of the material, and
W/D = weight-displacement ratio of the cylindrical hull structure.

The "upper bound" pressure computed in this manner represents a state of complete stressing of the entire cross section up to the value of fracture strength used in each case.

Figure 1 is a presentation of "upper bound" strength-weight curves computed by using Equation (1), a material density compatible with glass-reinforced plastics (0.077 lb/in.^{3}), and three different values of fracture strength. These curves are for cylindrical hulls and may be applied to all stiffened designs, such as stiffeners, sandwiches, and corrugated shells, fabricated of GRP material. Tests of ring-stiffened cylinders have consistently shown that a collapse depth of 30,000 ft can be obtained at a minimum weight-displacement ratio of 54 percent. An inspection of Figure 1 quickly reveals that strengths on the order of only 100,000 psi were developed in these structures prior to failure. In contrast, stress levels of 170,000 psi have been realized with tests of thick-walled, unstiffened cylinders. If it were possible to develop stress levels of similar magnitude in stiffened structures, hull weights could be appreciably reduced.

It appears that the ring stiffener acts as a stress raiser at its junction with the shell wall, thus imposing a weight penalty for the overall design. Model tests have shown that failure, in general, occurs in this region of the shell and that oversized frames can seriously reduce the overall strength. Since filament-wound structures in particular are

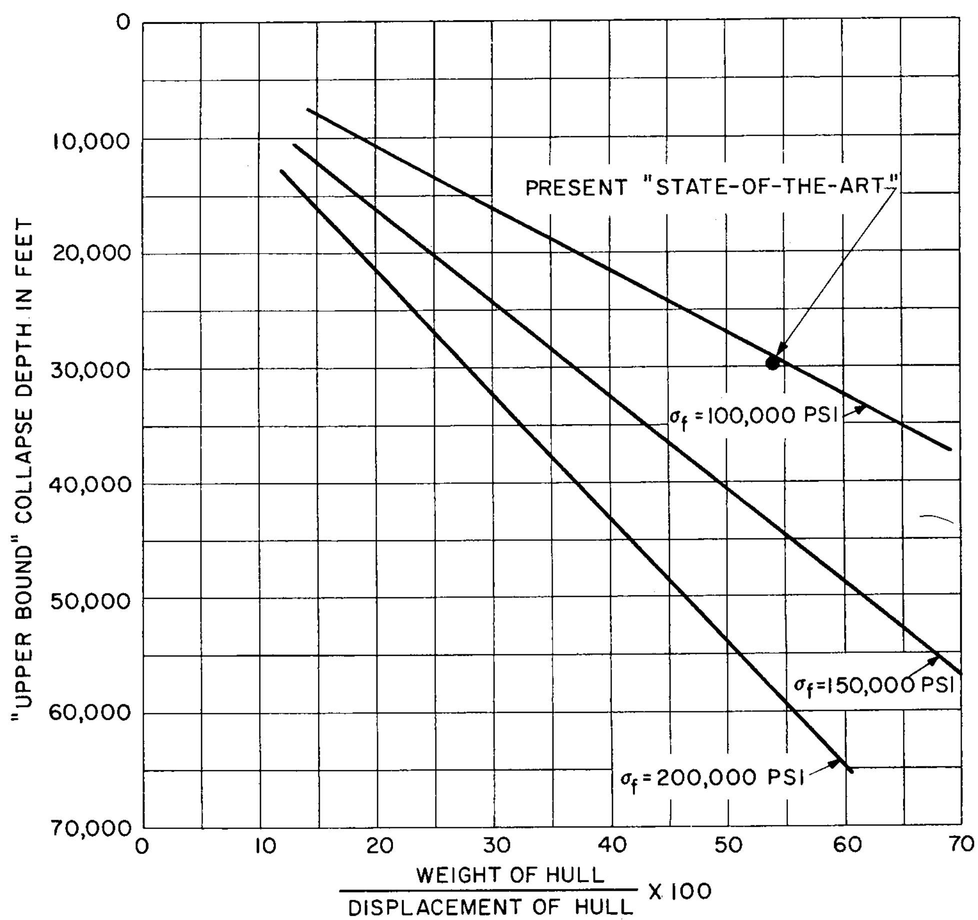


Fig. 1 - "Upper bound" collapse depth for GRP pressure hulls

prone to failure by interlaminar shear, the importance of reducing localized bending stresses cannot be overemphasized; the allowable shear stresses of GRP in many instances cannot be designed to more than 1/20 of the compressive design limit. There are indications from structural model tests that all failures so far have been due to failure of the resin, that is, by interlaminar shear, and that the full strength potential offered by glass filaments has not been capitalized. Tests of two ring-stiffened cylinders of identical geometry and having the same resin systems in which one was fabricated of E-glass and the other of S-glass (20 percent higher tensile strength) produced identical collapse strengths. Based on these observations, the potential of GRP material can markedly be improved if resins are developed with higher shear and compressive strength properties. Investigations in this area are now underway at NRL and Union Carbide Plastics Company.

Recalling that interlaminar shear strengths between the highly anisotropic layers in an FRP can be as low as 1/20 of the limits placed on the principal stress values, it is clear that structural utilization of composite materials must minimize shear and bending stresses. Sandwich hulls with uniform cores may be a solution to this problem. This type of structure, in a sense, distributes the effect of the stiffeners along the wall rather than concentrated at discreet points thus reducing localized bending stresses. Figure 2 shows types of sandwich structures that should be investigated. The thickness of the

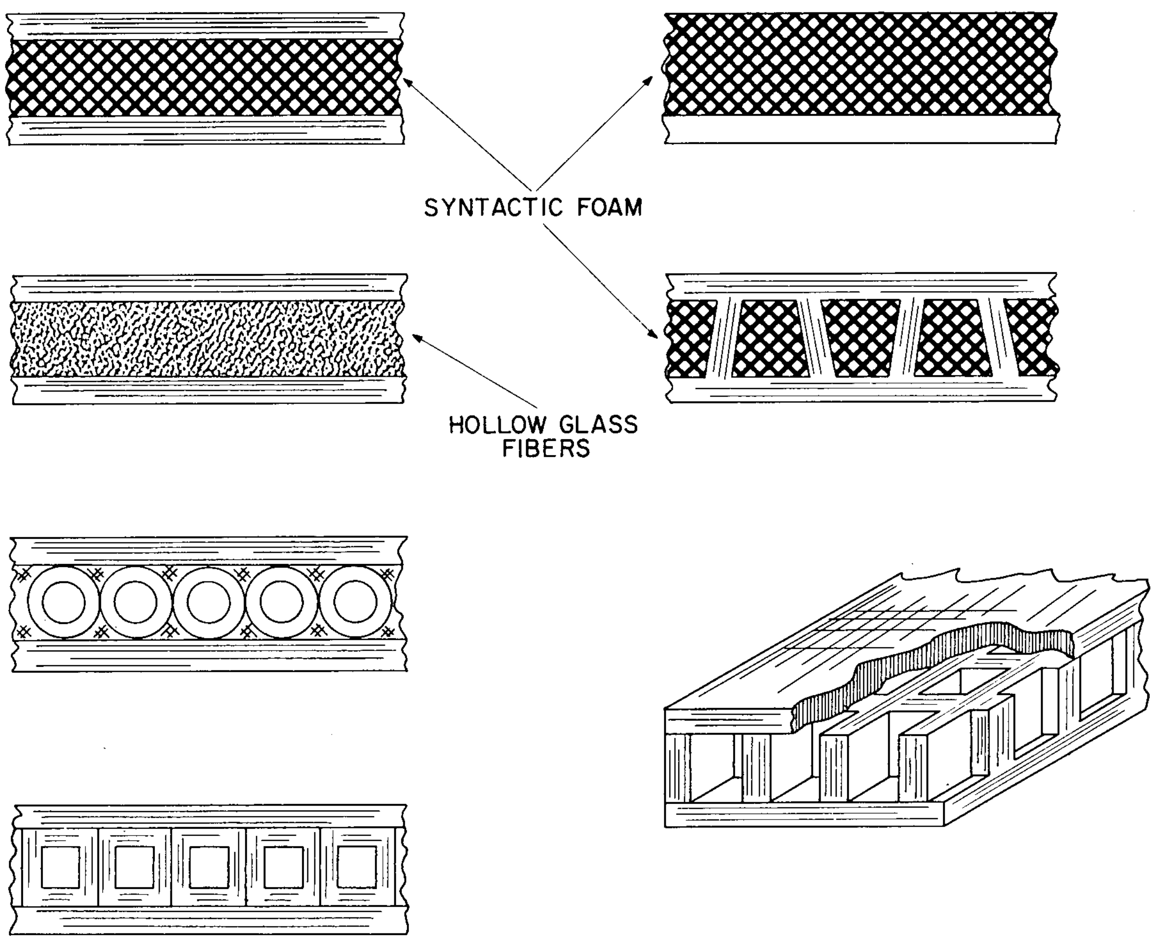


Fig. 2 - Shell support systems

sandwich walls should be that required for membrane compression and spacing of the walls to forestall instability failure. The major design difficulty now lies in selecting a core configuration and material for this sandwich. The core must perform three functions. First, it must transmit a portion of the applied load through to the inner shell; second, it must develop a sufficient shear bond between the facings so as to make them act together to obtain the desired wall stiffness. Finally, the core must provide support to the facings so as to inhibit local failure of the facings. It appears that an optimum sandwich design may be capable of achieving weight/displacement approaching 40 percent with a 160,000 psi compressive strength shell at a collapse depth of 30,000 ft. The core material assumed is 49 lb/cu ft syntactic foam capable of withstanding compressive stresses of 19,000 psi. Another core of interest may be hollow-glass-fiber composite material. If the weight of core material is higher than desired, it could be employed in a perforated form or machined to some other desired shape or form—honeycomb.

Pressure hulls fabricated with composite materials in which the reinforcement material has a higher modulus than glass, such as, alumina, carbon, and boron fibers, may alleviate the stiffener problem; they would inherently have higher resistance against the instability mode of failure. Lighter frames would be required. Thus, shear and bending stresses would be reduced and may lead to higher structural strengths.

Figure 3 shows a ring-stiffened shell with variable shell thickness. Shells with this type of cross-section can be designed to behave as membranes, that is, without bending; it should lend itself to low shear-strength materials. Since material is removed near the mid-bay region and added to the shell near the stiffeners where failure is prone to occur, higher strength should be realized. This is another area where structural research may prove fruitful for the use of composite materials.

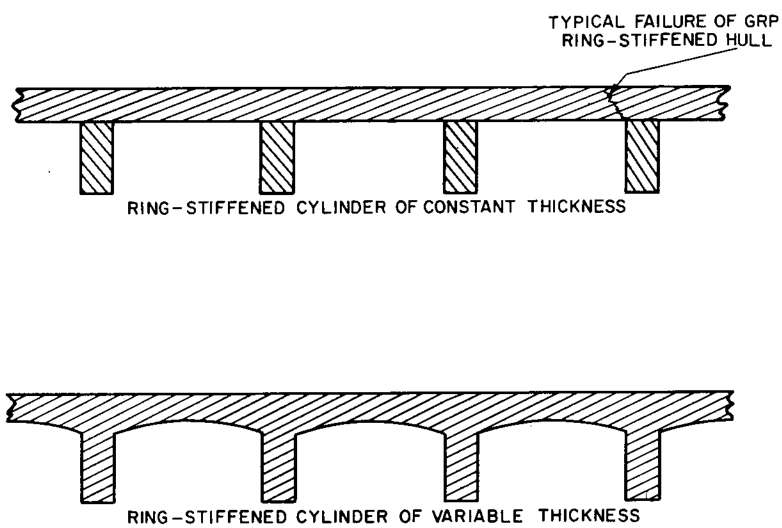


Fig. 3 - Ring-stiffened shells

Even with present-day performance, GRP pressure hulls are extremely attractive for deep-submergence applications, and there are indications that a "lot-of-room" is available for further expansion in areas of structural designs and material improvements.

APPLICATION

A study is now underway to demonstrate the capability of resolving problems associated with the overall design of GRP pressure hulls. These problems include:

1. Least-weight design
2. Hull penetrations
3. Head closures
4. Cylinder joints
5. Head-cylinder junctures
6. Structural fatigue
7. Long-term exposure to a deep-sea environment

To study these problems a ring-stiffened cylindrical pressure hull was chosen as the basic configuration. This shape can easily be wound to almost any desired length-diameter ratio while aligning the fibers in the directions of the principal loads, that is, circumferential and longitudinal. It can be readily and compatibly sealed with hemispherical end closures. It stands out as one of the most practical and promising shapes. The following specifications were established for this study:

1. Collapse depth of 30,000 ft
2. 10,000 excursions to a depth of 15,000 ft without loss in overall strength
3. Opening in the closure head and cylinder equal to 1/5 the diameter of the pressure hull
4. Overall length of the pressure hull equal to 5 diameters

The various structural problems were studied individually with small-scale (6-in. diameter) models. Figure 4 is a scale drawing of the entire pressure hull and the problem areas investigated.

The basic ring-stiffened cylinder (see Figure 4) represents a least weight hull determined by analysis and considerable model tests. The reinforcing rings are relatively lightweight and in conjunction with the shell provide resistance to premature failure due to overall instability. The frames utilize only 19 percent of the material in the region representing efficient hull design; the weight/displacement is 54 percent. In the region of the cylindrical-hull opening, a thicker shell, larger frames, and greater frame spacing were used. The latter geometry, representing a weight/displacement of 62 percent and less efficiency, was selected in order to provide sufficient space for an opening in the shell without cutting the frames. The shell is of S-glass filament wound to a 4C:2L fiber distribution; the frames are of the same type of material but utilize a 9C:1L fiber distribution.

The end closures consist of glass cloth layups with a composite strength of 60,000 psi and are attached to the cylindrical hull by adhesive-bonded lap joints. An end frame and outer splice ring provide local support adjacent to the bearing surface of the laminate to enhance the ultimate bearing strength of the joint. A disconnectable transverse joint was incorporated in the cylindrical hull to provide a means of access for equipment and machinery.

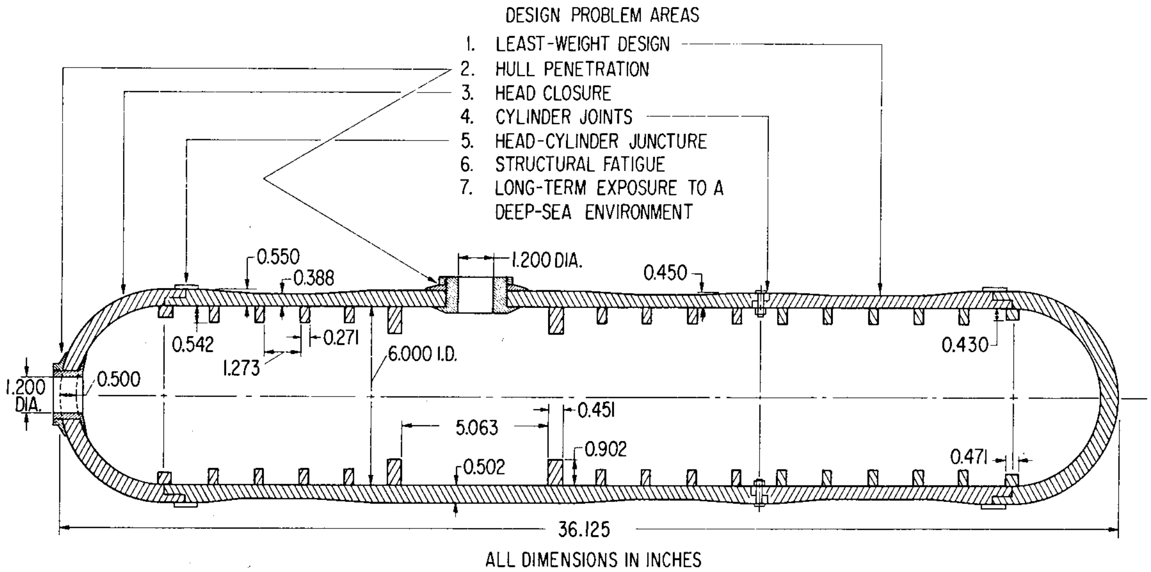


Fig. 4 - Design problem studies for deep submergence GRP vehicle

The openings into the pressure hull, shown in Figure 4, are reinforced by 17-4 PH stainless steel fittings designed to carry in-plane shell loads about the opening in hoop compression and bending. Light flanges were provided to locally support the cut-fiber ends of the shell and thereby assist in the transfer of high compressive bearing loads into the fitting.

Hydrostatic pressure tests and fatigue tests were conducted with small-scale, 6-in. diameter models incorporating individually each of the aforementioned design problems. The designs which met the established specification is represented in the composite scale drawing of Figure 4. Approximately 50 models, related directly to this study, were tested. Figures 5 to 9 are photographs showing collapse failure of some of the models. Test results obtained with individual structural components indicate that it is possible to resolve problems associated with nonweldable materials such as GRP for deep-submergence application, that the overall weight of GRP hulls designed for a 15,000 ft operating depth is not prohibitive for oceanography, and that it is possible to design GRP hulls to stress levels of 50,000 psi at operating depth with no appreciable strength reduction after 10,000 cycles to test depth.

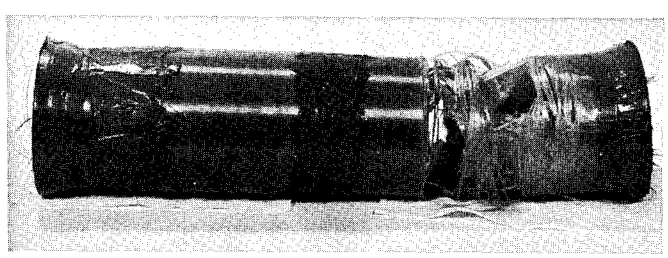
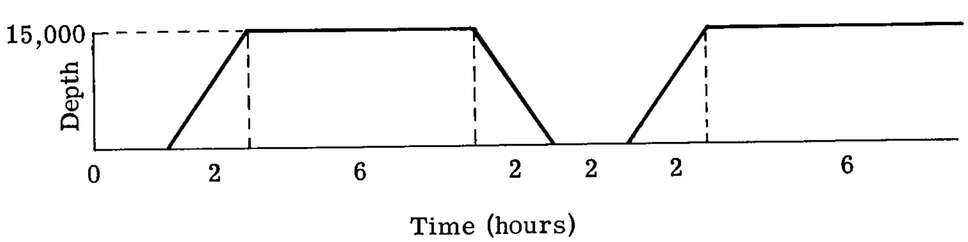


Fig. 5 - Cylinder failure

Fig. 6 - Closure failure

Fig. 7 - Closure-to-cylinder joint failure

Small-scale models are now being fabricated of the entire pressure hull, incorporating all of the structural details shown in Figure 4, for static strength and long-term cyclic loading studies. The latter studies will be conducted to determine the structural response under long-term loading; the models will be subjected to the following load schedule for a period of 2 years:



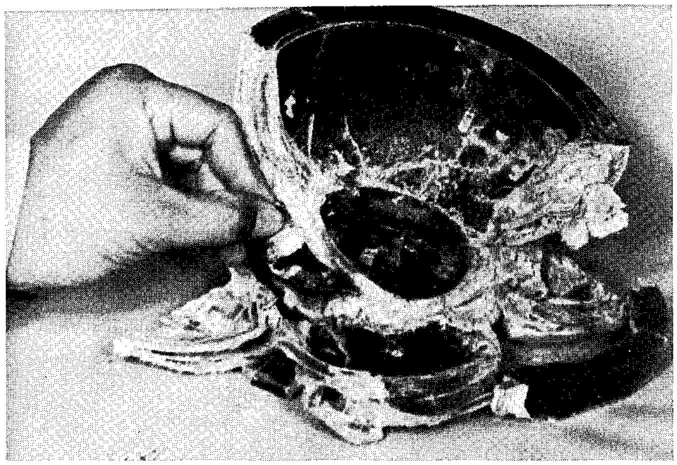


Fig. 8 - Closure cutout failure

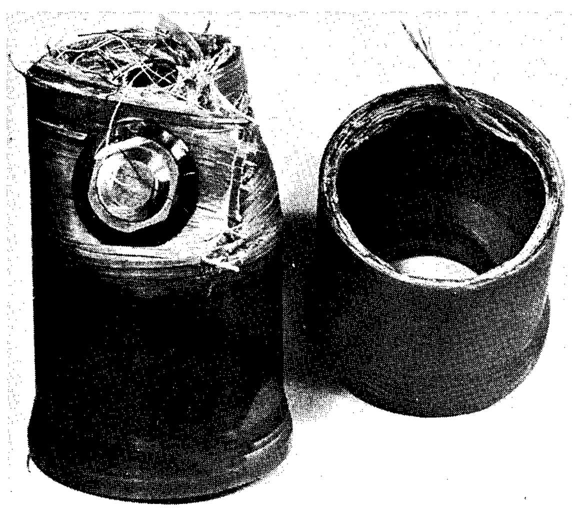


Fig. 9 - Cylinder cutout failure

Plans are also underway to fabricate two 3-ft diameter models for static and fatigue strength studies. These models will also provide information concerning fabrication techniques and scale-up effects of thick-walled laminates.

Model tests to determine optimum geometry of ring-stiffened cylinders related to the aforementioned studies indicate that we are far short of taking full advantage of the ultimate strength available in filament-wound composites. Analytical and experimental studies are needed to more fully understand the failure mechanism of laminated, orthotropic structures so as to establish failure criteria which apply directly to hulls fabricated of such materials. Due to nonexistence of these tools, investigators have been confronted with using engineering methods to modify existing criteria established for thin-walled hull structures fabricated from ductile, isotropic materials. Such is the case for the strength-weight curves shown in Figure 10; they represent to a first approximation the potential strength-weight characteristics of ring-stiffened GRP cylinders.

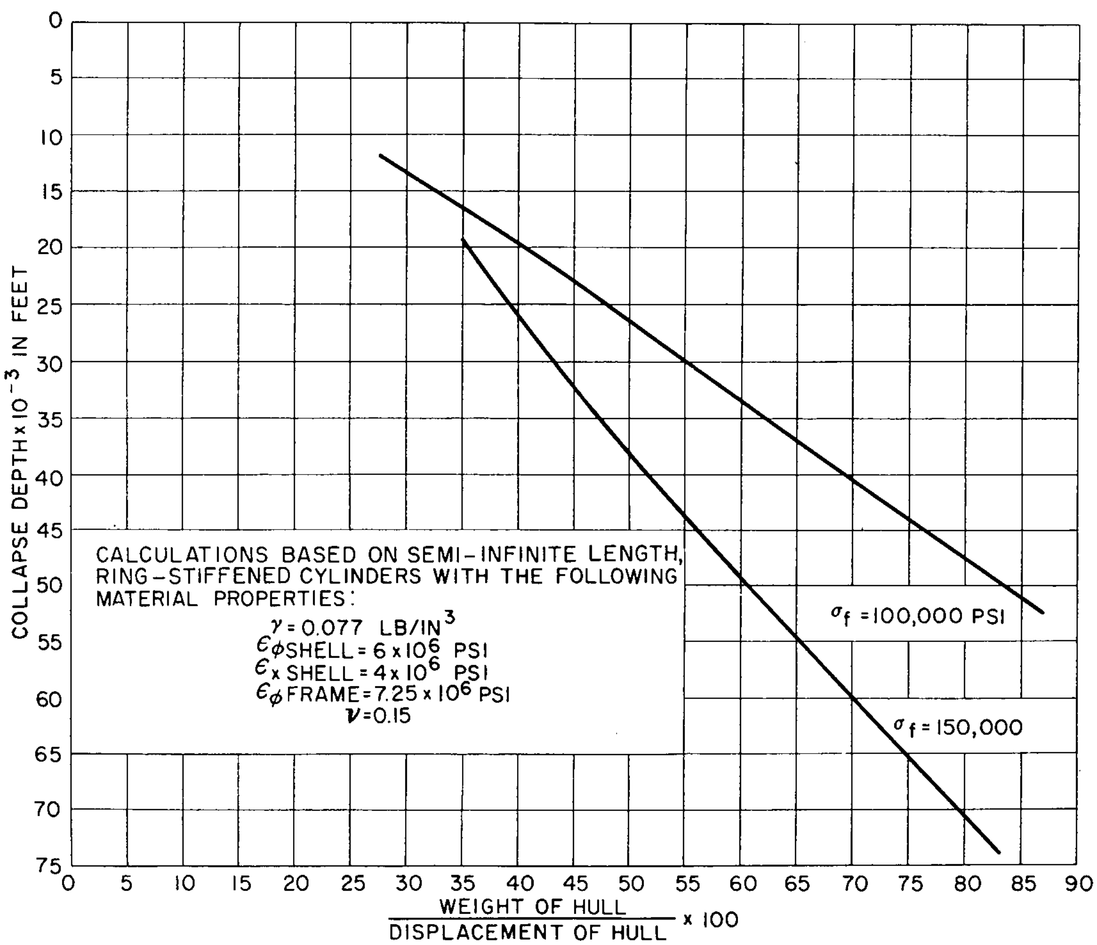


Fig. 10 - Strength-weight characteristics of ring-stiffened GRP cylinders

Similarly, Figure 11 gives the thickness of the shell required and is presented to give the reader an indication as to the size of the structure; as an example, for a 15-ft diameter hull having a collapse pressure of 15,000 psi, a 1-ft thick shell may be required.

At the onset of the program to study problems related to submarine hull design, the fatigue characteristics of filament-wound, glass-reinforced plastics were of primary concern. Investigations by IIT Research Institute under Bureau of Ships Contract NObs 86461 indicated that composite stress levels on the order of 50,000 psi will meet the aforementioned specification of 10,000 cycles without appreciable loss in overall strength. This was based on results obtained from uniaxial compression specimens and thick-walled, unstiffened cylinders subjected to external pressures.

The IIT studies have served as a guide to the structural research engineer in the design of GRP pressure hull components. However, there existed prior to 1963 little experimental data of cyclic tests conducted with external pressure vessels incorporating design features similar to those that might be expected in actual deep-depth vehicles, that is, similar to those shown in Figure 4. In light of studies which indicated the GRP hull structures fall short of taking full advantage of the ultimate strength determined from simple cylinder tests, the need for cyclic tests with actual pressure hull models, to supplement the IIT studies, became highly desirable. The only known facts on cyclic tests of actual pressure hull structures, published prior to 1963, are those given in

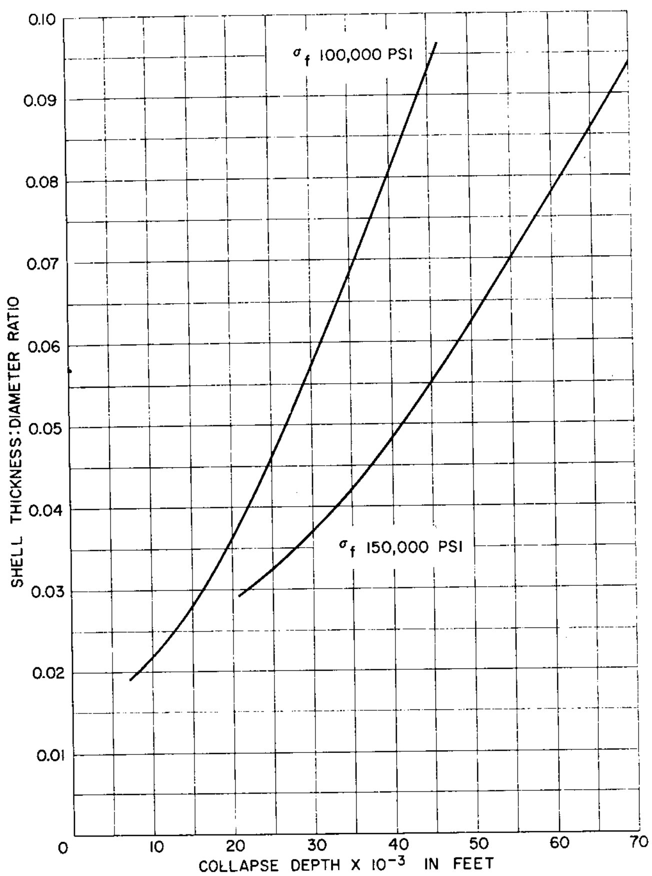


Fig. 11 - Shell thickness of ring-stiffened GRP cylinders

David Taylor Model Basin Report 1653 (Nov 1962). The results were extremely discouraging. Two ring-stiffened cylinders were cyclic-tested to two-thirds of the collapse pressure of similar models collapsed under hydrostatic pressures. The cylinders were cycled at a rate of approximately 10 cycles per hour and failed after 86 and 442 cycles. These cylinders represented an early "state-of-the-art" in both material and fabrication of external pressure vessels.

Recent fatigue tests with structural models having structural features such as those shown in Figure 4 have been much more successful. H. I. Thompson Fiber Glass Company (HITCO), under Bureau of Ships Contract NObs 88351 to study problems in the design of closure heads, large openings, and joints in filament-wound pressure hulls for a collapse depth of 30,000 ft, has consistently obtained with structural models 10,000 cycles without failure. These models were pressure cycled to a depth of 15,000 ft which generated stresses in the structure on the order of 50,000 psi. The models were fabricated from prepreg E-HTS/E787 and S-HTS/E787, 20-end rovings with a resin content of 20 ± 2 percent. The cycling rate was 9 cycles per minute, which is over 50 times as fast as that imposed on the cylinders reported in DTMB Report 1653.

The high cycling rate used by HITCO coupled with their excellent results opened a question as to whether similar results could be obtained at lower cycling rates. Very recent test results obtained with a structural model subjected to a pressure cycle which incorporated 1-minute dwell time at maximum and minimum pressures showed no signs of structural failure after 10,000 cycles. Although the results are limited, in the sense that only one model was tested, they appear to be promising. Further studies are necessary to obtain the coefficient of variation; studies should also be extended to incorporate pressure cycles on a time scale similar to that which might be experienced by future deep-depth vehicles. Studies with structural models cycled at stresses higher than 50,000 psi should be carried out. Such studies would assist in determining the design limitations of filament-wound structures. Confidence levels must be established to give the designer assurance that the materials in the hull structure will perform in accordance with established design criteria.

A limited experimental investigation pertaining to the process of water absorption in glass-reinforced plastic laminates subjected to a water environment was conducted by Battelle Memorial Institute under Bureau of Ships Contract NObs 86871. The results of this limited study indicated a serious degradation of filament-wound, glass-reinforced plastics due to water absorption; open-end, hoop-wound cylinders tested after exposures for 2300 hr in water at a pressure of 10,000 psi showed a loss in strength on the order of 30 to 40 percent. Similar strength reductions have been noted in cylindrical structural models tested at the David Taylor Model Basin where cut fibers on the surface of the laminate were exposed to the pressure medium for a duration of time much less than the 2300 hr reported by Battelle. Thus, it appears that the effect of water absorption is an even more serious problem for laminates having cut fibers exposed directly to the pressure medium. Had the Battelle specimens been fabricated not only with hoop windings but also with longitudinal fibers, it is possible that a more serious strength reduction would have been observed. When the cut-fiber surfaces on the cylinder models tested at the David Taylor Model Basin were protected by a rubber-base sealing compound, no apparent strength reductions occurred. It should be noted, however, that these latter models were exposed to a water pressure medium for only a relatively short duration, that is, a maximum of 700 hours with one model.

One must not jump to premature conclusions concerning fiber-reinforced plastics exposed to a high-pressure water environment. The state-of-the-art in resin development is still in its infancy; the resin systems included in the present-day studies are off-the-shelf items and are hardly representative of what can be anticipated in the future. To date, it appears that the improvement of resins has received too little attention, possibly for lack of new or original approaches to the problem. Resins with greater resistance to water and greater affinity to the fiber reinforcements are needed in addition to resins with higher compressive strength, shear, and modulus.

Other possibilities toward alleviating the apparent shortcoming of fiber-reinforced plastics to attack of high-pressure water may exist in protective coatings or metallic sheathings. Studies have been initiated along these lines. Figure 12 shows a drawing of a 9-ft diameter hull designed for collapse depth of 30,000 ft which utilizes a titanium jacket as a means of protecting the GRP hull from the deep-sea environment. Hydrostatic tests with 1/9-scale models have shown that a titanium jacket provides a feasible method of protecting GRP laminates and that it can be done with very little weight penalty, if any, to the overall structure. Fatigue tests are needed to determine the structural integrity of the titanium jacket. Models are presently being fabricated to determine suitable types of closures (see Figure 13) and closure-cylinder joints. Fatigue and static strength studies are now underway with models having small penetrations in the cylindrical hull such as that shown in Figure 12. These penetrations would provide hull openings for piping and electrical outlets. Plans are also now underway to fabricate models of closure heads with access hatches and viewing ports such as those shown in the figures. It is intended that a 3-ft diameter model incorporating the best of the aforementioned features be fabricated for fatigue studies. If sheath construction proves successful, the jacket will not only serve as a protective device but it will be a convenient means of containing the various GRP elements in place and provide a possible means of replacing damaged GRP hull elements. If major hull openings are located in the closure heads,

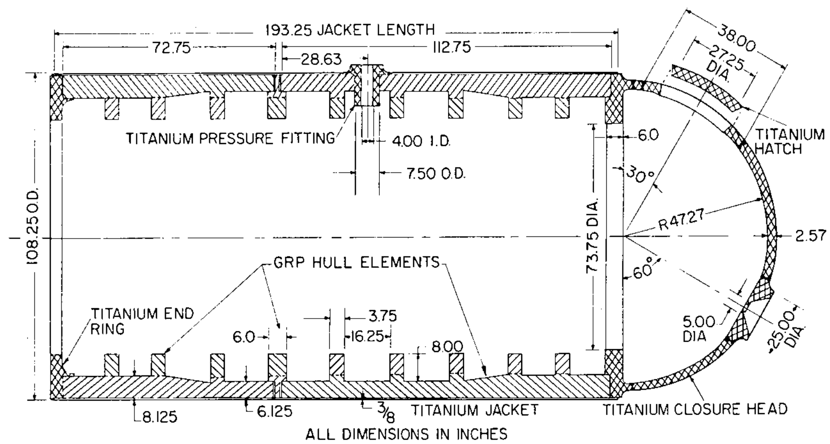


Fig. 12 - GRP hull with titanium jacket and closure head

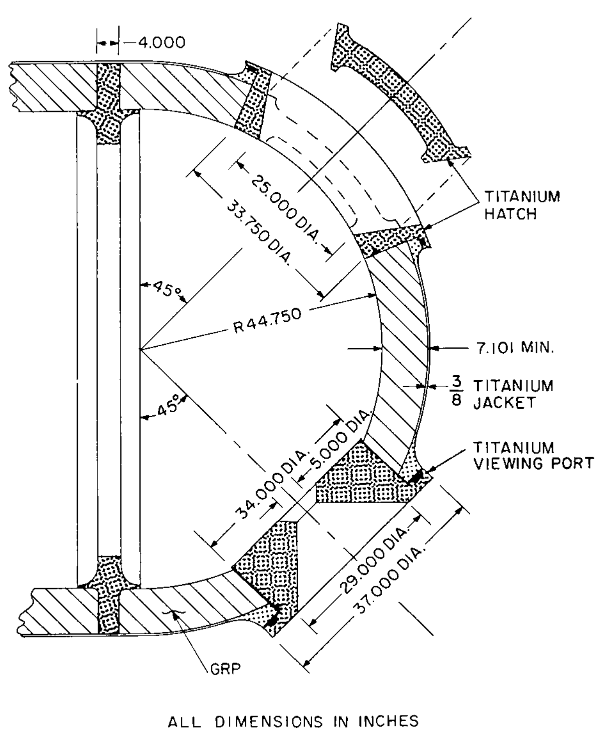


Fig. 13 - Optional closure head for GRP hull with titanium jacket

such as may be the case of a research vehicle, an all titanium head appears very attractive, from a weight viewpoint, since smaller reinforcements around the openings are required.

OVERALL STRUCTURAL EFFICIENCY

At the present state of technology, when a basic ring-stiffened cylinder incorporates design features similar to those that might be expected in the pressure hulls of deep submersibles having hull openings, joints, closure heads, etc., an appreciable increase in weight/displacement for the overall structure exist. As mentioned previously, a ring-stiffened cylinder fabricated with present-day GRP materials can demonstrate a collapse depth of 30,000 ft with a weight/displacement of 0.54. If this cylinder now incorporates two closures, joints, penetration in one closure, a cylinder penetration, and frame retainers, (see Figure 4) the overall weight/displacement goes up to 0.65. This is 20 percent higher than that for the basic cylinder. Figure 14 depicts the various design problems and their contribution to the overall structural weight for the pressure hull shown in Figure 4. The major contributions to this increase are the joints and cutouts in the hull. Due to the use of nonweldable materials, it is understandable as to why these first efforts give rise to weight-problem areas. It does, however, indicate areas of research where new or original approaches to the problems may give appreciable savings in hull weights.

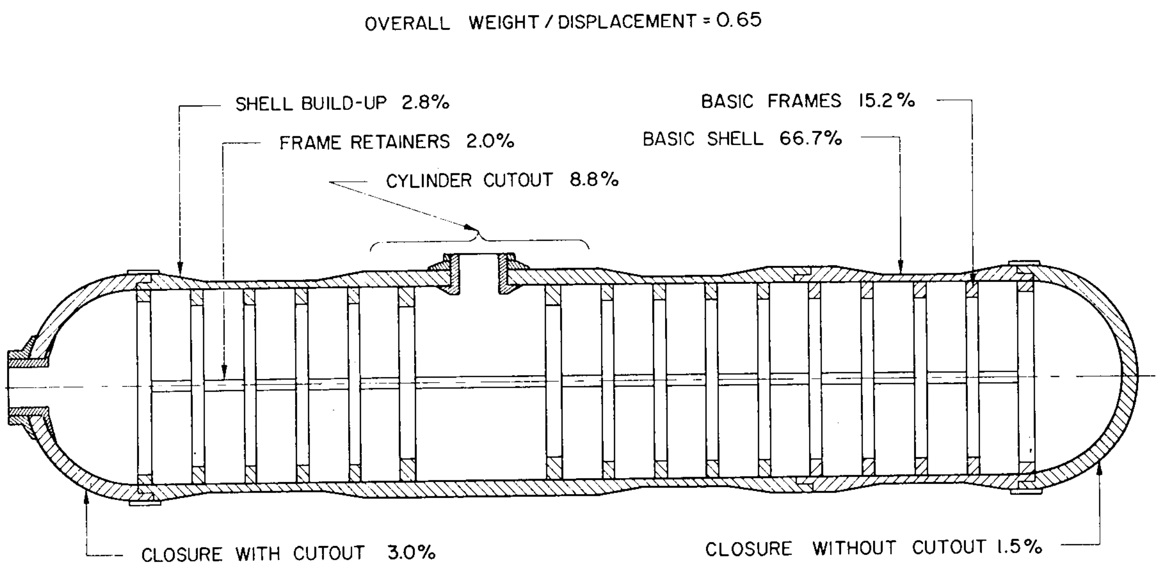


Fig. 14 - Contribution of individual items to total weight-displacement

Experience with joints and openings for ultra-deep depth has been rather limited. One can gain much from the experience of these problems with mine cases developed at NOL. The following section deals with this effort.

JOINTS AND OPENINGS

Three basic types of joints have been investigated for use in the Mark 57 mine case; these are: adhesive joints, wound-over-joints, and mechanical joints.

In the Mark 57 mine case several types of adhesive joints have been tried. Tapered scarf joints have been built into the main cylinder. These have included the nose hemisphere-to-sidewall joint (plastic-to-plastic) and the sidewall-to-joint ring attachment (plastic-to-metal). Sleeve-type joints have been used to provide penetration into the sidewall. The main problem in working with such joints is to obtain adequate strength and reliability. Joint machining tolerances must be close enough to assure adhesive thicknesses of 3 to 8 mil in order to obtain maximum strength. Mating surfaces must be carefully prepared as to smoothness and cleanliness. Application of the adhesive, joint assembly, and adhesive cure must be done under exact conditions. Then, when the joint is finally assembled, the only way to determine its adequacy is to test it by service loading. Poor joints lead to mechanical failure, poor joint loading levels, and moisture leakage. Good joints can be designed to carry large tension bending and compression loads, survive aircraft and transport vibration, external hydrostatic loads, etc. However, the general ordnance philosophy has been to avoid adhesive joints in critical areas whenever possible.

The current technique of attaching the nose to the sidewall of the Mk 57 mine case involves a permanent wound-over-joint. The nose is first molded. Then the nose skirt is machined on the outside to give an undulating surface. The noise is then mounted on the sidewall mandrel and the sidewall is formed over the mandrel and over the skirt of the nose. Thus, the sidewall and nose are married together as the sidewall portion is cured. This type of joint has successfully passed every service requirement of the Mine Mk 57 with a wide margin of safety.

A mechanical joint provides a parting line between the buoyant section and the charge compartment of the Mine Mk 57. This joint is made by heaving up the butting ends of the two cylindrical sections. In one half, a ring of bolts are imbedded with their axis along the axis of the cylinders. Their threaded ends protrude and mate with holes in the joining section. In the second cylinder, slots are cut at the head of the holes so that as the bolts from the first cylinder extend through, nuts can be put on and tightened. The seal between the two parts is provided by O-rings. Again, this joint has met all service requirements with a wide margin of safety.

A large opening in the charge section of the Mine Mk 57 has required special fabrication techniques in order to provide strength and water tightness. After the cylinder is wound, a hole is cut at the proper point and the sidewall material is chopped down into a recess in the mandrel. Thus, at the junction between the cylinder and the opening, a joint is avoided. The transverse tube which forms the sides of the opening is then closed by a metal assembly which clamps its ends and gives it full support against shear failure.

Several penetrations are required in the Mk 57 mine case for the attachment of different hardware. The design used provides that the part passing through the case material fit tightly so that it supports the case when the latter is under compressive loading. In addition, provision is made so that when the part is put in place, it will act as a clamp on the thickness of the case material. This provides support against interlaminar shear failure, spreads the loading, and prevents undue deformation when the attachment is loaded. An identical concept is now in model studies (see Figure 4) as a way of providing a major opening in a deep submergence vessel. The design has withstood 10,000 cycles to a depth of 15,000 ft.

In reinforced plastics structures, permanent joints are estimated to be from 75 to 90-percent weight efficient while separable joints are not more than 50-percent efficient. In the case of large openings, efficiencies can be predicted at about the 85 to 90-percent level. On the other hand, with small penetrations, we are probably not concerned with weight efficiency because of the small part of the overall hull involved.

From the above it is seen that major hull joints present the greatest problem at present. A goal of at least 90-percent efficiency should be obtainable for all cases through design research and development.

The gains to be expected for large openings are less than for joints. Nevertheless, openings are still a major question as regards general performance in the deep submergence environment. They, therefore, need to be developed vigorously to a higher state-of-the-art level so as to be fully compatible with the rest of the hull structure.

In addition to the broad improvements aforementioned, some improvements in the ability to seal openings are anticipated. This must be accomplished for the depths to which these vessels must go and yet permit free access through the opening after a dive.

Many new joint designs exist. These need to be evaluated at high pressures and under pressure cycling conditions. Other concepts are needed to reduce the material in a joint by using it at higher stress levels and by introducing secondary reinforcements, thus making it more efficient, more reliable, and easier to fabricate. Probably the separable joints will be of greatest importance as these will ease the problem of maintenance and repair by making it possible to have ready access to the vessel interior or even to replace hull sections, as necessary.

Current ideas on penetrations and openings need to be evaluated under deep submergence service conditions. Again, concepts are needed to reduce the materials involved and thus increase efficiency.

SUMMARY

I. State-of-the-Art

1. The cylinder stands out as one of the most practical and promising shapes for FRP pressure hulls of deep-submergence vehicles. This shape is particularly applicable to filament-wound materials since it can easily be wound to almost any desired length-diameter ratio while aligning the fibers in the direction of the principal loads.

2. Because of instability problems, full advantage has not been taken of the ultimate strength available in GRP materials. Model tests of ring-stiffened cylinders show performance in the 100,000 psi stress levels. This is in contrast with simple structures having little bending and shear stresses; these structures, although impractical for pressure hulls, develop stresses on the level of 170,000 psi.

3. Tests with GRP structural models after 10,000 cycles at stress levels of 50,000 psi show no appreciable strength reduction.

4. Model tests have demonstrated the capability of resolving problems of closures, joints, and penetrations in pressure hulls fabricated from nonweldable materials such as glass-reinforced plastics. However, additional refinements in these areas are necessary to obtain more efficient structures.

5. The effects of water absorption for laminates having cut fibers exposed to the pressure medium appear to be serious. The problem may be overcome by protective coatings or metallic jackets. Also, resins with greater resistance to water and greater affinity to the fiber reinforcements may alleviate this problem.

6. Hydrostatic tests with GRP hull elements held together with a protective metallic jacket have shown that this type of construction is of practical consideration.

7. Little is known about filament-wound hulls in the following areas:

a. structural response to dynamic loading

b. structural response to long-term exposures to a deep-sea environment

c. repairs of damaged hulls made of nonweldable, low shear strength materials

d. the use of other reinforcements besides solid-glass fibers with circular cross-section

e. the use of other matrices besides epoxy resins

8. The use of composite materials for deep-submergence hulls is in its infancy. There is much room available for expansion in areas of structural designs and material improvements. Even with present-day performance, GRP pressure hulls appear to be extremely attractive for deep-submergence applications.

II. Identification of the R&D Needs

1. Develop hull structures which lend themselves to composite materials, that is, structures which minimize shear and bending stresses.

2. Develop high strength, high modulus, light-weight core materials for application to sandwich type pressure hulls.

3. Investigate hull shapes other than the cylinder, such as spheres and prolate spheroids.

4. Develop analytical tools and conduct experimental studies to more fully understand the failure mechanism of laminated orthotropic structures so as to establish failure criteria which apply to pressure hulls fabricated of such materials.

5. Conduct studies which assist in determining the design limitation of filament-wound structures.

6. Investigate hull structures fabricated from composite materials other than glass-reinforced plastics.

7. Determine the structural response to dynamic loading of hulls fabricated from composite materials.

8. Determine structural response of FRP pressure hulls subjected to a deep-sea environment.

9. Explore new concepts and improve weight efficiency performance and reliability of joints and openings in FRP pressure hulls.

10. Develop resins with high shear strength, compressive strength, modulus, resistance to water and affinity to the fiber reinforcements.

11. Explore concepts related to the repair of damaged hulls made of composite materials.

12. Investigate methods for the installations of equipment and the mounting of heavy machinery to nonweldable hulls.

MASSIVE GLASS FOR DEEP SUBMERGENCE

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STATE-OF-THE-ART-GLASS

Numerous discoveries and developments in glass have taken place during the last eighty years, Table 1. This accumulated knowledge now makes it reasonable to propose the use of massive glass in primary structures for deep submergence. The salient characteristics of glass as a structural material and the state of its art are reviewed briefly in the following sections and in the accompanying charts and graphs.

Table 1
Historical Milestones

Year	Event
1891	Otto Schott in Germany strengthened glass viewports for pressure vessels by means of low expansion overlays.
1940	Percy Bridgman stressed glass to 800,000 psi by external pressure on closed-end cylinders for one week without flow or fracture; at 1,250,000 psi he caused glass to yield.
1950	Corning Glass Works began a static creep test program on glass rods bent to a stress of 200,000 psi.
1952	Isaacs and Maxwell at Scripps imploded glass balls in deep water as a sound source; noted that a large force was needed to implode them in deep water.
1958	Corning Glass Works produced and proof-tested glass floats to 16,000 psi for use in deep oil wells and oceanography.
1959	H. A. Perry at NOL began study of massive glass for the primary structures of buoyant mine cases, etc.
1960	P. Acloque of St. Gobain developed an improved optical meter for measuring surface compression stresses in tempered glass.
1962	S. S. Kistler of Univ. of Utah published a paper on non-uniform, monovalent ion-exchange treatments which induced stresses in glass surfaces up to 120,000 psi and enhanced their strength.
1962	D. Stookey at Corning Glass Works published paper on compositions of glass and thermal treatments which produced B-eucryptite crystals in glass surfaces, thereby inducing intense compression stresses and enhancing their strength (CHEMCOR).

(Table continues)

Table 1 (Continued)
Historical Milestones

Year	Event
1962	P. French at Pittsburgh Plate Glass adapted optical stress meters to the measurement of stresses in various types of thermochemical-treated glass surfaces (HERCULITE II).
1962	H. A. Perry, NOL, predicted quantitatively in May to the Navy Advisory Council on Materials and to the MAB that hollow glass structures would have an economical, all-depth capability and would become resistant to underwater explosions damage while in deep water; recommended that the Navy investigate massive glass for the primary structures of all-depth weapons and vehicles; presented a paper in December on this subject at the Navy Workshop on Deep Submergence at DTMB.
1962	M. Krenzke at DTMB published a report on the buckling of PYREX tubing.
1962	J. Stachiw at ORL, Penn State Univ. investigated ceramics for torpedo hulls.
1963	H. A. Perry, NOL, developed means for suppressing the propagation of cracks in surface-compressed parts by mechanical constraints; project work begun on "Feasibility of Massive Glass for Deep-Submergence Primary Structures."
1963	M. Krenzke at DTMB published a report on the buckling of one-inch hemispheres which confirmed that the bearing strength of annealed glass against hardened steel exceeds 300,000 psi.
1964	H. A. Perry and R. Mead at NOL began environmental exposure tests on glass under stress in Pacific, North Atlantic and Caribbean waters.
1964	Pittsburgh Plate Glass Corp. produced 1500 lb. castings for NOL of a surface-compressible glass (HERCULITE II); began development of windows containing HERCULITE II for TFX plane.
1964	Corning Glass Works pressed precise (± 0.020") PYREX hemispheres, 10" diameter, and fusion-sealed them into hollow spheres using semi-automatic process (NOL Test Spheres, Type II).
1964	Pittsburgh Plate Glass Co. pressed and ground precise (± 0.005") hemispheres and treated them. The HERCULITE II hemispheres were assembled to form spheres using an epoxy adhesive. (NOL Test Spheres, Type III).
1964	H. A. Perry and W. Faux of NOL confirmed depth-hardening theory by explosions tests down to 21,000 feet in the Puerto Rico Trench using Type II and III NOL Test Spheres.
1964	M. Krenzke and others at DTMB began project work on a parallel investigation of the feasibility of massive glass for deep submergence primary structures.
1964	PPG assembled 10" HERCULITE II hemispheres with a lapped hatch at one pole and a titanium plug at the other. Silver-ribbon feedthrus were inserted in the adhesive seam. (NOL Test Sphere, Type IV.) PPG is producing discs (33" dia.) spherically-curved (r = 33"), x 2" thick, of HERCULITE II for mechanical testing at NOL.

(Table continues)

Table 1 (Continued)
Historical Milestones

Year	Event
1964	CGW is producing fusion-sealed, hollow torus-shaped structural parts for testing at NOL.
1964	Electric Boat is assembling 10" segmented spheres using eight similar parts with adhesive bonds.

Properties of Massive Glass - The properties of the vitreous silicates, alumina and beryllia are given in Table 2a. The engineering properties (present state-of-the-art) of glass, steel, titanium and aluminum are given in Table 2b. The relative weights of structural parts for "equal-performance" for these materials are given in Table 2c. The modulus of rupture value used in Table 2c is 35,000 psi.

Table 2a
Ranges of Properties

Form	Silicate Glasses* (Vitreous)	Alumina† (Polycryst.)	Beryllia† (Polycryst.)
Specific Gravity	2.18	3.37-3.84	2.85
Specific Heat (cal/gm - °C)	0.17	0.21	0.29
Thermal Conductivity (cal/sec-cm-°C)	0.0025	0.075	0.60
Coefficient of expansion (10^{-7}/°C)	8 to 127	34	31
Refractive Index	1.47 and up	Opaque to translucent	
Photoelastic Fringe Constant (5461 A)	1150 lbs/in.-order	Opaque to translucent	
Light transmission	up to 90%	Opaque to translucent	
Dielectric constant	3.8 and up	9	6.7
Dielectric strength (volts/mil) (0."25)	250	230	250
Volume resistivity (ohm.cm)	10^{12} to 10^{17}	10^{14}	10^{17}
Poissons Ratio	from 0.18 to 0.24	0.21	0.32
Young's Modulus of Elasticity (10^6 psi)	from 8 to 17	33-52	44-46
Compressive Yield Stress (psi)	800,000 to 1,250,000	>300,000	>225,000
Flexural Strength (psi) (small rods)	see Table 3	43,000	25,000
Delayed elastic recovery	0.5% of unit strain	ND	ND
Creep after 10 years at 200,000 psi	Zero	ND	ND
Creep after 168 hours at 800,000 psi	Zero	ND	ND
Maximum temp. for no creep (500 hrs.) (°C)	330 to 710	ND	ND
Anneal point (°C)	350 to 1200	ND	ND
Softening point (°C)	400 to 1500	ND	ND
Working point (°C)	750 to 1700	ND	ND
Toxicity	None	None	Yes

*Properties vary with composition but not with method of manufacture.
†Specific gravity and other properties vary with purity and method of manufacture.

Table 2b
Structural Properties of Commercial Materials

Material Type	Steel (HY80)	Titanium (64 or 821)	Aluminum (7090)	Bridgmanite Glass (Surface-Compressed)
Specific Gravity (Sp. gr.)	7.9	4.45	2.7	2.3 - 2.5
Young's Modulus of Elasticity (E_H) x 10^6	29.0	16.0	10.4	12.4
Guaranteed Yield Strength - psi	80,000	120,000	60,000	---
Reduced Strengths - psi (F_s = 1.5)				
Compression (S_{co}/F_s)	54,000	80,000	40,000	>300,000
Bending (S_B/F_s)	54,000	80,000	40,000	35,000* 46,000†‡

*Conservative estimate -- see Table 8.
†$\bar{X}-5\sigma/1.5$ (probability of lesser value = 1/1,000,000)
‡Type B, Table 8.

Table 2c
Relative Weights of Structures Using Commercial Materials

Basis of Comparison	Parameter	Numerical Values			
		Bridgmanite (Surface-Compressed)	Aluminum* (7079)	Titanium (64 or 821)	Steel* (HY80)
In Compression					
Equal deflection	ρ/E (x 10^{-9})	9.0	9.2	10.3	10.0
Equal load capacity	ρ/S_{co} (x 10^{-7})	<3.0	24.5	20.5	53.0
In Bending					
Equal deflection	$\rho/E^{1/3}$ (x 10^{-4})	4.1	4.5	6.6	9.4
Equal load capacity	$\rho/S_B^{1/2}$ (x 10^{-4})	4.8	4.9	6.4	11.7
Equal Buckling Pressure					
Of cylinders	$\rho/E^{2/5}$ (x 10^{-4})	1.4	1.6	2.1	2.9
Of spheres	$\rho/E^{1/2}$ (x 10^{-5})	2.8	3.0	4.1	5.3
Equal Elastic Energy					
In bending	$\rho E/S_B^2$ (x 10^{-5})	72.0	61.0	41.0	285.0
In compression	$\rho E/S_{co}^2$ (x 10^{-5})	<1.0	61.0	41.0	285.0

*Does not include an allowance for corrosion.

The probable trends for the modification of strengths, moduli and densities through 1980 are given in Fig. 1.

Depth-Hardening Effect - A hollow structure, made of ordinary glass, offers the bonus property of becoming increasingly and outstandingly resistant to damage by mechanical impacts or underwater shockwaves at great depths (Figs. 2 and 3(a)). This is the opposite of the "depth-softening" effect of external pressure which occurs with hulls made of ductile alloys (Fig. 3(b)). A brief statement of theory is given in Appendix 1.

