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Accelerating Utilization of New Materials

A Report of the

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ACCELERATING UTILIZATION OF NEW MATERIALS

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PREFACE

Today, more than ever before, the advance of technology of industry and, indeed, of our civilization depends upon materials. It is well known that our progress in the fields of space, defense, electronics and atomic energy is directly linked to the solution of crucial materials problems. Likewise materials are a major consideration in the planning, design and manufacture of systems devices and equipment that are and will be needed in such national programs as high speed transportation, the reduction of air and water pollution, exploration of hydrospace and urban renewal.

To meet these needs great advances have been made in the development, processing and application of engineering materials and in the past materials have been developed at an exponential rate. Yet even with the advances and the wealth of new materials, engineers' imaginations and the newer technologies are outstripping our materials capabilities and substantial materials barriers remain in the way of the solution of national problems.*

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* H.R. Clauser, "Challenge of the Materials Explosion," Materials Engineering, Vol. 68, No. 6, 1968.

ABSTRACT

Because of concern regarding the slow rate of introducing new materials into national programs, the Committee sought to identify the factors that promote or inhibit their use. The advantages to be derived from new materials are documented. Case histories of past material introductions are discussed. Using these histories as a foundation, the factors that constrain or which promote progress in introducing new materials into hardware are identified. The "constraints" and "promoters" are organized into four categories; technical, economic, contractual, and management and organization.

Principal recommendations are:

1. A continuing function should be established under a government organization to (a) review the status of new materials and processes, (b) identify those with a potential for wide applicability that can benefit by coordinated support, (c) organize a cooperative program to assure timely application of the selected materials and processes in government-sponsored systems and (d) in addition, discourage the expenditure of time and money for development of new materials whose properties are not adequately known.
2. A contractual clause is recommended for use by government agencies to define a quantitative scale of incentive payments to compensate for the cost involved in achieving levels of performance beyond the minimum specified.
3. Component development programs should utilize present hardware systems as test beds for new materials applications.
4. Materials cost-effectiveness analysis should consider benefits over the full lifetime of the system.

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I INTRODUCTION

A. Background

In recent years there has been a growing concern within government, industry, and academic circles concerning the pace of utilization of new materials or improved materials in military and space systems products in the United States. This has been most vividly expressed by a task group of the National Aeronautics and Space Administration (NASA) Research and Technology Advisory Subcommittee on Materials,[1] by representatives of the DoD, by an NMAB Committee on Materials Evaluation Techniques,[2] and during an American Ordnance Association special program entitled, "The Challenge of More Effective Material Utilization," presented at the Air Force Materials Symposium 1970.[3]

Varying degrees of concern over the rate of utilization of new materials were expressed by these groups. These ranged from the conclusion that the rate was entirely too slow to reasonably exploit the potential advantages of advanced material utilization to the conclusion that, in some cases, too rapid an introduction of a new material or a poorly selected application of an advanced material had led to both economic and operational problems. There was general agreement, however, that the process whereby new and advanced materials are introduced involves many factors which can contribute to success or failure and deserves careful management attention, control, and direction.

The aforementioned NASA task group was formed to study the problem because the NASA Advisory Subcommittee on Aircraft Structures, in November 1968, had expressed concern over the slow pace at which new materials found their way into aircraft design. The task group released its final report on the "Utilization of New Materials in Aerospace Structures" on October 8, 1969. They confirmed the concern of the Advisory Subcommittee on Structures by concluding "the rate of integrating new materials in systems design is extremely slow" and recommended that a more thorough investigation be conducted. Since the Department of Defense was similarly concerned with the problem, the National Materials Advisory Board was asked to conduct an in-depth study of the subject under the joint sponsorship of DoD and NASA.

In approximately this same or slightly later time frame, a new policy of procurement was emerging from DoD. In a memorandum dated May 28, 1970, the Deputy Secretary of Defense outlined "Policy Guidance on Major Weapon System Acquisition" and made it plain that before a commitment would be made to go into production, certification must be made that the following actions had been taken:

1. All the milestones that demonstrate the achievement of practical engineering design have been accounted for.
2. All important engineering problems encountered during the development have been resolved with regard to appropriate trade-offs with stated operating requirements so that production, maintenance, and operating costs are optimized.

The impact of this policy, where applied to materials utilization, was succinctly stated by the Director of Defense Research and Engineering before the Air Force Materials Symposium '70 on May 21, 1970, as follows: "We can no longer indulge in the expensive practice of incorporating into every system the most exotic materials and advanced technology merely because they are advanced. The improvements must be necessary and reliable and economical." It was further pointed out that where improved materials are required, they must be obtained at an economically feasible cost. The above references to economics were construed by the Committee to mean that improved materials must be cost-effective for the benefits received, taking into account the entire system as implied by paragraph 2 above.

It was within this somewhat modified but clarified context that this NMAB study concerning new materials utilization was initiated and carried forward.

B. Purpose of Study

The NMAB Committee on Accelerated Utilization of New Materials was formed in January 1970. Its purpose was to identify factors that promote or inhibit use of new materials, such as availability, economics, techniques for selection, fabrication technology, and design practices, and evaluate the influence of the factors so identified with a view to recommending measures that could be taken to encourage the prompt utilization of new materials and processes in newly designed systems in which they would provide advantage.

For the purpose of this report, a "new material" is defined as one possessing properties substantially different from those of any existing material. Included in this broad definition is the span of materials ranging from those materials that differ only in heat treatment or in composition from a conventional material all the way to the radically new types, such as pyrolytically deposited forms or fibrous composites. A changed product form (sheet, compared to bar or castings, for example) can qualify as a new material since mechanical properties and formability may differ significantly.

The factors for which an investment is required before a new material may be considered relatively mature and acceptable for production applications are:

(1) Optimization of composition.
(2) Optimization of heat treatment.
(3) Development of production processes to make a uniform, reproducible product.
(4) Development of a sufficient range of product forms.

(5) Development of fabrication processes such as forging, forming, and the wide variety of metal removing processes.

(6) Development of appropriate joining processes, such as mechanical fastening, brazing, welding of all kinds, diffusion or adhesive bonding, etc.

(7) Development of oxidation and corrosion protection systems for environmental protection.

(8) Establishment of suitable design mechanical properties, especially for fatigue and for fracture mechanics criteria.

(9) Preliminary service experience to motivate confidence in a material.

C. Scope

Engineering materials for DoD/NASA systems include a broad spectrum: structural materials, fuel and lubricants, paints, adhesives, electronic materials, etc. In this report, primary emphasis has been given to structural materials as a model. It is quite probable that factors that promote or inhibit the use of a new structural material also are fairly good measures for other kinds of materials. Similarly, there are many materials the use of which extends over a broad spectrum of the economy, and it is believed that accelerated development and utilization of new materials over the entire economy can be beneficial to the country at large. While no attempt has been made to examine this broad materials picture, the measures evolved in this report may be useful in connection with this broader problem. Our concern throughout relates to materials that have emerged from the laboratory — getting recognized materials of promise actually used.

II COMMITTEE APPROACH TO THE TASK

The Committee reviewed and discussed the activities described in the Introduction. It was decided that in order to understand better and define constraints and promoters, it would be very helpful to study actual case histories of projects involving the use of new or improved materials to determine what factors had promoted progress and what factors had inhibited or restrained progress. Brief summaries of a few of these case histories appear as part of the section on "Findings" to illustrate how these case histories contribute to identifying actual constraints and promoters that can and do occur in product development, design, and production.

Based on these case histories, on Committee discussion, and on his own experience and understanding, each Committee member was then asked to summarize his thoughts regarding:

1. What are the major constraints to rapid material development and introduction?
2. What can be done to remove these restraints? What are the factors that promote the rapid introduction and use of an advanced material?

To organize the material evident from the case history studies and from the summaries submitted by the Committee members, a tabulation was prepared which listed factors that constrain and factors that promote rapid utilization of new materials under the four general headings:

- Technical Factors
- Economic Factors
- Contractual Factors
- Factors involving Management and Organization

This is shown in Appendix A in tabular form based on the matrix below:

	Factors Constraining Use of New Materials	Factors Promoting Use of New Materials
Technical Factors		
Economic Factors		
Contractual Factors		
Management and Organizational Factors		

The resulting summaries appear in Section III of this report, entitled "Findings," which highlights and summarizes major considerations that the study identifies as affecting the introduction and utilization of advanced materials.

Based on the findings outlined above and summarized in Section III, the Committee then prepared "Conclusions" and "Recommendations," which appear in succeeding sections under those respective headings.

III FINDINGS

A. Benefits of Prompt New Materials Utilization

The benefits of a new material are usually expressed in systems capability gains only. Often this leads to a disenchantment, as soon as negative effects, such as higher material cost, development cost of adapted manufacturing techniques, or the initial lack of reproducibility of material and/or end-product properties, are taken into account.

These negative effects, which often are present during early use of a new material, become less significant when their temporary nature is recognized and their cost is prorated over the entire systems program. The advancement achieved in materials technology and application in presently evolving DoD/NASA systems provides the basis for more confident use in even more advanced material applications in the future.

As important as systems capability, of course, is the system's performance over its entire life. Increased component life and reliability, and reduced maintenance requirements, etc., often more than offset the initial negative factors, so that the total benefit is considerably higher than indicated by capability gain alone.

1. Definition of Benefits

In the following overview and classification of various types of benefits or payoffs, the term "product" is used in a very general sense, comprising complete systems as well as individual components.

Classification of Benefits Derived from the Use of Advanced Materials

(1) Primary Direct Benefits

  (a) Satisfaction of critical requirement for which no material existed
  (b) Product performance gain
  (c) Product cost reduction
  (d) Combination - Trade-off of (b) and (c)

(2) Secondary Direct Benefits

  (a) Increased product reliability
  (b) Improved producibility, repairability

(3) Indirect Benefits

  (a) Increased product life
  (b) Reduced maintenance requirements, cost
  (c) Generating advanced design concepts
  (d) Better utilization of resources

(4) Projected Benefits

  (a) Capabilities growth potential
  (b) Potential of new applications, markets
  (c) Providing for anticipated depletion of resources or future unavailability of presently used material
  (d) Readiness for future (forecast) critical requirements

Benefits are classified into the four major categories, which are discussed below:

Primary direct benefits are those that exhibit a direct relationship between the material property improvement (strength increment, for example) and the performance benefit. One case, which is rather rare, is 1(a), representing the complete lack of capability (material, design) to meet a critical requirement. A perfect example is the re-entry nose cone or heat-shield requirement of the early 1950's. It required little coordination, since its critical importance opened all doors to R&D and funding. Further, negative secondary characteristics, such as high cost or weight, were disregarded as long as the primary capability was achieved. Less dramatic examples are weldable high-strength aluminum alloys in the early 1940's or temperature-control coatings for the early satellites.

The effectiveness of materials in 1(b), 1(c), and 1(d), which are of a more conventional nature, is judged more carefully by a trade-off of positive and negative characteristics. The R&D efforts are (or should be) commensurable with the total systems gain derived from advanced materials. However, in the case of a national emergency, some otherwise conventional benefits may move into category 1(a).

The secondary direct benefits also permit a direct relation between materials characteristics and product effectiveness. However, the materials characteristics involved are usually – though incorrectly – considered of secondary importance and often enter the picture only after a material has been selected on the basis of primary properties. This applies particularly to producibility. Such benefits should be assessed in conjunction with the primary properties for determination of performance gains.

Indirect benefits are those that become apparent during product use, especially on a long-term basis. They consist either of positive benefits (product life, generation of advanced design concepts) or in the reduction of negative characteristics, such as maintenance cost, damage to the environment, or waste of resources.

The projected benefits are related to a gradual growth in capabilities and applications, or to forecast critical requirements. In both cases, the benefits become more tangible as time proceeds.

2. Measuring the Benefits

Only in very rare cases can the properties of a new material be used directly as a measure of its benefits. The most meaningful measure of benefits is the gain obtained in product applications.

Anticipated benefits should be assessed at the interface point between basic and applied research and the determination should be decisive for the initiation of materials development. Since at this point there is no existing material for hardware demonstration, the expected benefits have to be assessed analytically. As soon as experimental material becomes available, the gains indicated by the analytical assessment should be verified by typical hardware evaluation before the new material is announced or any production investments are made.

The failure to recognize the necessity of an early and critical definition of benefits has, in the past, led to disappointments among researchers and economic losses in the material-producing industry.

In the analytical assessment, the gains should be expressed, whenever possible, in numerical terms, relating material properties, or a parametric expression of a set of properties, to the gains obtained in the final product. Numerical methods are described in AFML-TDR-64-94, "Improved Technique for the Assessment of Materials Requirements for Future Weapon Systems."

The form or dimension in which the benefits are expressed depends, of course, on the type of product and the user. For some products and users, it may be defined by one single term, for others, by the trade-off between several terms or the combined benefits encountered by various users (e.g., the material producer, the product manufacturer, and the government).

For the definition of total effectiveness, a trade-off is further necessary between gains and negative factors, i.e., investments and return. The cost of R&D is, of course, always a negative factor. In the context of this study, the ultimate measurement for the value of a new materials development program is a trade-off between R&D investments, and the net total gain comprised of all post-R&D positive and negative factors.

3. Role of Benefits in Materials Acceptance

The significance of gains in the acceptance and success of a new material is apparent. What requires emphasis is that considerable time is required for the growth of a new material, during which the benefits cannot fully materialize. The growth of a new material consists of a sequence of phases; the maturing phases from R&D to systems integration and service are characterized by several acceptance points. The overall growth rate is highly dependent upon the quality and precision of the gain analysis.

The ultimate success of a new material is marked by acceptance by the product user and return on investment by the user, product manufacturers, and material producers as well as supplying industries (equipment manufacturers, etc.). Eventually the cycle should be closed by a back-feeding of an appropriate portion of profits into the R&D sector in support of new ventures.

In promoting the utilization of new materials, a word such as "worthy" modifying "new materials" is strongly implied. It is possible to point to cases in which the accelerated use of a new material that had not been adequately characterized and had a latent weakness has resulted in dismal performance and costly replacement. Therefore it is emphasized that great care must be exercised in fostering early utilization of new materials.

B. Typical Case History Studies

As indicated in Section II, the Committee studied a number of case histories involving the development and introduction of new materials to determine what factors constrained and what factors promoted the prompt introduction of advanced materials. Following are brief summaries of four of these case histories to illustrate how they contributed to identifying actual constraints and promoters that can and do occur in product design, development, and production. The unabridged case histories are contained in Appendix B.

ALUMINUM CONDUCTOR TELEPHONE CABLE

For some time the telephone industry had recognized that it was deeply affected by the availability and price of copper used in telephone wire and cable. The supply and the cost of copper have fluctuated periodically in recent years owing to many factors, some of which are beyond the direct control of the United States. As a result, a major telephone utility company began an extensive development program aimed at finding an alternate material to copper for telephone cable. Requirements were established for a material that would replace copper. Because these requirements extend from design to manufacturing and installation, it was clear that a systems approach had to be followed. Metallurgists, cable designers, manufacturing development engineers, and installation engineers worked together to develop a satisfactory alternate material.

It was known that aluminum met most of the requirements. Earlier, this company had unsuccessfully experimented with aluminum conductors. Corrosion problems were catastrophic because of the type of insulation available at that time. This problem was surmounted by advances in non-corrosive plastic insulation and cable design. Other problems, such as obtaining the optimum temper, were encountered but overcome by metallurgical and manufacturing development efforts. A pilot line provided valuable production experience and data, and produced cable for a successful set of field trials. Limited commercial production is now under way.

This case history is significant because it illustrates several important ingredients or conditions that assist in the introduction of new materials or the development of materials for new uses.

1. There was an economic driving force;
2. The development agency and the user of the product were all within one overall corporate enterprise;
3. A total management decision and commitment was made;
4. A total systems approach, involving people from a range of disciplines, was used; and
5. Adequate resources were supplied.

HY-80 STEEL FOR SUBMARINE STRUCTURE

The U. S. Navy Bureau of Ships purposely embarked on a program to develop a new steel to be used on submarine pressure hulls. The steel was required to be worthwhile in terms of improved military characteristics. In order to meet this requirement, its yield strength would have to be significantly higher than the steel then in general use and would also have to be consistent with the attainment of good ductility, toughness, and resistance to low cycle fatigue. In other words, together with higher yield strength, all other desirable properties must be close to or better than those of its predecessor. Since the high tensile steel in use had a yield strength of 47,000 psi, it was decided that the new steel should have a minimum yield strength of 80,000 psi or almost twice as much.

A steel with these properties, called HY-80, was developed. It was thoroughly tested in the laboratory and in ship-type structural components. New welding materials were developed concurrently. As is often the case, certain development problems were encountered in early production, but with applied effort and care these were overcome. Finally the material was used in submarine production and is now available under Military Specification MIL-S-16216. This development resulted in the production use of a structural material far superior to the previously used material. Although the material is more expensive, the cost of pressure hulls was approximately the same for submarines of equal military characteristics. However, by utilizing the newer material, it is possible to design submarines of greatly increased performance.

This case history demonstrates key factors that hasten or make possible the introduction of a new or advanced material with superior physical characteristics.

1. A requirement for increased performance was a driving force;
2. The requirement was met by the total-phased development (metallurgy, welding development, fabrication techniques, etc.) of a weldable steel having greatly increased yield strength;
3. The newly developed material was competitive on a strength to cost basis; and
4. The requirement-establishing agency, the design agency, and the ultimate user were all part of a single, large-management structure, namely an arm of the U.S. Government.

HIGH-MODULUS, HIGH-STRENGTH COMPOSITES

High-strength and high-stiffness continuous boron filaments produced by chemical vapor deposition were reported in 1959. A short time later, boron fiber-reinforced plastics demonstrating good properties were tested. Because of the latent potential for development of a structural material of greatly increased strength-to-weight and stiffness modulus, the Air Force Materials Laboratory (AFML) in 1960 initiated programs to characterize boron-epoxy composites. In 1965, the AFML created the Advanced Composites Division to develop and exploit the use of this material in aircraft structure.

Under funding of about 10 million dollars per year, all phases of boron filament and boron composite material production, characterization, and fabrication into prototype components were forcefully accelerated. Good quality pre-impregnated tapes became available in 1967, and automated-type laying machines were demonstrated as having a capability of efficiently producing multi-oriented boron/epoxy laminates. Early structural components, such as the F-111 horizontal stabilizer, CH-47 helicopter blades, and various test torque boxes were fabricated by hand layup.

Today's (1970) prices vary from $250 to $350 per pound for the fibers, with an additional cost of $100 to $150 per pound for resin impregnation. Specifications covering raw materials and pre-preg processing have been developed and are considered adequate. However, specifications are only part of the job. Since nondestructive test techniques are not always effective, and since advanced composites are high value items, quality and reliability must be manufactured into the product. Nondestructive testing techniques and the ability to use them require further development.

Some considerable design data have been developed, but they are not yet of adequate depth for all design functions. Additional data are required on fatigue and crack propagation behavior under biaxial load, and effects of holes and cut-outs.

Secondary structural components for a variety of aircraft have been constructed using advanced composites. This effort was sponsored by private industry with assistance from AFML, who furnished the filament material. Items such as F-5 landing-gear door, F-111 flap, and F-4 rudder, to name a few, have or are undergoing static, dynamic, and flight testing.

The AFML programs to design, fabricate, and test boron/epoxy aircraft components have been oriented toward primary structure. Major problems have been encountered in these programs with concerted effort being expended to solve them. Some of the problems that were considered were:

1. Joints and attachments;
2. In-process quality control;
3. Low quality of hand layup; and
4. Component design essentially uninspectable via nondestructive testing methods.

Three programs were aimed at flight demonstration of structural components:

CH-47A	rotor blades
F-111	horizontal stabilizer
C-5A	high-lift slat

Satisfactory engineering solutions have been found for all the problem areas except 3 and 4 above. It is also significant to note that the horizontal tail of the F-14 will employ an all-boron/epoxy construction.

Realistic cost figures for the manufacture of boron/epoxy composite structure have not been developed. It is reasonable to assume, however, that as production capacity and production of boron fibers increase, a cost of $150 per pound is achievable.

The previous two case histories were examples where promoters of new-material utilization were illustrated. Although boron fibers have been available for only about ten years, and progress within that time period toward developing an advanced capability structural material has been going forward with continuous support of the government, this case history identifies some constraints to the rapid utilization of a new material with potentially superior characteristics.

1. Lack of adequate design data and increasing need for more complete material characterization;
2. High material costs;
3. High production costs in the early stages; and
4. Difficulty of using nondestructive test methods for inspection.

It should be noted, however, that the emphasis placed on and funds allocated to the development of boron/epoxy composites by the United States Air Force and other government agencies, have been powerful continuing promoters for the utilization of a new material.

THE TITANIUM FAMILY

The modern history of titanium started about 1947 with the U.S. Bureau of Mines' work on extraction, consolidation, processing, and properties of magnesium-reduced titanium sponge. Production was by the Kroll process. The timing was exceptional since with the termination of the war, aerospace research and development could undertake longer-range programs. Both the defense agencies and the aircraft industry focused on the development of jet aircraft, and titanium was considered to be an important structural material.

However, at that time when intensive research in the titanium family was initiated, there was no production, no alloys, and no technology -- only visions of what might be possible. Based on those visions, the metal producers and the government strenuously attacked the problems of titanium development. As a result, by 1950/1951 commercially pure titanium and several alloys, including Ti-6Al-4V, were available for early commercial exploitation.

Some notable factors emerge from this period of intense activity pertinent to this report:

(1) Early plants were built by industry assisted by fast write-off by the government.

(2) Sponge production was subsidized by government purchase contracts.

(3) Research on all facets of titanium metallurgy was conducted by government laboratories (physical metallurgy) and industry (process metallurgy) with assistance from universities and research institutes.

The significant role of massive government financial support is inescapable in assessing the development of the titanium family. Government contracts pertinent to titanium alloy development and evaluation were large in number, especially in the period 1950 to 1958. Beyond that period, they dropped off sharply consistent with the government policy change from manned aircraft defense to missiles. Titanium production dropped to 6 percent of available capacity at the same time. Since then, contracts per year have remained stable, but titanium production gradually grew as the titanium industry slowly struggled to regain military markets. In this effort, the aerospace industry was a willing helper since titanium alloys were introduced into jet engines (military and commercial), helium bottles, Minuteman cases, and many other applications.

During the period of the 1950's, the extensive government support of physical metallurgy provided a large body of information on phase diagrams, crystal structure, and mechanical properties as affected by composition, heat treatment, and processing history. Industry support (metal and aerospace) concentrated on alloy development, product and process optimization, and fabrication problems. The Titanium Metallurgy Laboratory* was funded by the DoD to assist in the all-important process of disseminating the accumulating titanium technology to hasten the process of utilization. The DoD titanium sheet-rolling program was a response to the needs of the aircraft industry and was responsible for the development of fabrication processes for producing flat, thin-gage sheet without defects and within commercial thickness and flatness tolerances.

