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REPORT OF THE

COMMITTEE ON GUN TUBE TECHNOLOGY

NATIONAL MATERIALS ADVISORY BOARD
Division of Engineering - National Research Council

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February 1971

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ABSTRACT

The object of the study was to recommend long-range improvements in the manufacture and concept of gun barrels, as well as to suggest solutions to current gun manufacturing problems. Improved steels are listed and coatings for the bore proposed, which might result in better performance or lower cost. Alternate metalworking and casting methods are discussed. The manufacture and inspection of barrels are described and some advanced technology proposed. A limited number of advanced concepts for launching projectiles were examined. Of the conclusions reached, the foremost two are the need for better understanding of the interrelationships among the factors responsible for the degradation of gun barrels during service, and the need for the consideration of a barrel as part of an ammunition-propellant-gun system and not as an isolated entity.

ADVANCED TECHNOLOGY FOR NAVAL GUN TUBES

I. BACKGROUND

A. INTRODUCTION

In a Navy Department request, the National Materials Advisory Board of the National Research Council was asked to review Gun Tube Technology from several aspects hereinafter described in the Section on "Scope." The results of the study were desired in a reasonably short time, which fairly well defined the extent or depth to which it should be carried.

The subject is obviously a broad one. It was under intensive review during and to the conclusion of World War II. Since that time, there does not seem to have been any organized study of the subject involving experts from outside the Armed Services and authorized to consider weapons utilized by all Services.

The Committee on Gun Tube Technology was carefully chosen to represent some experience in gun barrel manufacture, and also to include others without any background in the subject but with skill in modern manufacturing techniques, knowledge of materials, and principles of design. It was thought that such a group could combine the freshness of approach of certain experts, somewhat tempered in discussion by the experience of others. Liaison members from the three Services also attended meetings and contributed technical input as requested. Visits to Navy and Army installations were valuable for obtaining information and for the opportunity to see the problems

in perspective. It is recognized that requirements may differ substantially from one military Service to another, but since World War II, the Army has undertaken substantially more development and production of barrels than has the Navy. Therefore, it is instructive to look to the experience of the Army for both valuable innovations and for mistaken paths to be avoided. The sizes of the gun barrels considered by the Committee (over 3-in. or 75-mm), precluded extensive participation on the part of the Air Force.

In pursuing this work, the Committee was accorded splended cooperation by representatives of the Armed Services as well as of individual companies.

B. THE SCOPE OF ACTIVITIES OF THE COMMITTEE

The objectives of this project, contained in the contract between the Navy Department and the National Academy of Sciences, defined the scope of the activities of the Committee. They also set the basis for this report of the work.

"(a) The National Materials Advisory Board of the National Academy of Sciences shall establish a Committee to review the 'State-of-the-Art' for manufacture of gun barrels and gun liners.

"(b) The Board shall make recommendations for solution of current manufacturing problems.

"(c) The Board shall make recommendations for long-range improvement in manufacture of these weapons. These recommendations may take the form of improvement in materials, manufacturing technology, redesign effort, and the identification of possible sources for manufacture of such weapons."

C. ORGANIZATION OF THE COMMITTEE ON GUN TUBE TECHNOLOGY

It was considered advisable by the Committee to consider the task assigned to it in three aspects:

a. Current manufacture of gun barrels and the history of such manufacture, together with evolution in materials, design, and service conditions since World War II.

b. Suggestions for the improvement of current methods, current designs, etc.

c. Long-range possibilities for radically changed gun barrel manufacture possibly involving entirely different principles of design and propulsion, and utilizing advanced materials.

The Committee was subdivided into four task groups, each of which considered the three aspects mentioned above.

a. The Task Group on Materials
George Timmons, Chairman

b. The Task Group on Methods of Casting or Forming
Arnold L. Rustay, Chairman

c. The Task Group on Manufacturing Methods
Abraham Hurlich, Chairman

d. The Task Group on Entirely New Concepts
Jack A. Yoblin, Chairman

D. BASIC DESIGN CONSIDERATIONS

Specifications in use recently by the Army and the Navy include:

MIL-T-10458	Tubular Parts for Cannons Over 30-mm, Steel Forgings for
MIL-S-46119	Steel Forgings, Tubular Parts for Cannons, High Yield Strength (160,000-180,000 psi)

The service requirements for gun barrels differ between the Navy and the Army. The effects of these differences on the guns used by the two Services are important and are evidenced in the design philosophies of each. The latest revision of specification MIL-S-46119, as used by the Army, incorporated increases in the notched bar impact requirements along with some reduction in yield strength. Autofrettage was resorted to to permit these guns to meet the performance requirements established for the original higher strength weapons.

a. Navy Gun Barrels. In the past, weight was not as critical a factor with Navy guns as in the case of Army guns. The reason is that Navy guns are shipboard mounted and need not have the same degree of mobility as Army guns. This weight factor may be of decreasing importance, but it certainly has been a prime consideration in the past. Therefore, Navy guns tend to be heavier, wall thicknesses tend to be greater, and unit fiber stresses may be lower. However, in recent years, the trend of the Navy to mount large caliber guns on smaller vessels makes the weight of Navy guns an important factor in their design.

It has been possible, therefore, to use material of lower tensile strength in such barrels. Lower strength material (typically, 65,000 psi yield strengths materials were used in the past) may be expected to have greater ductility and fracture toughness, although this is not necessarily so. This material may also exhibit lower resistance to erosion and wear. In the past, erosion and wear have been considered the principal factors in determining the life of Navy guns.

The tensile strength of the alloy steels used in gun barrels, particularly for Naval service, was quite low prior to the World War II period. This does not mean that they had consequent high fracture toughness, because much improvement in this respect has been the result of greatly improved techniques for steelmaking. It is stated that a number of gun barrels of low

strength alloy steel still exist in stock. Gun barrels of calibers 5- and 6- in. were usually autofrettaged. Larger guns of this period were of the shrunk-on hoop and liner construction.

To maintain the proper perspective on the problems of gun barrel technology, it should be noted that the performance record of Navy barrels of this period appears to be excellent.

The "loose-liner" technique was developed by the Navy to obviate the expense and time-consuming job of replacing worn gun barrels on shipboard. The "loose-liner" as used by the Navy is practically a gun barrel in itself. It is inserted in the "hoop" or "breech section" at room temperature, using a lubricant. The tube and the liner are joined by intermittent threads and "keyed" in place. The liner can be inserted in a breech section while the ship is at sea. Formerly, replacing worn barrels involved withdrawing the ship from service for a period. The barrels were taken off the ship in a shipyard or similar facility, where they were salvaged by drawing out the worn liner, boring the tube, and shrinking in a new liner.

b. Army Gun Barrels. The problem of excessive weight has always been a major factor in the design and selection of materials for cannon barrels for use by the Army. Field artillery, as distinct from that mounted in fortifications (or in ships), has to be moved about with the field forces. The importance of this was emphasized in World War II. It was found possible to combine high fire power with such light weight that artillery could move with great rapidity when mounted either in tanks or on somewhat similarly constructed motorized gun carriages. The objectives of maximum fire power with minimum weight were achieved by utilizing steels of higher unit strengths, up to about 180,000 psi yield strength. Such strengths were obtained by increased alloy content and by heat treatment. The loss of toughness that tends to accompany high strength became a problem. This was met by determining a minimum acceptable value

of toughness (and a test to measure it), and by close control of processing to avoid dangerous embrittlement.

The use of heat treated high-strength alloy steels (140,000 psi yield strength and over) presents unique problems. In old low-strength steel guns, there was not only less heat checking and bore cracking due to the high temperatures reached by the explosive charge, but much of the cracking was erased by erosion of the barrels caused by the shells, the bands, and the gases. It was found that bore cracking was perhaps more severe when high-strength alloys were used, erosion was less, but cracks progressed more rapidly and some failures were experienced as a result. The possible onset of fracture, rather than dimensional changes of the bore, became the life-limiting factor.

The relationship between the rate of crack growth in fatigue to the microstructure began to be understood during World War II. Research determined that the progress of fatigue cracks was slowest for a given steel in a tempered martensite structure (as compared to tempered bainite or other "upper" transformation products).

This required the use of gun steels with sufficient alloy content to produce a tempered martensite structure after heat treatment. It was found practical to test the success of the heat treatment procedure by Charpy notched bar testing at low temperatures, and requirements for this test became an important part of cannonbarrel specifications.

Water was definitely favored for quenching from the heat-treating temperature. Sufficient quenchant circulated through the bore helped to reduce quench cracking. The best equipment actually introduced water first to the bore surfaces, and later to the outside. Theoretically, bore quenching

leaves the bore surfaces in compression.

At times, autofrettage has been used to advantage in Army gun barrels. In fact, all Army gun tubes designed since approximately 1955 are autofrettaged. The Army technique of expanding into a fixed cylinder does not uncover weak areas as the Navy open mandrel methods do, but it is economical and efficient. It was an important part of the successful use of centrifugally cast gun barrels by the Army during World War II. The centrifugal casting technique requires special facilities that are useful for no other purpose. Many vitally needed guns for World War II were produced by casting, demonstrating the practicability of this process. However, it might not produce the necessary degree of fracture toughness that is an important requirement today.

Multi-layer shrunk gun barrels have not appealed to the Army because of the expense involved, and also because this type of design is particularly applicable to large wall thicknesses rather than the small ones desired for Army use.

Modern fracture mechanics concepts have been applied to determine yield strength/fracture toughness ratios found serviceable. Furthermore, crack propagation is understood to an extent that permits safe service lifetimes to be determined, and guns in the field are replaced when the limit of safe life is reached. Improved instrumentation makes possible more exact studies of the progress of cracks. Charpy impact test specifications have been adjusted to assure acceptance only of barrels with satisfactory fatigue and toughness characteristics.

Both the Army and Navy recognize the paramount importance of fail-safe design such that cracks, if they occur, will not propagate catastroph-

ically in a brittle fashion. At the same time, the wear life of barrels has been extended by the use of propellant additivies, leading to a service life limited by fatigue rather than be erosion. Therefore, the presence and growth rate of cracks is a matter of greater significance now than it was formerly. Not only is an understanding of the role of cracks and flaws important, the ability to detect and evaluate such discontinuities is also of increased importance. While in some circumstances it may be easy to detect cracks, there is the additional problem of assessing crack growth. Recent developments in sound attenuation effects may provide a means.

E. SUMMARY

The conclusions and recommendations of the Committee are stated at the end of chapters II, III and IV. All are combined in the final chapter, Conclusions and Recommendations.

Two findings of the Committee are considered of such importance that they are stated at the outset:

I. The Committee recognizes with regret that there is not a positive test or procedure for evaluating gun barrels, which might be used to indicate the effects of any changes made.