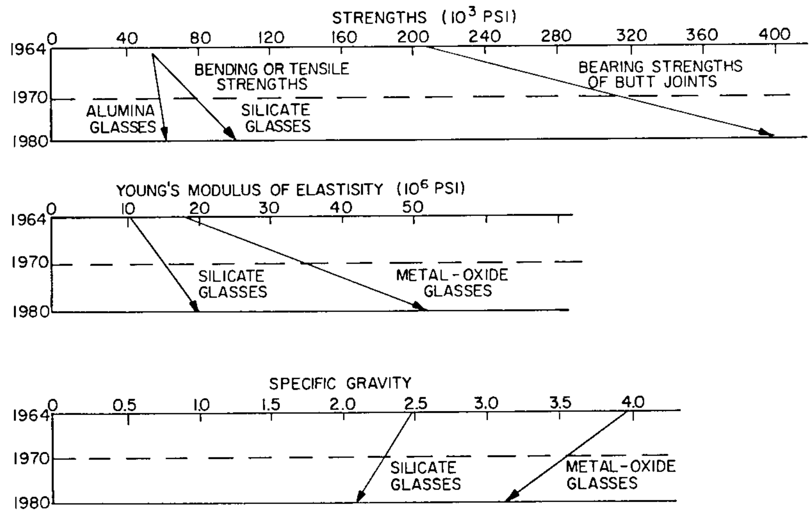


Fig. 1 - Trends - 1964, 1970, 1980

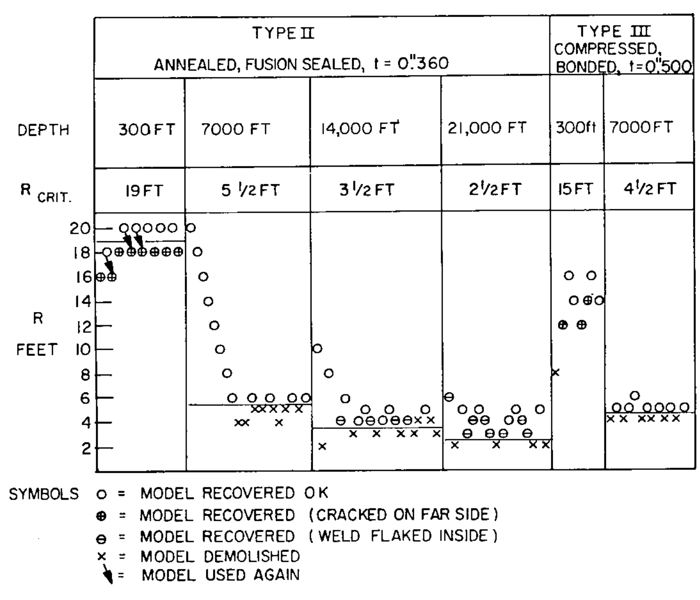


Fig. 2 - NOL test spheres - 10 inch

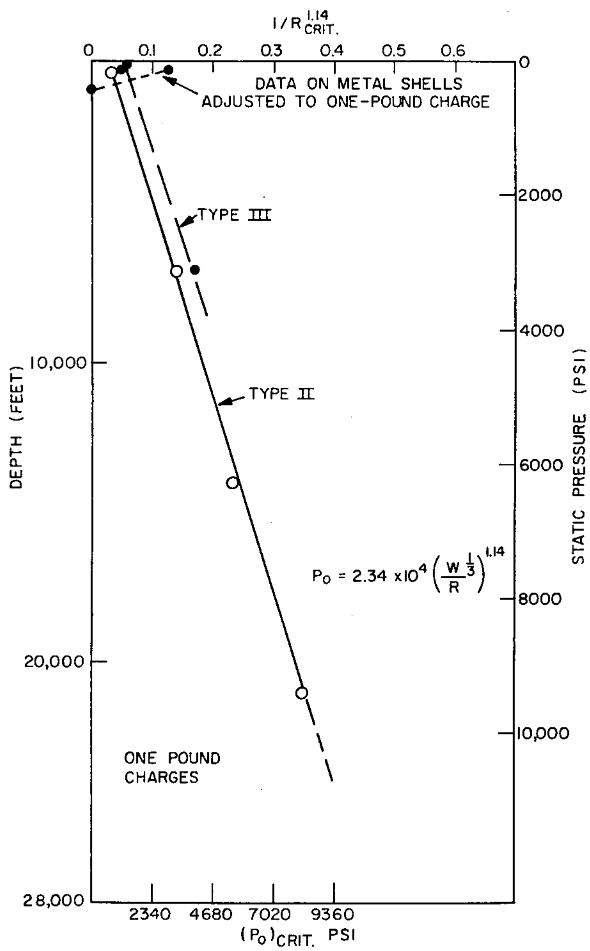


Fig. 3(a) - NOL test spheres (See Fig. 2)

Non-ductility - A high-silicate glass shows a ductile yield point ~~over~~ 10^6 psi or about E/10. Also, it does not creep at ordinary temperatures. No success at all has been had in trying to make a high-silicate glass ductile at lower stresses. Were it possible to do so, the material would lose something of its most attractive properties for use in buoyant, ocean-bottom structures, i.e., its immense compressive strength and creep resistance.

Its high yield strength is in its random structure and its high-energy bonds. All dislocations are blocked. Its silica tetrahedra are bonded randomly and strongly into a three-dimensional network. Creep or flow necessitates breaking these bonds.

The intrinsic compressive strength of a high-silicate glass is that of its random networks. It does not depend on the size, or shape or mass of the part.

Thermochemical Strengthening - Abraded glass parts are notoriously weak in tension and in bending. This is due to the high concentration of stress which arises at the tips of cracks while the part is under load. Cracks originate exclusively from surfaces and interfaces. Cracks never seem to start within the body of a glass part. This may be because the glass' random networks are as strong in tension as they are in compression.

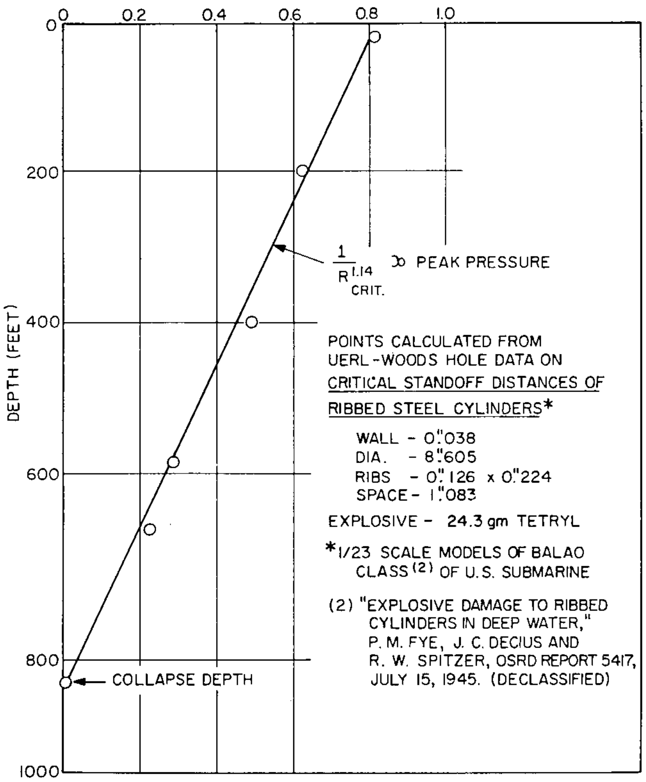


Fig. 3(b) - Effect of depth on the critical dynamic pressure for damage to steel shells by explosions

It has been found that thermochemical treatments can be performed on glass parts which leave all of the surfaces of the parts in a permanent state of compression. These treatments have included chill-tempering. They now include swelling all surfaces by an ion-exchange reaction with a molten ionic salt bath. They also include superficial phase-changes which can be made to occur in certain glass compositions. Small, transparent, low expansion crystals are generated in all surfaces during a heating cycle. These crystals reduce the coefficient of thermal expansion of the outer layers which then shrink less, during cooling, than the rest of the part. All of these treatments lead to an intense permanent compression of the surface layers of the part, to varying degrees. They strengthen a part by keeping its surfaces from getting into tension while under a load.

Abraded glass parts, without prior treatment, may be as weak as 2,000 psi in bending or tension. By contrast, thermochemical-treated glass parts, even those which have flawed surfaces, have strengths up to 120,000 psi, in tension or bending.

Thermochemical-treated glasses are now in production. The manufacturers are the Corning Glass Works (CHEMCOR) and the Pittsburgh Plate Glass Company (HERCULITE II). Research is continuing toward the development of improved types. Some engineering properties of the commercial thermochemical-treated glasses, in their present state, are given in Table 3. The guaranteed minimum bending strength (modulus of rupture) for abraded commercial parts at the present time is 35,000 psi.

Table 3
Properties of Thermochemical-Treated Silicate Glasses with Flawed Surfaces

Type	Condition	Modulus of Rupture - psi		
		1964	1970	1980
A	Annealed	2,000		
B	Chill-tempered	20,000		
C	Swelled by ion-exchange	120,000		
D	Devitrified, low-expansion surface	80,000		
E	Experimental goals	---	300,000	500,000
	Guaranteed minimum for Types C, D and E	35,000	150,000	250,000
Young's modulus of elasticity (10^6 psi)		10-17	12-20	15-30
Density		2.44	2.30	2.20

The modulus of rupture of a thermochemical-treated glass part is that of its surfaces. It does not depend on the size, shape or mass of the part.

Durability - The high-silicate glasses are resistant to early deterioration in saline solutions. This is shown by the well-preserved condition of ancient artifacts which have been recovered from the sea.

No long-time data are at hand on the strength-retention of thermochemical-treated glass parts in saline solutions. Their behavior will depend on the leaching rate of essential elements from the compressed surface layer and on its thickness. The depth of treatment of glass surfaces to compress them depends solely on the time of treatment. Long soaks can produce compressed layers many millimeters thick. Calculations indicate that large parts can be treated in a practical manner so that their surface-compression stresses will be retained in saline solutions for centuries.

Very few data are at hand on the effects of marine organisms, particularly of marine borers and molluscs, on glass of any kind. Until data are obtained, and in all prudence, it must be assumed that glass surfaces should have some sort of isolation or protection from attack by these animals.

A long-term program of marine exposure tests on many glasses has been started by NOL. Bare, unprotected specimens are now being exposed in Pacific, North Atlantic and Caribbean waters. PYREX, CHEMCOR and HERCULITE II specimens are being held in jigs in these tests under a strong bending load, a condition which causes stress-corrosion failures in corrodible alloys. Others are not bent.

Dimensional Stability - High-silicate glasses do not creep under stress nor undergo permanent deformations at ordinary temperatures. But glass parts go through a period of delayed elastic deflection or recovery after loading or unloading them. This is due to the slight mobility of ions through the network at ordinary temperatures. However the time-dependent portion of glass' elastic response to stress is less than one percent of its instantaneous elastic response. Thus, if a load causes an instantaneous unit strain of 0.03 inch/inch then the delayed unit strain is less than 0.0003 inch/inch. The delayed stress generated by these delayed strains in a glass ($E = 10^7$ psi) would be less than 3000 psi. An effect of this small magnitude will not cause serious dimensional or stress problems in a practical structure. Its manufacturing tolerances may be about 0.01 inch/inch. Therefore misfits could have a larger effect than delayed elastic strains.

Optical Inspection - The dimensional stability, optical clarity and photoelastic properties of the silicate glasses offer a unique opportunity for detailed examinations of the condition of massive glass primary structures.

Extensive inspections can be performed on a simple, economical, non-destructive basis, as follows:

a. Seeds and stones (bubbles and dirt) in a structural glass part can be seen, examined by microscope and photographed using visible light.

b. "Striae," "cord" and other types of unwanted streaks and layers of dissimilar glass can be revealed visually in a structural part by their differential refraction effects. These can be measured by light meters and photographed.

c. Unwanted local strains in a structural part can be seen using crossed polaroid sheets, measured and photographed.

d. Surface-compression stresses which have been specified for a thermochemical-treated structural part can be measured using a birefringence stress meter. These measurements can be performed all over its surface, inside and out. The realizable modulus of rupture of the part can thus be assured.

e. The type, grade, approximate composition and probable treatment of glass in a given structural part can be identified by its spectrum of refractive indices with wavelength and depth.

f. Adhesive bonds, fusion-sealed (welded) joints, metal inserts, bearing surfaces and the like can be inspected visually by direct observation, even through the glass parts; the state of stress in the parts around inserts, in joints and near bearing surfaces can be inspected by photoelastic means, while at rest or under load.

Bonus Properties - Glasses are transparent, dielectric, non-magnetic and thermally insulating and these properties permit:

a. Viewing of environment in close quarters, using floodlights; inspection of bottom installations without entering.

b. Installation of electrical connections through hull without danger of short circuits.

c. Concealment from electromagnetic detection; denies use of magnetic limpet location-telltales.

d. Savings on power to maintain an internal temperature for comfort and/or optimum operability (as of solid propellants) while in cold waters.

STATE-OF-THE-ART - PRETENSIONED BINDINGS

The exploitation of thermochemical-treated glass as a primary structural material in a composite design for bottom vehicles, weapons and structures may call for the use of pre-tensioned bindings in wire, ribbon or ring-like form. The functions of these open-mesh bindings are given in Table 4.

Table 4
Functions of Pretensioned Bindings for Primary Glass Structures

Function	Titanium Alloy	Glass-Fiber Plastic	Boron-Fiber Glass
Shrink on by heat (NITINOL)	Yes	No	No
Precompress joints in structure	Yes	Yes	Yes
Suppress self propagation of fractures in strengthened glass	Yes	Yes	Yes
Aid in mounting external equipment on glass structures	Yes	Yes	Yes
Detectable using electromagnetic instruments	Yes	No	No
Permit optical inspection of primary structures	Yes	Yes	Yes
Permit viewing of external environment	Yes	Yes	Yes

The light weight materials which can be used for tensioned wires, or ribbons or rings include the following:

a. Titanium alloys, including nickel-titanium (Nitinol). The latter has the property of shrinking and developing tensile stresses up to 60,000 psi when heated after cold-drawing, and is resistant to corrosion.

b. Glass fiber reinforced plastics, provided that an adequate minimum tensile strength is guaranteed for long times under load in a marine environment.

c. Boron-fiber reinforced silicate glass, provided that an adequate minimum tensile strength is guaranteed for long times under load in a marine environment.

The tensioned parts of the bindings for axisymmetric shapes can be arranged in great-circle or geodesic cage-like configurations. For example, assuming full efficiency at a stress of 60,000 psi, a cage of titanium alloy wires would suppress self-propagation and weigh less than 1% of the shell it encloses.

STATE-OF-THE-ART - JACKETS AND LINERS

The use of thermochemical-treated glass for a primary structure will probably require the use of a jacket and liner. The functions of the jacket and liner for the glass may be as shown in Table 5.

Table 5
Functions of a Jacket and Liner Materials for Primary Glass Structures

Function	Ductile Alloy	Structural Alloy	Clear Polymer	Fiber-Reinforced Rubber
Allow inspection and/or viewing	No	No	Yes	No
Prestress glass parts	No	Yes	No	Yes
Mitigate shocks and impacts	Yes	No	Yes	Yes
Isolate glass from the sea	Yes	Yes	Yes	Yes
Insulate wiring from the sea	No	No	Yes	Yes
Reduce Sonar reflections	No	No	Yes	Yes
Reduce sound propagation into sea	No	No	Yes	Yes
Emit an anti-fouling agent	Copper, Yes	No	Yes	Yes
Furnish tear-resistance to the composite structure	Depends on fracture-toughness of the alloy or polymer			Yes
Aid in concealment from EM detection including radar	No	No	Yes	Yes
Aid in shielding from radar	Yes	Yes	No	No
Aid in shielding from lasers	Yes	Yes	Opaque, Yes Clear, No	Yes
Aid in attaching internal equipment (liner)	Yes	Yes	Yes	Yes

A wide range of possible functions and materials must be considered before a final selection is made for a particular system. For small craft, particularly for workboats and search vehicles, a clear polymer is recommended. Candidates include the polycarbonates, polyolefins and modified polymethyl methacrylates.*

STATE-OF-THE-ART - DESIGN AND FABRICATION

The proposed use of thermochemical-treated glass for primary structures will be a challenge which can be met by modern designing and fabrication technology.

Advanced Design Concepts - The uses of syntactic foams, containing glass microspheres, of hollow glass fibers and of hollow glass balls of various sizes as supplementary flotation materials had been studied for years.

*A bonded sandwich of the latter with a core of CHEMCOR did not breakup when the core was fractured and feels stiff and strong.

Many materials approaches were reviewed at the Workshop on Deep Submergence, December 1962. J. Stachiw at ORL, Penn State, had considered the use of polycrystalline alumina and opaque devitrified glasses (PYROCERAM) while developing advanced designs for torpedo hulls. However, Perry of NOL recommended consideration of transparent glass and other unyielding materials in large primary structures for deep submergence, including manned vehicles. The proposal included various segmented, geodesic designs with butt joints for hemispheres, cylinders and large domes. These designs are being studied further by Krenzke of DTMB. Plastic mockups of one design were assembled later on by Stachiw at ORL. The concepts have been developed further by Ernsberger, Mihalik and J. Smith of PPG and by G. Smith, J. Blizard, et al., of Corning Glass Works, who also considered fabrication advantages in such parts.

Blizard, et al., at CGW proposed that glass cylinders and ogives be centrifugally cast permanently into metallic shells and into the coves of metallic sandwich designs.

Krenzke, et al., at DTMB suggested pretensioned titanium jackets over assembled parts, analogous to design concepts developed earlier for rib-stiffened cylinders made of unweldable metals.

Perry also suggested pretensioned metallic or non-metallic loops or bindings in a geodesic open cage around the primary structure (spherical or cylindrical) to facilitate inspection and viewing while performing other functions (Table 3) and of transparent plastic jackets and liners (Table 4). He proposed a simple hatch and a metallic insert for spherical shells, each comprising a circular spherical segment with conical bearing surfaces, the apex of which coincides with the center of the spherical shell. Krenzke and Charles are studying hatches with other cone angles.

In a paper for the ASME, Nov. 1963 (63-WA-219), Perry proposed a method of constraining a thermochemical-treated part while cutting or drilling it, to prevent self-propagation of fractures from the fresh surfaces, retreating the latter and then removing the constraints. The purpose is to permit changes in finished parts. He also proposed the use of buoyant tubular longerons, curved frames, hollow donuts and other structural parts for vehicle "aqua frames," vehicle work-arms and bottom structures, the same to be equipped with bindings, jackets, etc., as required.

Later proposals at NOL include: the insertion of wires and ribbons in non-metallic seals between glass parts and the use of printed circuitry on the hull walls; the transfer of electrical signals and impulses in and out of the hull by optical, electrical, magnetic or acoustic coupling through the glass walls and the use of special areas of the glass walls as elements in optical systems for illuminating and examining terrain and objects.

It is highly probable that some existing ideas have not been mentioned which should have been. Many new ideas will crop up as the need becomes apparent. For example, does anyone want a photochromic (light darkening) hull? A built-in thermopile temperature control? A water-shield wiper? A neutral-buoyancy work-arm? A felf-buoyant energy sink for hydraulic systems which use the inflow of sea water at great depths to actuate mechanisms? A deep capsule for a pop-up system which is self-opening at or near the surface?

Thus there is no dearth of ideas to consider while planning systems or while designing structures for the systems.

Basic Design Principles - The principles of designing external pressure vessels with an unyielding material are well advanced.

Krenzke and others at DTMB studied the buckling failures of unstiffened glass cylinders and small hemispheres. Failures of all models were by buckling. The highest stress was attained in small hemispheres and was 300,000 psi. They developed formulae for predicting buckling of shells with known eccentricities.

Perry tested buoyant glass spheres under pressure and explosive loading. Some of these had deep internal "ribs" at the equator due to the intrusion of molten glass during the process of fusion-sealing the hemispheres together. Some ribs flaked off under extreme combinations of static and dynamic stress (21,000 ft. deep and a one-pound charge exploding 3-5 ft. away) leaving the shell intact and unbroken. Spheres with flexibly-bonded ribs or floating ribs were not tested.

In brief, the rules for designing with an unyielding material are: avoid buckling; avoid principal stresses in tension; avoid gross or sudden variations of wall thickness. Fortunately, the "Hookian" or elastic behavior of glass simplifies all design computations. Also, photoelastic stress analyses can be performed on actual structures instead of models.

Joints - Krenzke, et al., at DTMB stressed glass in a hemisphere up to 300,000 psi at an annealed-glass/hardened-steel butt joint just prior to a buckling failure. The annealed glass bearing surface had been ground flat but not polished.

Perry tested two other types of joints in deep-sea explosion tests: fusion-sealed butt joints in annealed PYREX spheres and epoxy adhesive butt joints between HERCULITE II hemispheres. In neither design did critical explosions-damage seem to begin at the joints.

Thus, so far, it appears that butt joints between sections can carry the loads. No data exist on how close their dimensional tolerances should be to avoid premature damage. However, tolerances as tight as you please can be furnished during grinding and polishing.

Bindings, Clamps and Metal Inserts - Designs and fabrication techniques for developing suitable joint-clamps and pretensioned bindings for primary structures can be borrowed from existing metals or filament-winding technologies. It is also expected that metallic connectors and wiring for glass hulls can be developed by borrowing and scaling up the arts of glass/metal seals and/or printed circuitry.

Advanced design concepts for bindings, such as the use of a boron-fiber reinforced glass, would require the development of whole new technology.

Jackets and Liners - If a metal jacket is to be employed it can be designed and built by drawing on existing metals technology. If non-metallic jackets and liners are to be used they can be designed and built either by drawing on the arts of designing and processing unfilled plastics or by turning to the techniques for designing and producing tire carcasses, reinforced inflatables and the like.

Glass Technology - The production of massive thermochemically-treated glass primary structures for vehicles and the like has never been attempted by the glass industry.

The prospects for doing so have been examined in detail by the Corning Glass Works and the Pittsburgh Plate Glass Corp. Each independently arrived at the conclusion that all necessary techniques exist for producing large parts. Large melting facilities now exist, handling up to 20 tons/day, which could be converted temporarily to this use. However new independent facilities would be needed for very large production. Also, a major scale-up of forming equipment, tooling, post-treating equipment and facilities for handling and assembling large parts is feasible and necessary. No technical obstacles are foreseen which would preclude a major scale-up of processes and equipment for producing and treating very large parts. A vigorous engineering scale-up program would be necessary and sufficient to obtain the desired production capabilities.

Shipyard Technology - The assembly of massive, thermochemically-treated glass primary structures for vehicles and the like has never been attempted by the shipbuilding industry.

The prospects for doing so have been examined by the Electric Boat Division, General Dynamics. They conclude that the assembly and launching of large composite structures, with an unyielding material for the primary structural elements, is feasible. However, wooden pegs, spikes and welding torches will have to be set aside.

EB foresees no technical obstacles to the development of adequate designs and shipyard practices for the assembly of massive glass composite structures. A vigorous shipyard design and familiarization program would be necessary and sufficient to obtain the desired competence.

STATE-OF-THE-ART - ECONOMICS OF GLASS

The cost of glass sand is between 2 and 3 cents per pound. The cost of glass, molten and ready for forming is between 3-1/2 and 40 cents per pound, depending on the degree of fining required.

The cost of production parts of glass for deep-submergence (after R and D, prototype development, testing and tool up) is now estimated to be \$3 to \$8 per pound.

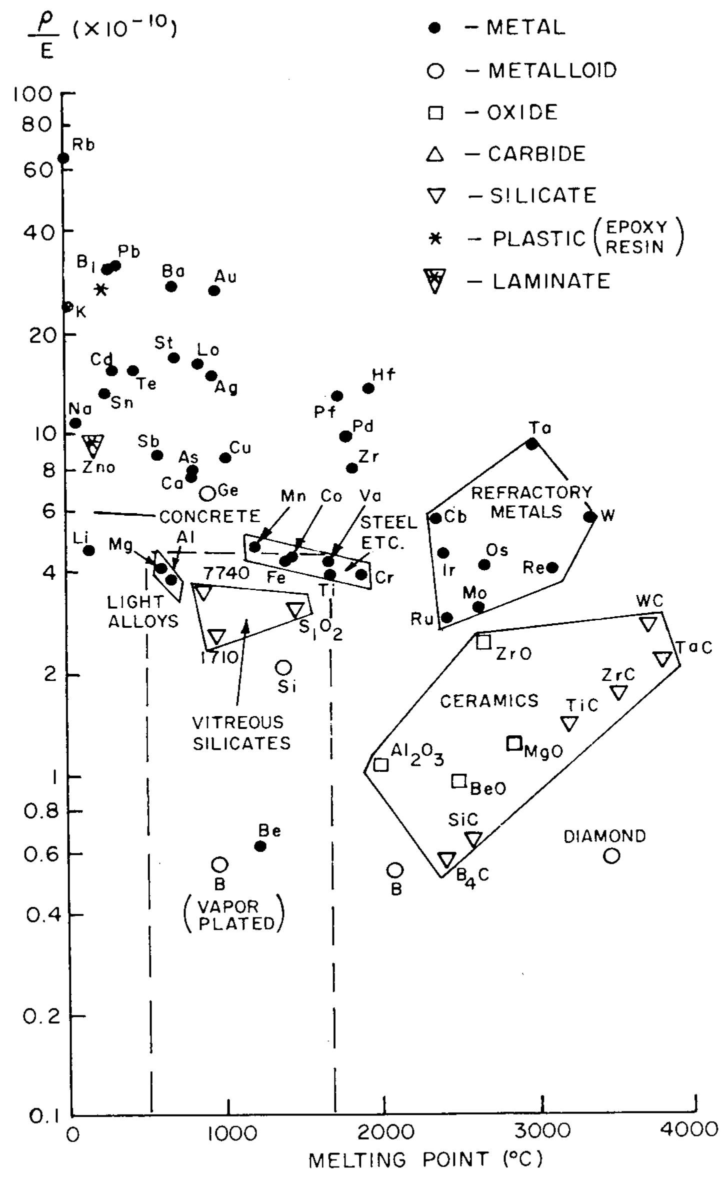
STATE-OF-THE-ART - OTHER INORGANICS

Other lightweight materials can be considered for use in the primary structures of deep-submergence hulls. Figures 4, 5 and 6 indicate the relative standings of various materials in terms of their relative weights for structural uses versus their melting or processing temperatures. The relative-weight parameters used in Figs. 4, 5 and 6 are for "equal-deflection," "equal buckling pressures for spheres" and "equal buckling pressures for ring-stiffeners," respectively. Relative weights for equal buckling pressures for rib-stiffened cylinders ($\rho/E^{2/5}$) fall between the values in Fig. 5 and Fig. 6.

Pure boron, boron carbide and silicon carbide offer weight advantages over the vitreous silicates. Alumina may offer slight weight advantage (if fully densified, Table 2) over glass.

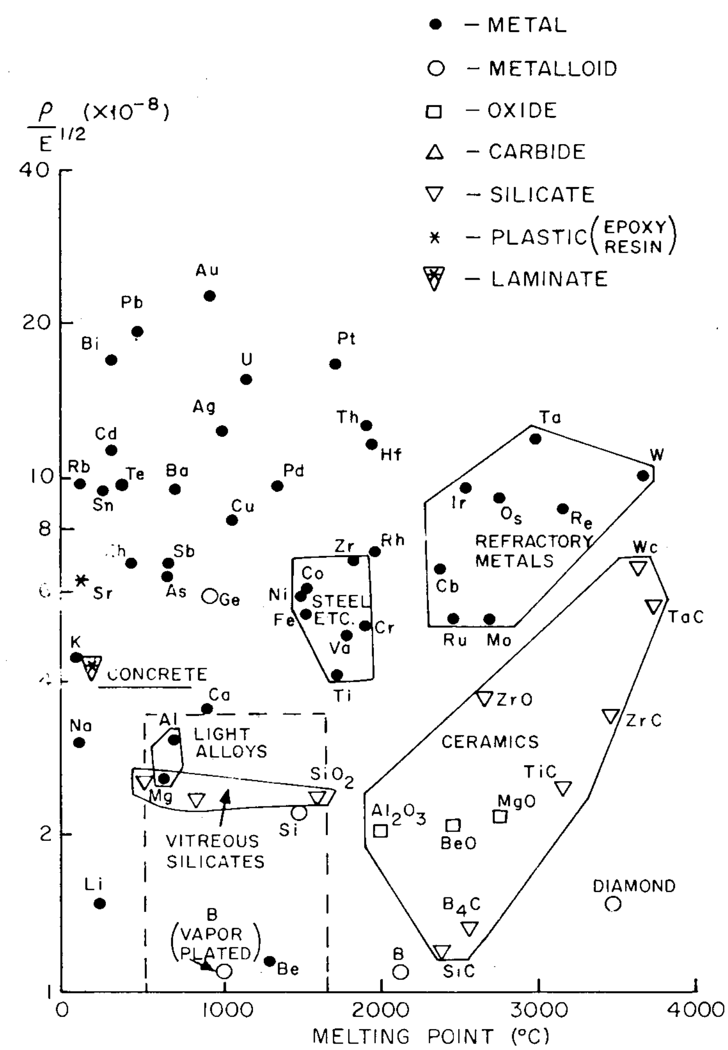
These crystalline materials can also exhibit high compressive strengths if properly processed. However, they are less available, harder to process and are equally opaque. It is not known whether their limited strength in tension while scratched or flawed can be enhanced by any process analogous to the thermochemical treatments for the vitreous silicates. Nor is there an inspection tool for assuring their tensile strengths like the stress-meters now in use on glass. Except for sapphire, none yet offer an opportunity for optical inspection or viewing.

Their reliability and cost/effectiveness in hulls might be increased greatly if low-cost processes were to be developed for fabricating them into large, fully-dense, transparent structural parts of high strength. Programs of research and development on fabrication processes would be justified if a good approach toward this goal were to be proposed. However, it is unlikely that these materials will offer as many advantages as glass for deep submergence in the immediate time period.



ρ/E (×10^-10)
• – METAL
○ – METALLOID
□ – OXIDE
△ – CARBIDE
▽ – SILICATE
* – PLASTIC (EPOXY RESIN)
– LAMINATE
Rb
Bi
Pb
Ba
Au
K
Cd
St
Lo
Te
Ag
Sn
Hf
Na
Pf
Pd
Sb
As
Cu
Zr
Zno
Ca
Ge
Mn
Co
Va
CONCRETE
STEEL ETC.
Ta
REFRACTORY METALS
Cb
W
Li
Mg
Al
Os
7740
Fe
Cr
Ir
Re
Ti
LIGHT ALLOYS
Mo
Ru
SiO2
WC
1710
ZrO
TaC
Si
ZrC
CERAMICS
TiC
VITREOUS SILICATES
Al2O3
MgO
BeO
SiC
Be
DIAMOND
B
B4C
B
(VAPOR PLATED)
MELTING POINT (°C)

Figure 4



• – METAL
O – METALLOID
□ – OXIDE
△ – CARBIDE
▽ – SILICATE
* – PLASTIC (EPOXY RESIN)
– LAMINATE
ρ/E^1/2 (×10^-8)
40
20
10
8
2
1
0
1000
2000
3000
4000
MELTING POINT (°C)
Au
Pb
Bi
Pt
U
Ag
Th
Hf
Cd
Rb
Te
Ba
Pd
Sn
Cu
Sb
Sr
As
Ge
K
CONCRETE
Ca
Na
Al
LIGHT ALLOYS
Mg
SiO2
Si
VITREOUS SILICATES
Li
B (VAPOR PLATED)
Be
B
Zr
Rh
Co
Ni
STEEL ETC.
Fe
Cr
Va
Ti
Ta
W
Ir
Os
Re
REFRACTORY METALS
Cb
Ru
Mo
Wc
TaC
ZrO
ZrC
CERAMICS
TiC
Al2O3
MgO
BeO
B4C
SiC
DIAMOND

Figure 5

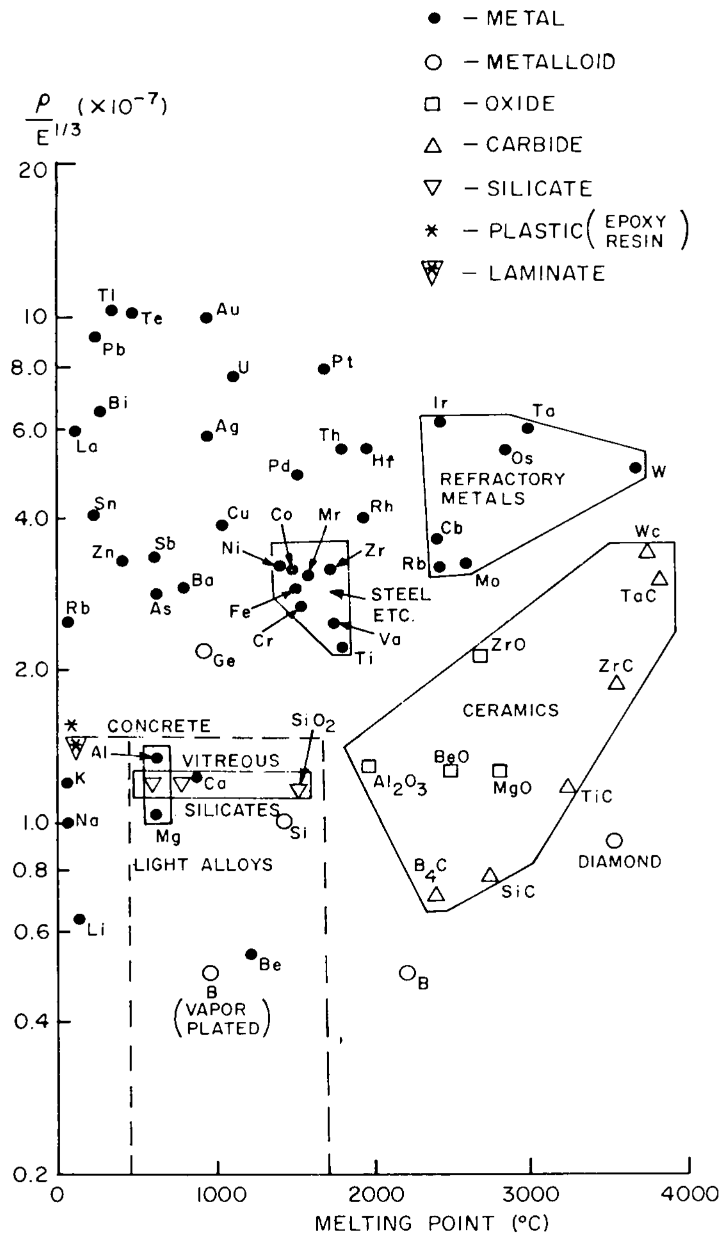

● – METAL
○ – METALLOID
□ – OXIDE
△ – CARBIDE
▽ – SILICATE
* – PLASTIC (EPOXY RESIN)
– LAMINATE
ρ/E^{1/3} (×10^{-7})
20
10
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0
1000
2000
3000
4000
MELTING POINT (°C)
Tl
Te
Au
Pb
U
Pt
Bi
Ag
La
Th
Hf
Pd
Sn
Cu
Co
Mr
Rh
Ni
Zr
Zn
Sb
Ba
Rb
As
Fe
STEEL ETC.
Cr
Va
Ti
Ge
Ir
Ta
Os
W
REFRACTORY METALS
Cb
Rb
Mo
Wc
TaC
ZrO
ZrC
CERAMICS
CONCRETE
SiO2
Al
VITREOUS
Ca
K
SILICATES
Na
Si
Mg
LIGHT ALLOYS
Li
Be
B
(VAPOR PLATED)
B
Al2O3
BeO
MgO
TiC
B4C
SiC
DIAMOND

Figure 6

PROGRAM COSTS

The many items listed in Table 6 must be completed by government and industry while preparing for the production of composite structures for deep submergence, based on massive glass as the primary load-bearing material.

Table 6
R and D Mileposts

I. Navy Department

Requirements·

Missions (search, recovery, construction, launch, attack, etc.)
Configurations and accommodations
Performance (depths, speeds, ranges, maneuverability, etc.)
Safety and Reliability (collisions, depth-hardness, etc.)

Logistics and Support

Management

II. Materials Suppliers

Parts designs and testing
Tool up and engineering
Supporting R and D (materials, processes, seals, etc.)
Prototype Fabrication

III. Navy Laboratories

1. Materials and Processes (glasses, alloys, ceramics, polymers)
2. Accessory developments (search, devices, workarms, weapons, etc.)
3. Inspection Methods; classifications of defects
4. Environmental Simulation Testing
5. Structural Design Principles (hulls, hatches, frames, fairings, etc.)

IV. Shipyards

Layouts
Equipment
Details
Tooling
Supporting R and D (handling, assembly, modification, etc.)
Assembly
Launching
Testing

Glass Suppliers - Two glass firms are engaged in the production of thermochemical-treated glass: Corning Glass Works (CGW) and Pittsburgh Plate Glass Corporation (PPG). No others are known to be engaged at the time of writing.

Navy Laboratories - Firm figures on the costs of R, D and E in Navy laboratories in support of this program cannot be given at the present time. Many topics and details have to be worked out as the program develops for which exact costs cannot now be developed. No estimates at all can be given on R, D and E on work-arms, rescue devices, armaments, power supplies, electronics and many other accessories that may call for the use of glass in their construction, for which there are no firm requirements.

There are a great number of basic tasks that would have to be carried out if glass is to be used at all. These would be approximately the same, whatever sized goal is set. They can be organized into two main groupings as follows:

I. MATERIALS, PROCESSES AND RELIABILITY ASSURANCE

The goals are to develop and specify a set of improved materials for use in composite structures for external pressure vessels for deep submergence, and for their secondary structures and accessories, which include unyielding, load-bearing materials. These may include: glasses; ceramics; alloys for hull penetrations; alloys for external bindings, clamps or jackets; alloys for bearing surfaces and seals; polymers for jackets with special combination of properties (Table 5); polymers for liners, adhesives, sealants. Inputs include: Navy requirements, environmental factors; design factors, fabrication limitations. Work includes: synthesis; compounding; alloying, processing; treating; fabricating; testing of materials and inspection of structures. Output includes formulae; materials manufacturing procedures; recommended fabrication and treatment practices; materials test methods and specifications; structures inspection methods and classifications of defects; guidelines for improving designs.

II. DESIGN PRINCIPLES FOR UNYIELDING MATERIALS

The goals are to develop and describe a set of engineering principles and procedures for designing external pressure vessels made of unyielding, load-bearing materials in a composite construction. Inputs include: Navy requirements; environmental factors; fabrication limitations and materials properties data. Work includes: development of theories and computer programs for mathematical stress analysis; experimental stress analyses on models; dynamic model testing; comparison of proposed configurations and details for their potential weight, reliability, performance and costs. Outputs would include: general design principles; recommended design practices; design formulae, curves, tables; guidelines for direction of improving materials, processes and inspection methods for structures; predictions of service performance.

APPENDIX 1

EFFECT OF MATERIALS PROPERTIES ON THE RESISTANCE OF HOLLOW STRUCTURES TO BENDING WHILE UNDER EXTERNAL PRESSURE

A bending moment (M) generates tangential tensile and compressive stresses ($\pm$ Mc/I) on opposite surfaces of a hull wall of section modulus (I/c). An external pressure (P) generates a tangential compressive stress (σ_p) throughout the hull wall. These stresses can add up to exceed the tensile strength (S_T) or the compressive strength (S_C) of the wall material and cause failure. The question is whether failure will occur first on the tensile side or the compressive side.

If $S_C \approx |S_T|$, as in a ductile alloy or a plastic, the failure due to bending while under external pressure will occur when $\sigma_p + (Mc/I) > S_c$. Also, the bending moment which can be just carried by the hull is

$$M = (S_c - \sigma_p)\,\frac{I}{c}\,. \tag{1}$$

On the other hand, if $S_c >> |S_T|$, as in a dense alumina, vitreous silicate, etc., the failure due to bending while under external pressure will occur when $\sigma_p - (Mc/I) < -S_T$. Also, the bending moment which can be just borne by the hull is

$$M = (S_T + \sigma_P)\,\frac{I}{c}\,. \tag{2}$$

Equating (1) and (2),

$$M_{max} = \left(\frac{S_T + S_C}{2}\right)\frac{I}{c} \tag{3}$$

when

$$(\sigma_p)_{opt} = \frac{S_C - S_T}{2}\,. \tag{4}$$

Again, if $S_C \approx |S_T|c$, $(\sigma_P)_{opt} \approx 0$ and the allowable bending moment is a maximum at or near the surface of sea, as in metal hulls (Fig. 3(b)). This diminishes to zero when $\sigma_p = S_c$ [Eq. (1)].

But if $S_c \to \infty$, as in glass or a strong ceramic, the bending moment which can be borne becomes very great at extreme depths, even though its tensile strength is reduced by surface imperfections.

If a thermochemical-treated glass is used to build the hull, and if all surfaces contain a compressive stress (σ_t) due to the treatment,

$$M = (S_T + \sigma_t + \sigma_p)\,\frac{I}{c} \tag{5}$$

until the stress due to external pressure is increased to $(\sigma_p)_{opt}$. At that point Eq. (3) still holds. Beyond that pressure,

$$M = (S_c - \sigma_t - \sigma_p)\,\frac{I}{c} \tag{6}$$

until $\sigma_p = S_c - \sigma_t$, when M becomes zero.

CONCRETE FOR UNDERWATER STRUCTURES

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Concrete is a versatile construction material which should be suitable for the construction of underwater structures for housing personnel and equipment for extended periods of time.

The primary considerations with respect to the use of concrete would appear to be:

1. Concrete strength, in particular compressive strength

2. Permeability

3. Resistance to sea water attack

4. Structural design

5. Construction procedures

Concrete strength. Present day concretes can attain compressive strengths in the range of 5,000 to 10,000 psi at 28 days' age, depending upon cement type, aggregate properties, degree of control of concrete making operations, i.e., proper selection of ingredients and adherence to proven principles for attaining quality. Higher strengths, up to 15,000 psi, are currently obtainable in the laboratory. In addition, the time at which such strengths are attained can also be varied by proper selection and proportioning of materials and curing environment. Tensile strength, if it needs to be considered, will be of the order of 7 - 10 percent of the compressive strength, with the percentage somewhat greater in the lower compressive strength range.

Type of aggregate influences concrete density. Sand and gravels or crushed stone yield concretes weighing approximately 150 lb. per cu. ft. Manufactured lightweight aggregates produce densities of the order of 100 lb. per cu. ft. Densities ranging up to about 300 lb. per cu. ft. can be produced using heavy aggregates such as portland cement clinker, magnetite, ilmenite, limonite and steel punchings. The approximate maximum 28-day compressive strengths currently obtainable under controlled conditions would be about as follows, at least as a guide to presently attainable levels.

Aggregate Type	Concrete Density in lb./cu. ft.	Approximate Maximum 28-Day Compressive Strength, psi
Lightweight aggregate	100	8 - 10,000
Sand and gravel or crushed stone	150	12 - 15,000
Heavy aggregates	200 to 300	9 - 11,000

Concrete strength is influenced only slightly by size of section. For example, a 6-inch diameter by 12-inch high cylinder is the usual test specimen used to obtain strengths noted above. The same concrete in a 12-in. diameter by 24-in. high cylinder would show strengths about 9 percent lower. For more massive sections, a further reduction of up to a maximum of 5 percent would be experienced.

It is probable that the level of strengths cited above will prevail for the next 5 to 10 years, with a probable increase of about 20 percent at the end of that period. By 1980-1985, it is probable that a further increase of 25 percent in strength will be possible.

Permeability. Like many construction materials, concrete is permeable to liquids and gases. By proper proportioning, i.e., low water-cement ratio, use of dense aggregates, and adequate moist curing, the permeability can be reduced to very low values. Such flow follows Darcy's law. A high quality, high strength concrete made with a dense and relatively impermeable aggregate, cured moist and kept moist until submerged to a depth of 1500 feet (about 650 psi) permit the passage of about 0.001 to 0.005 lb. of sea water/day/ft.^{2}/ft. thickness (0.004 to 0.020 for 6000 ft. depth). This considers the effect of maintaining the humidity inside the structure at some value well below 100 percent, i.e., increasing the effective force driving water through the concrete. Permeability to fresh water would be approximately one-third greater. If constructed above water, concrete should be kept saturated until submerged since drying markedly increases permeability. If no passage of water can be tolerated, an impermeable sheath on the exterior would be required.

Resistance to Sea Water Attack. The use of high quality, high strength concrete necessitated by structural and other considerations would provide a high degree of protection against sea water attack (sulfates in solution in sea water) and the leaching of lime from the concrete during passage of sea water. Resistance to chemical attack by sea water can, if deemed desirable, be further enhanced by limiting the tricalcium aluminate content of the cement. If sheathing is required in order to avoid passage of water through the concrete, concern for sea water resistance and leaching would be eliminated.

It is anticipated that corrosion of steel bar reinforcement would be no problem. Steel encased in a high quality concrete (an alkaline medium) continually submerged should resist corrosion well, provided the concrete cover is at least 2-1/2 to 3 in. thick. The use of prestressing (utilizing small diameter wires) is not indicated in this application.

Structural Design. Structural considerations for spherical and cylindrical units are set forth in the attached "Preliminary Study of the Structural Design of Underwater Concrete Structures."

Construction Procedures. Any one or a combination of present concrete construction techniques would appear to be suitable. These include casting-in-place as a complete unit or precasting elements to be joined to produce the total structure on land or barge. Handling equipment would limit the size of the structure, in addition to other considerations. For in-place underwater construction, tremic concreting methods may be suitable or prepacked (forms filled with aggregate and grouted to produce concrete). In the latter methods, the metallic form or a metallic liner on the outside form can be utilized as a sheathing. For cast-in-place construction, continuous casting operations can be utilized and thus remove the restriction on size due to handling noted above.

Suggested Areas for Research and Development. It would appear desirable to develop work programs designed to obtain information on the following:

1. The permeability of concretes to sea water. Variables to be included would be water-cement ratio, curing, aggregate type, sea water pressure and temperature, varied temperature and humidity on interior surface (downstream side in test), etc. Include leaching of lime from concrete.

2. New techniques for markedly increasing concrete strength.

3. Resistance to corrosion of reinforcement under the varied exposure conditions contemplated.

4. Construction practices required to attain the specified concrete properties and structural design features.

PRELIMINARY STUDY OF THE STRUCTURAL DESIGN OF UNDERWATER CONCRETE STRUCTURES

For this preliminary study, certain simplifying assumptions were made. Only two shapes were considered, spheres and cylinders. Hydrostatic pressure was assumed to be uniform from top to bottom of structure. Stresses near openings in the structure were not considered. Cylindrical structures were assumed to be infinitely long and not affected by bending stresses.

Spheres. The axial (or tangential) stress in psi is:

$$s = 0.444 \frac{A_o}{A_c} \text{(Depth)}$$

where the depth is in feet. The coefficient 0.444 is the hydrostatic pressure in psi of a head of one ft. of sea water weighing 64 lb. per cu. ft. The stress "s" is the compressive stress in the concrete if there is no reinforcement, or it is the weighted average stress in the concrete and steel if the concrete is properly reinforced. A_o is the area of a circle having a diameter equal to the outside diameter of the sphere. A_c is the cross sectional area of the concrete shell. Both A_o and A_c are in the same units, e.g., square feet. See Fig. 1.

Cylinders. The tangential stress in the shell is:

$$s = 0.444 \left(\frac{D_o}{2t}\right) \text{(Depth)}$$

where the depth is in feet. D_o is the outside diameter of the cylinder in feet, and t is the shell thickness in feet. See Fig. 2.

Buoyancy. The unit weight of concrete was assumed to be 150 lb. per cu. ft. This is a typical value for normal weight concrete (non-air entrained). Other values ranging from about 100 to 225 lb. per cu. ft. can be obtained. Only the weight of the shell was considered, i.e., equipment or partitions within the shell were not considered. The effect of reinforcement on the unit weight is relatively minor. The unit weight of concrete weighing 150 lb. per cu. ft. will be increased about 7 lb. per cu. ft. for each percent of reinforcement (1 percent in each direction).

General Considerations. Bending stresses in the shell should be avoided wherever possible. Bending stresses are induced by non-uniform loading of the shell and by changes in shell thickness. Non-uniform loading could result from the use of ballast if the structure were buoyant. It would be advisable to make the shell thick enough to cause

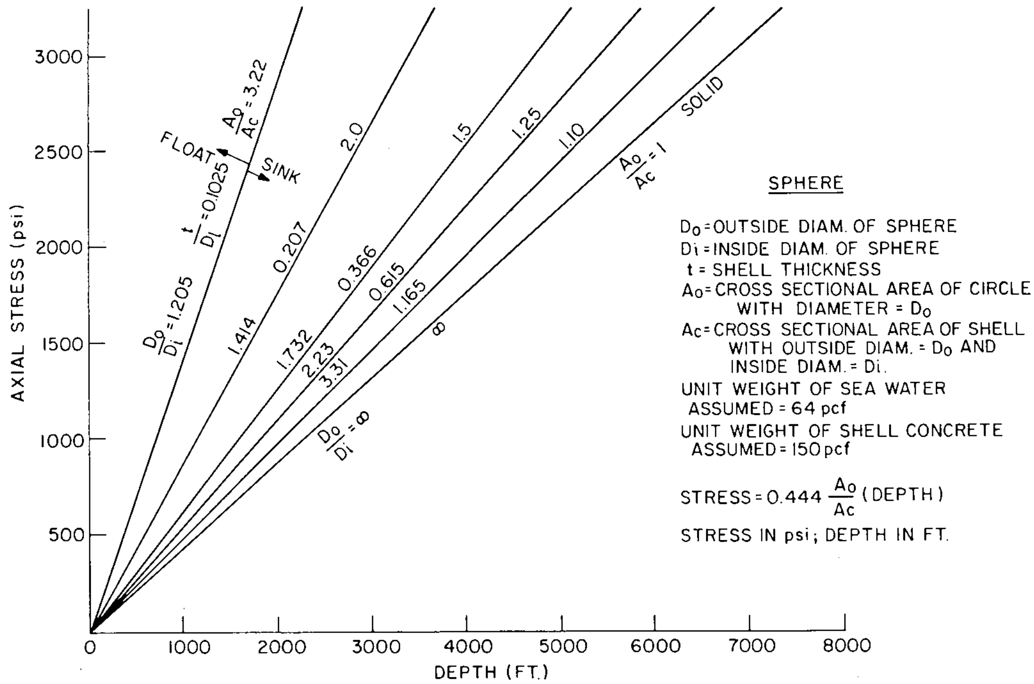

Figure 1

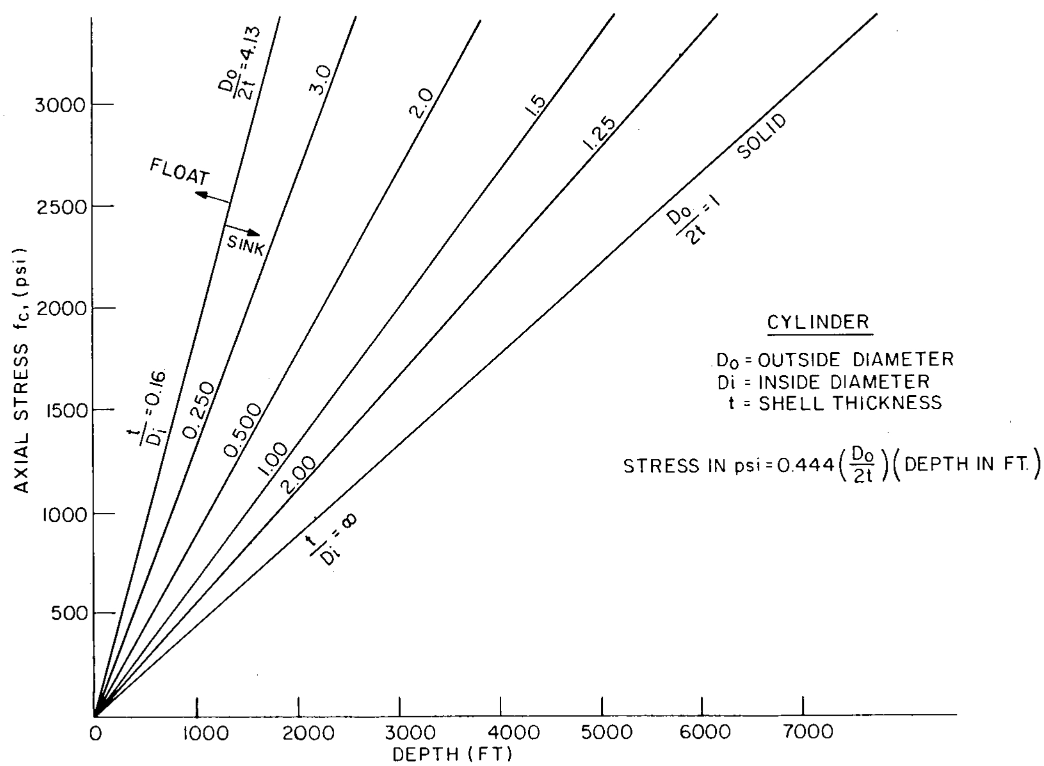

Figure 2

the structure to submerge. On the other hand, the thinner the shell is, the better it is able to accommodate bending stresses, especially those that occur at openings. It would thus seem that the most appropriate thickness would be one that would be just thick enough to cause submergence.

Figure 3 is a re-plot of Figs. 1 and 2 in terms of shell thickness. Figs. 4 and 5 are magnified views of a part of Fig. 3. Figs. 4 and 5 include the influence of reinforcement, and the influence of increasing the unit weight of the concrete on the buoyancy of the structure.

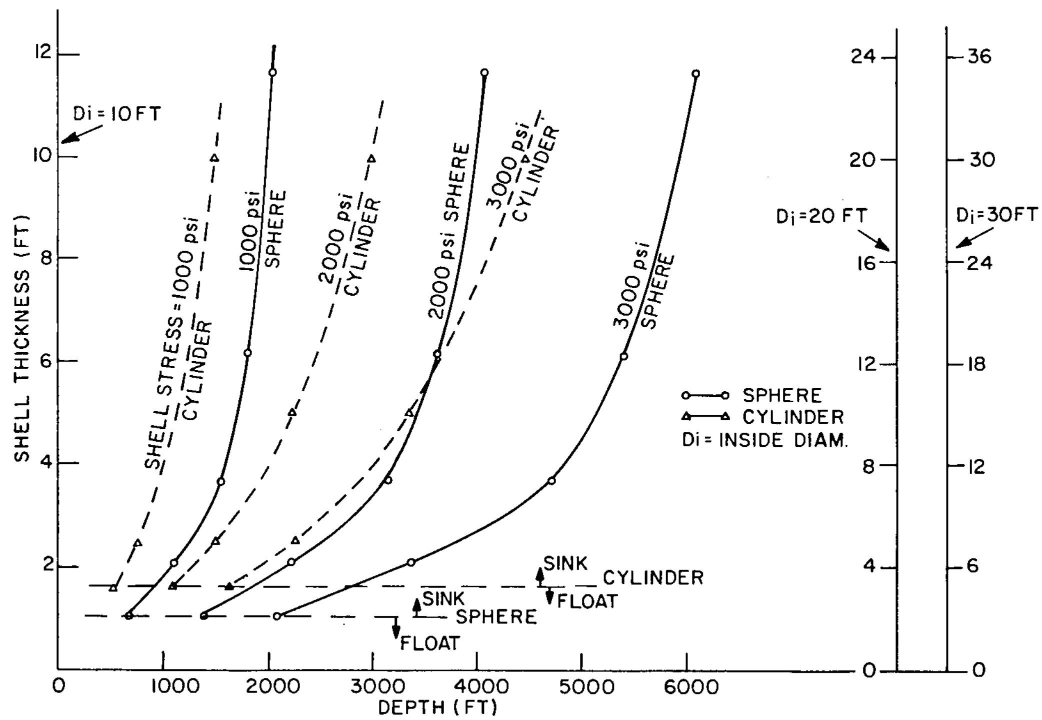

Figure 3

The stresses shown in Figs. 1 through 5 are the calculated stresses due to the hydrostatic pressure. To assure an adequate factor of safety, the concrete strength should be at least 2 or 3 times as high as the calculated compressive stress.

Figure 6 shows the influence of unit weight of concrete on the buoyancy of the structure.

Ends of cylindrical structures should be hemispherical to minimize bending stresses.

Reinforcement should consist of two equal mats of bars or welded wire fabric placed symmetrically within the shell. Small diameter bars are preferable to large bars but the openings in the mats should be no less than about 4 × 4 in.