On the other hand, government support for titanium research and development during the 1960's, although diminished, has been more strongly oriented to current applications and is characterized as applied research. The titanium industry has carried the brunt of alloy, product and process development, and the aerospace industry has carried forward with the practical but detailed research in production processing and fabrication, as well as detailed

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* Forerunner of the Defense Metals Information Center

characterization of new and old alloys in the titanium family. This latter effort is an important one and is tied closely to the problem of evolving structural design methods and confidence.

From extensive case histories provided to this Committee by the Boeing Airplane Company and by Lockheed-Georgia, it was shown that for cargo and transport jet aircraft, each succeeding airplane had a larger use of titanium alloys than did the previous one. Sometimes the reasons for increased use were a consequence of the special properties of titanium, sometimes as a result of the addition of new alloys and new product forms. The major reason was an economic one. The average price of titanium products decreased from about $18 a pound in 1951 to about $7 a pound in 1970. At the same time, the utilization rate (ratio of the pounds of alloy purchased to pounds actually used) dropped from about 7 to 3.5. Both factors increased the economic incentive to the use of titanium.

It should be stated that over this approximate 20-year period, the titanium family has matured through massive government/industry financial efforts to the point where four major aircraft presently under development will use large weight fractions of titanium alloys. Developments still continue to evolve that promote the role of titanium. The fruition of several years of intense effort has produced, within the last three years, for that old alloy, Ti-6Al-4V, aircraft structure of electron-beam welded section, an overaged heat treatment for high toughness and stress-corrosion resistance, continuously rolled sheet, and now precision castings. This is the maturing process at work.

From that brief review, among the factors that promoted the use of titanium are the following:

(1) Establishment of a strong interest by DoD agencies and the aerospace industry in titanium as a potentially important material.

(2) Provision by the government of economic incentives to the metal producers: tax write-off and subsidies.

(3) Massive infusion of government funds to stimulate and amortize research and development.

(4) Stimulation of the consolidation and dissemination of titanium technology to industry.

(5) The development of new alloys and products by the titanium industry.

(6) The consistent desire by the aerospace industry to find uses for titanium to take advantage of its special properties.

(7) Substantial government funding support for applications not cost-effective at that time.

(8) The government support of titanium usage at the crucial application stage and the benefits of the material itself enabled the production of the metal to increase, thereby reducing the cost to where its use can be justified on an economical basis and on an increasing product base.

The above discussion shows that government policy decisions have had a strong influence in promoting utilization. The discussion also shows that if the support is withdrawn, the growth in utilization is retarded.

C. Summary of Findings

The discussion below derives directly from the tabulations of Appendix A which summarize factors that constrain or that promote use of new materials.

TECHNICAL CONSTRAINTS

a. Gross lack of adequate design data: There is a great reluctance to use a material in a DoD/NASA system until a large amount of property data regarding it has been determined. This is especially the case for structure and process sensitive properties, such as fracture strength, fatigue strength, fatigue-crack propagation, and environmental effects. Acquisition of this data is both time-consuming and costly and results in real delays in new material utilization, if not outright rejection in favor of an off-the-shelf material.

b. Limited availability of a variety of product forms: At the time a new material reaches the stage where the producer is offering it in the market place, it rarely occurs that the material is available in the variety of product forms, shapes, and sizes that would rapidly promote widespread use in a short span of time. The delays are genuine and reflect the relationship between the real market for the material and the limited resources of the developer/producer company.

c. Limited availability of processing and fabrication information: A large percentage of user expense in adapting to a new material is involved in learning to process and fabricate useful structural components. The time spent by individual companies in developing techniques and reliable process specifications for welding, brazing, forming, forging, machining, heat-treating, etc., contributes to the delay in utilization of new materials.

d. Uncertainty of performance and reliability of a new material in service: While this factor relates to the adequacy of design data, it is more strongly related to the time-consuming process of accumulating end-item experience. To minimize the inherent risk factor, most companies prefer to evaluate a new material in noncritical applications. As confidence builds up in its performance, wider usage of the materials occurs in the more critical locations.

TECHNICAL PROMOTERS

a. Advanced development programs involving the use of new materials: One of the main ingredients to stimulate confidence in a new material is its actual use under service conditions. Advanced development programs are an important mechanism to bring this about. During such programs, material and process optimization can be achieved, design and production experience gained, and real life experience can be generated.

b. System requirements that stimulate the need for new materials: DoD agencies and NASA can stimulate the desire to use new materials when systems requirements necessary to meet performance objectives are established so that their attainment requires the use of advanced materials.

c. Materials tailored to specific product requirements: The clear and timely recognition of specific attributes required of a new material to achieve a recognizable advance in DoD/NASA systems can provide a stimulus and target for new materials development.

ECONOMIC CONSTRAINTS

a. Low volume production and sales with high attendant costs: Since the real market for a new material is small compared with its potential market, initial pricing is high until the mass market appears. This reflects the developer/producer's need to recoup research and development costs. The potential user can only conservatively estimate the final market price in making cost judgments in competitive procurement. This is a real and discouraging bar to new material selection, unless the material has specific characteristics that outweigh all competitors in achieving performance aims.

b. Processing and fabrication cost uncertainties: Coupled with the basic high price of many new materials is the concomitant uncertainty of how much it will cost to learn to fabricate and process new materials and the final production costs, after processing and fabrication steps have been established.

c. New materials and product forms may require extensive new production facilities: The requirement for new production facilities occurs for some materials and product forms both at the producer level and at the user level. The initial low-volume market inhibits acquisition of equipment needed in order to make certain product forms.

d. Difficulty of demonstrating cost effectiveness: At the time when material selections are made, several cost figures are usually uncertain:

1. Cost during future production of conventional materials (several years ahead, at the time of actual production of hardware).
2. Future costs of improved conventional materials.
3. Most uncertain of all, future costs of a newly developed material, which may not have gone beyond pilot production.

Not only is the estimating of costs difficult, but the benefits to be derived also involve a degree of uncertainty (will its corrosion-resistance really be as good as anticipated? Will dimensional control permit the weight-saving anticipated, etc. ?).

ECONOMIC PROMOTERS

a. Demonstrable economic advantage or technical advantage: New materials, product forms, and processing innovations that clearly project reduced costs and meet product requirements invariably boost early acceptance and utilization. Of these three factors, new product forms and processing innovations may provide more clear-cut channels to the forecast of reduced cost.

b. Large market potential: Although the DoD/NASA materials market may be large, it is not universally so for all new materials. Thus, the recognition and adaptation of new materials in other commercial markets of substantially higher volume is a positive stimulus to the developer/producer of a new material.

c. Stimulation of facilities development: At some stage for certain materials, it can be recognized early that rapid exploitation of a new material can be stimulated by the development of special processing facilities that cannot be underwritten either by the producer or by the user based on a limited initial market. Assistance by government agencies either by outright purchase or through tax advantages can be a positive influence in promoting such materials.

CONTRACTUAL CONSTRAINTS

a. System specifications deny the use of new materials: System specifications frequently restrict the use of other than fully developed materials. If technology is to advance, means must be found to encourage alternative materials approaches in contracts.

b. There is an implied unilateral risk to the contractor: While there may be no bar in a contract to the use of new materials, the contractor may experience an implied risk that is unilaterally faced. Although preliminary information on a new material may suggest that performance benefits may accrue by its use, unless proper recognition is given in the contract, it is the contractor alone who may have to assume the responsibility with regard to cost, performance, and unforeseen retrofit requirements.

c. Accelerated procurement schedules discourage the use of new materials: Certain recent major procurements have compressed prototype and production models to the point where there are no alternatives available but the use of conventional materials. Phased development, which provides realistic separation between prototype and production models, offers far greater opportunity for performance gains possible from use of advanced materials, with much lower attendant risk.

CONTRACTUAL PROMOTERS

a. Contractual innovations: There are a variety of contractual innovations that can be considered for the purpose of encouraging the use of new materials. One of these is opportunity for financial reward proportional to various levels of performance advantage, or cost reduction, through use of new materials. Another is to contractually permit alternate materials exploration with separate funding through the prototype development.

b. Contractually requiring sharing of information: During the course of systems development, materials and process optimization and design data acquisition frequently are developed at government expense. Development scheduling and other factors tend to defer or deny accessibility of this information to companies other than the contractor in a timely fashion to prevent duplication of effort in the case of new materials. Contractual devices should be developed to provide, as a line item in procurement contracts, for the documentation and dissemination of this information. Existing DoD information centers may be given a larger role in this activity.

MANAGEMENT AND ORGANIZATION CONSTRAINTS

There appears to be a strong reluctance in the program management offices of DoD agencies and NASA toward the assumption of and participation in the risks associated with the use of new materials.

a. Company management assumes the risk: When new materials are used, it is company management that bears the risk and is charged with the responsibility of cost guarantee and performance warranty. It is a lonely place to be and can result in negative attitudes at the company management level.

b. Management has concern for higher costs: This factor obviously relates to the former one in that with new materials there may well be a feeling of optimism at the technical level, not necessarily shared at the management level. The major difference is the awareness at that level by intuition or experience that there is a potential for higher than estimated cost and/or increased program risks associated with the use of newer materials.

c. Management finds it easier to bypass technology advances: Management tends to weigh more heavily inadequacies of processing information and the design data base available in new materials than do the technical people. Because of this, they may find it far easier to rationalize that the gains by choosing new materials are not adequate particularly if the system specifications, cost, and design can be met with the use of off-the-shelf materials.

MANAGEMENT AND ORGANIZATION PROMOTERS

a. Long-range planning of DoD/NASA development products: Materials development and promotion (optimization) can be accelerated if future needs are identified far enough in advance by government agencies. If the attainment of these needs is based on the need for new materials and if the needs are shared with materials producers and the users, some stimulation in promoting new materials can be expected.

b. Government-wide emphasis on new material applications: It is recognized that the materials people in the government agencies, in discharging their normal functions, do plan their developmental programs so as to focus on the most promising new materials, secure needed design information, ensure producibility, etc. However, the Committee felt that the effectiveness of their efforts in introducing advanced materials could be enhanced by placing additional emphasis on coordination, among the various government agencies, within an agency among the people responsible for materials, systems, design, and manufacturing, and with the non-government activities involved in producing and using materials. The Committee considered that the most effective instrument for accomplishing such coordination would be an organization representing all agencies with materials and systems interests. Such an organization could focus broader attention and resources on the development, optimization, and application of new materials. The Committee felt it to be inappropriate and beyond its charter to specify an organization mechanism for achieving this objective. The principal functions would be to identify new materials of potential wide applicability, to describe the necessary development program, and to reach agreement as to which parts of the task would be handled by each of the interested agencies.

c. Total systems approach to new materials utilization: Definition of total benefits of a new material by an assessment of the effect on all elements of the total system, including design considerations, manufacturing factors, material cost over an entire contract, service performance gains, and reliability and maintenance considerations, can promote new materials usage.

d. Management benefits from the advantage of new materials: Although company management bears the risk when new materials are used, it also benefits from the performance and/or cost advantage of the new materials. The rewards and competitive advantages gained from these benefits can cause a positive attitude at the management level on the use of new materials.

e. <u>Total management commitment</u>: The accelerated utilization of new materials is strongly stimulated when operating management sets up a total plan in which each segment of an organization commits its resources as appropriate. This is equally true in government or industry. An industry example is given in the case history "Aluminum Conductor Telephone Cable."

IV CONCLUSIONS

1. It was the concensus of the Committee that an undesirable delay does exist in the introduction of promising new materials in system applications. Minimizing this delay through a systematic and timely introduction of new materials in operational and currently developing systems is essential to the achievement of economic and necessary performance advantages. This will provide the base for more rapid improvement in future systems through extensive use of new materials.

2. The major causes of delay in introducing new materials into use are:

   a. Technical

      1. Uncertainties in performance and reliability in service.
      2. Limited availability of adequate design data.
      3. Limited availability of adequate fabrication data.
      4. Limited availability of product forms.

   b. Economic

      1. Cost/volume bottleneck.
      2. High capital facilities investment.
      3. Difficulty in demonstrating cost effectiveness.

   c. Management and Organization

      1. Innate conservatism.
      2. Additional management tasks associated with use of new materials.

   d. Contractual

      1. Procurement specifications limit use of new materials.
      2. Unilateral risk to contractors.
      3. Accelerated procurement schedules.

3. It should be possible to prevent, or minimize, delays caused by most of the factors listed above because, although very real, they are technical or administrative in nature and should be amenable to solution by administrative action or by technical development programs designed for their solution. Additionally, improvement should be possible by emphasizing and utilizing, where appropriate, the factors that promote early applications. The people responsible for materials programs in a given agency are aware of the influence of these positive and negative factors, and take this into account in their normal operations. The individual agency programs, however, do not provide sufficient basis for establishing broad concurrence on all the applications for which new materials are needed, on the identification of promising candidate materials, and on appropriate timing for development and introduction.

Among the attributes of a successful technical development program are:

a. Critical selection of the materials to be developed, limiting attention to only those that support the most significant and needed new system capabilities. With limited funding, selection is necessary to concentrate effort on those candidates with the largest potential payoff. Expenditure of effort in developing inadequately characterized materials, or those that will not fill a genuine need, would be discouraged.

b. Development of the material, its production base, and engineering design information base so that all the prerequisites to its use are met.

c. Providing adequate financial support to the development and establishing the needed communication link between developer and user to ensure that the requirements of 3b above are met or, alternatively, to halt development when insuperable obstacles are met.

4. To the extent that the delaying factors can be reduced and the promoter factors applied, the psychological impediments of 2c should be correspondingly diminished.

5. In view of the above, the Committee believes that there are steps, which can and should be taken on a national basis, to accelerate the prompt use of advanced materials and processes in applications wherein their use would provide large advantages for the system involved and which would not involve unacceptable risks or costs.

V RECOMMENDATIONS

1. A continuing function should be established under the auspices of an interagency government organization to assure the accomplishment of the objectives set forth below. The membership of this functional group should be broad enough to represent, with authority to commit resources, all necessary sectors of the various agencies (e.g., representatives from design, manufacturing, materials, systems, etc., as appropriate). Inputs from nongovernment sources may be obtained. Its jurisdiction should not include the basic research stage. The objectives of this function are as follows:

   a. Review the status of new materials and related process technologies through periodic discussions with producers, potential users, and materials information centers.

   b. Through critical review, identify those new materials and related process technologies that show potential of wide applicability to national problems, and that are ready to move beyond the laboratory stage and into extensive testing, development of manufacturing technology, and initial systems applications. These materials are often faced with the cost-volume bottleneck, the lack of a manufacturing technology, the lack of adequate testing, lack of design data, and other related problems. The functional group would determine the materials systems which are worthy of coordinated support among various government agencies. Concomitantly, the scale-up of materials with deficiencies, or the processing of which has been inadequately developed, or whose properties are not adequately known, would be discouraged.

c. Organize a cooperative interagency program to support coordinated efforts in advancement of technology for new materials and related process and testing methods.

2. Develop a new contractual clause for use by government agencies in connection with systems contracts. The clause should define a quantitative scale of incentive payments for the use of advanced technology, including the introduction of new materials, to be made when desired gains in performance, reliability, or cost beyond the specification values are achieved. Contractual devices should be developed to provide, as a line item in procurement contracts, for the more effective documentation and dissemination of design information relative to the new materials utilized which were developed under the contract.

3. The procuring agencies should encourage the use of present hardware systems as test beds for component materials development and testing (incorporating new materials into existing systems to get low-risk development testing).

4. Procuring agencies should insist that cost analysis associated with the cost and introduction of new materials should be computed to the degree possible on a systems-lifetime basis and not merely on a hardware-delivered basis.

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APPENDIX A

FINDINGS

In Section II, Committee Approach to the Task, it was indicated that the Committee findings from the case history studies and from committee member summaries were tabulated as either constraints or factors promoting the use of new materials and classified under the generic headings of: (1) Technical Factors, (2) Economic Factors, (3) Contractual Factors, and (4) Management and Organizational Factors.

The tables on the following pages are the result of this classification process.

FACTORS CONSTRAINING USE OF NEW MATERIALS

– TECHNICAL FACTORS –

CONSTRAINT	LACK OF ADEQUATE DESIGN DATA AND INCREASING NEED FOR MORE COMPLETE MATERIAL CHARACTERIZATION	CHARACTERISTICS DO NOT MEET ALL THE DESIGN REQUIREMENTS	INABILITY TO SPECIFY MEASUREABLE PROPERTIES AND/OR PROCESS PROCEDURES NECESSARY AND SUFFICIENT TO ASSURE MATERIALS THAT CONSISTENTLY MEET SERVICE REQUIREMENTS; INADEQUATE MATERIAL SPECIFICATIONS	INADEQUATE ENVIRONMENTAL SIMULATION AND LACK OF ACCELERATED TEST METHODS	MATERIAL AVAILABILITY	INADEQUATE FABRICATION KNOWLEDGE	INADEQUATE COMMUNICATION BETWEEN MATERIALS PRODUCERS AND DESIGNERS
POSSIBLE SOLUTION OR ACTION	Identify requisite design data and indicate approximate property values necessary for the intended application. Cite acceptable tradeoffs. Screen candidates. Select only the most promising for complete characterization in order to conserve effort. Design information is not always available where it is needed; thus, effort is needed to communicate design data information to those deciding materials selection. Store, share, review & make available to all, through materials information centers, the accumulated data available.	Identify desirable attributes such as strength characteristics and material interaction and compatibility requirements for material developers. Development needs such as modifications in composition, form or thermo-mechanical treatment to meet hardware requirements should be identified and disseminated.	An essential part of the material development process is the early development of a descriptive material specification including material qualification requirements to assure consistent performance of the material as procured. Review and updating of specifications should be continued on a periodic basis. Determine process parameters, optimize, establish controls, prepare process-oriented specifications. Identify quantitative property characteristics necessary for satisfactory service performance. In conjunction the users and producers establish at least some tentative specifications early in the material development phase.	Development and evaluation of methods to 1) simulate complex service environment and/or 2) predict long-term performance on the basis of accelerated testing. Time dependent phenomena are especially troublesome, such as corrosion, elevated temperature behavior, and fatigue. Improve means, analytical and experimental, to maximize information acquired from tests and assure applicability to production hardware.	Emphasize early change-over from pilot plant to production. Users should provide guidance on materials, forms, quantity, sizes, etc., estimated to be required. Develop multiple sources of supply and establish standards of quality. Combine user orders to increase production quantities.	Provide, through existing DOD information center activity, for more extensive collection and dissemination of production fabrication technology information. Establish active fabrication methodology development organizations under DOD and NASA that sponsor development of fabrication processes for new materials. Encourage the early involvement of manufacturing personnel in R&D programs & in establishing process specifications.	Emphasize wide dissemination of processes and instructions for design applications. Encourange communications between materials producers and potential users by including them in advance planning teams.

FACTORS PROMOTING USE OF NEW MATERIALS

- TECHNICAL FACTORS -

PROMOTER	ESTABLISH SYSTEM PERFORMANCE REQUIREMENTS WHICH DICTATE OR ENCOURAGE APPLICATION OF NEW MATERIALS	PILOT LINE DESIGN AND PRODUCTION	USE OF PROTOTYPES UNDER SERVICE CONDITIONS	PROVEN NON-DESTRUCTIVE TEST TECHNIQUES AVAILABLE	UNIQUE MATERIAL CHARACTERISTICS (WHICH MAKE POSSIBLE THE ATTAINMENT OF ADVANCED GOALS) OR A MATERIAL TAILORED TO MEET ADVANCED PRODUCT REQUIREMENTS
COMMENT OR ACTION	U.S. is denying itself competitive or military advantages by not exploiting new materials attributes. Publish advanced system requirements to encourage development of new materials and manufacturing technology (SST example). Communicate advance needs to materials community.	Demonstrates repeatability of design and production functions. Limited production, test and evaluation of critical components should be encouraged as precursor of larger production runs. Demonstrate readiness to move beyond laboratory & into extensive testing technology development & systems applications.	Exercises design & manufacturing functions, demonstrates practicality of use and builds confidence. Continue to require designs of alternate materials and develop replacement components of new materials for in-service aircraft, adequately instrument and document to insure knowledge acquisition and transmission.	Raises confidence in quality of product, helps assure satisfactory material performance in service. Techniques need be developed for material and product, part and assembly, and in-service quality control.	One or more characteristics are developed to meet the advanced requirement (example: ablative materials). Self-motivating examples: weldable aluminum, beta III titanium for high strength rivets.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- ECONOMIC FACTORS -

CONSTRAINT	HIGH MATERIAL COSTS UNCERTAIN MATERIAL COST PREDICTIONS	HIGH FABRICATION COSTS UNCERTAIN FABRICATION COST PREDICTION	SHORTAGE OF RESOURCES AND PRODUCTION FACILITIES AND LACK OF FIRM ORDERS CONTRIBUTE TO EXCESSIVE DEVELOPMENT TIME	SIZE AND AMOUNT OF MATERIAL REQUIRED TO EVALUATE FOR USE, AND TO BE ACTUALLY REPRESENTATIVE OF SIZE TO BE USED, CAN BE COSTLY FOR PRODUCER (I.E., REQUIREMENT FOR HEAVY ALUMINUM PLATE)	LACK OF FACILITIES FOR MATERIAL PRODUCTION AND HARDWARE FABRICATION
POSSIBLE SOLUTION OR ACTION	Material producer should be encouraged to lower material costs. Nonaerospace uses of materials should be sought to broaden usage base. A good predictive method or sound estimate on future anticipated cost trends would help the system planner in his forward planning. Material information centers should establish a good historical base of costs and disseminate information regarding improved estimating techniques. Overcome cost-volume bottleneck by increasing usage volume through contractual incentives.	Improved and novel approaches to tooling and manufacturing methods by development contracts or incentive clauses in systems contracts.	Creation of sources, facilities and demand in advance of production requirement seems only way to attack this constraint. A joint industry, user, government planning activity appears necessary. Joint programs to establish capability such as giant press, special extrusion facilities, and equipment pools, in advance of need are warranted.	Potential users should aid producers to establish use parameters for new materials, shapes, or forms. The government may find it necessary to support initial parameters determination where large quantities or sizes beyond producers' resources are involved.	If benefits from use offset facility cost this is self-motivating. Commitment of funds for pilot size trials. Contractual inventives or rapid recovery through tax adjustment for special facilities for new materials. Encourge the development of universal machines such as digitally guided tape layers, large presses, by government funding or fast tax writeoffs.