It would be desirable to establish significant evaluation parameters for barrels by the systematic firing of a number of guns to destruction. However, the very considerable expense entailed by such a program precludes this effort, particularly in times of restricted availability of funds. It is believed possible to develop simulated laboratory tests as well as scale-model gun-ammunition systems to permit, at reasonable cost, a correlation of the factors as well as the interrelationships among the factors responsible for the degradation of gun barrels resulting from firing. To the greatest extent possible, barrels that have been fired should be examined and the findings compared with the results of simulated firing tests.

The Committee strongly encourages the development of laboratory or subscale tests that simulate the behavior of actual barrels. It is mandatory that the validity of such tests be confirmed by concurrent firing trials of full-scale weapons. Attention has been called to such developments as an erosion test rig at Dahlgren and a pressure fatigue test at Watervliet. We endorse this activity and encourage continuing work so that changes in materials, heat-treatments, processing, etc., can be checked out readily and with confidence. The essential aspect is the establishment of the probable failure mode and duplication of such failures in a rapid and inexpensive manner. It is mandatory that the probable failure mode be understood before hardware incorporating any radical innovation is released to the fleet.

2. At the time of the next major redesign of a gun, efforts should be made to utilize a "systems" approach. In the past, attempts to make guns of greater reliability, longer life, or increased fire power were divided into an effort on gun barrels, an effort on projectile design, or propellants, etc. By considering all factors at an early design stage, it is possible to consider trade-offs so that final performance and economy are maximized to a greater degree than would be possible by working on one item at a time.

II. MATERIALS

A. EXISTING SPECIFICATIONS

1. Chemical Composition

For many years, specifications used by the Armed Services for the procurement of gun barrel forgings have not contained definite requirements or restrictions on the chemical composition of the steel. It is required that the bidder on gun barrels state the limits of analysis to which he will work. When these limits are approved by the procurement agency, they have the effect of being a specification.

There is general agreement that the steel most commonly used today, and which has been in use in recent years, is what is loosely described as AISI 4330 modified. It is "modified" considerably; two typical varieties of this steel are given herewith.

a. Typical Compositions of Gun Barrel Steels—Nominal Analysis

Medium Strength		High Strength	
Carbon	0.34	Carbon	0.35
Silicon	0.30 max*	Silicon	0.30 max*
Manganese	0.65**	Manganese	0.75**
Nickel	2.00	Nickel	3.10
Chromium	0.85	Chromium	1.00
Molybdenum	0.55	Molybdenum	0.55
Vanadium	0.07	Vanadium	0.12

*The deoxidation practice may result in lower silicon contents.

**The manganese content may be lower.

There are no data giving a comprehensive view of the effects of chemical composition on the useful life of a gun barrel. This is one of the factors that might well be clarified if valid laboratory or scale-model testing methods were developed.

The steel manufacturer, working to the specifications given to him, provides sufficient alloy content to give his steel the necessary hardenability, so that it will be possible to quench and temper it to obtain the specified minimum tensile properties, and, at the same time, have sufficient toughness as evidenced by Charpy V-notch tests at the low temperature specified.

In general, the chemical composition should be such that it is possible, on quenching, to obtain an essentially martensitic structure. Furthermore, it should be such that the tempering temperature required to produce barrels with the tensile strength within the specified range will not produce temper embrittlement. It is generally agreed that the tempering temperature should be 1000°F or higher, with over 1100°F desirable.

In the period of alloy shortage in World War II, this need for sufficient alloy content to enable the transformation of the structure to martensite was recognized. Accordingly, quenching facilities and equipment had to be efficient.

2. Methods and Techniques of Steel Manufacture

The trend to steels of high strength levels coupled with good fracture toughness, led by the requirements for thin-walled highly stressed gun barrels, has resulted in the utilization of the best modern practices, particularly vacuum treatment during steelmaking, in the current manufacture of gun barrels. Details of this will be found in Chapter IV of this report.

3. Suggested Improvements

This section will consider possible improvements in the materials now being used, as well as developments in steelmaking processes that might result in improvements in gun barrels. "Improvement" means either better gun performance (longer life, higher muzzle velocities, etc.), or equal performance at lower cost, lighter weight, or with less drain on limited resources.

There has been considerable experimentation and development work to establish optimum alloy compositions. The basis for decision has usually been the ease of meeting applicable specifications at an overall minimum cost. It is important that such variations be correlated with realistic appraisal of the resulting product, either by full-scale testing or by a proven simulated service test. The Army has attempted to develop a practical simulated service test for gun barrels by initiating the usual bore cracking by explosive charges and completing the test by subjecting rifled cylinders to hydraulic fatigue cycling. This may constitute a practical and valid means of evaluating new developments in gun barrels. It should be noted, however, that the Army cycling test is not necessarily applicable to the Navy's two-piece barrel since the effect of the tube in mitigating the amplitude of the liner strain is not known and cannot be predicted without specific test programs.

The need to squeeze the last bit of advantage from the material, due to the desire for maximum performance, requires that all possible areas of improvement be explored. One such improvement may be the more careful selection of raw materials and the control of "incidental" or "tramp" alloying elements. The rather extensive investigations in recent years into the brittle characteristics of steels used for turbine rotors have demonstrated the extreme importance of this factor.

In an emergency period, a shortage of alloying elements can be expected. There will be the necessity to salvage metal by remelting and also pressure to derive the maximum benefit from alloying metals. Concern has been expressed by those who recall periods of shortages in the 40's and 50's with regard to the suggestion of using highly alloyed compositions. However, a major improvement in performance will require a higher alloy content. In an emergency, controls will be instituted in order to assure the availability of scarce materials for priority needs such as gun barrels. It is for the Navy to balance economy and availability against weapon performance.

B. SUGGESTED NEW MATERIALS

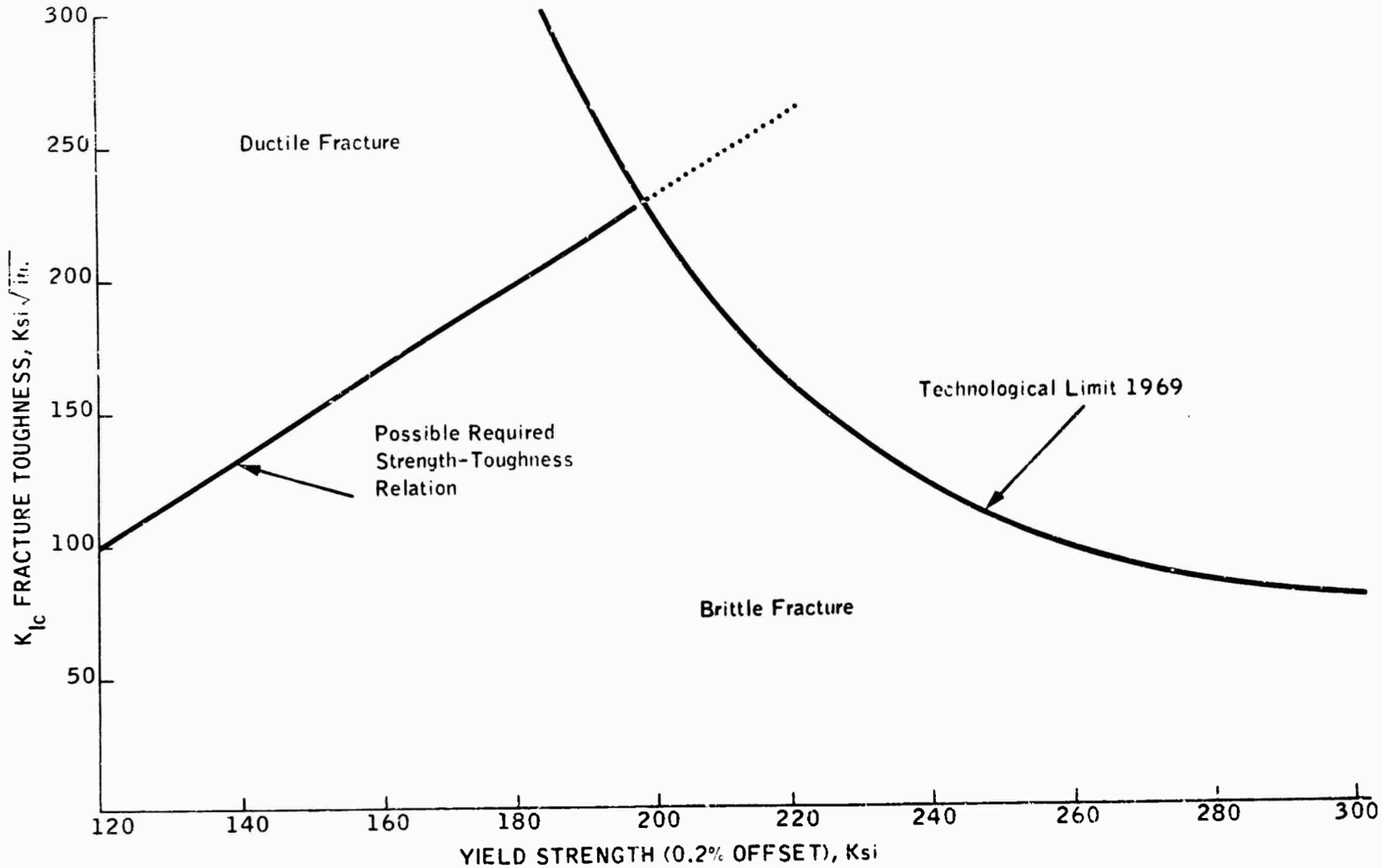
A logical course of action leading to improved performance of gun barrels lies in the development of suitable steels or other metals that may be used at higher strength levels than those now in service.

Further improvements in fracture toughness at high strength levels must be obtained for the long-range development of higher strength steels for gun tubes, if the same degree of safety against brittle fracture is to be maintained. As shown in Figure 1, the fracture toughness of the steel must be above some minimum value for a given yield strength, to prevent brittle fracture regardless of specimen geometry. Present knowledge of high-strength steels limits the maximum yield strength to about 200,000 psi to assure ductile failures in heavy wall gun tubes—as shown in Figure 1 by the line marked "Technological Limit." These practical limits may be raised by future developments in steel technology.

To achieve the full-strength toughness potential of modern high-strength steels, the following four steels are proposed for experimental gun tubes. Studies of fracture mechanics have indicated the increasing importance of irregularities or imperfections in steel as the strength level increases. It is essential that consideration be given to this when steels of 140,000 psi yield strength or over are used. The steelmaking process is an important factor in this respect.