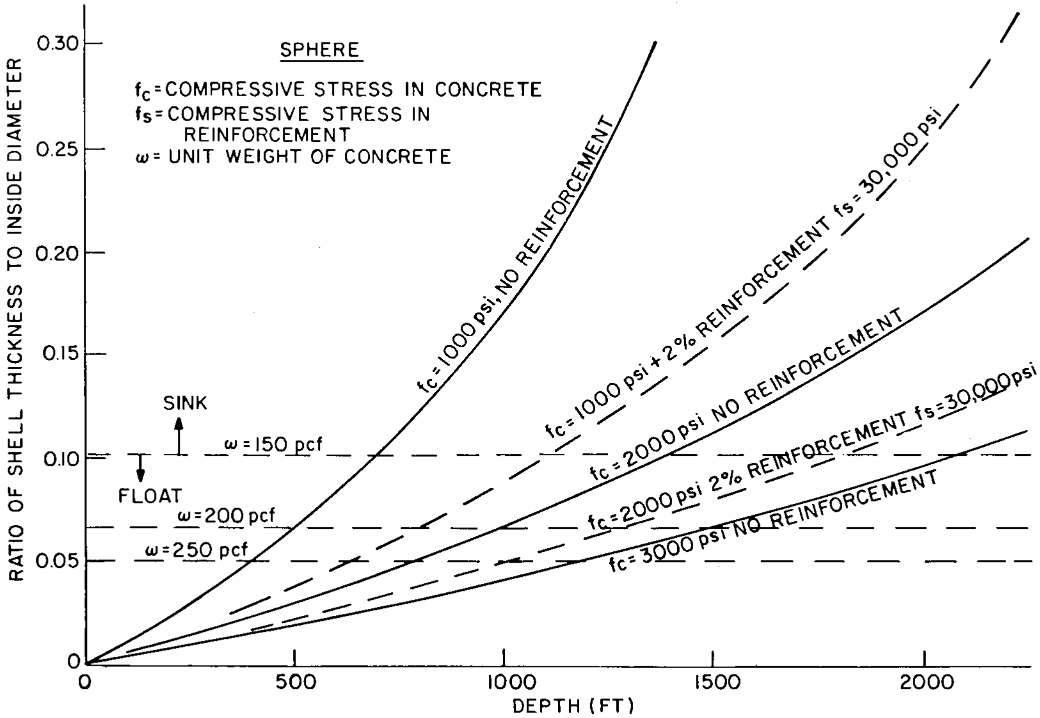

Figure 4

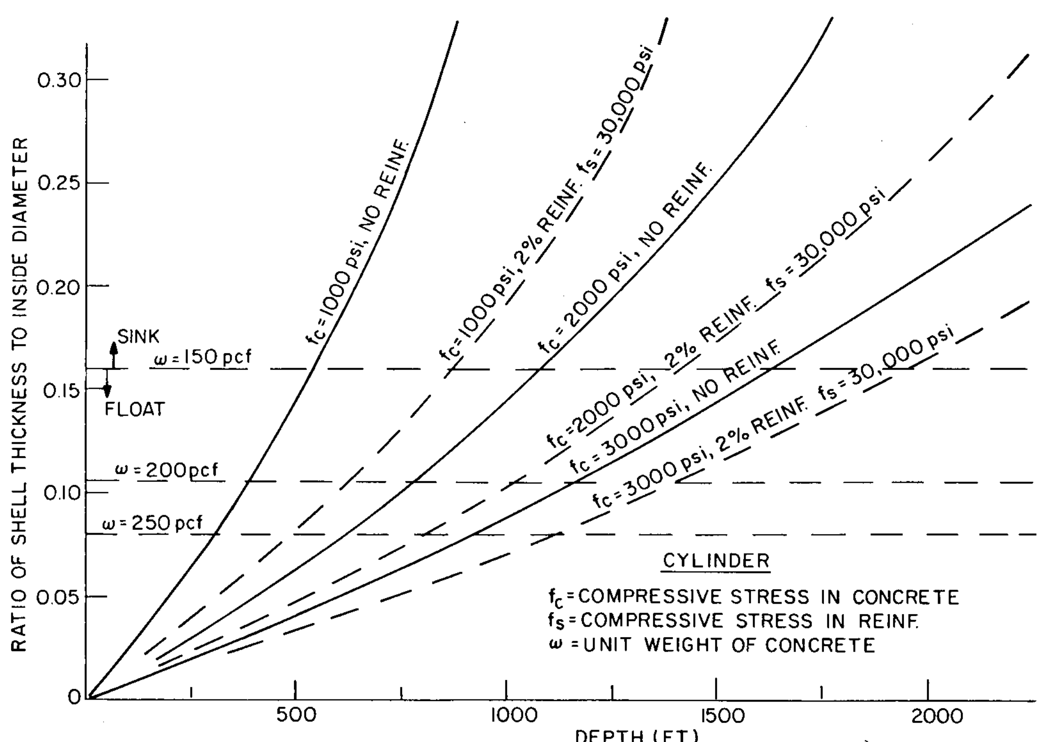

Figure 5

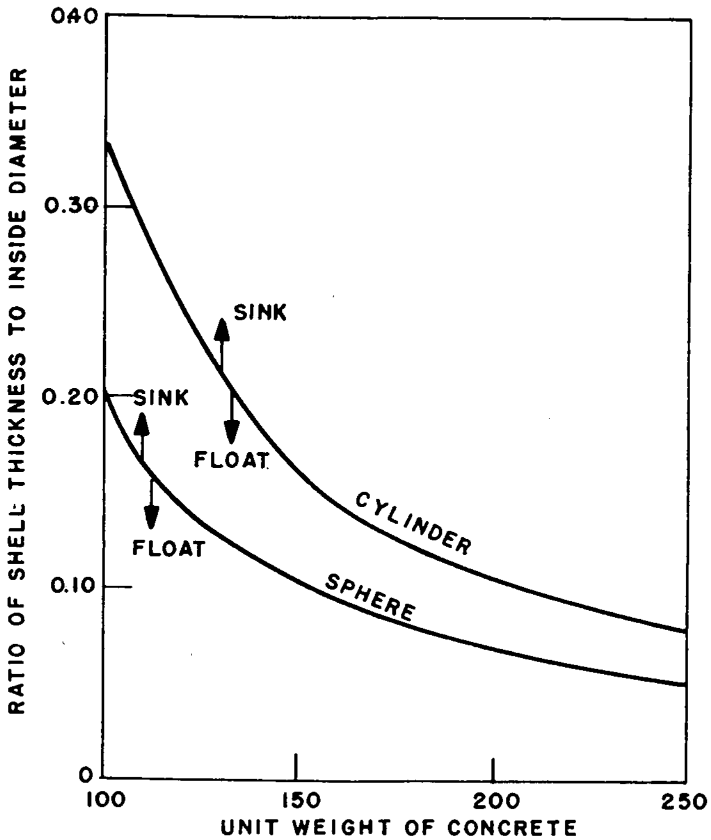
0.40
0.30
0.20
0.10
0
RATIO OF SHELL THICKNESS TO INSIDE DIAMETER
SINK
FLOAT
SINK
FLOAT
CYLINDER
SPHERE
100
150
200
250
UNIT WEIGHT OF CONCRETE

Figure 6

ADDENDUM TO CONCRETE FOR UNDERWATER STRUCTURES

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The information provided in the previous section was utilized to develop a Frame of Reference Chart (FRC) for concrete structures. Because of the relative insensitivity to section size and narrow range of possible compressive strength levels, the subject chart is relatively simple compared to those developed for metals.

It should be noted that the chart, Fig. 7, relates to small, medium, and large structures defined as unstiffened spheres and cylinders of 10, 20, and 40 ft. inside diameter. Three levels of materials density are indicated—100, 150, and 300 lb/ft^3. These represent the extremes and the commonly used material of average density. The following formulae may be used to calculate the structural density for wall thicknesses other than those indicated directly by the charts.

For Spheres

$$D = \frac{P(d_o^3 - d_i^3)}{d_o^3}$$

For Cylinders

$$D = \frac{P(d_o^2 - d_i^2)}{d_o^2}$$

$$d_o = d_i + 2t$$

where

D = structural density
P = concrete density
d_o = outside diameter
d_i = inside diameter
t = shell thickness.

A sphere was arbitrarily chosen as the model for calculations; however, the structural densities of spheres and cylinders with equal inside diameters were approximately the same.

An arbitrary cut-off was made at a relatively high structural density which corresponded roughly to a wall thickness equal to the inside diameter of the structure. The 1970 projections are based on compressive strength levels that can be readily obtained at this time—major improvements are not anticipated within the projection period.

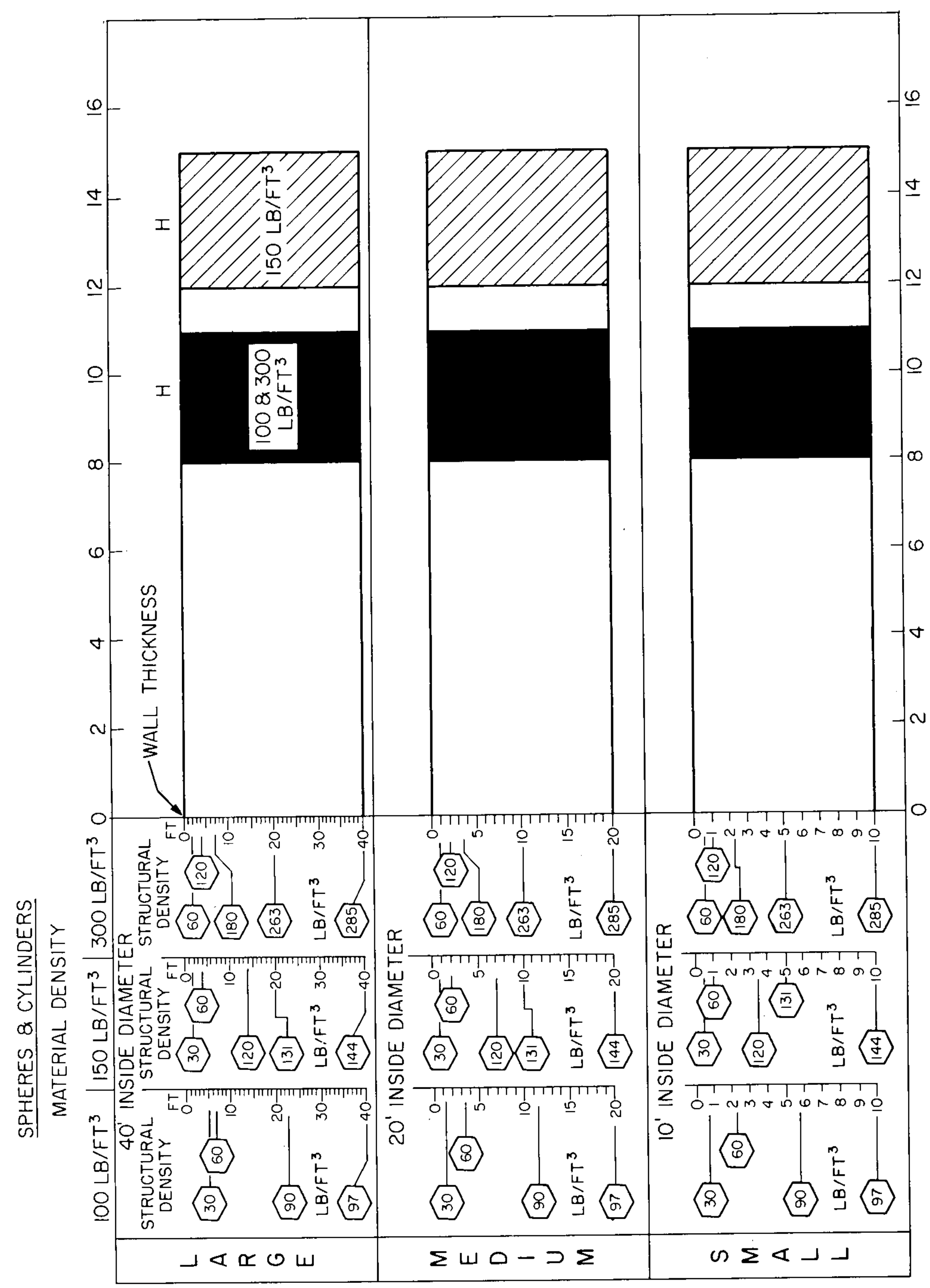

Fig. 7 - Frame of reference chart - concrete - 1970 forecast

Figure 8 presents a summary of depth capabilities based on a 3000 psi design compressive strength, representing a "safety factor" in the order of 3 to 4. The zero buoyancy point for 150 lb/ft^3 concrete is indicated by a vertical line, noted as "float-sink" boundary. The approximate maximum depth of the continental shelf regions is indicated at approximately 1500 ft., as a point of reference. This chart suggests interesting possibilities for the use of concrete structures.

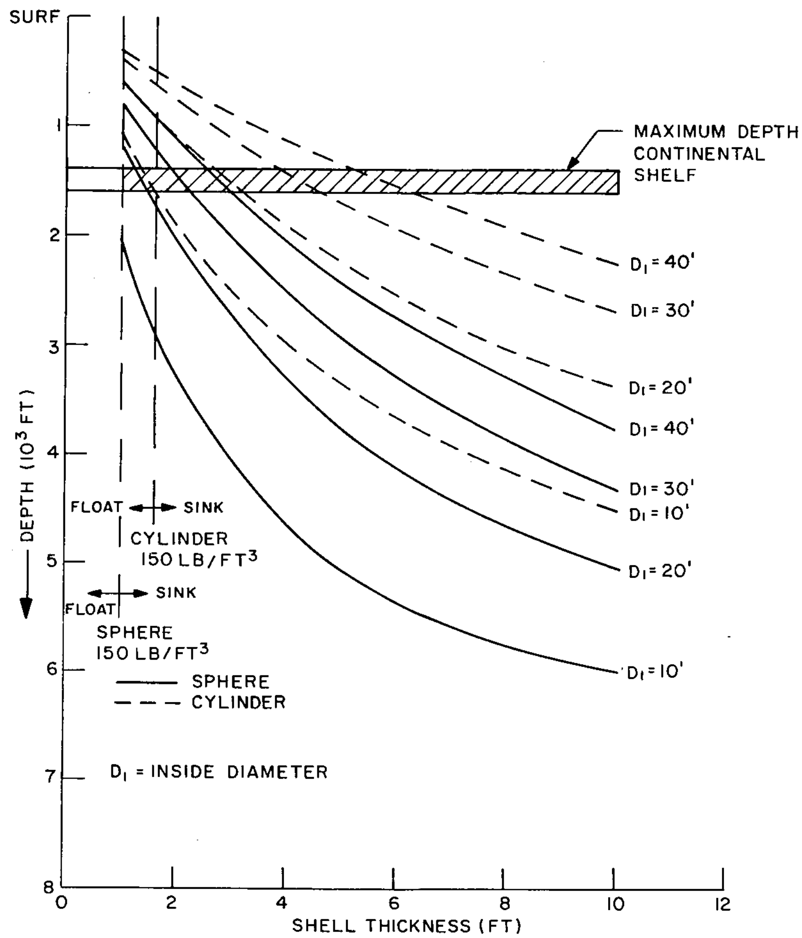

Fig. 8 - Capabilities of concrete hydrostatic compressive stress of 3000 psi

BUOYANCY MATERIALS

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INTRODUCTION

This paper will discuss buoyancy materials insofar as they may apply to deep ocean uses either as void fillers or structural components. These materials include low density liquids and solids and most significantly syntactic foams. It does not include other buoyancy techniques involving air or gas filled structures (submarines, capsules, etc.).

MATERIALS AND THEIR POTENTIALS

LOW DENSITY LIQUIDS

Properties — Low density liquids such as naphtha, gasoline, concentrated ammonia solutions and silicone oil derive their buoyancy from the fact that they are less dense than water. They are enclosed in a light-weight thin-walled shell which permits the internal and external pressures to be equalized, and they provide a good buoyancy to weight ratio. A comparison of the properties of these materials is tabulated in Table 1 below.

Table 1
Comparison of Low Density Liquids

Property	Gasoline & Naphtha	Ammonia Solutions	Silicone Oil
Cost	Low	Low	High
Compressibility	High, causing a loss of buoyancy at great depth, thereby causing a trim stability problem	Low, nearly the same as sea water	High
Bulk Modulus $\times 10^5$ psi	1.4	4	1.5
Fire Hazard	High, both aboard the vehicle and the mother ship	None	None
Thermal contraction	High, causing a loss in buoyancy	----	----
Relative buoyancy, pcf. (at 20°C) in 20°C water	17	17.5	3-7
Effect on aluminum and copper base alloys	None	Highly corrosive	None

Potentials of Low Density Liquids — The potentials of low density liquids as buoyancy materials are seriously limited since all such materials require a thin walled shell to contain them (e.g., Trieste). Damage to the shell can be catastropic; this becomes increasingly significant during surface handling of the vessel and increased depths of operation. Another serious limitation is the hazardous nature of two of the three types noted above. The gasoline is flammable and the ammonia solution is corrosive. Conversely, the third type, silicone oil is very high in net cost and low in net buoyancy. New low density buoyancy liquids may be developed with time and adequate R&D support but the container strength limitation will still apply. Consequently, no further discussion will be undertaken on low density liquids in this paper.

LOW DENSITY SOLIDS

Properties — The low density solids which may be considered for deep submergence applications include lithium metal, woods, organic polymers such as polyethylene and polypropylene, expanded plastics, inorganic (metal or ceramic) foams, and syntactic foams. A comparison of the properties and limitations of these materials is tabulated in Table 2 below.

Table 2
Comparison of Properties of Low Density Solids

Material	Density	Bulk Modulus $\times 10^5$ psi	Comments and Limitation
Lithium metal	0.53	22	Reacts vigorously with water releasing hydrogen. It must be contained in suitable non-corrosive metal containers which reduce buoyancy.
Wood	0.4-1.3	--	Has low compressive strength, absorbs water rapidly at pressures greater than 500 psi.
Solid Polyethylene, Polypropylene	0.9-0.95	2.6	Marginal compressive strength. Low buoyancy.
Expanded plastics	wide range	--	Have low strength. Are permeable to water and must be packaged in a barrier material.
Inorganic foams	wide range	--	Have low strength or open celled structure.
Syntactic foam	0.65-0.75	5.5	Offer exceptional promise for use at 10,000 psi.

Potentials of the Low Density Solids — The potentials for lithium metal or wood as a buoyancy material for deep submergence is extremely limited. As described in Table 2, lithium is very reactive and needs a container; woods have low strength and high water absorption. The foamed plastics and inorganic foams have the serious limitations of permeability and low strength. R&D effort may reduce the permeability of the plastic foam, and increase the strength of inorganic foams to some extent, but not enough for consideration as promising candidate materials. The low density plastics have limited buoyancy as a class, but they may have applications in the form of thick walled spheres or sections for buoyancy at moderate pressures. However, in this form they are air filled structures which are discussed elsewhere. The syntactic foams offer exceptional promise for use at deep submergence pressures.

BULK MODULUS

The bulk modulus values for low density liquids and solids are included in Tables 1 and 2 and are illustrated in Figure 1. These values are representative of a class of materials, since the bulk modulus of materials such as gasoline or silicone oil will depend on the specific material composition. Values for expanded plastics and woods have not been included since at 10,000 psi these materials would be permanently deformed. Only lithium and syntactic foam have values greater than the bulk modulus of water.

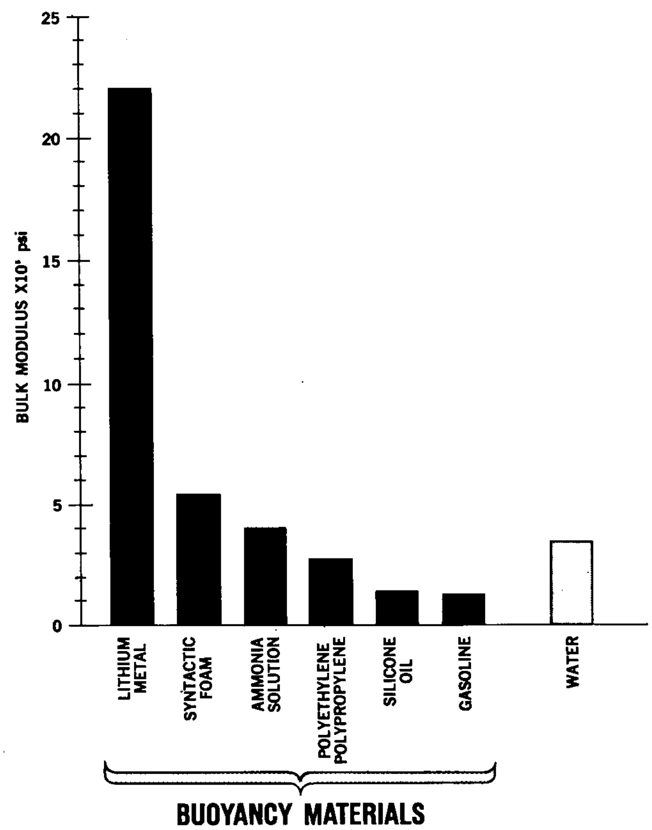

Fig. 1 - Bulk moduli of buoyancy materials at 10,000 psig hydrostatic pressure

SYNTACTIC FOAM

State of the Art — Syntactic foams consist of extremely small hollow glass, ceramic or rigid plastic spheres in a plastic matrix. These materials offer potential as structural materials in sandwich core construction. This subject will be covered in another paper on structures. Other properties of the syntactic foams are discussed below.

The best constructions found to date are the formulations ML-B2 and ML-B3 developed by the NAVAPLSCIENLAB and two commercially available materials, wherein hollow glass spheres having an outside diameter of 20 to 90 microns are embedded in a rigid epoxy matrix. These foams, when used in an equalized pressure design, eliminate the disadvantages of liquid buoyancy materials used at present and offer reliability with reasonable economy. The present cost of these syntactic foams is $8.00 to $18.00 per pound of net buoyancy which is high as compared to $1.00 per pound of net buoyancy afforded by gasoline. However, the cost of buoyancy for syntactic foams is low compared to that obtained by use of aluminum or titanium rigid pressure vessels, or by lithium in an equalized pressure container. Although many of the properties of the syntactic foams have been investigated, there is limited information on service performance. Studies of syntactic foam show that several of them, based on specific compositions, are suitable for underwater applications if the hydrostatic pressure does not exceed 10,000 psi. Experience has shown that adherence to the formulations as well as control of material and processing variables are essential to achieve successful results. Formulations ML-B2 and ML-B3 and the best commercially available formulations may be expected to have representative physical properties such as listed in Table 3.

Table 3
Representative Physical Properties of Syntactic Foams Presently Available, NAVAPLSCIENLAB and Commercially Developed

Principal Properties	
Nominal density, pfc	44
Net buoyancy, pcf	20
Initial compressive strength	
2% offset yield, psi	15,000
Ultimate, psi	18,000
Compressive modulus, psi	550,000
Compressive strength after hydrostatic immersion*	
2% offset yield, psi	14,000
Ultimate, psi	17,000
Compressive modulus, psi	520,000
Water absorption %†	1.5
Additional Properties	
Shear strength, psi	6,000
Tensile strength, psi	5,000
Tensile modulus, psi	600,000
Bulk modulus, psi	550,000
Impact strength, ft. lbs/in.	0.25
Fatigue, No. of cycles (between atmos. and 10,000 psi hydrostatic pressure) that material will withstand more than	10,000
Creep, no permanent deformation after 10 days hydrostatic immersion at pressures up to	12,000 psi

*1000 cycles, each 20 min., between atmospheric and 10,000 psi hydrostatic pressure.
†Specimen size 1 x 1 x 1 in. Material shows lower percentage of water absorption as specimen size increases.

FIRST STEP - 1970 PROJECTION

Material and Fabrication Parameters

The significant material and fabrication parameters and the technological developments expected in the 1966-1970 period are described in the following paragraphs. These projections are based on technology at the NAVAPLSCIENLAB and on discussions with suppliers of the foam components such as resin and hollow spheres, as well as suppliers of syntactic foams in both uncured and molded forms. The industrial representatives with whom the projection in this presentation for syntactic foam properties and component properties were reviewed, were in general agreement with the projections in their cognizant areas. It should be noted that, since the foam properties are dependent on the properties of the resin or filler components, changes in the components and their ratio permit improvement in one or more properties, usually with a consequent reduction in values of other properties.

1. Compressive strength — The strength properties of syntactic foams are dependent on the strength of the resin and filler components and on fabrication procedures. Existing foam values in Table 3 are based on formulations containing a resin system having an ultimate compressive strength of 22,000 psi and hollow glass spheres which are reported to show negligible breakage at 10,000 psi. Formulations for normal 44 pcf density foam are based on optimum resin to glass ratios. The resin has greater compressive strength than the filler; therefore, as the percentage of lightweight filler is increased, the compressive strength of the foam as well as its density will decrease. Development of higher strength resin systems and higher strength glass spheres would be expected to improve the compressive strength of the nominal 44 pcf density foam as shown in Figure 2. Projections for compressive strength properties as well as other properties are based on the following considerations:

a. A 50% improvement in resin compressive strength as a medium projection by FY 1970. Polyester and epoxy resin systems having 30,000 psi compressive yield strength representing an increase of more than 50% over the present strength values, are now under laboratory investigation.

b. A 50% improvement in the strength of newly available glass and ceramic materials which may be used as hollow sphere filler, and the development of better coupling agents and fabrication technology.

2. Bulk Modulus — Foam used for buoyancy applications should have a bulk modulus approximately that of water. The high strength 44 pcf syntactic foam presently available has a bulk modulus of 500,000 to 600,000 psi as compared to 350,000 psi for water; which is preferable to a bulk modulus lower than that of water. The bulk modulus of the foam will decrease as its density decreases. No increase in bulk modulus beyond that noted above, is needed for free flooded types of buoyancy applications. Bulk modulus of syntactic foam would be expected to increase in relation to any increase in compressive modulus of the resin system and of the filler used. This is an advantage for structural applications. Expected increase in bulk modulus by 1970 is shown in Figure 2.

3. Density — Development of resin systems having either higher strength or lower density or both, and of stronger and more uniform low density fillers will result in lower density buoyancy materials than those cited in Table 3. The use of larger size hollow glass spheres, up to several inches outside diameter, in a syntactic foam matrix offers opportunities for density reduction. To produce an optimum material (with highest buoyancy), the problem of relative sphere size, sphere thickness and spacing of spheres in the matrix must be studied mathematically and experimentally. Projections of density reduction (increase in buoyancy) by 1970 are shown in Figure 2 and are included in the calculations for projections of cost of buoyancy in Figure 2.

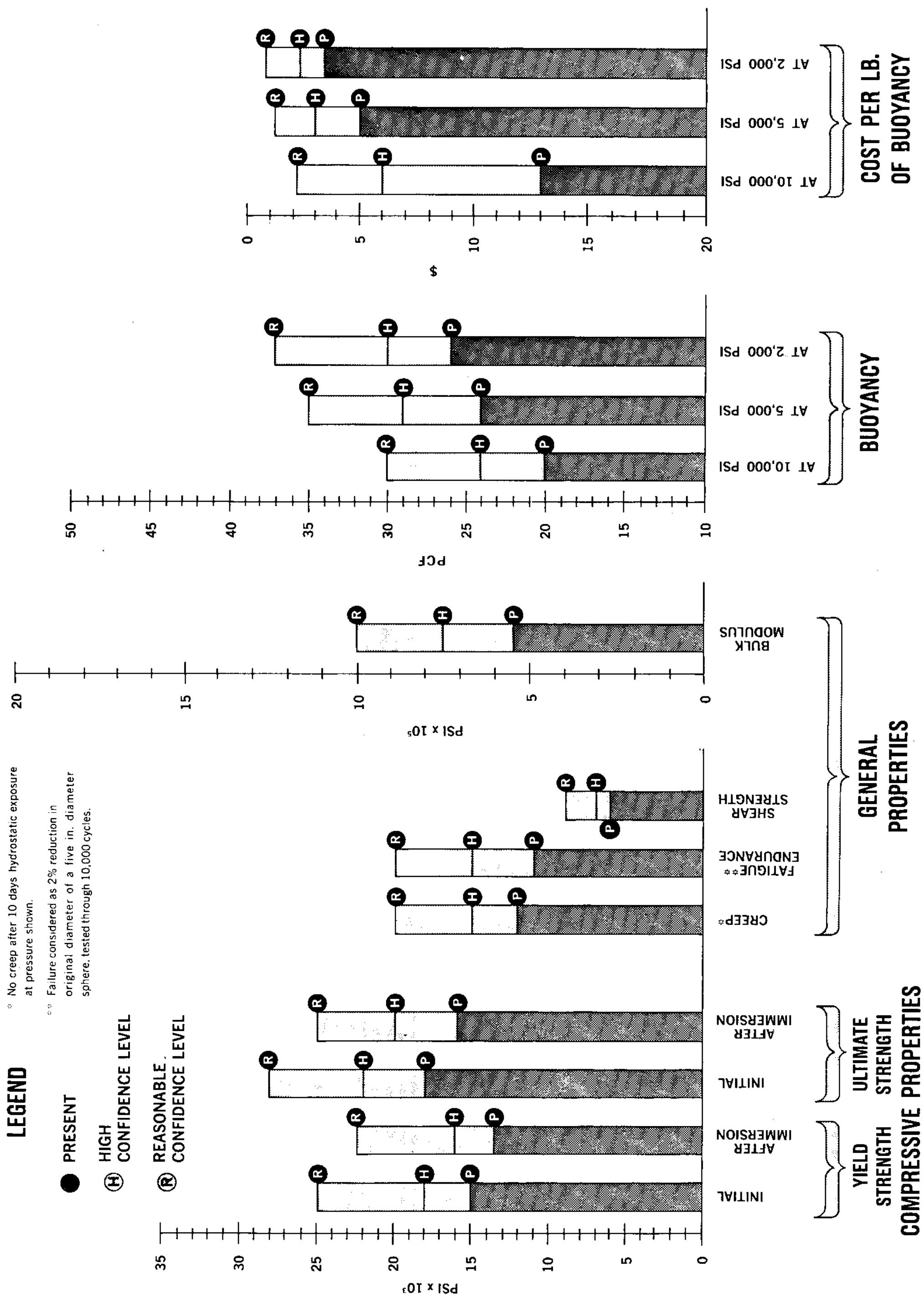

Fig. 2 - 1970 forecast of properties and cost per pound of buoyancy materials

4. Creep — Data on creep of foam is limited. Available creep data for the resin components show that, as with other materials, creep is dependent on the stress level. For example, at 30% of compressive yield strength (6,720 psi) strain is 0.013 in./in. after 11 days, and, at 42% yield (9,600 psi), strain is 0.021 in./in. after 20 days; in both cases the curve levels off at these points. The strain increases when the specimen is loaded at higher stress levels. With the development of resins having higher strengths, the materials would show less creep. Better organic resin and cure systems, and the development of inorganic or metallic matrices, such as aluminum around the hollow spheres may change the creep picture. To date, only flat plates have been cast of glass sphere aluminum composites, but no great difficulties are reported to exist for applying the same construction to other shapes. Syntactic foam specimens exposed up to 10 days at hydrostatic pressures of 10,000 psi and 12,000 psi showed no permanent deformation, but did show deformation when exposed to pressure of 14,000 psi. Limiting the stress applied to the foam to less than 30% of compressive yield strength should minimize creep problems. Projections showing the hydrostatic pressure at which conventional types of syntactic foam will withstand creep are shown in Figure 2.

5. Fatigue — Changes due to repeated stress are dependent on the stress level. Fatigue tests performed on 5 in. diameter spheres of syntactic foam have shown projected values of over 10,000 cycles at pressures to 10,000 psi before the spheres exhibited a 2% reduction of original diameter. Tests to 14,000 psi test pressure show 3900 cycles to the 2% reduction in diameter change. Pressures at which syntactic foam will withstand 10,000 cycles at present, and projected to 1970, are shown in Figure 2.

6. Shear — Improvements in the strength of the resin and filler components will produce increases in shear strength properties. Projections for shear strength are also shown in Figure 2.

7. Environmental Effects — Small samples ($1/2 \times 1/2 \times 1$ in. or $1 \times 1 \times 1$ in.) have shown some loss of compressive strength (approximately 10% after 1000 cycles of immersion. There are indications that damage to the foam occurs at the surface and progresses inward. The rate of damage is influenced by the stress level. Larger size specimens show a higher percentage of strength retention. There is also some evidence to indicate that finishes or treatments applied to the glass spheres would further improve strength retention in water. Therefore, it would be expected that strength retention or reliability after 1000 cycles would be about 90% of the original values. As the initial strength properties of the foam improve, the strength after immersion will increase proportionately, although the percentages of strength retention should remain constant. The expected ultimate compressive strength and yield strength before and after sample exposure are illustrated in Figure 2.

8. Costs — The present 44 pcf syntactic foam suitable for use at 10,000 psi hydrostatic pressure ranges in cost from \$4.00 to \$9.00/lb depending on quantity used; the cost/lb of net buoyancy is \$8.00 to \$18.00. These values are based on resin system costs of approximately \$0.90/lb, glass spheres between \$5.00 to \$12.00/lb, plus fabrication costs. Lower strength spheres suitable for 5,000 psi applications recently become available at a price of \$0.65/lb, although similar spheres (from another supplier) cost \$5.00 to \$10.00/lb. The most promising, area for decrease in price of syntactic foam lies in reduction in manufacturing costs of the highest priced ingredient - the glass sphere filler. This may be expected to occur if and when there is a substantial increase in market demand for this material. It is estimated that up to 1 million lbs of syntactic foam will be needed for buoyancy applications for project MOHOLE. It is planned to provide buoyancy equal to 90% of the weight of the approximately 18,000 feet of riser pipe by using cylindrical wafers of syntactic foam around each 45 ft length of riser pipe (casing). It is also planned to employ syntactic foam in the float of the DRV Trident. A forecast, based on higher strength, lower density foams for net cost per pound of buoyancy at 10,000, 5,000 and 2,000 psi hydrostatic pressure is shown in Figure 2. This forecast showing

Table 4
1970 Forecast - Cost of Materials and Net Buoyancy

Confidence Level of Predictions	Present	1970	
		High	Reasonable
10,000 psi			
Cost/lb of Material	$ 6.00	$3.50	2.00
Cost/lb of Buoyancy	$13.00	$6.00	2.10
Density (pcf)	44	40	34
Buoyancy (pcf)	20	24	30
5,000 psi			
Cost/lb of Material	$ 3.00	$2.50	1.50
Cost/lb of Buoyancy	$ 5.00	$3.00	1.25
Density (pcf)	40	35	29
Buoyancy (pcf)	24	29	35
2,000 psi			
Cost/lb of Material	$ 2.50	$2.00	1.00
Cost/lb of Buoyancy	$ 3.60	$2.40	.75
Density (pcf)	38	35	27
Buoyancy (pcf)	26	29	37

cost per lb of material, cost per lb of buoyancy, density (pcf), and buoyancy (pcf) at 10,000, 5,000 and 2,000 psi is also listed in Table 4.

9. Acoustic Properties — The fact that the composition of the foams can be varied throughout a wide range, raises the possibility that such foams can be tailored to fit definite acoustical requirements. Such foams could possibly be used for:

a. acoustic absorption lining for submarines and mines

b. housing for sonobuoys, and

c. acoustic barrier for deep submersibles.

10. Explosive Loading — No data is available on the effects of explosive loading of syntactic foams, however such loading in other cellular materials results in considerable mitigation of the shock wave. Shock mitigation may be enhanced by a matrix (resin) that is employed to isolate spheres one from another. The subject of shock loading requires exploration.

11. Fabrication Parameters — Due to the newness of the syntactic foam, there has been relatively little development of fabrication procedures. In addition to component properties, the properties of the foam and its cost would be affected by mixing and handling of the components, mold types and materials, cure conditions and schedules, size of module, etc. Some information on syntactic foam material and fabrication techniques will be developed for buoyancy materials to be used on project MOHOLE, (See paragraph 8, costs). Present technology limits production to modules of several cubic feet maximum. Substantial additional work on all aspects of fabrication of the modules, as well as combining of the modules into larger sections by adhesives, resins or fasteners is needed.

12. Adhesives and Fasteners — The foam modules can be combined in the structure by several techniques, such as:

a. Bonding — An adhesive or resin system may be used to bond modules. A higher density resin will reduce net buoyancy somewhat. Uncured syntactic foam used as an adhesive and cured in place may have lower compressive strength than the foam in the module.

b. Mechanical fasteners — These fasteners consisting of bolts, or straps may reduce buoyancy or create areas of stress concentration. Methods of fastening and installation of the foam to provide maximum buoyancy and quality assurance should be studied.

13. Repairability — One advantage of the use of syntactic foam is its relative ease of repair. If a section is damaged or found to be defective, the damaged part can be cut out and replaced by one or more modules using one of several bonding methods. For applications at pressures of 5000 psi or less, trowel-in-place repairs may be feasible.

14. Quality Assurance — These newer foams will require modification of existing performance criteria and the development of new testing procedures. This will require development, both of coupon (destructive), as well as nondestructive techniques for the foam components, modules and larger structures containing the modules. Present nondestructive test (NDT) methods, including those in current use for metals and plastics inspection, have been found unsuitable for detection of defects in syntactic and other types of foam materials. Development of satisfactory methods will require extensive effort. Prospects for success do not appear as good as might be expected with a similar effort in the metals and plastics area. Of the very few techniques available for NDT of syntactic foam, the following show some promise of usefulness and potential for successful further development.

a. Low frequency ultrasonic or sonic transmission and attenuation measurement are possible through foam materials and probably can disclose gross voids. This should be further investigated and developed.

b. Neutron absorption procedures with and without absorption additives such as boron or cadmium compounds have shown promise and should be further developed for void detection and estimation of density variability.

c. Microwave techniques may have applications for modules without metal facings.

PROPOSED R&D EFFORTS

The properties of the syntactic foams are based on the following factors:

1. Component Materials

   a. Type of resin system.

   b. Type of low density filler.

2. Interaction Between Components

   a. Percentage of filler.

   b. Distribution of filler in matrix.

   c. Strength of bond between resin and filler.

3. Processing Variables

   a. Cure of resin system.

   b. Entrapment of air or moisture.

   c. Amount of broken spheres.

These factors require investigation to develop stronger and lighter syntactic foam buoyancy materials. In addition, as discussed previously, information will be needed concerning the properties of the foam and component materials after exposure to environmental and service conditions (e.g., explosive loading) in order to characterize its properties for design information and for subsequent improvement of material properties. Additional investigative efforts will be particularly required on syntactic foams over a range of densities to develop information on properties, such as fatigue, creep, acoustic properties, etc. under high hydrostatic pressure, since only limited information is available in these areas.

SECOND STEP - 1980-1985 PROJECTION

STRENGTH PROPERTIES

In addition to improvement in the conventional resin and matrix materials currently available, new higher strength organic as well as inorganic materials having relatively low densities are expected to be available. Ceramic-like materials such as oxides of aluminum, beryllium and boron, boron carbide in small and large spheres, as well as improved higher strength glass formulations should provide higher strength, lower density components. For example, boric oxide and beryllium carbide have specific gravities of 1.85 and 1.9, respectively, which are lower than presently available glass and metals. The use of resins or foam as surface coating or matrix to reduce the hazard of implosion of large spheres made of these materials may also supply a substantial increase in compressive strength and other strength properties. A substantial reduction in density of the foam used at 10,000 psi pressure appears feasible. Figure 3 projects 1980-1985 property values, and buoyancy figures based on anticipated technology. The values shown for compressive strength is for a 44 pcf foam. It should be noted that such strength may not actually be necessary for buoyancy applications since the maximum ocean depth is approximately 35,000 ft and with an added 50 to 70% safety factor maximum compressive strength of 25,000 psi should be adequate. Consequently, even higher buoyancy and lower cost projections may be feasible. Emphasis should be in the direction of reduction of density and cost.

COST ESTIMATES

Projected 1980-1985 values for cost per pound of buoyancy at 10,000, 5000 and 2000 psi pressures are included in Figure 3. These projected cost values and related buoyancy projections are shown in Table 5.

ACKNOWLEDGMENT

The authors wish to acknowledge the cooperation of the Technical Staff of the U.S. Naval Applied Science Laboratory and Dr. J. Irgon of Proteus, Inc., who contributed to these projections.

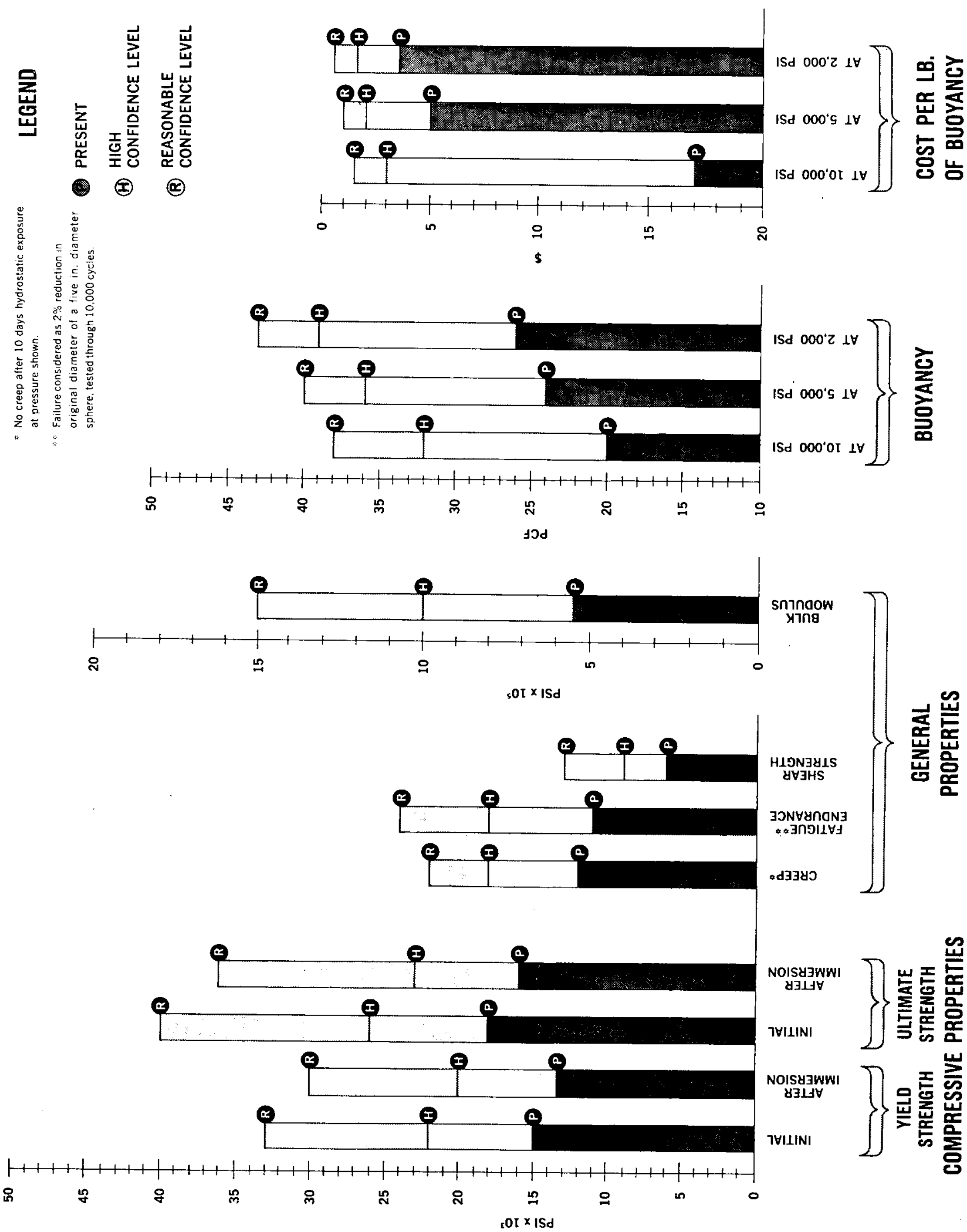

Fig. 3 - 1985 forecast of properties and cost per pound of buoyancy materials

Table 5
1980-1985 Forecast - Cost of Materials and Net Buoyancy

Confidence Level of Predictions	1985		
	Present	High	Reasonable
10,000 psi			
Cost/lb of Material	$ 6.00	$3.50	$2.00
Cost/lb of Buoyancy	$13.00	$3.10	$1.40
Density (pcf)	44	30	26
Buoyancy (pcf)	20	34	38
5,000 psi			
Cost/lb of Material	$ 3.00	$2.50	$1.50
Cost/lb of Buoyancy	$ 5.00	$2.00	$1.00
Density (pcf)	40	28	24
Buoyancy (pcf)	24	36	40
2,000 psi			
Cost/lb of Material	$ 2.50	$2.00	.90
Cost/lb of Buoyancy	$ 3.60	$1.30	.50
Density (pcf)	38	25	21
Buoyancy (pcf)	26	39	43

HARD SEA WATER SYSTEM MATERIALS

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Section 1 - CURRENT STATUS

INTRODUCTION

As submarine design and construction are improved to permit greater operating depths, the internal pressures which hard sea water systems must withstand increase. In order to provide this greater pressure capability, it has been necessary to increase substantially the nominal wall thickness of various components in the system as we went from NAUTILUS to THRESHER depths.

From the standpoint of the Navy, the suppliers of components and mill items, and the submarine builders, increasing wall thickness of hard salt water system components has several undesirable consequences:

1. The total weight of the system in each submarine increases. For weight limited submersibles, this is critical.

2. The total cost of the hard sea water system materials increases.

3. The use of heavier sections in most currently specified copper alloys introduces fabrication problems such as difficulty in brazing. Also, non-destructive examination of heavy castings is a serious restriction.

4. Due to limitations of manufacturers' equipment, thicker components cannot be produced and in some cases such as seamless tubes the heavier walled tubes needed for piping and fittings for today's depths cannot be produced in lengths as long as those available with thinner walls. Because of this reduction in length capability, the number of welded joints increases and this is accompanied by correspondingly higher fabrication and inspection costs. Table 1 extracted from MIL-T-16420 indicates how short are the lengths of seamless 70-30 copper nickel alloy tube which can be supplied using available mill equipment.

Table 1
Lengths of Copper Nickel Tube

Outside Diameter (inches)	Working Pressure (psi)	Wall Thickness (inch)	Lengths (feet)
5.563	700	0.220	10 - 16
8.625	700	0.340	4 - 8
9.625	700	0.340	3-1/2 - 7
10.750	700	0.380	3-1/2 - 7
12.750	700	0.454	3-1/2 - 7
5.563	1650	0.425	4 - 7
larger	1650	NA	NA

SCOPE

The hard sea water systems are mainly associated with nuclear main propulsion plants. These systems include those machinery equipments and components that are exposed to sea water pressure. These encompass cast and wrought forms. The major components which are involved are listed in Table 2.

Table 2
Hard Sea Water System Components

Valve Body and Bonnet	Pump Shafts
Manifolds	Bolting
Pumps Casing	Seamless Pipe
Pipe Fittings	Welded Pipe
Pipe End Connections	Condenser Tube
Sea Chests	Condenser Tube Sheet
Strainers	Condenser Shell (if heat exchanger is located outside the hull)
Pump Impeller	Water Box
Wear Rings	Flexible Connections (hose and end)
Condenser Head	Weld Metal
Valve Stem	Brazing Alloys
Other Valve Trim	

In addition to the main propulsion plant, certain auxiliary systems such as brine overboard discharge, garbage disposal, ballasting, circulating water for jet propulsion, and torpedo tubes see full submergence pressure. However, they offer no greater problems than those associated with the main propulsion plant and will not be treated independently as far as materials fabrication, manufacture and inspection are concerned.

SIZING OF COMPONENTS

Design

In the design of hard sea water systems, although many material and fabrication considerations are involved, the following are the ones which are used in calculations leading to thickness of metal:

Ultimate tensile strength
Tensile yield strength
Modulus of elasticity
Low cycle fatigue
Coefficient of thermal expansion
Creep
Corrosion (for corrosion allowance)

The general approach taken by designers of hard sea water systems is to calculate thickness of components based on allowable fiber stress at designated temperature. The allowable stress is based on considerations of tensile strength, yield strength and creep. Low cycle fatigue at specified number of cycles and shock requirements are also considered. Flexibility of the system is calculated so that the computed expansion stress will not exceed the allowable stress range specified in the ship specification. In determining the structural adequacy of any configuration of condenser inlet-outlet waterboxes, the following procedure is used: the pressure stresses and the stresses due to the piping loads on the nozzles are calculated. Appropriate stress concentration factors are applied to each (stresses are broken down into membrane and bending, primary and secondary).

These stresses are added algebraically (which is a conservative assumption assuming that they occur at the same point) to form a stress range. This stress range is then corrected for mean stress effects by use of a modified Goodman Diagram. The resultant "pure" alternating stress is then used to enter the fatigue curve and the number of cycles that the waterbox is "good for" determined. Present design criteria is 25,000 cycles. Thus, in designing new heads, trial and error procedure is necessary.

Metal Thickness

To point up the need for cast and wrought materials with higher allowable stresses the wall thickness and weights of a number of components in sea water systems required to withstand pressures up to 35,000 feet were calculated using current allowable stresses and the results presented in Fig. 1. Also included are the calculations for allowable stresses 2X, 4X and 7X present. For any appreciable increase in depth capability, improved materials will be essential for hard sea water systems. This will be necessary not only because of the weight increases but because of manufacturing limits for wrought products and increased space requirements for heavy wall components.

MATERIALS CURRENTLY SPECIFIED

General

Materials used in hard sea water systems in submarines have been elected as much on the basis of corrosion resistance, ease of fabrications and cost as on basis of strength/density ratio. With weight limited submarines higher strength materials become necessary. Since manufacturing of components, fabrication, installation, or cost problems are prime considerations with the lower strength materials, to date we have attempted to avoid the use of alloys and tempers or conditions which will lose strength, endurance or corrosion resistance in heat affected zones resulting from welding or brazing. Thus, the various alloys which can be hardened by cold work, precipitation, Q&T, or ordering mechanisms if specified where hot forming, welding, or brazing is required have been specified in soft or annealed tempers only.

Table 3 lists the alloys considered for sea water service and upon which the predictions of this report are based. The non-corrosion resisting alloys are of interest as load bearing materials and would be developed as outer portion of a composite structure. (CuNi or NiCu on inside for corrosion resistance.) This list by no means includes all the alloys which have been investigated. Complete information is not available for any. Since wrought alloys (other than bar and rod) have been used most extensively in hot rolled or annealed tempers the specification values for 1" material can be used for heavier thicknesses. Where castings are involved it has been shown that serious deterioration in properties, particularly ultimate tensile strength and elongation, is possible with increase in section size. This section size effect is most pronounced for low shrinkage type alloys (tin bronzes) and less so with the higher shrinkage alloys such as aluminum bronze.

Wrought 70-30 Copper Nickel Alloy

Currently the wrought metal most generally used for hard sea water systems is annealed 70-30 Cu-Ni. Seamless and welded pipe, condenser tube, tube sheets, welded water boxes, welded fittings, and other components are made of this alloy. 70-30 Cu-Ni is a single phase solid solution alloy. Approximately 0.5 percent iron is added to increase its resistance to corrosion erosion. It can be hardened by cold work but the increase in strength of cold worked material is not made use of when welding or brazing are employed to fabricate either the part or the system. Drawn tempers in pipe increase difficulty of

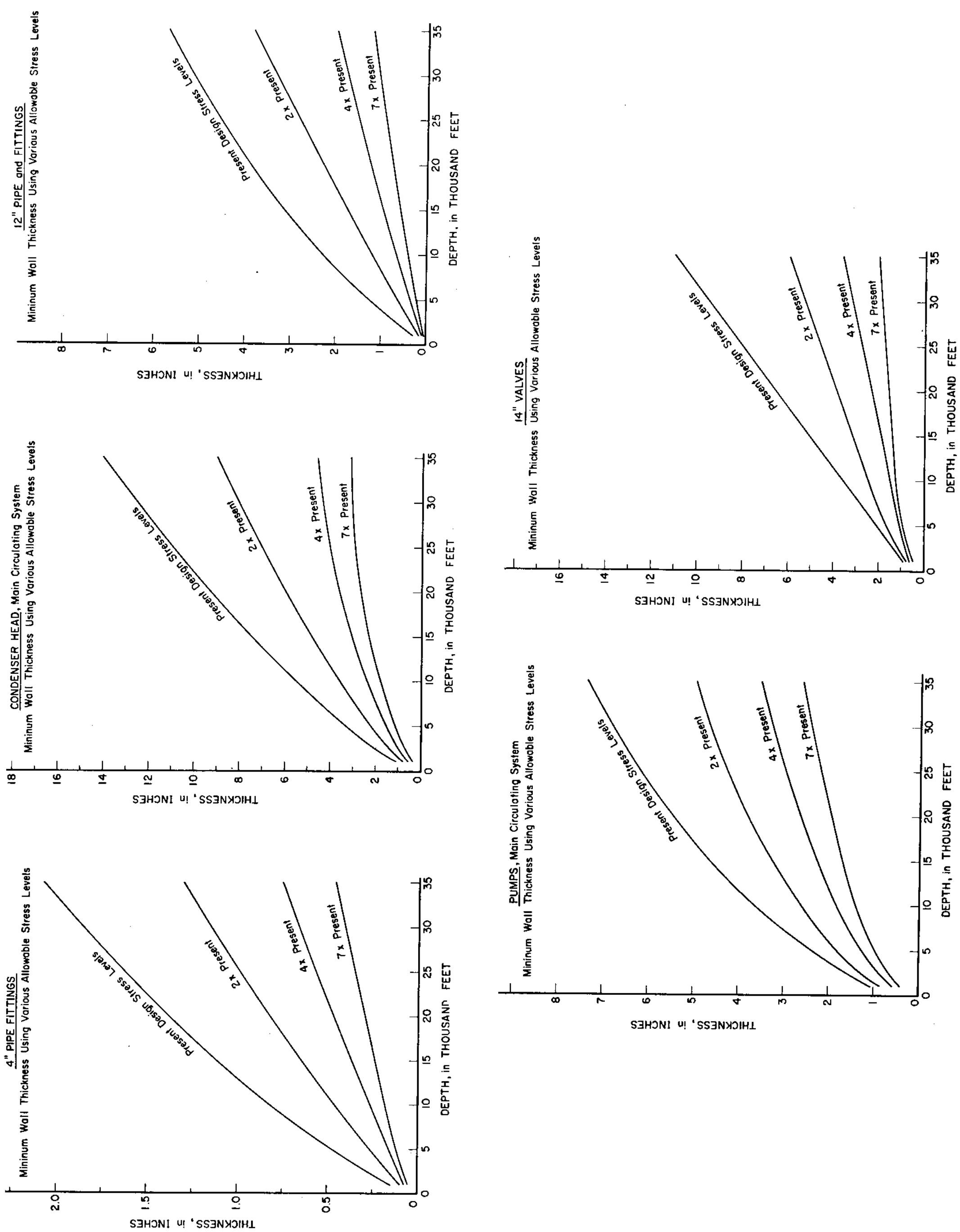

Fig. 1 - Minimum wall thickness of hard sea water system components using various allowable stress levels

Table 3
Metals Considered for Hard Sea Water Systems

Metal	Composition
COPPER ALLOYS	
70-30 Cu Ni	68.9 Cu, 30 Ni, 0.6 Mn, 0.5 Fe
70-30 Cu Ni(Be)	69 Cu, 30 Ni, 0.5 Fe 0.5 Be
70-30 Cu Ni (Cb)	66 Cu, 30 Ni, 1.5 Cb, 1.5 Mn, 0.75 Fe
70-30 Cu Ni (Al)	66 Cu, 30 Ni, 2 Al, 1 Mn, 0.75 Fe
70-30 Cu Ni (hi Fe)	64 Cu, 30 Ni, 5 Fe
CuFenLoy 40	55 Cu, 42 Ni, 2 Fe, 1 Mn
G-Bronze	88 Cu, 8 Sn, 4 Zn
M-Bronze	88 Cu, 6 Sn, 4Zn, 2Pb
Phosphor Bronze	95 Cu, 5 Sn, 0.25 P
Ni Al Bronze	79 Cu, 9 Al, 4 Fe, 5 Ni, 3 Mn
Mn Si Alloys	94 Cu, 2 Si, 1 Zn, 1 Mn, 2 Fe
Cu Ni Sil Alloy	97.5 Cu, 2 Ni, 0.5 Si
Superston Series	65-87 Cu, 0-14 Mn, 3-5 Ni, 3-5 Fe, 6.5-11.5 Al
Cu Be Alloy	98 Cu, 2 Be
Cu Al Si	91 Cu, 7 Al, 2 Si
Cu Zn Si	90 Cu, 9 Zn, 1.2 Si
Al Bronze (hi Ni)	15 Ni
ALUMINUM	
7079	4.3 Zn, 3.3 Mg, 0.6 Cu, 0.2 Mn, 0.2 Cr, Bal Al
5086	4 Mg, 0.5 Mn, 0.15 Cr, Bal Al
5456	5 Mg, 0.7 Mn, 0.15 Cu, 0.15 Cr, Bal Al
X7002	0.7 Cu 3.0 Mg, 4.0 Zn, 0.2 Cr, Bal Al
X7106	2.0 Mg, 4.2 Zn, 0.11 Cr, 0.12 Zr, Bal Al
X7039	2.8 Mg, 4.0 Zn, 0.2 Cr, Bal Al
FERROUS	
316 CRES	17 Cr, 10 Ni, 2.5 Mo, Bal Fe
17-4 PH	16.5 Cr, 4.25 Ni, 0.25 Cb, 3.6 Cu, 0.04C, Bal Fe
Maraging Steel	12 Ni, 5 Cr, 3 Mo, Bal Fe
Worthite	24 Ni, 20 Cr, 3 Mo, 3.2 Si, 1.8 Cu, Bal Fe
HY-150	5 Ni, Cr Mo V Steel
NICKEL ALLOYS	
Monel	66 Ni, 1 Mn, 1 Fe, 32 Cu
K-Monel	66 Ni, 3 Al, 2 Fe, 1 Mn, 1 Si, 27 Cu
Inconel 718	53.5 Ni, 18 Fe, 19 Cr, 0.5 Al, 0.8 Ti, 5 Cb, 3 Mo, 0.2 Si
Hastelloy C	16 Mo, 16 Cr, 5 Fe, 4W, Mn + Si + Co, Bal Ni
Inconel 625	62 Ni, 22 Cr, 9 Mo, 4 Cb, 3 Fe
Inconel X750	73 Ni, 16 Cr, 7 Fe, 2.5 Ti, 0.5 Al, 1 Cb
Ni-O-NEL	42 Ni, 21 Cr, 3 Mo, 2 Cu, 1 Ti, 31 Fe
TITANIUM ALLOYS	
Pure	98.9 - 99.5 Ti
6-4	6 Al, 4 Va, Bal Ti
3-2-1	7 Al, 2 Cb, 1 Ta, Bal Ti
Alpha Beta Alloys	
Betal Alloys	

fabrication. Specifications for 70-30 mill products list a single strength value (18,000 psi) for all thicknesses of annealed or soft material except that tube over 4-1/2" O.D. has a minimum Y.S. requirement of 15,000 psi. Welded annealed tube must meet the mechanical requirements of seamless tube.