FACTORS PROMOTING USE OF NEW MATERIALS

- ECONOMIC FACTORS -

PROMOTER →	A SIZEABLE MARKET AND ACCEPTABLE RAW MATERIAL COST	AVAILABLE FACILITIES	A MATERIAL THAT PROVIDES AN ECONOMIC ADVANTAGE OR IS UNIQUELY CAPABLE OF MEETING AN ESSENTIAL REQUIREMENT: I.E., COMPETITIVE ADVANTAGES AND PROCUREMENT	MULTIPLE SOURCES OF SUPPLY AND MULTIPLE FORMS
COMMENT OR ACTION	The aerospace market continues large; however, corollary uses of aerospace materials in other trades should be sought out and encouraged by communications and experimental demonstrations, to increase market base, reduce unit costs and improve revelance. Use of new material is accelerated when material costs are acceptable or advantageous on a cost effective basis.	Pooling of tools, development of adaptive complimentary tools such as universal tape laying equipment in composites industry.	Self-motivating by cost-effectiveness or performance gains.	Material "availability" assures adequate basic supply on schedule. Tend to reduce raw material cost and potential program schedule impact costs.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- CONTRACTUAL FACTORS -

CONSTRAINT	THE WEAPON SYSTEM PROCUREMENT SPECIFICATION DESCRIBES AN ITEM WHOSE PERFORMANCE REQUIREMENTS CAN BE MET WITHOUT USE OF NEW MATERIALS. SINCE NEW MATERIALS ARE GENERALLY LESS ATTRACTIVE FROM COST, AVAILABILITY, RELIABILITY, OR SIMILAR VIEWPOINTS, THIS INHIBITS THEIR CONSIDERATION EVEN THOUGH SUCH USAGE MIGHT BE ADVANTAGEOUS FOR FUTURE SYSTEMS	UNILATERAL RISK BY CONTRACTOR, PARTICULARLY IN FIXED PRICE CONTRACTS	CONTRACTUAL REQUIREMENTS AND COMPETITIVE ENVIRONMENT DEMAND MULTIPLE SOURCES FOR MATERIALS. CAN CONSTRAIN USE IF MATERIAL IS PROPRIETARY
POSSIBLE SOLUTION OR ACTION	Contractual relief of the manufacturer/designer from penalties incident to new material usage. Contractual requirement or incentive to use new materials. Risk taking should be encouraged, especially where human life or essential system functions are not endangered, or where the potential gain offsets the hazard involved.	Increased incentives in systems contracts for effective utilization of new materials. Recognizing value of increased performance for defined increments such as range and speed, by contract incentives.	Incentives for multiple sources must be established, perhaps by subsidy, or special contractual arrangements. Relax contractual requirement on items scheduled for limited procurement.

FACTORS PROMOTING USE OF NEW MATERIALS

- CONTRACTUAL FACTORS -

PROMOTOR →	INCENTIVE OR DEMAND CLAUSES: LEGALLY THERE IS PROVISION FOR GREAT FLEXIBILITY IN MILITARY CONTRACTS	COMPREHENSIVE CONTRACTUAL COST ANALYSIS
COMMENT OR ACTION	A form of contract which provides a schedule of incentives for performance greater than contract minimums could encourage application of advanced materials where specific gains can be achieved.	When judging whether the use of a new material is cost effective, the cost analysis should be based on the initial cost plus the inventory lifetime cost. Some advanced materials have superior corrosion or wear characteristics and will require less maintenance. This should be considered in the selection procedure. Present contract cost analyses appear to consider only material and manufacturing costs with very limited consideration of system employment costs.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- MANAGEMENT AND ORGANIZATION -

CONSTRAINTS	MANAGEMENT CONCERN OVER THE RISK OF BEING FIRST TO USE A NEW MATERIAL BECAUSE OF HIGHER COSTS, QUESTIONABLE AVAILABILITY, ETC.	MANAGEMENT LACK OF CONFIDENCE BECAUSE OF INSUFFICIENT PROPERTY KNOWLEDGE, LACK OF ASSURANCE AGAINST DEFICIENCIES AND LACK OF ASSURANCE OF PRODUCTIBILITY	MANAGEMENT CONSIDERS GAINS ARE INADEQUATE BECAUSE SYSTEM SPECIFICATIONS, COST ESTIMATES AND DESIGN CONCEPTS ARE BASED ON OFF-THE-SHELF MATERIALS
POSSIBLE SOLUTION OR ACTION	Provisions in contract to encourage or incorporate backup programs. Solution is to extend material development effort beyond what has been normal practice. Recognition of risk factors in contracts.	This constraint can be solved through expansion of our knowledge base by prototype programs, pilot line operations and experience acquisition.	Provide incentives in contracts which encourage new material exploitation. These might take form of premium allowable costs for new material use and/or added financial gains for improved system performance increments.

FACTORS PROMOTING USE OF NEW MATERIALS

- MANAGEMENT AND ORGANIZATION -

PROMOTER	PATRIOTISM–THE NATIONAL DRIVE TO DISCOVER, DEVELOP AND CONSTRUCTIVELY APPLY INCREASING KNOWLEDGE AND TECHNICAL CAPABILITY AS AN INTEGRAL ELEMENT OF NATIONAL STRENGTH AND WELL-BEING	NATIONAL EMPHASIS ON NEW MATERIAL APPLICATIONS AND EXPLOITATIONS	LONG-RANGE PRODUCT PLANNING TO DETERMINE AND INSPIRE ADVANCED MATERIAL CHARACTERISTICS DEVELOPMENT	TOTAL SYSTEMS APPROACH– R & D, DESIGN, MANUFACTURING, SERVICE ENGINEERING, ETC., ALL APPLIED TO USING A NEW MATERIAL IN A PRODUCT
COMMENT OR ACTION	An intangible but real motivating force of our American system that needs to be encouraged on a national scale thru activities of universities, non-profits, and government agencies.	Establish a concerted and continuing effort on a national scale to maximize and accelerate near-term utilization of new materials perhaps by assignment of responsibility to a national agency. Definition of objectives for development of new materials for the next 5, 10, 15 years should be the highest priority assignment. Establish and maintain a consistent and continuing management commitment, whether government or industry, to a total plan to develop and utilize a new material for advantages which will accrue.	Foster long-range coordinated planning by producers, systems manufacturers and government agencies to discover and establish the needs for and potential rewards of new material development. Feedback to material developers is essential.	Identify and recognize the total near- and far-term advantages of new materials applications to systems, i.e., performance advantages, serviceability advantages, etc. Avoid uncoordinated proliferation and application of new materials by establishing and maintaining technical communication between producers, manufacturers, and government agencies.

APPENDIX B

Selected Case Histories of Materials Introductions

ALUMINUM CONDUCTOR TELEPHONE CABLE

Prepared for NMAB Committee on Accelerated
Utilization of New Materials June 1970
By
M. W. Sagal

It has been apparent for some time to the telephone industry that it is deeply affected by the availability and price of copper used in telephone wire and cable. Though the copper industry has said for many years that there are adequate copper reserves to meet demand, recent history has shown that the supply and cost of copper fluctuate periodically, due to strikes, control of export levels and prices by foreign governments, and occasional political unrest. Consequently, about five years ago, the Bell System began an extensive development program directed toward finding an alternative to the use of copper for telephone cable.

There are several requirements for any material that would replace copper:

1. It must be plentiful and reasonably inexpensive.
2. It must be mechanically strong enough to stand up under the stresses of manufacture and use.
3. It must be an adequate electrical conductor.
4. The material must be capable of being processed into wire.
5. The cable must be able to undergo the splices and terminal connections needed in installation.

Because these requirements extend from design to manufacturing and installation, it was clear that a systems approach had to be followed in developing a substitute material. Thus, metallurgists, cable designers, manufacturing development engineers, and installation engineers would have to work together from the early stages of the program to develop a satisfactory alternative which would meet all of the above requirements.

It was known that aluminum met most of the requirements. Aluminum is readily available and cheap. Although its conductivity is less than that of copper, it can be made equivalent by increasing the conductor sizes two gauges. The Bell System had unsuccessfully experimented earlier with aluminum conductors. Corrosion problems, particularly acute in aluminum, were catastrophic with the earlier pulp-insulated conductors. Let us now examine some of the problems that were recognized and encountered together with some of the approaches that were taken to solve them in a development program over the last five years.

Although the problems of design and manufacture are not easily separable, we can first consider some of the major design problems. One of the most significant is the corrosion problem mentioned above. Since earlier pulp insulator cable had proven unsatisfactory, it was decided at the very beginning that only plastic insulated aluminum wire could be used. However, improved cable designs were necessary to provide a proper moisture barrier to protect the aluminum wire against corrosion. Over a period of time, a new moisture barrier cable sheath was designed and developed for aluminum conductor cable to guard against conductor corrosion. In one design, a thin aluminum tape, coated on both sides with an organic adhesive, was placed between the core of wire conductors and the inner jacket of the cable. The tape provides a moisture barrier, to protect the aluminum wire against corrosion that takes place in the presence of water. Development work is continuing on new cable designs to further improve moisture protection.

Other design problems were connected with methods that had to be developed for installation, conductor splicing and termination, joining cable lengths together, and locating and repairing troubles. Many of the problems unique to aluminum were connected with finding ways to protect against corrosion, which essentially means preventing the aluminum wire from ever getting wet. One technique, used in field trials, involved encapsulating joined wires and their associated connector in a moistureproof thermosetting resin.

As mentioned earlier, the manufacturing problems are not really separable from the design problems. However, some of the manufacturing problems present unique challenges that are worthwhile mentioning here.

A serious processing problem is related to the strong dependence of aluminum mechanical properties upon temper. Normally, with copper wire, the wire is drawn down to final size through a series of dies, annealed, and insulated. It was found that this procedure would not work with aluminum. Fully annealed aluminum wire broke frequently, even on relatively slow-speed insulating lines. On the other hand, insulating hard-drawn wire was also unsatisfactory. The hard-drawn wire was not ductile enough to stand up during installation. Thus, an intermediate temper was needed. One possibility, of course, would have been to anneal to an intermediate temper. This proved to be too critical an operation to be reliable in manufacture. It was rather decided to anneal the wire at an intermediate gauge, and then draw the wire down one more gauge to final size. This has turned out to be a successful operation.

The in-line annealing part of this process has also presented many problems, again because of the peculiarities of aluminum. For example, electrical-resistance heating (by passing a current through the wire) is unsatisfactory because the growth of aluminum oxide in the heated wire surface prevents satisfactory electrical contact. Novel induction-heating techniques had to be developed in which a loop of moving wire creates a "moving" short circulated transformer secondary.

This apparatus and other associated machinery were combined into a pilot line at Western Electric Company in Baltimore. The pilot line served to provide invaluable production experience and data, and served to provide cable for an extensive set of field trials carried out in the late 1960's.

Western Electric Company has now gone into limited commercial production of aluminum wire, using techniques developed during the development program. Further design and manufacturing innovations, such as the recently announced high-pressure hydrostatic continuous-wire extrusion, are continuing.

The success of this development program can be traced to the following factors:

1. A recognition of a specific need;
2. A decision to bring all involved parties (research, design, manufacturing development, etc.) together early in the program; and
3. A willingness to commit sufficient resources of manpower and money to carry out the development in a reasonable time scale.

SYSTEMS APPLICATIONS OF NEW MATERIALS

High-Modulus - High-Strength Plastic Composites

By

W. P. Conrardy

BACKGROUND

Glass-fiber reinforced plastics (GFRP) were introduced into military aircraft in 1941. The first volume application was in radomes which utilized polyester resin and E-glass fibers. The first successful flight test of glass-reinforced plastic aircraft structures was made at Wright Air Development Center (WADC). Fiberglass reinforced plastics were first conceived, developed and designed for light aircraft structures by the Air Force, WADC, Structures Laboratory and Materials Laboratory. In March 1944 the BT-15 aircraft with a plastic fuselage was first flown at Wright-Patterson Air Force Base, Ohio. This was considered the first successful major structural component of an aircraft using glass-reinforced plastics to be developed and flown.

In 1956 glass-reinforced plastic wings for the AT-6 aircraft were successfully flight tested. During the time period between 1954 and 1960 major improvements were made in glass fibers, fiber-resin coupling agents, and resins. High strength E-glass, S-glass, and epoxy resins were made commercially available. Major structural applications of glass-reinforced plastics were made in 1960 with the successful production of filament-wound S-glass/epoxy POLARIS missile motor cases. In this time period, several commercial aircraft manufacturers developed all plastic light aircraft and one of the major commercial aircraft manufacturers (e.g., Boeing) began utilizing extensive amounts of glass-reinforced plastic laminate and sandwich material.

A chronology for the applications of glass-reinforced composites is shown in Table 1.

TABLE 1. Chronology for Applications of Glass-reinforced Composites

Year	Event
1938	First commercial availability of E-glass, fibers
1940	High-quality polyester resin commercially available
1942	AF-WADC plastic aircraft R&D initiated. ANC-17 & 23 initiated
1943	Static-tests on Vultee BT-15 plastic fuselage
1944	Flight-test of BT-15 aircraft fuselage
1946	Static-test of AT-6 plastic wings
1946	Commercial introduction of epoxy resins
1953	Flight-test of BT-15 fuselage
1960	POLARIS motor case production
1962	Flight-test of all plastic Piper "Papoose"
1962	Boeing 727 - 5000 lbs of glass-fiber reinforced plastics, (GFRP)
1962	All GFRP aircraft "Marvelette" flown
1966	All glass/epoxy CH47A helicopter rotor blades flown
1967	First flight of Windecker "Eagle 1" all glass/epoxy (6g) aircraft
1967	All plastic aircraft LFV 205 flown in Germany. Wassmer all plastic aircraft introduced in France.
1968	Boeing use of over 10,000 lbs of GFRP in 747 aircraft

As can be seen from Table 1, in the case of glass-reinforced plastics, six years after the introduction of glass fibers, a full size GFRP fuselage was flown and nine years later the all-GRFP wings. Significant advancements have been made in all phases of GFRP but to date no significant amounts of GFRP have been applied in military production aircraft. Proposals by North American Aviation, Inc. (NAA) to produce all plastic (GFRP) YAT-28 and OV-10 aircraft were turned away as being too speculative; in addition, the USAF had no requirement for such plastic aircraft. The facts that the GFRP aircraft would be stronger, lighter, and more corrosion-resistant than the aluminum aircraft were not considered important. Thus it is seen that, regardless of successful feasibility demonstrations many years ago, no GFRP are presently utilized in structural applications in military aircraft.

Some of the reasons suggested for this are as follows:

a. Analytical methods for structural (stress) analysis of composite materials were inadequate. (There are certainly some prime examples of inadequacies in this area on metal structures also.)

b. Inadequate data base.

c. Lack of design experience with composites.

d. Inefficient or vulnerable joints.

e. Lack of demonstrated serviceability, environmental compatibility, and maintainability.

f. Tooling and manufacturing facility deficiencies.

g. Inspectability and repair problems.

h. Reluctance of any special project office to be "first" in use of new materials and fabrication concepts not essential to fielding a new weapons systems on time and within budget.

i. High-level pressures to minimize risk and embarrassment.

High-Modulus, High-Strength Composites

In 1959 Texaco Experiment Inc. reported for the first time the high strength and high stiffness of chemically vapor deposited (CVD) continuous boron filaments. Very soon thereafter, boron reinforced plastics demonstrating good translation of properties were tested. Boron filaments are produced on a tungsten core. Today's prices vary from $250 to $350 per pound with an additional cost of $100 to $150 per pound for resin impregnation, depending upon quantity and quality requirements. The present combined production capacity of boron filaments (AVCO and Hamilton Standard) is somewhere in the 6000-lbs/year range. The boron-filament production process has not yet been really fully optimized and some problems have been encountered in the production of good- or specification-quality filaments. Low tensile strength has been the major contributing factor here.

The availability of the boron/epoxy composite with its excellent specific strength and stiffness made possible the consideration of this material for high performance structural applications in military aircraft.

Air Force Materials Laboratory (AFML) programs were initiated in 1960 to characterize the boron/epoxy composite. In 1963 "Project Forecast," a comprehensive program to evaluate the impact and application of this composite to large aircraft structures, was implemented. In 1965 the AFML created the Advanced Composites Division to rapidly exploit the use of this material in aircraft structures. Under the Advanced Development Project (ADP) funding of about $10 million per year, all phases of boron filament production and boron composite material, characterization, and fabrication were forcefully accelerated.

Good quality pre-preg tapes were made available in 1967 by both NARMCO and 3M.

Lacking any real automated fabrication technique, except for filament winding which is not suited for many aircraft structures, the first ADP programs involved the hand lay-up of structural components of aircraft from boron/epoxy pre-preg tape and broad goods. Early structural components such as the F-111 horizontal stabilizer, CH47 helicopter blades, and the various torque boxes tested were fabricated via hand lay-up.

With the advent of high-quality pre-preg tapes, several sources began the development of numerically controlled or otherwise automated 3D-tape laying machines. Today several machines exist that have successfully demonstrated a capability of efficiently producing multi-oriented boron/epoxy laminate lay-ups.

Additional work in the precise control of gaps between tapes and in the lay-up of compound curvature lay-ups is still required.

Specifications covering raw materials, and pre-preg processing have been developed and are adequate for their purpose. In this technical area, however, specifications are only part of the job. There will be no substitute for a well-trained, motivated, and conscientious work force and knowledgeable inspectors. Since our nondestructive inspection (NDI) techniques in many instances are not effective due to design constraints, and since advanced composite parts will always be high value items, quality and reliability must be manufactured into the part.

Proper part design that will allow nondestructive testing (NDT) access to all bonded joints, etc., is mandatory. NDI standards and critical flaw sizes must be developed. Work to improve our understanding of what the various NDI techniques are telling us must be accomplished.

Data-generation programs on boron/epoxy composites have been and continue to be thorough but due to fund limitations have not been of adequate depth. Additional data-generation programs are required in the following areas now:

1. Static and dynamic fatigue under aggressive environments.
2. Properties under biaxial loading.
3. Crack propagation under biaxial load.
4. Durability and reliability of joints (bonded and mechanical) under load exposed to aggressive environments.
5. Demonstration of part reclaim or repair.
6. Effects of holes, discontinuities, and cut-outs.

Adequate lightning protection of composite components is presently available. 0.002 to 0.004 coatings of aluminum have withstood the most severe laboratory static discharges with only minor damage to the aluminum coating. This minor damage was readily repairable.

Secondary Structure

Company-sponsored static, dynamic, and flight testing of advanced composite secondary structures have been numerous. Due to the AFML Advanced Composites Division's assistance in furnishing filament material for worthy programs, many items were manufactured and flown. These include the following:

F-5 landing gear door	boron/epoxy
A-4 speed brake	boron/epoxy
F-111 boron flap	boron/epoxy
A-4 flap (wing)	boron/epoxy
F-4 rudder	boron/epoxy
A-6A boundary layer fence	boron/epoxy
707 boron composite/Ti (floor beam)	boron/epoxy

All of the above tests were concluded or are proceeding satisfactorily.

Primary Structure

All of the AFML-ADP programs to design, fabricate, and test boron/epoxy aircraft components have been oriented toward primary structural assemblies. Major problems have been encountered in these programs and are being vigorously attacked. These problems include:

1. Joints and attachments
2. In-process quality control
3. Low quality of hand lay-up assemblies
4. Component design essentially uninspectable via NDT methods

Three programs are geared toward the flight demonstration of structural components. These are:

CH47A	boron/epoxy rotor blades
F-111	boron/epoxy horizontal stabilizer
C-5A	high-lift slat (boron/epoxy)

Satisfactory engineering solutions have been found to all of the problem areas except 3 and 4 above.

Suspect component quality and ineffectiveness of NDI techniques have cast some doubt as to structural reliability and integrity of these components. Many solutions have been discussed such as component proof-testing prior to flight. The successful production and flight testing of the S-glass/epoxy blades for the CH47 helicopter and the successful flight of at least four all-glass epoxy aircraft should lend some confidence for the flight-testing of these boron/epoxy components.

A summary of the cost and availability of materials for the programs described is given below:

Boron Filament Costs

	1965	1966	1967	1968	1969	1970	1972	1975
$/lb of filament*	600	500	500	400	375	350	300	250
Production capacity (1000 lbs)	.1	.5	.7	1	2	6	8	10
For cost of pre-preg add about 35% additional cost.								

*Predictions based on the production quantities indicated.

Realistic figures concerning the costs (manufacturing) of advanced composite structures have not yet been developed. It is reasonable to assume that as production capacity and increased production of boron filament ensue, costs of about $150/lb are achievable. Automated tape lay-up will allow drastic reduction in part lay-up manhours. It should be realized that advanced composite parts will always be more expensive than the aluminum counterparts. Improvements in fatigue, weight reductions of from 10 to 50%, reduced corrosion, etc., must be figured into the overall lifetime costs of the structure.

A chronology of the applications of boron filament follows:

Year	Event
1959	Texaco experiments reported boron fibers
1960	High-modulus high-strength boron/epoxy laminates produced
1963	"Project Forecast" initiated
1965	AFML Advanced Composites Division ADP
1966	Start of AFML ADP Structures Programs
1967/ 1968	Flight-testing of significant number of secondary structural components
1969	Static-testing of primary structural components; C-5A high-lift slat; static and dynamic-testing of F-111 horizontal stabilizer, static-testing of CH47A boron/epoxy blades
1970- 1972	(Projected) - Whirl-tower and flight-testing of CH47A blades Flight-testing F-111 horizontal stabilizer Flight-testing C-5A high-lift slat Static-test of advanced composite fuselage and wing assemblies

As can readily be seen, the technology-forcing (time-compressing) functions of the AFML-ADP will allow the system structural applications of boron/epoxy components starting in about the 1972-1975 time frame.

Work progressing on graphite composites should allow the introduction of graphite/epoxy structural components in about 1975.

Survey of Composite Aircraft Components

Item/Component		Material
F-111 strake		Fiberglass/epoxy
F-5 landing gear door		Boron/epoxy
A-4 speed brake		Boron/epoxy
F-111 boron flap		Boron/epoxy
C-5 high lift flap		Boron/epoxy
A-4 flap		Graphite/epoxy
A-4 flap actuator		Graphite/epoxy
F-111 horizontal stabilizer		Boron/epoxy
A-4 composite landing gear		Boron/epoxy
F-111 composite wing skin		Boron/epoxy
Rocket cases:	Polaris	S-glass/epoxy
	Poseidon	S-glass/epoxy
	Sprint	S-glass/epoxy
	MM 3rd S.	S-glass/epoxy
Pressure bottles		S-glass/epoxy
CX6 (VSTOL) wing		Boron/epoxy
A. C. wing structure		Boron/epoxy
H53 (Trans. housing)		Boron/glass/epoxy
CH47 blade		Glass/epoxy
CH47 blade		Boron/epoxy
Bolkow blade		Glass/epoxy
Boron landing gear (AFML)		Boron/epoxy
Boron landing gear (AFFDL)		Boron/epoxy
Wing box (filament wound) (aerojet)		Glass/epoxy
R. V. structure (cone)		Epoxy phenolic/boron
Turbine compressor blades		Boron/epoxy
F-4 rudder (McDonnell-Douglas)		Boron/epoxy
F-4 vertical fin door (MAC-AIR)		Boron/epoxy
F-4 stabilator box (MAC-AIR)		Boron/epoxy

A CASE HISTORY - THE TITANIUM FAMILY

By
Walter S. Hyler

The modern history of titanium started about 1947 with the Bureau of Mines' work on extraction, consolidation, processing, and properties of magnesium-reduced titanium sponge. Production was by the Kroll process. The timing was exceptional since, with the termination of the war, aerospace research and development could undertake longer-range programs. Both the defense agencies and the aircraft industry focused on the development of jet aircraft, and titanium was considered to be an important structural material.