Steel A. Lower residual version of the current gun-tube composition

C	Mn	P	S	Si	Ni	Cr	Mo	V
0.35	0.20	0.005	0.005	0.05	3.25	1.10	0.55	0.12



Relationship Between Fracture Toughness and Yield Strength for Ductile and Brittle Fracture and The Present Day Technological Limits (After Pellini - NRL Report 6957)

FIGURE 1

This steel would be produced by vacuum-carbon deoxidation in a vacuum-induction furnace. No additions of strong deoxidizers (aluminum, titanium, calcium, etc.) would be made, and the silicon content would be kept as low as possible to eliminate silicate-type inclusions. Manganese and phosphorus would be kept low to minimize temper embrittlement, sulfur would be kept at the lowest possible level to provide highest possible toughness. The resulting steel would have very low levels of nitrogen, oxygen, and strong deoxidizers, and thus be free of nitrides and nonmetallic products of deoxidation. The steel would be tempered at temperatures in excess of 1000°F. The toughness of the steel should be superior to current gun-tube steels at 140,000 psi yield. Therefore, it could be heat-treated to, and used at, a higher strength level—possibly 170,000 psi minimum. Expected Charpy V-notch energy absorption at -40°F would be 25 ft.-lbs. minimum.

Steel B. Lower carbon, higher nickel, lower residual modification of the present gun-tube composition

C	Mn	P&S	Si	Ni	Cr	Mo	V
0.22	0.15	0.005	0.05	7.0	1.50	0.75	0.08

This steel would be produced to the same low-residual practice discussed for Steel A. Improved toughness would be achieved by reducing the carbon content. To compensate for the loss in hardenability from the lower carbon content, the nickel, chromium, and molybdenum content would be raised.

Steel C. Experimental HY-180 steel

C	Mn	P	S	Si	Ni	Cr	Mo	Co
0.12	0.15	0.005	0.005	0.05	10.0	2.0	1.0	8.0

This composition represents a steel that has exhibited the highest notch toughness obtained with present technology. To achieve the maximum toughness, the steel must be vacuum-arc remelted after the initial low-residual vacuum-induction melting. The vacuum-arc remelting lowers the oxygen of the steel from about 25 ppm to less than 10 ppm and raises the notch toughness at a yield strength of 180,000 psi from about 40 ft.-lbs. to about 90 ft.-lbs. at -40°F. The steel has sufficient hardenability to develop 180,000 psi in sections six inches thick. A strong secondary hardening reaction occurs when the steel is tempered at 950°F. Additional strengthening is achieved from the 8% cobalt. For these reasons, the steel can achieve yield strengths in excess of 180,000 psi, although only 0.12% carbon is present. The steel does not exhibit temper brittleness, and thus a low tempering temperature is not harmful. Since the low carbon content of the martensite in the 10% nickel steel will result in a tougher, lower-hardness layer at the inner surface than would be produced from re-austenitizing a 0.35 carbon steel, the low carbon content may be beneficial in gun tubes, and the dilational strain resulting from the transformation would be less. However, the effect of lower carbon content upon mechanical wear, such as occurs toward the muzzle end of the gun barrel, is unknown at this time.

Steel D. Experimental HY-200 steel

C	Mn	P&S	Si	Ni	Cr	Mo	Co
0.15	0.15	0.005	0.05	10.0	2.0	1.0	13.75

This steel would be produced in the same manner as the 10% nickel HY-180 steel. The somewhat higher carbon and cobalt content will result in a steel with a predicted yield strength of 210,000 psi when tempered at 950°F with notch toughness expected to be over 25 ft.-lbs. at -40°F.

Maraging and stainless steels, which may have some future application for gun tubes, should also be considered in any development program. The following steels are proposed.

Steel E. 12-nickel maraging steel

C	Mn	P&S	Si	Ni	Cr	Mo	Ti	Al
0.005	0.15	0.005	0.05	12.0	5.0	3.0	0.25	0.25

Maraging steels are very sensitive to embrittlement from the formation of TiS and Al_2O_3 particles on solidification and from the formation of Ti(CN) and AlN particles during subsequent elevated-temperature processing. To obtain high toughness in maraging steels, they must be melted to very low levels of carbon, nitrogen, oxygen, and sulfur. This is best accomplished by vacuum-induction melting a low-carbon, low-sulfur, electric-furnace iron since vacuum-carbon-deoxidation reactions and vacuum degassing during vacuum-induction melting lower the carbon to below 0.01% and reduce oxygen and nitrogen levels to low values prior to the addition of the oxidizable alloying elements (Ti and Al). The 12 Ni-5Cr-3Mo maraging steel produced to very low levels of carbon, nitrogen, oxygen, and sulfur will exhibit 50 to 60 ft.-lbs. at -40°F and a yield strength of 180,000 psi. Again, the effect of very low carbon content upon mechanical wear characteristics is an unknown factor.

Steel F. 18-nickel maraging steel

C	Mn	P&S	Si	Ni	Mo	Co	Ti	Al
0.005	0.15	0.005	0.05	18.0	3.0	8.0	0.25	0.020

This steel behaves very much like the 12% nickel maraging steel. The same precautions must be observed in melting the steel if optimum toughness is to be obtained. The 18% nickel maraging steel generally exhibits about 10 ft.-lbs. higher notch toughness at 180,000 psi yield strength, a higher resistance to stress corrosion, and a more rapid reversion to austenite at temperatures in excess of 900°F than a 12% nickel maraging steel of the same strength level.

Steel G. Precipitation-hardened stainless steels

There are several different grades of precipitation-hardened stainless steels. A typical composition is illustrated by that of Stainless W:

C	Mn	P&S	Si	Cr	Ni	Ti	Al
0.07	0.50	0.015	0.50	16.75	6.75	0.80	0.20

Precipitation-hardened stainless steels generally exhibit low notch toughness. This low notch toughness can be improved by low-residual, vacuum-melting practices, as in other high-strength steels. However, current steel compositions of this type are generally not optimized to produce maximum toughness, but are high in chromium to produce resistance to corrosion. Thus, even when these steels are melted to the lowest levels of residual elements, it is doubtful that the Charpy V-notch energy absorption at -40°F when the steel is aged to a yield strength of 180,000 psi would be higher than about 20 ft.-lbs.

The corrosion resistance of the precipitation-hardened stainless steels may be an advantage in preventing corrosion fatigue in gun tubes. As a result, even though current steels of this type probably do not possess sufficient notch toughness for gun-tube applications, their superior corrosion resistance may make it desirable to develop low-residual, high-toughness modifications for gun-tube applications.

C. LINERS AND INSERTS

During firing operations, the bore surface of a gun barrel suffers unique and severe service conditions. The explosive charge develops high temperatures and gases that may be corrosive; and the rotating bands on the shells engage the rifling at the forward end of the firing chamber. As the projectile progresses down the barrel, the bore surface is exposed to the friction of the band and to the elevated temperature and corrosive gases resulting from the explosion.

Coincidentally, a complicated stress pattern is imposed on the barrel because of internal pressure developed by the charge.

Efforts have been made in the past, and are continuing, to provide special materials, when necessary, to meet special conditions—temperatures, corrosive gases, cutting effects, and erosion. Liners of heat-resistant alloys and refractory metals have been successful in the case of guns of smaller caliber than those covered in this report. Consideration was given to the possibility of advantages that might be obtained in barrels of 5-in. Naval guns. The melting ranges of most alloy steels are similar, and the strengths of the low-alloy steels at temperatures to which the bore surfaces of guns are subjected do not vary greatly. It is apparent that a "quantum jump" in performance of 5-in. guns will require a change of composition at least at the surfaces of the gun tubes near the breech ends.

During World War II, the Office of Scientific Research and Development recognized the need to improve performance of Naval gun tubes and supported some research whose ultimate objective was to line Navy guns with refractory metals. Only one gun tube, a 3"/70 caliber type containing a molybdenum liner, was ever fired. This gun was designed as an automatically firing hypervelocity weapon for antiaircraft use. The muzzle velocity was 3000 fps at a maximum true pressure of 60,000 psi. The gun was intended to fire at a rate of 90 rounds

per minute for as long as one minute. Apparently, the records of the firing are no longer available. However, in the memory of a few Navy engineers, the performance of the experimental gun tube was less than satisfactory due to cracking of the molybdenum liner. Therefore, there are no Navy test data relating to the improvement that might be expected from the use of high melting-point metals or alloys at the bore surfaces of Naval guns.

The Committee has been forced to draw on the results of the Army and Air Force small arms experience to appraise the potential value of high-temperature metal liners in Naval gun tubes. One of the best sources of information on the behavior of nonferrous metals in gun barrels is the Summary Technical Report of Division 1, National Defense Research Committee on Hypervelocity Guns and The Control of Gun Erosion, published in 1946.

The study of hypervelocity guns revealed that steels—or high iron alloys—lacked resistance to thermal and chemical attack by powder gases during firing; and, therefore, show no promise as bore surface materials under severe firing conditions using conventional propellants. "It was tentatively concluded as a working hypothesis (which subsequent experience confirmed) that severe erosion is inevitable in a steel gun tube, regardless of the type of steel, when fired under hypervelocity conditions with present day (1945-1946) propellants." Only the following materials were resistant to attack by powder gases: chromium, molybdenum, tantalum, tungsten, cobalt, and copper. Only the first four have sufficiently high melting points for severe service hypervelocity conditions where melting is an important factor in the failure of a steel gun bore surface. Tests on pure nickel and high-nickel alloys (superalloys and Hastelloys), under less severe laboratory test conditions, showed that they were subject to severe intergranular attack by powder gases. Their performance barely equaled, or was inferior to the performance of steel.

Preliminary tests of molybdenum liners emphasized the importance of hot hardness and ductility as characteristics of a successful gun liner material. Although molybdenum was highly resistant to attack by the powder gases and it did not melt or heat check in actual firing tests, unalloyed molybdenum liners of that period suffered severe swaging of the rifling and cracking of the tube walls. The hardness was low and ductility was minimal.

The Stellites, which are cobalt-chromium alloys, have somewhat higher levels of hot hardness. They are erosion resistant so long as the bore surface temperatures are not too high. Application of this discovery led to a remarkable increase in performance life of the .50-caliber aircraft gun. "Stellite 21 (28% Cr-2.5% Ni-5% Mo) installed in the .50-caliber machine gun has given a solution that was successful to the point of being spectacular." The liner was a short breech liner; the remainder of the bore was electroplated with chromium. The Stellite-lined barrels were used in the latter months of World War II in the Pacific theatre after very favorable acceptance test results on some 200 barrels on several firing schedules.

A measure of the success of Stellite can be obtained from the following:

> At a meeting of the Ordnance Committee on January 4, 1945, approval was given to recommendations that "Barrel D-7461580 having a Stellite liner be approved for manufacture as the preferred design for use in guns: Machine, Browning calibre .50 M_2 aircraft basic gun, Machine calibre .50 T36 aircraft basic; and Gun, Machine calibre .50 T25F3 aircraft basic," and that "the barrel assembly presently in manufacture (D-28272) be produced only in such quantity as may be required to balance the Army Supply Program for the Gun, Machine calibre .50 M2 aircraft basic."