Wrought Nickel Copper Alloys

Monel and K-Monel are used for shafting, valve trim, bolting, lining of steel parts, fabricated valves and other components. In general, these alloys have equivalent corrosion resistance. K-Monel is precipitation hardenable by virtue of its aluminum and silicon content so that it has higher strength than Monel and is generally used only in that condition. While extensively used in salt water, Monel does not resist pitting to extent of 70-30 Cu Ni. K-Monel can be welded but requires reheat treatment to avoid reduction in properties of HAZ. Annealed Monel has a yield strength of 25,000 psi. Various processing or size variables permit yield strengths of considerably higher values but advantage can not be taken of these values if welding is employed.

Cast Valve Bronze and Gunmetal

Gunmetal and valve bronze are extensively specified casting alloys for sea water service in applications such as pumps, valves, fittings, heat exchangers, strainers, etc. These complex bronzes are alloys of tin and copper with zinc and lead added. Tin bronzes containing zinc are known as gunmetals. When they contain lead also they are called leaded gunmetals. The structure is essentially a matrix of copper-tin-zinc solid solution with tin rich and lead constituents. Serious problems in producing large castings in these alloys which will pass radiographic inspection requirements as well as a need for lighter weight, smaller components has led to evaluation and use of 70-30 Cu-Ni, Monel and aluminum bronze for a number of applications as alternates for tin bronze. Ni modified tin bronze (not heat treated) is sometimes used in lieu of gun metal without change in allowable stresses where improved pressure tightness may be a factor.

Cast 70-30 Cu-Ni

This alloy which is a casting modification of the wrought analysis is used in lieu of tin bronze where better corrosion-erosion properties, higher strength, better weldability, greater soundness in heavy sections and/or higher strength are required.

Aluminum Bronze

This family of alloys has been extensively investigated and used because of its relatively high allowable stress limit. Aluminum bronzes are essentially copper-aluminum alloys containing usually not more than 10-percent of aluminum and appreciable quantities of iron, manganese and nickel. The alloys fall into two groups. The alloys in the first group contain up to about 7.5% aluminum and have a homogeneous structure. These alloys are of interest only in wrought form. The alloys in the second group contain higher aluminum, have a duplex structure and are of interest in both wrought and cast forms. Due to eutectoid transformation, castings of the higher aluminum content alloys and those with less than 4-percent nickel regardless of aluminum content can exhibit a microstructure containing a gamma-2 network and will be subject to catastrophic deterioration in sea water service by de-aluminization. Proper heat treatment can minimize this deleterious network but there is no non-destructive test to determine whether castings have been properly heat treated. Currently, in addition to limited use in salt water systems, aluminum bronze is specified for air and oil H.P. fittings.

Clad or Lined Parts

Steel, lined or clad with copper nickel alloy or nickel copper alloy is specified or permitted in critical locations such as hull and backup valves and condenser waterboxes. Current designs for hull valves call for an HY-80 casting which is welded to the hull plating. The interior of the valve which sees sea water is fitted with a Monel liner. This design eliminates need for hull insert, separate sea chest and bolting.

Flexible Connections

These are required to minimize problems in thermal expansion and other movement due to loading of the system. Non-metallic hose as well as proprietary designs for flexible fittings are now used. Problems with the hose revolves around reliability under shock, end connections and deterioration of metallic reinforcement. It appears that the latter may be mitigated by use of dacron reinforcement. Since flexible connection tests at MEL have shown that dacron reinforced hose is suitable for sea water service, use of metallic hose will probably be discontinued.

Manufacture of Pipe and Tube

Pipe and tube for sea water service is procured either seamless or welded. For tube sizes under about 6" OD the seamless tubes are cold drawn from hot extruded shells. For seamless tube sizes over about 6" OD, the tubes are produced by a cold cupping and drawing practice using hot-rolled heavy gage circles as starting stock. The American Brass Company (only producer of large diameter seamless 70-30 Cu-Ni) is already unable to supply some of the sizes of seamless tube desired by fabricators of fittings who use seamless tube as base stock. Any increase in wall thickness required for higher pressure service will offer a serious facility problem for large diameter seamless tube.

Welded tube is produced in 12-20 foot lengths in temper resulting from forming and seam welding fully annealed 70-30 flat stock. All weld reinforcement is removed.

70-30 tube welded or seamless is furnished either bright annealed or annealed and acid pickeled finish.

Fabrication of Hard Sea Water Systems

Piping, wherever size permits, is bent to radii which will not thin the wall more than 10%. 3D bend radii are common. Heating for bending of copper-nickel pipe is permitted. Allowable stresses for design of 70-30 Cu-Ni systems are based on annealed metal properties and no reduction in base metal properties is expected due to heat of welding, brazing or forming. Silver brazing is permitted for pipe sizes up to 4". Above this size, all joining must be by welding, except of course, for bolted flange connections.

Section 2 - R&D TO YEAR 1970

Desired Characteristics

The characteristics desired in materials for hard sea water systems are as shown in Table 4. These properties are applicable to base metal and welded joints. It is expected that materials for hard sea water systems will be developed to complement any hull material development.

Table 4
Desired Characteristics

Density	Low
Tensile	High proportional limit, yield strength and ultimate tensile strength. Without need for heat treatment.
Toughness	Will not fracture in a brittle manner under severe plastic deformation at 0°F or lower.
Modulus	High for bar, rod and plate; low for pipe so as to permit more compact expansion loops.
Fatigue	High in both high and low cycle with and without notches — axial, hoop and bending loads; in air and under sea water.
Corrosion-Erosion	Not susceptible to stress corrosion, low general and pitting corrosion rates under static, impingement, crevice, high and low velocity and cavitation conditions; no selective phase attack.
Fouling	Resists
Stability	No creep at 200°F.
Weldability	95% or better joint efficiency in as welded condition for yield strength, toughness and fatigue strength.
Formability	Hot formed or cold formed to shape without undue thinning or necking and without need for subsequent heat treatment.
Machinability	Good
Repairability	Weld repairable under service conditions.
Compatibility	Parts of system, electrically connected to have potential difference less than 0.060V in running sea water.
Castability (Castings)	Good
Weld Wire	Available in essentially base metal composition.
Availability	In large sizes and quantities at reasonable cost.

Screening tests will be on basis of yield strength, corrosion resistance and weldability. However, a complete material evaluation will include the following tests for base metal and weldments:

Density
Heat Transfer Coefficient (condenser alloys)
Yield Strength - tension, compression
Moduli - tension, shear
Ductility - elongation and reduction in area
Toughness - notch tensile, charpy
Weldability - resistance to cracking under restraint
Formability (wrought products) - hot and cold and accompanying properties
Fatigue - notched, un-notched, low cycle, high cycle
Corrosion - stress, fatigue, static in marine atmospheres and sea water velocities 3-30 foot/sec.
Creep - various loads and temperatures
Response to thermal cycling
Effect of residual stresses and stress relief conditions
Castability - for castings
Residual stress in weldments - relief
Location in galvanic series
Cavitation resistance

R&D Goals

The following goals must be obtained in order to meet objectives for any vehicles requiring a hard sea water system.

1. The development of useful materials for hard salt water systems.

2. Development of manufacturing techniques for these materials.

3. Development of fabrication techniques for these materials.

4. The development of proper and adequate inspection procedures for pre-process, in-process and post process periods.

5. The development of criteria for full scale performance evaluation and testing of major assemblies.

Alloys to be Considered

The short time remaining for this development will not permit an extensive alloy development. Accordingly, most of the work will be involved in evaluation of known alloys with some modifications anticipated for improved welding, casting, etc.

1. Wrought copper base alloys

   a. 70-30 modified with Al, Cb, Mo, Be, Fe, which permits increased Y.S. with proper heat treatment
   b. Duplex aluminum bronze
   c. Maraging aluminum bronze
   d. Matrix stiffened copper nickel alloys

2. Cast copper base alloys

   a. Heat treatable Cu-Ni
   b. Aluminum bronze
   c. Cu-Si-Al alloys
   d. Matrix stiffened copper nickel

3. Wrought nickel base alloys

   a. Inconel 718
   b. Hastelloy C

4. Cast Ni base alloys

   a. Inconel 718
   b. Hastelloy C

5. Wrought titanium alloys

   a. 6-4
   b. 7-2-1

6. Cast titanium alloys

   a. Commercially pure
   b. Alloy

7. Wrought aluminum alloys

   a. 5000 Series
   b. 7000 Series

8. Cast aluminum alloys

   a. Improved foundry controls for existing alloys

9. Iron corrosion resisting castings

   a. Worthite
   b. 20 alloy
   c. Precipitation hardened

10. Composite

   a. HY-150-Cu Ni or Ni Cu
   b. Maraging – 70-30 Cu Ni or Ni Cu

DISCUSSION OF FRAME OF REFERENCE CHARTS

General

Selection of materials for hard salt water systems will be governed by the pressures which these systems must withstand. Simplification and reliability will require elimination, wherever possible, of bolted and brazed connections, minimization of number of connections and reduction in size. Thus, at hull openings it can be expected that valves will be welded to the hull structure. Heat exchangers may become integral with the hull. Piping systems will contain more shop bends to reduce number of fittings. For aluminum hulls, if developed, unless complete isolation of the hard salt water system is effected, the system will have to be essentially aluminum or aluminum plus CRES. A titanium hull will no doubt see a titanium hard salt water system. High strength steel hulls will either have a strengthened version of current alloys or a titanium system. The latter appears very attractive from a strength/weight standpoint.

An important consideration that should not be overlooked is the fact that as we are required to go up in yield strength we have to face problems which we have been able to avoid before. These include:

1. Need for welding heat treatable alloys and subsequently restoring properties by heat treatment.

2. Materials other than those with high copper will foul in sea water. Thus, hot water or chlorine treatment techniques may be required.

3. Stress corrosion becomes a greater potential source of trouble.

4. Endurance properties do not increase in proportion to yield strength.

5. Fracture toughness is generally less in higher strength materials.

6. Costs of higher strength materials is greater.

7. Resistance to corrosion generally decreases with higher strength alloys.

8. Dissimilar metal contacts may offer serious galvanic corrosion problems.

Thus, the material selected will not have all the best of all the characteristics listed in Table 4, but based on engineering judgment will have the best combination of these characteristics.

Copper Alloys (Fig. 2)

It is expected that greater use will be made of the aluminum bronzes and that the heat treatable copper nickel alloys will be further developed. Fabrication of these heat treatable alloys so that use can be made of their higher strengths will be major effort. Cu-Be alloys will be used for small high strength parts.

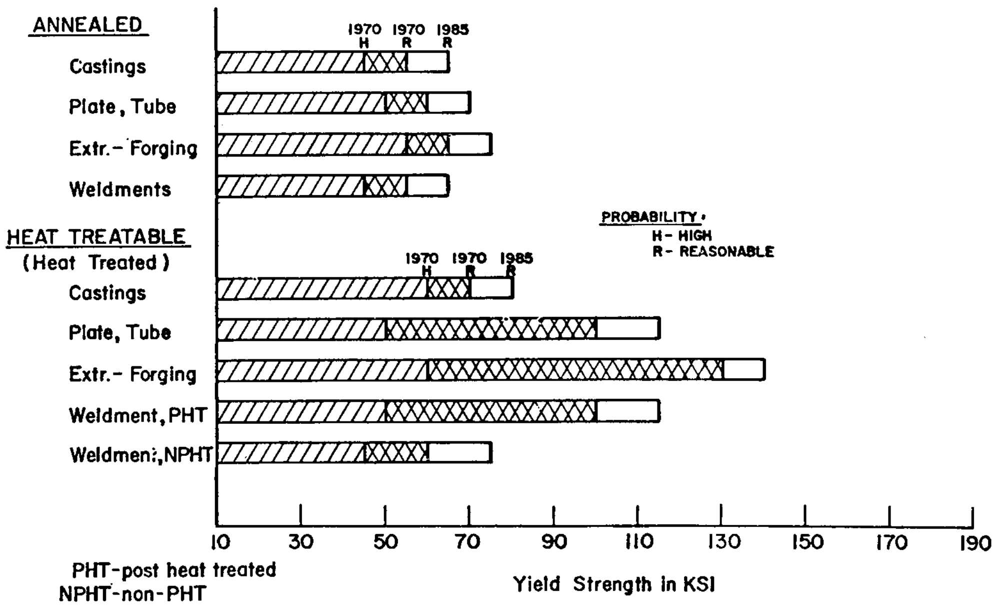

Fig. 2 - Hard salt water systems frame of reference chart - 1970-1985 forecast - copper alloys

Nickel Alloys (Fig. 3)

In addition to more complete evaluation of alloys currently used in sea water service, alloys which have been developed for high temperature service such as the Nimonics, Inconel 625, Inconel 718 and Inconel X750 must be evaluated for possible use in sea water service. Inconel 625 is matrix stiffened while Inconels X750 and 718 are strengthened by heat treatment. The International Nickel Company has under development a Nickel Base Alloy which is expected to have a yield strength of approximately 190,000 psi after precipitation hardening.

Only limited experience exists on castings of the higher strength nickel alloys and if the alloys are otherwise desirable, the casting counterparts must be developed.

Titanium Alloys (Fig. 4)

These alloys offer great promise in hard sea water systems even if steel or other material hulls are used. They are virtually immune to sea water corrosion and they will

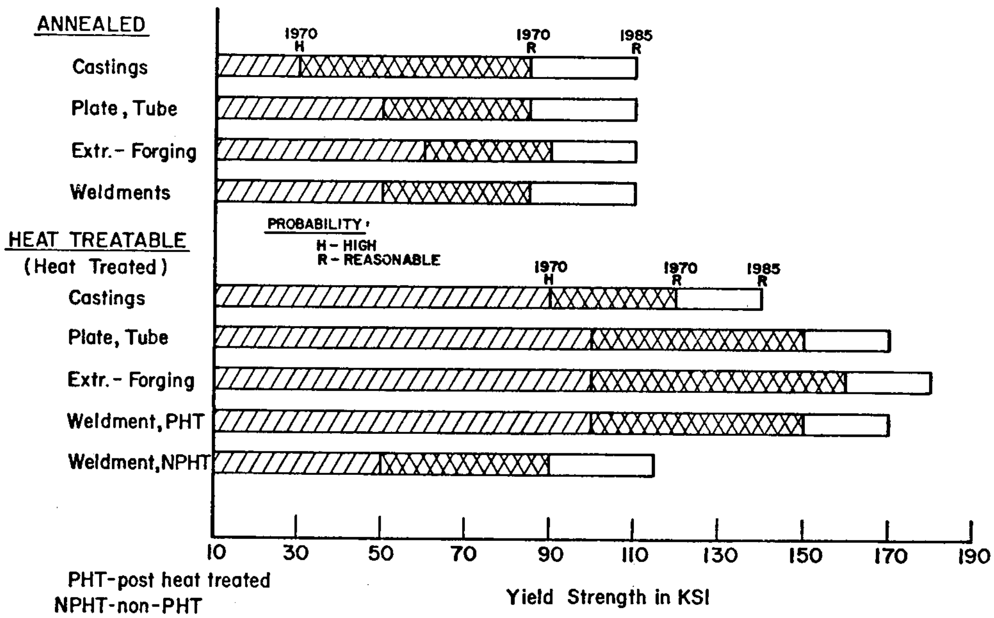

Fig. 3 - Hard salt water systems frame of reference chart - 1970-1985 forecast - nickel alloys

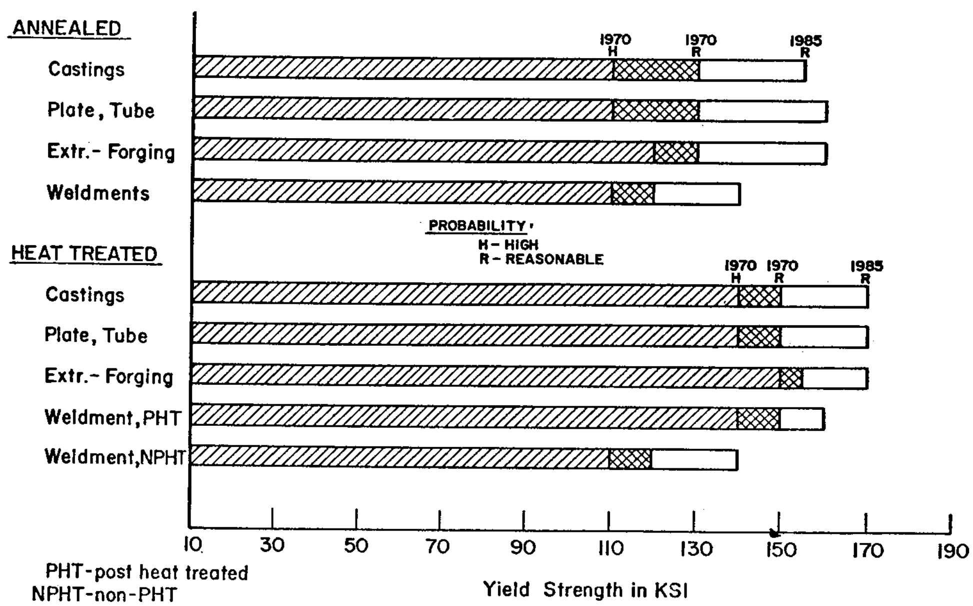

Fig. 4 - Hard salt water systems frame of reference chart - 1970-1985 forecast - titanium alloys

tolerate water velocities considerably above the 15 feet/sec. limits for Cu-Ni alloys. Heat transfer rates for titanium condenser tubes are good. To date castings have been a serious problem and weldable castings will require extensive development. However, castings need not be a limiting factor as forgings can be substituted.

Aluminum (Fig. 5)

An aluminum hard salt water system would be highly desirable for aluminum hulled submarines. However, the alloys which best resist corrosion in sea water (5000 series) are relatively weak. The 7000 series of alloys require protection and offer the additional problems of having to be heat treated and being subject to stress corrosion cracking. It is expected therefore that aluminum, if used, will be supplemented with CRES parts and extensive use of cladding will be required. Galvanic couples must be watched and copper in the system avoided. Aluminum casting improvement will go along the lines of higher purity and improved foundry practice.

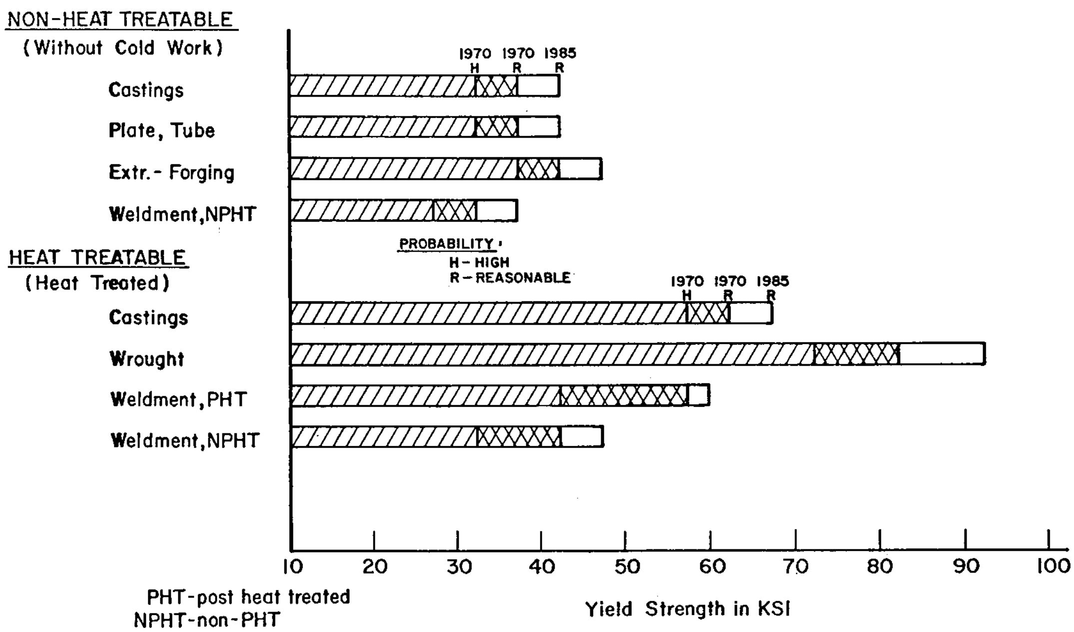

Fig. 5 - Hard salt water systems frame of reference chart - 1970-1985 forecast - aluminum alloys

Ferrous (Fig. 6)

If steel hulls are used, an effort must be made to develop castings of similar composition and strength. This will permit major components such as hull valves to be welded to the hull. Suitable corrosion resisting liners will be used. Work must be done in area of welding composites particularly monel or copper-nickel lined high strength steel. Use of corrosion resisting steel alloys such as Worthite and 20 alloy must consider galvanic couple problems and fouling.

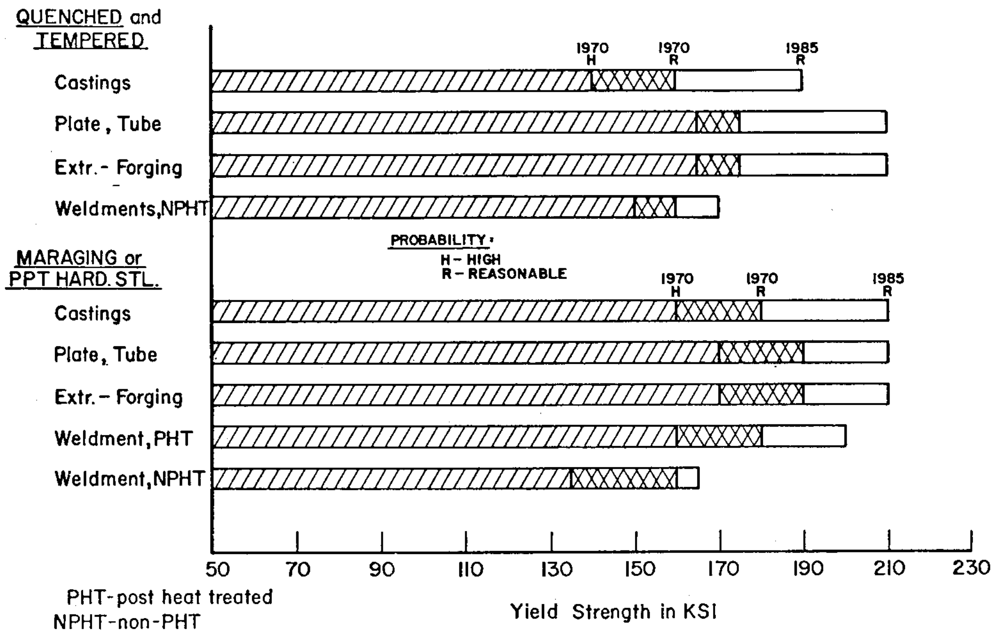

Fig. 6 - Hard salt water systems frame of reference chart - 1970-1985 forecast - high alloy steels (corrosion resistant) or composite steel (corrosion resistant alloy, clad or lined)

Section 3 - R&D TO YEAR 1985

Longer range developments should be undertaken. These will include:

1. Alloy development
2. Casting development — titanium and other alloys available as wrought products
3. Maraging phenomenon in corrosion resisting alloys
4. Tube manufacture — improved techniques
5. Fabrication of piping systems
6. Clad metal development
7. Non-destructive test methods
8. Improved heat treatment procedure
9. Cladding techniques
10. Fabrication of clad systems

It is expected that major improvements in the future will come from better utilization of available alloys. Improved fabrication methods, including techniques for welding heat treated alloys, clad or lined parts and dissimilar metals will permit use of higher strength alloys. Of particular importance will be development of techniques for heat treating in situ welded joints and means for non-destructively testing such joints.

FABRICATION PROCESSES FOR METAL HULL STRUCTURES

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INTRODUCTION

This section describes the objectives and general directions Navy supported Research and Development programs should take in order to meet the projected needs for the fabrication of hull structures and piping which will be needed for deep water technology. Two periods are covered; FY 1966 through FY 1970, and FY 1971 through FY 1980. Limitations related to industrial capacity have not been considered if they can be overcome by extension of known technology, without additional Navy effort.

The discussions which follow cover the characteristics, advantages, limitations and problems anticipated in the fabrication of deep submergence pressure hulls from high strength steel, titanium, and aluminum. They also include brief comments on metals being considered for hard sea-water piping systems which will form part of such marine structures.

The programs presented and accomplishments expected are based on the ability to fabricate small (8' - 10'), medium (15' - 20'), and large (30' - 40') diameter spheres and cylinders with wall thicknesses as follows: steel 1 to 8 inches, titanium 1 to 13 inches, and aluminum 3 to 22 inches. Estimates of the properties of the finished fabrications should be made from both the discussions of individual material properties in this section and in the separate dissertation treating the basic material.

This document is based on the use of plate in its conventional form (nonlaminated). Fabrication with laminates, wherein hull plate is formed by combining layers of plate of identical or different metals is recognized as a possible alternate method of construction. A discussion of all of the aspects pertinent to the use of laminated plates for hull structures is the subject of a separate dissertation.

Work required and cost of fabricating and testing models have not been included because they are covered by the section on fatigue and by the general comments of the summary document.

FABRICATION PROCESSES

The development of procedures suitable for the construction of any structure must take into consideration the fabrication processes which include the production of the basic alloys, the product forms, and specific fabricating operations that are required to assemble the completed structures. A listing of each process includes brief comments wherever pertinent.

Melting

In the manufacture of ingots for wrought products and items cast directly to shapes, the melting process may profoundly influence soundness, mechanical properties and fabricability and the limitation on usable strength may depend on the ability to produce certain alloys with very high purity.

Rolling

Rolling is used to manufacture structural plates and shapes. The rolling of thick sections of very high strength materials may require special rolling procedures in order to obtain optimum properties through the thickness.

Forming

Plates are contoured by cold of hot forming. Hot forming will probably be required to form thick-section high strength metal.

Shapes

Extruding, casting and forging are methods used to manufacture complex or specialized shapes. Tee shaped extrusions are used extensively for stiffeners in submarine construction. Castings are used where structural shapes cannot be produced by rolling and are used in lieu of complex welded structures and forged components which are difficult and expensive to produce. A very large casting can comprise a major segment of a structure. Casting may play a more important part in nonwelded structures than in welded structures. Forgings have applications similar to castings but unlike castings, they are restricted to relatively simple shapes. Forgings also permits the development of a fiber structure which can be favorably oriented to the direction of applied stress. Structural shapes may also be produced by rolling.

Heat Treating

To obtain the desired mechanical properties and corrosion resistance, heat treatment is required for many alloys. Consideration should be given to the development of procedures and facilities suitable for heavy plates, structural shapes, formed components, and massive forgings and castings. A need also exists for the development of techniques for heat treating large welded structures under field conditions.

Thermal Cutting

Thermal cutting is rapid. However, methods must be developed which will minimize post treatment, and not significantly degrade the cut surface and the adjacent area.

Machining

No major problems anticipated.

Cleaning

Surface contaminants can be removed by chemical, mechanical or ultrasonic means. These processes are used in preparation for welding and may be required for subsequent painting or coating operations.

Joining

For relatively large structures, welding is the most desirable method of joining the various component parts to form the completed structure. The use of this technique, however, depends on the successful development of weldable alloys and filler materials. Further development of brazing techniques may be required for piping assemblies. Adhesive bonding or mechanical joining mechanisms must be developed for structures of nonweldable alloys. For structural materials that are difficult to weld, adhesive bonding might be desirable in order to minimize the amount of welding, particularly for miscellaneous attachments where high strength and shock resistance are not essential.

Quality Assurance

Quality assurance methods predict in-service performance of fabricated items. Heavy sections fabricated with new materials will require new concepts, criteria, test methods, and standards to obtain adequate performance of the fabricated components under service conditions. Types and sizes of permissible flaws and metallurgical variations must be established. In addition, rapid, reliable and more sensitive nondestructive techniques (NDT) need to be developed to assure structural integrity of the completed structure. NDT techniques will be desired to determine possible deterioration of mechanical properties, metallurgical structure, or corrosion resistance caused by fabricating operations. Meaningful NDT standards related to service performance must be generated to provide realistic criteria. Automation for increased speed and reliability will also be required.

Laminated Plate

Hull plate could be formed by using laminates of identical or different metals of various thicknesses. Layers of the laminates may not require bonding to each other. When bonding between layers is required, direct metallurgical bonding, brazing, adhesive bonding or combinations thereof could be considered.

HIGH STRENGTH STEEL ALLOYS

The steels considered have the following broad general characteristics:

Quenched and Tempered (Q&T)

These steels, which obtain their properties from a quenching and tempering treatment, have been used extensively in complex commercial and Naval applications. HY-80 (80 ksi yield) steel, which is of this type, is being used for fully combatant submarines. Programs are now underway which aim at upgrading Q&T steels from HY-80 (80 ksi) to HY-150 (150 ksi) for large submarines. A high degree of transfer of skills and knowledge to be acquired with the HY-150 steel, may in turn form a basis for extending the useful range of Q&T steels to HY-200 (200 ksi yield) for welded structures and up to HY-300 for unwelded applications.

Maraging Steels

Strength of these alloys is developed by solution heat treatment, followed by aging at elevated te.nperature (approximately 900°F for current alloys). Maraging steels are less sensitive to quenching rates than the Q&T steels. Since they are a new family of alloys different from the Q&T sttels, less is known about their metallurgical characteristics. Therefore, there will be less transfer of skills and techniques from the HY-80 technology. The fact that these alloys are relatively low in strength in their solution annealed condition (prior to aging) simplifies the forming and complicates welding. Forming can take place with a material at a relatively low strength level, and the finished shape can be strengthened by the final low temperature aging treatment. In welding, however, maraging weld deposits must be strengthened by exposure to aging treatment after deposition. Utility of this material would be markedly enhanced if the required post aging treatment were lowered from 900°F to approximately 500°F, or field procedures for applying a 900°F aging treatment to welds were developed. The alloys are at present being used at strength levels of approximately 250 ksi yield and above for thick-wall (approximately 1 in.), large-chamber rocket motor cases. It is anticipated that there will be appreciable carryover of technology from the aero-space industries, when maraging alloys are used for hydrospace applications.

HIGH STRENGTH TITANIUM ALLOYS

General Characteristics

High strength titanium alloys fall into two broad classifications: alloys which do not respond to a strengthening heat treatment (alpha and some beta alloys) and alloys which may be heat treated to increase their strength (alpha-beta and some beta alloys).

1. Alpha alloys — These alloys have good welding characteristics and may be formed at room temperature, although forming at elevated temperature requires less power. The yield strength levels of currently available alpha alloys range up to 120 ksi.

2. Beta alloys — The one beta alloy currently available may be heat treated to strength levels up to 230 ksi. This alloy is weldable, but the ductility of heat treated welds is low and the strength potential of the alloy is not currently attainable in welded structures. Formability at room temperature is excellent.

3. Alpha-beta alloys — These alloys contain both the alpha and beta phases and are therefore intermediate between alpha and beta titanium. They may be heat treated to strength levels in the range of 180 to 200 ksi. Certain alpha-beta alloys have moderately good weldability. Formability at room temperature is intermediate between the alpha and beta alloys.

Current emphasis is on the development of alpha type alloys for applications requiring the use of heavy section thicknesses in weldable structures because of the good weldability and satisfactory formability of these alloys. However, much higher strength levels may be obtained by the use of heat-treatable beta and alpha-beta alloys and, if welding problems and the low notch toughness associated with these alloys can be overcome, the alloys offer significant potential for future high strength, lightweight applications.

ALUMINUM ALLOYS

The aluminum alloys under consideration may be broadly classified as follows:

Non-Heat Treatable Alloys

Increase in strength of these alloys is obtained from strain hardening (cold working). Weldable alloys of this type (5000 series, approximately 30 ksi yield) are being used in Naval surface vessels. This series represents the highest strength level currently available in the strain hardened varieties. Their principal limitations are that welding decreases strength of the heat affected zone to approximately that of the annealed material and work hardening is not feasible in sections thicker than approximately 5 inches.

Heat-Treatable Alloys (For Welded Structures)

Strength of these alloys is developed by solution heat treatment followed by aging at room or moderately elevated temperature (approximately 300°F). An alloy of this type (6061-T6 35 ksi yield) had been used in Naval surface vessels but was found deficient because of degradation of the heat-affected zone in weldments. The welding operation destroys the effect of the prior treatment in zones brought to high temperatures and results in overaging in zones brought to lower temperatures (above the aging temperature). This degradation takes the form of loss of strength, ductility, toughness, and corrosion-resistance. The degradation may be removed by complete heat treatment. Recent claims by the aluminum industry indicate that this degradation may not be as serious in some of the 7000 series alloys (50,000 psi yield), the highest strength level of alloys being considered for welded structures. Back-up data to substantiate these claims for heavy structural welding are lacking.

Heat-Treatable Alloys (For Nonwelded Structures)

Weldable alloys of the 7000 series could be used. However, higher strength (70 ksi yield) is available with nonweldable alloys, such as 7178-T651. These higher strength alloys are susceptible to sea water exposure and must be protected by a coating such as "Alclad."

HARD SEA-WATER PIPING SYSTEMS

These systems include all components, exclusive of the hull structures, that are exposed to sea water at deep submergence pressures, e.g., pumps, valves, piping and pipe fittings and involve various product forms such as plates, bars, tubing, pipe, forgings and castings. Alloys of concern are copper alloys (e.g., cupro-nickel and bronzes), nickel alloys (e.g., monel 400), aluminum, titanium, and steel. Composites of these materials (high strength material external with metallic or non-metallic liners) may also be considered. The wide diversity of materials and prevalent forms precludes a detailed discussion of each. Accordingly, this discussion will be confined to highlighting some of the major anticipated problem areas.

Castings are essential for complex configurations, not readily produced by other methods. High strength-weight ratios in the as-cast or non-heat treated condition may be required in welded systems to prevent deleterious welding effects. Improved casting designs may be necessary to obtain quality and reliability. Improvement in quality of copper base alloy castings is required. Alloy systems have to be designed for optimum weldability and resistance to sea water exposure.

In composites, corrosion resistant liners may be joined to high strength metal by metallurgical bonding, brazing, adhesive bonding or metallurgical diffusion. Lining without bonding, or nonmetallic coating of metals might also be used. The drawbacks of composites lie principally in the area of processability and in joining into a completed system, particularly if brazing and welding are contemplated. While some process history experience has been gained in the cladding field, the other areas require development for applicability to hard sea-water systems.

Joining problems may be minimized by giving due consideration to this factor before selecting an alloy. Many past difficulties are attributable to the fact that material selections are made on the basis of base metal properties, rather than considering whether these properties will be retained after the overall fabrication.

Rapid, dependable and more searching nondestructive testing techniques need to be developed to assure structural integrity of components, after incorporation into the completed system, and to permit repeated testing during its service life. Problems peculiar to sea water systems include NDT methods for assessing deterioration due to corrosion (both macro and micro), integrity of brazed joints, integrity and uniformity of composites, and deterioration of mechanical properties, metallurgical structures, and corrosion resistance caused by fabricating operations.

PROPOSED R&D FABRICATION PROGRAMS

Tables 1, 2 and 3 indicate the approaches for R&D fabrication programs for steel, titanium and aluminum, respectively. The successful execution of the R&D programs described therein will provide the information and techniques necessary for fabrication of the vessels shown in the enclosed "Forecasts of Fabrication Capability" charts. It should be noted that these charts merely indicate feasibility of fabrication in terms of retaining approximate base metal properties in the final structures. The charts are not intended to imply adequacy of material properties or designs; it is assumed that these matters will be treated in other dissertations. A discussion of methods proposed for fabrication of the vehicle hulls of the enclosed charts follows:

HULL FABRICATION

High Strength Steels

The extensive research and production background required in the HY-80 submarine construction program provides a good base for predicting the extension of that technology to higher strength steels and for predicting problem areas likely to be encountered.

1. General — Construction of the hulls shown in the charts will be based on the development of high strength steel shapes for major structural components and of automated welding processes specially adapted to heavy thicknesses. By 1970 it is expected that procedures will be available for applying heat treatment for aging or stress relieving of welds in large subassemblies. Methods will be developed for the utilization of steels of dissimilar strength levels in the same hull. This will reduce cost by using the less expensive, lower strength steels (80 to 150 ksi yield) as components of hulls that are basically composed of 180 to 300 ksi yield steels. The feasibility of these goals has already been established by the following:

a. Shapes. Castings (1), forgings, and extruded tees of HY-80 have been used as major structural components in Polaris submarines.

b. Automated welding processes. Electroslag welding has been used for single pass welding of 2-1/2 inch thick HY-80 hemispherical heads in submarines (2). Exploratory studies of automatically welded 2-inch thick HY-80 narrow gap weldments, which required less weld metal than conventional techniques indicated excellent explosion bulge performance (3). Semiautomatic vertical welding and automatic flat welding of HY-80 have been accomplished in shipyards (4).

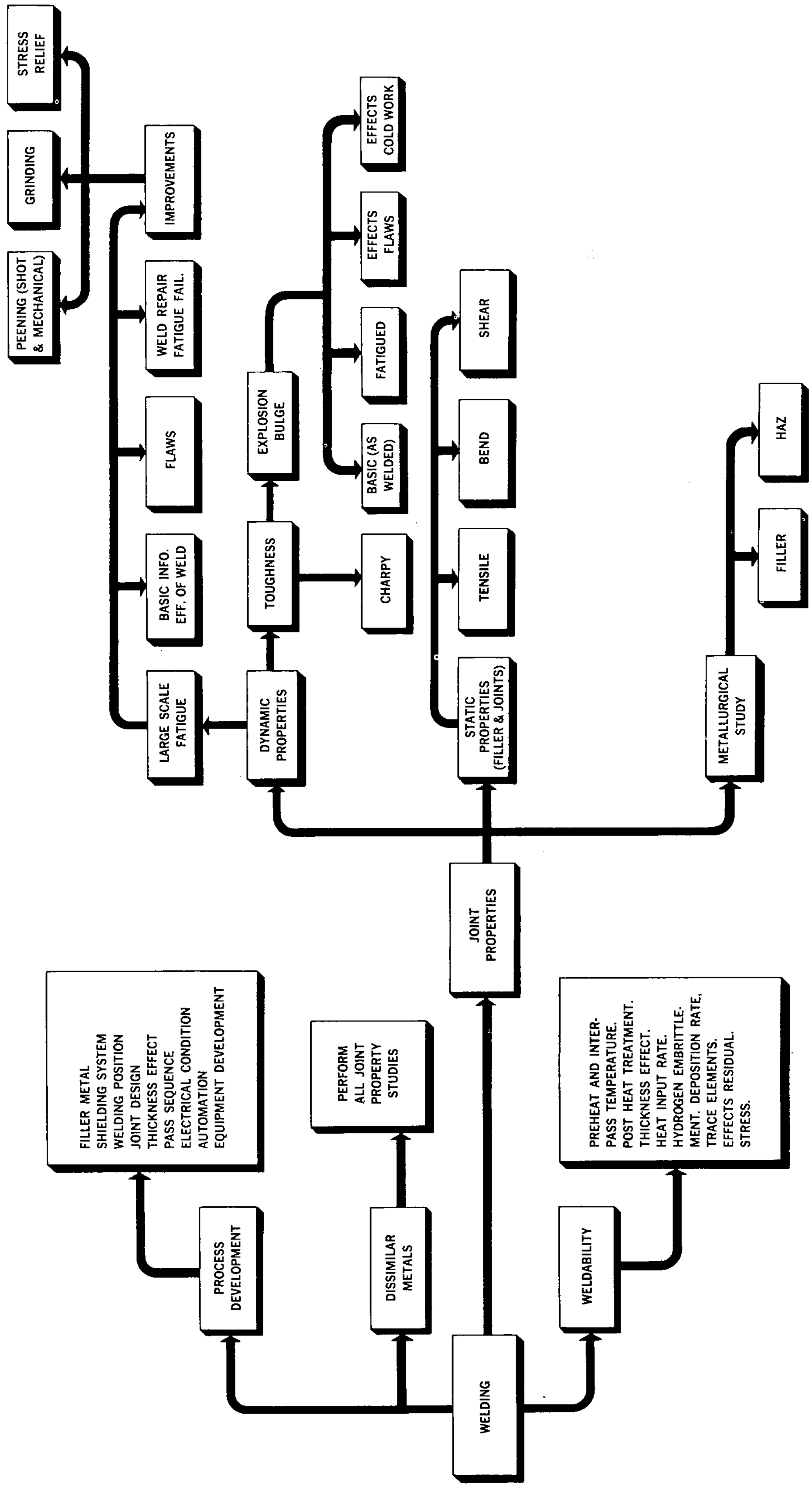

Fig. 1 - General requirements for welding fabrication study

Table 1
Proposed R&D Program - High Strength Steel Fabrication

	FY 1966 through FY 1970	FY 1971 through FY 1980
1. Melting	Determine trace impurities which have deleterious effects on fabrication process.	Extend to new and higher purity steels.
2. Rolling 3. Forming	Develop rolling and forming techniques for HY-150/200 steels up to 6" thick.	Extend to steels up to 300 ksi yield and 8" thick.
4. Shapes (Extruding, Casting, Forging and Rolling to Shape)	Develop techniques for producing large shapes to serve as major structural components in HY-150/200 steels.	Extend to steels above HY-200. Include applicability new processes, such as explosive forming.
5. Heat Treating	Develop field procedures for applying aging and stress relieving heat treatments to welds of unlimited size structures and full heat treatments to large subassemblies equivalent in size to 10 ft diameter spherical welds.	Develop procedures to fully heat treat structures of larger size and complexity.
6. Thermal Cutting	Determine optimum methods (include study plasma-arc cutting).	Apply to new steels, investigate new methods (electron beam, laser, etc.).
7. Machining	None required.	Develop new methods (such as electrochemical, lasers).
8. Cleaning	Extend HY-80 pickling techniques and develop ultrasonic techniques.	Extend to higher strength steels and adapt ultrasonic techniques to large scale production.
9. a. Welding	Conduct detailed studies shown in Fig. 1 on steels up to HY-200. Investigate new procedures (such as electroslag, narrow gap plasma-arc, electron beam). Develop automated welding methods for all position field welding.	Continue all studies in steel over 200 ksi yield. Develop complete automated shipbuilding welding procedures.
b. Mechanical and Adhesive Bonding	Study basic methods for joining steel to steel and steel to overlaying metals.	Develop methods for structural applications.
10. Quality Assurance	Determine applicability of current HY-80 criteria and test methods (destructive and NDT tests) for HY-150/200 weldments up to 6" thick; modify and automate as required.	Continue for steels and weldments above HY-200. Develop NDT techniques for adhesive bonds.

Table 2
Proposed R&D Program - High Strength Titanium Alloy Fabrication

	FY 1966 through FY 1970	FY 1971 through FY 1980
1. Melting	Develop increased ingot size capacity for producing large thick plates.	Further expand ingot size capacity.
2. Rolling	Develop rolling techniques to optimize properties of large thick plates of HY-100/140 alloy titanium.	Extend techniques to higher strength alloys.
3. Forming	Investigate application of conventional forming techniques to heavy section HY-100/140 alloy titanium.	Extend to higher strength alloys and new techniques.
4. Shapes (Extruding, Casting, Forging and Rolling to Shape)	Develop technology and capability for producing large shapes in HY-100/140 alloy titanium for use as major structural components.	Extend to higher strength alloys and investigate methods for improving quality and reducing cost.
5. Heat Treating	Develop stress-relieving, annealing and strengthening heat treatments for thick sections and large structural elements under field conditions.	Extend to higher strength alloys and investigate new methods.
6. Thermal Cutting	Investigate oxy-acetylene, plasma arc, electron beam and other methods to develop optimum techniques.	Investigate new methods as developed and extend to higher strength alloys.
7. Machining	None required.	Investigate application of new techniques for high strength alloys.
8. Cleaning	Develop optimum techniques for removing surface contamination (due to high temperature forming) from heavy sections and develop methods to assess effectiveness of techniques.	Develop methods for protecting titanium surfaces from contamination during high temperatures forming operations.
9. a. Welding and Brazing	Conduct welding studies, per Fig. 1, on HY-100/140 titanium alloys. Develop new processes for welding thick sections such as submerged-arc, electroslag, narrow-gap, etc. Develop methods for welding titanium to other metals. Develop brazing techniques. Develop manual and automated techniques for all-position field welding.	Extend studies to higher strength alloys. Investigate new welding techniques, as developed. Investigate methods to improve quality and reduce costs.

(Table continues)

Table 2 (Continued)
Proposed R&D Program - High Strength Titanium Alloy Fabrication

	FY 1966 through FY 1970	FY 1971 through FY 1980
9. b. Mechanical and Adhesive Bonding	Develop materials and techniques for mechanically fastening and/or adhesive bonding high strength, HY-150/180 non-weldable titanium alloys to themselves and other materials.	Investigate new methods and extend adhesive bonding to structural applications.
10. Quality Assurance	Develop new criteria, test methods and standards for welded and unwelded alloy titanium structures to assure adequate service performance with special emphasis on heavy sections, fracture toughness, effects of flaw sizes, weld contamination, and related NDT.	Extend to new alloys and heavier sections. Refine and automate NDT techniques. Develop NDT for adhesive bonded joints.

Table 3
Proposed R&D Program - Aluminum Alloy Fabrication

	FY 1966 through FY 1970	FY 1971 through FY 1980
1. Melting	None required; industrial ingot capacity needs expansion.	Same.
2. Rolling 3. Forming	Develop techniques for current alloys in thicknesses up to 12".	Extend to new alloys and heavier sections.
4. Shapes (Extruding, Casting, Forging and Rolling)	Technology adequate; R&D necessary to investigate properties of shapes and forgings. Castings not recommended.	Same - New alloys and heavier sections.
5. Heat Treating	Develop field aging procedures for sections up to 12"; current heat treatable alloys.	Same - New alloys and heavier sections.
6. Thermal Cutting	Determine optimum methods for sections to 12".	Extend to new alloys and heavier sections.
7. Machining 8. Cleaning	None required - no problems anticipated.	Same.
9. a. Welding	Conduct studies shown in Fig. 1 with emphasis on heavy sections and new processes to increase productivity (e.g., electroslag) - current alloys.	Same - New alloys, heavier sections and more complex fabrications.

(Table continues)

Table 3 (Continued)
Proposed R&D Program - Aluminum Alloy Fabrication

	FY 1966 through FY 1970	FY 1971 through FY 1980
9. b. Mechanical and Adhesive Bonding	Develop techniques for joining main structural elements and minor attachments. Explore composite laminates.	Improve techniques and apply to large structures.
10. Quality Assurance	Develop performance criteria and NDT methods and standards for welded structures.	Extend to new alloys and heavier sections. Study NDT techniques for adhesive bonding and composites.

c. Heat treatment. Metallic arc and electroslag weldments in 2-1/2-inch thick hemispherical heads, over 15 feet in diameter are currently being fully heat treated (1).

d. Steel strength. Steels are available in yield strengths as high as 300 ksi. The price of steel 80 to 150 ksi yield is 50¢ a pound or less. Higher strength steels may be in the 80¢ to $1.50 per pound price range.

It must be recognized that the effect of flaw size varies directly with strength. Therefore in comparison with HY-80 structures higher levels of quality and smaller permissible flaws in the shapes and weldments of the proposed hulls may be required. This will in turn require extensive research to establish performance criteria for shapes and welded joints. In order to assure quality during fabrication, and in service, techniques for nondestructive testing (NDT) will have to be increased in sensitivity and definition.

2. One to three inch thicknesses. Fabrication of high strength steel hulls up to 3-inches in thickness, will follow the general approach described above which is an extension of HY-80 fabrication (see Table 1).

3. Three to eight inch thicknesses. For thicknesses in the 3 inch to 8 inch range, the development of new rolling and forming techniques may be required. The development of suitable casting, forging or extruding techniques will become increasingly important for the production of subassemblies of the required shapes and sizes. In some cases these may be the only methods of producing heavy sections with sharp curvatures or complex contours. With appropriate development work, heavy thickness vessels could be fabricated by joining preformed shapes. Fabrication of 10-foot diameter vessels by this technique should present no difficulty. Welding of steels in the 3 inch to 8 inch range will become increasingly dependent on the new processes specifically designed to weld heavy thicknesses. For weldments which can be subjected to subsequent full heat treatments, the electroslag process would be the method of choice. This method is capable of single pass welding of thicknesses in the 2 inch to 8 inch range with a minimum of edge preparation. Where full heat treatments of welds are not feasible, new processes (such as MIG narrow gap welding) specifically designed for welding heavy thicknesses will be required. Techniques for quality assurance (performance criteria and NDT) for HY-80 are primarily applicable to thicknesses up to 3-inches. Evaluation techniques and criteria for prediction of service performance of weldments and manufactured shapes from 3 to 8 inches thick will be required. NDT developments for these thicknesses will probably be confined to ultrasonics.

4. Fabrication forecasts. The 1970 and 1980 fabrication forecasts for steels are only limited by the contemplated strength level of alloys, applicable weld metals which may be anticipated, and the size and complexity of the structures. It is assumed that by

1970 techniques will be developed to stress relieve welds of any size at temperatures up to 1100°F and to fully heat treat segments of hulls up to 10 ft in diameter.

In the 1970 forecast chart, the strength levels indicated for the 8 ft to 10 ft vehicles (180-250 ksi) are based on alloy types similar to those being used in the aero-space industry for large rocket motor cases (approximately 1 inch thick) and those alloys being considered in a current feasibility study being conducted under BUSHIPS contract (5). The high confidence levels shown for the 15 ft to 20 ft diameter (medium size) hulls are based on the weldable HY-150 alloy (150 ksi yield) and filler wires being developed for submarines under the same current BUSHIPS contract (5). The medium confidence level shown for these hulls is at the same strength level as the high confidence level shown for the 10-foot hull.

In the case of the 30 to 40-foot (large diameter) hulls, in view of the large size and the complexities of subassemblies the confidence levels have been placed 10 to 20 ksi lower than those for the medium diameter hulls.

The 1980 forecast chart is based on the development of technologies to automatically weld structures of unlimited size. With this capacity, the limitations indicated merely reflect estimate of the properties of the alloys and filler metals which will be available at that time.

HIGH STRENGTH TITANIUM ALLOYS

The fabrication technology for the construction of hulls of heavy section alloy titanium is now in the initial stages of development. Therefore, the predictions as to the use of titanium in deep submergence hull structures can only be based on extrapolation and good engineering judgement, using the limited data and experience available. Recent advances in titanium alloy fabrication for aircraft suggest that there are no insurmountable problems to be faced in the use of this new material in a difficult application.

General

One of the more significant problems, in the use of titanium alloy for the deep ocean vehicles shown on the accompanying charts, is the lack of industrial capacity to produce large size ingots. Except for the smaller and medium sizes of vehicles, on the lower end of the hull thickness range, the largest titanium ingots currently produced are not large enough to provide plate of sufficient length and width to make the fabrication of large thick walled vehicles either practically or economically feasible. At present no requirement exists, either in the civilian or military economy for production of heavy sections of titanium alloy in the shapes or sizes that would be needed for the fabrication of large deep diving submersibles. Therefore, little or no effort is being made, by the titanium producers, to expand their capacity to provide larger ingots, plates, and shapes. If titanium alloy is to be used by the Navy in the fabrication of large deep diving vehicles, Navy support of a program to further develop industrial capacity is essential.

The methods of forming and fabricating heavy sections of titanium alloy into hull structural configurations will be, to some extent, similar to those currently used in the fabrication of steel-hull submarines.

Castings, forgings and extruded tees, which are used as structural components of steel-hull submarines will also be required for the fabrication of titanium hulls. Forging titanium presents no special difficulty and the technology is fairly well established. The capacity and experience required to produce shapes and sizes of forged parts for small and medium size deep ocean vehicles with hull plating between 1 to 6 inches thick should be adequately developed by 1970 and capability to produce larger sizes can be expected by 1980. Capacity and experience for producing dished or hemispherical heads for small and medium size vehicles by hot spinning, forging or explosive forming are also realizable developments by 1970. Extension to larger sizes is foreseeable by 1980. Casting large titanium shapes for deep ocean vehicles poses a problem of significant magnitude and extensive research and development support will be required to make even modest size castings available by 1970. By 1980, large size titanium castings should be available provided that sufficient market for such items has developed. Large titanium extrusions are not currently available, but industrial capacity can be expected to provide such extrusions by 1970.

Welding processes which have been and are being developed for welding steel and aluminum can and are being adapted for welding alloy titanium. Although welding titanium poses a problem of shielding the weld from contamination by the atmosphere at elevated temperatures, recent developments in this technology, based on laboratory data, indicate that it is feasible to produce high quality 2-inch thick titanium alloy welds, out-of-chamber, by using inert gas shields. The metal-inert-gas (MIG) and tungsten-inert-gas (TIG) welding processes appear to be useful for section thicknesses between one and three inches. Other processes, for example the narrow-gap welding process currently under development for welding steel, offer potential for welding thick sections of titanium alloy. A sufficient number of welding processes should be available by 1970 to permit the production of quality welds in alloy titanium up to 6 inches thick by manual, semi-automatic, or automatic methods. Welding of heavier sections, up to 13 inches in thickness, will require technical breakthroughs, which may be possible by 1980.

Welding titanium alloys at yield strength levels above approximately 120 ksi will require that the welds be heat treated to develop optimum properties. It is expected that procedures for heat treating welds in large titanium subassemblies can be developed by 1970.

Quality control requirements for titanium alloy hulls will be as stringent as those indicated for high strength steel hulls. The nondestructive testing requirements for titanium hulls will also require an advance in the state-of-the-art, particularly in methods for detecting and assessing contamination in titanium welds.

Small Vessels, 8' - 10' Diameter

1. <u>1970 Forecasts</u> — Fabrication of welded alloy titanium hulls of this size, at strength levels in the range of 100 to 120 ksi and sections up to approximately 6 inches in thickness, is feasible within this time frame based on:

a. Current availability of weldable alloy titanium at the lower (100 ksi) strength level and anticipated alloy development to 120 ksi by 1970.

b. The capability of fabricating alloy titanium weldments as thick as 2 inches has been demonstrated in the laboratory, as reported in Refs. (6) and (7). It is reasonable to expect that technological developments, by 1970, will permit fabrication in thicknesses up to 6 inches.

c. Current industrial capacity for producing ingots up to 9000 pounds can be increased by 1970 to produce 15,000 to 20,000 pound ingots. These ingots will make possible reasonably large size plates up to 6 inches thick.

The confidence levels for expanded wall construction, shown on the forecast charts, are somewhat lower than those for single wall construction because of anticipated greater difficulties in weld shielding in the expanded wall design.

The fabrication of bolted and/or cemented (B-C) titanium alloy hulls up to 6 inches thick at the 140 ksi strength level is based on the use of a heat treatable alloy which can be formed in the low strength, annealed condition, and then solution treated and aged to higher strength level prior to assembly. The lower confidence levels shown in the chart for B-C vessels fabricated with 160/180 ksi alloys reflect the uncertainty of developing suitable alloys at these strength levels.

Fabrication of welded or B-C hulls, with walls greater than 6 inches in thickness, is considered to be beyond achievement in this time period because of ingot size limitations.

2. <u>1980 Forecasts</u> — Welded titanium alloy hulls 8' - 10' in diameter, in the 120/140 ksi strength range with section thicknesses up to 11 inches are forecast for this period on the basis of:

a. Development of improved weldable alpha or alpha-beta alloys capable of achieving the desired strength levels without heat treatment, or by local weld heat treatment.

b. Improved capability for welding very thick sections by electroslag, electron beam, narrow-gap or other welding processes that will be developed in this period.

c. Increased ingot sizes (30,000 to 40,000 pounds) by 1980 to yield very thick plate of reasonable length and width.

d. The development of new or improved rolling and forming techniques for thick sections.

The fabrication of B-C hulls of alloy titanium at strength levels of 180/220 ksi and section thicknesses up to 11 inches is considered feasible by 1980 based on:

a. The development of suitable heat treatable alloys (alpha-beta or beta).

b. The development of industrial capability to produce 30,000 to 40,000 pound ingots and the development of new or improved casting, forging, extruding and forming techniques for heavy sections.

Medium Vessels, 15' - 20' Diameter

1. <u>1970 Forecasts</u> — The fabrication of welded alloy titanium hulls of this size, at strength levels between 100 and 120 ksi sections as thick as 3 inches is based on essentially the same development as has been indicated for the 8' - 10' diameter vessels in the 1970 time frame. The thickness limitation of approximately 3 inches for the welded 15' - 20' diameter vessels is again based on probable limitations in the size of ingots that will be available by 1970 (15,000 to 20,000 pounds). Fabrication of this size vessel in 100/120 ksi weldable titanium alloys which require no heat treatment, would be based, to a great extent, on techniques currently employed in the construction of HY-80 steel submarines, and, as indicated in Ref. (8), appears to be possible by 1970.