However, at that time when intensive research in the titanium family was initiated, there was no production, no alloys, and no technology - only visions of what might be possible. Based on those visions, the metal producers and the government strenuously attacked the problems of titanium development. As a result, by 1950-1951 commercially-pure titanium and several alloys, including Ti-6Al-4V, were available for early commercial exploitation.

Some notable factors emerge from this period of intense activity pertinent to this report.

1. Early plants were built by industry assisted by fast write-off by the Government.
2. Sponge production was subsidized by Government purchase contracts.
3. Research on all facets of titanium metallurgy was conducted by Government laboratories (physical metallurgy) and industry (process metallurgy) with assistance from universities and research institutes.

The significant role of massive government financial support is inescapable in assessing the development of the titanium family. This massive support is visually displayed in Figure 1, which shows the distribution of United States government-supported research contracts during the years 1945 to 1965.* The figure shows that research contracts built up dramatically in number in the late 1940's, peaked in 1955, and dropped off sharply after 1958. They have not increased in number substantially since about 1963. Figure 2 provides a view of past and predicted titanium consumption made in 1965.** It shows that consumption was at a peak in 1957, but that by 1958 a severe cut-back occurred (similar in time to the cut-back in government-sponsored research) that was directly related to the U. S. Government policy decision to change the defense from manned aircraft to missiles (in 1958).

Figure 2 shows the further growth of titanium production from that epic low as the titanium industry slowly struggled to regain the military markets. In this effort, the aerospace industry was a willing helper as titanium alloys were introduced into jet engines (military and commercial), helium bottles, Minuteman cases, and many other minor applications. Beyond 1965, the projected rate presupposed the development of the SST, but did not account for the substantial quantities of titanium to be used in the F-14, F-15, and B-1 aircraft.

During the period of the 1950's, the extensive government support of physical metallurgy provided a large body of information on phase diagrams, crystal structure, and mechanical properties as affected by composition, heat-treatment, and processing history. Industry support (metal and aerospace) concentrated on alloy

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* Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (April 1, 1965)

** Wood, R. A., private communication, Battelle Memorial Institute, Columbus, Ohio, April 1, 1965.

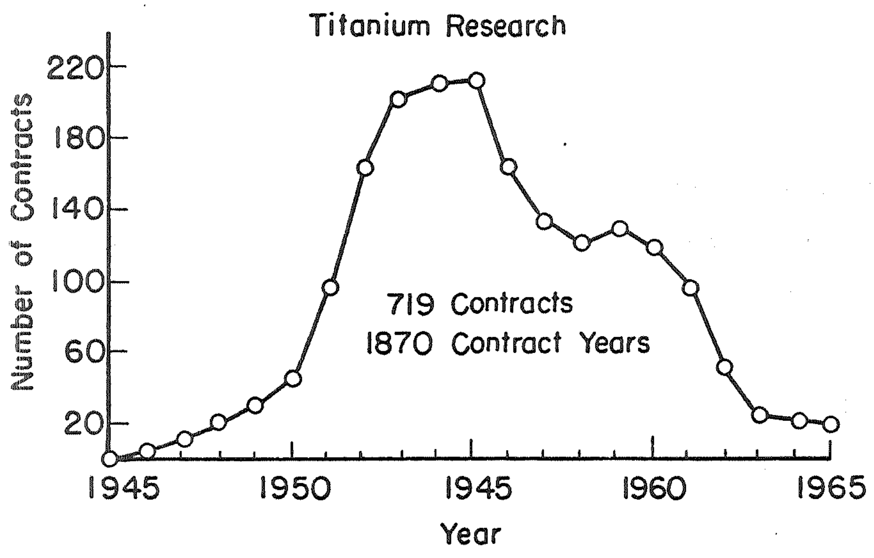
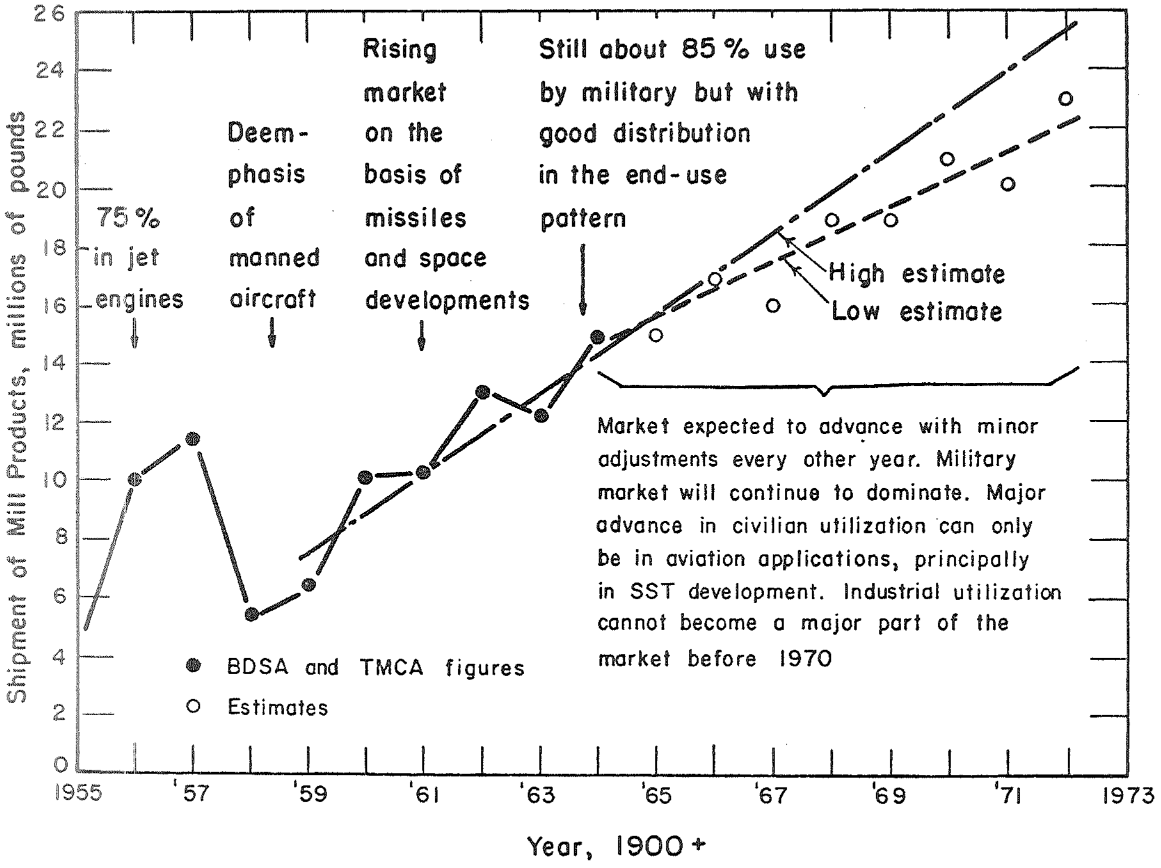


FIGURE 1. DISTRIBUTION OF U.S. GOVERNMENT-SUPPORTED RESEARCH CONTRACTS FROM 1946-1965



Market expected to advance with minor adjustments every other year. Military market will continue to dominate. Major advance in civilian utilization can only be in aviation applications, principally in SST development. Industrial utilization cannot become a major part of the market before 1970

FIGURE 2. TITANIUM CONSUMPTION: RECENT, PRESENT, AND FUTURE UTILIZATION

development, product and process optimization, and fabrication problems. The Titanium Metallurgy Laboratory* was funded by the DoD to assist in the all-important process of disseminating the accumulating titanium technology to hasten the process of utilization. The DoD titanium sheet-rolling program was a response to the needs of the aircraft industry that was responsible for the development of fabrication processes for producing flat, thin-gage sheet without defects and within commercial thickness and flatness tolerances.

On the other hand, the diminished government support for titanium research and development during the 1960's has been more strongly oriented to current applications and is characterized as applied research. The titanium industry has carried the brunt of alloy, product, and process development, and the aerospace industry has carried forward with the practical but detailed research in production processing and fabrication, as well as detailed characterization of new and old alloys in the titanium family. This latter effort is an important one and is tied closely to the problem of evolving structural design methods and confidence.

To illustrate the growth in use of titanium in airframes, Tables 2 and 3 provide a brief history taken from more extensive case histories provided to this Committee by the Boeing Airplane Company and Lockheed-Georgia. In both cases the footnotes to the tables clearly show that economic factors have played a major role in determining the rate of incorporation of titanium in commercial and military aircraft. In addition, special properties such as heat- and corrosion-resistance and fracture toughness and a good strength-to-weight ratio provided continued reasons for using titanium. Many applications in the mid 1950's also were the result of USAF stimulus, even though it was not cost effective. With regard to the use of titanium in cargo and transport jet aircraft, with but one exception, each

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* Forerunner of the Defense Metals Information Center.

TABLE 2. Utilization of Titanium in Production in Boeing Aircraft

Year	Aircraft	Pounds/ Aircraft	Why Used?
1950	B-47	100	Weight savings, heat resistance, experience
1952	B-52A	660	Weight savings, heat resistance
1956	B-52G	2,000	Same as B-52A, push by USAF
1958	707	180	Weight savings, heat resistance
1963	727	650	Weight savings, heat resistance
1967	737	750	Weight savings, heat & corrosion resistance
1969	747	8,150	Weight savings, heat & corrosion resistance, cost effective
1970	SST	140,000	Temperature eliminated aluminum structure, titanium most effective material

During the period 1950 to 1970, the average cost per pound decreased from \$18 to about \$6. From 1963 to 1970, the utilization factor (ratio of amount purchased to amount used) decreased from 7 to about 3.5.

TABLE 3. Utilization of Titanium in Production in Lockheed-Georgia Aircraft

Year	Aircraft	Pounds/ Aircraft	Why Used?
1954	C-130	300	Weight savings, heat resistance
1959	C-140	100	Weight savings, fracture toughness
1961	C-141	600	Weight savings, heat resistance
1965	C-5A	9,950	Weight savings, heat & corrosion resistance, fracture toughness

During the period 1954 to 1965, the average cost per pound decreased from about $18 to about $7. In the same period of time, the utilization factor decreased from 6 to 3.

succeeding airplane had a larger use of titanium than did the previous one. Some times the reasons for additional use were a consequence of the special properties of titanium. The major reason, however, was an economic one. Also, attributing to the increased use was the confidence gained from the past experience.

It should be stated that over this approximate 20-year period, the titanium family has matured through massive government/industry financial efforts to the point where four major aircraft presently under development will use large weight fractions of titanium alloys. Developments still continue to evolve that promote the role of titanium. The fruition of several years of intense effort has produced, within the last three years, for that old alloy, Ti-6Al-4V, aircraft structure of electron-beam welded section, an overaged heat treatment for high toughness and stress-corrosion resistance, continuously rolled sheet, and now precision castings. This is the maturing process at work.

The SST development warrants some additional comments in regard to this maturing process. It is one thing to put several thousand pounds of titanium in an airframe, it is quite another to employ over 140,000 pounds. Heat-treat and process optimization, materials characterization and formidable metal removal, and fabrication development have been carried out that have provided unique and economic production processing. The encouragement by the FAA for Boeing to disseminate this information within the aerospace industry has provided an exceptional example of the technology gains that can be achieved by a national program with immediately derivable results to other programs of widespread national interest.

CAPTAIN S. R. HELLER, JR., IVO FIORITI, and JOHN VASTA

AN EVALUATION OF HY-80 STEEL AS A STRUCTURAL MATERIAL FOR SUBMARINES

PART I

The cooperation of Mr. Ivo Fioriti of the Naval Ship Engineering Center and Mr. P. Puzak of the Naval Research Laboratory in supplying original photographs is acknowledged with appreciation.

THE AUTHORS

Captain Heller, an Engineering Duty Officer of the United States Navy, received his undergraduate education at the University of Michigan in Naval Architecture and Marine Engineering and in Mathematics. Following typical shipyard duty during World War II he received postgraduate instruction at the Massachusetts Institute of Technology leading to the degrees of Naval Engineer and Doctor of Science in Naval Architecture. Since then he has had design responsibilities in the Bureau of Ships, had a maintenance assignment with the Fleet, directed structural research at the David Taylor Model Basin, engaged in submarine design and construction at Portsmouth Naval Shipyard, and is now Head of Hull Design in the Bureau of Ships. Captain Heller is a member of ASNE, SNAME, Tau Beta Pi, and Sigma Xi.

Mr. Fioriti is the Materials Engineer in the Hull Scientific and Research Section, Bureau of Ships, with responsibility for materials and fabrication processes that are used in the construction of ship hulls. Mr. Fioriti attended the University of Pittsburgh, receiving the Bachelor of Science degree in Metallurgical Engineering in 1951. He took postgraduate work at the University of Maryland, receiving the Master of Science degree in 1960. From 1951 to 1956 he worked in the Metals and Metallurgy Section of the Bureau of Ships where he planned and administered research programs on metals for ships. He was associated intimately with the development of HY-80 steel and prepared the first specification used for its procurement by the Navy. In addition, he was responsible for the development of dimpled armor plate for aircraft carrier flight decks. In 1956 he assumed his present position where he has been active in the

Ship Structure Committee research program, the low cycle fatigue structural program and the hydrofoil materials research program.

Mr. Vasta is Head of Hull Scientific and Research Section, Bureau of Ships, with the responsibility for planning, initiating and technically monitoring research in the fields of structural mechanics and hydromechanics. Mr. Vasta attended New York University, receiving the Bachelor of Science degree in Mechanical Engineering in 1930. He took postgraduate work at the Massachusetts Institute of Technology, receiving the Master of Science degree in 1931. From 1931 to 1938 he worked at the United States Experimental Model Basin in the structural mechanics group. After a short duty at the Headquarters of the United States Coast Guard he joined, in 1939, the staff of the United States Maritime Commission where he held various positions of responsibility in the Technical Division. He was associated intimately with the design development of the reinforced concrete ship program, first as Assistant Chief and then as the Chief of the Section. Thereafter, he was appointed Assistant Chief of Technical Research, handling full-scale ship structural tests and studies related to the fracture of welded ships. Mr. Vasta has been an active member of the Board to Investigate into the ship fracture problems and its successor the Ship Structure Committee, from their inception. He is also a member of many research panels of The Society of Naval Architects and Marine Engineers and of the Welding Research Council. In early 1948 he joined the Bureau of Ships to assume the duties of his present position, having been promoted to Assistant Chief Naval Architect for Engineering Sciences.

INTRODUCTION

A NECESSARY first step in the evaluation of any material for use in any structure is an understanding and appreciation of the environment to which the structure will be exposed. In this context, *environment* is taken to include not only the physical characteristics of the medium in which the structure functions, but also the loads to which it may be exposed during its operating life and the length of life itself. The second such step is, of course, a consideration of the disposition of the material—the *structural configuration.* After these two steps have been taken, then the desirable properties of material can be set forth. These desires then become the yardstick by which the material under consideration is measured.

Environment

A submarine is, by definition, "a ship which functions or operates under water." In the naval sense, this means operation under the vast expanse of oceans and seas—hence, under salt water.

The salinity of sea water is customarily expressed as the weight of the dissolved solids in a million parts by weight of sea water on the assumption that all the bromine is replaced by its equivalent of chlorine, all the carbonate converted into oxide, and the organic matter burnt. The average salinity of the oceans is 35,000 parts per million (ppm) with almost 90 per cent of this in chloride form, about 10 per cent in sulphates, about 0.2 per cent in carbonates, and only traces of bromides.

Water temperatures vary widely with latitude. Near the poles the surface temperature will approach the freezing point, +28°F., while near the equator in the Pacific and Indian Oceans the mean annual temperature is about 84°F. with a maximum of 90°F. In the Persian Gulf during summer months, the surface temperature reaches 90°F. With the exception of the polar regions, temperatures decrease with depth. Near the poles the temperature increases gradually to depths of about 500 fathoms and then decreases slowly toward the bottom. Thus, for submerged operations, the probable range of temperatures would be from +28°F. to +85°F.; for surface operations, the corresponding probable range would be from −30°F. to +120°F. [1]

The following excerpt from [1] is a pertinent rationale for the probable life of a submarine:

> "A warship may be as short-lived as the mammouth Japanese aircraft carrier, *Shinano,* which was sunk just ten days after commissioning by USS *Archerfish.* Or it may lumber through two world wars and the interval of peace between them as did USS *Arkansas,* a pre-World War I battleship. For design purposes, however, a probable life of 20 years can be used. This is not a capriciously chosen number. It reflects the replacement period used in the Naval Treaties following World War I; it reflects existing practices; it reflects obsolescense trends."

A submarine pressure hull is always required to withstand the hydrostatic loading of uniform external pressure associated with the depth at which it is operating. In addition, for any of a wide variety of tactical considerations, it may be required to change depth. It is evident that such depth excursions may be executed many times during a submarine's life with a resulting accumulation of many cyclic loadings. By the indirect reasoning in [1], a gross range of 10,000 to 30,000 cycles seems appropriate. Furthermore, because submarines are warships, they may be attacked by enemy combatants. Although no potential enemy would be foolish enough to furnish specific details of his method of attack, it can be safely assumed that the attacks may be delivered with the submarine at any operating depth and that the dynamic loading will be in the form of a shock wave.

Structural Configuration

The inherent strength of a circular section in resisting uniform external pressure is immediately obvious intuitively and readily demonstrable analytically. It is not surprising, therefore, that spheres and cylinders have long been considered prime geometries for submarine pressure hulls. Superficially, at least, the sphere is the better geometry of the two for resisting hydrostatic pressure. The sphere, however, has two basic disadvantages, compared with the circular cylinder [2]:

a. For a given gross volume, its *usable* volume is less, and
b. Its greater susceptibility to instability failure.

For these reasons, pressure hulls are normally cylindrically with spheres being used only for special items such as end closures, sea chests, and escape trunks.

Implicit from the loading is that submarine structure is in compression. Hence, not only must the state of stress be considered in sizing the structure, but also its geometry must be properly proportioned to forestall instability. This latter consideration virtually forces the cylinder to be stiffened periodically along its length by rings.

The foregoing discussion has been concerned with the so-called "single" hull only. A submarine also has the requirement for some "double'" hull construction wherein the inner hull is the pressure-resisting structure, the outer hull forms the streamlined hydrodynamic shape, and the space between is used for tankage. The tankage may be either for liquid fuel or reserve buoyancy (main ballast tanks) on the surface. In any event, because there is such a requirement for transition from single to double hull construction, there is a concomitant requirement for a transition between cylinders of different diameters. This requirement naturally leads to the use of cones. To avoid high bending stresses at the sharp intersections of cylindrical and conical shells, curvature in the form of short spherical, toroidal, or ellipsoidal transitions [3] may be used.

The two ends of the pressure hull must be closed. Flat stiffened bulkheads have been used as have spherical and ellipsoidal heads. The latter are usually convex to the loading to gain usable volume and buoyancy, and also for ease of fabrication.

In summary, a typical submarine pressure hull is composed of ring-stiffened cylinders with stiffened conical transitions between cylinders of different diameters and the ends closed by shells of revolution convex to the pressure.

Desirable Material Properties

In consideration of the environment to which it will be exposed, a material suitable for submarine pressure hulls should have modest resistance to corrosion and relatively stable physical properties in the range of temperatures from −30°F. to 120°F. Because of the typical structural configuration used and the manner in which loading is applied, a high modulus of elasticity is desirable to prevent premature instability failure. In combination with the high modulus of elasticity, low density and high yield strength are also desired.

In recognition of the possibility of enemy attack, not only the material itself, but also its connections must be tough and resistant to fracture. Similarly, in recognition of the possibility of cyclic loading, the base material and its joints must also be resistant to low-cycle fatigue.

The material must be readily available not only in plate form, but also in shapes, either rolled or extruded, for use as the ring stiffeners. Castings and forgings should also be available for attachments to and penetrations of the hull. Equally important as availability is ease of fabrication. The material, whatever its delivered form, should be readily (consistent with its yield strength) shaped cold by rolling, bending, or pressing with usual shipyard facilities. It should be weldable in normal shipyard environment. The importance of cost of base material and fabrication procedures cannot be overemphasized or underestimated.

It is against these yardsticks that HY-80 steel will be evaluated as a structural material for submarines.

BASE MATERIAL

McKee [3] has stated that greater strength of submarine structure is *always* desired, and, to achieve a *balanced* design, this leads to the desire for a steel of higher yield strength. Once steel has been selected—and it is a sound choice when judged against the vast experience with it in shipbuilding—then, regardless of composition or heat treatment, modulus of elasticity is fixed at about 30×10^6 psi and density at about 0.284 lb./cu.in. To make a *new* steel worthwhile in terms of *improved* military characteristics, its yield strength should be significantly higher than the steel then in general use and should also be consistent with the attainment of good ductility, toughness, and resistance to low-cycle fatigue.

Basic Mechanical Properties Desired

It is inevitable that any new steel will be compared to that in general use at the time it is proposed. It is also inevitable that, aside from its yield strength which must represent a significant increment, all other desirable properties must be essentially equal to those of its predecessor.

Since the steel formerly in general use, high tensile steel (HTS), had a yield strength of 47,000 psi, the new steel should have a minimum yield strength of 80,000 psi—almost twice. Hence the term HY-80 which is an abbreviation for "High Yield Strength-80,000 psi minimum."

Ductility, that property which governs forming, resistance to fracture at stress concentrations, and deformation under dynamic load, is usually measured by elongation obtained during a standard tensile test. Since the specification for HTS required a minimum elongation of 20 per cent (over a 2-inch gage length), so it was desired that HY-80 have the same minimum elongation.

Toughness or resistance to fracture is simple in concept but difficult to measure in terms of structural significance. Frequently, the common Charpy V-notch test for impact strength in the presence of a notch is used for evaluating structural steels with the explosion bulge test developed by the Naval Research Laboratory. In this section wherein base material only is considered, the discussion will be confined to the Charpy V-notch test. In this test a large number of notched specimens, each at a different temperature, are broken by impact and the energy for fracture measured. The results are plotted as a curve of energy vs. temperature; a typical example is shown in Figure 1 which includes an indication of the lowest service temperature. Figure 1 shows three general regions of impact strength: higher impact energy at elevated temperatures; lower impact energy at low temperatures; and a transition zone connecting the two levels each of relatively constant, but different, impact energy. Because of their ferritic microstructure, which is sensitive to temperature, structural steels are termed *transition temperature materials* in recognition of this typical S-curve.