In this particular application, a Stellite liner lasts long enough to furnish a useful gun barrel life, but when it fails, it does so by melting along surface cracks.

However, experience with Stellite liners in the .60 caliber machine gun, which has a muzzle velocity of slightly over 3500 fps, showed that this alloy was marginal when used in hypervelocity guns, and that "the most promising material for service in hypervelocity guns appears to be hardened molybdenum. During the war, sufficient progress was made in its development that the Navy Department continued to support the efforts of the Westinghouse Electric Company to make this material in a form suitable for large gun liners" (presumably the 3-in., 70-caliber).

The successful experience with Stellite in small arms gun barrels should justify some trials to determine how much improvement might be effected in the performance of Naval guns. These trials should be at the level of pressure-erosion testing and should be made in gun barrels of slightly longer caliber. Stellite is the lowest priced material that might be used for this application, and procedures for its manufacture are probably the best established of all candidate nonferrous materials.

The pressure-erosion test assembly and the Mark 11, 20-mm, smooth bore, gun barrel insert that have been developed at the Naval Weapons Laboratory, Dahlgren, Virginia, comprise excellent tools for the appraisal of new materials considered to be candidates for partial bore liners for larger Naval guns with higher power. Costs of operating these test units appear to be several orders of magnitude less than firing tests for the 5-in. guns or even the 3-in., 70-caliber guns.

It is recommended that preliminary appraisals be made of the Stellites and alloys of columbium, molybdenum, tantalum, and tungsten in the pressure-erosion test assembly, and then in the Mark 11, 20-mm gun. The alloys should be produced by the most advanced technology and should be qualified by mechanical property tests prescribed by Army and Navy engineers before the more expensive test specimens for the two Navy tests are prepared. Such a program would

entail a modest research and development expense. Firing tests in full sized gun barrels should not be contemplated until the preliminary tests have been critically reviewed. If a metal or alloy tested satisfactorily, then a program of gun tube construction and firing tests would be justified.

In 1946, refractory metals were usually produced by the powder metallurgy process, sizes were limited, the amount of working (to develop mechanical properties) was limited, and little could be accomplished by alloying. The technology for refractory metals has advanced markedly since 1950. Vacuum arc melting, electron-beam melting, improved isostatic pressing, and extrusion and coextrusion of metals in high speed presses have been developed and are now established. Mechanical properties of the metals and alloys produced by these new technologies are far superior to those of metals produced prior to 1950. Although this new generation of refractory metals has found application in missiles, space vehicles and other space hardware, and in some industrial applications, lack of funding has apparently prevented the inclusion of these metals in research and development of gun barrels for any of the Services.

Although expense may be a limitation, there should be no concern about the availability of refractory metals in the quantities needed for gun barrel applications, nor should there be any anxiety regarding manufacturing facilities. There are many consumable electrode, vacuum-arc furnaces in the United States that can be used for melting any of these metals. There are also ample extrusion facilities and forging presses that can extrude the refractory metal alloys, or coextrude them with steel to produce refractory liners.

D. COATINGS

An obvious possibility for increasing gun barrel life is to reduce the erosive effect of the band of the projectile where it passes from the breech

to the muzzle. Encouraging results have been obtained in one government laboratory by the use of additives to the propellant charge.

Gun barrels are usually chromium plated in the bores principally to reduce corrosion damage. Plating or coating with other metals or with lubricants may offer additional advantages.

This Committee saw a particular advantage that might be gained by gas phase deposition of metallic tungsten on the bore surface. This has been tried with a degree of success in the case of small-caliber guns.

The following requirements for an ideal coating or liner material are:

- High melting point
- High strength (impact, yield, tensile, compression) at elevated temperature
- High specific heat
- High thermal conductivity
- Thermal expansion coefficient comparable to or lower than that of substrate material
- Low coefficient of friction with material of rotating band
- Low compressibility
- No embrittlement by interstitial elements

In examining the physical and mechanical properties of available materials, the selection points toward the superalloys and refractory metals. However, the element, tungsten, comes closest to the ideal material. Tungsten cannot practically be deposited electrolytically, but it can be applied using a chemical vapor-

desposition process. The properties of tungsten follow. These represent commercially pure tungsten, since information is not available for vapor phase plated tungsten.

1. Tungsten has the highest melting point of all known metallic elements. MP = 6170°F (3410°C).
2. Tungsten retains a substantial amount of strength above 2000°F. Ultimate tensile strength of commercial tungsten at 2400°F is 45,000 psi.
3. Pure tungsten has the lowest thermal expansion coefficient of all metals (range $2.2 - 6.3 \times 10^{-6}$ in./in./°F), depending on mechanical and thermal history.
4. Strength, hardness, and toughness, and probably other properties of vapor-deposited tungsten can be varied over a wide range depending on deposition parameters such as temperature and WF_6/H_2 flow rates and ratios. Hardness range of VPP tungsten: R_C40 - 60 (DPH 393-695).
5. Tungsten has one of the highest thermal conductivities (range 31.5- 96.9 BTU/hr/ft^2/°F/ft).
6. Tungsten has the lowest compressibility of any known metal (0.28×10^{-6}/megabar). This means a smaller temperature increase after release of compression stresses and therefore lower bore surface temperatures.
7. A computer study shows that a thin tungsten coating in a gun barrel bore will considerably reduce bore surface temperatures.

To deposit a coating of tungsten on steel, the chemical vapor deposition method is suggested because of its high deposition rate and high purity, density, and strength of the deposited tungsten film.

E. SUMMARY OF RECOMMENDATIONS

For "Materials" intended for Naval gun barrels of large caliber, in addition to the general recommendations for a simultaneous laboratory and limited full-scale testing program and a "systems" approach to problems concerning cannon, the Committee specifically recommends the following:

1. Consideration should be given to the use of steels that can develop higher yield strengths than the currently used "AISI 4330 modified" without sacrifice of the fracture toughness: yield strength ratio developed by this composition at the 140,000-160,000 psi yield strength level. Use of these higher strength steels may permit lighter weight guns without sacrificing range, projectile weight, or muzzle velocity, or, at the same weight as the present 5-in., 54-caliber guns, heavier projectiles, longer ranges and/or increased muzzle velocity may be achieved.

2. Improved life and/or the opportunity to use higher energy propellants could be achieved by using such nonferrous materials as Stellite 21 and/or the refractory metals, columbium, tantalum, molybdenum, or tungsten as inserts at the breech ends of the guns (extending forward from 1/5 to 1/3 of the length of the tube and including the origin of rifling and origin of the bore). Development of these inserts should start with the pressure-erosion assembly and the Mark 11, 20-mm gun with the smooth bore insert, and gradually advance to larger calibers after experience is gained in design and behavior.

3. Inserts made by coextrusion of the refractory metals and steel should be considered for the use of much higher energy propellants approaching "hypervelocity" gun performance. Full length, relatively thin-walled liners of coextruded refractory metal (bore surface) and steel (supporting sleeve) may eventually be used in the larger guns.

4. Parallel development of rifled gun tubes, coated with vapor-deposited tungsten for increased resistance to erosion, should be pursued starting with tests on small caliber guns and progressing toward the 5-in.. 54-caliber gun after each stage has produced successful results.

III. FORMING METHODS

A. EXISTING PRACTICE—FORGING

Conventional forging practice, when applied to gun barrels of the size considered in this report, has usually comprised reduction of an ingot of suitable size on an open die forging press of ample capacity. Individual forge shops have preferred flat, as well as V-dies, and some have used swage dies.

In the past, the amount of forging reduction from the cast ingot to the forged round barrel has been kept to a relatively low figure (3/1 to 4/1 or less), since reduction favored directionality of properties unfavorable to hoop stresses. Excessive reduction of a too-large ingot occasionally made it difficult to obtain specified ducility properties (transverse reduction in area).

The widespread use of vacuum-treating processes applied to the molten metal has lessened the importance of forging reduction by improving the cleanliness. Gun-barrel forgings have been successfully made from large rolled billets or blooms, but this intermediate step has not been general. Automated press and handling equipment may reduce direct forging costs.

1. New Forging Developments

Two fundamentally different forging processes offer promise. The first of these, compression forging of the rifling, is under investigation at Defense Department installations. While it is difficult to believe that relatively thick-wall tubes can have the rifling forged into the barrel to the same tolerances as those being machined, the process does have merit because increased material yields might be obtained if even a smooth bore can be hollow forged on a mandrel.

A second and more interesting development is rotary forging. Large rotary-forging machines have been developed by at least two equipment manufacturers, Gesellschaft für Fertigungstechnik und Maschinebau GMBH (GFM) and Sack Maschinenfabrik GMBH (SACK). These machines are capable of forging an ingot directly to a finished round billet, and from a pierced billet directly to a full size gun tube (of varying cross section) and, in some cases, complete with I. D. rifling.

According to the manufacturers, it would be feasible to forge, from an ingot, a gun tube 56-feet long, 16-inch I. D. by 36-inch O. D. at the large end to 20-inch O. D. at the muzzle end (a 16-inch Naval gun tube). Existing machines can forge gun tubes 25-feet long, 5-inch I. D. by 14-inch O. D. at the large end to 7-inch O. D. at the muzzle end.

American Schiess Corporation, representing the SACK Forging Mill in the United States, indicate they can produce necessary equipment to manufacture both the 5-inch gun barrel and the 16-inch gun barrel. Depending on tooling, such as solid mandrels or expanding mandrels, both mills can be equipped to manufacture gun barrels with rifling.

The equipment required to produce the 5-inch barrel is SACK's 880-ton machine at an approximate price of $1,750,000.00. To produce the 16-inch barrel would require a 1,650-ton machine, which would cost approximately $5,000,000.00. Both machines would have versatility and could produce many other items. However, it should be noted that these machines are used in this country only if large quantities of identical or nearly identical parts, such as axles or billets, are required. The economies would have to be carefully evaluated by comparison with existing methods.

Of considerable interest is the fact that these machines are made to be tape controlled. Therefore, once an approved forging sequence is developed, subsequent runs can be made for any quantity by "unfamiliar" operators providing the input steel meets specifications and proper thermal practice is maintained.

The outstanding characteristic of forgings made in this way would be uniformity, despite the use of semi-skilled labor. Assuming sufficient throughput, the investment need not be a major deterrent.

B. EXTRUSION TUBE MILL PROCESSES

There is a possibility that solid- or hollow-extruded tubes may be an improvement over the current forged tubes. For purposes of discussion, a 5"/54 Navy gun tube was selected as typical. The statements are based on discussions with Dr. Kent of E. I. Division, Baldwin-Lima-Hamilton, formerly Loewy-Hydropress; J. Warnock, Curtiss-Wright, Buffalo; William Speith, American Steel Foundries Research, Bensenville; and Cameron Iron Works, Houston, Texas.