B-C hulls of this size, limited to wall thicknesses of about 3 inches and fabricated of heat treatable alloys at strength levels of approximately 140 ksi should pose fabricating problems no greater than those for the smaller, thicker walled vessels discussed above.

Medium size hulls with walls greater than approximately 3 inches thick are not considered feasible within the 1970 time frame because of ingot size limitations.

2. <u>1980 Forecasts</u> — The forecast for 15' - 20' diameter welded titanium alloy hulls in the 120/140 ksi strength range is based on section thicknesses up to about 8 inches and on technological developments that will take place by 1980 as outlined above for the smaller and thicker hulled 8' - 10' diameter vessels. The section thickness limitation of 8 inches for the medium size vessels is imposed by the anticipated maximum ingot size available by 1980.

Fabrication of 15' - 20' diameter B-C hulls with walls up to 10 inches thick at strength levels ranging as high as 220 ksi is based on the same developments outlined for corresponding construction of 8' - 10' diameter hulls. Section thicknesses up to 10 inches are predicted for bolted construction as against only 8 inches for welded construction, since it is believed that it will be feasible to use forged or cast and machined rings for bolted construction. This would give a greater utilization of material from the ingot than would be possible by reducing the ingot to plate. In addition, whereas welding and subsequent heat treatment of 10 inch thick sections is considered to by beyond technological achievement by 1980, heat treatment of forged or cast rings prior to assembly in a bolted hull would appear to be entirely feasible.

Large Vessels, 30' - 40' Diameter

1. <u>1970 Forecasts</u> — Limited ingot sizes available in this time period would complicate fabrication of vessels with 3 inch wall thickness because of inability to produce plates in sufficient length or width to make fabrication of a hull practical. However, if a critical requirement exists for a vessel of this size, its fabrication would be possible.

2. <u>1980 Forecasts</u> — In this time period, with projected increases in ingot sizes, up to 30,000 to 40,000 pounds, the production of plate, up to about 6 inches thick, in widths and lengths of 10 to 20 feet, should be possible. These sizes of plate would make fabrication of large size vessels practicable. The technical developments and experience gained by 1980, from the fabrication of small and medium size vessels, should provide the technology required for the fabrication of welded hulls of this size at the 120/140 ksi strength levels and slightly thicker walled (8 inch) B-C hulls at the 180/220 ksi strength levels. Hulls of this large size, with walls greater than 6 or 8 inches in thickness, are not considered feasible because of the plate or forging size limitations imposed by ingot size.

Aluminum Alloys

Current data and techniques applicable to the fabrication of thick aluminum hulls for deep ocean vehicles might be extrapolated for 1970 to 5 inch thicknesses for welded hulls and 8 inch for unwelded hulls. Development of fabrication capability for appreciably heavier thicknesses by 1970 is not contemplated. Fabrication of hulls in these greater thicknesses would require development of a new "heavy wall" fabrication technology along the lines indicated in Table 3 for the 1966-1980 period.

1. <u>Weldability</u> — Weldability data for the strain hardening type alloys (5000 series, 30 ksi yield) is available and could probably be applied to thicknesses up to 5 inches (9). Use of these alloys in thicknesses appreciably greater than 5 inches is not feasible by 1970 for the reasons noted in the materials discussion. While it is reasonable to assume that modification of the current strain hardening techniques may be developed in the distant future and might increase their available thickness to some extent, long range applicability of these alloys in thicknesses appreciably above 8 inches does not appear likely.

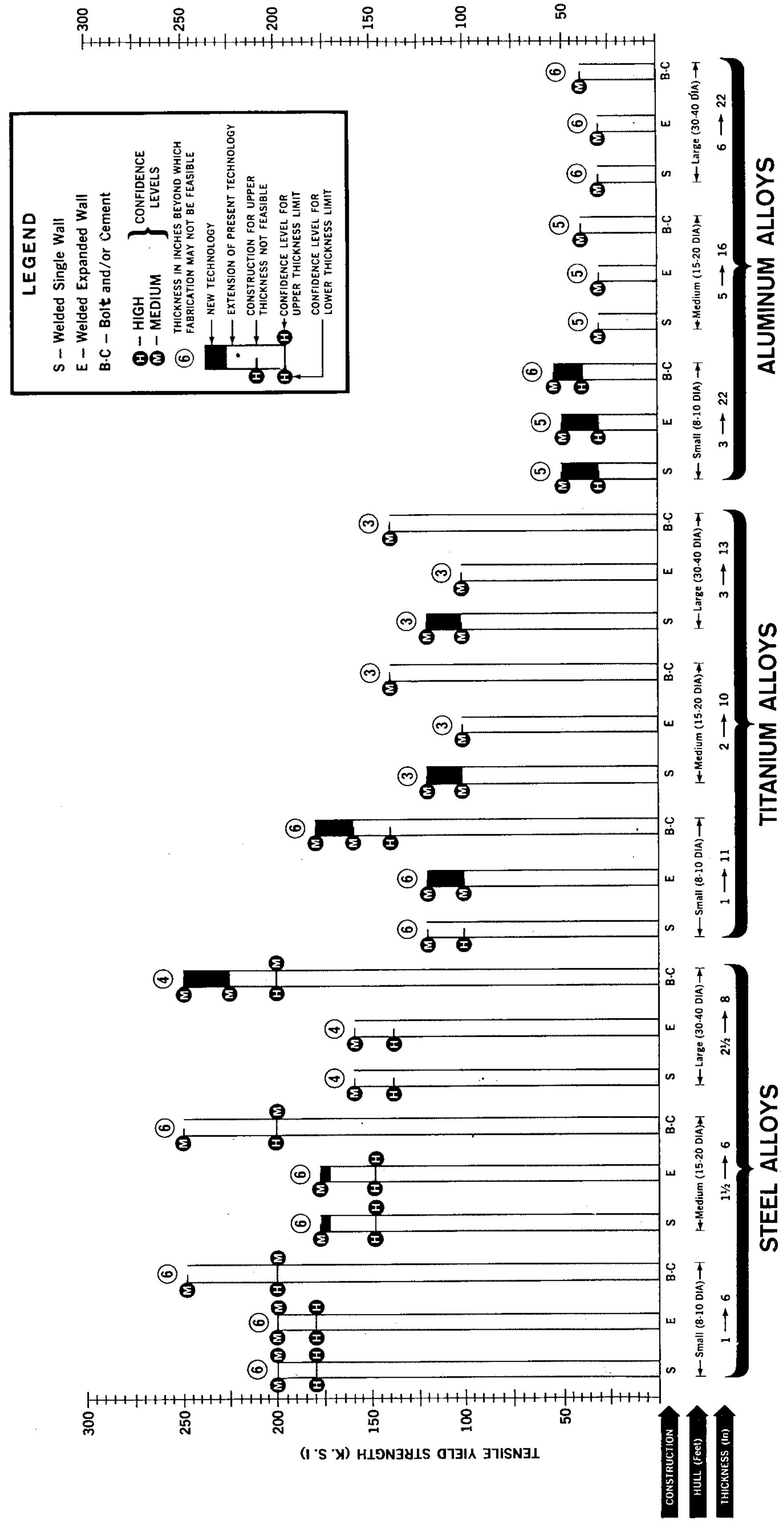

Fig. 2 - 1970 forecasts of metal fabrication capability - hulls for deep ocean vehicles

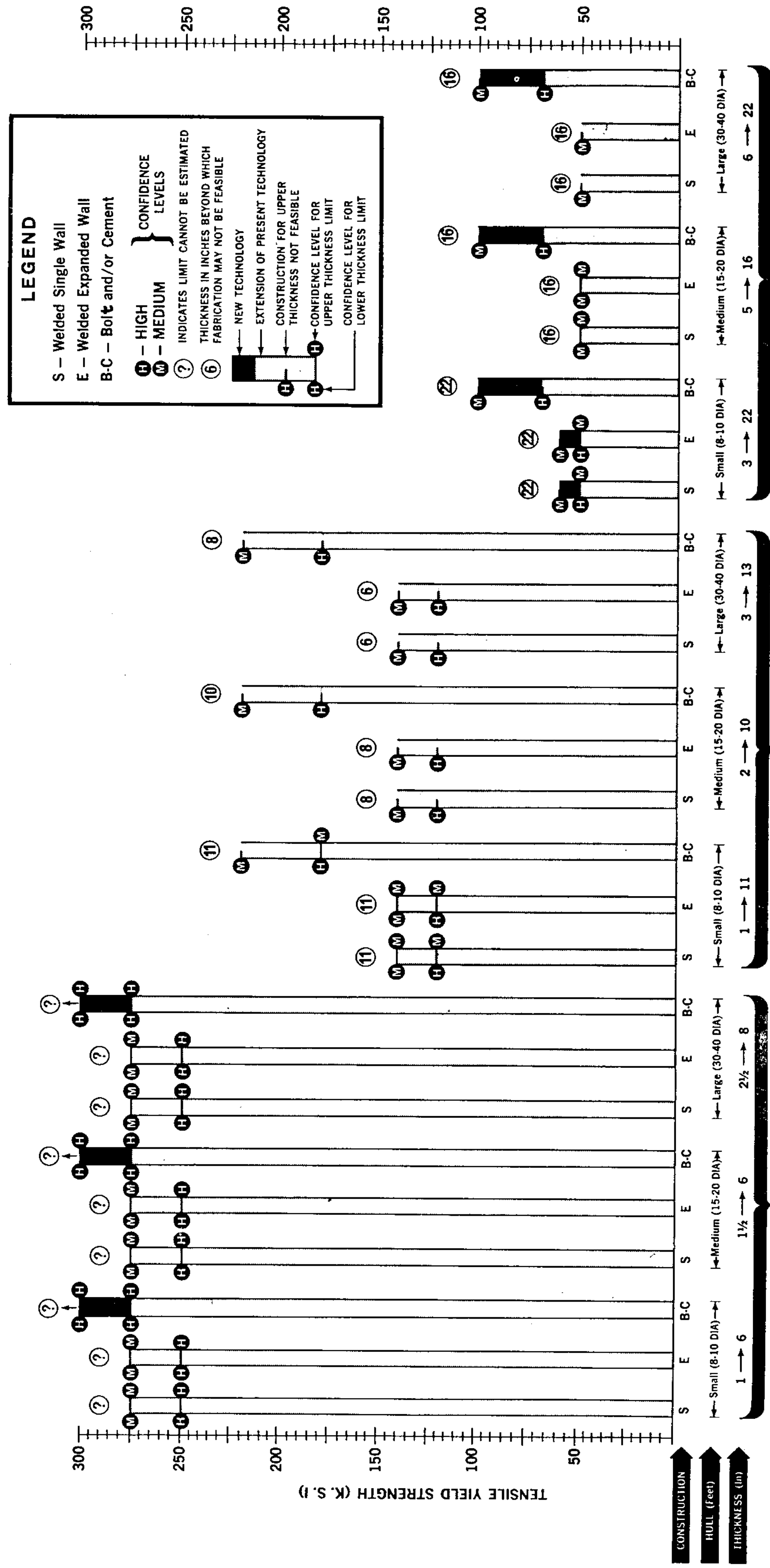

Fig. 3 - 1980 forecast of metal fabrication capability - hulls for deep ocean vehicles

In view of the above, it is expected that, for hulls appreciably above 5 inches in thickness, heat treatable alloys (such as the 7000 series) will be used. However, as noted in the materials discussion, welding of these alloys introduces degradation in the heat affected zone (HAZ) adjacent to the weld. A breakthrough in technology or alloy development will be required to overcome this factor. While commercial claims have been made that the 7000 series might include alloys which will minimize HAZ degradation, bases for these claims are not apparent.

2. 1970 Fabrication capability — Construction of a small (10' diameter) welded hull using the 5000 series (30 ksi) alloys in thicknesses up to 5 inches can be expected with high confidence based on R&D expansion in current technology.

Small vessels using materials over 30 ksi in strength will require use of heat treatable alloys. These alloys (7000 series) might be used for welded construction in their annealed condition. Complete reheat treatment of major subassemblies will then be utilized to minimize deleterious effects of welding in the HAZ areas. An alternate approach is to use these alloys in their solution annealed condition and apply any necessary thermal aging treatment to the hull. Since construction of these welded hulls may involve the use of new heat treatable alloys for which only limited proprietary data is available, and in view of the fact that properties of the HAZ areas in these welds have not been established, a medium confidence factor has been assigned.

The unwelded (B-C) structures will use the heat treatable alloys. Higher strengths than those shown for corresponding welded structures are indicated for the high and medium confidence levels, because of the absence of the deleterious welding effects. Unwelded (B-C) construction in these alloys in thicknesses to 8 inches appears feasible by 1970, in view of the 6-1/2 inch thick, 8 ft diameter vessel under current construction (Aluminaut).

Confidence levels for the medium diameter hulls are decreased from those indicated for small hulls at corresponding strength levels, because of the increase of minimum wall thickness and the complicating effects of increased size and mass. Large diameter (30' - 40') vessels with walls of this thickness will not be practical at this time due to complicating size and thickness factors. However, if a critical requirement exists for a vessel of this size, its fabrication would be possible.

3. 1980 Fabrication capability — The 1980 forecast assumes the development of a new higher strength heat treatable alloys. Development of alloys which exhibit a minimum of weld HAZ degradation and development of new welding techniques could result in a considerable lessening of the HAZ degradation in welded structures.

The proposed R&D program will develop a technology to form aluminum and fabricate hulls in heavy thicknesses. However, extension to thicknesses in the 16 to 22 inch range may prove difficult, and construction of large hulls in this thickness range does not appear feasible.

The confidence relationships between different hulls shown in the forecast chart approximate those in the 1970 forecast. For welded structures, confidence levels at a given strength level decrease as hull size or thickness increases. Higher strength levels at a given confidence level may be anticipated for unwelded structures, because of the absence of the deleterious welding effects.

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ADVANCED METALS JOINING TECHNOLOGY

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ADVANCED METAL JOINING ESTIMATES

The object of this discussion is to provide a frame of reference for technical forecasts on metals-joining techniques that will be available for fabrication of structures and vehicles for deep-ocean technology in 1970 and in the 1980-1985 period. This report points out those metals-joining techniques and processes which appear likely to be useful in the future with the materials which are likely to be available and for the structures which will be needed. Consideration is directed primarily at structures which will be subjected to sea pressure. An estimate is made of the development that is needed over the next five years to advance the processes to the point where they will produce the needed structures at a reasonable cost.

This discussion considers only the welding of thick plates of heat-treatable steels (including maraging steels), titanium alloys, and aluminum alloys.

In order to make estimates of the state of the metals-joining art in the future it has been necessary to make some assumptions as to the criteria which will govern the usefulness of the structures produced. Basically, two criterion have been used in the evaluation of metals-joining techniques. First, it is assumed that for certain types of structures weldments will have to have fracture properties equal to the minimum requirements for the base plates from which they will be fabricated. These properties can be summarized as a low probability of fracture in the presence of small plastic strains. These criterion are the basis for the estimates shown in the forecast sheets. Second, it is assumed that there will also be a need for structures which will not need this fracture behavior. In this case, the criteria for fracture resistance is no failure under the elastic stresses imposed by normal design loads. Such structures can be considered brittle. While no forecasts are given for them much higher yield strengths could be obtained in such structures than in ductile structures.

The discussion of welding metals-joining processes has been considered from the viewpoint of two sizes of structures. The smaller size is one which is considered feasible for full heat treatment. At present, the diameter of a sphere or cylinder which can be given a full heat treatment is approximately 10 feet. Therefore, this has been used as the limiting diameter for the smaller size structures. Even when the diameter can be accommodated in a furnace the thickness of the materials used in the structure or the complexity of the structure may make heat treating extremely difficult or impossible. Consequently, it has been assumed that there is a maximum thickness that can be given a full heat treatment. For steels and titanium this maximum thickness has been set at about 2-1/2 inches. For aluminum the maximum thickness has been assumed to be about 4 inches. An attempt was made to work a complexity index into the estimates, but it was decided that this was not possible. While the limiting figures for diameter and thickness chosen may not be exactly correct and will without doubt change in the future they certainly indicate the sizes and thicknesses of structures which can be heat treated.

In addition to picking limiting sizes and thickness for heat treatments it was also decided there was probably a limiting thickness for nonfurnace tempering or aging treatments. This thickness will of course vary as the treatment temperature varies and as the material changes. It will be less as the treatment temperature becomes higher. This means it is easier to temper a weldment at 200 F to 400 F than it is to temper or age it at 800 or 900 F. It is probably easier to age a high conductivity material at a low temperature than a low conductivity material at a high temperature.

The whole discussion of welding techniques is based on extensions of present-day technology. Certainly for 1970 forecasts this is the only reasonable approach. Even for the 1980-1985 needs there are no unusual development in sight. Table 1 summarizes the evaluation of welding processes, the forecasts for 1970 and 1980-1985.

Table 1
Summary of Status of Metals Joining Processes and Their Potential for Use with Materials and Needs of 1970 and 1980-1985

Process	Present State of the Art	Expected YS in Weldment Over 1 Inch Thick, ksi*		Development Potential	Probability of Successful Development
		1970	1980-1985		
MIG and TIG	Good	S-150 Ti-110 Al-25	S-180 Ti-140 Al-25	Excellent	Excellent
Electron Beam	Fair	S-180 Ti-110 Al-40	S-200 Ti-140 Al-40	Good	Fair (thickness limitation)
Solid-State Bonding	Fair	S-None Ti-110	S-None Ti-140	Good	Fair (thickness limitation)
Submerged Arc including Electroslag	Good	S-150 Ti-None Al-None	S-150 Ti-None Al-None	Poor	Good
Coated Electrode	Excellent	S-150 Ti-None Al-None	S-150 Ti-None Al-None	Poor	Good
Miscellaneous	--	--	--	--	--

*Yield strength is value believed to have high probability of being attained in tough weldments of all sizes and thickness.

In addition to the discussion and forecasts for structural weldments this report also contains brief discussions of the needs for developments in obtaining data to prepare specifications, development of pipe-welding techniques, and development of inspection techniques. These are problems separate from the main theme of the report, but they are believed to be of as much importance.

PROBLEMS OF THICK STRUCTURES

Evaluation of potential weldment needs for the future indicate that there will be two problems which will have to be faced if requirements are to be met. These are:

1. Need for weldments having high compressive yield strengths
2. Need for thick weldments.

These two needs interact. Weldments of very high strengths (higher than estimated to be attainable) would reduce the problems which thickness induces. Ways of making thick structures without welding thick plates would reduce the problems encountered in trying to reach very high yield strengths in weldments. Since ultrahigh-yield strength weld metals are not foreseen it will be necessary to develop optimum ways of welding thick plates or ways of making thick structures without having to weld thick plates.

Narrow Welds in Thick Plates

Evaluation of the joining processes with potential for future application deep ocean technology needs indicates that fusion-welding process will probably be most likely to produce the structures needed. Fusion welds are unique materials. They are highly specialized castings which are made under highly transient conditions. Heating and cooling rates are very high, probably higher than encountered in any other metallurgical operation. The molten metal produced by the process is subject to composition alteration from the base metal, air, and in some processes the atmospheres and slags produced by the process itself. The combination of unusual thermal cycle and potentially varying composition can lead to unusual segregations, structures, and defects.

Unfortunately, basic knowledge about the effects of the variables encountered in most welding processes is not very extensive. What is available does indicate two things. First, it is best to weld in uncontaminating atmospheres if possible. Inert gases are good, vacuums are even better. Second, it is a great advantage to restrict the width of the total heated zone (weld metal plus base metal heat-affected zone) as much as possible. The narrower the weld the better. The ideal would be to eliminate the fused metal from the joint and keep the base metal heat-affected zone as narrow as possible. Unfortunately, this is not often possible especially on large weldments. However, any steps which can be taken to narrow the total heated zone will be of great value in making it easier to obtain sound welds with the properties needed in high-strength weldments.

The fusion-welding processes which are considered in the forecasts are ranked below with respect to the minimum width of weld which can be presently produced in thick plates welded from one side.

Process	Minimum Weld Width, inch
Coated electrode (manual)	3
Submerged arc (automatic)	3
Electroslag (automatic)	1 - 1-1/2 (?)
Inert-gas shielded (automatic)	3/16 - 3/8
Electron beam (automatic)	0.050 - 0.100

Narrow welds do not only aid in producing welds with desired properties, but are desirable for other reasons also.

It has been shown that residual stresses can exert a significant influence on the behavior of weldments under various types of loading. Evidence has been obtained that shows that the critical crack size in high-strength weldments decreases significantly when a notch or crack is located in areas where high tensile residual stresses exist. For example in mild steels the existence of high-tensile residual stresses can reduce the critical crack size for fracture below the yield from 4 inches to less than 1 inch. There is also evidence available to indicate that residual stresses affect the fatigue behavior of structures. Residual stresses can cause plastic fatigue in structures which are subjected to compressive loading. Research on a variety of materials has shown that as a first approximation the width of the zone of residual tension stress in the vicinity of a weld is proportional to the volume of weld metal per unit length of weld. That is, the narrower the weld the narrower the zone of residual tension stress and the less the residual strain energy built into the weldment.

A final advantage of narrow welds is in reduced cost. A common estimate of the costs of a pound of mild steel weld metal in place is $3.50. High-strength-steel weld metals cost much more and titanium weld costs soar into the stratosphere. Figure 1 shows the estimated cost per foot of weld for three different arc-welding processes.

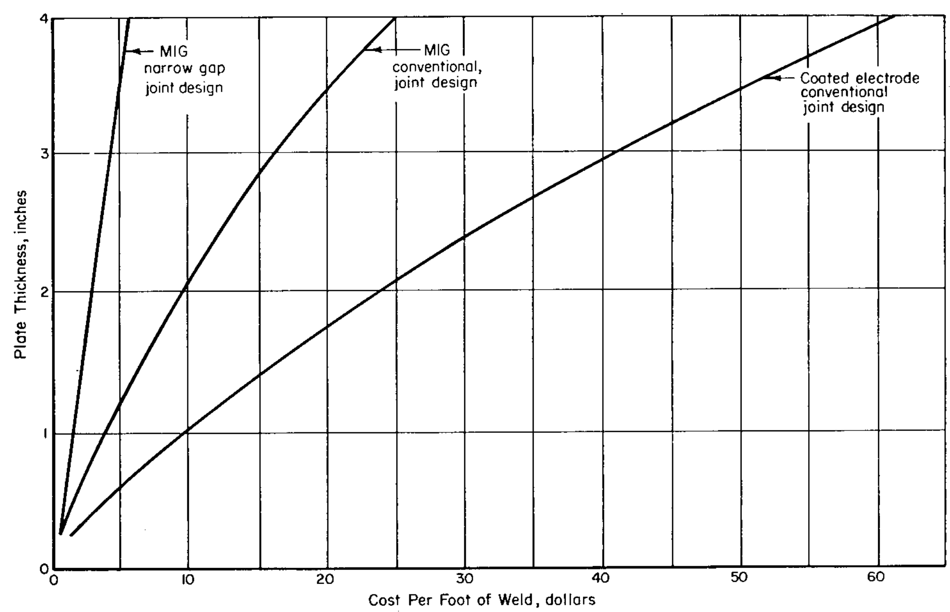

Fig. 1 - Comparative costs of various welding processes for HY-80 weldments (costs include cost of materials and labor - no overhead costs included)

Layer Construction

One way to avoid the problems of welding thick plates is to use layer construction. This is a standard technique used for building cylindrical pressure vessels for high pressure. Several thousand vessels in diameters up to 10 feet have been built. Larger diameter vessels are being considered. The vessels are assembled layer by layer by arc welding. The only reason for the layer construction is to reduce the thickness of the plate used in the construction. Vessels several inches thick are built up from plate 1/4 to 1/2 inch thick. Higher quality plate, higher quality welds, and the elimination of a continuous weld metal path through the wall are additional advantages which are obtained.

While designs and methods of fabrication of layer vessels for compressive loading are not well developed, the advantages of this type of construction are such that development efforts should be started. Layer vessels have been built primarily by arc welding, although brazing and resistance-welding processes also have been used. At present, there is fairly extensive effort underway to devise ways of using high-frequency resistance welding in making helical welded vessels from ultrahigh-strength metals up to 22 feet in diameter. This process appears interesting for application to compressively loaded multilayer vessels also. Plate, strip, rod, or even wire could be used. The process will butt weld strip in thickness up to 1/2 inch thick (steel) at speeds up to 50-75 feet per minute. The process is essentially an upset-butt-welding process which leaves no fused metal in the weld joint. (It is the ultimate in narrow-gap techniques.) High-efficiency joints have been produced by high-frequency resistance welding in such hard-to-weld alloys as 7075 aluminum (75 per cent joint efficiency). Uncracked welds have been produced in 18 per cent maraging steel strips heat treated to 250,000 psi. These welds had joint efficiencies of 60 per cent in the as-welded condition.

BASIC RESEARCH ON WELD METALS

Research on weld metals for use in tough structures has reached a point where additional basic information is needed if high-strength welds are to be obtained. Tough weld metals are available at yield strengths up to about 150,000 psi in steels. Toughness degenerates rapidly as yield strength increases. A basic question is why is this degeneration more severe in welds than in wrought materials. There is no answer to this question at present. If higher strength weldments are to be obtained, the question must be answered. Basic research is needed to supply the information needed.

METALS JOINING TECHNIQUES

The metals-joining techniques used in the forecases were rated on the following basis:

1. Consideration was given to the present state of development of the process. Its adaptability to the materials being considered, the sizes of structures, the plate thicknesses and the property requirements were evaluated. If the present state of development was high and the adaptability of the process to deep ocean technology requirements appeared good the process was given a high rating.

2. An estimate and evaluation of the amount of research development presently underway on the process was made. If considerable effort appeared to be in progress a high rating was given the process.

3. The potential of developments already underway or suggested reaching a conclusion by 1970 was considered. If the potential was high the process was given a high rating.

4. The potential of the process for adaptation to presently undeveloped unknown metals or alloys was considered. If this was high the process was given a high rating.

5. The potential of the process for producing quality weldments at reasonable costs was evaluated. If this was high, the process was given a high rating.

The evaluation of a number of processes on this basis are given in Table 2. Six processes were further evaluated for the forecast charts.

Table 2
Evaluation of Metals Joining Techniques on Basis of Several Criteria for Use in Fabricating Structures of Interest in Deep Ocean Technology (DOT)

Process	Present State of Art					Amount of Development Underway Applicable to DOT	Development Potential to 1970		Potential for Application to Presently Undeveloped Materials	Fabrication Cost Bias
	Steel	Titanium	Aluminum	Large Structures	Thick Plates		Moderate Strength	High Strength		
MIG	G	E	G	G	G	E	E	E	E	G
TIG	G	E	G	G	P	G	E	E	G	P
Electron Beam	G	E	G	F	F	F	E	E	G	G
Solid State Bonding	G	E	G	P	F	UN	G	G	G	E
Submerged Arc Electro Slag	G	N	N	E	E	F	G	P	P	E
Coated Electrode	G	N	P	G	F	P	F	P	P	P
CO_2 Shielded	F	N	N	G	F	P	P	P	P	G
Gas-Slag	F	N	N	F	F	P	F	P	P	G
Laser	UN	UN	UN	UN	UN	G	UN	UN	UN	UN
Brazing	G	F	P	P	P	P	F	P	P	P
Hi Frequency Resistance Welding	G	G	G	N	N	P	E	E	F	G
Upset Butt Welding	G	G	G	N	N	P	G	G	G	F
Friction Welding	G	UN	UN	N	N	P	UN	UN	UN	UN
Ultrasonic Welding	F	F	G	N	N	N	N	N	N	UN
Explosive Welding	F	F	F	N	N	N	G	G	UN	UN

E - Excellent; G - Good; F - Fair; P - Poor; N - None; UN - Unknown.

The six metals joining processes which were chosen for consideration in the forecast charts are described briefly on the following pages. They are discussed in descending order of development potential. Each process is described in terms of the way joints are made, and very brief descriptions of the present state of the art, the state of present development, and a projection as to developments by 1970 and 1980-1985 are given.

Table 3 lists metals-joining processes which were considered, but rejected. The major reason for rejecting each process is mentioned in this table.

Table 3
Metal Joining Processes Considered and Rejected

CO_2-Shielded Consumable Electrode - Rejected because active gas shield not usable with high-strength steels, steels containing easily oxidized alloys or reactive metals and alloys.

Gas-Slag Shielded Consumable Electrode - Rejected for same reasons CO_2-shielded process was rejected.

Induction Plasma - No better source of energy than arc plasma and much more restricted in power.

Laser - Lasing source of magnitude needed for continuous welding not available and not foreseen in next five years.

Brazing - Fit-up requirements unobtainable for large structures.

Upset Butt Welding (including flash welding) - Equipment problems insurmountable for sizes being considered.

Friction Welding - Difficulty of developing relative motion between parts of size and mass which will be encountered.

Ultrasonic Welding - Thicknesses much too great and joint designs not amenable to this process.

Explosive Welding - Type of joint not suitable for explosive welding.

INERT-GAS-SHIELDED CONSUMABLE-ELECTRODE PROCESSES (MIG)

Fusion-welding process using arc between a consumable wire electrode and work as heat source. Welding torch furnishes shield of inert gas to arc vicinity to protect molten metal from atmosphere.

Present State of Art

A major commercial process for welding steel, aluminum, and titanium. Potentially useful for all materials of construction. High-speed process capable of both manual and automatic operation. Process has fair out-of-position capabilities. Present equipment needs improvement. Better power supplies and controls would add to versatility of equipment.

Major problem is weld-metal porosity particularly with steels and aluminum. Lack of fusion also a problem particularly in low voltage shorting transfer applications.

Joint finishing rate of 2-3 feet per hour in 2-inch-thick plate.

Present Development Status

Probably more development activity underway than in any other arc process. Development of power supplies and controls underway. Investigations of influence of electrical characteristics of power circuitry underway. Investigations of influence of shielding-gas mixtures on arc characteristics underway. High deposition rate procedures being investigated. Narrow joint procedures being developed for thick plates of steel and aluminum alloys.

Development Potential

1970. New information on arc characteristics in inert-gas shields, influence of power supply and circuitry, and control development indicate promise of greatly expanding usefulness in next five years. Development of procedures for narrow joints should with the other developments lead to process which is capable of producing welds with compositions, properties, and soundness as well controlled as is now possible with TIG and with much higher joint finishing rates. Automatic out-of-position capability will be developed. Joint finishing rate of 6-10 feet per hour in 2-inch-thick plate.

Beyond. Information being developed on circuitry and arc characteristics could lead to further refinements in process and make it the outstanding arc-welding process from both quality and cost considerations. Some indication that constricted-arc techniques can be applied to MIG process.

INERT-GAS-SHIELDED NONCONSUMABLE ELECTRODE (TIG)

Fusion-welding process using an arc between a nonconsumable electrode (usually tungsten) and work as heat source. Welding torch furnishes shield of inert gas to arc vicinity to protect molten weld metal from atmosphere. Filler metal added if needed. Modification of process known as "plasma arc" or "constricted arc" is one in which a long arc is forced through a cold wall constriction and heats shield gas to higher temperatures than obtained in standard TIG torch.

Present State of Art

A major commercial process for welding a wide variety of metals and alloys. Is being used on high-strength steels (200,000 psi yield strength and higher), aluminum alloys, and titanium alloys. Process provides best control of weld composition and best shielding of all arc-fusion-welding processes. Highly versatile, can weld in all positions on wide range of thicknesses with good control of weld penetration and bead thickness. Easily adaptable to either manual or automatic welding. Highly developed controls available for automatic welding.

Major problem is joint finishing speed in plate thicknesses of interest in deep ocean technology. Maximum is probably 1/2 foot per hour in 2-inch-thick plate. More normal speed is of the order of 4 hours per foot of joint in 2-inch-thick plate.

Present Development Status

Considerable development work is underway on the plasma-arc torch. While most of this is aimed at cutting some is aimed at welding. Some interest in arc characteristic and effects of power supply and circuitry on them. Studies of deep-penetration techniques underway for aluminum.

Development Potential

1970. Joint finishing rate will be increased sufficiently so that process can be considered for plate thicknesses up to 2 and perhaps 3 inches. Process may be quite useful for layer construction.

Beyond. No estimate possible.

ELECTRON BEAM

Fusion-welding process using a focused beam of electrons to furnish energy for joining. Filler metal added by wire feeder when used. High vacuum required at electron gun. Moderate vacuum (10^{-4} Torr) required in welding chamber if small focal spot is desired.

Present State of Art

Presently well developed for welding in vacuum. Used with parts in fixed chamber or with movable chamber on large parts. Excellent protection from atmospheric contamination of weld. Narrowest weld and heat-affected zone of all presently available fusion processes. Can be used with nearly all materials.

Process is capable of very high welding speeds, but over-all welding time increased by pump-down requirements. Out-of-position capabilities in vertical position, but overhead and horizontal capabilities unknown. Strictly automatic process.

Process has very narrow fitup tolerances, lowest of all processes discussed.

Major weld defect is porosity.

Present Development Status

Research is underway to develop atmosphere welding capabilities and improve vacuum welding capabilities. Development of moving chamber vacuum equipment underway.

Development Potential

1970. Both vacuum and atmosphere capabilities will be available for thickness of 3 to 4 inches in steel and titanium and thicker in aluminum. Versatility of process will be improved by development of small movable vacuum chambers.

Beyond. Improved atmospheric capabilities, increased thickness capabilities, and increased fitup tolerances with filler material will be developed.

SOLID-STATE BONDING

Process makes welds by causing coalescence of metals across an interface without melting of base material or interface material. Two techniques. Gross plastic deformation to break up surface films and bring uncontaminated metal into contact. Use of high temperatures and microdeformation to cause diffusion across interface and produce bond.

Present State of Art

High pressure, high-temperature diffusion techniques developed for producing critical components such as nuclear fuel elements. Roll-bonding techniques (room temperature and high temperature) developed for commercial applications. A wide variety of materials has been bonded including all of the materials of interest for deep ocean technology requirements, but not in probable thicknesses.

High-speed low-cost process for volume production. Also relatively low cost method of producing parts where close dimensional tolerance and lack of contamination are important.

Unbonded areas only real flaw and this is not serious if well developed procedures are used.

Major problem at present is panel thickness limitation.

Present Development Status

Research is underway to develop methods of producing sandwich structure by solid-state-bonding techniques including both hydrostatic pressure bonding and roll bonding. Titanium alloys, aluminum alloys, stainless steels, ferritic steels, zirconium alloys, beryllium, and the refractory metals are all being investigated.

Development Potential

1970. Development of procedures for making sandwich panels in steel, titanium, and aluminum, in thickness to perhaps 4 inches and densities of 60 pounds per square foot in steel. Techniques for cladding high-strength materials with poor corrosion resistance with low strength or brittle materials of high-corrosion resistance. Might be adaptable to layer vessel construction.

Beyond. Increase in size of sandwich panels that can be produced.

SUBMERGED ARC

Fusion-welding process using arc between consumable electrode and work as heat source. End of electrode and arc are buried in a granular mineral flux which melts and protects molten weld metal from air.

Present State of Art

A major commercial process for welding steels. Not usable with aluminum or titanium because of reactivity of flux. High deposition rate process. Process usable only in downhand position or in special setups in horizontal position, cannot be used in other positions. Commercial equipment rigged and dependable. Present control systems simple. Not adaptable to manual operation, although some semiautomatic welding is done.

Flux wire combinations presently available for mild steels, low-alloy constructional steels, low-alloy high-strength steels, HY-80 and some nickel-base alloys.

Major defect is slag inclusions. Major problems are lack of out-of-position capability and coarse grain size in weld.

Joint finishing rate 5-7 foot per hour in 2-inch plate.

Present Development Status

Some effort underway to develop fluxes for steels of HY-150 class.

Development Potential

1970. Development of filler wires and fluxes for HY-150.

Beyond. No estimate.

ELECTROSLAG

A fusion-welding process in which single or multiple wires or a plate electrode are fed into a vertically positioned joint into a molten slag bath which floats on the molten weld pool. Initial heating of the electrodes occurs by self-resistance heating. Final heating and melting occur by electrolytic heating in the slag bath. Slag and molten metal are held in place by water-cooled copper shoes. An arc is not maintained between filler wires and pool.

Present State of Art

Developed for welding thick sections and has been used on a variety of steels. Theoretically any thickness can be welded, thickest reported is 40 inches. Process offers considerable savings over other welding processes above some minimum thickness (reported to be about 4 inches). Very little is known about the requirements for application of the process to high-strength steels. The process is not applicable to titanium and probably not applicable to aluminum.

Major problem is grain size of weld deposit.

No joint preparation is required.

Present Development Status

Investigations of fluxes and filler wires required for a variety of steels are underway. Studies of effects of vibration, vertical electrode oscillation, and horizontal electrode oscillation on the grain size of the completed weld are being made. The effects of slag, viscosity, conductivity, and boiling point on the continuity of the process are being studied.

Development Potential

1970. Development of process for welds in HY-150. Has potential for narrow-gap welds.

Beyond. No estimate.

COATED-ELECTRODE ARC WELDING

Fusion-welding process carried out with a wire-cored electrode covered with a dipped or extruded mineral coating. The coating dissociates in the arc area during welding and produces an active gas which shields the arc area from the oxygen and nitrogen in the air.

Present State of Art

Process is major arc-welding process used with steels including present submarine-hull steels. Electrodes are available for use with ultrahigh-strength steels if weldment can be heat treated after welding. Electrodes are available for welding aluminum, but welds are low strength. Process cannot be used for titanium because of reactivity of titanium and gases and slags produced by covered electrode.

Process is relatively slow, but has excellent out-of-position capabilities.

Problems are cracking, porosity, slag inclusions.

Present Development Status

Research is underway to develop electrode coatings for steel to achieve as-welded yield strengths of 130-150 ksi with useful fracture properties. No research of aluminum electrodes. Most of research and development effort on this process aimed at present commercial uses.

Development Potential

1970. Coated electrodes will be developed for use with steels of HY-150 class. No developments for aluminum or titanium foreseen.

Beyond. No developments foreseen. Coating decomposition products (CO, CO_2) introduce contaminants to weld metal which adversely affect strength and fracture properties.

FRAME OF REFERENCE CHARTS

The frame of reference charts for advanced metal-joining techniques are contained in Figs. 2 through 14. These charts forecast on the basis of process and material. Some charts cover more than one process. This has been done when charts overlapped so that there was little or no difference between them. Usually, there is a forecast chart for 1970 and one for 1980-1985. The lack of a 1980-1985 chart means that no significant advance over 1970 is visualized for the material-process combination being considered.

In the charts, H means high probability of producing weldments with the yield strength indicated, and R means reasonable probability. A vertical line on the chart means the yield strength of the weldment is governed by the weld metal. A slanted line means the yield strength is governed by the unaffected-base metal.