It is important to know the transition temperature characteristics of structural steels, so that one having a transition temperature zone below the lowest service temperature of the structure may be selected. If this is done, the structure will always be operating at its maximum impact strength. For submerged operations, the lowest service temperature is about 28°F; hence the desired transition temperature zone for HY-80 should be below 28°F and preferably below zero. *It is pertinent to note that this is generally not the case for most HTS structures in service today.*

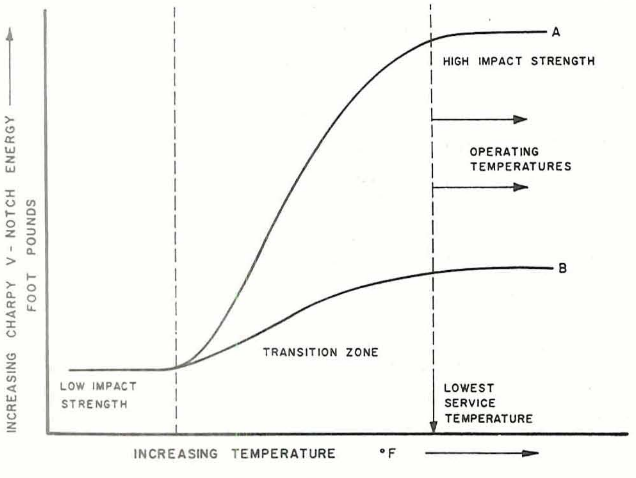

Figure 1. Typical Charpy V-Notch Energy-Temperature Relationships.

In addition to transition temperature characteristics, the magnitude of the higher impact energy level, also called *upper shelf,* is an index of toughness. For example, in Figure 1, Steel A would be considered tougher than Steel B because it has a higher upper shelf even though the transition temperatures are the same. The significance of the upper shelf has been amply demonstrated in dynamic tests both by drop-weight and explosive loadings. Steels with high upper shelves absorb energy by deformation and fractures are confined to the deformed area; steels with low upper shelves deform only slightly and cracks extend beyond the deformed area into areas stressed elastically. For HY-80, a minimum upper shelf energy of 50 foot-pounds was desired for both the principal direction of rolling and that transverse to it.

Since the importance of resistance to low-cycle fatigue is a relatively recent newcomer among mechanical properties of materials, there is not now available a quantitative value for measurement. Instead reliance must be placed on qualitative evaluation. Because initiation of a fatigue crack may not always be prevented (despite desires to the contrary), acceptable resistance to low-cycle fatigue will be obtained IF:

1. The rate of crack propagation is slow.
2. The fatigue crack does not initiate a brittle or low energy shear-type fracture.
3. When a fatigue failure does occur, it is a slow leak with the structure retaining its static strength at maximum operating depth.

Chemical Composition

In the search for a steel with higher yield strength, several modified versions of HTS were tried. To appreciate the significance of this search, the basic composition of HTS must be known and understood. An upper limit of 0.18 per cent was set for carbon (C) for good weldability. Because of its detrimental effect on ductility and toughness, an upper limit of 0.04 per cent was set for phosphorous (P). Because sulfur (S), when combined with iron (Fe) as iron sulfide (FeS), becomes liquid at normal rolling and forging temperatures, it is undesirable. This tendency to *hot-shortness,* as the phenomenon caused by iron sulfide melting is known, can be successfully offset in two ways. One is by limiting the sulfur and the other is by adding manganese (Mn) so that manganese sulfide (MnS) is formed rather than iron sulfide. The latter approach is important since the melting point for manganese sulfide is well above normal hot-working temperatures. Manganese also is a strengthening alloy which exerts its influence in three ways: by strengthening ferrite; by increasing the proportion of pearlite to ferrite; and by decreasing the lamellar spacing of pearlite. Thus, for HTS, an upper limit of 0.05 per cent was set for sulfur and up to 1.30 per cent was permitted for manganese. In this case, manganese was both a preventer of hot-shortness and a strengthening alloy. As is typical of structural steels, silicon (Si) in the range of 0.15 to 0.35 per cent is used for de-oxidation. Thus, the carbon and manganese are primarily responsible for the strength of HTS and this strength is present in the *as-rolled* condition directly from the steel mill. Normalizing of HTS improves its toughness without any change in strength.

The modified versions of HTS, which were characterized by modest amounts of alloying elements, produced only small increases in strength and toughness. This result persisted in both the as-rolled and normalized conditions. Although this series was a failure, it demonstrated clearly that a different approach was needed. The calendar was figuratively turned back more than half a century to the excellent Krupp quenched and tempered armor steel originally produced in 1894. This Krupp product was characterized by modest use of nickel

TABLE I—*Specification Limits of HY-80 Chemical Composition*

LADLE ANALYSIS—PER CENT

C	Mn	P*	S*	Si	Ni	Cr	Mo	Ti	Va	Cu
.18 Max.	.10 to .40	.025 Max.	.025 Max.	.15 to .35	2.00 to 3.25	1.00 to 1.80	.20 to .60	.02 Max.	.03 Max. (Residuals	.25 Max.
CHECK ANALYSIS—PER CENT—OVER UPPER LIMIT										
.02	.05	.003	.000	.03	.07	.06	.03			
CHECK ANALYSIS—PER CENT—UNDER LOWER LIMIT										
—	.00	—	—	.03	.07	.06	.03			

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* On both Ladle and Check Analysis the per cent of phosphorous and sulfur together shall not be more than 0.045.

TABLE II—*Chemical Composition for HY-80 Thin, Thick, and Insert Plates*

NOMINAL ANALYSIS—PER CENT

Thickness	C	Mn	P	S	Si	Ni	Cr	Mo
Thin Plate (Up to 1¼ in. Incl.)	.14	.30	.015	.020	.20	2.35	1.15	.30
Thick Plate (Over 1¼ in. to 3 in. Incl.)	.16	.30	.015	.020	.20	2.85	1.55	.45
Insert Plate (Over 3 in. to 6 in. Incl.)	.17	.30	.015	.020	.20	3.10	1.65	.55

TABLE III—*Specification Limits of HY-80 Mechanical Properties*

Property	Plate Thickness Less than ⅝ in.	⅝ in. and over
Ultimate Strength (psi)	For Information	For Information
Yield Strength at 0.2% Offset (psi)	80,000 to 100,000	80,000 to 95,000
Min. Elongation in 2 in. (per cent)	19	20
Reduction in area (per cent)		
Longitudinal	—	55
Transverse	—	50

CHARPY V-NOTCH IMPACT ENERGY REQUIREMENTS

Plate Thickness	Specimen Size (mm.)	Foot Pounds (Min.)	Test Temperature (Degrees F.)
¼ in. to ½ in. Excl.	10 x 5	For Information	—120
½ in. to 2 in. Incl.	10 x 10	50	—120
Over 2 in.	10 x 10	30	—120

(Ni), 3.5 per cent, and chromium (Cr), 1.5 per cent, and possessed excellent toughness. This basic Krupp steel with modifications in the carbon and nickel content and with the addition of molybdenum (Mo) appeared to have the most attractive combination of all desired properties. This modified Krupp steel, originally known as low-carbon Special Treatment Steel (STS), was the forerunner of that which is now known as HY-80 steel.

Unlike HTS which possesses its strength in the as-rolled, or mill, condition and has its toughness enhanced by normalizing, HY-80 is a low carbon alloy steel which acquires strength and toughness through quenching and tempering. HY-80 is, therefore, a *hardenable* steel, the properties of which are achieved by heat treatment. Its composition must be balanced to give the desired strength, toughness, and hardenability.

In amplification of the statement that HY-80 is a low carbon alloy steel, a detailed study of the composition is warranted. As with HTS, an upper limit of 0.18 per cent is set for carbon. Also as for HTS, silicon is used as a de-oxidizer and the same range, 0.15 to 0.35 per cent, is permitted. Closer control of phosphorous and sulfur is required for HY-80 than for HTS: the upper limit for these detrimental elements is set at 0.025 per cent individually and 0.045 per cent collectively. Because of this stringent restriction, HY-80 is considered more refined than HTS and requires greater care in the steel-making process. Since other different alloys are used for strength, manganese is used primarily for sulfur control. For this reason and because manganese in amounts greater than about 1.0 per cent embrittles steel during heat treatment, a range of 0.10 to 0.40 per cent only is permitted. Molybdenum is used primarily to minimize the susceptibility to temper embrittlement, but it also increases hardenability. Nickel is primarily responsible for toughness, and has the secondary effect of increasing hardenability. The complete chemical composition is set forth in Table I.

It will be noted that the ranges in Table I for the several elements are broad. This was done intentionally to permit the steel manufacturers to melt for different levels of hardenability for different plate thicknesses. For example, smaller amounts of alloying elements are required for thin plate than for thick plate. By *thin* plate is meant thickness up to and including 1¼ inches; by *thick* plate is meant thickness over 1¼ inches but up to and including 3 inches. Plates over 3 inches thick are usually considered as *insert*, or reinforcement, material. The nominal compositions for thin, thick, and insert plates are given in Table II.

Method of Manufacture

HY-80 steel is made by either the open hearth or the electric furnace process. The resulting steel is fully killed and fine grained. Plates are rolled directly from either ingots or slabs. To achieve the desired strength and toughness, a final heat treatment of quenching and tempering is required. This is the step in the manufacture of HY-80 which is distinctly different from the usual process of making structural steel.

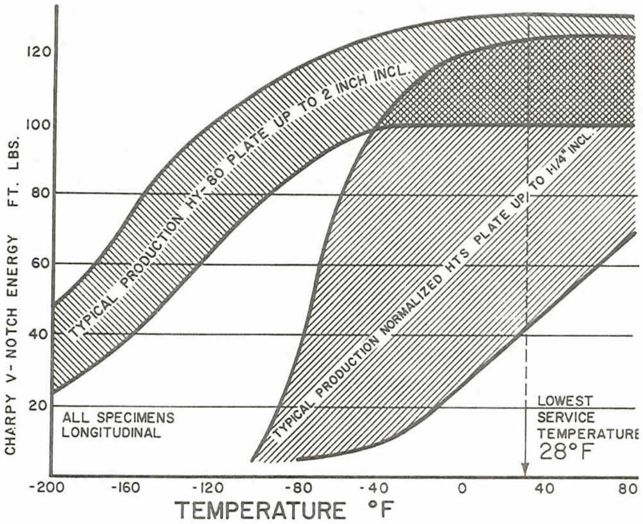

Figure 2. Typical Charpy V-Notch Energy Bands for Production HTS and HY-80.

The steel manufacturer may use his own heat treatment preference to produce plates of the required mechanical properties subject to only two limitations:

1. The final tempering temperature shall not be less than 1100°F.
2. The microstructure at mid-thickness of the plate must contain not less than 80 per cent martensite.

In actual practice, however, the heat treatment consists of austenization in the ranges of 1550°F to 1650°F followed by a water quench, and tempering in the range of 1150°F to 1250°F followed by a water quench.

Quality control requirements during the steel-making process are particularly stringent regarding surface imperfections, internal soundness, and variations of both thickness and hardness. Documentation of the final inspection at the mill is required.

Basic Mechanical Properties Achieved

During the early development of HY-80 it was learned that the low carbon alloy steels, when quenched and tempered to form a martensitic structure, exhibited a significant increase in strength and toughness. For these steels, it was also learned that yield strength increased to a significantly greater extent than did ultimate strengh. Because of this relationship, HY-80 has almost twice the yield strength of HTS, but only about 1.25 the ultimate strength. Despite this close relationship between yield and ultimate strength in HY-80, considerable ductility is available after yielding takes place. In fact the ductility requirement is the same as that of HTS.

The mechanical properies of HY-80 required by specification are set forth in Table III. After final heat treatment, *each* plate is sampled for mechanical properties by using specimens cut from *each* end. Failure to achieve specification requirements is, of course, cause for rejection.

In contrast to usual procurement practice for structural steels, tensile specimens in both the longitudinal and transverse directions (relative to principal mill rolling) are required. Minimum requirements for yield strength and ductility as measured by elongation in *both* directions must be satisfied for acceptance. Moreover, for additional assurance of ductility, there are minimum requirements for reduction in area: 55 per cent in the longitudinal direction and 50 per cent in the transverse direction. This latter requirement is not set forth in the specification for HTS.

Charpy V-notch impact tests are performed on samples taken from two plates selected at random from all plates of a single nominal thickness from each heat of steel. Of particular significance is the requirement for testing at a temperature as low as −120°F. This low temperature was deliberately chosen to assure a complete picture of impact strength extending well below the lowest service temperature. Typical curves of Charpy V-notch impact energy vs. temperature are shown in Figure 2 for both HY-80 and HTS. The latter is included for ready comparison. It is apparent from Figure 2 that the transition temperature zone for HY-80 is below 0°F as desired. Indeed, at 0°F, upper shelf energy level has been obtained. It is also apparent from Figure 2 that the upper shelf energy level is well above the desired minimum of 50 foot-pounds. Moreover, the marked superiority of HY-80 over HTS with respect to impact strength in the presence of a notch is clearly shown in Figure 2.

Availability of Shapes, Forgings, and Castings

The availability of a material in plate form is a necessary first step for production use of that material. And much can be done once plate is available. Indeed, more than twenty submarines were built of HY-80 with the ring stiffeners and other reinforcements fabricated from flat plate. This, however, is evidence only of ingenuity and will to do. It is obvious that greater flexibility of production operations would be permitted if a full family of shapes, forgings, and castings were available.

While the aforementioned twenty-odd submarines were being built, the Bureau of Ships and its submarine building shipyards were keeping unremitting pressure on the steel producers to solve the heat treatment problem associated with shapes other than flat plate. In 1960, a "breakthrough" occurred with the availability of extruded structural tees. Rolled shapes followed in 1961. At about the same time, acceptable forgings and castings, sufficient in size to be used as insert reinforcements, became available. Today the full family, which was eagerly awaited, is now available.

In the development of this full family, minor adjustments have been made in requirements to suit the individual products. For example, the minimum required Charpy V-notch impact requirement was increased slightly for extrusions and forgings, decreased slightly for castings, and kept the same for rolled shapes as for plates. There are now available Military Specifications for procurement of the several HY-80 steel products:

1. MIL-S-16216 for plate
2. MIL-S-22644 for extrusions
3. MIL-S-22958 for rolled shapes
4. MIL-S-23008 for castings
5. MIL-S-23009 for forgings

ELECTRODE MATERIAL

In the fabrication of any structural material by welding, it is desirable to use electrodes which produce welds that have properties *at least as good* as those of the base material. For a submarine structural material, these desirable properties have been previously identified as strength, ductility, toughness, and resistance to low-cycle fatigue. To *overmatch* all these properties is, indeed, a tall order. To accomplish this in the *as-welded* condition for a high yield strength weldment, such as that made from HY-80 steel, is an even more awesome task. A measure of the magnitude of the task is given by three significant differences between base and weld metal.

1. Weld metal is, in effect, cast material which, by virtue of being an integral part of a massive structure, is not susceptible to beneficial treatments which a mill plate receives: homogenization, rolling, and heat treatment.
2. No matter how rigid and exhaustive an inspection system is employed, some flaws or defects, such as inclusions, porosity, and incomplete fusion, escape detection.
3. The properties and characteristics of weld metal are influenced by many factors which can neither be measured nor controlled with precision. Restraint, joint design and preparation, weld position and accessibility, cooling rate, transformation, shrinkage, and reaction stresses are but a few of the imponderables.

The foregoing serves to highlight the complexity of the weld metal problem. When the measurable and controllable factors, such as electrode composition and size, amount of deposit, preheat and interpass temperature, heat input, coating composition and moisture content, and atmosphere, are considered, it is not surprising that rigorous controls are required in the shipyard to produce suitable structural welds. Fortunately, several of the factors are interrelated, so that, by control of these key factors, satisfactory HY-80 welds can be made.

Search for Strength with Toughness

An understanding of the influence of these factors and remedial controls developed slowly over a period of years. The *first* real accomplishment which, according to Griffin [4], made the welding of high strength steels such as HY-80 possible, and not prohibitively expensive, under shipyard conditions was the development of *low-hydrogen-ferritic electrodes* during the period 1944-1946. Such an electrode was available when the development of HY-80 steel was begun. Concurrently with the development of HY-80 steel, the U. S. Navy was developing a high strength version of the low-hydrogen ferritic electrode suitable for welding ballistic steels. This electrode, Type MIL-26015(16) of Military Specification MIL-E-986, naturally became the first to be used with HY-80. Its strength was more than adequate, but its toughness left much o be desired. Even after several years of steady improvement, the best obtainable Charpy V-notch impact energy requirement was only 20 foot-pounds minimum at 0°F. Clearly, a new electrode with markedly increased toughness was needed.

A *two*-pronged search for tougher weld metal continued through the following decade. One path of the search led to a stick electrode for manual welding; the other headed for an electrode wire suitable for an automatic or semi-automatic welding process. These two goals were achieved almost simultaneously during the period 1955 to 1957: the iron powder stick electrode of the XX18-type as reported by Sagan and Campbell [5] and the B88 type electrode wire as described by Sibley [6]. Although the welding processes in which these two electrodes are used are markedly different (manual for all welding positions for the stick and both the semi-automatic and automatic metal inert gas (MIG) process in the downhand position only for the wire), the welds have equivalent toughness and consistently meet the Charpy V-notch impact energy requirement of 20 foot-pounds minimum at −60°F. Further exploration of the iron powder stick electrode led to three different strength levels with the same toughness. Of course, the selection of a specific type is dependent upon the joint efficiency required by the design.

The *fourth* major step forward in the welding of HY-80 steel was the development of an electrode-flux combination suitable for the submerged-arc welding process. As described by Lewis, Faulkner, and Rieppel [7], this combination of electrode, flux, and process produces weld metal of adequate strength and a toughness slightly superior to that achieved by the manual stick and MIG welding processes. As with the MIG process, submerged-arc welding is limited to the downhand position.

The *fifth* major achievement was the development of a heat treatable electrode weld deposit that acquires strength and toughness through the same quenching and tempering heat treatment as does HY-80 steel. This electrode, an iron powder type stick electrode for manual use, is identified as MIL-8218YQT. The strength of its deposit *matches* that of the base metal and the toughness of this weld metal is equivalent to that of its non-heat-treatable counterpart. With the successful development of this electrode whose weld deposit is heat-treatable, great flexibility of fabrication was achieved. Now subassemblies involving castings, forgings, extrusions, and even spun ellipsoidal heads can be welded first and then heat treated. The only limitation now is furnace and quenching capacity.

A complete listing of electrodes currently used in welding HY-80 steel is given in Table IV. In addition, the appropriate Military Specifications, type designation, welding processes, positions, and applications are also included in Table IV.

Chemical Composition

Since the basic type of electrode has been described, it is now necessary to consider the chemical composition of electrodes and its influence on mechanical properties and overall performance of the weldment.

Results of a recent survey conducted at Battelle Memorial Institute [8] have shown that the composition and microstructure of weld metal have a complicated dependency on electrode material, base material, and welding process. The inevitable intermixing of base and electrode materials is variable since the amounts of each cannot be controlled precisely. In multi-pass welds, the passes near the base material will be more affected by base material composition than will those in the center of the weld. Thus, there are zones of varying compositions. In addition, if the welding process involves a flux or slag, the reactions of these with the molten weld metal (which are dependent on temperature, time, and quantities of constituents) will have an effect on weld metal composition. Since the inert gases used as protective atmosphere are not 100 per cent pure, they too can effect the weld metal composition. Other more subtle, but equally important, effects include variations in burn-off of elements, precipitations and diffusion of elements, and micro-segregations. In summary, it is apparent that, at best, only generalizations can be made concerning the effects of electrode material composition on weld metal behavior.

The role played by each of the different elements in steel has been discussed earlier (see *Base Material*), and their ranges or limits have been related to the steel-making process. These roles or effects of the elements are the same for the weld metal [5, 8], but the applicable ranges or limits will be different since the weld metal is not susceptible to treatment after deposition. To provide the maximum resistance to weld cracking and improve notch toughness, carbon is limited to a maximum of 0.10 per cent; phosphorous and sulfur to a maximum of 0.03 per cent each. As for the base material, about five times as much manganese as sulfur is required to prevent hot-shortness, but, since no heat treatment is involved and thus embrittlement is not a factor, up to 2.0 per cent manganese is allowed with the excess over that required for sulfur control contributing to strength and toughness. Again, as for the base material, silicon is a deoxidizer. Since silicon also promotes the fluxing action of the slag, it influences bead contours, provides immunity from porosity, and facilitates out-of-position welding. Silicon, however, has a tendency toward decreasing toughness and resistance to hot cracking in amounts greater than that required for usability. Thus, a maximum of 0.60 per cent is permitted. As for the base material, nickel is the principal contributor to toughness. Fortunately nickel has only a moderate effect on strength, so relatively large amounts of nickel can be added to offset the decrease in toughness normally associated with increase in strength. Although there is no unanimity of opinion concerning the effect of vanadium, it is believed to contribute to a decrease in toughness (which can be further aggravated by thermal stress relief) and hence is limited to a maximum of 0.05 per cent. The only exception is MIL-B88 wire for which 0.10 to 0.20 per cent vanadium is permitted for strengthening and for which thermal stress relief is prohibited. Since chromium is a less effective strengthener in as-deposited weld metal than manganese, molybdenum, and nickel and has an adverse effect on toughness in amounts in excess of about 1.0 per cent, it is not an essential addition. Consequently, maximum limits are usually imposed on residual chromium to keep the total alloy content within bounds. Molybdenum strengthens weld metal to a greater extent than can be predicted by solid solution hardening. It is believed that the added strength results from changes in the size and distribution of carbides in the low-carbon ferritic matrix. This change in microstructure contributes to the stability of weld metal strength under the variety of heating and cooling conditions typical of welding. Experience has shown that these beneficial effects can be obtained without adverse effect on

TABLE IV—*HY-80 Welding Electrodes and Application*

Elec. Type	Spec.	Process	Position	Application
MIL-11018	MIL-E-22200/1	Shielded metal arc	All	All
MIL-10018	MIL-E-22200/1	Shielded metal arc	All	Fillet, Fillet Groove or Groove Joints
MIL-9018	MIL-E-22200/1	Shielded metal arc	All	Limited Use
MIL-B88	MIL-E-19822	Semi-Automatic or Automatic Metal Inert-Gas Arc	Flat or Horizontal	All
MIL-EB82*	MIL-E-22749	Submerged Arc	Flat	All
MIL-MI88**	MIL-E-22749	Submerged Arc	Flat	All
MIL-8218Y QT	MIL-E-22200/5	Shielded metal arc	All	Limited to Procedure Approval

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* Granular Flux Particle Size 10 x 50. ** Granular Flux Particle Size 12 x 150.