One extrusion press having a capacity sufficient to produce a 5"/54 gun tube is the Loewy 12,000-ton press at Curtiss-Wright, Buffalo. The Curtiss-Wright press could accommodate a billet possibly up to 30" O.D. x 68" long. This would be roughly 14,000 pounds, which is approximately the weight that would be required to produce a 5"/54 tube. It is preferred that the L/D ratio of the billet be one or more, and the billet-to-forging yield would be approximately 90%. It would be possible to extrude the tube with a 4" bore; and it would be possible to forge it with a stepped outside diameter. A tapered O.D. would not be possible, but it would be possible to use a hollow billet.

Other possible sources include the presses operated by the Cameron Iron Works, Inc. They have a 20,000-ton press capable of producing an extrusion up to 32 feet long, and up to 36-inch O.D., with a maximum of 18,000-pound input weight at Houston. At their plant in Livingston, Scotland, there is a 30,000-ton extrusion press that is capable of an extrusion up to 36 feet long, 54-inch diameter, and 25,000-pound input weight. In addition they have in design for installation at Houston a 35,000-ton press that will be capable of an extrusion up to 40-feet in length, up to 54-inch diameter, and 30,000-pound maximum input weight. The project of forging gun tubes by extrusion should be explored for economy and for quality of product.

The mechanical properties of an extruded tube are considered by some to be superior to those obtained by conventional forging because in the extrusion process there is lamellar flow between the container and the die opening. Also, the metal throughout the cross-section is worked very thoroughly and uniformly from end to end (except for the nose and butt of the extrusion). However, there are no data to substantiate these claims for gun tubes.

C. PREPARATION OF BLANKS

1. Pressure Casting

Some work has been done on pressure castings for preforms at Curtiss-Wright in conjunction with the American Steel Foundries. Preforms could be produced by pressure casting; however, the facilities are not presently available and would require development. To produce a pressure casting of the size required for a 5"/54 gun tube would involve the same problems in freezing that are present in the casting of large ingots. Some experimentation has been done in this field, but the size of castings for tube and piping applications has been relatively small. For economy and quality, this possibility should be developed not only for preforms for extrusion but also for press forging.

2. Centrifugal Casting

A program to develop centrifugal castings for preforms has been under way at Curtiss-Wright, aided by Wisconsin Centrifugal Foundry, Inc. and the U.S. Pipe and Foundry Company. It is believed that preforms could be produced by centrifugal casting. Nevertheless, facilities appropriate for making gun barrels may not be presently available but would require development.

D. POSSIBLE USE OF CENTRIFUGAL CASTINGS FOR GUN BARRELS

Prior to World War II, Watertown Arsenal produced many thousands of centrifugally-cast tubes. During that war, a second similar facility was built at Houston. Both have been dismantled. No comparative cost or performance data are available for comparing centrifugally-cast versus forged tubes. However, the cast tubes were used in combat. An attempt should be made to compare this technique with the other suggestions herein. If any of these tubes can be located, consideration should be given to testing them.

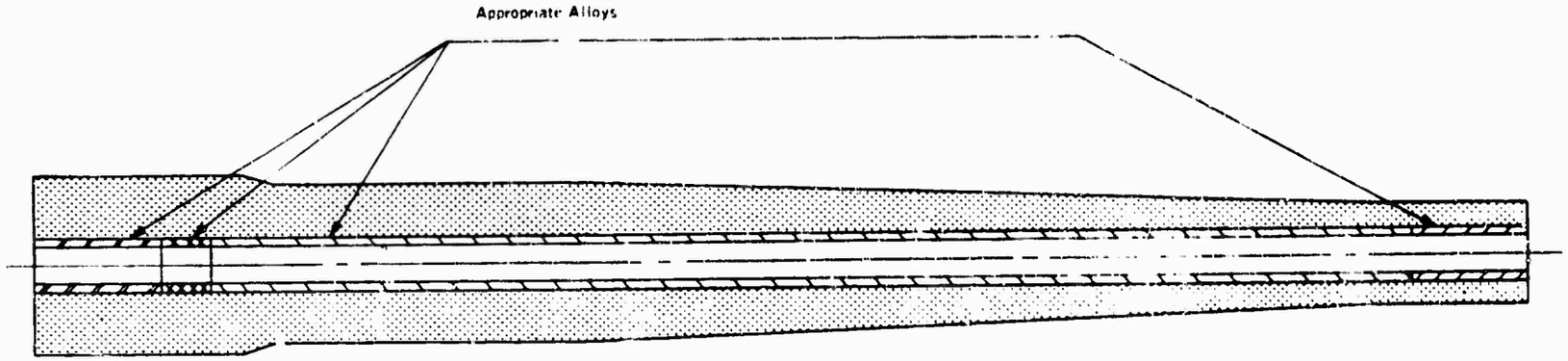
E. FRICTION WELDING OF LINERS

Tubular liner sections can be friction welded so that appropriate materials may be used at critical areas of wear, erosion, and fatigue. Friction-welding of dissimilar materials has been done but would require a development program for tube materials and some scale-up for full size components (See Fig. 2). Applying the "fail-safe" design approach, as used in aircraft structures, any liner will also function as a crack stopper. The crack stopper technique may be useful if the cooler propellants reduce wear so that fatigue now becomes the predominant life-limiting factor.

F. SHEAR FORMING OF GUN TUBES

Shear forming (also called shear spinning or power rolling) is a metal deformation process in which the metal, mounted in a lathe, is displaced by a set of rollers. The metal is squeezed over a mandrel, ahead of hardened rollers. Substantial reductions (i.e., 40%) are possible in a single pass, metal utilization is high, and close dimensional tolerances are possible.

Investigation of one of the major developers of unique shear forming equipment (Rollmet, Inc.) has disclosed an existing capability to shear form gun barrel materials. The "Live Die" machine has a 25 ft. bed. This would allow for manufacture of a tube up to 50-feet in length working from both ends. Although to date



Location of various materials comprising a Friction-Welded Liner

FIGURE 2

this machine has rolled only 1.5-inch walls, it is believed it could readily handle 2-inch thick walls and reduce to whatever thickness is required. The O.D. range is from 4 inches to 12 inches in diameter.

Development work and modification to the existing machine might provide a capability to r . perhaps as much as a 4-inch wall thickness with a finished I.D. of 7 inches.

It is recommended that a development concept, as noted above, be pursued to determine the exact limits and costs for this type of gun tube manufacture. The process constitutes an excellent quality control procedure because latent defects would be opened up. The severe cold-working of the metal would result in a desirable microstructure. Further examination would be required to establish whether any resultant preferred orientation imparted to the grain structure would be in a desirable direction.

G. SUMMARY OF RECOMMENDATIONS

A study of the several forming processes described herein is recommended to evaluate realistically the probable degree of success and the probable costs. Then, if warranted, test programs should be inaugurated to establish manufacturing parameters and probable real costs. Such a feasibility program could then be followed by tests to evaluate the various products as gun tubes.

It is instructive to recall the tragic experience of February 28, 1844, when a new 12-in. gun exploded, killing five men of national prominence, two of them members of the cabinet. Investigation by the Franklin Institute disclosed that the wrought iron gun had been inadequately forged.* While our technical capability is much greater today, we still need to confirm, such as by sufficient actual firings, the validity of proposed improvements in processing or changes in design.

*The "Princeton" and the "Peacemaker": A Study in Nineteenth-Century Naval Research and Development Procedures. Lee M. Pearson, Technology and Culture, Vol. VII, No. 2, pp. 163-183, (1966).

IV. MANUFACTURE

A. EXISTING METHODS

1. Gun barrels, produced as steel forgings, are made of steel which is melted and refined by those methods that are generally agreed to produce steel of high quality. Extremely high standards for bore surfaces free from defects, requirements for good ductility to be evidenced in transverse tests, as well as Charpy V-notch requirements at low temperatures, combine to make quality steel necessary for gun barrel manufacture.

Performance and testing requirements have been constantly rising, and it appears that this rise will continue. If the product is to be satisfactory, the steelmaker will have to continue to utilize techniques commensurate with these requirements.

Vacuum degassing and vacuum deoxidizing practices are effective means utilized by steelmakers to meet special requirements. There is no doubt that they will be, and in some cases have been, applied to the production of gun steels. At this time, it does not seem necessary to demand use of these processes in the production of gun steel in all cases. The suggested testing program may lead to this, but this remains to be seen. At one time, ingot mold design, ingot dimensions, and forging reduction were extremely important subjects in gun barrel manufacture. The use of vacuum processes tends to lessen the importance of these factors.

Forging of gun barrels is an uncomplicated process. As stated in the previous section, extremely clean and gas-free metal lessens the danger · overreduction and the attendant loss of ductility in transverse tests. Developments lie in the direction of automation, which speeds up the process and lowers costs. This equipment has been successfully applied to gun barrel manufacture.

2. Machining, Boring, and Rifling

Much attention has been given to the operations that machine and bore a gun barrel from a solid, cylindrical section forging because a large part of the cost and the time consumed in manufacture is attributable to these operations.

An outline is given of typical machining operations and their sequence. This description includes the "rough machining" operations that are carried out before quenching and tempering the gun barrels, as well as the "finishing" operations that are carried out after quenching and tempering.

a. Work done by material supplier. The operations of the supplier include straightening and stress-relieving. The forging is usually annealed and drawn to enhance machinability.

(1) Tooling locating bands. Ends are centered and the tooling bands are turned, depending on length and complexity of the O.D. contour. Tooling bands are usually supports for saddles to be used as the basis for subsequent machining operations. Supports are usually within 10 to 13 feet of each other.

Tooling bands are made to a tolerance of ± 0.015-in. diameter and usually are considered to be in alignment with each other if within 0.010-in.

(2) Rough turning. After tooling bands are made, the tube is measured to assure that all areas will meet the drawing requirements as rough machined and bored. The tube is rough turned using the tooling bands, and a finish of up to 1000 microinches is permitted, but this usually does not exceed 600. Tolerance on turning operations is typically ± 0.030-in.

(3) Boring or trepanning. Trepanning is a more efficient method for bores over 2-1/2" diameter. The variation of the bore from end to end is about + 0.020/- 0.000-in. on diameter. Straightness

of these bores is usually within 0.060-in. to the centerline, but drifts to 0.100-in. have been encountered. The maximum runout is not expected to exceed 0.001 inches in 10 inches of bore depth. The finish evenness on this bore normally exceeds 125 microinch variation.