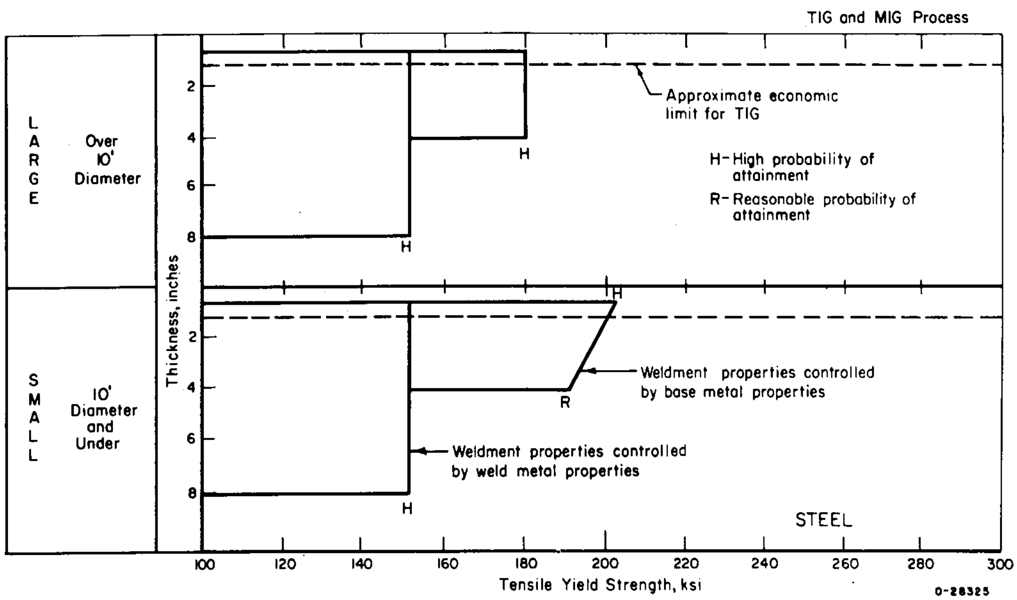

Fig. 2 - Forecast for steels for 1970

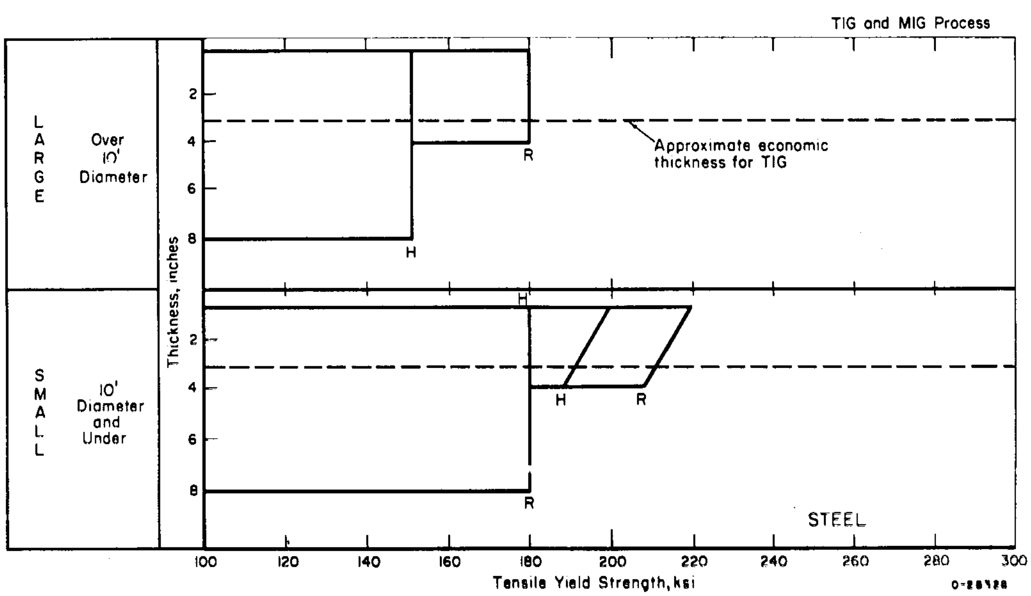

Fig. 3 - Forecast for steels for 1980-1985

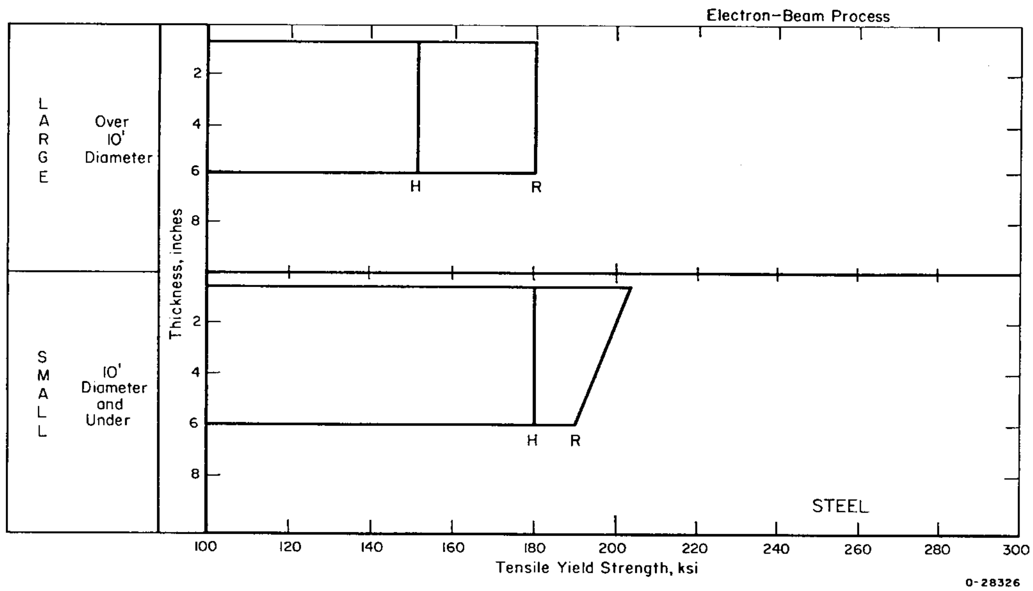

Fig. 4 - Forecast for steels for 1970

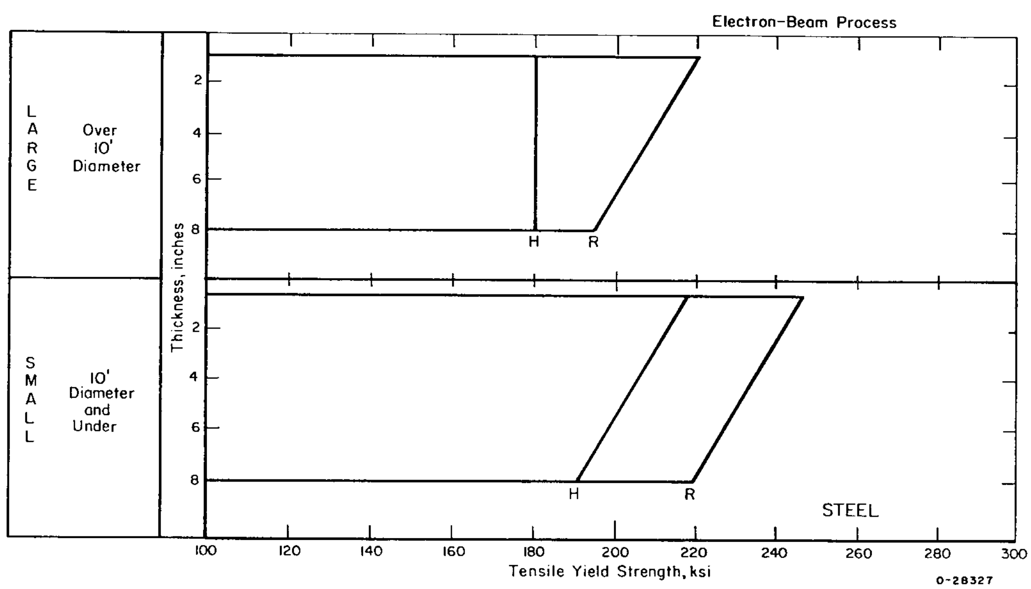

Fig. 5 - Forecast for steels for 1980-1985

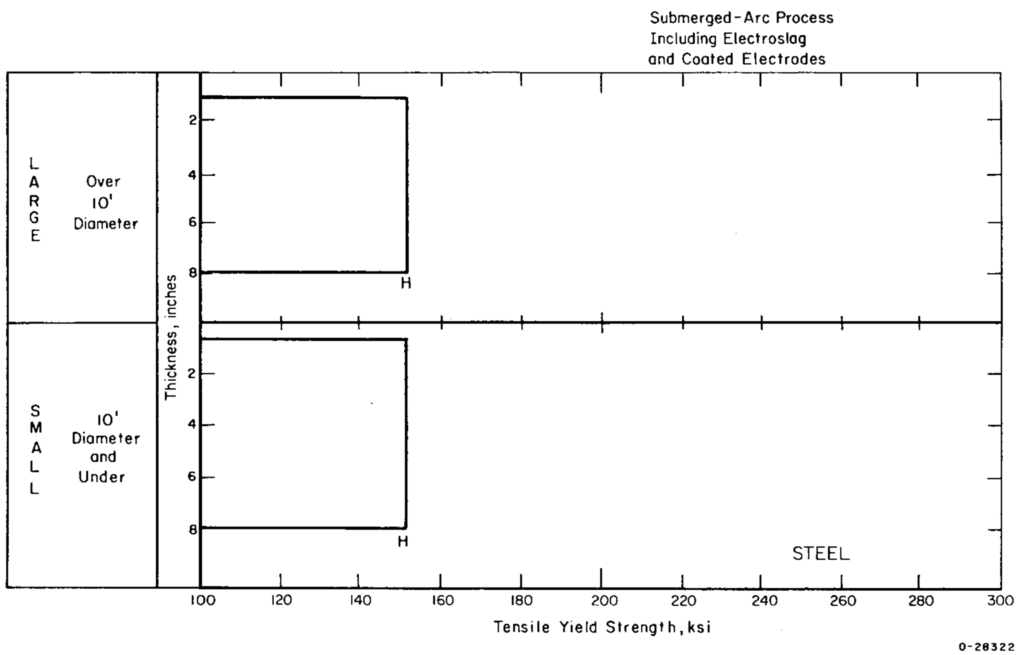

Fig. 6 - Forecast for steels for 1970

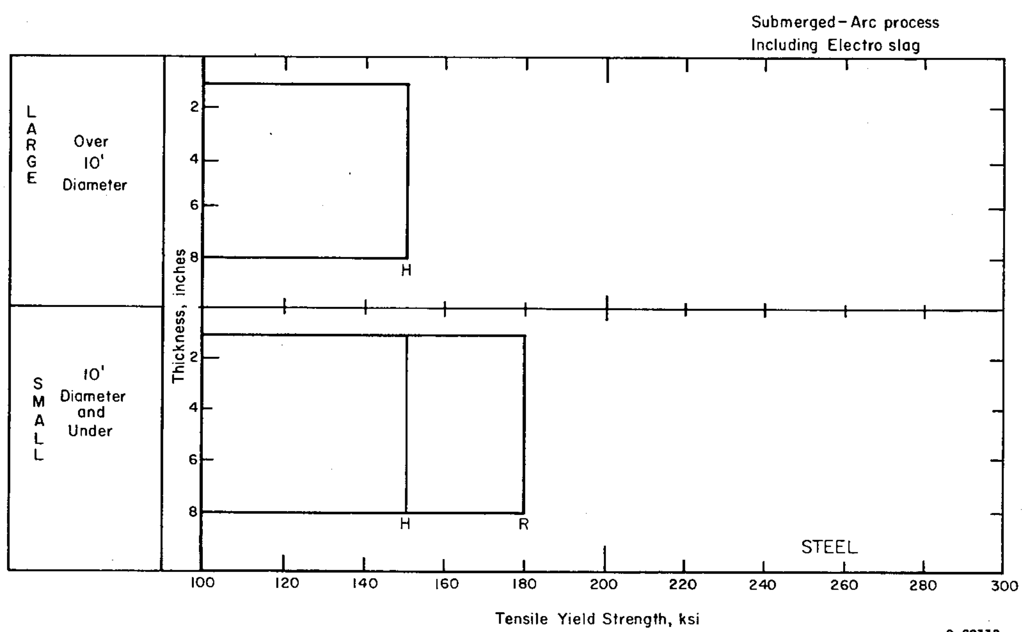

Fig. 7 - Forecast for steels for 1980-1985

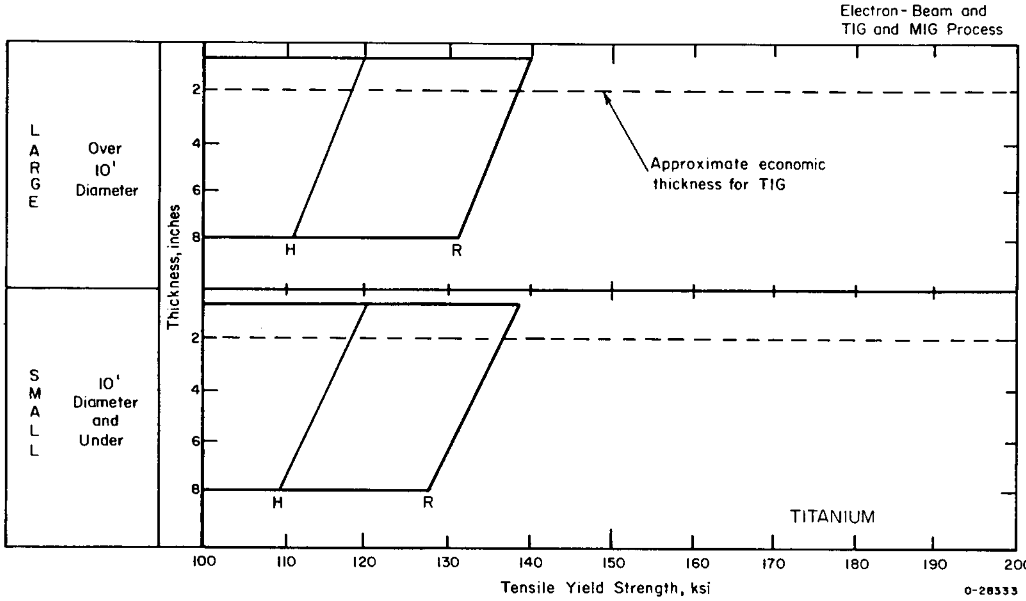

Fig. 8 - Forecast for titanium for 1970

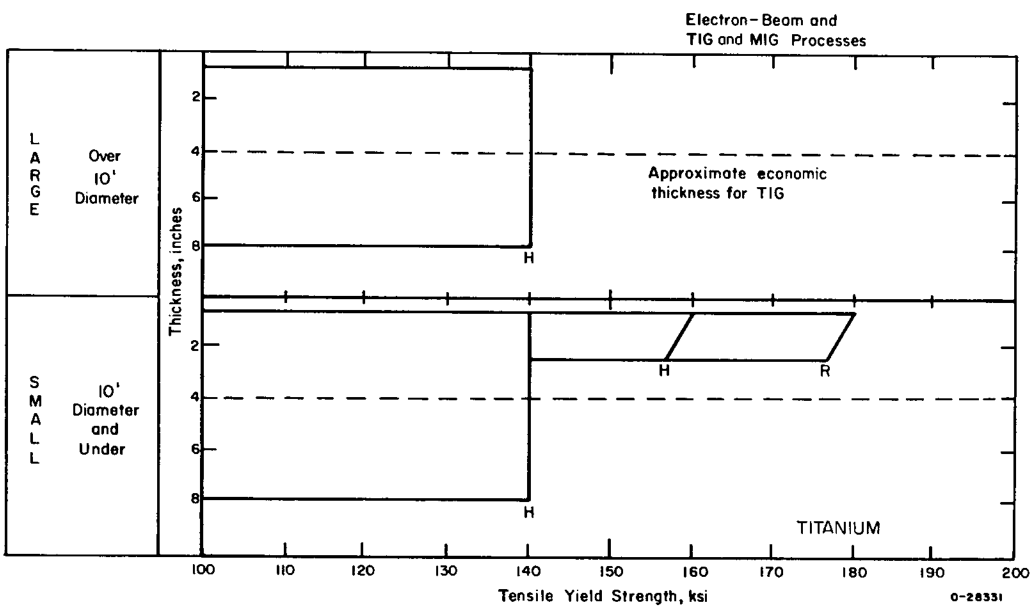

Fig. 9 - Forecast for titanium for 1980-1985

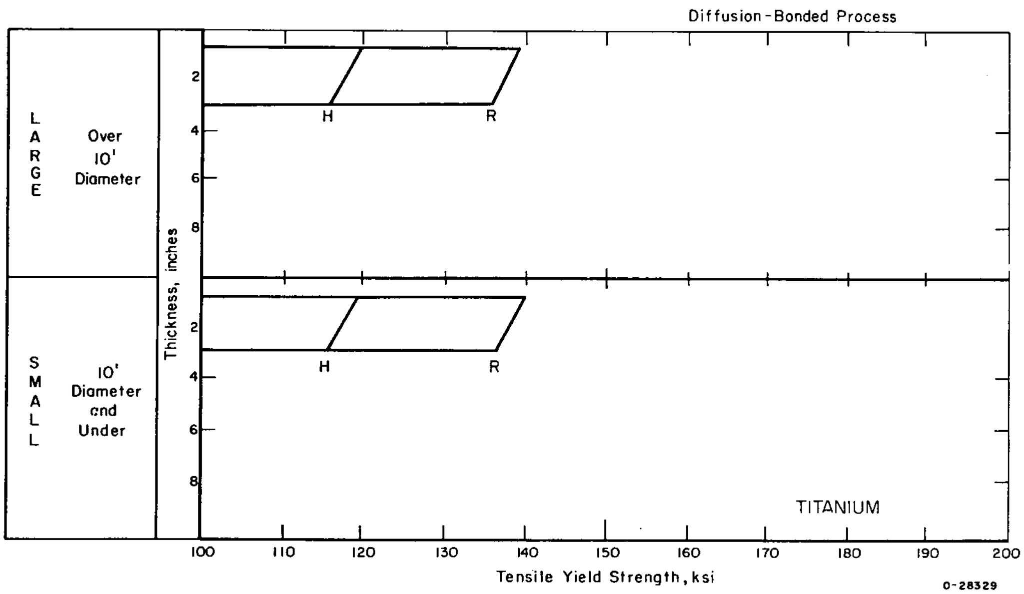

Fig. 10 - Forecast for titanium for 1970

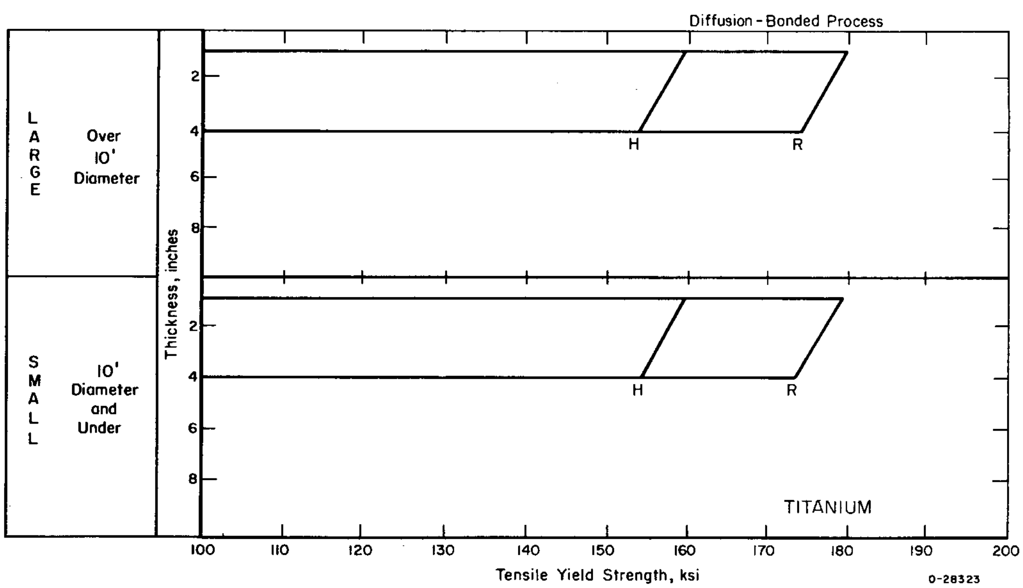

Fig. 11 - Forecast for titanium for 1980-1985

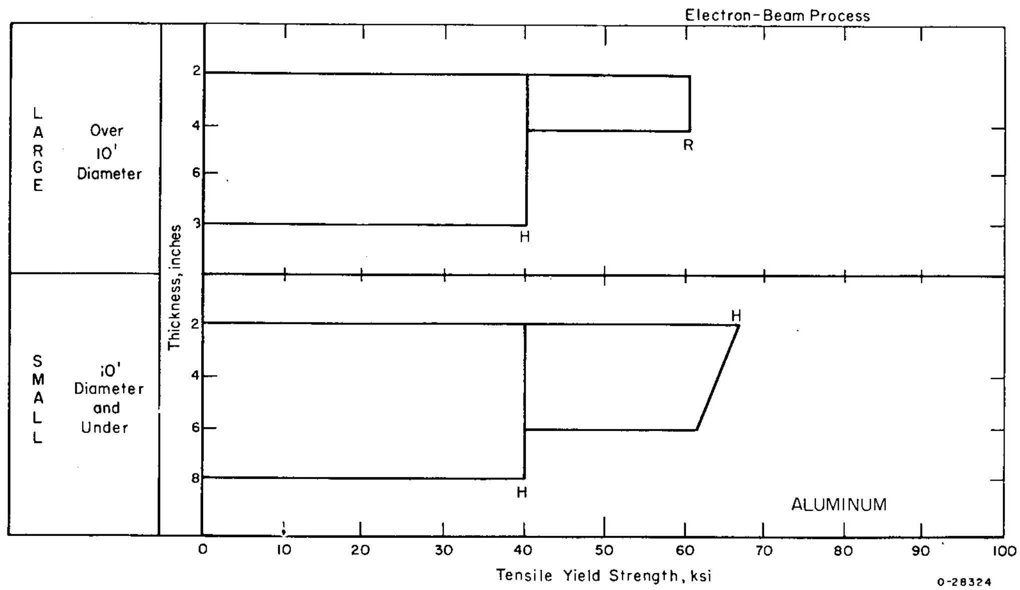

Fig. 12 - Forecast for aluminum for 1970

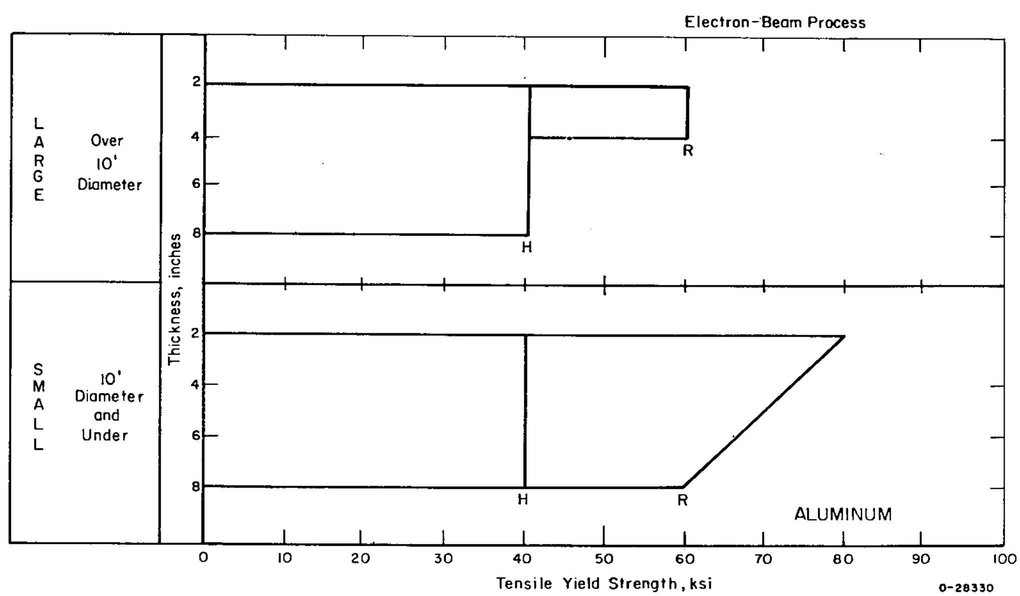

Fig. 13 - Forecast for aluminum for 1980-1985

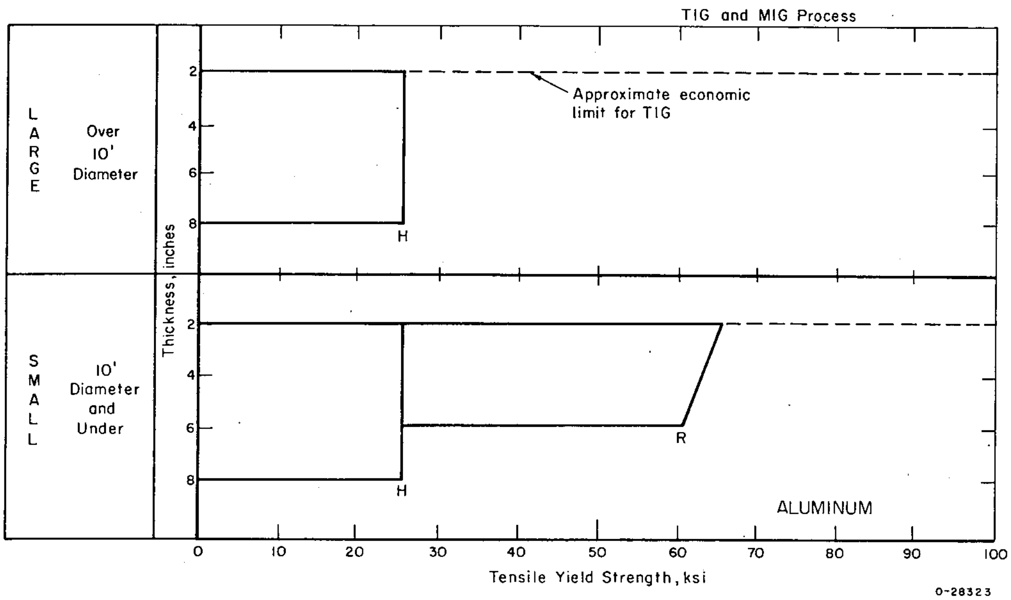

Fig. 14 - Forecast for aluminum for 1970 and for 1980-1985

SPECIFICATIONS

Present welding specifications are not based on objective data. It has been shown that in some cases specifications are too restrictive and in other cases not restrictive enough. As higher strength and unfamiliar materials come into use, specifications will have to become more objective.

Fabrication specifications consist of at least three parts. One, a procedure part which sets forth the permissible ways of fabricating a structure. Two, a performance part which details the tests to be used to qualify the procedures. Three a flaw accept-reject criteria part which sets forth the ways of deciding what flaws are acceptable. The procedure part is generally based on reasonably good information as to what current materials, processes, and techniques will work and produce a satisfactory weldment. The performance part usually uses test techniques which subject the weldment to stresses and strains well beyond what it will see in service. Accept-reject criterion are generally chosen in ignorance of the effect of flaws on service behavior. This ignorance - a result of lack of data - produces criterion which in general are overly conservative but which in some cases prove not to be conservative enough. Too much conservatism leads to excess costs and delays. The other end of the scale leads to disaster.

Two types of unexpected failures must be considered when choosing accept-reject criteria for flaws - catastrophic fracture and fatigue failure. Catastrophic fracture limitations are well known for present materials and fabrication techniques. Methods of experimentally determining fracture behavior for various types of loading have been developed. These have been used to study the effects of flaws. This type of effort must be continued on future materials and as new fabrication techniques are developed. Generally, methods of studying the effects of flaws on fatigue behavior of weldments are well known. Unfortunately, little fatigue data has been produced which can be used to evaluate and choose accept-reject criteria. More research is needed on weldments made with present materials and fabrication techniques and this research must be extended and expanded as new materials and processes are developed and used.

PIPE WELDING

Deep-ocean vehicles will certainly contain piping. Other deep-ocean structures may also contain piping. Since piping in both vehicles and other types of structures may be exposed to sea pressure it is necessary that joints in the piping system be as good in all aspects as other structural joints. All of the processes which have been discussed for fabrication of structures have been at times been used for welding of piping. In present-day submarines pipe joints are made by manual welding with coated electrodes or by brazing. These processes are just acceptable for present-day needs. They will not be usable with the materials of the future and they will not produce the quality of joint which will be needed in the future. It is important that nonmanual techniques for producing pipe joints be developed. It is important also that the designer of piping realize that automatic welding processes have to be used and makes provisions for the insertion of tooling and welding equipment when he is designing the piping.

Three processes appear to be of interest for making joints in piping. First, the inert-gas-shielded processes seem to have the most potential for the pipe-wall thicknesses that are encountered. Two of these processes were not considered at all for structural joints. In present-day piping systems, the manual TIG process is quite suitable. In the future, it should be mechanized. In future piping systems, wall thicknesses will probably increase and in this case it would be well to consider development of automatic MIG processes for welding pipe joints.

A second process that has been used with success on some types of piping is the induction-heated upset-butt-welding process. This process can produce high-quality joints in a wide variety of materials. Useful joints have been produced in mild-steel pipe up to 6 inches in diameter and in copper-base-alloy pipe up to 3 inches in diameter. There is no molten metal involved in making the joint. The process offers good possibilities for development for higher strength pipe materials.

The third process which should be considered for advanced piping systems is friction welding. In essence, this is another upset-butt-welding process, but the energy for bonding is produced by friction between the parts being welded. Normally, one part is rotated against the other to produce required heating. However, this does not have to be done. The necessary heating can be obtained from an oscillating motion of the parts to be joined. A coupling can be rotated or oscillated between the pipe ends to be joined and the necessary heat developed with no motion of the pipe. Normally, it is necessary to have some axial motion of the two pipes to obtain the upset which produces the weld. However, it may even be possible to develop means of eliminating the axial motion.

In some piping systems, it may be necessary to make joints between dissimilar metals. Both upset-butt and friction welding can be used to make dissimilar-metal joints. However, it would be useful to have standard transition fittings for use in dissimilar-pipe systems assembled by arc welding. These fittings could be produced by diffusion bonding, upset-butt welding, or friction welding short pieces of the dissimilar pipe together. The fitting would then be installed with two similar metal-arc welds.

A useful piping composite for sea water systems might be a high-strength, low-corrosion resistance material internally clad with a low-strength, high-corrosion resistance material. Composite pipe made in this way could have a much thinner wall than pipe made only from the corrosion-resistant material. Diffusion bonding offers an excellent method of making composite pipe.

INSPECTION

As the strength of materials and weldments increases, the effects of flaws on the service and failure behavior of structures becomes more important. In high-strength weldments, critical flaws become smaller in size and brittle fracture may be induced by a defect which is not important at lower strength levels. Defects also become more important in influencing fatigue behavior as strength increases. Unfortunately, plate thicknesses will also increase as strengths go up. This will make it more and more difficult to inspect weldments using present-day inspection techniques. The thicker plate will require higher power radiation source and longer times. This will lead to increased safety hazards and increased down time for inspection. Delayed cracking may become more of a problem as strength increases and it will be necessary to be able to inspect for this type of flaw.

Evaluation of presently available inspection techniques indicates that ultrasonic inspection offers the best chance for developing a high reliability, high speed system for deep-ocean structures. Ultrasonic inspection today is used on parts with thicknesses of the order of those that are visualized being needed in the future. The major problem is to develop techniques for applying ultrasonic inspection to complex parts such as those that will no doubt be encountered in deep-ocean structures. It will also be necessary to develop recording techniques to make permanent inspection records available for this inspection process.

LOW-CYCLE FATIGUE OF MATERIALS (LABORATORY INVESTIGATIONS)

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INTRODUCTION

To accomplish their mission successfully, it is desirable if not mandatory, that deep submergence vehicles be designed to a minimum hull-weight to displacement-weight ratio consistent with predescribed risk limitations. Present design procedures incorporated yield strength as the controlling material property. This approach is based on experience and tests which have shown that plastic instability is the primary mode of failure of externally pressurized ring-stiffened structures fabricated of steels having 100,000 psi yield strength and less. On the basis of this design approach, the maximum permissible depth excursion for a given hull weight will be proportional to the yield-strength to weight ratio of the material. Accordingly, much emphasis is currently being placed on the development and utilization of materials of high strength-to-weight ratio.

Questions arise as to whether other material properties such as fatigue, stress-corrosion, fracture toughness, ductility, etc., may not become important and perhaps controlling factors in the life of structures with high strength-to-weight ratios. It is the purpose of this phase of the report to discuss the fatigue phenomenon in somewhat general terms to point out the complexity of the problem and the various factors which influence it.

The ASM Metals Handbook (1) defines fatigue as the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of the fluctuating stress. By definition, fatigue failure represents malfunction after the application of two or more stress cycles. The fluctuating stress may be the result of changing loads, pressures, or thermal gradients. In underwater vehicles, the primary source of stress is the pressure of sea water acting on pressure-resistant hull structures and on all internal systems openly connected to the sea. Fluctuation of the stresses is caused by the lowering, raising, and maneuvering of the vehicles to various ocean depths.

The majority of engineering problems involving fatigue are concerned with adequate life under many millions of stress cycles; for example, rotating shafting, antifriction bearings, gears, turbine blades, etc. Essentially the approach to such problems is to design for infinite life, and over the years designers have developed adequate design procedures based on elastic theory and empirical data. As one might expect, the infinite life approach exacts a penalty, especially in weight, when only short or finite fatigue life is required.

It is apparent that the pressure fluctuations imposed upon deep submergence structures will be finite in number. A bottom-based structure may require ten or less depth excursions during its lifetime, whereas a combatant submarine may be expected to undergo an equivalent of several thousand dives to operating depth during its lifetime. In subsequent sections, we will frequently use the terms "low-cycle" and "high-cycle" fatigue. Generally speaking, 10^5 cycles to failure represents the dividing line between these two terms.

SUMMARY OF INFORMATION

Over 95% of our knowledge of the fatigue behavior of materials has developed from laboratory tests of relatively simple test specimens. Some 200 laboratories in the United States are engaged in fatigue studies. The number outside the United States is estimated to be even larger. It can be assumed that nearly all of these laboratories are generating specimen data of one form or another.

In spite of all the information developed, the fatigue behavior of materials is not completely understood. The following paragraphs briefly describe the effects of various factors on the fatigue behavior of metals. As will be seen, the subject is highly complex and, to a great extent, continues to remain empirical in nature.

All of the results presented in this report have been obtained from flexural tests of round and flat cantilever type specimens. The criterion for failure in the low-cycle fatigue tests was the initiation of one or more 3/16" to 1/4" long cracks in the test section of flat specimens. The criterion for failure of the high cycle fatigue tests was complete fracture of round specimens. The difference between crack initiation and complete fracture in the high cycle tests is minimized by the log-log diagrams used in presenting the data.

STATIC STRESS AND STRAIN

For the most part, engineering structures are designed on the basis of stress. The use of stress normally implies elastic behavior of the materials and conformance to elastic theory. Figure 1 is an ordinary stress-strain diagram for a metal showing general yielding at stresses above the proportional limit. This diagram is typical of HY-80 and higher strength steels and most nonferrous alloys. At Point A, stress and strain are proportional, and the theory of elasticity holds. At Points B and C, however, plastic deformation has occurred and stress is no longer proportional to strain. The stress at Point A is a true stress. The stresses at Points B and C may be nominal or true stresses depending upon whether the initial or instantaneous cross-sectional area was used in the stress calculation. Most engineering design calculations are based on nominal stress. Under these conditions, the stress is calculated from the applied loads on the basis of elastic theory even though the material may have undergone changes in shape and/or dimensions.

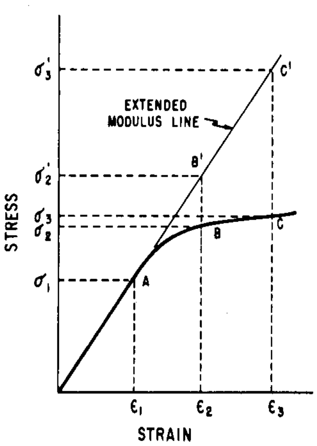


Fig. 1 - Stress-strain diagram

Low-cycle fatigue failure of many metals entails plastic deformation during the loading and unloading cycles. Under these conditions, true stresses are not calculable by elastic theory, and plastic theory is not sufficiently advanced to handle such problems. It is easier, therefore, to control and analyze low-cycle fatigue studies on the basis of strain rather than stress. In this connection, strain is frequently handled as an apparent or pseudo-stress wherein stress is the product of strain and Young's modulus. These stresses are shown as σ_2' and σ_3' in Fig. 1.

CYCLIC STRESS AND STRAIN

The stress-strain diagram shown in Fig. 1 is typical for a metal loaded statically either in tension or compression. Figure 2, on the other hand, shows the stress-strain relationships likely to develop under cyclic loading conditions. The relationship in 2(a) occurs when the applied force or moment is completely reversed but within the elastic

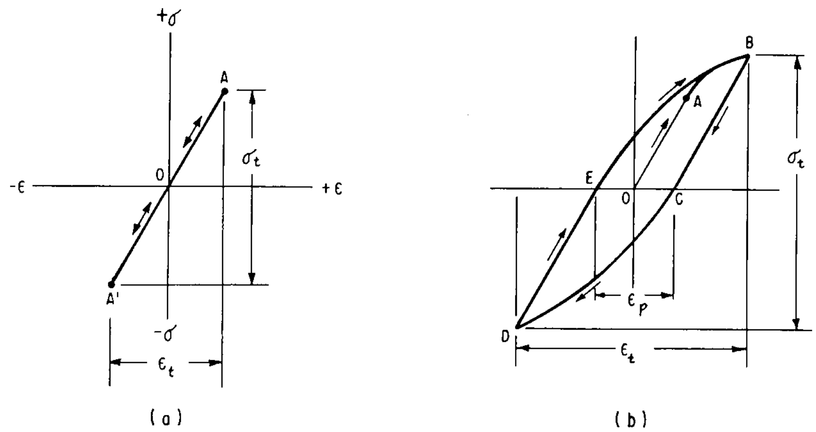


Fig. 2 - Stress-strain relationships under cyclic loading

region. σ_t is the total stress range and ϵ_t is the total strain range. Figure 2(a) shows the relationship that develops under reversed loading into the plastic region. The stress-strain relationship is no longer linear but follows the hysteresis loop BCDEB during each cycle. σ_t is the total stress range but in this instance may be nominal or true as mentioned previously. The total strain range, ϵ_t, consists of two parts: (1) the elastic strain range, ϵ_e, and (2) the plastic strain range, ϵ_p, where $\epsilon_t = \epsilon_p + \epsilon_e$. Reference will be made to the parameters of Fig. 2(b) in subsequent discussions.

S-N RELATIONSHIPS

High-cycle fatigue results are normally presented in the form of S-N diagrams similar to that shown in Fig. 3. Inasmuch as the cyclic stresses required for failure in the high-cycle region are well within the elastic region (Fig. 2(a)), it is unimportant whether we use stress or strain as the independent variable.

This is not the case for low-cycle fatigue. The preponderance of evidence developed over the past 10 years has demonstrated that strain becomes the dominant factor with decreasing fatigue life. Figure 4 shows the low-cycle fatigue results (2) obtained for unnotched (smooth) specimens by the U.S. Navy Marine Engineering Laboratory. The yield strength of the steels ranges from 41,000 to 230,000 psi. The plot is on the basis of total strain range versus cycles to failure. Noteworthy is the similarity of behavior irrespective of yield strength. Of even greater significance is the fact that the behavior appears to be independent of material as shown in Fig. 5. One would conclude from these observations that if strain is the controlling factor in low-cycle fatigue, then it would make little or no difference as to the strength or type of the structural metal used. Recent tests at SWR for PVRC (3) on pressure vessels tend to support this view for steels having yield strengths ranging from 30,000 to 90,000 psi. However, it is well known that high-cycle fatigue strength of materials varying in strength level are markedly different. Accordingly, the relationships shown appear to be valid only in the restricted range of 100 to 10,000 cycles. In

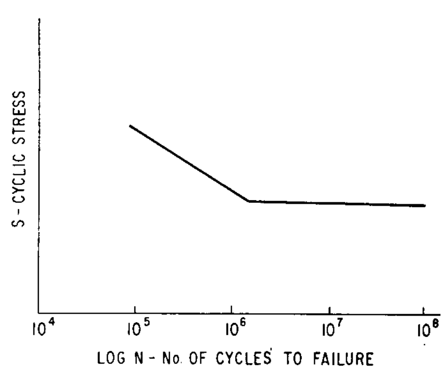


Fig. 3 - Typical high-cycle S-N diagram

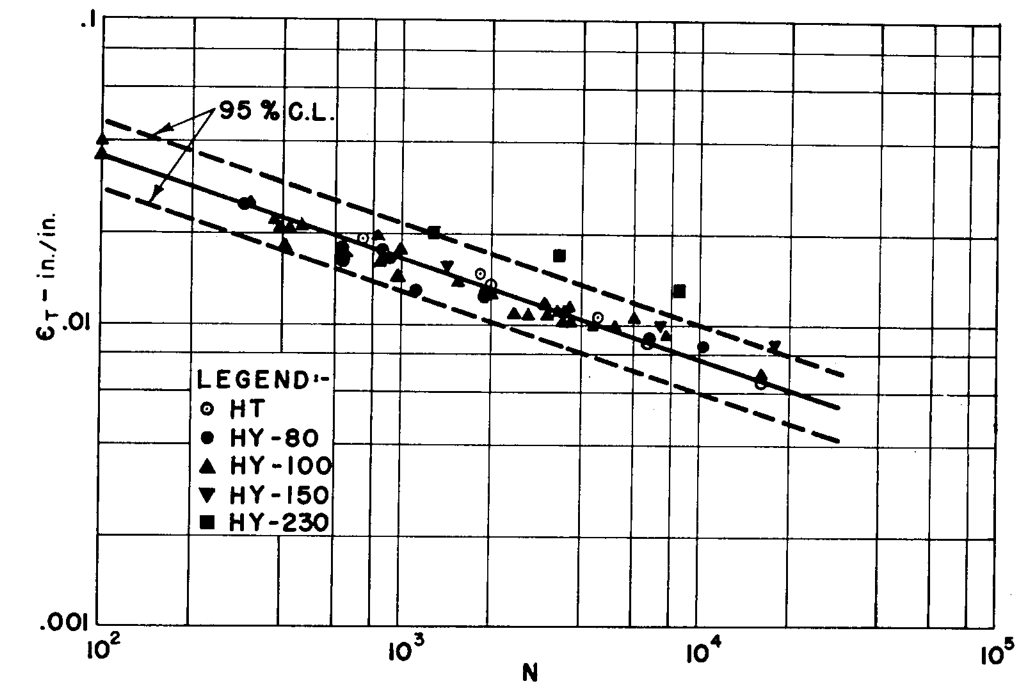


Fig. 4 - Total strain range vs cycles to failure for steels in air

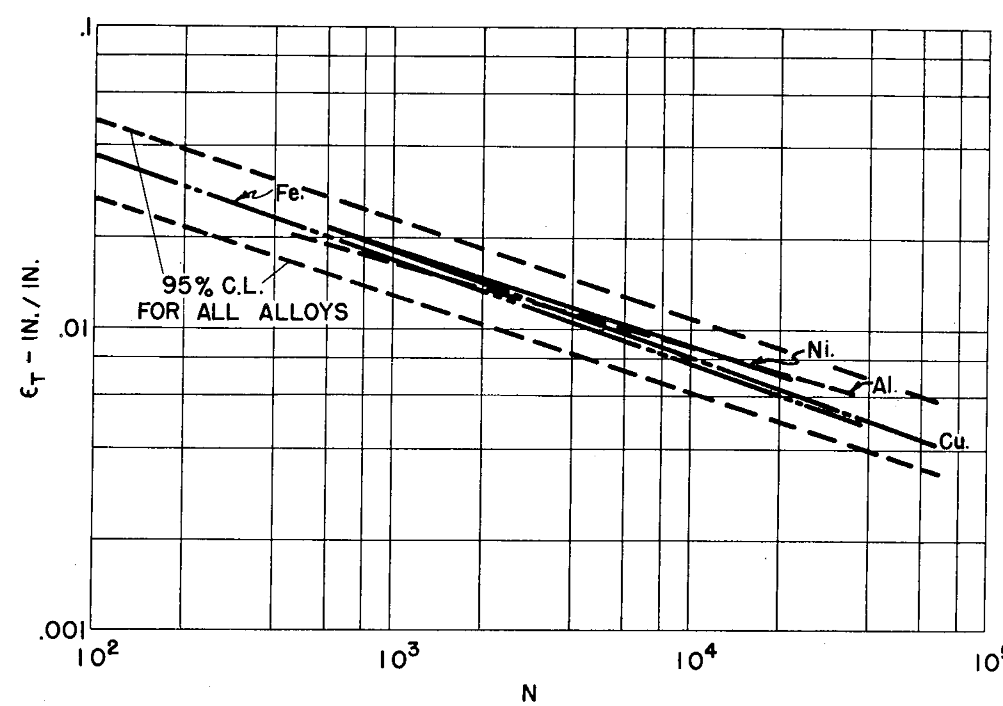


Fig. 5 - Total strain range vs cycles to failure for alloys in air

fact, divergence from the relationship is apparent for the HY-230 steel in Fig. 4. MEL's current thinking on this matter is shown in Fig. 6 for three steels of markedly different yield strength. Figure 7 schematically shows the relationship for one material. For the case shown, the material follows a relationship common to all materials in the range of 100 to 10,000 cycles to failure. Above 10,000 cycles, the material follows an all-elastic relationship leading to high-cycle endurance strain. One could conjecture, from Fig. 7, that the transition point from elastic to inelastic behavior should bear some direct relation to the proportional limit or yield strains obtained from a monotonic tensile test. The data obtained thus far, however, does not bear this out at all strength levels.

Figure 6 is encouraging in one respect but discouraging in another. Advantages for materials at high yield strength are apparent above 1000 cycles. On the other hand, for a given cycle life greater than 1000, say 10,000, the relationship indicates that the high yield-strength materials can suffer low-cycle fatigue failure while apparently being cycled elastically. This has actually occurred in tests of HY-230 steel and certain aluminum alloys. In general, MEL's observations tend to support those of Manson and Hirschberg (4).

STRESS CONCENTRATION

The localized concentration of stress (or strain) by geometric discontinuities such as cracks, notches, fillets, holes, surface imperfections, etc., constitutes by far the most deleterious factor affecting the fatigue life of metals. The ability of a discontinuity to concentrate stress is dependent upon its shape and size. Cracks have the highest stress concentrating effect whereas generous fillets with a smooth, polished surface have the lowest. Analytical methods have been developed for calculating the stress concentrating effects of discontinuities based on geometry, dimensions, and assumed elastic behavior. The effect arrived at in this manner is called the theoretical stress concentration factor (K_t). However, the actual effect of a given stress concentration may vary both within and among materials. By means of tests, it is possible to establish the reduction in fatigue strength caused by a particular stress concentration factor for a particular material at a particular strength level. By comparing these data with unnotched (smooth) test data, one can arrive at the so-called fatigue strength reduction factor (K_f). From K_t and K_f the notch sensitivity index (q) of the material can be calculated as follows:

$$q = \frac{K_f - 1}{K_t - 1} .$$

For most metals the notch sensitivity tends to increase with increasing strength. Thus, in the presence of sharp notches ($K_t \approx 3$), it is not unusual to find little or no advantage in fatigue strength for high-strength materials.

Figure 8 shows notch data ($K_t \approx 3$) obtained on three steels of varying strength levels. Superimposed on this data are the unnotched relationships of Fig. 6. The detrimental effects of stress concentration on both fatigue strength and fatigue life are obvious.

MAXIMUM AND MEAN STRESSES

The maximum tension stress or strain developed in the cycle has an important bearing on fatigue life. The results discussed thus far have been based on completely reversed (equal tension and compression) cyclic stress or strain independent of any steady state conditions. This is the exception rather than the rule. Most practical applications results in stress-time patterns of the type is shown in Fig. 9. It is apparent that if the maximum and minimum stresses are known, then all constant stress amplitude problems can be resolved into mean stress and alternating stress components. The interrelationship

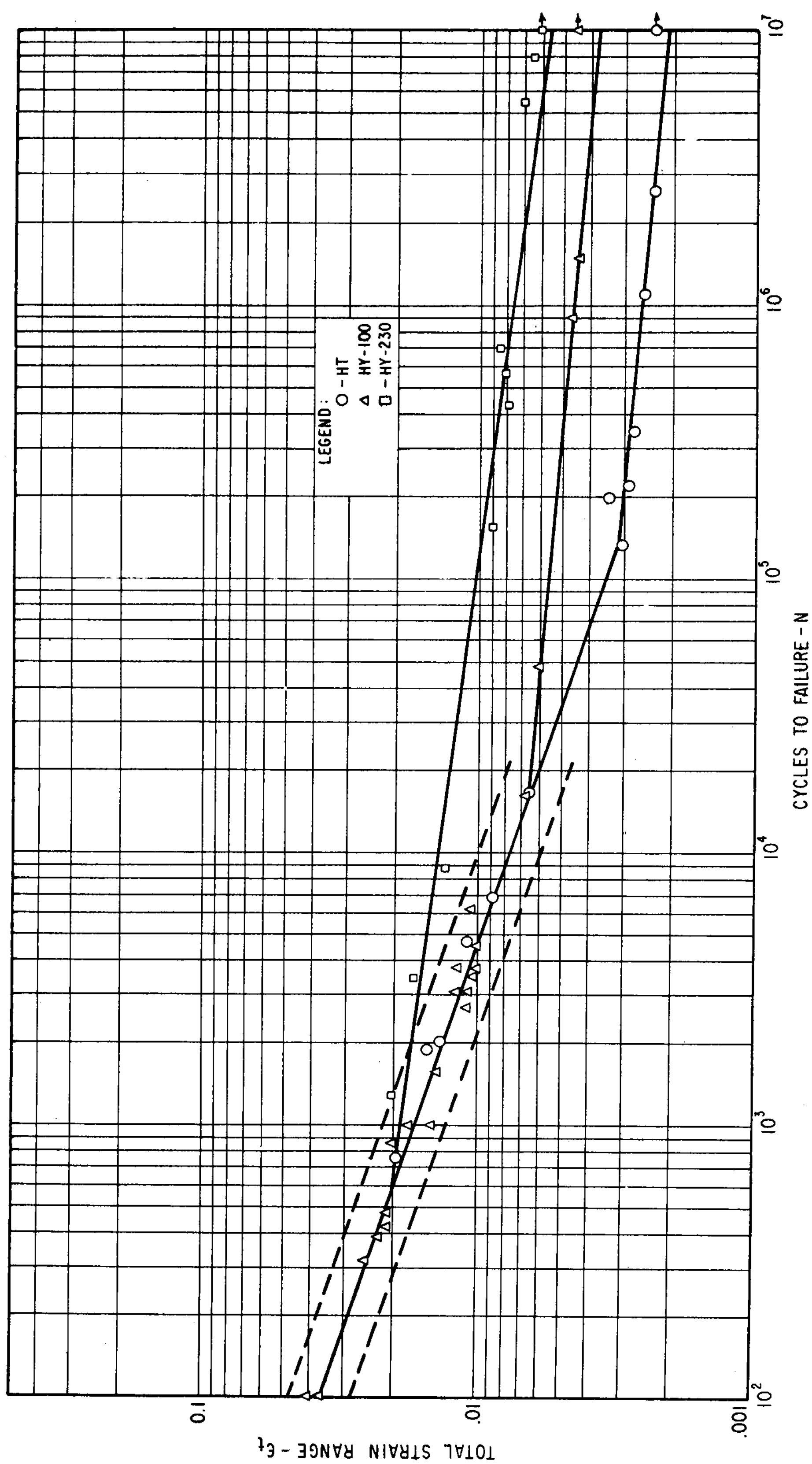


Fig. 6 - Fatigue relationships for steels (completely reversed strain)

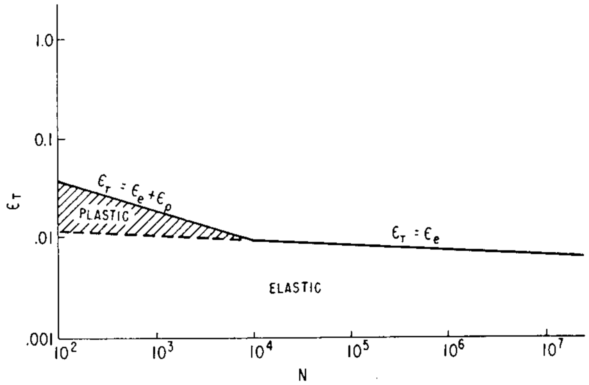


Fig. 7 - Schematic log-log strain-cycle relationship

between these two components and fatigue life is too complex for this limited discussion. It can be said, however, that in the high-cycle region, the permissible alternating stress decreases with increasing mean stress. Furthermore, through the use of mathematical or diagrammatical relationships, it is possible to convert the stress conditions shown in Fig. 9, to an equivalent, completely reversed, stress condition. Figure 10 shows one such diagrammatical relationship for axial tests of HY-80 steel plate.

It is important to recognize that maximum stress controls the whole course of events. If the maximum stress equals or exceeds the yield strength, the mean stress is decreased and a new set of conditions come into play. Factors most likely to alter the mean stress are stress concentrations and residual stresses.

The influence of mean stress decreases with decreasing fatigue life, and when the alternating stress equals or exceeds the yield strength, the mean stress becomes zero. Accordingly, whether or not mean stress is an important factor in low-cycle fatigue depends upon the strength level of the material. Figure 6 indicates that mean stress must be given consideration in high strength materials at fatigue lives ranging down to 100 cycles.

RESIDUAL STRESSES

The effect of residual stresses on fatigue can be considered to be identical to that of mean stresses. Unlike mean stresses, however, residual stresses are not anticipated or calculable from the applied loads or forces. Residual stresses are balanced internally and have their origin principally from heat treatment, welding, misfits, cold deformation, and stress concentrations.

The means for detecting and measuring residual stresses leave much to be desired. Two techniques have general application: the X-ray and mechanical methods. The X-ray method is nondestructive but has not been developed to the point of being practical for general on-site use. All of the mechanical methods are destructive in nature; some totally, others partially. DATMOBAS (5) has recently evaluated a hole-drilling method and has found it to be of acceptable accuracy. How successfully it can be applied to critical areas in complex structures has yet to be established.

Assuming that the residual stress can be determined or reasonably estimated at the point of interest, then the total stress to be considered for fatigue will be the combined

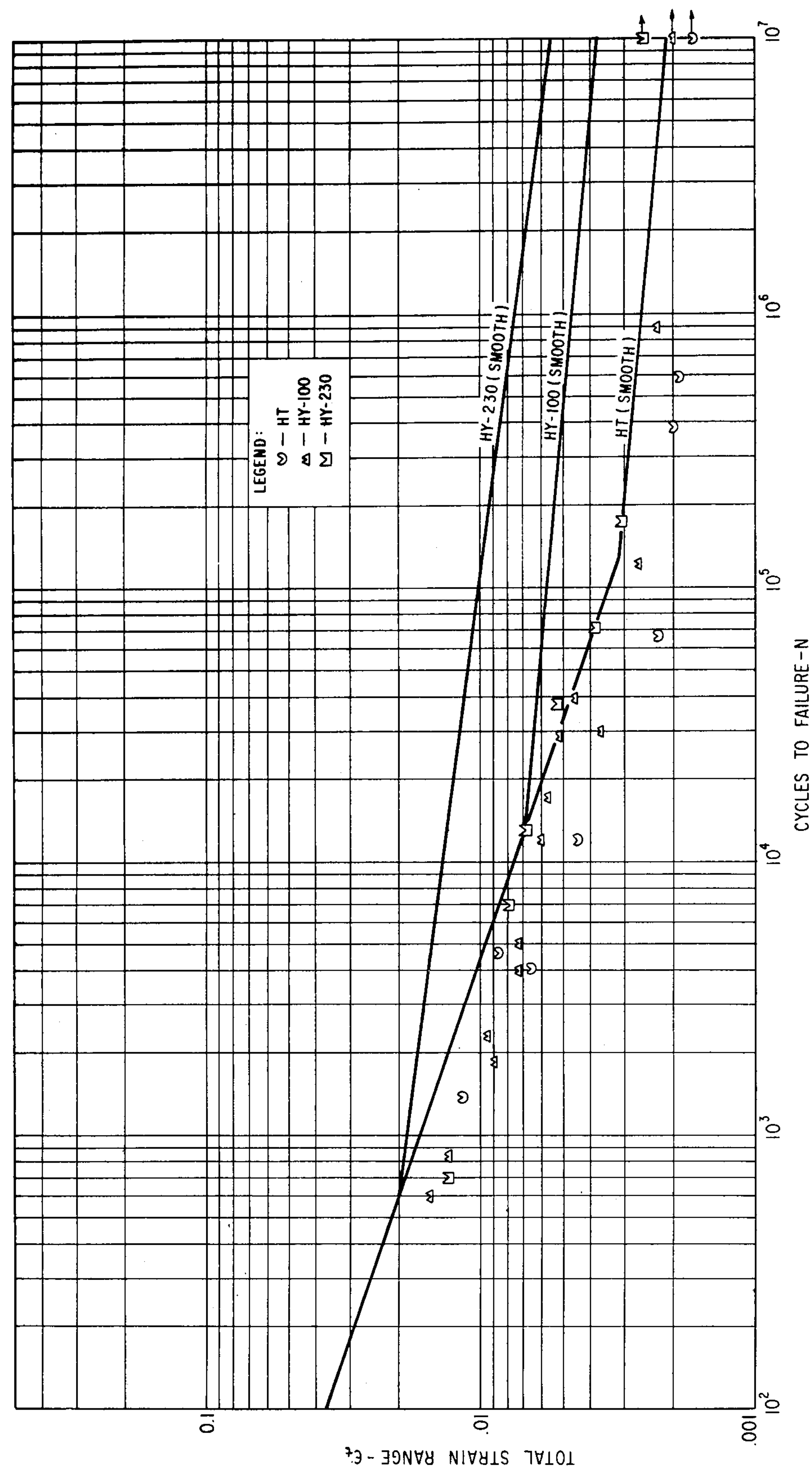
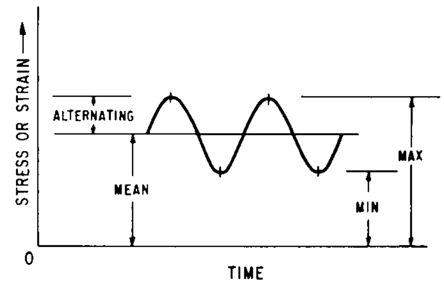


Fig. 8 - Effect of notches ($K_t \approx 3$) on low-cycle fatigue of steel (completely reversed strain)

Fig. 9 - Cyclic stress or strain vs time pattern



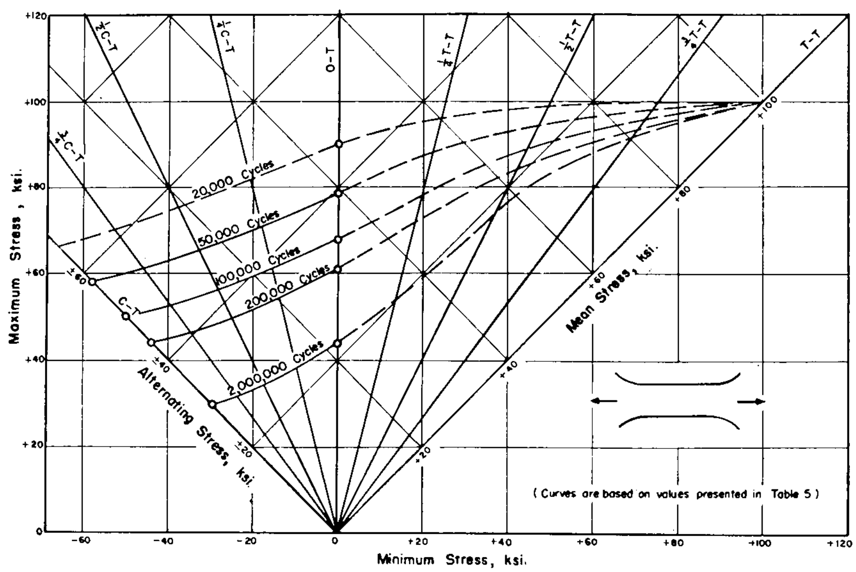


Fig. 10 - Modified Goodman diagram for as-rolled HY-80 plate

residual and applied state of stress. If this combined state of stress exceeds the condition of yielding, then an adjustment in residual stress will occur. Accordingly, the residual stresses affecting fatigue life will be those present after shakedown.

It is possible to relieve unfavorable residual stresses in metals by a so-called stress-relieving heat treatment and thus improve their fatigue resistance. This treatment requires that the materials be heated to elevated temperatures. The applicability of the stress-relieving treatment is limited by facilities for handling large size structures and by the fact that the temperature required for stress relief may have a detrimental affect on other properties such a yield strength and impact resistance.

SURFACE COLD WORKING

Surface cold working, as used here, implies cold deformation of the metal surface by stressing techniques such as hammer peening, shot peening, and cold rolling.

The major benefit of cold working is derived from the development of a compressively stressed metal layer. This layer either prevents initiation or delays or stops crack propagation. Accordingly, such a layer can be beneficial against the deleterious effects of fatigue, corrosion-fatigue, stress-corrosion, and frettage-corrosion.

In order to produce the desired effects, it is necessary that the stressing technique plastically deform the surface layers of the metal. It is estimated that 80% of the improvement in fatigue resistance is due to favorable residual stress development and 20% to physical change of the surface metal. Thus, the previous comments on the effects of "Residual Stresses" are pertinent to this discussion.

The benefits in fatigue of surface cold working tend to decrease with (a) increasing yield strength and (b) decreasing fatigue life. The decrease with increasing yield strength is probably threefold: (a) the higher forces required to deform the surface metal result in a shallower layer, (b) the notch sensitivity of both the deformed and undeformed metal is higher, and (c) the higher yield strength to tensile strength ratio of the high strength material is subject to stressing-technique-induced cracks.

The extent of the beneficial effects of cold deformation on low-cycle fatigue over a range of strength levels have yet to be established. Considerable effort will be directed to this area in the future. Caution, however, is advised in considering cold deformation as the panacea for fatigue and stress corrosion problems. Normally, the stressing techniques are most helpful in marginal situations and tend to get you over the "hump" so to speak. They should not be a substitute for poor design or improper material selection. Furthermore, the techniques to be effective must be closely controlled inasmuch as overworking (excessive force) or unintentional notching (poor tool surface or broken shot) can be disastrous. Also, accessibility to critical locations in complex structures may present a difficult problem.

CORROSION

The combined effect of salt water corrosion and cyclic stressing can be highly detrimental to the fatigue life of metals. This is particularly true in the case of ferrous materials wherein the high-cycle, corrosion-fatigue strength is about the same regardless of the strength of the metal. In general, the effect of corrosion on low-cycle fatigue strength appears to be similar to that of notches. Corrosion, however, is a time-dependent phenomenon, and therefore, the rate of cycling must be considered.

Figure 11 shows low-cycle, corrosion-fatigue data obtained for HY-100 steel at cycle rates differing by a factor of 360. It is apparent that in this case the rate of cycling had little effect over the range of 1000 to 10,000 cycles to failure. Analysis of the data in Fig. 10 showed that below 10,000 cycles, corrosion caused a general but statistically insignificant decrease in the fatigue life of HY-100. Above 10,000 cycles, corrosion becomes increasingly important. One would also conclude that, for ferrous materials, the importance of corrosion in low-cycle fatigue will increase with increasing strength as in the case of notches (Fig. 8).

Considerable more work needs to be done to establish how serious a factor corrosion is in low-cycle fatigue. Currently, low-cycle corrosion-fatigue studies are under way at MEL on HY-100, HY-150, and maraging steels in the notched and unnotched conditions. NRL is also studying the effect of environment on the rate of crack propagation.

CRACK PROPAGATION

The rate at which a crack grows will determine the life of a structure in which failure is defined as something other than crack initiation. It is almost certain that cracks either

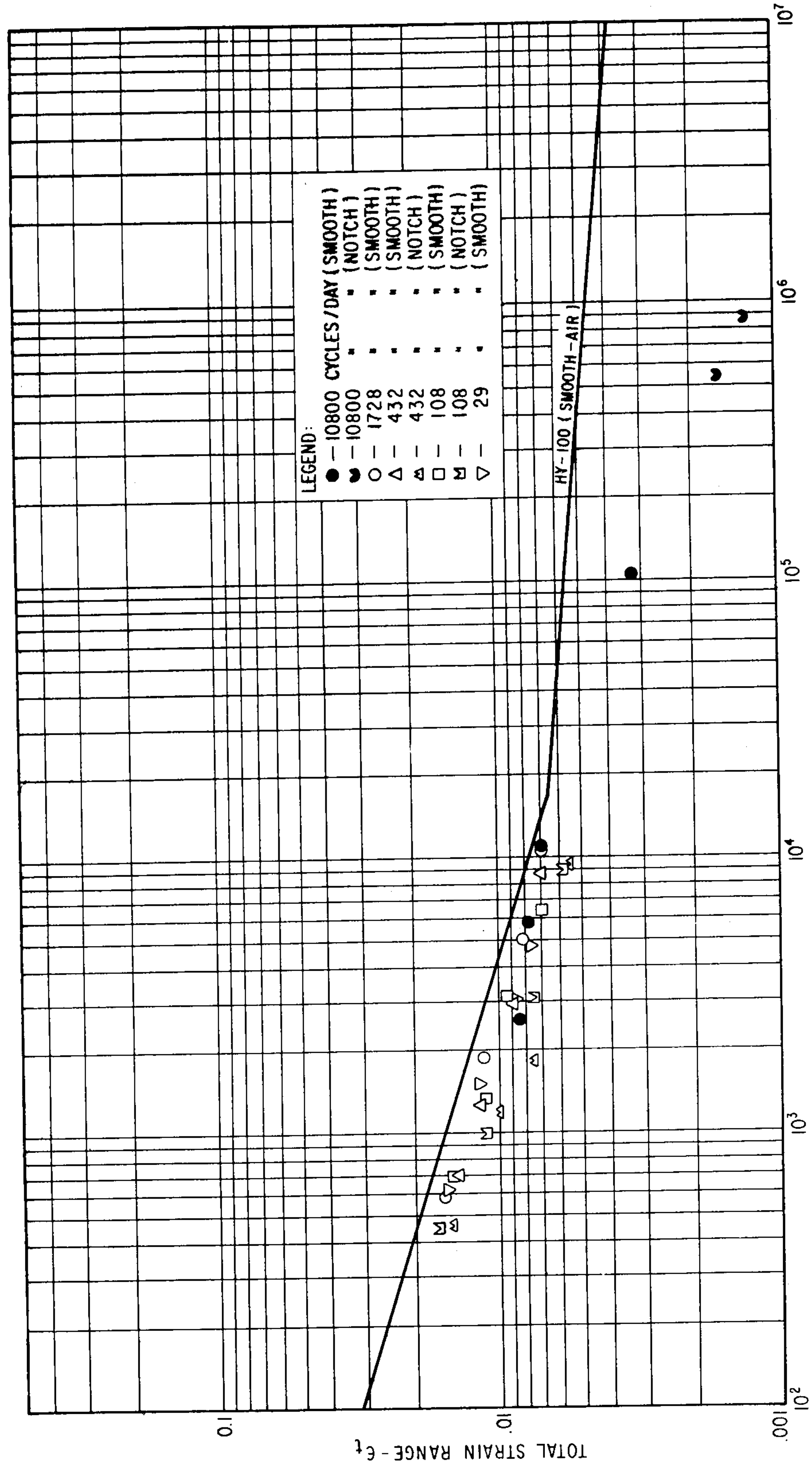


Fig. 11 - Low-cycle corrosion fatigue of HY-100 steel (smooth and notched specimens in salt water)

will be initially present or will develop in the highly stressed locations of complex structures subjected to low-cycle fatigue. Accordingly, there should be a distinct advantage for materials having low crack-growth rates.

NRL has been studying this problem for several years. Recent studies (6) point to total strain range as a singularly important factor in affecting the growth rates of low-cycle fatigue cracks. The relationship shown in Fig. 12 indicates that the crack growth rate is proportional to the fourth power of the total strain range for quenched and tempered steels. Whether or not other materials conform to this relationship has yet to be determined. If Fig. 12 is correct, then all materials, regardless of strength, will have essentially the same resistance to the growth of low-cycle fatigue cracks. The advantage of a high-strength material would lie in its ability to support larger stresses in the low strain, elastic region.

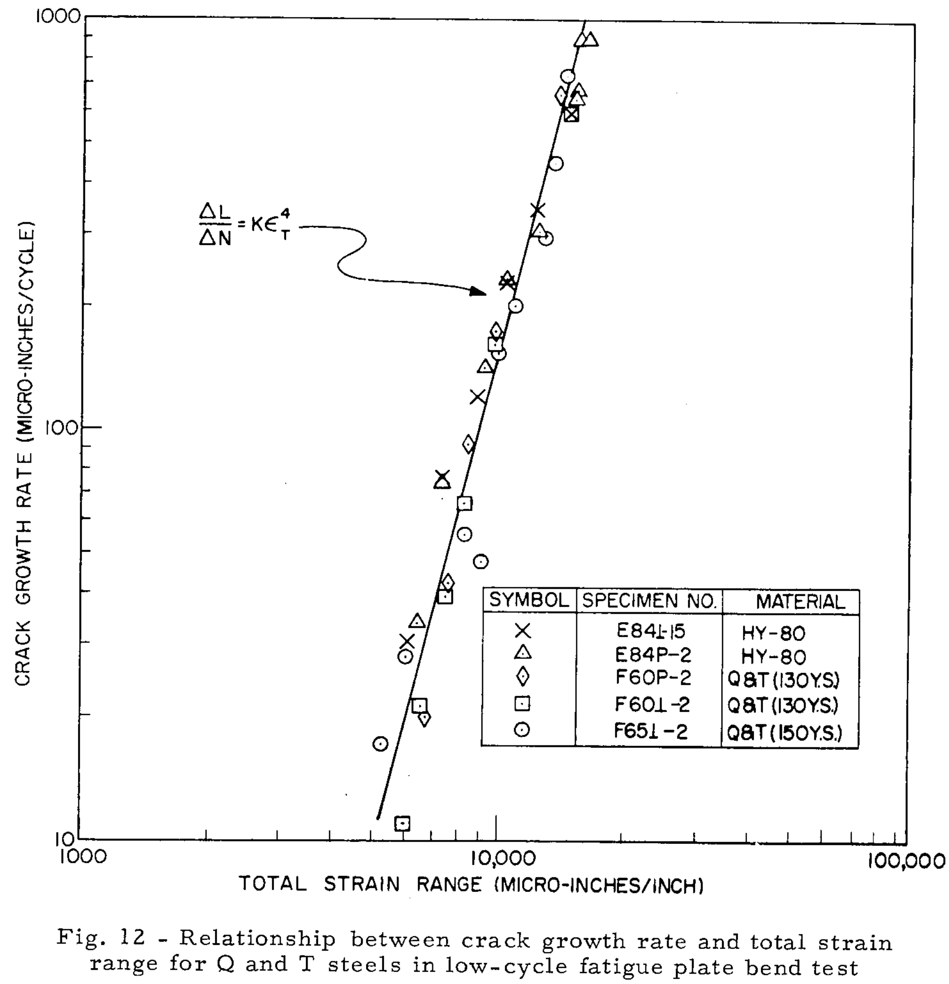


Fig. 12 - Relationship between crack growth rate and total strain range for Q and T steels in low-cycle fatigue plate bend test

OTHER FACTORS

The foregoing sections have discussed many of the important factors which affect low-cycle fatigue behavior. Other factors which may have importance are cumulative damage, prestressing, metallurgical structures, weldments, creep, temperature, surface finish, surface protection, size and stress state. Scatter in expected life also deserves mention. The scatter experienced in low-cycle fatigue is considerably less than in high-cycle fatigue. It is not unusual, however, to observe variations in low-cycle fatigue life by a factor of five or more.

COMPARISON OF MATERIALS

Figure 13 compares the fatigue strength in air of seven alloys on an equivalent weight basis. The alloys are compared on the basis of (a) pseudo-elastic stress (Fig. 13a) and (b) nominal stress (Fig. 13b). Results are given for both unnotched (smooth) and notched specimens at three different life levels. The location of the yield stress is shown for each case.

The pseudo-elastic stress comparison (Fig. 13), in reality compares the material on the basis of total strain. This has been discussed previously under "Static Stress and Strain." On this basis there is little or no advantage of one material over another regardless of yield-strength level for 1000 cycles to failure. At 10,000 and 100,000 cycles unnotched high strength steels and titanium alloys show a distinct advantage because of the divergence discussed under "S-N Relationships." In the presence of sharp notches ($K_t \approx 3$), all of the materials are quite similar, regardless of life level.

The nominal stress comparison (Fig. 13b), shows an advantage for higher yield strength material at all life levels. Particularly important in all of the comparisons is that the gain in fatigue strength is not commensurate with increased yield strength.

The question arises as to which, if either, of the two bases of comparison in Fig. 13 is correct, i.e., does a complex structure behave in accordance with 13a or 13b? MEL currently has this question under study (7). It is apparent that the answer will be of increasing importance with decreasing fatigue life.

OTHER MATERIALS

The previous discussion concerned the behavior of metals likely to be used for pressure resistant hull structures. A lesser, but substantial, amount of low-cycle fatigue data has been generated on nickel and copper base alloys for use in sea water connected piping systems and equipments.

Extensive fatigue testing is also under way on nonmetallic materials such as GRP. The results of these studies are presented and discussed in other reports. It is of interest to note, however, that low-cycle fatigue strength is a controlling strength factor in GRP materials.

CONCLUSIONS AND COMMENTS

The low-cycle fatigue behavior of materials is dictated by many factors, the importance of which may vary depending on the life region of interest. Stress raisers such as cracks, notches, fillets, holes, surface imperfections, etc., are by far the most damaging. The effect of corrosion in iron base alloys appears to be similar to that of sharp notches. Residual stresses may be either beneficial or harmful depending upon (a) their magnitude, (b) whether they are tensile or compressive, and (c) the associated stress fields. Highly compressive residual surface stresses are usually beneficial in fatigue. Such stresses can be developed by surface stressing techniques such as hammer peening, shot peening, and cold rolling. However, the effects derived from these techniques are highly variable and to be effective require rigid control.