TABLE V—*Specification Limits of Deposited Weld Metal Chemical Compositions*

Element	FOR HTS		FOR HY-80						
	MIL-7018	MIL-8018	MIL-9018	MIL-10018	MIL-11018	MIL-B88	MIL-EB82	MIL-MI88	MIL-8218YQT
Carbon	.12	.12	.10	.10	.10	.08	.12	.06	.10-.15
Manganese	.40-1.25	.40-1.10	.60-1.25	.75-1.70	1.30-1.80	1.15-1.55	.80-1.25	1.00-1.50	.80-1.15
Phosphorous	.030	.030	.030	.030	.030	.025	.020	.010	.030
Sulfur	.030	.030	.030	.030	.030	.025	.020	.010	.030
Silicon	.80	.80	.80	.60	.60	.35-.65	.80	.50	.30-.60
Nickel	.25	.80-1.10	1.40-1.80	1.40-2.10	1.25-2.50	1.15-1.55	.80-1.25	1.40-1.90	1.50-2.00
Chromium	.15	.15	.15	.35	.40	—	.30	.10-.30	.90-1.20
Molybdenum	.35	.35	.35	.25-.50	.30-.55	.30-.60	.15-.60	.20-.40	.45-.75
Vanadium	.05	.05	.05	.05	.05	.10-.20	.05	.05	.02
Copper							.40-1.10	.10-.30	
Titanium								.10	
Zirconium								.10	
Aluminum								.10	

NOTE: Per cent-Single values are maximum toughness if molybdenum is kept within the range of 0.15 to 0.75 per cent.

It must be emphasized that the foregoing ranges and limits apply to the as-deposited *weld metal* composition—NOT to *electrode* material composition. As such, they can only be checked *after* deposition of weld metal in a groove of *base* material. Thus, the specifications for electrodes require that *deposited* weld metal have prescribed compositions. Table V is a summary of existing specification requirements for chemical composition of weld metal deposited by electrodes approved for use with HTS and HY-80 steel. It is important to note that the compositions of the weld meals are tailored to provide adequate strength and toughness of the weldment in the "as-welded" condition and the total alloy content has been adjusted for the strength required. Of course, the composition of the heat treatable electrode, MIL-8218YQT is based on the hardenability obtained from the heat treatment after welding.

Method of Manufacture

Because of the highly competitive aspect of the industry, the manufacture of welding electrodes is, for the most part, proprietary to each producer. This is particularly true of electrode coatings. To the user, this is not too important since all interest is in the deposited weld metal. It should be recalled that the specifications require weld metal compositions and mechanical properties in the as-welded conditions. The only exception to this is the MIL-B88 MIG bare electrode wire for which chemical composition of the wire itself is specified.

Since moisture must be kept below a given level for control of porosity and hydrogen cold cracking, moisture content in the electrode coatings is specified at 0.2 per cent maximum water content by weight. Iron has been found to be favorable to higher deposition rates, easy slag removal, improved bead appearance, and steady smooth arc characteristics [9]. Hence, an iron content of not less than 15 per cent is specified for the XX18-type. These are the only limitations imposed on the chemical composition of electrode coatings.

The moisture content of the flux for submerged-arc welding is restricted to half that of electrode coatings, 0.1 per cent maximum water content by weight. The only other requirement imposed on the flux is one of particle size.

In addition to the general requirements for coatings of handling, concentricity, uniformity, dielectric strength, release of fumes, slag removal, stability, and extent of covering, electrodes must satisfy a number of weld tests.

1. *Qualification tests* are conducted on the first lot offered on the first contract or order received by the manufacturer. Every twelve months these same tests are repeated at which time they become known as comparison tests; i.e., the results are compared with the initial qualification. Qualification tests are not the same for each electrode but, rather, are peculiar to the particular electrode involved. These tests, as a group, may contain explosion bulge and crack starter tests, fillet weld usability test, restrained fillet weld test, restrained full penetration cruciform fillet-reinforced test, restrained or unrestrained groove weld tests in the flat, horizontal or vertical positions, flaking or cracking of coating bead on plate test, and chemical analysis of pads of weld metal.

2. *Acceptance tests* are performed on every lot of electrodes presented for inspection by the manufacturer. These tests are generally neither as difficult nor as involved as qualification tests since they are designed to *maintain* the level of quality established by the qualification tests. Explosion bulge and crack starter tests and the flaking and cracking of coating bead on plate tests are not included. In acceptance testing, an alternate method for chemical analysis is the taking of sample drillings from deposited weld metal of groove welds that are used for mechani-

TABLE VI—*Specification Limits of Deposited Weld Metal Mechanical Properties*

PROPERTY	FOR HTS		FOR HY-80						
	MIL-7018	MIL-8018	MIL-9018	MIL-10018	MIL-11018	MIL-B88	MIL-EB82	MIL-MI88	MIL-8218YQT
Ultimate Strength (psi)	70,000	80,000	90,000	100,000	110,000	—	—	110,000	—
Yield Strength at 0.2% Offset (Psi)	60,000- 75,000	70,000- 82,000	78,000- 90,000	90,000- 102,000	95,000- 107,000	88,000	82,000	88,000	82,000
Elongation in 2 in. (per cent)	24	24	24	20	20	14	16	20	18
Charpy V-notch Impact Energy (Ft/Lb)									
At - 10°F	20	20							
At - 60°F			20	20	20	20		30	20
At - 80°F							20		

NOTE: Single values are minimum.

cal tests. Acceptance tests may include a restrained or unrestrained groove weld for mechanical properties, either a groove or fillet weld usability test, a vertical groove weld test for manual electrodes for soundness, and a restrained fillet or restrained full penetration cruciform fillet-reinforced test.

Mechanical Properties Achieved

As has been indicated earlier, welds that have properties *at least as good* as those of the base material are desired. Again, as has been pointed out earlier, no matter how rigid and exhaustive an inspection system is used, some flaws or defects escape detection. To offset this loss in strength and to obtain superior performance under dynamic loading, it has long been considered desirable for the weld metal to *overmatch the strength* of the base material. For this reason, there has been developed a large family of XX18-type electrodes which, according to [8], can provide a range of ultimate strength from 70,000 to 120,000 psi. It is possible, therefore, to select from Table IV an electrode which will undermatch, match, or overmatch the strength of HY-80 as desired or required by the design. The weld metal mechanical properties which can be achieved consistently (specification requirements) in production use of these electrodes are set forth in Table VI.

In addition, it is desirable for the ductility of the weld metal to match that of the base material. Comparison of Tables III and VI reveals that matching ductility is realized by the use of *all stick electrodes* and MIL-MI88 wire for submerged-arc welding. Table VI also shows that MIL-B88 wire (for MIG welding) produces welds with the lowest ductility, 14 per cent elongation in 2-inch gage length. Despite this low level of ductility, *all* MIL-B88 welds on HY-80 steel, including large structural models and dynamic tests, have had no adverse effect on performance.

Although it is desirable for the toughness of the weld metal to match that of the base material, the very great toughness of HY-80 steel has, thus far, outstripped that of the best welds. Nevertheless, this has not been and is not a disqualifying defect.

Toughness has been qualitatively measured by Charpy V-notch impact energy. Pellini [10] has shown that a Charpy V-notch impact energy of 20 ft.-lb. can be taken as that corresponding to the *nil-ductility transition (NDT)* temperature as measured in the drop-weight test. This temperature is of great significance since, at tempertaures below the NDT, brittle fracture is possible under conditions of *static elastic loading* if the yield strength is exceeded at a notch. For this reason, the minimum Charpy V-notch impact energy is specified as 20 ft.-lb. in Table VI. Naturally, there must be a temperature associated with this impact energy. Ideally, of course, this temperature should be the NDT of the base material. Failing that, the temperature should be at least 100°F *below* the lowest service temperature of the structure. It is here that weld metals fall short of the desired. Except for MIL-EB82 deposits, the lowest NDT obtainable as a production minimum is −60°F. Although the difference between −60°F and the lowest service temperature (28°F) is somewhat short of the desired 100°F, the NDT achievable is sufficiently low that, at service temperature, the weld metal impact energy is at or near the upper shelf. Because of this, excellent performance has been obtained in all dynamic tests involving severe plastic deformations in the presence of notches.

PRE-FABRICATION EXPLORATIONS

Once the basic material had been developed and produced in small quantities and it had been demonstrated that this material could be welded satisfactorily—at least under near-laboratory conditions—fabrication under field conditions needed study. It is trite to observe, but important not to forget, that, no matter how attractive are laboratory results, material properties are no better than those obtained in the field under production conditions.

Forecastable Difficulties

It was obvious, even before HY-80 steel became available in production quantities, that a steel with a yield strength much in excess of the steel then in general use would pose fabrication problems. The first, and most obvious, such problem was that involving forming equipment. Since forming involves stressing the material in excess of its yield strength to obtain a permanent change of shape, the forces required to be exerted by the forming equipment are, for constant geometry, directly proportional to yield strengths. But the shipyards in the United States possessed, for the most part, rolls and presses that had been in constant use throughout World War II when the common submarine hull materials were medium and high-tensile steels (yield strengths of 33,000 and 47,000 psi, respectively). Now these same shipyards were about to be called upon to form steel with a yield strength of about *twice* that previously used—and with the *same* equipment. This prospective burden was patently too great for existing equipment. Hence retooling was necessary.

A second, and almost as obvious, prospective difficulty in fabrication was that of weldability. From antiquity, when welding was confined to hammer and forge methods, the introduction of a "new" material has been accompanied by weldability problems. The usual manifestation of the problem has been the appearance of fissures in the heat-affected zone of the base material adjacent to the welds—in the vernacular, *cold cracking*. As has been ably and clearly stated by Griffin [4], such conditions prevailed in the fore welding era, persisted in both bare-wire and covered-electrode welding, and "stalked rampant through our submarine building yards of World War II." It would be extremely fortuitous, then, if the introduction of a new material in mid-Twentieth Century was not accompanied by similar troubles. Griffin [4] had several words of caution for the rash and headstrong: "To believe other than this is folly and to carry out a contrary belief in practice is a direct invitation to cracking difficulties which should make Grandfather's pale by comparison."

Although acquistion of new equipment could and did provide an easy solution to the forming problem, such a simple, ready-made solution to the weldability problem was not foreseen. Years spent in overcoming similar troubles in the past had given rise to the aphorism: *Laboratory research provides the "know-why" of welding; field experience provides the "know-how."* Extensive laboratory investigations, conducted under government sponsorship during and after World War II, had, however, led to an excellent understanding of the behavior of the heat-affected zone in the base metal and, therefore, of the cold-cracking phenomenon. These same investigations were also directly responsible for the development of "low-hydrogen" ferritic electrodes without which the welding of HY-80 steel would be prohibitively expensive and perhaps even impossible under shipyard conditions.

The explanation of the cold-cracking phenomenon which follows is an abbreviated and paraphrased version of the excellent summary by Voldrich [11]. That portion of the base metal adjacent to the weld, commonly known as the heat-affected zone or HAZ, is, in reality, composed of *two* zones. The inner of these two zones, the one closer to the weld itself, is heated during welding to a temperature and for a time sufficient for austenization, the extent of which is dependent on the time. As this zone cools, it transforms into a product that is stronger and harder than the base metal. The outer zone, the one closer to the colder base metal, is not heated to the transformation temperature, but is heated sufficiently to reduce its hardness and strength. For martensitic steels such as HY-80, the effect of welding may be a reduction in toughness or in ductility in the presence of a notch rather than a reduction in strength. Under unfavorable welding conditions and when the specified procedures are not followed, HAZ cracks may occur during or soon after welding.

1. Cracking that takes place while the weld is still very hot (and usually while the joint is highly stressed) is *intercrystalline* denoting weakness between grains. If these cracks are not discolored (caused by exposure to air), they may be mistaken for cold cracks.
2. Cracking that takes place after the weld has cooled below transformation temperature, or even several days later, is associated with martensite and is usually *transcrystalline*. Crack formation and extent depend on the presence of diffusible hydrogen and on stress in the joint.

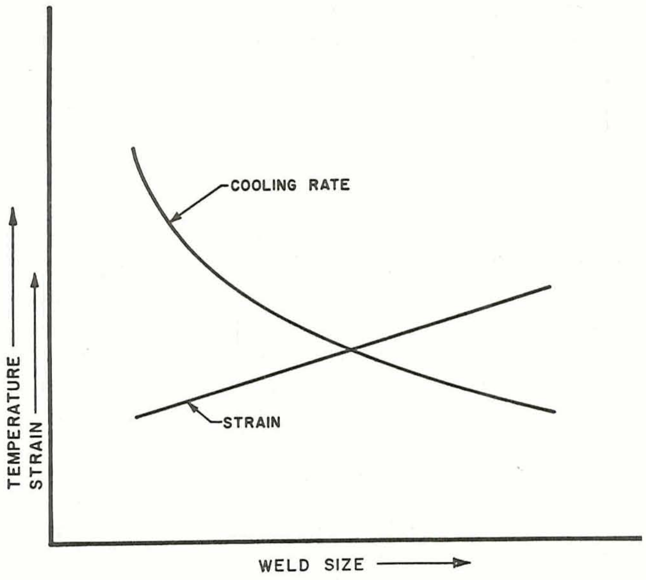


Figure 3. Relationship of Cooling Rate and Strain with Weld Size.

It should be noted that cracks arising from flaws, laminations, or directional weakness in the base metal have been specifically excluded.

From the foregoing it is evident that cold cracks start only in martensite. This is not to say that cold cracking is a necessary by-product of martensite, but only that martensite is a necessary ingredient of the phenomenon that produces cold cracks. The other principal ingredients are hydrogen and the stresses produced in the welding operations. The latter, which are of major importance, include [4]:

1. Weld shrinkage and the resulting stresses associated with restraint or rigidity of the structure.
2. Stresses produced by the internal pressure of hydrogen.
3. Thermal stresses associated with welding and plate temperatures.
4. Stresses arising from changes in volume during transformation.

All but the last are within the control of the fabri-

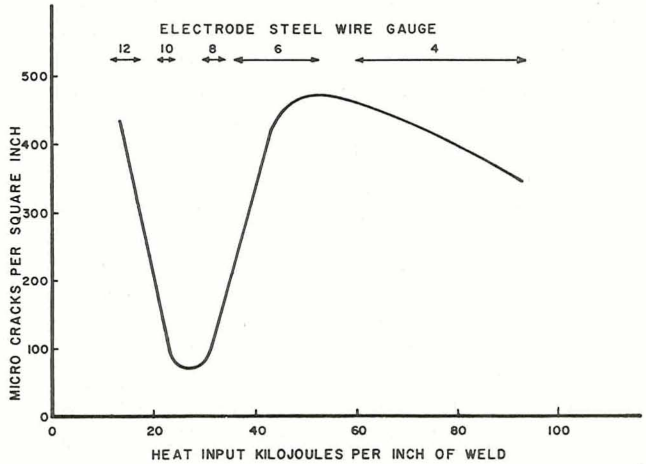


Figure 4. Relationship of Cracking with Heat Input.

cator; the last is a matter of electrode-base metal compatibility. To combat the first kind of stress calls for easing rigidity by minimum use of strongbacks, spiders, and similar bracing. Preheat to expedite the escape or diffusion of hydrogen will forestall the second kind of stress. The use of *uniform* preheat will safeguard against the third kind of stress.

The reduction of hydrogen, an implicit measure to prevent the second kind of stress, can be achieved in two ways:

1. Reduction of hydrogen available in the welding arc by control of the coating of the electrode.
2. Sufficient preheat temperature. It had been found experimentally [12] that preheat to 100°C (212°F) markedly suppresses hydrogen embrittlement fissures and that preheat to 150°C (302°F) afforded practically complete protection.

The third preventive measure, uniform preheat, is not self-evident. By straightforward reasoning, however, a qualitative picture of the effect of thermal stress can be constructed (see [12]). Cooling rate is *inversely* proportional to the cross-sectional area of the weld; contractional stresses are *directly* proportional to dimensions of the weld. These trends are shown graphically in Figure 3 (after Figure 47 of [12]) as plots of cooling rate and strain respectively as functions of weld size. Without preheat and for very small welds, the cooling rate is very high and the strain is very low. This combination is sufficient to produce many cracks. As weld size increases, the cooling rate drops hyperbolically whereas strain increases linearly. This combination produces fewer cracks. Eventually, with increasing weld size, strain becomes dominant and more cracks are produced. Finally, however, as weld size increases further (submerged arc-welding), the cooling rate becomes so slow that cracks cannot form regardless of the magnitude of strain. These trends are shown in Figure 4 (after Figure 45 of [12]) as a plot of cracks versus heat input. Although Figure 4 shows clearly the need for preheat, the desired preheat temperature cannot be derived therefrom. Moreover, the desired temperature is inextricably related to the quantity of hydrogen and the magnitude of stress in the joint present. An increase in either beyond a critical level must be accompanied by a decrease in the other, OR preheat and interpass temperature must be increased in compensation.

All the foregoing factors were well known qualitatively before the first arc was struck for production welding of HY-80 steel. The potential difficulties and the preventive measures had been clearly identified.

Explosion Bulge Tests

Early in 1950, Hartbower and Pellini [13] devised a novel, yet simple, test for measuring the deformation of metal plate and weldments under a *combined stress* field. In this test the specimen under evaluation is placed over a circular die opening with chamfered edges and an explosive is detonated a given distance above the plate. The force of the explosive acts uniformly on both the supported and unsupported areas of the specimen. If the metal is fully ductile, the unsupported area of the test plate is forced down into the die cavity by plastic deformation; if the metal is fully brittle, the test plate will shatter. If the metal is in transition, as may be the case with steel, the test plate will have various degrees of plastic deformation and cracking depending on how close the metal is to being fully ductile or fully brittle at the test temperature. Test temperatures can be varied from ambient as desired by cooling or heating the specimen before it is placed on the die. In addition, notches can be introduced into the tension surface of the specimen to create a more severe test condition. From the combination of explosion and a resulting bulge has come the name: "explosion bulge test."

In addition to temperature and notch effects, the test conditions can be varied to accommodate *any* thickness or strength level of plate. For example, as the thickness increases, the diameter of the die cavity and the other dimensions of the test plate are also made larger. As the strength or thickness of the test plate increases, the amount of explosive can be increased or the explosive stand-off distance can be decreased. A shot is defined as the weight of explosive and stand-off distance required to produce a 3 per cent reduction in plate thickness on the first shot of the test.

The results are measured as surface strain, thickness reduction, and bulge depth. When cracking occurs, it is evaluated as to:

1. Length and depth (shallow or through cracking).
2. Type (brittle or ductile or a combination of these).
3. Location as to unsupported (plastic stressed) area or supported (elastic stressed) area, or through both.
4. Location as to initiation point and propagation path (base metal, HAZ, or weld metal).
5. Direction with respect to the major rolling direction of the plate.

Plain plates in the as-rolled mill condition were the first to be evaluated. It was noted [13] that, *without a surface notch present,* all types of steel (medium, HTS, and HY-80) performed very well at temperatures considerably below the lowest service temperature for ship structures. *Actual* ship structures, however, contain *notches* of varying severity such as the changes in geometry at welds, flaws of various types (porosity, cracks, lack of fusion, undercut), arc strikes, and metallurgical notch effects. Hence, the introduction of notch effects into the explosion bulge was necessary to give this test structural realism.

From this pioneering effort have evolved two standard evaluation tests for *all* structural metals used in naval ships:

1. *Explosion bulge test.* The test specimen has at its center a butt weld which may be deposited using any joint preparation, material, welding electrode, and procedure for which an evaluation is desired. The as-deposited geometry of the weld is retained for the test. The realistic notch effects are those created by the toes of the weld, the grooves between beads, the ripples in the weld metal, and the inherent weld metal and HAZ flaws that escape detection.
2. *Explosion bulge crack starter test.* This is the explosion bulge test with an *artificially introduced brittle crack.* By use of the crack starter, plain plate as well as weldments can be evaluated. The crack starter is obtained by depositing a hard brittle weld bead, approximately ½ inch wide by 2½ inches long and moderately high crowned, in the center of the plain plate specimen. For weldments constructed of plate up to, but not including, 1½ inches thick, the brittle weld bead is placed in the center of the weld parallel to the longitudinal axis of the weld. For weldments constructed of plate 1½ inches and over in thickness, two crack starter beads are deposited so that the outside edges of the crack starter welds are 1/16 inch or less from the edges of the weld at the toe areas. The hard brittle bead is notched at mid-length using a thin abrasive disk. The length of the notch is the full width of the bead; the width, the thicknsss of the disk; and the depth remains within the bead itself. The specimen is positioned so that the crack starter will be on its tension surface; i.e., on the side opposite from the charge. Upon detonation a brittle crack is initiated at the base of the notched brittle bead and forced into the test plate. This brittle crack realistically simulates a sharp weld metal or HAZ crack, a fatigue crack, or a dormant base metal brittle crack that may be present in ship structure.

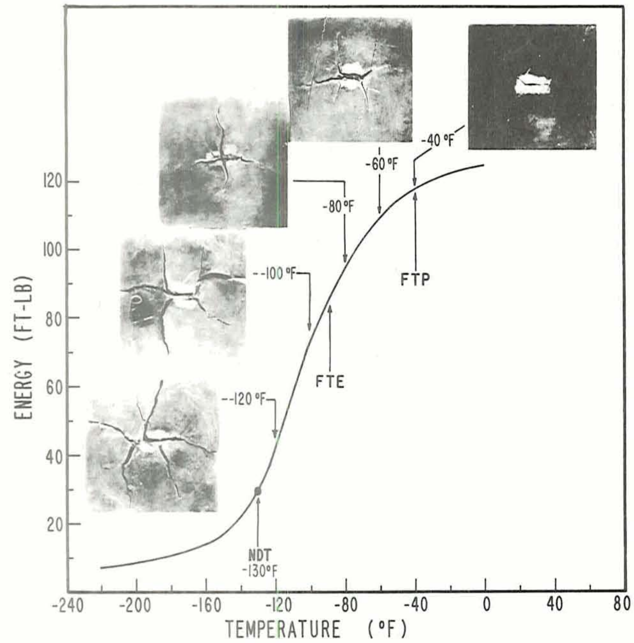


Figure 5. Typical Relationship of Explosion Bulge Crack Starter Tests and Charpy V-Notch Energy with Temperature for HY-80 Plain Plate One-Inch Thick.

One of the main attributes of the explosion bulge test is the *reproducibility* of results on repeat tests at various shot levels prior to fracture. Another special feature of the explosion bulge test, rarely, if ever, achieved in other evaluation tests, is that, for weldments, simultaneous and equal demands are placed on the base metal, HAZ, and weld metal. The fracture may propagate in any of the three zones and naturally selects the weakest. If the three zones are completely brittle, cracking will occur in all three and the specimen shatters on the first shot with a "flat break" (no bulge). Conversely, if the three zones are completely ductile, or of a high level of toughness, a deep bulge is obtained with a large reduction in thickness. In this case, no weak path is present and the specimen fails by shear tearing when the ultimate strength of the weldment is exceeded. Normally, however, the base metal, HAZ, and weld metal have different transition temperatures, so the weak fracture path concept holds. Although the fracture seeks the weakest zone, weld metal of higher yield than the base metal will force the latter to deform first and thus will influence fracture initiation and propagation.