(4) Final turning. After the boring operation, the supplier may perform several thermal treatments that can have an effect on straightness, etc., and there is a required check on finished part dimensions, straightening, etc., with a final O.D. turning operation to improve alignment and contour on barrel O.D. These final turning operations by the material supplier involve tolerances of ±0.020-in. on diameters and a finish of 800 microinch maximum.

b. Work done by barrel finishing shop. On receipt of the rough-turned barrel, this is the sequence of operations to make a finished barrel:

(1) Machine center. Barrel is indicated and centers placed in both breech and muzzle end of gun, T.I.R. not to exceed 0.100-in. over total length.

(2) Starting O.D. machine. Tooling bands are cleaned up and O.D. contours semi-machined to ±0.015-in. Major controlling bands are round within 0.001-in.

(3) Rough boring. Rough bore is started on both ends of the barrel, checking alignment and tools every 4 feet. Finish bore is completed from muzzle end with packed boring head. The bore is honed to within 0.002-in. diameter.

(4) Chamber. The chamber is rough bored with template, leaving grinding stock. The barrel is then placed on the grinder and the chamber is ground to size and 32-microinch finish.

(5) Finish machining, O. D. All incomplete O. D. surfaces are finished to size, and any mounting dimensions are controlled. The barrel is finish honed to pre-broach size from muzzle end.

(6) Rifling. Rifling grooves are broached by multiple broach operations from the muzzle end of gun barrel.

(7) Final machine operations. Any milling or threading required on the barrel is completed in accordance with drawing and barrel indexing established previously during broach operations.

(8) Other processing. Deburr, as required, and lap rifling if required. Clean and identify.

3. Equipment. Turning operations are primarily performed on conventional lathes with extended beds, using tooling supports because of the length involved, and live center because of the weight of the barrels. Contour machining is generally performed with templates.

Special equipment is required for boring and trepanning, some of which has been developed over the years by the manufacturing facilities.

B. ADVANCED TECHNOLOGY

Drilling, reaming, and trepanning are accomplished today with improved tooling and carbide cutters using high pressure coolant with internal chip disposal. The design of this tooling has been perfected to provide improved accuracy—0.000 + 0.010-in. diameter and straightness of 0.001-in./ft. in a 50-foot long hole with speeds of penetration ten times that of conventional spade drills or wood packed boring heads. The high-pressure coolant enters from the outside of the boring bar and past the cutting tool; then the coolant picks up the chips and brings the chips back through the tool support, which is of tubular construction.

Accuracy of boring depends considerably on the type of tooling, starting bore, and condition of the guide bushing at the oil pressure seal.

A typical bore of 4-1/2" (i.e., trepanning) would be accomplished at a speed of 400 s.f.p.m. with 0.005- 0.006 i.p.r. feed. The pressure volume for the coolant would be about 190 gpm at 275 psi.

The cutting edge for these operations is of replaceable carbide and will usually bore up to 50-foot lengths before requiring resharpening. The contour of the tooling cutter usually provides a chip breaker to control the size of the particle that must be carried out of the bore. With a single cutting edge, wear pads are required to maintain balance of cutting forces. One pad is approximately 180° behind the cutting edge and controls the size of the hole, and another pad is located 90° behind the cutter to steady the head and balance the cutting forces.

A multiple lip internal chip removal reamer has been developed. This reamer has cutting edges at 180° from each other, which reduces the load on bearing pads. When started from a properly aligned starter bushing, this tool produces a fairly precise diameter hole (0.002-in. diametral tolerance). The reamer uses economical throw-away carbide inserts that may be indexed and held in a removable tool holder that enables quick revision of tool geometry for unique requirements.

Ceramic tools can be employed for scale removal and the rough semi-finish and finish turning of the exterior surfaces of gun tubes. High density aluminum oxide cutting tools are mechanically clamped against a carbide backup plate fitted in a heavy duty toolholder, with a carbide chip breaker plate between the clamp and the ceramic tool. In rough machining, cuts up to 5/8" in depth can be made at speeds of 300-500 s.f.p.m. and 0.022" feed. In turning-off operations, ceramic tools can remove metal at a rate in excess of twice that of the best

carbide tools with only a slight increase in tool cost. The ceramic inserts used for machining gun tubes at Watervliet Arsenal are 3/4" square and 1/4" thick.

In order to improve the straightness of boring, both the Army and the Navy have developed guiding equipment in conjunction with their reaming operations.

In the Watervliet equipment, a force is applied laterally to the back portion of the reamer, which, in effect, turns the head and the cutting edge. Thus, it corrects or straightens the bore. This guidance system is controlled by providing a sinusoidal hydraulic force to one of the pads at the back end of the reamer head. The pad provides a force of less than 200 lbs. at the maximum position. The signal for controlling the force is supplied from a sensor (accelerometers mounted in the forward portion of the head). Using this boring guidance head, tolerances have been held to less than 0.007 inches in the length of a 35-foot barrel.

Present rifling equipment utilizes heavy duty gearing to produce the helix angle during the broach operation. This is a somewhat recent improvement in the rifling operation and replaces the older method where the helix angle was generated by a master bar.

The broach tooling consists of progressive full diameter, high-speed steel broaches. There can be as many as 60 progressive broaches required to produce the rifling of one barrel. Rifling is accomplished from the muzzle end of the barrel, and it is usually done with one progressive broach at a time. The accuracy of the broaches and the resetup of each successive pass make this operation one of the key areas of cost in gun tube manufacture. The high-speed steel tooling requires continual resharpening, and there is some problem of breakage in the long length of continual splining that is required.

Electrochemical boring of tubes and machining of rifling are being explored. Essentially, electrochemical machining (ECM) involves passing current through an electrolyte in the gap between the workpiece and a suitably shaped tool. The

workpiece is the anode and the tool is the cathode (exact opposite of electroplating). If conditions are correctly chosen, the surface of the workpiece is dissolved away until it approaches the mirror image of the cathode (tool).

The rate that metal is removed from any part depends upon the conductance of the electrolyte, the voltage applied across the electrodes, the shape of the electrodes, and the gap or distance between the tool and the workpiece. The tool (cathode) is usually made of some material that has good conducting characteristics. Copper is the most commonly used cathode in the ECM of steel. The electrolyte can be almost anything that has good conductance and is water soluble. Water solubility is essential because it is necessary to replace the electrolyte since it is consumed by the electrolysis. It is essential too that the electrolyte be kept clean and well-filtered of the sludge that develops during the process. A well-filtered electrolyte eliminates tool wear that is necessary to meet the high degree of tolerances and surface finishes required for boring and rifling gun tubes and liners.

ECM has tremendous potential in the ordnance field, particularly in the machining of forgings including gun barrels. Development work done with ECM by the Naval Ordnance Station at Louisville should be pursued with vigor. This process offers the possibility of boring, honing, and rifling a complete gun barrel from rough forging to finished bore in a single pass of the electrode. This is accomplished in less than half the time required for conventional machining methods, with less capital equipment since there is only one machine instead of four to buy or provide shop space for and with fewer operators. In addition, tooling (the electrode) does not erode as in EDM, and is therefore long lasting and dimensionally consistent. Corrosion due to electrolyte is now controlled largely by preventative additives.

Electro-discharge machining (EDM) has potential for boring and rifling which may be developed for future use. However, apparent disadvantages are:

EDM (a) leaves a thin surface layer of cast material which probably must be honed in a separate operation,

(b) electrode erodes allowing dimensional errors requiring tool replacement,

(c) produces a heat affected zone of about 0.003" with surface crack initiations,

(d) is slower than ECM,

(e) uses more expensive dielectrics.

C. HEAT TREATMENT — QUENCHING EQUIPMENT

For many years, it has been the practice to liquid quench and temper gun barrels in order to develop the necessary strength and toughness.

During World War II, "effective" quenching became very important because the shortages of some alloying elements made it necessary to obtain the most good from the available amounts. One means of doing this would be "drastic" quenching, provided that such practice does not result in cracking.

Experience and investigation revealed the importance of "toughness" in gun barrels. Progressive stress damage in high strength gun barrels became of great concern, and theories were developed that have influenced heat treatment practice with regard to the importance of transformation in the martensite portion of the curve.

The heat treatment of gun barrel forgings prior to "rough machining" is conventional, aimed at protecting the forging from any form of cracking during cooling from the forging heat. This is followed by normalizing and tempering to leave the metal in condition for optimum machinability with reasonable dimensional stability.

Vertical type furnaces, with gun barrel forgings suspended in them, are most convenient for heat-treatment operation. They are less essential for the preliminary treatment operations than they are for subsequent quenching and tempering. Gun barrels may be suspended singly or in clusters, depending upon the design of the equipment and its effectiveness to provide uniformity in heating and cooling. The number of guns quenched simultaneously must permit cooling sufficiently rapidly. It is essential that provision be made for the ample circulation of the coolant in the bores. The quenchant is usually water because it makes very rapid cooling possible.

Forced circulation of coolant in the bores and also leading the quench by passing water through the bores before immersion are means for effective quenching that have been found valuable. Furnace and quenching fixtures must be designed to permit good circulation and uniform cooling.

Tempering is best done vertically for uniformity and for the maintenance of straightness, although this practice is not always followed because of limited facilities. Holding times should be long for stress relief. For the same reason and to obtain maximum toughness temperatures should be as high as possible. Cooling from the

tempering heat may be accelerated by quenching, provided uniformity is maintained.

Improvements in conventional heat treatment will be in equipment that can perform the necessary operations more efficiently, at less cost, or more effectively.

D. PLATING

The bore surfaces of Navy gun barrels are usually hard chromium plated. They should be carefully conditioned for the removal of any hydrogen that may be introduced into the metal as a result of the plating operation.

E. TESTS AND INSPECTION

1. Nondestructive Examination

At the present time, all gun tubes and liners are subjected to numerous nondestructive evaluations both at the forging manufacturers' plants and at the ordnance plants that finish them.

Typical manufacturing procedures employed at the forging manufacturers' plants are given below, showing the sequence of operations and the stages at which nondestructive evaluation is performed. The nondestructive evaluation tests are underlined.

a. Forge to forging drawing dimensions.

b. Heat treat for machining.

c. Hot straighten and retemper.

d. Turn O. D. and trepan bore to drawing dimensions.

e. Measure wall variation by ultrasonic technique.

f. Wet magnetic particle inspect O.D. and end faces (175-mm gun tubes only).

g. Heat treat for required mechanical properties.

h. Hot straighten and retemper.

i. Cut discard and discs for macroetch and mechanical property tests.

j. Cut tube or liner to shipping length.

k. Wet magnetic particle inspect O.D. and end faces.

l. Measure O.D. and I.D. and indicate for straightness.

Upon receipt of the rough-machined, heat-treated forgings at the ordnance plants, they are again ultrasonically inspected for wall thickness variations, checked for straightness, and, if necessary, straightened. The sequence of machining operations is interrupted by frequent measurements and checking of wall variation and dimensions with visual examinations of the bore surfaces by means of borescopes. Wet magnetic particle inspection of the O.D.'s of autofrettaged gun tubes is conducted before and after coldworking. If necessary, straightening of the tubes and liners is done between various machining, boring, and honing operations. Wet magnetic particle inspection is also performed after shrink fitting the slide hoops on gun tubes.