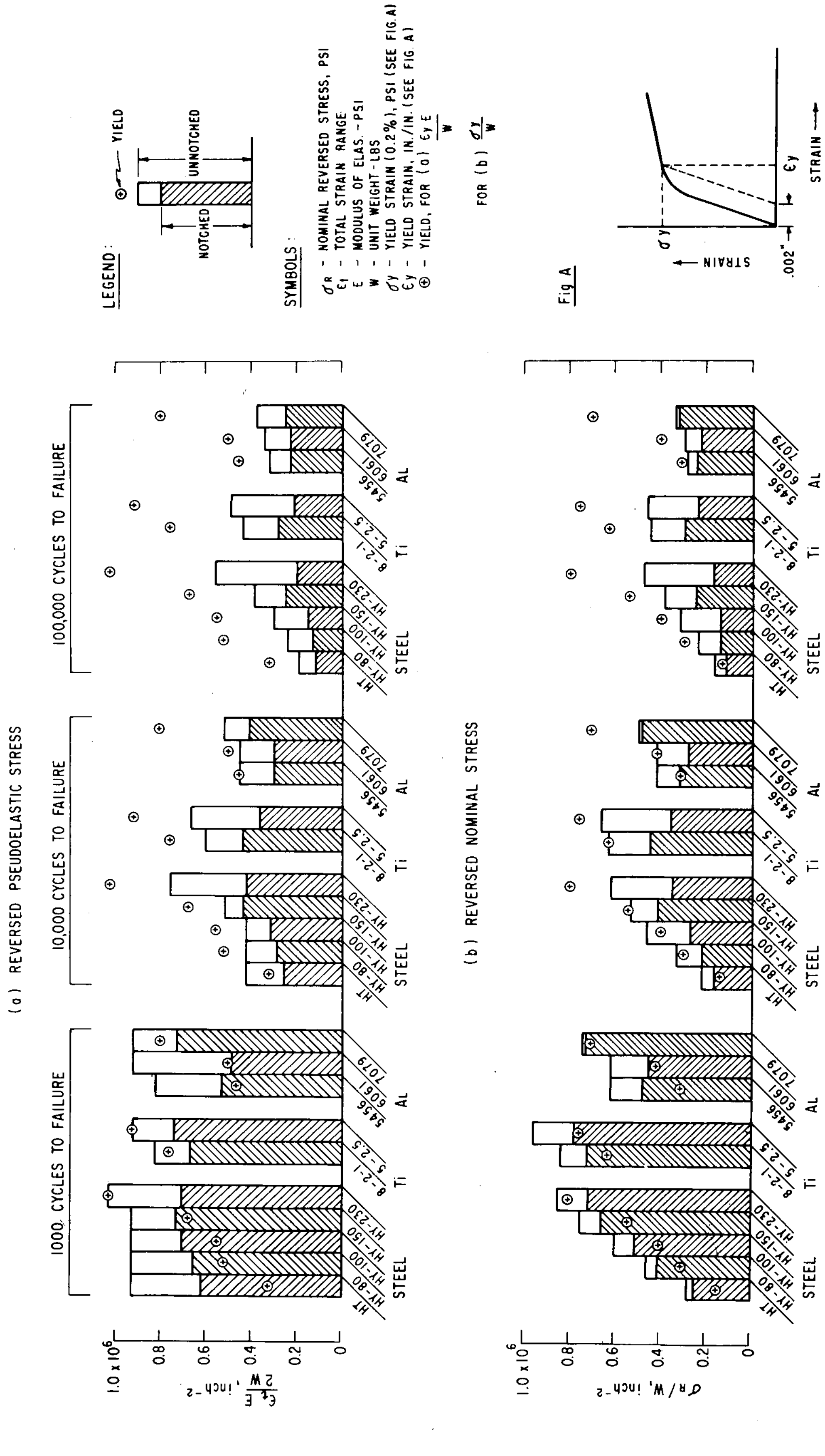


Fig. 13 - Comparisons of the fatigue strength of materials on an equivalent weight basis

Low-cycles fatigue appears to be a strain-dependent phenomenon inasmuch as the various factors tend to correlate best with strain. The only material property having a direct bearing on fatigue life appears to be corrosion resistance. Even this may prove to be at present unimportant for lives of less than 10,000 cycles. High yield-strength materials offer improved fatigue resistance at 10,000 cycles and over. However, the increase in fatigue strength is not commensurate with the increase in yield strength.

Low-cycle fatigue will become an increasingly important factor in determining the life of underwater structures utilizing high-strength materials. It is expected that this is a problem which we will have to learn to live with as has the aircraft industry. We cannot hope to prevent it entirely and yet take advantage of the advancing technology of the high-strength materials. Our approach should be to control the initiation and propagation of fatigue failures in critical locations through the judicious application of materials and design. Material selection should be based principally on differences in notch sensitivity, corrosion-fatigue resistance, and crack-propagation rate. Major improvements, however, in the low-cycle fatigue resistance of structures will come from design, principally in the reduction of stress concentrations. Supplemental improvements to good design may be effected by (a) improved surface finishes, (b) stress relieving, and (c) peening.

In spite of our best efforts, periodic inspection of critical areas will be mandatory. Depending upon conditions observed, decisions will have to be made to determine whether to continue, repair, or decommission.

R&D PROGRAMS

The preceding discussions have served to point out the extreme complexity of the fatigue problem. The evaluation and reduction to design practice of the independent factors discussed is a slow and arduous task. The ideal situation would be to establish the quantitative effect of each major factor so that the low-cycle fatigue life of a complex structure could be predicted from laboratory-type specimens. Both PVRC (8) and DATMOBAS (9) have developed design procedures which represent the first step in this direction. It is obvious that such procedures should be under continuous modification so as to incorporate new knowledge as it develops.

Nearly all of our knowledge on fatigue and material behavior originates from simple, laboratory-type specimens. This is because such specimens are inexpensive as compared to structures, and test variables can be isolated and controlled. Accordingly, one would expect this trend to continue over the years.

Our five year laboratory efforts should be directed towards studying the low-cycle fatigue behavior of a wide variety of materials and strength levels. Except for MEL, the work to date in BUSHIPS Laboratories has been restricted generally to materials currently in use, principally HY-80 steel. Broadening the scope of materials will serve to pinpoint near future and long-range problem areas both in material and design. With respect to evaluation of materials, more information is needed relative to the effects of notches, environment, crack propagation, and stress history. Long-range objectives should be directed towards incorporating laboratory test data into design criteria.

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FATIGUE-STRUCTURAL MODELS

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INTRODUCTION

Structural fatigue may be defined as the progressive deterioration of a structure arising from repeated alternating loading. This loading develops surface cracks that propagate into the principal structural members under load and, if sufficient cycles are applied, eventually brings about the ultimate failure of the structure. The pressure resistant structure of a submersible is subjected to such loading due to changes in pressure occasioned by excursions from one depth to another. Unlike high-speed reciprocating machinery components which are exposed to a reversal of load several thousand times a minute, however, the pressure cycle variation which a submersible experiences is of a relatively long duration period. Consequently, with machinery components the designer is concerned with a large number of cycles (usually greater than 10^5 cycles) and hence with relatively low stresses and the endurance limit of the material, while in submersible structure he must reckon with the fatigue life of highly-stressed details in the low-cycle range (10 to 20,000 cycles).

The design operating depth of manned submersibles, both military and oceanographic, has been increased by several fold in the last two decades, with the continuing trend to increase still further present depth capabilities for the different types of submersibles. To maintain overall ship capabilities, these increases in operating depth require use of lighter and stronger material for the pressure resistant structure. Inherent with such materials is a reduction in ductility and a decrease in the margin between yield strength and ultimate strength. Consequently, due to the dependency of fatigue on ultimate strength, the importance of fatigue increases with use of higher strength materials.

BACKGROUND

In late 1959, the Bureau of Ships conducted a comprehensive review of the overall problem attendant to use of HY-80 in submarine construction. Recommendations contained in the report of this study (1), formed the basis for initiation of the current submarine structural program (2,3). This broad program is basically comprised of two principal parts: fabrication and production control, and fatigue strength.

The study of the fabrication problem in new construction led to the issuance of Ref. (4) while, for ships already built, this document is supplemented by results obtained from the Submarine Surveillance and Inspection Program (5).

The second part of this broad program, viz., fatigue strength, resulted in the establishment of the Submarine Structural Fatigue Program. A detail summary of the interim results obtained under this test program appears in Ref. (6), while a brief description of the scope of the program appears in the final section. Basically, this program is divided into three groups of tests: 1) Full-scale submarine ballast tank structure, and several complex large-scale cylindrical models containing submarine pressure hull structural details suspected of being fatigue prone; 2) smaller scale structural models comprised of structures which simulate fabrication and stress levels associated with typical highly stressed structural details; and 3) basic material specimens and small welded specimens. Under group 1) two model scales were employed for the complex cylindrical models: 0.80 scale and 0.33 scale. The testing of large and medium large-scale geometrically similar cylindrical structural models was intended to assess the influence of scale effect, and establish a correlation between the fatigue resistance of the prototype and the models. Under group 2) two types of full-thickness specimens were employed: an "hourglass" series in which the cone-cylinder juncture was proportioned to simulate approximately the same stress levels as were obtained on the prototype, and the "diaphragm-with-rib" series which simulated the juncture attachment of the hull ring frame to the pressure hull shell. Under group 3) different types of specimens were used, varying from small polished notched bars, to small rectangular flat plates containing notches, or transverse or longitudinal butt welds, all of which were tested in air as well as salt water.

This fatigue test program for HY-80 is important to future work in this field in that it forms the present basis for fatigue evaluation of all new materials.

PRESENT STATE OF THE ART

In a complex submarine structure a fatigue crack develops first in the highly stressed areas in regions of geometrical discontinuity. In such cases yielding is possible at the root of the notch. Once yielding develops, a stress-strain hysteresis loop is developed. The small volume of material that has experienced plastic flow would, on unloading, experience a residual stress opposite in character to the load-induced stress. Thenceforth, on succeeding loading cycles, this small volume of metal will experience a high alternating stress range (from tension to compression) resulting in a marked influence on the fatigue life of the structural detail. The fatigue resistance of the structure is therefore directly dependent on the presence of a geometrical discontinuity, representing a notch of finite acuity, located in a moderately high stressed area environment. Moreover, since at a geometrical discontinuity there is usually a welded joint, additional adverse side effects may be thus introduced. Weld bead surface irregularities, sharp re-entrant angles at the toe of the weld, residual welding stresses, and metallurgical notches are additional deleterious influences. It becomes axiomatic therefore that the higher the local stress intensity at a particular discontinuity, the lower the number of cycles required to initiate a structural fatigue crack.

When the current HY-80 fatigue test program was initiated in 1960 strong advice was given to the effect that to assess the fatigue life of an engineering structure realistically, such as a submarine, one must seriously consider building and testing nearly full scale models of the prototype. With this advice, however, there was an accompanying admonition that since fatigue data are characterized by some scatter even in very large scale models one must not expect the results from the large scale models to check the fatigue life of the prototype with an accuracy better than one order of magnitude (factor of ten).

The inherent advantage in testing full-scale structural models is that it yields fatigue data which can be considered as having a correlation factor of one-to-one with the prototype. This follows from the implication that a large scale structural model, because of its size, presents a large statistical population (in terms of linear feet of detail) of the simultaneous behavior of many specific structural details. Hence the wide scatter that is obtained with testing much smaller laboratory type specimens should be thus minimized. Large structural models, however, can still exhibit a certain amount of scatter in fatigue performance. This reflects principally such fabrication variables as fit-up, mismatch, variations in mechanical properties of the material, and residual welding stresses.

Since testing full size structural models is a very expensive and time consuming endeavor, it becomes vital that other test approaches be critically exploited. This explains why the HY-80 fatigue test program encompassed the three test groups mentioned above. The principal aim here was to devise a small, and relatively cheap but realistic test specimen which could yield fatigue behavior comparable to that obtained from the large 0.8 scale structural models. This small test specimen, however, has to satisfy several important requirements. It must be constructed of full plate thickness. It has to be of such size and geometry to reproduce the biaxial restraints present in the prototype detail. To develop comparable residual stresses it must have intersecting structural elements requiring welding which must be deposited with the same electrode following the procedure used in welding the prototype. And finally, the small specimen has to be loaded so as to reproduce the same stress field calculated or measured in the full scale structure. Not all of these requirements could be satisfied in a single test piece. But suffices to note, however, that the test specimens selected in group 2), and some of the welded specimens in group 3) are giving results which compare favorably with the fatigue results obtained from the relatively large and complex cylindrical models, group 1).

To improve the fatigue resistance of the structure one must eliminate local notches and sharp discontinuities in the hull contour. Discontinuities in the hull can be eliminated by fairing welded plate sections, such as the use of toriconical transitions between hull sections of different diameters, or rounding corners of flat plate tanks, or use of spherical or toroidal tanks. Elimination of local notches, in turn, can be achieved principally by the use of castings, or forgings, with the attendant gradual transitions and radii. The use of castings was tried on the "diaphragm" specimens of group 2) with very promising results. The fatigue resistance of this detail was improved by several orders of magnitude over the weldment. In practice this means that to create a reasonably crack-free structure new structural shapes must be developed chiefly to ease the geometrical transition at the intersection of structural members. Another useful technique which has been explored and which has given beneficial results is to mechanically post-treat the weld at geometrical discontinuities. By either mechanically peening the toe of the welf or grinding this area to a gentle contour, some remarkable improvements have been measured. The peening operation, in addition to reducing the local concentration through changing the otherwise sharp notch at the toe of the weld, has the advantages of placing the small volume of metal in a state of residual compressive stress and increasing the yield strength of the material through cold working. These are factors that enhance the fatigue resistance of a structural detail.

Experience from the HY-80 submarine fatigue test program is indicating that relatively small, and inexpensive laboratory-type specimens and simplified full-thickness models can be used as a realistic basis for prediction of the fatigue life of the prototype structural details in the 20,000-cycle range. Correlation with the results obtained from these small specimens with those obtained from the more expensive and structurally more complex large models has shown to be remarkably good. Having tested models in both of these groups, it is possible now to conclude that a reliability factor has been established, and that the premise advanced about the basic requirements for a small laboratory-type specimen has been largely confirmed. With the correlation obtained between large and small scale models it may be further concluded that there will be little need to test further full scale structures for fatigue strength determination in the low cycle range. Relatively cheap, but well-designed small-scale models can be relied upon to give a satisfactory engineering answer, with only a possible periodic requirement for a confirming test of a larger-scale structural model.

PREDICTION — R&D TO 1970

A. Structural Model Tests

The background developed from the HY-80 structural fatigue program is expected to provide a valuable basis for projection into the future for the new higher strength-to-weight materials being developed. The same factors that were found to influence the behavior of the HY-80 structure are expected to influence the fatigue behavior of structure made of the new materials. It is a question of determining the degree to which each factor will influence the fatigue behavior of each new material, viz., how tolerant each material will be of notches (design, fabrication and metallurgical), residual stress, ultimate strength and type of loading. An insight has been obtained on the tolerance of various steels for notches, i.e., HT steel can plastically flow to a greater extent at the base of a notch for cyclic lives under 10,000 than HY-80, and HY-80 is more tolerant than HY-100. It would be expected, therefore, that as the strength of the material increases the tolerance of the material to notches will decrease because of restrictions on the ability for plastic flow. It follows that to avoid a fatigue problem the design of the structure must be made much "smoother" and "cleaner" for the higher strength materials.

In addition to the factors of significance observed under the HY-80 fatigue program, it is apparent that new factors may develop that will place further limitations on the use of higher strength materials. One of these factors is the relationship of fatigue crack propagation to the toughness of the material. As a result of the toughness of HY-80, crack propagation is always slow and relatively extensive prior to leakage, and even then the leak produces only a slow weep. Similar performance will be desired for the higher strength materials. Another area of concern is the weld metal and HAZ. In HY-80 structure the fatigue cracks have shown no preference for base metal, HAZ and weld metal. The cracks have progressed in a direction normal to the principal stress. The higher strength material weldments must be similarly developed so that there is no preferential weak path.

The HY-80 fatigue program has shown that residual tensile stress is an important factor in initiation of fatigue cracks. As new high strength materials become less tolerant to fatigue, the need for thermal stress relief or for surface strain hardening (change of tensile residual to compressive residual stress by peening) will require investigation.

For the future more attention will be required on the effects of environment on fatigue, e.g., corrosion may have a more detrimental effect in higher strength materials than in lower strength materials as is the case of stress corrosion of structural steels.

In the determination of the suitability of the high strength-to-weight structural metals from a fatigue standpoint, it is expected that only simplified full thickness types of models (hourglass and plate diaphragms will need to be tested. After a material and design have been established for a particular vehicle, a small scale fatigue model of the design should be tested to locate any fatigue prone details. Any details thus found to be susceptible to fatigue would be improved to eliminate the problem.

The preceding discussion points to the fact that the high strength structural metals can be used for a deterrent system provided their fatigue limitations are developed and these limitations adhered to in the design. For Filament Reinforced Plastics (FRP) the fatigue projection is much more difficult. This stems from the lack of material reproducibility which has technically precluded any extensive small and large scale fatigue program to establish the significant factors as was done in the case of the HY-80 program. For the period of R&D to 1970 it is hoped to establish the tolerance for fatigue of all the materials now being considered for submersibles.

The task of establishing a time frame in which fatigue information will be available is made difficult because material suitability from a strength-toughness point of view must be developed first (and later perhaps weldability) before fatigue data can be developed. In addition, since fatigue tests of structural models are expensive, they must be restricted to materials termed potentially suitable for the submersible.

B. Material Prediction

Steels — Fatigue data on both HY-130 to 150 and HY-180 to 210 should be developed during this period.

Aluminum — The fatigue design limitations of the nonweldable 7079-T6 alloy in a composite type structure will be developed. Fatigue data on the 7002, 7005, 7139 and 7106 type high strength weldable alloys may become available on simple and composite type models. The latter tests will be dependent on a decision to explore these alloys for possible prototype application.

Titanium — Fatigue data on both 100 ksi (present best 7-2-1 alloy) and 120 ksi titanium alloys should be developed.

FRP — It is expected to develop the most suitable type of design configuration, e.g., sandwich or composite structures, during this period. The objective will be to eliminate or reduce bending stresses so that interlaminar shear by fatigue will not occur. Design limitations will be established. Once having established the proper configurations it is anticipated that the present maximum shell working stress to 50,000 psi may be raised to 100,000 psi. Work will be concentrated on scale effects and penetrations. The availability of a suitable submersible structure prior to 1970 is unlikely.

C. Costs

As mentioned in section A above, fatigue tests of structural models are expensive, in particular for medium size models (5' to 8' diameter) but even including the small-scale full-thickness type of model. For the simplified full-thickness type of model it is estimated that a cost of approximately $0.5M will be required for each new material alloy. This would include both the hourglass and the diaphragm types of models. In addition, for each specific ship design using a new hull material, should the need arise for fatigue testing of a medium scale model, it is estimated that such a model will cost be- $1M and $1.5M for each material design.

DETAILS OF BUSHIPS PROGRAM ON LOW CYCLE FATIGUE TEST MODELS AND RELATED STUDIES

Three different groups of structural fatigue tests are being conducted. These involve: (1) complex large-scale models containing structural details of submarine pressure hull sections suspected of having a greater fatigue propensity, (2) simplified small-scale full-thickness models simulating the most critical sections of the pressure hull, and (3) basic material and weldment specimens.

A. Complex Submarine Models

As shown on Figs. 1-4, this group contains four basically different types of models which are comprised of detail reproductions of the more critical pressure hull sections. These models are subjected to constant-cycle (periscope to test depth) hydrostatic pressures, and are loaded at a rate of approximately one cycle per minute.

1. F-A Model (Fig. 1) — These models contain pressure hull details of the older types of HY-80 SS(N) submarines. Two different series of geometrically similar models are being tested. One series of three models is 8/10 of the size of the prototype, while the other series of three models is 1/3 of the size of the prototype. While the three

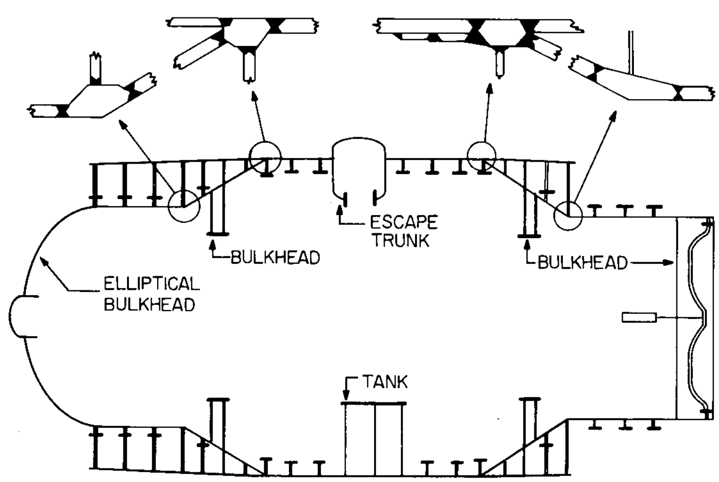
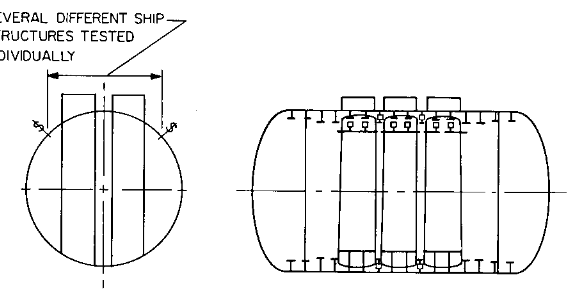


Fig. 1 - Fatigue model F-A (models built to 8/10 and 1/3 scale

Fig. 2 - Fatigue Model F-C (under design) (1/5 scale)



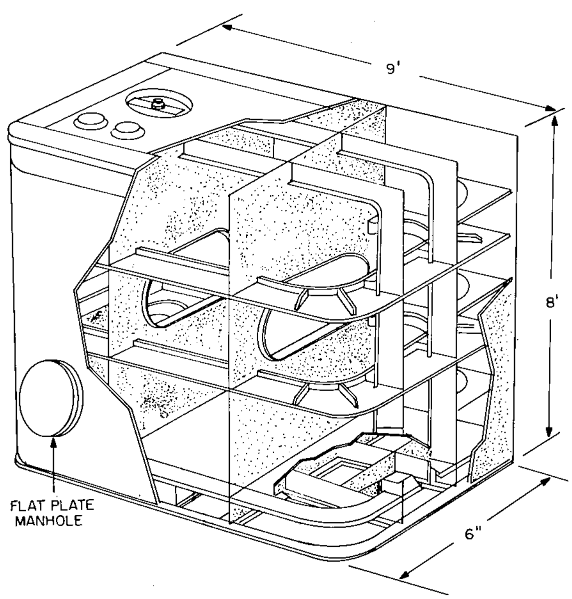


Fig. 3 - Flat-plate structure ballast tank (full scale)

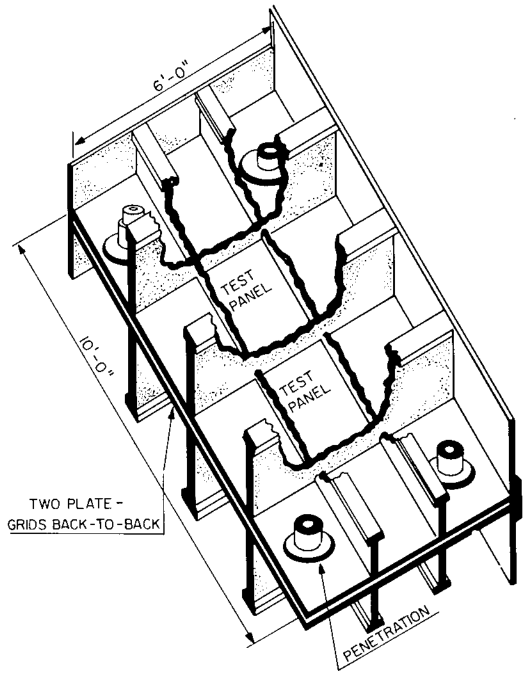


Fig. 4 - Flat-plate structure simplified plate grids (full scale)

1/3-scale models have all representative submarine details essentially identical to each other and to the first 8/10-scale model, the second and third 8/10-scale models are built with some structural details modified in several different ways to obtain relative fatigue performance (1) of welded and cast structure, and (2) of critical welds left in the as-deposited condition with those subjected to mechanical surface-treatment (peening, and contour-grinding with and without peening).

2. F-B Model — This model, somewhat similar to the F-A model, contains pressure-hull details of the newer types of HY-80 SS(N) submarines, and includes an experimental hemispherical closure. Only one model, 8/10 of the size of the prototype, is being built.

3. F-C Model (Fig. 2) — This model will contain structure representative of a typical portion of the missile compartment in a POLARIS submarine. It is planned to structurally modify this model several times, and subject each modification to cyclical loading. Each modification will reproduce one of the different reinforcement schemes used on current submarines at the crown intersection of missile-tubes and pressure hull. Only one model, 1/5 of the size of a prototype, will be built.

4. Flat-Plate Structure

a. Ballast Tank (Fig. 3) — This model represents, in full-scale proportions, structure sized by the different design criteria used for stiffened flat-plate hard-tanks of all HY-80 submarines. Only one model of the dimensions shown was built.

b. Simplified Plate-Grids (Fig. 4) — The purpose of this series of approximately ten plate-grids is to extend test data obtained from the ballast tank above, but without the repair expense and time losses incurred during testing of this tank. In addition, the beneficial effects on fatigue of mechanical post-treatment of welds are being evaluated on these grids.

B. Simulated Submarine Models

Owing to the large time and cost expenditures attendant to construction, test, and intermittent repair of the large complex submarine models, structural details found from these large model tests to be most critical are being studied further on small-scale, full-thickness models. In addition, structural modifications for possible backfit application are subjected to preliminary evaluation on these smaller, less-expensive models. As shown on Figs. 5-8, this group is currently comprised of two basically different types of models.

1. Cone-Cylinder Intersections (Hourglass Model) (Fig. 5) — These models are fabricated with plate having prototype thickness, with the cone angle and pressure selected to

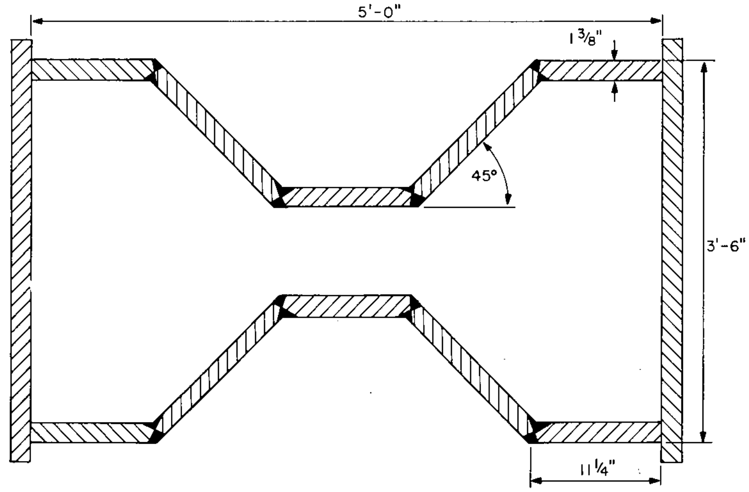


Fig. 5 - "Hourglass" models

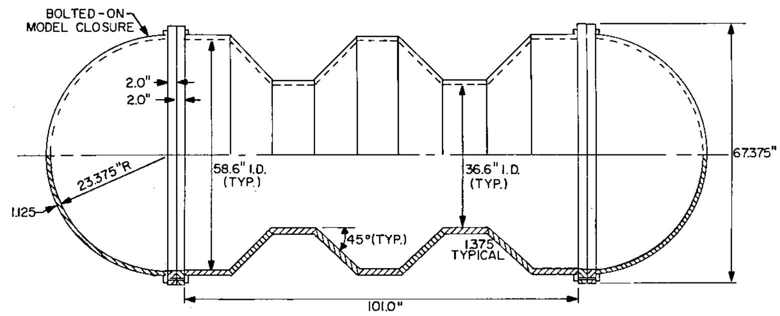


Fig. 6 - Cylicone model (double hourglass model)

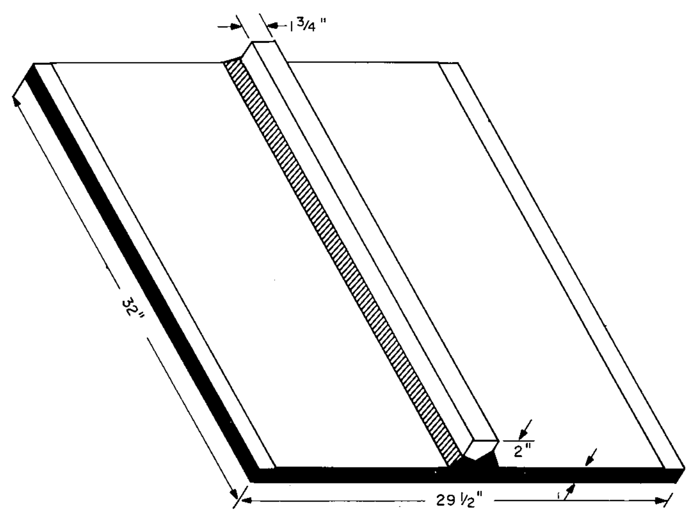


Fig. 7 - Large scale diaphragm fatigue specimen
(Applied Science Lab., NYK)

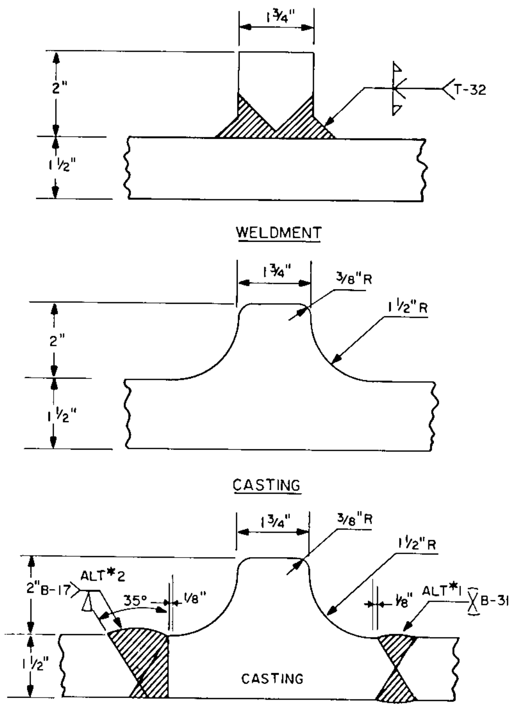


Fig. 8 - Flat-plate diaphragm tests (diaphragm dimensions are 29-1/2 inches wide and 32 inches deep)

simulate stress levels obtained on the prototype. Two series of "Hourglass" models, with approximately ten models per series, are being tested. In addition to "as-welded" intersections tested in both hourglass series, the second series includes stress-relieved models. To speed up testing of simulated cone-cylinder intersections, a "cylicone" model (Fig. 6) will be tested, and will include intersections left as-welded and those subjected to mechanical treatment (contour-ground, ground-and-shot-peened, and mechanically-peened).

2. Stiffened Flat-Plates (Diaphragm-Type) (Fig. 7) — These models are constructed of prototype-thickness plate, with different specimens loaded to produce a range of stress similar to that experienced by the prototype. Included in the approximately ten series of diaphragms being tested are those with as-welded, shot-peened, mechanically-peened, contour-ground, and ground-and-shot-peened T-welds subjected to cyclic loading with the weld in tension, and those in the as-welded condition with the weld tested in compression. In addition, cast diaphragms with integral ribs, and plate diaphragms with butt-welded cast ribs (Fig. 8) are being tested. For comparison purposes, a series of butt weld specimens and plain plate were also fatigue tested.

C. Basic Material and Weldment Specimens

In addition to large complex submarine models and smaller simulated models, a third group of fatigue tests, composed of basic material and weldment specimens, is being conducted. These laboratory tests (discussed in more detail in the "Laboratory Tests" Section on Fatigue), designed to supplement data obtained from the model-testing phase of the fatigue program, are being performed at five activities:

1. MEL — At the Marine Engineering Laboratory, Annapolis, the fatigue resistance of small polished, notched, and welded specimens of HTS, HY-80 and HY-100 has been established at all stress levels and cyclic lives of interest. Tests are now being conducted on push-pull specimens designed to qualitatively establish the relationship between different levels of compressive and tensile stress, and varying cyclic loading, on fatigue strength of the basic metal.

2. ASL — At the Applied Science Laboratory, Brooklyn, from fatigue tests on beam-type specimens the effects of grinding, peening, and grinding-and-peening have been demonstrated for high-cycle fatigue.

3. Univ. of Illinois — At the University of Illinois, push-pull types of fatigue tests have been conducted on virgin plate, transverse and longitudinal butt welds, and various attachment welds. In addition, limited special tests were made on effects of weld strength, interpass temperature, combined longitudinal and transverse butt welds, and lack of complete weld penetration.

4. SWRI — At the Southwest Research Institute, San Antonio, simplified, compressive specimens (notched and welded) are being fatigue tested to determine the low-cycle fatigue life of plates and welded joint materials subjected to cycles of strain similar to those experienced by some of the more critical details of submarine hulls. This is a basic type of study that will attempt to determine what happens at the base of a notch during fatigue in terms of plastic flow, residual stress and load-induced stress.

5. NRL — At the Naval Research Laboratory simple cantilever beam specimens with built-in mechanical notches have been tested to determine the rate of crack growth for various strain levels under cyclic loading. In addition, preliminary flaw-size stress relationships for fracture of quenched and tempered steels, maraging steels, and titanium alloys have also been developed.

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CORROSION CONTROL FOR STRUCTURAL METALS IN THE MARINE ENVIRONMENT

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INTRODUCTION

Forthcoming projects in the marine environment offer new challenges in the way of corrosion control, whether one is concerned with very high speed vehicles, deep diving submarines and submersibles, apparatus for physical oceanography, acoustic surveillance devices, or bottom-mounted structures of various types and purposes. Some of these projects may be hazarded because of corrosion problems - not because of any new corrosion principle involved in the deep ocean environment (none has been detected), but because of requirements for materials and geometries with which there has been little or no experience in the sea, and in many cases because of unfavorable maintenance or inspection possibilities. In order to avoid or at least minimize such hazards, it is necessary to determine the effects of sea water on the new materials (the use of which is usually dictated by mechanical properties and fabricability) and if necessary to devise measures to control these environmental effects. The effects may include stress corrosion cracking, hydrogen embrittlement, and corrosion fatigue, and the possible countermeasures are principally cathodic protection and protective coatings. With respect to academic disciplines, the effects area includes applied electrochemistry, mechanical metallurgy, and physical metallurgy; and the coatings area includes organic chemistry and (for antifouling paints) marine biology or biochemistry. Although these disciplines are unrelated to each other academically, they are highly interdependent when in the context of practical corrosion control in the sea, and any competent program in corrosion control must take account of this interdependence.*

CORROSION EFFECTS AND CATHODIC PROTECTION

Corrosion control measures which have been developed during the past 15 years have offered impressive economies to the Navy in the form of reduced maintenance costs, especially for ship hulls. With the new materials and new geometries of components and structures for various deep ocean projects, and with the often drastically reduced availability for maintenance, the primary need for corrosion control has shifted from one of maintenance economy (though of course this is as desirable as ever) to one

*As one brief example of this interdependence, cathodic protection of a ship hull by galvanic anodes was impractical with the older paints because of their low dielectric properties which placed an exorbitant demand for current; but it _is_ feasible with the newer paints. Likewise, some paint systems are long-lived with cathodic protection whereas they might be rapidly undercut by corrosion at small defects in the coating if cathodic protection is not superimposed.

of survival of the component or structure. Thus, for example, one of the goals of corrosion control a few years ago was to extend the period between dry dockings and to reduce the number of hull plates needing replacement because of corrosion. By contrast, a typical current corrosion control problem posed by deep ocean requirements is corrosion or corrosion fatigue of high-strength armor wire for communication cable. Unless this problem can be solved by a novel cathodic protection system, a material fundamentally new to marine engineering will have to be developed as armor wire if we are to prevent the present loss of critical components suspended by these cables. This example illustrates not only the survival goal characteristic of current marine corrosion control efforts, but it also illustrates one of the new types of problems, in this case the problem of either cathodically protecting a long length of wire by an anode located at one end or suitably cladding a high-strength wire, or making a high-strength wire of an inert alloy.

This and other examples of current corrosion control problems are sketched in Fig. 1. Some of these problems have already occurred, some are occurring now, and some we would hope to avoid. These examples have been selected in order to form the bases of discussions of the various current technological areas of corrosion and its control.

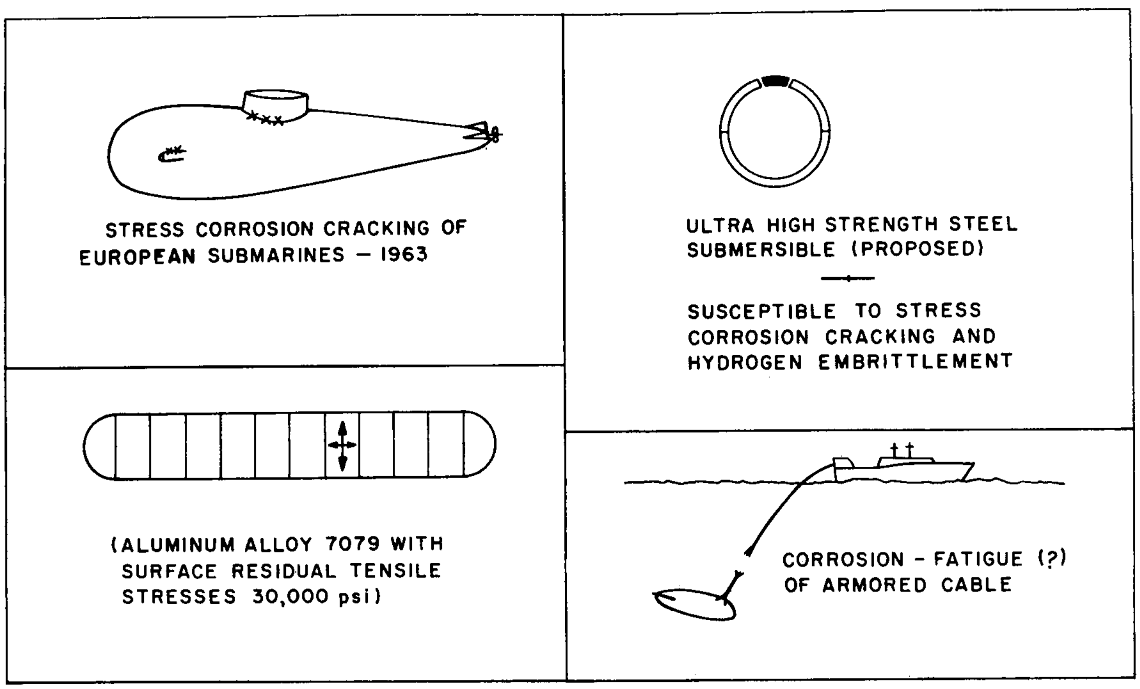

Fig. 1 - Types of current or possible future corrosion control problems

The first case in Fig. 1, that of the recent non-magnetic European submarines, is one in which a new material - a high manganese austenitic steel - was used in sea water after preliminary experiments on the base plate but apparently not on welded specimens, and it was at welds that the service failures occurred as stress corrosion cracks.

There is as yet no positive test for immunity to stress corrosion cracking, and none in prospect, and one can only report either susceptibility or "no cracking after time T under X conditions of stress, environment, etc." It is by no means certain that specimens of all materials stressed beyond the yield are more susceptible to cracking than those stressed under the yield, or that specimens immersed in salt water are more likely to be cracked than those exposed to distilled water (the reverse has been reported), or that notching the specimen will consistently lead to more tendency to cracking, or that anodic stimulation of corrosion will in fact speed cracking. On the basis of experience to date it appears that an acidified salt solution containing H_2S will crack more steels, and in general crack them more quickly, than any other medium. But it is not entirely certain that this is the case with all steels, and, more importantly, it is not known whether the cracking behavior in this particularly severe environment gives a significant order of merit for behavior in sea water, marine atmosphere, or condensate environments. Thus until test concepts are in better order, it will be necessary to make extended tests, at several stresses, with several specimen configurations, in at least three environments, with and without cathodic protection, of welded specimens as well as unwelded, in order to feel confident of avoiding ugly surprises of the same sort as the European submarines. This indicates the need for careful screening of material put into the stress corrosion cracking program in order to avoid allowing the number of tests to get out of hand. It also indicates the need for a strong, early program to improve test concepts in order to both economize on and speed up evaluation.

The second case of Fig. 1 is not a Navy problem (at least, not yet); but it, too, offers lessons of potential usefulness to the Navy. This is a submersible of aluminum alloy 7079 chosen because of the high strength-to-density ratio of this alloy. This class of alloys is susceptible to selective corrosive attack and stress corrosion; and although progress has been made in minimizing the susceptibility to attack through control of heat treatment and composition, the optimum conditions for corrosion control do not always coincide with the optimum for other properties, or they may not be feasible because of section sizes. As a consequence, 7079 in some large forgings will go into service with tensile stresses at the surface of approximately 30 ksi. The aluminum would be given anticorrosive coats over which would be a coat of cuprous oxide antifouling paint. It is known that a sufficiently thick coating of a good anticorrosive paint will serve adequately to protect the underlying aluminum from effect of the antifouling paint. But at breaks in the coating the copper will tend to be reduced from the antifouling paint and will be deposited on the aluminum, where it will greatly stimulate corrosion (and, on susceptible alloys, probably also stimulate stress corrosion cracking). To attempt to offset this, galvanic anodes would be used. No sea water tests of the efficacy of the specified galvanic anodes, or of any other anodes, for the prevention of either stress corrosion cracking of this alloy or of accelerated attack by antifouling agents have been performed, and it is by no means certain that this is possible. (The use of this alloy for Navy projects is not distant: It is in use today for instrument cases for physical oceanography, but currently the immersion periods are relatively short, no antifouling paint is necessary, and anticorrosive coats of "laboratory bench" quality are used.) At present there appears to have been no experience in protecting any structure against stress corrosion cracking in sea water by cathodic protection techniques.

The third illustrative case in Fig. 1 is the stress corrosion cracking of a proposed submersible of very high-strength steel (designated H-11). This steel is highly susceptible to stress corrosion cracking at the proposed strength. If one attempts to counter stress corrosion in this material by the application of cathodic protection, a phenomenon intrudes to defeat this move. This phenomenon is hydrogen embrittlement, and all the high-strength steels (low alloy, hardenable stainless, precipitation hardening, and maraging) are susceptible to it when they are heat treated to sufficiently high strengths. Although the intention may be to form and heat treat such objects so as to avoid having residual tensile stresses in the surface and thus avoid stress corrosion cracking, this may not be achieved in many cases even of relatively simple geometry. One must then, if he is driven to use such a material, use a coating which has a special requirement placed on it: It must do more than merely prevent corrosion - it must be totally impermeable even to water vapor, for experience has taught that coating adequate to do that may not prevent cracking from traces of moisture permeating the coating.

The current estimate of the strength ranges for the three classes of steels at which they become susceptible to stress corrosion cracking is given in Fig. 2.* (The precipitation hardening steels are lumped with the other hardenable stainless steels in this figure.) In preparing this figure, only data for sea water, salt solutions (used in the laboratory), distilled water (representing condensate), marine atmosphere, and humid air were used. Omitted were data for the acidified salt solutions containing H_2S, and nitrate solutions, on the grounds that these are unrealistic for the marine environment. Figure 2 also indicates the range at which hydrogen embrittlement under sustained load might be expected to become a practical problem. Also shown in Fig. 2 are graphs for the expected cracking behavior of aluminum alloys, with the yield strength scale expanded. Titanium is also shown, although no incidence is known of stress corrosion cracking of any titanium alloy either in sea water or in other environments at room temperature.†

Returning to Fig. 1, the fourth illustrative case is one of corrosion fatigue of armored cable. It is obvious that if corrosion produces a pit, this can be expected to act as a stress raiser which could accelerate the fatigue process, and this is observed. Perhaps somewhat surprising, however, is the observation that although the titanium alloy B120VCA is essentially inert to salt water, when fatigued in salt water the life is sharply reduced compared with the life in air. It might be supposed that adequate cathodic protection should remove the "corrosion" component of cathodic protection, and this is observed for this alloy (Fig. 3). But in the case of steels of almost any strength level, the application of cathodic protection beyond a certain level (defined for only a very few conditions for a very few steels to date), once again a form of hydrogen embrittlement appears to intrude to counter the effect of corrosion protection and place a limit on the available effectiveness of cathodic protection.‡ An example of data showing this is given in Fig. 4. The study of corrosion fatigue is rather more formidable than that of stress corrosion cracking because of the requirement for machines in large quantities to produce the fatigue, whereas it is possible to use a bent specimen to produce its own stress field for stress corrosion cracking. Therefore it is imperative to design any program with the utmost care to ensure that the results have broad applicability.

In addition to the major phenomena illustrated in Fig. 1, there are a considerable number of relatively small corrosion problems usually not involving stress which will be needed to be solved on a continuing basis to answer the developing questions as deep ocean hardware continues to expand in types of materials and geometries. As an example of this is cited the problem of O-ring seals, which are widely used to exclude sea water from instrument cases intended for prolonged service at great depths. A relatively minor amount of corrosion aroung the O-ring may break through the seal. It is

*The bar graphs of Fig. 2 show the transition from "resistant" to "susceptible" strength levels as a stippled zone. Toward the left of these zones the stresses required for cracking may be lower, the times for cracking longer, some members of the class may be largely immune, or special heat treatments or special environments may be required to cause cracking. Toward the right-hand end of these zones the heavier shading is intended to indicate that most members of the alloy class are susceptible to cracking in short times at moderate stresses in common media.

†Two instances have been reported in which titanium alloy plate specimens containing circular welds were observed to be cracked after a period of exposure to laboratory atmospheres. But not enough information was given to be sure that these were not in fact brittle running fractures perhaps triggered by an aging reaction, and the appearance of the cracks supported this conjecture.

‡Such behavior was not observed in the few earlier studies of the application of cathodic protection to the corrosion fatigue problem because hydrogen embrittlement is strain-rate sensitive and does not appear at the high cycle rates used in the earlier studies, so that complete recovery was indicated even with indiscriminately high levels of cathodic protection.

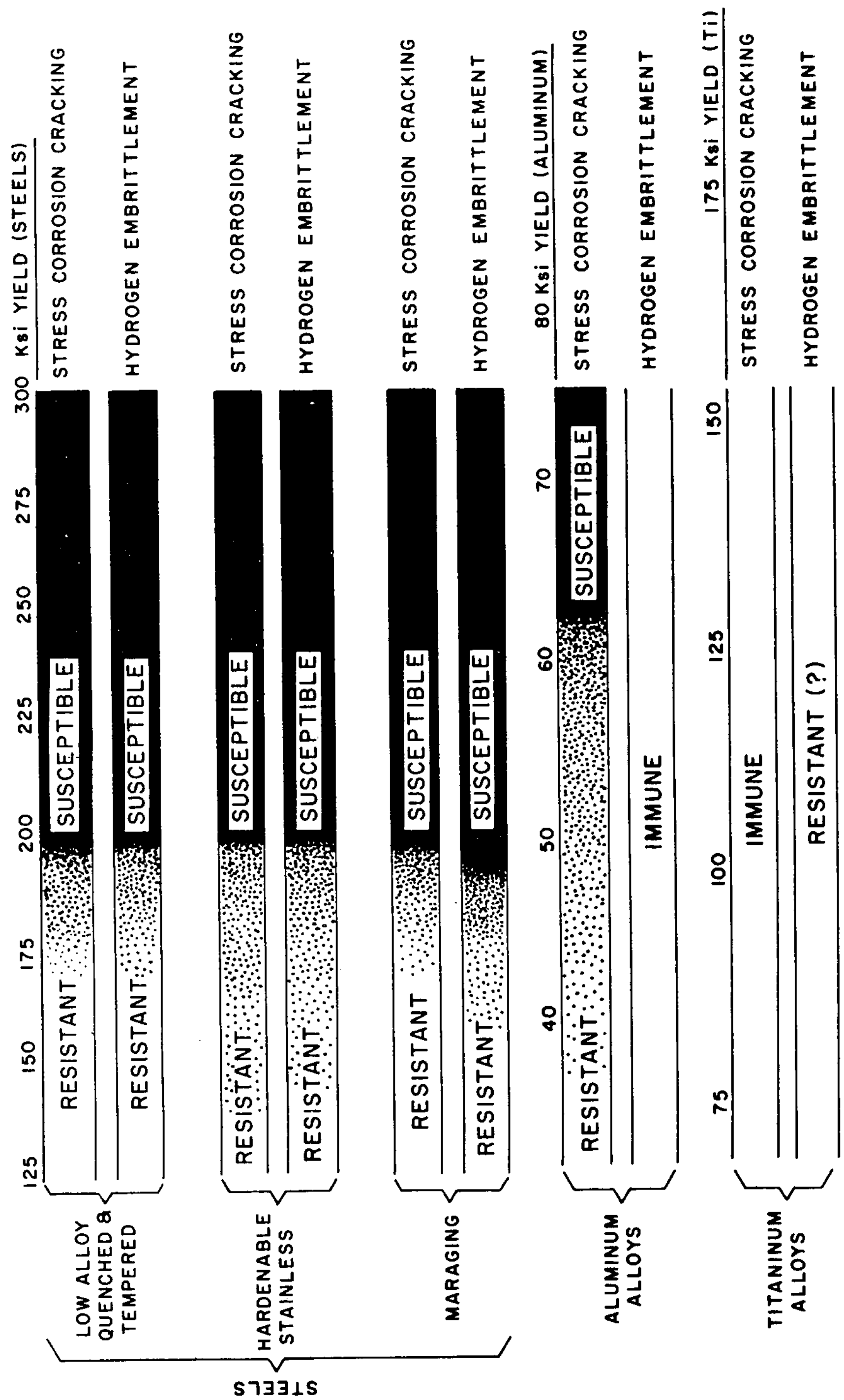

Fig. 2 - Estimated strength ranges for susceptibility to cracking in sea water, fresh water, or humid atmospheres

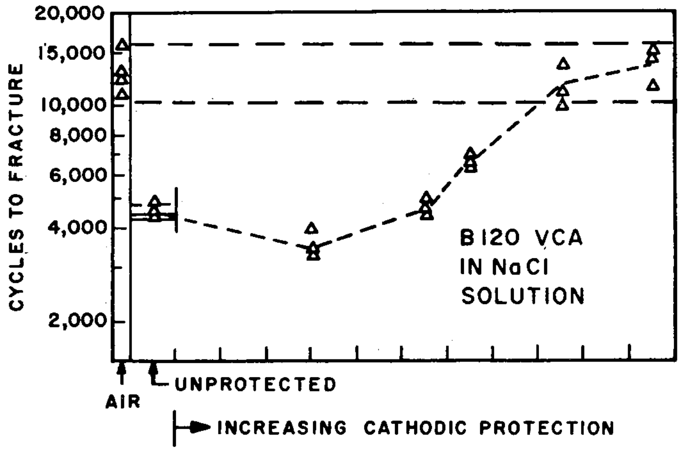

Fig. 3 - Cathodic protection of high-strength titanium alloy against corrosion fatigue

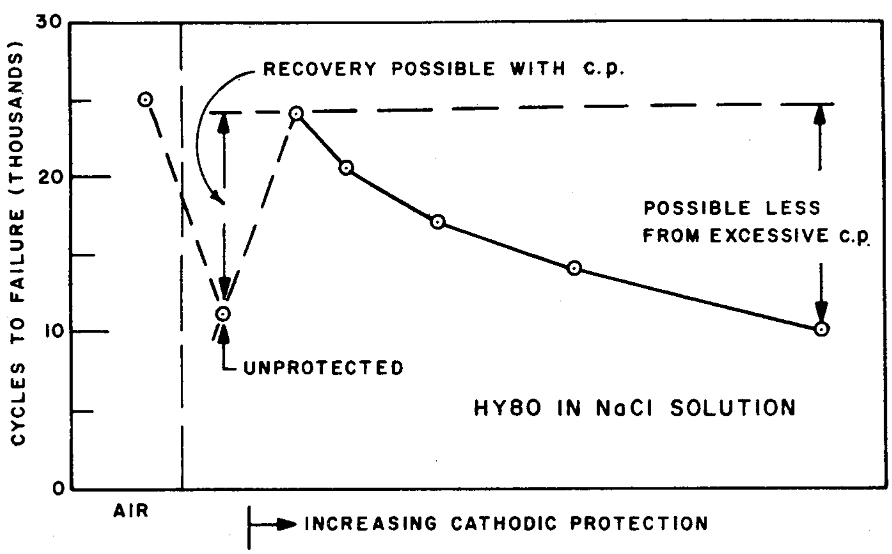

Fig. 4 - Effect of cathodic protection on corrosion fatigue of steel at low-cycle frequency (100 c.p.m.)

possible that cathodic protection techniques can delay this for very long times - of the order of many years. But this must be examined experimentally at a marine site. A large number of similar new small problems requiring a sophisticated examination at a marine site could be cited based on experience with ocean surveillance and similar deep ocean projects.

RECOMMENDED RESEARCH PROGRAM FOR CORROSION EFFECTS AND CATHODIC PROTECTION

Although the problem areas discussed above are described in terms of deep ocean projects, it is not because the environmental effects are any more severe or otherwise different to an important degree from those at the surface, but simply that the deep ocean projects require new materials, geometries, and often they do not admit of frequent maintenance. Experience to date has failed to disclose any important difference in an engineering sense, in corrosion control technology at great depths compared with that in shallow sea water, and no fundamental reason is known to expect a difference, aside from the fact that the essential absence of macroscopic fouling below a few hundred feet may permit relaxing requirements on antifouling paints on some structures. Therefore none of the following recommended program areas envisions a requirement for a high-pressure facility or extensive deep sea exposure tests.

5-Year Period [66-70]

(1) Development of a reliable test concept for determining the relative susceptibility of various high-strength materials to stress corrosion cracking and hydrogen embrittlement in environments of interest (i.e., sea water, marine atmosphere, fresh water, condensate, and humid inert gas). This is urgently needed to economize on other efforts in this field and also to speed evaluation and permit succinct characterization of materials.

(2) Development of economical method for studying corrosion fatigue through separating time for incubation of crack, rate of crack growth, and the effect of electrochemical environment (including cathodic protection) on these.

(3) Solution of "special corrosion control problems" (such as cathodic protection of O-ring closures and similar miscellaneous problems).

(4) Routine investigation of the stress corrosion susceptibilities and relative response to corrosion fatigue for selected alloys.

(5) Development of light-weight high efficiency galvanic anodes for cathodic protection of weight-limited structures.

15-Year Period [70-80]

A continuation of Items (3) and (4) above.

COATINGS

The principal objective of a coating program is to develop and evaluate new and improved coating systems (including anticorrosion and antifouling properties) and application techniques for underwater surfaces and for special needs resulting from military developments (for example: sonar equipment with more powerful transducers).

A special program for deep-sea resistant coatings only is not considered necessary. It is believed that a well balanced and properly supported program for marine coatings, with both short range and long range objectives, will provide the answers which will be required by future developments in deep sea technology. It is felt that the problems generated by an expanding oceanographic program are essentially the same as those generated by new military development in a conventional marine environment, and that both have common solutions.

Antifouling

Ships require antifouling measures only for those surfaces continuously under the water and are docked periodically for repainting. Docking intervals are continuously being extended, and the search for long term antifouling protection goes on. Hence, developments for underwater hulls of ships and their appendages can be extended to applications on deep sea equipment, some of which will be located within the fouling zone and may not be available for removal of accretions for long periods.

Present status of Navy antifouling paints is as follows:

The Navy uses three types of antifouling paint systems — vinyl, hot plastic, and cold plastic, all premised on use of copper toxic which provides antifouling protection for two to four years. These are based on high rosin content sufficient to provide an exfoliating surface or a continual slight surface breakdown that continuously exposes underlying toxic particles.

By removing the solvents from the cold plastic (conventional paint) and by adding waxes and other low melting materials, a coating that can be melted and applied hot has been achieved. Since a very thick coating (more than twice the thickness of three coats of cold plastic) can be applied with good exfoliation characteristics, hot plastic is formulated with a low percentage of toxic, and is superior to the cold plastic system in durability.

The vinyl coating is a modified cold plastic where only rosin and vinyl resin comprise the binder and with more copper toxic. The vinyl reduces the exfoliation to a minimum which increases the durability of the film.

Recently, a great surge of testing organic materials has been underway. For the first time in current technology, some of these have shown broad spectrum antifouling activity. To date, tributyltinoxide (TBTO) is possibly the best of the lot. Much development work still remains to be done.

Anticorrosive

The basic objective of a coating system for underwater surfaces is to provide protection against corrosion. In the case of antifouling systems, the anticorrosive must also serve as a suitable substrate for the antifouling paint. Included among desired properties are water resistance, resistance to ionic passage, resistance to osmosis, dielectric strength, chemical resistance, adherence, abrasion resistance, resistance to undercutting, inhibitive action, easy application, easy touch-up and repair, and "age resistance" (maintain protection effectively over a period of many years under widely different environmental conditions).