Puzak and Pellini [14] performed explosion bulge crack starter tests on a large number of medium, high tensile, and quenched and tempered steels in the plain plate condition. Of the steels tested, HY-80 exhibited the best performance. The results for 1-inch thick HY-80 plates are shown in Figure 5. The photographs of the test specimens show the amount of cracking that took place at the various test temperatures. A Charpy V-notch impact energy curve is included for added significance. The data of Figure 5 indicate the following:

1. The amount of cracking decreases with increasing temperature and Charpy V-notch impact energy, while the depth of bulging and plastic deformation increase.
2. The flat break shattering type fracture occurs at temperatures below −130°F indicated by the NDT temperature (heavy black dots).
3. The cracks remain in the plastically deformed zone at −80°F and at −100°F they run beyond the plastic zone into the elastically loaded area indicated by the FTE (Fracture Transition Elastic) temperature.
4. Only short shear tears occur at −40°F which correspond to the upper shelf of the Charpy V-notch curve indicated by the FTP (Fracture Transition Plastic) temperature.

Since the lowest service temperature for submarine structure is 28°F and fully plastic shear type frac-

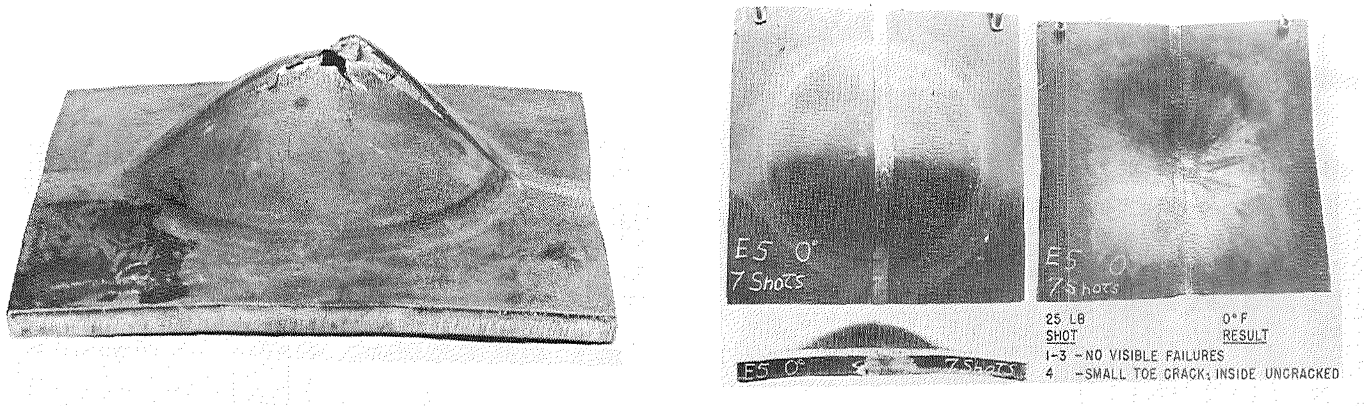


Figure 6. Typical Explosion Bulge Test Results of Welded HY-80 at 0°F.

A—Machine Welding of One-Inch Thick Plate using MIG Process with MIL-B88 Wire (From Pellini and Puzak—NRL Report 6030).

25 LB SHOT	0°F RESULT
1-3	No visible failures.
4	Small toe crack; inside uncracked
5	Toe crack (1½"); Plate Thickness not penetrated
6	Toe crack (2"); plate thickness still not penetrated
7	See Photographs

B—Manual Welding of Two-Inch Thick Plate using MIL-11018 Electrode (from Puzak and Babecki—NRL Memo Report 878).

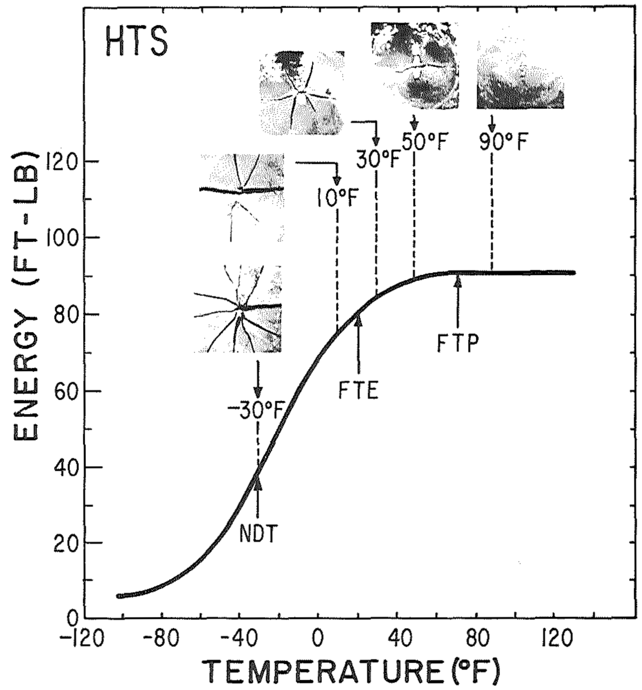


Figure 7. Typical Relationship of Explosion Bulge Crack Starter Tests and Charpy V-Notch Energy with Temperature for Normalized HTS Plate One-Inch Thick.

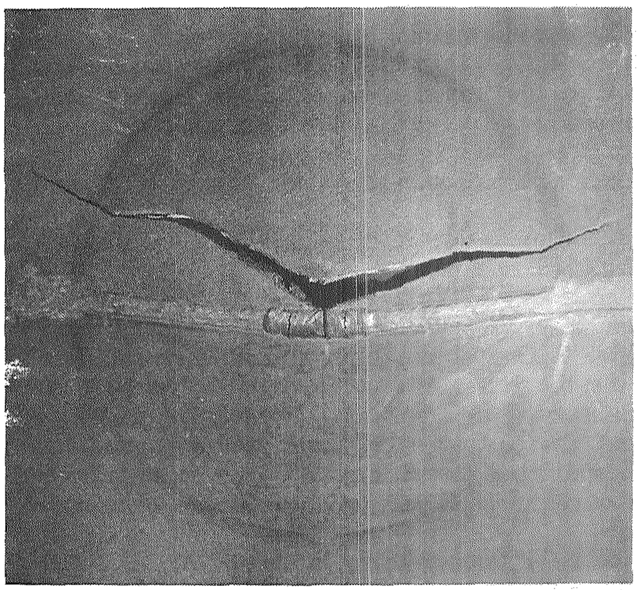


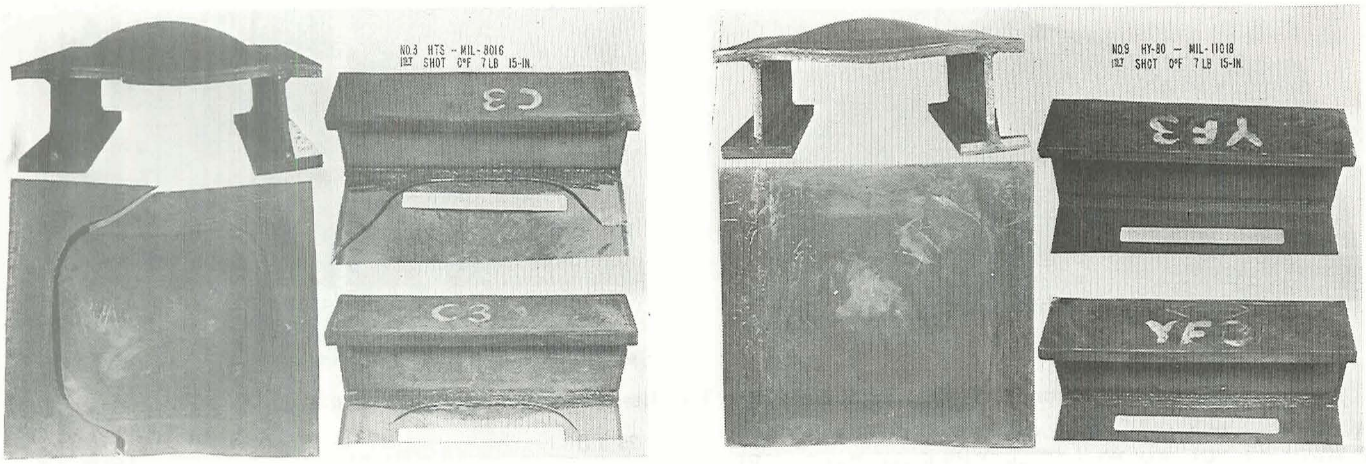
Figure 8. Explosion Bulge Crack Starter Test Results of HTS Welded to HY-80 (One-Inch Thick Plates) at 60°F (Furnished by Pellini and Puzak of NRL).

tures are obtained down to −40°F under explosive loading in the presence of a sharp crack, HY-80 plain plate is more than adequate.

Numerous explosion bulge and explosion bulge crack starter tests have been conducted on weldments of HY-80 plate up to 2 inches in thickness. These included welds made by manual electrodes (MIL-9018 and MIL-11018), machine welds of the MIG process (MIL-B88 electrode) and the submerged-arc process (MIL-EB82 and MIL-BI88 electrodes), and heat-treatable electrodes (MIL-8218YQT). All the weld metals, attendant HAZ, and final welding procedures were proven satisfactory down to and including 0°F. The photographs of Figure 6 show the typical results obtained for the various electrodes.

Satisfactory performance in the explosion bulge test is defined as the development of a full hemisphere bulge without failure. The bulges obtained can be seen in Figure 6. Reductions in plate thickness near the apex of the bulge, adjacent to the welds, are of the order of 10 to 20 per cent. Failure occurred by shear tearing only after the ultimate strengths of the plain plate, weld metal, and HAZ had been exceeded. It can be seen in Figure 6 that the shear tearing had no preference for any of these zones. All of the HY-80 weldments sustained from four to seven shots before failure.

In the explosion bulge crack starter test, satisfactory performance is defined as the ability of the



A—HTS Assembly

B—HY-80 Assembly

Figure 9. Explosion Bulge Test Results of Assemblies of One-Inch Thick Numbers at 0°) (From Babecki and Puzak—NRL Memo Report 966).

specimen to withstand two shots without the fractures leaving the plastically deformed zone. As indicated in Figure 6, the cracks remain in the plastic zone and show no preference for the plain plate, HAZ, or weld metal.

Since HTS was the submarine structural material prior to the introduction of HY-80, several tests comparing the materials have been conducted:

1. explosion bulge crack starter tests of prime plate,
2. explosion bulge crack starter tests of HTS welded to HY-80, and
3. explosion bulge tests of small-scale submarine hull weldments.

The results of the crack starter tests of plain plate have been reported [14] and are represented in Figure 7. One of the main difficulties encountered in the toughness evaluation of HTS has been the wide spread in transition temperature zones between the best and the worst production material indicated in Figure 2. Figure 7 represents an average curve of HTS performance. It should be noted that:

1. the NDT temperature is at −30°F,
2. the FTE temperature is at +20°F, and
3. the FTP temperature is at +70°F.

These three temperatures are well over 100°F higher than the corresponding temperatures for HY-80. Figue 8 shows the result of the explosion bulge crack starter test of HTS welded to HY-80. In this test all the cracking was confined to the HTS plain plate material. In the third comparative test, tee frames were welded to flat plates and the assemblies subjected to explosion bulge testing. Figure 9 shows the results of this test. Note the bulge and plastic deformation of the HY-80 weldment as opposed to the extensive cracking in the HTS weldment. Without exception, all these comparative tests have clearly indicated that the toughness of HY-80 is significantly superior to that of HTS.

EDITOR'S NOTE: *Part II of this paper will be published in the next (April 1965) issue of this Journal.*

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CAPTAIN S. R. HELLER, JR., USN, IVO FIORITI, and JOHN VASTA

AN EVALUATION OF HY-80 STEEL AS A STRUCTURAL MATERIAL FOR SUBMARINES

PART II

Editor's Note: Part I of this paper was published in the February 1965 issue of THE JOURNAL. *Biography of the author will be found on page 29 of that issue.*

FABRICATION

THE DISCUSSION of pre-fabrication exploration in Part I was concerned with difficulties which were forecast on the basis of past experience with welding new materials and on the metallurgical structure of the material itself. Also covered was "near-laboratory" experience in preparing specimens for evaluation of material-electrode combinations and qualification of welding processes. It is time now to turn from theory and laboratory to actual shipyard experience.

Early Experience

For several years after the end of World War II, the Bureau of Ships was engaged in a research program for the development of a high yield strength steel which program has been mentioned earlier. One of the several materials under investigation, that previously referred to as *low-carbon Special Treatment Steel,* stood out above all others as the possessor of the best combination of all desirable properties. This "low-carbon STS" was used by the Norfolk Naval Shipyard in the fabrication of several medium-sized ship-type structures for testing by the Shipyard's Underwater Explosion Research Division. The results of this testing were extremely encouraging. At about the same time, the University of California, under contract with the Ship Structure Committee as part of its research program for solution of the brittle-fracture problem, used it in tests of the highly restrained welds associated with hatch corner reinforcements. In these torturous tests, the low-carbon STS showed ductile behavior at failure and much greater energy absorption at fracture than the other quenched and tempered steels tested. Thus, the steel had performed excellently in small-size laboratory specimens and in large-size shipyard specimens; fabrication under these conditions had presented no great problems. Now was the time to work it into a ship.

At the outbreak of the Korean Incident two significant ships were in the preliminary design stage in the Bureau of Ships. One of these became the experimental submarine USS *Albacore* (AGSS569); the other, the lead ship of a new class of aircraft carriers, USS *Forrestal* (CVA59). Both were to have low-carbon STS used in important structural features.

Low-carbon STS was specified for the pressure hull plating of *Albacore* but with framing of HTS. At first glance this combination may appear strange. Actually it was a continuation of earlier practice in surface ship protection systems which practice had been evolved because of the non-availability of shapes rolled or extruded of STS. The plating was purchased by the Navy Purchasing Office, Washington under Contract N600s-S-11751 of 22 February 1951 to the chemical composition shown in Table VII. In addition, yield strength was specified to be between 80,000 and 95,000 psi at 0.2 per cent offset with a minimum elongation of 20 per cent in a 2-inch gage length. Furthermore, Charpy Keyhole impact energy, for thicknesses between ½ inch to 1¼ inches inclusive, was required to be 40 foot-pounds at −40°F. Similar Charpy impact energies of 25 foot-pounds for plates thinner than ½ inch and of 40 foot-pounds for plates thicker than 1¼ inches were expected but not required.

Portsmouth Naval Shipyard fabricated the *Albacore* hull during 1951-1952 using electrodes conforming to Military Specification MIL-E-986, Grade 260, of 1 November 1949 for all butt welds in the hull plating and the semi-automatic metal inert gas (MIG) welding process with AirCo A650 wire for the attachment of the HTS frames. At this time the specification for the Grade 260 electrodes required a minimum Charpy Keyhole impact energy of 23 foot-pounds at 0°F and a minimum yield strength of 110,000 psi for the weld metal in the *as-deposited* condition. There were no specific requirements for chemical composition or for inspection tests for acceptance. Moisture content of the electrode coatings was, however, required not to exceed 0.2 per cent.

In Fall, 1953, Portsmouth Naval Shipyard reported the results of *Albacore* construction. No problems worthy of mention were encountered in rolling the pressure hull plating to shape. Although the initial flatness was not as good as for HTS, rolling to shape eliminated the irregularities. Using normal quality control in welding; i.e., careful conformance to specified preheat and interpass temperatures, normal back-chipping of butt welds to sound metal magnetic particle inspection of root pass and final pass, and X-ray inspection of completed butt welds, the combination of HY-80* plate and Grade 260 electrodes proved to be very weldable. Not only did Portsmouth report that there were fewer repairs of butt and seam welds required than in any of the last three submarines built at the shipyard, but that *there were no occurrences of structural cracking of welds or plate material during the entire construction.*

On 12 June 1952, HY-80 steel (formerly called low-carbon STS) was approved for use in the side protection system in *Forrestal*. Plating was purchased using Military Specification MIL-S-16216A of 13 August 1952 to the chemical composition shown in Table VIII. It will be noted that the chemical composition limits in Table VIII are essentially the *same* as in Table VII except that the standard tolerances of the American Iron and Steel Institute for check analysis have been added. The mechanical properties specified were also the same as for the low-carbon STS in *Albacore*.

As for *Albacore*, electrodes conforming to Military Specification MIL-E-986, Grade 260, of 1 November 1949 were used for all butt welds in HY-80 plating. Attachments to plating, including stiffeners, were welded with electrodes conforming to Military Specification MIL-E-16715, type MIL-31015(16); this is the electrode commonly called "25/20" and formerly identified as Grade IV of Navy Specification 46E4 of 15 October 1944.

Although Newport News Shipbuilding and Drydock Company, the builders of *Forrestal*, did not submit a formal report on fabrication and weldability of HY-80, information available within the Bureau of Ships and from the Supervisor of Shipbuilding indicates that there were no problems encountered. It has been specifically noted that the plates procured for *Forrestal* were well within flatness tolerances.

The next use of HY-80—and the last prior to widespread adoption for submarine construction—was for the plating and framing of the missile hangars in USS *Growler* (SSG577) being built at Portsmouth Naval Shipyard. *Growler* had been started as an attack submarine and was converted during construction to a guided missile submarine. HY-80 steel was used in this ship for weight-saving. Plating was purchased using Military Specification MIL-S-16216B of 20 May 1953 which required the chemical composition shown in Table VIII.

All welding—butts and attachments—was accomplished using electrodes conforming to Military Specification MIL-E-18038, type MIL-10015(16), of 9 July 1954. Chemical composition, minimum Charpy Keyhole impact energy of 23 foot-pounds at 0°F, and a minimum yield strength of 90,000 psi were specified for the weld metal in the *as-deposited* condition. Moisture content of the electrode coatings was required not to exceed 0.2 per cent. The specification, however, did not require lot inspections or weld tests for verification of the specification requirements.

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* The name "HY-80" was given to low-carbon STS on 15 August 1951 when Military Specification MIL-S-16216 was issued.

TABLE VII

Chemical Composition (Per Cent) for Pressure Hull Plating of USS ALBACORE (AGSS569)

Thickness (Inches)	C (Max.)	Mn	P (Max.)	S (Max.)	Si	Ni	Cr	Mo
Up to 1¼	0.20	0.15–0.35	0.035	0.040	0.15–0.35	2.00–2.50	0.90–1.40	0.15–0.25
Over 1¼	0.20	0.15–0.35	0.035	0.040	0.15–0.35	2.75–3.25	1.35–1.84	0.40–0.60

TABLE VIII

Chemical Composition (Per Cent) for HY-80 Steel Used in USS FORRESTALL (CVA59)

Thickness (Inches)	C (Max.)	Mn	P (Max.)	S (Max.)	Si	Ni	Cr	Mo
Up to 1¼	0.22	0.10–0.40	0.04	0.045	0.12–0.38	1.93–2.57	0.84–1.46	0.13–0.27
Over 1¼	0.23	0.10–0.40	0.04	0.045	0.12–0.38	2.68–3.32	1.29–1.91	0.37–0.63

Normal quality control was used; no cracking problem was noted. The only incidence of cracking observed was in the connection of the light hangar plating to the heavy reinforcement rings where the difference in thickness was in the ratio of 3:1. When adequate preheat and quality control were applied to this connection of plates of greatly different thicknesses, cracking disappeared.

Based on the impressive characteristics of HY-80 steel as revealed by extensive tests and the encouraging results of pilot usage in the field, the U. S. Navy approved HY-80 as the basic structural material for future submarine construction. USS *Skipjack* (SS(N)585), the contract design of which was completed on 11 June 1956, became the first *combatant* submarine with structure subjected to submergence pressure specified at the outset to be of HY-80 steel.

Production Experience with Submarines

Construction of *Skipjack* was begun with use of MIL-260 and MIL-10015(16) electrodes permitted for welding HY-80 steel just as had been permitted in the construction of *Albacore* and *Growler*. The general construction practices—fit-up, welding controls, inspection, and the like—employed were essentially the same as had been used successfully for the earlier nuclear submarines—*Nautilus, Seawolf,* and *Skate*—which had HTS hulls of about the same scantlings. No appreciable welding problems were encountered. Indeed, the earlier experience with *Albacore, Growler,* and *Forrestal* was being repeated. Construction continued apace.

In the spring of 1958, MIL-11018 electrodes, whose superiority in notch toughness over earlier electrodes had been demonstrated, was authorized for use in submarines subsequent to *Skipjack* after existing stock was exhausted. At about the same time, although in a *totally unrelated* manner, extensive cracking was discovered in the HY-80 structure of *another* submarine. Consequently, reinspection of *Skipjack's* structure was initiated. Because of the advanced state of outfitting and the consequent difficulty and prohibitive expense involved in making a *complete* reinspection, *Skipjack* was subjected to a limited reexamination. Very few defects were discovered and those were minor. *Skipjack* was considered structurally sound. Nevertheless, inquiry into the difficulties encountered on the *other* submarine was begun.

During the early stages of this inquiry, cracks were found in the connections of frame webs to shell. When this problem was probed further, it was discovered that cracking persisted in the repair welds. In a few cases as many as six cycles of welding and inspection were required before successful repair was achieved. Furthermore, welds previously inspected and found satisfactory were, on reinspection as much as three weeks later, found to have severe cracks. Sleuthing pointed to reheating to make a weld in the vicinity as the culprit. Still later, boundaries of "hard" tanks were reexamined and found to have cracks although previous inspections, some as much as four months earlier, had resulted in acceptance. These defects were attributed to high restraint. All the forecastable difficulties were belatedly appearing.

The inquiry was broadened to include *all* submarine building yards and the cognizant Supervisors of Shipbuilding. As might have been expected, each "expert" interviewed espoused a different factor as contributing to the problem and each proposed a different remedy. The consensus was, however, that compliance with BUSHIPS Notice 9110 of 2 July 1958 would be a big step toward eliminating the problem. The guidance contained in this BUSHIPS Notice 9110 included controls for

a. Preparation, storage, and issue of electrodes
b. Preheat and interpass temperature

c. Heat input
d. Welding sequence

In addition, from all the contributing factors cited and the remedies proposed during the inquiry came the realization of the need for

1. Protection from the weather
2. Avoiding highly restrained construction
3. Standardization of inspection procedures and records
4. Better training and qualification of welders and inspectors.

In summary, all concerned with submarine construction became convinced of the *necessity for close control* of the entire fabrication process.