Variations in wall thickness are measured by ultrasonic means, e.g., the Vidigage, and measurements are made completely around the O.D. at various stations along the lengths of gun tubes and liners. Bore straightness is measured with optical gauges along optical lines of sight. One advanced system now in use includes a wire tautly stretched through the bore from which is suspended a proximity sensor device that relays a signal to an electronic console when the gun tube is rotated.

Magnetic particle inspection at the forging manufacturers' plants is done in air, with an iron powder-kerosene mixture sprayed or brushed onto the magnetized forging. Occasionally, magnetic particle inspection is done by the wet fluorescent method, which provides a more sensitive inspection technique. The surface appearance and the condition of the rifling and chamber of gun tubes and liners are inspected by means of a borescope, which is time consuming and tedious.

For the nondestructive evaluation of the chambers and rifling of gun tubes before and after firing, a magnetic recording borescope has been developed that can detect, locate, and make a permanent record of surface and near-surface discontinuities, such as cracks, inclusions, and fracture, or loss of rifling lands within the bores of previously magnetized gun tubes. This device has been successfully used at proving grounds and in the field to evaluate firing damage in cannon. This equipment also permits a reasonable estimate of crack depths. It is recommended that this equipment be thoroughly evaluated and considered for use by all Services for the nondestructive evaluation of gun tubes and liners during manufacture and in service. This type of equipment may prove to be invaluable for deciding condemnation limits for guns whose useful life is determined by crack growth rate rather than by bore wear. In connection with the study and assessment of the fatigue life characteristics of eannon tubes, Watervliet Arsenal has developed an ultrasonic crack depth measurement technique. This technique has been extensively utilized both in the laboratory and at the three U. S. Army Proving Grounds for fatigue crack detection and growth measurements in a variety of tubes ranging from mortars to 8-inch cannon. In its current state of development, it is possible to detect cracks emanating from the bore surface of nominally 0.050 to 0.1 inch in depth, with an estimated inaccuracy of $\pm$ 0.040 to 0.050 inch in up to a 4-inch wall thickness. A development effort is under way to increase even further the accuracy and sensitivity of this technique

and to automate the process to reduce time consumption during inspection and to simplify signal interpretation.

Closed circuit television systems have been applied to the borescoping of gun barrels. This combination permits a detailed examination of the inside of gun tubes and liners under various magnifications with excellent illumination and with minimum fatigue to the operator. It is recommended that this improved borescoping equipment be generally adopted for the examination of bore and chamber surfaces.

Further work is recommended to develop nondestructive examination equipment and procedures for the reliable quantitative measurement of crack depths in gun barrels. While the AMMRC magnetic recording borescope has had limited success in estimating crack depths, wide scatter in results has been experienced. The nonradial nature of many of the cracks and erosion of the bore surfaces and rifling are factors that contribute to the difficulty of measuring crack depths.

There are Navy guns in service which were built many years ago — some probably made from straight nickel steels rather than the Ni-Cr-Mo compositions used since the Second World War. The processes used then included acid and basic open-hearth. The quality of products of that area, using obsolete processes, would not be expected to meet today's specifications. Inspection techniques were also less well developed then. Because of these two factors, it is recommended that tubes in service and in storage be examined for inherent flaws and for cracks, to enable the retention of tubes that may be expected to give safe service.

2. Macroetching and Mechanical Testing

Conventional testing of gun barrels has included macroscopic examination of deep-etched discs cut from both ends of each barrel. Specimens for mechanical tests are cut at lengths sufficiently removed from the end surfaces

to avoid excessive "end-quench effect." Tests are taken from prescribed locations, "transverse" to the axis of the forging. They include conventional tension tests as well as V-notch Charpy tests at stated low temperatures.

Macroetch and mechanical property tests are conducted at the forging manufacturers' plants in accordance with requirements of the applicable Army or Navy specifications. Magnetic particle inspection may be performed to specification MIL-M 11472 or to Watervliet Arsenal Drawing B8768747 and MIL-STD-271, as required. In addition, MIL-I 45208A and various Supplementary Quality Assurance Provisions (SQAP's) are applicable, as required, for the various types and calibers of gun tubes.

A disc is removed one wall thickness back from each end. Each disc is macroetched prior to having one or more Charpy test specimens and one or more tensile test bars removed to satisfy the batch section of the specification. The mechanical property specification requirements together with typical results of the batch tested forgings are as follows:

Specification MIL-T-10458	Strengths (ksi) Yield (.1%)	Tensile	% Elong.	RATS	Charpy (ft-lb) at -40°F
LINER REQ.	160/190	---	----	*	*
Typical - M.E.	170	190	11.5	35	17
- B.E.	173	193	12.0	38	20
TUBE REQ.	115/145	---	----	*	*
Typical - M.E.	125	145	13.0	33	40
- B.E.	120	140	15.0	40	45

*Specification uses sliding scale; values dependent on yield strength.

F. AUTOFRETTAGE OF GUN TUBES

The autofrettage process has long been used to effectively increase the strength of guns through the development of residual compressive stresses at the bores of gun tubes. During World War II, this process was applied to gun tubes having yield strengths in the range of 65,000 to 80,000 psi and, more recently, has been applied to higher strength guns in the yield strength range of 140,000-160,000 psi.

The three methods which have been generally applied in the United States to autofrettage gun tubes involve the application of internal pressure to expand the bore. One method involves the use of a massive vertical press to retain sealing plugs in the ends of the tube and a thick-walled container around the tube to limit its expansion and prevent ballooning during pressurization, the pressurizing fluid being a mixture of glycerine and water with a rust-inhibiting additive. A second method involves a short movable configuration with end packings so that internal pressure can be applied to successive sections of tapered gun tubes. The third method, which is currently being used to autofrettage the 175-mm M113E1 gun tube, involves the use of tapered swages, having diameters larger than the original bore diameters and made of high speed tool steel coated with flame-sprayed tungsten carbide, pushed or pulled through the gun tubes. In this third method, a mandrel only slightly smaller in diameter than the gun tube supports end seals. The tubes are lead-plated for lubrication during swaging. The prime advantage of the swage autofrettage process is the significantly lower hydraulic pressure required as compared to the conventional hydrostatic autofrettage. The reduction in the ultra-high pressures afforded by the swage autofrettage process makes it particularly attractive for the coldworking of high-strength gun tubes.

Inasmuch as cracking and other damage during firing occur earliest and are most serious in the region of the chamber and origin of rifling, these zones are most in need of the strengthening effect of autofrettage. Hence, the process currently applied to the 175-mm M113E1 gun tube is considered the most desirable and practicable of the above autofrettage processes. Only the first 151" section forward of the breech end of the tube (approximately 35% of the total length) is autofrettaged. The amount of autofrettage is controlled by measurement of surface strains at three locations along the portion of the tube subjected to pressure. In the case of the 175-mm M113 gun, the autofrettaged 140-160 ksi strength tube is expected to have 2.5 times the fatigue life of the nonautofrettaged 170-190 ksi yield strength version. The autofrettaged gun also shows a significantly longer life before initiation of cracks and a much lower rate of crack extension when cylindrical sections are subjected to hydraulic fatigue testing. Swage autofrettaging is also used in the manufacture at the 105-mm M68 cannon tube.

Areas in which further development is recommended include high pressure lubricants, improved high-strength and hard-surface coating materials for swages, and further evaluation of the relative merits of mechanical versus hydraulic push swaging. In addition, the development of rifling as well as autofrettaging by the swaging process merits further development.

"Explosive Autofrettaging," achieved by detonating an explosive charge (primacord) suspended along the center of the bore of scale-model tubes immersed in water, has demonstrated considerable potential in tests performed by the Army. Metallurgical analyses and residual stress measurements indicate that explosive autofrettaging produces results comparable to those achieved by more conventional autofrettaging processes.

In view of the economic advantages inherent in the explosive autofrettaging process, attempts to scale up this process to full size gun tubes should be continued to demonstrate the feasibility and reproducibility of this process.

1. Liner Insertion Techniques

The so-called "loose-liner" design and practice now utilized by the Navy represent a distinct advance in:

a. Time and cost of gun replacement on shipboard.

b. Efficient utilization of gun barrels.

However, the "loose-liner" itself is practically a cannon barrel in size and weight. Further development of this method should be encouraged.

The "loose-liner" principle, in which the breech area of the cannon is not supported by a shrunk-on hoop, is found to work. Excessive cracking or too rapid stress crack progression in the bores of such liners has not taken place. They are easily removed from the breech sections after service.

This experience indicates the possibility that the relative weights of the fixed and the removable portions of the barrel may be altered. The smaller the removable portion becomes, the more cost saving may be realized. It is not expected that these changes would result in improvements in the performance of the gun.

G. SUMMARY OF RECOMMENDATIONS

Recommendations found in other sections of this report are almost inevitably linked with "Manufacture," which is the subject of this section.

The use of newly developed steels or other alloys would necessitate developments in manufacture. The same may be said about linings, coatings, etc. Forging is a manufacturing process, covered separately in this report.

1. It should be the assigned duty of a responsible group to continuously appraise developing techniques of manufacture as they may be applied to gun barrels and to become aware promptly of developments in the other Services.

2. Machining methods are very important from a cost standpoint. EDM and ECM methods should be developed and tried for what they may have to offer.

3. Heat-treatment techniques for intermittently treated lots of guns may not, of necessity, adhere to the best current practices. If mass production of large quantities becomes a part of the problem, work should be done to develop automated fast-heating equipment and techniques and the steels that can utilize them.

4. Nondestructive examination, as well as all other testing procedures, offers opportunities to obtain greater safety and reliability of weapons. For these reasons, this area also offers possibilities of time and cost saving and should be actively followed.

V. ADVANCED CONCEPTS

A. NEED FOR OUTSIDE REVIEW

There is an inherent tendency for any organization to work on pressing current problems and to improve existing procedures rather than to attempt major innovations. An occasional review by an outside group is a desirable mechanism to force an internal review of present practices and to suggest radical changes. Therefore, a periodic survey by an outside group is recommended.