RECOMMENDED RESEARCH PROGRAM ON COATINGS

5-Year Period [66-70]

(1) Investigation of accelerated laboratory techniques for evaluation of antifouling materials, including laboratory rearing of fouling organisms (estimated achievement, 1969).

(2) Development of improved antifouling system for sonar equipment (1967).

(3) Improved internal coatings for living spaces (1967).

(4) Improved coatings for fresh water tanks (1967).

(5) Development of accelerated laboratory tests designed to provide reliable index of long term performance (1966).

(6) Improved epoxies, inorganic zinc silicates, polyurethanes, polysulfides, and other chemically catalyzed resins (1969).

(7) Investigation of new toxics as possible ingredients for antifouling paints.

15-Year Period [70-85]

(1) Coatings for cold damp surfaces.

(2) Water-base interior paint systems.

(3) Development of resins suitable for use in nuclear submarine coatings.

(4) Coatings for application under water.

(5) Primers that can be welded-over on high-yield strength steels.

(6) Durable coatings that can be applied over rusty surfaces.

(7) Evaluation of new resins developed by industry.

SUBMARINE SEALS

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INTRODUCTION

Submarine seals are required to provide closure against sea pressure for a variety of hull penetrations. The designs of seals have had to be widely diversified to cope with the range of size, speed, types of motion required and risk factor of failure. The seal design plays a considerable part in the materials selection. For the purposes of this report, it appears that a discussion of materials as part of the specific design will be more informative than attempting to discuss designs as part of a seal material discussion. Detailed discussion is presented of propeller shaft seals, periscope seals, radio antenna seals, operator rod seals, hatches, and electrical hull fittings in the following paragraphs. The general plan of the presentation is to state the functional requirements of the seal, discuss the present and alternate design and materials, detail the present capabilities and failure modes of the seal and forecast the required work to provide seals for the future.

SHAFT SEALS

Propeller shaft seals are required to control the leakage into a ship within two limits. The lower leakage limit is determined by the heat generated at the sealing surface, the upper by the maximum flow tolerable into the ship. The heat generated depends on shaft diameter, shaft speed and depth of submergence and on the materials and surface condition of the seal surface.

The propeller shaft seal is complicated by the necessity for accepting a variety of shaft displacements. In the axial direction the seal must accommodate uncertainties in the positioning of the shaft with respect to the after bulkhead, the displacement of the shaft resulting from changing operation from ahead to astern, and from surface to fully submerged. These relatively slow axial displacements are also accompanied by axial motions of small amplitudes occurring at shaft rotational speeds as a result of out-of-squareness of seal rotor and thrust bearing rotor. Other rapid axial oscillations are imposed on the seal by the periodically varying forces on the propeller blades. Radial displacements result from eccentricities in the seal rotor and the shaft sleeve and mass or hydraulic unbalances in the propeller shafting system. A long-term radial displacement results from wear and compression in the out-board water-lubricated propeller and stern tube bearings.

The propeller shafting system is designed with a hollow steel shaft provided with shaft sleeves about 3/4 inch thick in the way of the bearings and seals. The shaft sleeve material is of a wear and corrosion resisting material, usually bronze or monel. The shaft is protected between the sleeves by coatings of rubber or glass fiber-epoxy construction.

Figure 1 shows a very approximate arrangement of the submarine stern. The propeller and shaft are supported on flexible water-lubricated bearings. Fleet service seals

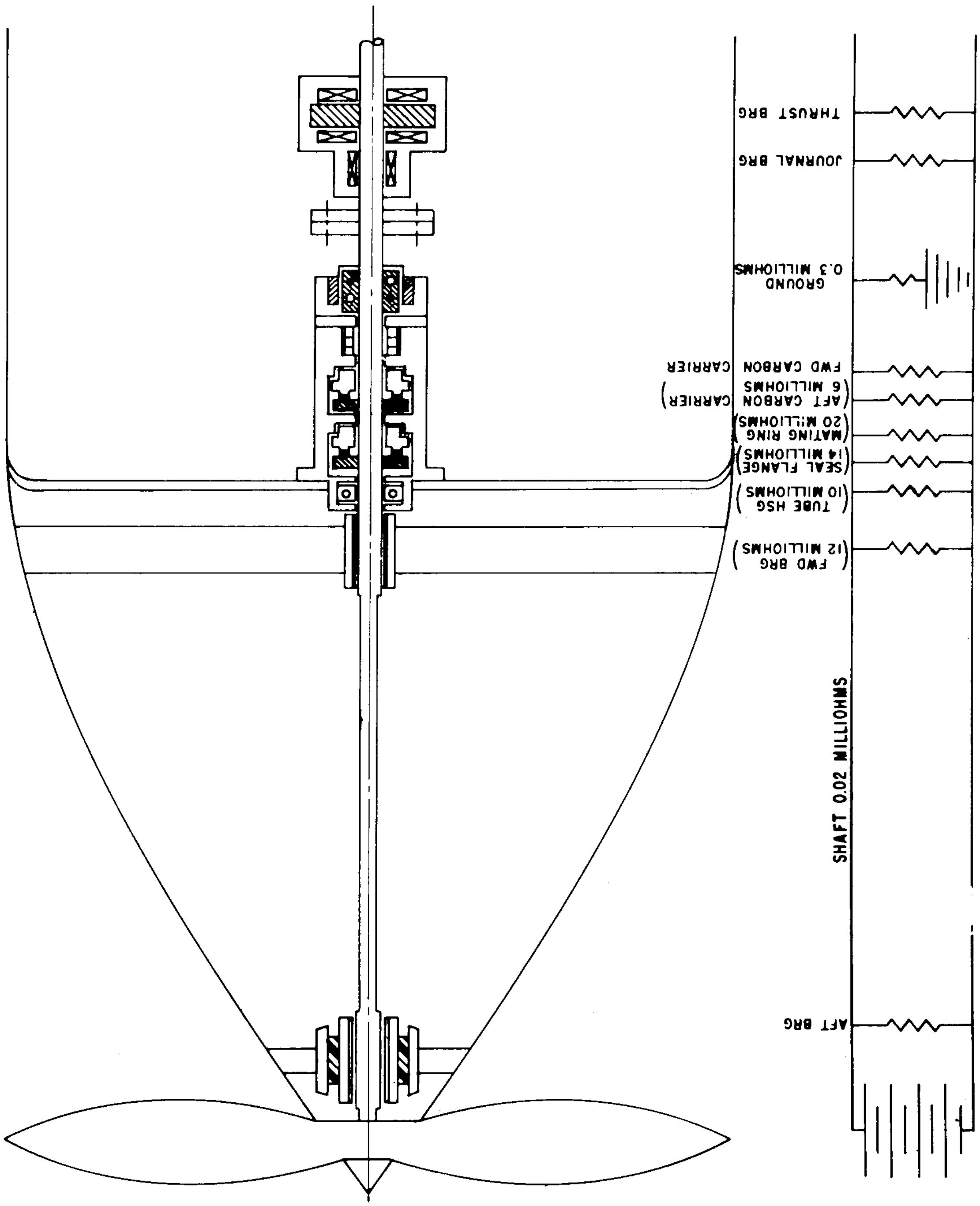
THRUST BRG
JOURNAL BRG
GROUND
0.3 MILLIOHMS
FWD CARBON CARRIER
(6 MILLIOHMS)
AFT CARBON CARRIER
MATING RING
(20 MILLIOHMS)
SEAL FLANGE
(14 MILLIOHMS)
TUBE HSG
(10 MILLIOHMS)
FWD BRG
(12 MILLIOHMS)
SHAFT 0.02 MILLIOHMS
AFT BRG

Figure 1

at the present time consist of an outboard inflatable safety seal, an installed spare face-type seal, the operating seal, and emergency packing. The outboard inflatable seal consists of a tube of rubber with piping to the ship's interior permitting inflation of the rubber against the shaft providing a seal. This seal is intended to be inflated only with the shaft stopped while the submarine is at rest on the surface or to a depth to provide required concealment. At the present time this seal has been tested to about one-half World War II (WW II) submarine depths. The seal has not been highly successful since a number of the inflatable tubes have been found to be torn or punctured. As yet it is uncertain whether this has resulted from installation or operation. The inflatable seal needs to be redesigned to reduce the damage possibilities under both installation and operation. It should be capable of providing sealing to any required depth of submergence without the development of new materials.

The installed spare face-type seal and the operating seal are identical. Valves placed in the cooling water supply to the seals determine which of the two is sealing. Weekly operation of the ships on the spare seal insures that its condition is known at all times. Figure 2 shows a typical submarine shaft seal. The face-type seals are of the balanced pressure type. A rotating member, the seal rotor, is keyed to the shaft sleeve to provide axial location and positive drive. An O-ring between the seal rotor and the shaft sleeve provides a stationary secondary seal along the leakage path between the rotor and shaft. The seal rotor is made in two halves so that it can be replaced without removing the shaft. The rotor is made of monel and is hard-faced with Stellite in the seal region on all except the deepest diving submarine, AGSS 555, where an insert of Tungsten carbide with a nickel binder has been selected for use. The seal stator is a monel ring carrying an insert of carbon or leaded bronze in the seal face. The seal insert is installed using an epoxy cement and sealant. Some seal inserts were attached mechanically and sealed on the outer diameter with an O-ring. An O-ring secondary seal is provided at a diameter calculated to provide a minimum excess of closing force over the opening force existing from pressure between the moving seal faces.

The pressure existing between the seal faces poses the most serious problem with seals. Snapp (1) has shown that the opening force may vary very widely depending on the deflected shape of the seal face and thus on the elastic characteristics of the materials. Indeed, for sufficiently high pressure, the seal's elastic deformation will cause excessive leakage even with the most favorable profile. The maximum opening force controls the required closing force and thus the balance diameter. If excessive closing force is

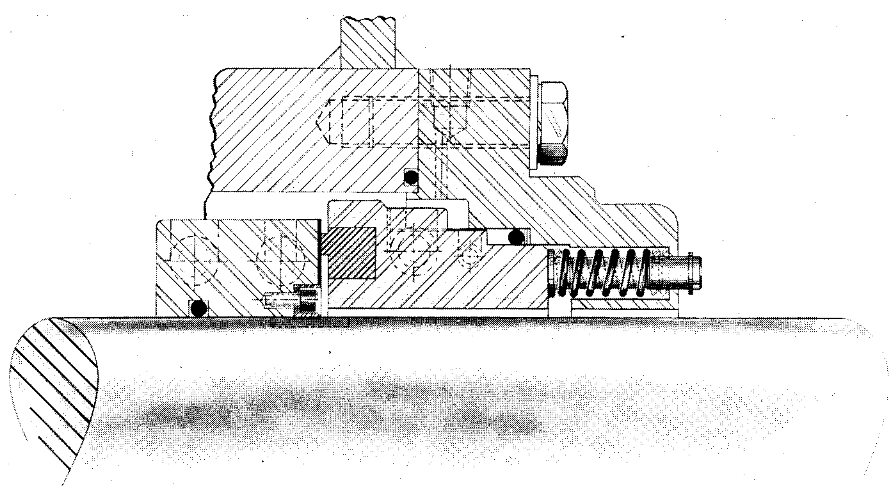

Figure 2

applied, leakage is reduced or stopped, contact pressures increase and excessive heating with high torque and wear will result. The development of analytical techniques for solving the coupled hydrodynamic and elastic equations for seals is required.

Submarine shaft seals are tested for 2000 hours at rated submergence and for an additional 200 hours at 1-1/2 times rated submergence. Seals for fifteen 17-3/8- and 28-inch shaft sleeve diameters have been developed and appear to be functioning well in service judging by the patrol reports from the Fleet. The 15- and 28-inch seals are for counterrotating shafts, the 17-3/8-inch seal is used on SSN and SSBN submarines. A 7-1/2-inch seal has been developed for AGSS 555 and tested at 6X WW II and at 9X WW II feet for the usual time periods. The 7-1/2-inch seal has made one aspect of the seal problem very evident. The load imposed by the seal balance area must be accepted by the main propulsion thrust bearing. This amounts to approximately 140,000 pounds at the 6X WW II level and to 210,000 pounds at the 9X WW II depth. The problem of starting the shaft from rest under these loads was a major factor in the selection of a spherical roller bearing ($f_o = 0.003$) for the main propulsion thrust in preference to a tilting shoe thrust bearing ($f_o = 0.2$). A major weight saving also resulted. The thrust bearing was mounted on the aft trim tank to prevent the return of the thrust to the hull causing a hard area and increasing the hull buckling hazard. The support of the hydrostatic thrust component resulting from hull penetrations appears to be a major future problem particularly when the penetration is required to move under pressure.

The present shaft seals appear to fail by corrosion and wear processes. We do not at present have evidence of the maximum pressure capabilities of our shaft seals nor of their failure under pressure alone. The corrosion affecting the shaft seals in service appears to be of two distinctly different types. One type is the result of the cell formed by the hull and the bronze propeller supplying a current of 25 ma per square foot of exposed bronze at about 1 volt. This type of corrosion is characterized by attack on the monel components attached to the shaft while monel components attached to the hull show no damage. Attempts are being made to correct this situation by installing a liquid grounding brush on the shaft and by increasing the electrical resistance of the cathodic components of the seal. The second type of corrosion occurs between the monel rotor and its Stellite hard facing. The monel-Stellite cell corrodes in a knife-edge attack at the monel-Stellite interface. The knife-edge attack progresses to a depth that endangers the strength of the Stellite. The use of cast inserts of Stellite retained by epoxy cements is being attempted. In addition, seal face materials, free from this type of attack, are being sought.

Shaft seal wear is the usual type of failure although corrosion is nearly always present. The degree of wear tolerated by seals without major leakage is quite surprising in view of the high degree of accuracy required for initial successful operation. The Stellite-carbon combination has given satisfactory service, but considerable concern is felt over the relatively low shock resistance of the carbon. The outboard unloaded seal carbon fractured badly during the shock tests of the THRESHER. The loaded inboard seal suffered no damage. Carbon under compression has considerable shock strength; but, if tensile forces can be imposed, carbon is quite weak. Seals in the Laboratory have operated successfully using a highly leaded tin bronze against Stellite and against Tungsten carbide. Later exposure of the bronze at the Harbor Island exposure site produced such severe corrosion that its future use is in serious doubt.

Alternative designs have been attempted, but so far with small success. More flexible face-type seals, radial seals, and buffered seals have all been found to be much less satisfactory than the more rigid face-type seals. It is possible that our present work on buffered seals may provide a usable answer in time.

Shaft seal materials and design need a great deal of additional work if large diameter seals are to be available for 6X WW II to 10X WW II depth by the 1970-1975 period.

The apparent degree of success so far achieved may be reduced if the submarine Fleet starts intensive operation near the limits of their design submergence. Sharply increased corrosion resistance and wear resistance in fairly ductile materials of elastic modulus in the 5 to 10 x 10^6 psi range appears to be needed. Some type of boundary lubrication in the presence of water should be an integral part of the materials constitution if long wear life is to be obtained. The interactions existing between design and materials need considerable clarification since small design changes have provided the difference between success and failure with specific material combinations. An analytical and experimental approach must be supplemented by actual seal development for any probable application. Until a full understanding of the seal behavior is attained, it will be necessary to continue the slow and costly cut-and-try development and proof testing.

The flexible packing inboard of the operating seal is intended as an emergency take-home device. The heat associated with this packing prevents the simultaneous use of both full speed and full submergence. This packing is the standard graphited flax packing set up manually by the crew in case of need. Development work is currently under way to overcome both the overheating and the slow set-up problems by a redesign of the seal to provide a hydrodynamically acting pressure breakdown bushing actuated by submergence pressure.

PERISCOPE SEALS

Periscope seals are a very different problem from the shaft seals. The periscope is a static seal except very near the surface. At this point the pressure is less than 25 psi. The seal may be required to accept translation and rotation with the rotation required at low torques. The periscope may suffer various amounts of whip as a result of the shedding of vortices. Leakage must be kept at a low level to avoid obscuring the eyepiece or distracting the user of the periscope. At full submergence the periscope is completely retracted and immobile. The present periscopes have a smooth continuous exterior surface free from the lubber's line previously cut along the scope. The seal is composed of an inboard packing used when the scope is operating and an outboard inflatable seal for use when the submarine is to make deep dives. With this arrangement the inner packing is free from high pressure at all times and thus never packs so tightly as to cause high torque in training the periscope. The inner packing is a typical Chevron "Vee-"type packing and the outer inflatable seal is of a fairly soft elastomer. Many alternate designs have been tested but until the lubber's line was removed, no really successful seal had been found. The present seals should have no difficulties until extrusion becomes a problem. The extrusion problem has been avoided, in at least one case, by moulding an insert of harder rubber integral with the inflatable sleeve. Failure in the present seals is limited to dirt and corrosion damage on the tube with resultant cutting and wear. As long as the periscope retains its present functions, future problems do not appear serious. If however, it is necessary to have large diameter shafts pass through the pressure hull and move with translation and/or rotation, a point will be reached where frictional forces will exceed reasonable values. It is probable that design will be more important than material in reducing the friction to tolerable levels.

RADIO ANTENNA SEALS

Radio antenna seals for the floating antenna are required to pass up to 3000 feet of floating wire into the sea against submergence pressure. The antenna seal must also permit retrieving the antenna, cut off the antenna, if required, and automatically seal the hull in the event the antenna breaks and pulls out of the pass through. The antenna seal system consists of an outboard ball valve welded to the hull; a ball check valve arranged to close in the event the antenna pulls out of the seal; an elastomer packing with external hydraulic compression control; a drain space and wiper; a moving opposed pair of endless tracks carrying plastic grippers over pairs of geared sprockets driven by hand or motors. The outboard ball valve is equipped with sharp edges, hardened ports, and geared closing devices to permit the antenna to be cut free promptly in the event the submarine must take evasive action. The ball of the ball check valve is forced aside by the entry of the wire into the ball check chamber. Any removal of the wire from the chamber and the ball will fall back into its seat under the action of gravity alone and should seal tightly if submergence pressure is added. The packing is a simple cylindrical sleeve of rubber with a hydraulic piston acting on its outboard end. Application of hydraulic pressure on the piston will compress the rubber cylinder to any desired amount to provide an acceptable rate of leakage. A drain chamber and O-ring wiper are provided below the rubber sleeve to keep as much leakage as possible off the track drive mechanism. The track consists of endless roller chains carrying moulded plastic gripper pieces. These grippers are arranged to hold the antenna over a length of several inches and pass it up through the wiper, seal, check valve, and ball valve into the ocean where the antenna will float up to its operating position. The force exerted by the grippers is adjustable to compensate for wear or other surface effects. The drive sprockets are geared together and alternatively driven by hand-crank or motor. The latest modifications seek to obtain 100 feet per minute speeds on either playout or retrieval. Some earlier designs used a pair of rolls to provide the friction drive. This arrangement damaged the antenna wire since the force had to be exerted over a small area. The antenna wire consists of an inner stranded core of aluminum wire surrounded by a syntactic foam and covered with an elastomer outer jacket.

The chief failure mode of the earlier systems was the result of worn places in the jacket developing from slippage of the rolls on the jacket. Since the endless track was developed, no further trouble has been encountered. The most obvious potential failures are the possibilities of cutting the inner surface of the seal rubber by dirt trapped on the surface of the antenna jacket and the accidental entry of salt water into the ball bearings of the drive mechanism. As greater depths are attained, the strength of the wire will have to be greatly increased, the length and power of the gripper drive must be increased, and the hardness of the compression seal will also probably need to be greater. It may be possible to use a sinking antenna and receive the low frequency ground wave at sufficiently great depths of submergence.

ROD SEALS

Operator rod seals are required to transmit rotary or translatory motion of small diameter shafts at low slow speeds through the pressure hull. In general, grease packed, standard design O-quad or Vee-ring packings are employed. These packings are self-acting in that increased pressure tends to reduce leakage. All of these seals provide for periodic relubrication from within the hull. Seal friction is the greatest limitation on the use of these seals. The grease lubrication reduces this friction while extrusion of the elastomer into the space between the rod and the housing increases the torque. Various types of antiextrusion rings are available, but so far they are not much used. Synthetic rubbers of shore hardness 45 to 65 are presently employed. Hardness up to 85 or 90 could be used, but the low-pressure leakage characteristics would be worse. Wear, corrosion, and excess friction are the typical failure modes of these seals. Increased depth will increase the wear and friction problem. Changes in materials to reduce the extrusion and friction are necessary.

HATCH SEALS

Hatches are also examples of flexible packing seals. Hatches are basically of two types; those where the pressure closes the hatch, e.g., access and muzzle hatches; and those where pressure tends to open the hatch, e.g., torpedo breech hatches. The hatches are basically flat-to-flat seals with an elastic lip-type seal between the surfaces. They may contain one lip for sealing in one direction or two-lip seals for sealing in two directions. As with most flexible seals, the elastomers are compressed about 10% of their free height to provide initial sealing. Even in large diameter missile seals, an initial out of flatness of 10 mils is of no consequence, since the pressure will flatten out the hatches. Such is not the case where the pressure tends to open the seal. Very little operating experience exists in operating such seals under the maximum submergence pressure of present submarines. It is possible to redesign such seals to provide self-closing seals. In the writer's opinion, such redesign will be necessary if weapons capable of employment at great depths are devised. The most difficult problem with present hatch seals appears to be protection against explosion. The pressures and vibration of the explosive wave are somewhat indeterminate and thus the design is problematical. The redesigned hatches have withstood the test conditions so far imposed. Development of hatch seals will follow hull developments without requiring substantial material changes.

ELECTRICAL SEALS

Electrical pass throughs are required to provide an insulated path for a number of conductors through the pressure hull. Mechanical stresses, other than pressure stress, are small. The present design utilizes glass-to-metal seals on the pin connectors. The glass bead or sphere is held in heavy compression by shrinking on an outer stainless steel plate. A number of connectors may be held in the same plate. Sealing against pressure in the fitting is accomplished by standard O-rings. The fitting is held by a hull fitting welded into the pressure hull. The seal between the electrical fitting and the hull fitting is also an O-ring seal. The present pass throughs are carefully designed so that pressure in all cases tends to narrow the gaps sealed by the O-rings. Test of the present fitting showed no failure up to 10,000 psi. This is especially noteworthy since the fitting was designed for 2000 psi. Fitting collapse appears to be the only possible or probable failure mode. It does not appear that any future depths would pose any problem for this fitting.

FUTURE PROGRAM

The research program for hull seals must be concentrated on the shaft seal. The shaft seal constitutes the highest risk and shortest lived of the seals presently used on submarines. The shaft seal research program should include the following:

1. Analytical — Seek a solution of the coupled navier-stokes, elastic and possibly energy equations for the face-type seal under rotation with periodically varying face waviness (or elastic modulus). This solution would be the complete analytical solution of face-type seals with real surfaces in contact. The magnitude of the required solution will probably dictate using simplified solutions for the immediate future.

Determine the required variation of pressure balancing diameters with pressure, with elastic modulus of seal ring materials and with elastic modulus of the supporting rings.

Determine the allowable range of material elastic constants as a function of sea and unit face pressures to predict the required material characteristics.

Determine the effect of complex forcing functions applied to the shaft system on the seal performance characteristics.

Calculate the dynamic behavior of the shafting-seal-thrust bearing system under propeller forces and hull inertial conditions.

2. Experimental — Seek experimental verification of the analytical solutions proposing new models to the analysts as indicated by the experimental observations.

Seek a bench wear test for materials evaluations yielding results interpretable in terms of full size seal performance.

Examine the corrosion behavior of material couples in sea water with and without externally impressed low potential currents.

Explore the flow behavior across the face of a low differential pressure seal involving the system sea water-buffering fluid. Determine the complete characteristics of this system to provide a model for developing an analytical treatment of buffered seals.

Explore the technical problems of minimal weight thrust bearing supporting systems including hydraulic vibration reduction system.

Develop quick acting, self-energized emergency secondary seal systems.

Determine seal behavior under low cycle (25,000) fatigue conditions.

Determine the complete pressure-speed-leakage boundary curve for basic designs and material combinations.

Explore the operation characteristics of new design concepts as such concepts arise from earlier work and provide guidance for model selection for analytical treatment.

3. Development — Develop seals to meet specific requirements for shaft size, speeds, pressure, and lives imposed by emerging machinery concepts.

PROJECTED PERFORMANCE

The projected performance of shaft seals is shown in Fig. 3. This projection is based on the experience of the past decade in obtaining increases in depth, shaft size, and seal surface speeds. The present essentially qualitative understanding of seal performance dictates that until a full scale seal is built and studied in the laboratory under the most carefully controlled environment, no real assurance of having fully determined the dimensions of the problem may be felt. The projections of performance have been made with the premise that a full analytical solution with experimental confirmation may not be achieved before 1975. Progress after securing such a firm engineering basis should

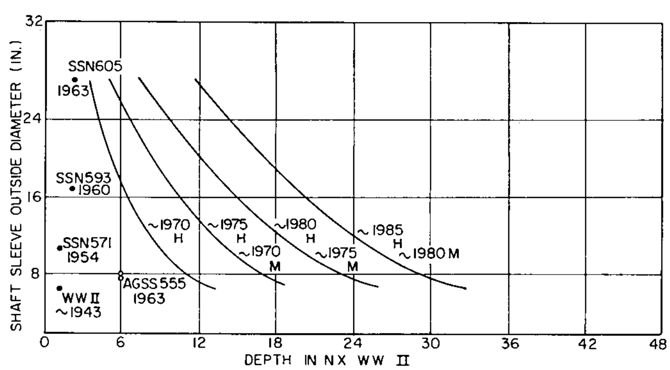

Fig. 3 - Shaft seal performance forecast

be far more rapid. Figure 3 thus shows two projections, the high confidence curve "H" is what we believe can be done on the qualitative approach basis, the medium confidence curve "M" reflects the potential with a really successful solution of the present analytical difficulties.

REFERENCE

1. Snapp, R. B., "Theoretical Analysis of Face-Type Seals with Varying Radial Face Profiles," M.S. Thesis, George Washington University, 1962.

APPENDIX A

FRACTURE TOUGHNESS CONSIDERATIONS FOR METALS

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The widespread use of metals in load bearing structures derives from the fact that plastic behavior is expected to precede fracture. Because geometric points of high stress concentration in a structure are considered to yield and redistribute loads, the designer does not need to define accurately the plastic stress state at such locations. Comfort that this situation attains was obtained for many years by reference to the per-cent elongation figure in a tensile test. Recognition that cracks or notches may reduce the flow capability of a metal to zero levels is of more recent origin; as the result, design consideration of fracture toughness ductility has replaced reliance on smooth tensile specimen ductility. The attainment of this level of sophistication in fracture-safe design for low strength steels was reached roughly 100 years following the introduction of the metal. By ensuring metal capabilities for ductility in the presence of flaws, the metallurgist has provided material which insures the designer from the inadequacies of stress analysis, fabrication and inspection.

It may be said that structures loaded in compression should not be subject to fracture at stresses below instability levels. This should be true if the designer is confident that ports, hatches, etc., do not result in the introduction of regions subjected to tensile stresses. An additional requirement for this idealized state is that no accidental loads of concentrated force are imposed on the structure.

In the full spectrum of possible applications of materials to pressure resistant structures there may be valid design bases for eliminating consideration of fracture toughness characteristics or conversely, for requirements of fracture toughness ranging from very high to definable low levels. It is not the purpose of this section to propose what these levels should be, but rather to define what levels of fracture toughness are inherent to metals of the full spectrum of yield strengths that may be considered of design interest. The information that is provided herewith was not available two years ago - it has been developed by an NRL crash-effort in response to a BuShips assigned research task. It represents the emergence of a first practical engineering approach which satisfies a combination of interacting requirements. As such it has provided a means of cross communication that did not exist previously.

There are three different, but interacting requirements for fracture toughness information: (1) for design, (2) for alloy development and for selection of optimum material for the strength level, and (3) for specification and quality control. A solution which provides only for design data based on expensive and difficult tests of large size is obviously unsuited for the other two requirements and as such automatically defeats the overall design requirements. The centerpoint of communication and common definition lies in understanding the significance of readily performed, small laboratory fracture tests such as the Charpy V (C_v) or the new NRL drop-weight tear test (DWTT). These tests provide practical means for characterizing the fracture toughness of a metal sample by a "number" which has translatable meaning in terms of the above stated requirements. For design, this information must translate to flaw size-stress level relationships for fracture initiation. For metals research and development, this information must translate to scale position with respect to maximum attainable levels of fracture toughness for the strength level, type of processing, and test orientation. For quality control and specification, the fracture toughness levels selected by the designer must be translated to procedures by which certification is provided that these will be present in the materials actually used in the structure.

The present state of knowledge is based on cross-correlation studies of plate materials of 1" thickness. These studies served two functions: (1) to characterize the effects of increase in strength on the fracture toughness of the materials and (2) to establish a correlation between the small laboratory tests and the performance of a large structural prototype element when subjected to elastic or plastic level loads in the presence of flaws. Based on these correlations it was then possible to estimate the metallurgical effects of section size.

A schematic illustration of the correlation technique and its significance to design is presented in Fig. A-1. The features of the DWTT are evident in the two specimens representing a fracture tough material and a relatively brittle material. A standard 1" × 3" section is fractured by a pendulum type impact machine. The fracture initiating notch is a brittle crack developed by the fracture of a brittle bar welded to the test element. For the illustrated material (Fig. A-1) of low fracture toughness, a "flat" (square break) fracture of low energy absorption progressed through the DWTT "test" element. For the illustrated material of high fracture toughness, the fracture changed to a 45° shear mode on entering the DWTT "test" element. The absorbed energies for the two illustrated types of fracture may range from less than 500 ft-lbs for the "flat" fracture to over 5000 ft-lbs for the 45° shear fracture. Figure A-1 also indicates the results of explosion tear tests of flat plates (1" × 22" × 25") of the same materials, featuring a 2" crack (introduced by welding a machined slit region with brittle weld material). These are related schematically to an idealized tensile stress-strain curve. This composite illustration dramatizes two extremes in fracture toughness - a low level which provides for initiation of fractures at elastic levels of stress and a high level which resists fracture initiation to levels of ultimate tensile strength. Extensive correlations of this type have provided

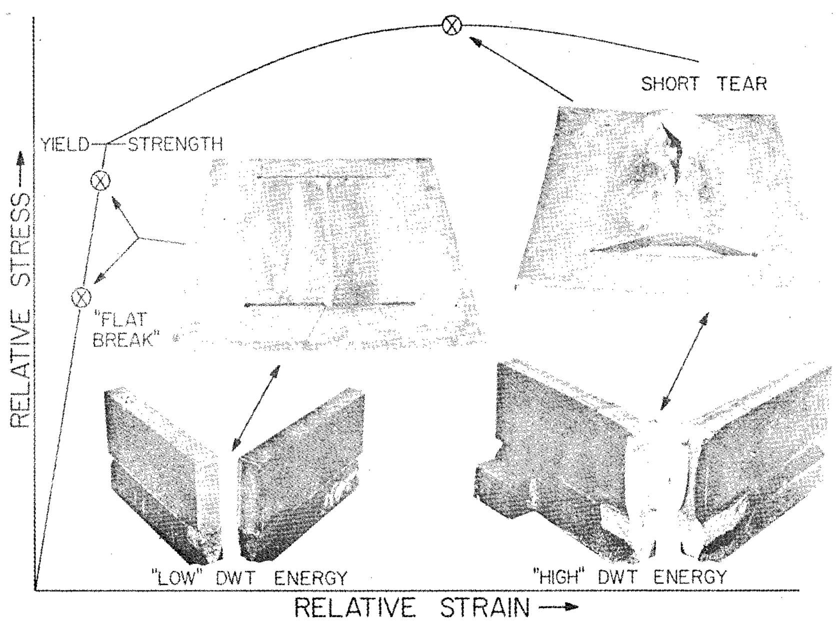

Figure A-1

information of the significance of DWTT fracture energies between the 500 and over 5000 ft-lb levels. DWTT results may now be used for preliminary predictions for the level of fracture resistance in the presence of flaws of various sizes which may be expected to be present as the result of fabrication or to be developed as the result of fatigue or other causes. Continued research is expected to provide for more exact definitions of flaw size-stress to fracture relationships.

Correlations between DWTT and the C_v test have provided a means for calibrating the significance of the C_v test which is the standard tool for fracture toughness evaluation available to industry. Figures A-2 and A-3 present these relationships, as developed to date. These correlations make it possible to use the C_v test values for prediction of fracture resistance in the presence of flaws.

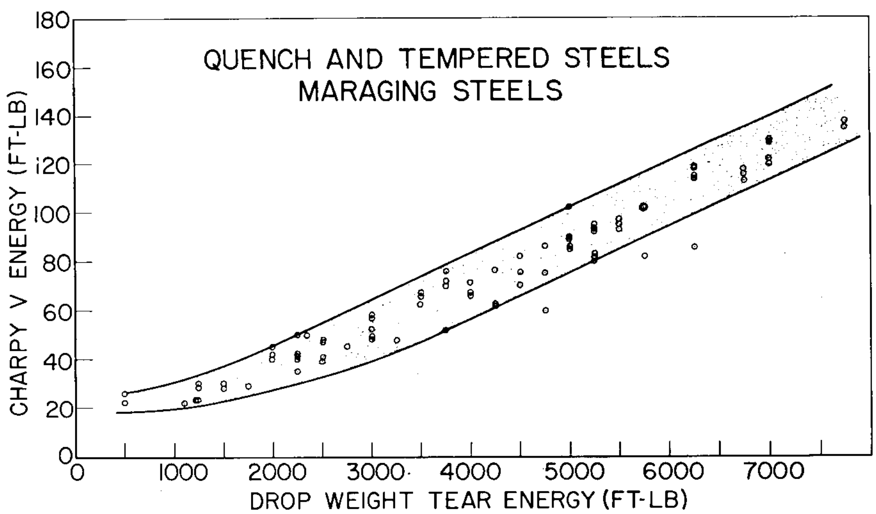

Fig. A-2 - Quench and tempered steels maraging steels

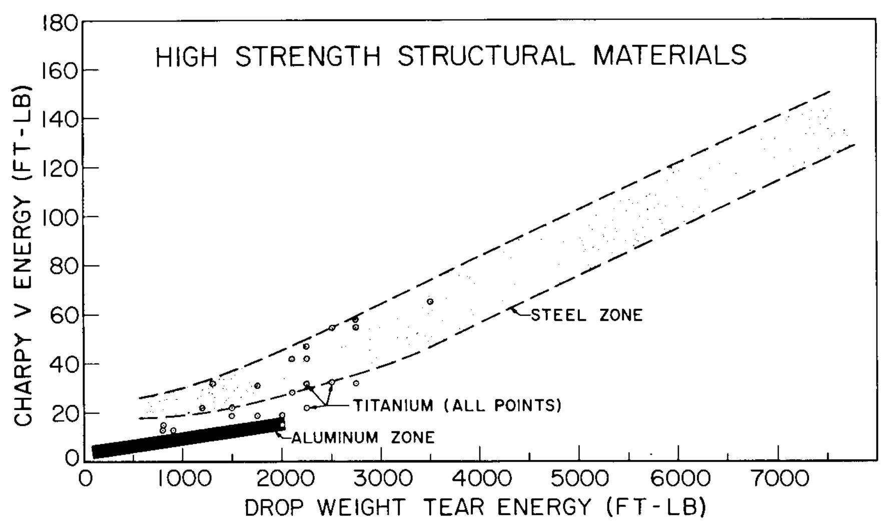

Fig. A-3 - High-strength structural materials

A summary of 30°F DWTT tests and C_v test equivalents for 1" thick titanium plates is presented in Fig. A-4 as a function of the yield strength of the test material. It should be noted that a wide range of fracture toughness may be developed by different alloys of the same strength level; however, the maximum for the strength level decreases with increasing strength level. The limiting, ceiling curve has been designated as the "optimum material trend line" (OMTL). This limiting curve may be recognized as the "yardstick" for evaluation of alloys, and as a point of reference for design and for specifications. Explosion tear tests conducted for a limited number of "points" shown in the figure established the pre-fracture strain cut-offs illustrated by the large arrows. By extrapolation to the OMTL, it is deduced that (for presently definable alloys) 135 to 145 ksi is the maximum strength level for which it is possible to develop pre-fracture strains in the order of 1 - 2%. It should be noted that in no case was it possible to develop over 5% strain without resulting in complete fracture of the titanium alloy plates.

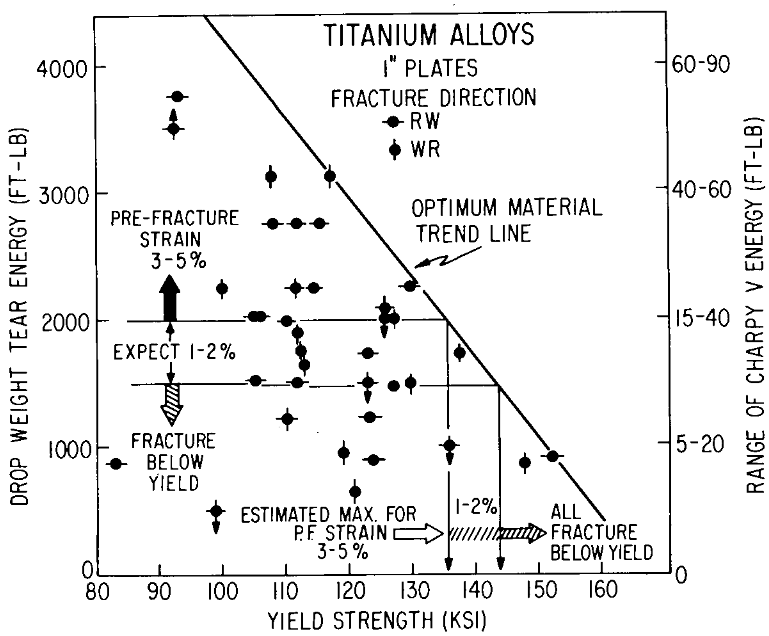

Fig. A-4 - Titanium alloys (1-inch plates)

A summary of similar 30°F test information for 1" thick steels is presented in Fig. A-5. These data are separated into two characteristic groups which relate to the processing of the metals. Conventionally processed steel features approximately a 3-1 cross-rolling ratio. As such it has a pronounced "fiber" direction and features lower fracture toughness in the fiber (longitudinal) direction. The data for conventional rolling relate to tests in the "fiber" or "weak" direction. Tests conducted across the fiber would result in much higher DWTT values and resistance to explosion tear test fracture. Special processing involving highly cross-rolled material and improved melting practices results in material which has essentially equal properties in all directions. (A similar separation was not made for titanium because the available material did not disclose significant directionality.)

A major point of difference between steel and titanium alloys that is evident from these data is the consistent rise in explosion tear test resistance with increase in DWTT energy to a point of fracture refusal. At levels over 4000 ft-lb DWTT energy, as much as five successive explosion load shots will not result in complete fracturing of the

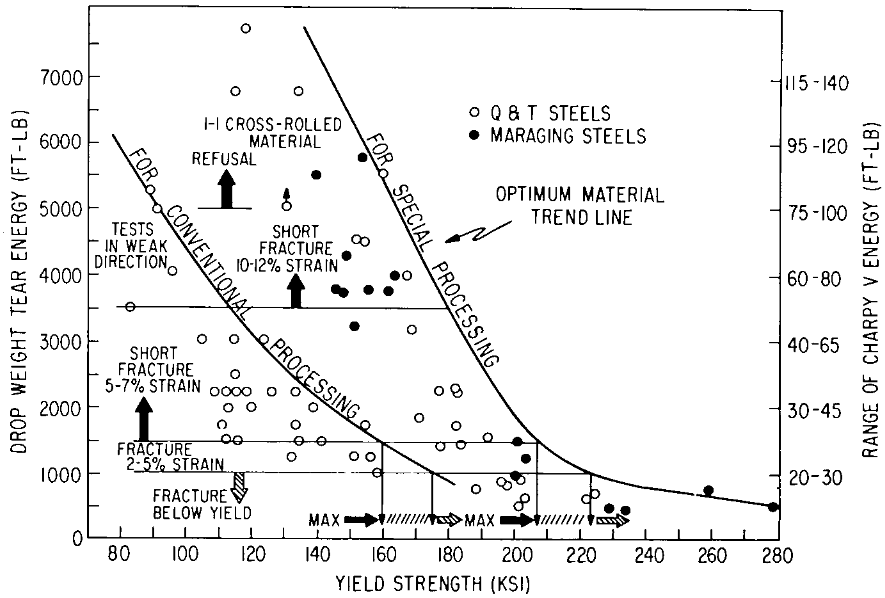

Fig. A-5 - High-strength steels (1-inch plates)

explosion tear test element (HY-80 performance). By extrapolation to the two respective OMTL curves, it is deduced that the maximum yield strength levels (of presently definable steels) for which it is possible to develop pre-fracture strains in the order of 2 - 5% are as follows:

(1) for conventional processing 160-175 ksi

(2) for special processing 205-225 ksi

The development of similar information for aluminum alloys is presently underway. The limited amount of available information is summarized in Fig. A-6. A summary comparison of OMTL data for these various materials on a strength to density basis is provided in Fig. A-7.

It is apparent from the presentation of these data that it is feasible to define the decrease in fracture toughness with increasing strength in terms of the OMTL relationships. Such definitions apply specifically to the optimum material for the strength level. On this basis it is then possible to "pinpoint" a narrow range of strength levels in which the optimum metal loses its ability for ductile (plastic) behavior in the presence of small cracks. The T-B bands of the FRC projections represent estimates of the described "transition" in fracture properties. It should be recognized that this definition is based on a flaw size which may be visualized as being in the range of 1" - 2". With increase in strength level it is well known (from rocket case studies) that the critical flaw size falls to levels of .1 to .01 inches. Thus materials of the highest strength levels indicated in the FRC charts, represent fracture toughness levels that may be classed as very low, i.e., the metal is highly brittle compared to the "brittle" designation of the B line of the T-B band. The T-B band may also be recognized as the transition zone to fracture toughness levels which provide for fracture mechanics analyses - the material is now sufficiently brittle for fracture at elastic level loads in the presence of reasonably small flaws. In other words, exact definition of flaw size and stress level is required for fracture-safe design at strength levels above the T-B band. At strength levels which do not exceed the band, fracture-safe design is decided by the inherent ductility of the

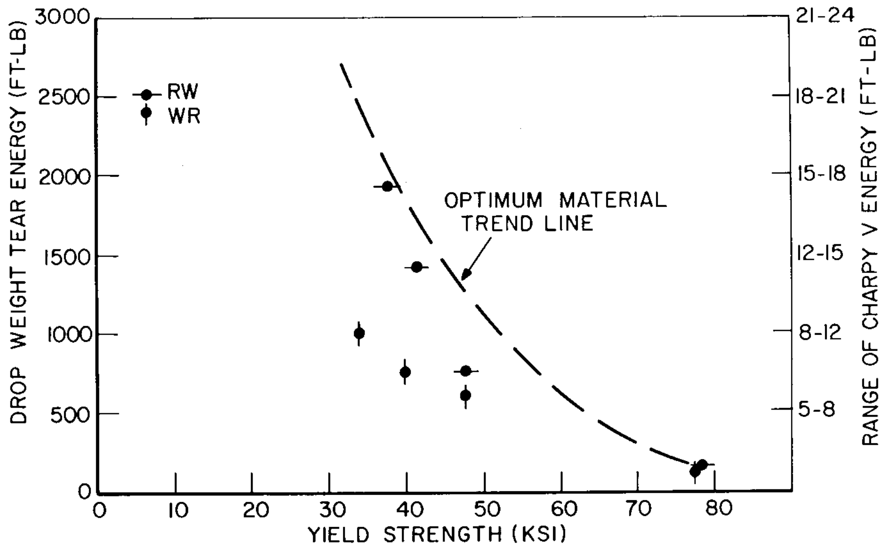

Fig. A-6 - Aluminum alloys (1-inch plates)

material, with good margin for stress and flaw size deviations. The important aspect is that a change from material ductility controlled fracture safety to flaw size-elastic stress control of fracture safety, occurs in a narrow range of yield strengths. The definition of the T-B range in the FRC projections for the base metals and for the weld zones represent a major forward step in understanding the characteristics of these high strength metals.

It should be recognized that regression to levels of yield strength below the T-B range provides increased fracture toughness following the slope of the OMTL curves for the material. Accordingly, design decisions to require high levels of fracture toughness will automatically result in decreasing the strength level which may be utilized for construction. Thus, fracture toughness should be recognized as a trade-off element - "going strong" means gradually losing fracture toughness and finally attaining a brittle state. The role of the materials field is to provide material which is of optimum fracture toughness for the strength level. The designer must decide "how much" fracture toughness is required for a specific application. When this decision is made the maximum level of strength is automatically identified.

For an expansion of this discussion, the reader is directed to the following references:

"Practical Considerations in Applying Laboratory Fracture Test Criteria to the Fracture-Safe Design of Pressure Vessels," NRL Report 6030.

"Metallurgical Characteristics of High Strength Structural Materials": First Quarterly Report, NRL Memo Report 1430; Second Quarterly Report, NRL Memo Report 1461; and Third Quarterly Report, NRL Report 6086.

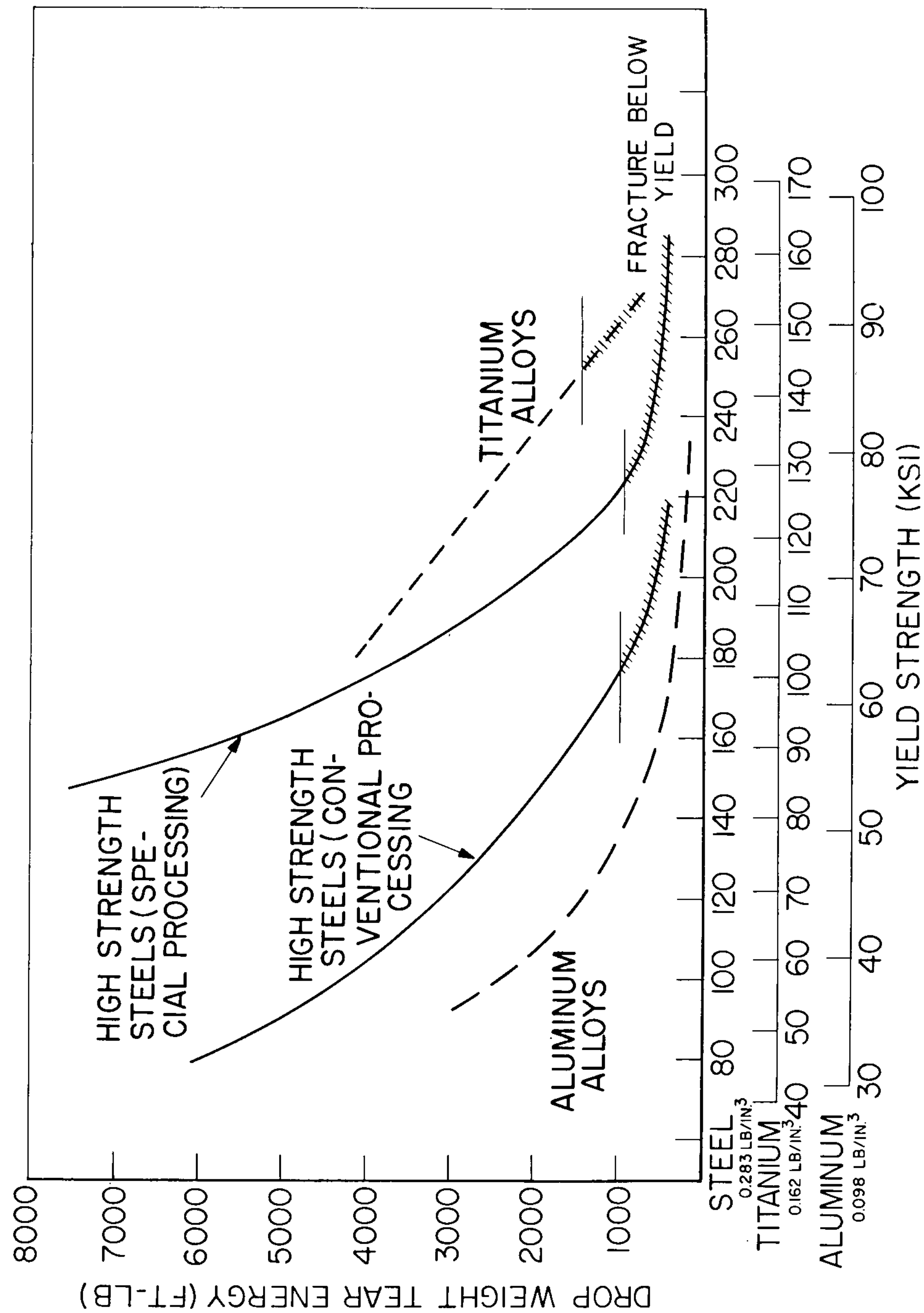

Fig. A-7 - Optimum material trend lines. High-strength steels, titanium alloys, aluminum alloys at equivalent strength-to-density ratios

APPENDIX B

FRAME OF REFERENCE CHARTS

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The frame of reference charts (FRC) were designed specifically for the purposes of this report. The intent was to provide a maximum amount of exact information in the most compact form. Figure B-1 provides interpretations of the relatively simple code system used in the charts. Each FRC relates to fabrication capabilities for a specific class of materials, as projected to approximately 1970 and to 1980-85.

A separation is made in the size of the structure and in the structural density ranges that may be of design interest for the size range. The shapes and structural concepts include spheres and stiffened cylinders of single and double wall construction. The wall thicknesses were determined from "broad brush," first order approximations based on the stated parameters. This information was obtained by consultation with the Vehicles Panel.

The structural aspects are detailed in the left-side "box" of the charts and serve as the point of entry in use of the charts. For example, a possible preliminary design question may be:

> "To what strength level is it possible to project fabrication of a slightly buoyant <u>steel</u> capsule ($50\#/ft^3$) of 20' diameter (a) if fracture toughness is considered a requirement and (b) if it is not considered?"

The answers for the particular set of projections (hypothetical for this example) illustrated in Fig. B-1, are given by the circled points noted as (a) and (b). An infinite variety of such questions may be formulated and answers obtained by reference to the various charts.

The separations of structural size and metal wall thickness serve to define levels of technological attainment that are sensitive to such factors. For example, the technological problems of fabricating a simple structure representing a 10' diameter sphere of 2" wall thickness may be quite different from those representing the fabrication of large diameter submarine of 8" wall thickness. These differences are reflected in the estimates provided for each size and for the range of wall thickness represented for each size. In some cases, fabrication capability cut-offs are indicated at certain limiting thicknesses. In each case, the projections are given for the range of thicknesses that are applicable to the size; or less, if these cannot be fully attained.

For the metals there are two "line" limits which designate yield strength attainability end points for the base metal. The highest level of strength that may be produced as curved plates or forgings (not necessarily as a full circle, but as sectors) is represented by the end "line" of the diagram. The highest level of strength that may be produced with retention of fracture toughness to the levels of T to B (defined in Appendix A) are designated by the "lines" which enclose the dashed band. The region between the dashed band and the end "line" limit is designated as "weld-brittle," bolt, or cement. This

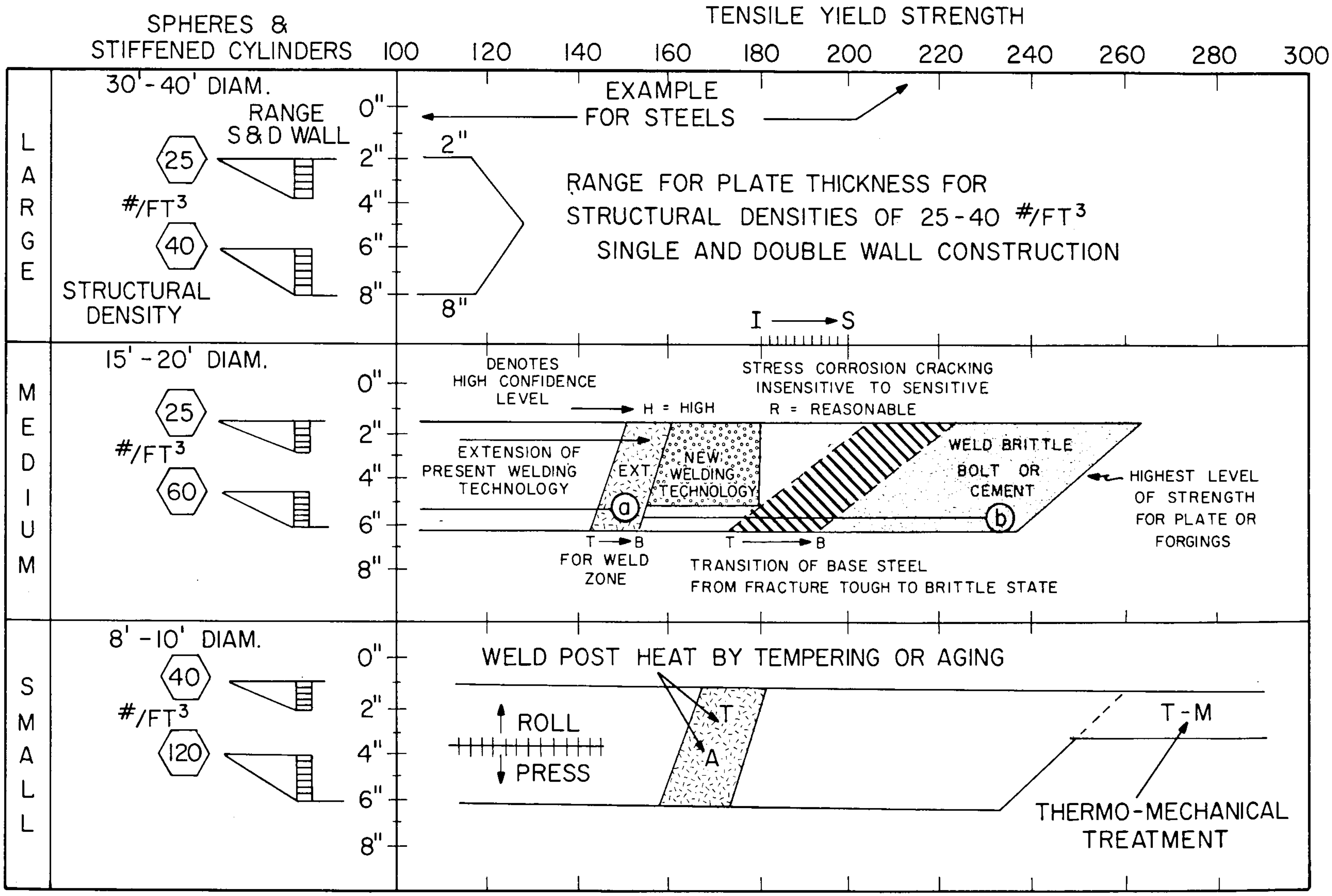

Fig. B-1 - Code of information presented in frame of reference charts signifies that the brittle metal may be joined by a brittle weld, by bolting or by cementing. It does not signify that the method of joining should be acceptable - it simply states capabilities to "assemble" material of the stated strength levels.

The highest strength levels which represent technological capabilities to produce weld joints with weld zone properties of T-B fracture toughness level characteristics are designated for two general types of welding. One of these relates to extensions of present (in use) welding technology. The subject band is coded "EXT." The other relates to the benefits expected from the use of the new welding technology and is coded as "NEW." The application of post-weld, heat treatment (as a requirement) is indicated by the designation of T (tempering) and A (aging). Thickness limitations in roll forming operations are noted by "ROLL-PRESS" which indicates a shift to press forming above the specified thickness.

Thermo-mechanical treatments may be applied to forgings of small diameter to greatly enhance the strength of the metal; such processing is thickness limited as indicated.

Stress corrosion cracking becomes a matter of design consideration in the strength range noted as a transition from the insensitive to the sensitive rate (I-S). Coating or cladding protection is required at and above the subject strength levels.

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A wide variety of hull structural materials may be expected to compete in the future for applications in both military submarines and deep-diving research vehicles. These include steels, titanium, aluminum, fiber-reinforced plastics, and glass. Additionally, composite construction incorporating different materials may be expected to be competitive. This report comprises a number of separate sections dealing with the state of the art and projections of feasible advances in the related processing and fabrication technologies. Similar dissertations are presented for ancillary materials such as hard sea water piping and buoyancy (syntactic) foams. A unique feature of these sections is represented by the use of "Frame of Reference Charts" which provide a graphical summary of the broad spectrum of strength level and fabrication techniques that may be utilized for the construction of metal structures. This information is applicable also for the construction of fixed bottom installations-of special interest in this respect is a section concerned with the utilization possibilities of concrete.

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	ROLE	WT	ROLE	WT	ROLE	WT
SEABED Hull materials Steel Glass Concrete Reinforced glass Pressure hulls Alloys Welding technique Hull structural materials Submarines Deep-diving research vehicles Titanium Aluminum Fiber-reinforced plastics Sea water piping Buoyancy foams Frame of Reference Charts						

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