Satisfied that the indoctrination afforded by the promulgation of the aforementioned BUSHIPS Notice 9110 and the lessons of the broad inquiry into fabrication practices were significant steps toward the solution of the cracking problem but not a panacea, the Bureau of Ships continued its efforts. The total fabrication process was attacked on a broad front. As described in earlier sections of this paper, base material specifications were improved and made more definitive, and electrode development was intensified. Non-destructive inspection techniques were improved and standardized; inspectors were carefully trained in their conduct and interpretation. Extruded and rolled shapes, castings, and forgings of HY-80 steel were produced, qualified, and authorized for use. Construction details were redesigned to avoid high restraint and stress concentrations. Finally, all these improvements were combined with the required controls into a single document, NAVSHIPS 250-637-3 of November 1960, which became the gospel for fabrication, welding, and inspection of HY-80 steel in submarine construction. Later revisions to this publication have removed ambiguity, closed loopholes, improved clarity, and incorporated results of research and development.

The effectiveness of this concerted effort is graphically presented in Figure 10 where the decline in the incidence of weld defects is related to time. The significant events—issue of BUSHIPS Notice 9110 in July 1958, the inquiry into construction practices in 1958-9, and the publication of NAVSHIPS 250-637-3 in November 1960—have been indicated in Figure 10. The most encouraging finding shown in Figure 10 is that the incidence of weld defects at *every* submarine building yard declined and this continued even when heavier scantlings were incorporated in later classes. The most annoying finding shown in Figure 10 is that a structure entirely free from flaws has not yet been achieved. Clearly this was never really expected although it was devoutly to be desired. Certainly the very low incidence of weld flaws at the present time is ample evidence that submarine construction can be and is "under control." Equally obvious is that careful attention to details, vigorous inspection, and constant vigilance are required. The seriousness of the few defects that defy detection must be determined. It is with this facet—the resistance to fracture in the presence of a flaw—that the next section is concerned.

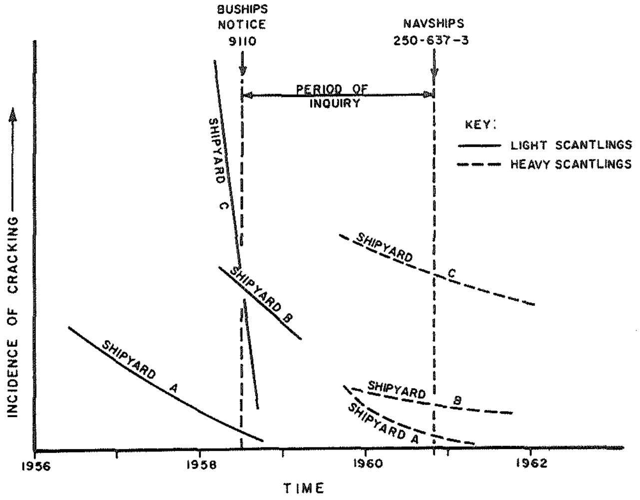


Figure 10. Incidence of Weld Defects Discovered During Submarine Construction.

RESISTANCE TO FRACTURE

Despite vigorous inspection during construction, there are always a few defects that defy detection. Submarines, however, are subject to cyclic loading because of depth excursions and may be subject to dynamic loading by enemy attack. The effect of these varying loads in the presence of these defects must now be explored.

Low-Cycle Fatigue

Since the fatigue performance of highly stressed details constructed of HY-80 steel was imperfectly understood, the Bureau of Ships undertook a comprehensive test program to obtain the needed data. Extensive experimental data have now been obtained from a variety of laboratory-type specimens, both plain and welded, as well as from testing nearly full-scale submarine structures incorporating structural details considered prone to develop early fatigue cracks. By building such large complex structures, it has been possible to represent the important variables associated with fabrication of welded HY-80 submarine pressure hulls under typical shipyard practice. Thus, size effects, welding procedure, restraint, residual stress, and such other elusive factors as random distribution of defects and flaws were contained in the large structures.

Just as for any other structural material subjected to repetitive loading, HY-80 steel will first develop a fatigue crack at a point of geometrical discontinuity where the stress intensity is highest. This fatigue crack will then characteristically grow with each loading cycle, and the rate of crack growth follows a consistent pattern. Because of its high notch

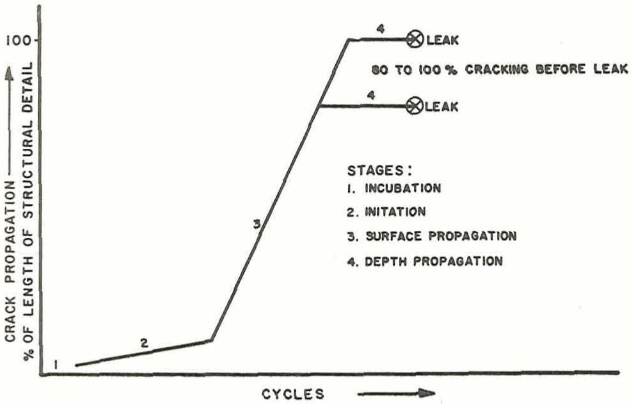


Figure 11. Schematic Representation of Fatigue Crack Growth.

toughness, HY-80 steel does not permit rapidly propagating brittle or low energy shear type fracture. Contrary to the behavior of some high strength steels currently being investigated for pressure vessel application, HY-80 steel, in the presence of fatigue cracks, has never exhibited any catastrophic failure tendencies.

The typical fatigue crack growth pattern for a highly stressed structural detail in the nearly full-scale HY-80 submarine test structures [15] is shown schematically in Figure 11. The pattern is composed of four stages:

1. *Incubation*—the crack is microscopic and defies detection.
2. *Initiation*—the crack is macroscopic and can be detected, but growth rate is very slow.
3. *Surface Propagation*—the crack grows in length at a faster rate.
4. *Depth Propagation*—after the crack has primarily propogated on the surface, it progresses through the plate to failure (a leak).

Of particular importance is that the structure has experienced extensive surface cracking (almost completely along the detail) prior to through cracking—and yet NO catastrophic fracture propagation has ensued. Indeed, through cracking (a leak) is of very short length.

Dynamic Loading

The foregoing has been concerned with propagation of cracks solely by cyclic loading. Also of concern is the performance of these fatigue-induced cracks under dynamic loads. To determine these characteristics a series of explosion bulge tests was conducted on flat plate specimens, each of which was 1½ inches thick and contained a central butt weld [16]. The specimens were loaded in bending to an approximate stress of 50,000 psi, with the number of cycles ranging up to 100,000—well beyond the expected number of depth excursions an actual submarine would experience. The specimens loaded up to 50,000 cycles had no discernible cracks (incubation stage); the specimens loaded up to 75,000 cycles had short cracks at the toe of the weld (initiation stage); the specimens loaded to 100,000 cycles had longer cracks at the toe of the weld (surface propagation stage). The overall effect of fatigue cracking is a decrease in the number of *succeeding* explosive shots that may be applied before the cumulative damage (length and depth of crack) causes failure. Nevertheless, once a crack developed, whether caused by fatigue or prior explosive loading, there was no discernible difference in resistance to explosion. In other words, the material is not sensitive to the cause of the crack, only to the existence of a crack.

A summary of test results [16] is given in Table IX. It is significant to note the depth of bulge and reduction in thickness *concurrent* with the progressive growth of the initial fatigue cracks under successive explosive loadings. This performance is a good example of the excellent toughness of HY-80 steel. Of even greater significance is that, for Specimen 5, *three* explosive shots were required to extend the several initial fatigue cracks, ⅛ inch long, to 12 inches and *even then* there was NO catastrophic fracture propagation.

Although much was learned from the explosion bulge tests with the welded flat plate specimens, the behavior of more complex structures was desired. Accordingly, a test program was devised to determine the performance of typical stiffened cylinders subjected to underwater explosion. Relatively large-

TABLE IX

Summary of Explosion Bulge Tests of Butt-Welded Plates Loaded Cyclically

Specimen No.	No. of Cycles	No. of Shots	Bulge Depth (in.)	Reduction in Thickness (%)	Crack Length (in.)	
					Initial	Final
1	0	7	4.75	16.0	0	2
2	12,500	5	5.9	17.6	0	½-1
3	25,000	4	5.3	15.3	0	4
4	50,000	5	6.6	24.0	0	plate separated
5	75,000	3	6.0	10.3	many ⅛	12
6	100,000	3	5.4	14.4	many up to 5	plate separated

NOTE: Specimen No. 1 was 2 inches thick; all others were 1½ inches thick.

scale models were constructed to assure realistic structures typical of shipbuilding practice. Three models were built:

Model 1—of HTS to represent a post World War II design

Model 2—of HY-80 steel with the *same strength* (same operating depth) as Model 1

Model 3—of HY-80 steel with the *same weight* (greater operating depth) as Model 1

Such a series would show not only individual performance of the models, but also *comparative* performance of the two materials.

All three models were loaded dynamically by detonating explosive charges placed alongside the models underwater at distances such that the test structures would be subjected to shock waves similar to those which an actual submarine might experience from enemy attack. Since the models had external "T"-frames welded to the shell, the most critically loaded details were the welds attaching these frames to the shell.

The performance of the two HY-80 models was most revealing. The first shot against Model 2 (same strength as Model 1) initiated several small cracks at the toes of the welds connecting the frames to the shell and some permanent deformation inward. The second shot of the same intensity caused a very slight propagation of these cracks into the shell plating and the permanent deformation inward to increase substantially. Thus, the structure had successfully withstood two explosion attacks of high intensity and was still watertight. Cracks had propagated only very slightly even in the presence of severe deformation. Indeed, the performance was very similar to the cyclically-loaded flat plate specimens which were subjected to explosion bulge tests described earlier. Similar tests but of greater severity were conducted against Model 3 with essentially identical results; very slight propagation of cracks into the shell plating and slightly further around the girth; substantial increase in permanent deformation inward.

In comparison to the performance of the HY-80 models, that of the HTS model (Model 1) was poor. The first shot against Model 1, although of the same severity as for Model 2 (same strength) but of less severity than for Model 3 (same weight), caused several brittle fractures of considerable extent in the framing system; see Figure 12. Model 1 can, for all practical purposes, be considered to have failed on the first shot. Clearly it would be expected to withstand neither another explosive shot nor any appreciable hydrostatic load.

Comparison of HTS and HY-80

For a specific operating depth requirement, an HTS submarine hull would require thicker shell plating and more massive frames than its HY-80 counterpart because of the difference in yield strengths. Not only would the HTS structure be heavier, but it would also suffer from some significant deficiencies in material properties. Because of the greater thicknesses, a decrease in toughness would be expected and welding difficulties would increase with attendant structural degradation. The combination of greater thicknesses and more massive welds could be expected to produce a greater number of defects that go undetected, higher residual stresses, and greater restraint all of which tend toward reducing fatigue life. Moreover, thicker HTS plates and heavier rolled sections, by the very nature of the chemistry and manufacturing process of HTS, contain relatively large bands of segregation. Furthermore, even the best grade of HTS has notch toughness properties, at the temperature of interest, that are inferior to those of HY-80 of similar thickness. When these material imperfections and inferior properties have construction and fatigue cracks superimposed, all the necessary ingredients are present for a structure having high susceptibility to brittle fracture propagation.

The thoughtful analyst may properly observe: Your reasoning is impeccable and your conclusions appear sound, but have you *actual* proof? The answer, of course, has been given earlier. Figure 2 is ample evidence that the notch toughness of HTS is inferior to that of HY-80. Figures 8 and 9, the comparative explosion bulge tests of the two materials, bolster this finding. The overriding factor, however, is the comparative performance under explosive loading. The dramatic failure of the HTS model (Model 1) shown in Figure 12 is proof positive that brittle fracture propagation in HTS not only can occur, but has been demonstrated. The predicted superiority of HY-80 over HTS where resistance to fracture is concerned has been confirmed.

COMPARATIVE COSTS (HY-80 vs. HTS)

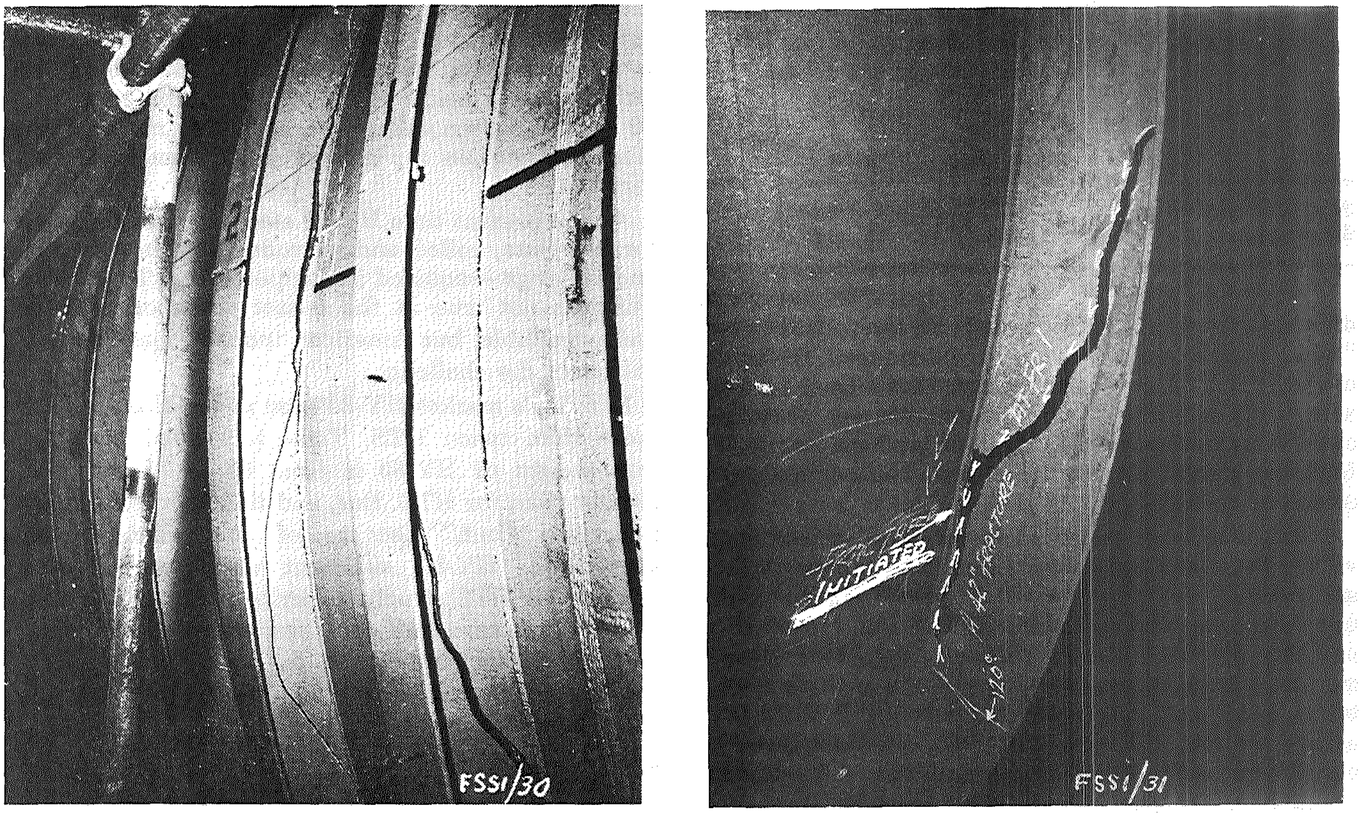
In the evaluation of any structural material, cost is a very important consideration. It not only determines the impact on the pocket book in terms of expense per unit; but it can also affect the total quantity procured. In times of essentially level annual budgets, the cost of submarine hull structure can determine the number to be built each year. The cost of a material may be appraised in two ways:

1. Material cost only
2. Total fabricated cost

Both will be explored.

Material Cost Only

Because HTS was in general use for submarine hull construction when HY-80 steel was initially developed, the comparison of the two materials is inevitable. Table X is such a comparison. Table X is based on the costs of plates 2 inches thick by 10 feet long by 8 feet wide loaded at the steel mill for shipment. As can be seen, HY-80 plate costs slightly more than twice HTS plate.



A—Overall View

B—Close-up View

Figure 12. Underwater Explosion Test Results of HTS Structural Model.

TABLE X

Comparative Costs of HTS and HY-80 Steel Plate

Item	Cost ($/lb.) Hy-80	HTS
Base Price	0.1000	0.0555
Specification Price	0.1360	0.0340
Thickness Extra	0.0265	—
Width & Thickness Extra	—	0.0050
Length Extra	—	0.0005
Normalizing & Flattening	—	0.0125
Ultrasonic Inspection & Gaging	0.0120	0.0090
Cleaning (2 side)*	0.0040	—
Painting (2 side)*	0.0050	—
Pickling & Painting (2 side)*	—	0.0119
Gas Cutting Extra	—	0.0028
Ultrasonic Scanning Extra	—	0.0031
Total	0.2835	0.1343

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* These operations have been subcontracted by the steel mills and prices tend to vary. Those given are typical.

NOTES:
1. Prices are F.O.B. at the steel mill.
2. Prices reflect the purchase of plate in quantity of a size 2" x 96" x 120".
3. Prices as of September 1964.

Total Fabricated Cost

Costs of submarine constructions vary with the shipbuilder. There are many factors that determine cost. The more significant include:

1. Type of facilities and equipment
2. Quality of personnel
3. Geographical location (weather, freight charges, wage scale)
4. Type of ownership (private or government)
5. Workload and schedule.
6. Whether or not the ship is first of a class

It is beyond the scope of this paper to analyze at length all these factors. Rather, only a gross, "ball park" comparison is necessary. The effects of the first three factors seem self-evident. The fourth factor has been studied in depth in recent times and, hence, will not be explored here further. The fifth factor involves such aspects as the number of kind of ships being built. If the ships are all of the same kind, special jigs and fixtures can become economically desirable and the same force can be used repetitively on similar jobs. On the other hand, if the workload is mixed, these economies cannot be realized. The effect of the sixth factor can be examined qualitatively also. When a submarine is first of a class, the design changes necessarily involve increased costs. This is not only true where the hull material is changed simultaneously with initiating a new class, but is also equally true for a new class using the same material. Ships subsequent to the first of a class, follow ships, are understandably cheaper since they reflect learning and experience.

An additional complication in comparing the cost of HY-80 construction with that of HTS is the

TABLE XI
Approximate Comparative Fabricated Costs of HY-80 and HTS Submarine Pressure Hulls

Ship	Total Fabricated Cost ($/lb.)	
	HY-80 (1964)	HTS (1955)
First of Class	3.50	2.00
Subsequent	2.50	1.50

difference in time. By "difference in time" is meant "what year" were the materials introduced. Significant changes in submarine design have been made since HTS was first used. With the passage of time came improved inspection methods and the demand for more stringent inspections. Also came increased costs due to inflation.

Data have been gathered from all shipyards involved in submarine construction. These have been analyzed and synthesized "ball park" approximations are presented in Table XI. The data presented in Table XI are given as costs per pound of pressure hull for nuclear submarines only; include material, labor, and overhead; and reflect HY-80 costs as of 1964 and HTS costs of 1955. The last factor may seem unfair because of inflation. Offsetting inflation in the case of HY-80 are simplification of design details and increased use of automatic welding. From Table XI it is seen that, for the first ship of a class, HY-80 construction costs about 1¾ times that of HTS whereas, for subsequent ships, HY-80 cost has dropped to about 1⅔ times that of HTS.

Cost per unit weight of material does not, however, give the total picture. Because of its higher yield strength, less HY-80 steel than HTS is required for a submarine of the same basic military characteristics: operating depth, speed, endurance, ordnance, electronics, and the like. Indeed, several comparative designs have been prepared all of which show that the pressure hull weights are essentially inversely proportional to yield strengths. Thus, for submarine hulls with the *same military characteristics*, those built of HTS will require about 70 per cent more material than those built of HY-80 steel. When this factor is considered in conjunction with the comparative costs per unit weight, the comparative costs of submarine hulls with the *same military characteristics* are about the *same*. If HY-80 steel were used, the first ship of a class would cost slightly more than for HTS whereas subsequent ships would cost slightly less.

CONCLUSIONS

From the foregoing discussion of the development of HY-80 base material and electrodes suitable for its welding, it has been clearly shown that HY-80 steel weldments do, in fact, satisfy the three primary requirements for a submarine structural material: strength-weight ratio, toughness, and resistance to fracture. The evidence validates this in the absolute sense, but is *overwhelming* when HY-80 steel is compared with its predecessor, HTS. Indeed, the substantiating evidence for the acceptability of HY-80 steel has been collected from much more extensive testing than for any previous structural material.

At the present time HY-80 steel is available in all forms—plate, rolled and extruded shapes, castings, and forgings—required for shipbuilding. To be sure this was not true at the outset when only plates were available, but American industry has successfully met the challenge.

In today's market HY-80 base material costs a bit more than twice HTS. Total fabricated cost per unit weight of HY-80 is from 65 to 75 per cent greater than for HTS. But, and this is an extremely important "but," because of the greater yield strength of HY-80, sufficient weight-saving over comparable HTS structure can be made, so that the costs of pressure hull for submarines of the same military characteristics are the same.

Although HY-80 steel is readily formed and can be satisfactorily welded in normal shipyard environment, its martensitic structure, the product of its chemical composition and heat treatment, demands careful control of the total welding process. This control and the consequence of its lack were forecast prior to the adoption of HY-80—and came to pass. The difficulties that arose because of failure to control stringently the total welding process have now been overcome and a rigorous control procedure imposed. So long as the required controls are followed, no further difficulties are anticipated.

In summary, HY-80 steel has an excellent strength-weight ratio, is tougher and more resistant to fracture than any other structural steel now available, is available in all forms required for shipbuilding, costs no more than its predecessor, HTS, for the same military characteristics, and, because of its greater yield strength, makes possible improved military characteristics. Its lone disadvantage is the rigorous control required for successful fabrication, but all complex structures, regardless of the materials used, require this.

On balance, HY-80 steel is clearly the *best* structural material now available for submarines.

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13. ABSTRACT

Because of concern regarding the slow rate of introducing new materials into national programs, the Committee sought to identify the factors that promote or inhibit their use. The advantages to be derived from new materials are documented. Case histories of past material introductions are discussed. Using these histories as a foundation, the factors that constrain or which promote progress in introducing new materials into hardware are identified. The "constraints" and "promoters" are organized into four categories; technical, economic, contractual, and management and organization. Principal recommendations are: (1) A continuing function should be established under a government organization to (a) review the status of new materials and processes, (b) identify those with a potential for wide applicability that can benefit by coordinated support, (c) organize a cooperative program to assure timely application of the selected materials and processes in government-sponsored systems and (d) in addition, discourage the expenditure of time and money for development of new materials whose properties are not adequately known. (2) A contractual clause is recommended for use by government agencies to define a quantitative scale of incentive payments to compensate for the cost involved in achieving levels of performance beyond the minimum specified. (3) Component development programs should utilize present hardware systems as test beds for new materials applications. (4) Materials cost-effectiveness analysis should consider benefits over the full lifetime of the system.

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