B. FLUID WATER CANNON PROJECTILE LAUNCH SYSTEMS

The concept of using a pressurized liquid, rather than an explosive charge, as a low-wear propellant was brought to the attention of the subcommittee by a small magazine article, dated 1967, which showed a picture and described a Russian invention. The title of the article is "Water Cannon for HER-Forming," and the picture caption reads "Water cannon being developed in Russia for high energy forging is said to eliminate need for trimming and grinding. We only polish the finished piece." The rest of the article then reads as follows:

> Newest entry in the field of high energy rate forming (HERF) is a Russian "water cannon" that delivers pressures up to 3000 atmospheres and can fire once every 4 seconds. The metal stamping machine is being perfected at the Institute of Hydrodynamics in Novosibirsk.
>
> The chief designer, Bogdan Voytsekovsky, says that the hydro-impulse machine differs from the Dynapak machine in the U.S.A. in that it uses water. "The American machine is entirely pneumatic," he explains, "whereas the Soviet machine builds up pneumatic pressure on water; its the water that does the work."
>
> Water is shot from a cannon at 655 to 9850 FPS, depending on the pressure of the compressed air. For forging, a second cylinder holds a closed die and the preheated work piece (2000°F).

The above represents the subcommittee's knowledge regarding the invention at this time. Further, there appears to be little reason to explore thoroughly the specific design features of the machine since it was designed for high velocity metalworking applications that require a horizontal ram. However, the description does serve to stimulate ideas relative to evaluation of high velocity hydraulic systems as projectile launch mechanisms.

Much of the wear that is currently experienced in large gun tubes is attributed to bore surface cracking and erosion, which results in large part from the severe thermal environment imposed by conventional propellants. If this is so, then the payoff in gun tube life (or improved accuracy throughout an equal lifetime) through the use of an ambient temperature pressurized fluid as the propellant may obviously be large.

1. Suggested Future Efforts

Evaluation of fluid water cannon projectile launch systems should comprise a brief literature search, followed by detailed engineering feasibility studies. Hydraulic accumulator and valving systems represent relatively advanced fields of engineering, and it is difficult to comprehend that the idea of a fluid cannon has not been advanced and studied previously. If so, the literature search should reveal the results of any past studies and/or experiments. Suggested feasibility studies would comprise the possible engineering approaches to rapid release of hydraulic pressure in such a manner as to launch a projectile. These might include: (a) a pneumatic-HER driven hydraulic system, as is described for the Russian water cannon: and, (b) quick release of accumulator tank pressure with a regenerative hydraulic recoil system to reduce both the pumping system horsepower requirement and the "water hammer" effect on the system. Economic and reliability trade-offs with the potentially simpler direct pneumatic-HERF launch systems should be made through these feasibility studies.

If progressive reassessment and funding techniques are employed. the risk and expense for evaluation of the concept should be low, because the concept does not require significant advancement of current states-of-the-art in materials, propulsion and recoil mechanism engineering, or fabrication techniques. Feasibility appears to rest largely on whether practical on-ship installations can produce sufficient horsepower to provide the necessary propulsion energy at the desired firing rate, which would be established early in the study.

C. HIGH ENERGY RATE (DYNAPAK TYPE) MECHANISMS FOR NAVAL GUNS

Assume a 100 lb projectile accelerated to a muzzle velocity of 3000ft/sec. Assume a barrel length(s) of 20 feet, 6 inches I.D.

Acceleration $= a = \frac{v^2}{2s}$

$$= \frac{(3000)^2}{2\,(20)}$$

$$= 2.25 \times 10^5 \text{ ft/sec}^2$$

Force $= F = ma$

$$= \frac{100}{32} \times (2.25 \times 10^5)$$

$$= 7 \times 10^5 \text{ lb}$$

Average Pressure $= P = \frac{F}{A}$

$$= \frac{7 \times 10^5}{28}$$

$$= 25{,}000 \text{ lb/in}^2$$

Kinetic Energy $= KE = 1/2\ mv^2$

$$= 1/2 \times \frac{(100)}{32} \times (3000)^2$$

$$= \underline{14 \times 10^6 \text{ ft lb}}$$

Based on recent design work on very large HERF hammers for the U.S. Air Force, a 14 x 10^6 ft/lb device is practical.

1 Horsepower = 550 ft lbs/sec

= 33,000 ft lbs/min

Assume 40 shots per minute:

$40 \times (14 \times 10^6) = 560 \times 10^6$ ft lbs/min

$\frac{560 \times 10^6}{33,000} = 17,000$ horsepower

17,000 horsepower is practical via a stationary gas turbine. Much lower horsepower pumps could be used if accumulators were employed.

It is recommended that this prospect be evaluated further, either by the U.S. Navy or under a development contract from the Navy to a suitable industrial company. Requests for proposals from industry would probably bring several bona fide responses.

D. STEAM PROPULSION SYSTEM FOR LAUNCHING A PROJECTILE

Since a steam catapult is used to launch a fighter aircraft weighing between 40,000 and 70,000 lb, this system was considered as a projectile propulsion system. Assuming that the catapult contributes approximately 100 ft per second to a 50,000 lb airplane, this is equivalent to 50,000,000 ft-lb per second. This represents sufficient energy to launch a 100-lb projectile at a velocity of 3,000 ft/sec, either by direct acceleration or by a momentum transfer technique. The problems to be resolved are the practical considerations of workable hardware. The concept seems sufficiently attractive to warrant the making of preliminary designs.

E. UNDERWATER LAUNCH TUBE

This idea was one of several presented to the Committee during a briefing at Dahlgren entitled "New Gun Concepts—Overview." A sketch was shown in which a large gun tube was mounted to a pivot pin from the side of a small (possibly 40- to 60-feet long) boat. The pivot was located so that the breech end was heavier and was submerged when the muzzle end was elevated for firing. The breech end was shown schematically as being positioned and held with a rope or cable from the stern, and the Committee was left to presume that it would be hoisted to a near-horizontal position (above the surface of the water) for reloading. The comment was made that the breech would be opened to the sea for cooling after firing and that the sea itself is a very stable platform. A second sketch then showed two similar guns mounted between the hulls of a catamaran-type small boat.

This concept appears to have been only recently advanced, and it can be presumed that it has not yet been subjected to a thorough engineering analysis for validity. It is recommended that the underwater launch tube concept be evaluated at a low level of effort, as time and funds permit.

F. TRANSFER RENEWAL OF LINER COATING

1. Background

It has been documented that, when the electroplated chromium liner coating is worn through, material loss at any point in the liner increases significantly at an approximately steady rate. This has led to a suggestion that the chromium layer might be renewed through some transfer mechanism from the rotating band of each round fired. The subcommittee is currently unaware of any past research, serious surface chemistry or thermodynamic studies involving the subject, or experimental evidence demonstrating the feasibility of the idea.

2. Suggested Future Efforts

Several aspects of the transfer renewal idea require further study-type exploration before the overall approach to its evaluation should reach an experimental stage. Liner wear is not uniform at all areas of the bore and is reported to be usually greatest at the origin of rifling. This is attributed to the engagement of the rotating band at this point and the rotary side thrust required in reaction to commencement of projectile rotation. If the material loss is principally due to galling-type wear, the concept requires that the body responsible for the removal also accomplish the renewal. Successful reduction to practice would be expected to be difficult here, and studies of lubricant systems carried by the rotating band might prove to be more beneficial. On the other hand, if the liner material loss is primarily due to thermal shock and erosion, the removal occurs as occasional loss of discrete pieces of cracked material. Such a removal mechanism is equally difficult to consider from the standpoint of uniform renewal from a rotating band.

Also, the fact that the overall liner loss is not uniform creates apparent difficulties in dealing with the concept. For example, if the renewal techniques employed apply a uniform thickness, then the caliber of the majority of the bore will decrease if the origin of rifling remains at a uniform diameter.

It is evident that the transfer renewal concept is currently too far removed from engineering implementation to suggest specific experimental approaches at this time. Instead, study of liner wear modes is indicated as a first step, followed by proposal and study of potential transfer renewal solutions to the wear "problem." For example, such a proposal might involve a dual rotating band in which the first applies spin stabilization to the projectile and the second applies the renewal layer to the liner. The accompanying study should involve heavy emphasis on surface chemistry and thermodynamics to provide the proper background for experimental efforts if they continue to be justified.

It should also be noted, if equivalent removal-renewal per round fired is the eventual goal, there would appear to be little reason to limit the material of either the original or the renewed layer to chromium.

3. Potential Payoff, Risks, and Expense

The payoff from successful development of rotating band material transfer to provide, in essence, a "no-wear" gun tube liner would be very large. However, the current lack of definition regarding the problem and specific transfer renewal solutions precludes estimation of feasibility and infers that the risk and the expense might also be very large if the concept were pursued experimentally at this time.

It is recommended that the transfer-renewal-of-liner-coatings concept be given further attention through study of the mechanism of liner wear and proposal of specific transfer renewal solutions to the wear problem with the object of establishing general feasibility and providing guidance for potential future efforts. In this manner, the expense involves only the study and proposal efforts until such time as the risk factor may be lowered.

G. APPLICATION OF EXPLOSIVE FORMING TECHNOLOGY TO GUN BARRELS

If requirements for longer barrel life, more rapid fire, or higher barrel temperatures and pressures are present, there could be a need for techniques that would provide standard barrel liners with a relatively thin (i.e., one-half inch wall) metal I.D. cladding capable of rigorous performance. A new technique of explosive welding a cladding to a tube, which produces a continuous metallurgically sound bond, has been developed (and proven in several applications). The solid-state nature of the junctions produced between both similar and dissimilar metals makes the method directly applicable to gun barrel fabrication.

Explosive forming does not appear to offer any significant advantages over current production forming techniques in the fabrication of gun barrels or associated assemblies.

Explosive bonding, or explosive welding, is potentially a very important facet of the explosive fabrication industry for future needs in gun barrel technology. A relatively thin cladding on the inside of a gun barrel can be selected for better corrosion and wear resistance; however, a good metallurgical bond is needed to insure proper heat transfer.

The current state-of-the-art of explosive bonding is such that almost any metal can be clad within another with minimal development. Limitations of the process arise primarily with respect to the geometry of the workpiece, but the cylindrical shape is probably the most adaptable to the use of explosive bonding. Size (diameter and length) offers no particular problem except that the amount of explosive would increase somewhat proportionately. Although medium strength 1-1/4" steel plates have been bonded to plates 2-1/2" in thickness, the thickness of the metal combination probably will impose some limitation.

Probably the most serious restriction would be predicted for the use of explosive bonding techniques on gun barrels that have finished exterior dimensions. This would be the case in the overhaul of existing liners and barrels. Although not necessarily extensive, some development would be necessary to permit cladding of a finished configuration without distortion of the outside diameter.

H. COMPOSITE GUN TUBES

The Navy is interested in reducing the weight of the superstructure on ships in order to improve the stability of the ship. Gun tubes contribute to this weight. One way to reduce weight would be to use lighter materials or to increase the strength of the material, which would allow a reduction in cross section and thus weight.

In the case of monolithic gun tubes, the material strength is usually obtained by heat treatment and/or plastic deformation (autofrettage). Other desirable properties, such as ductility, impact resistance, and corrosion resistance, are reduced in a large section if very high stress levels are attempted. There is also a limit to the amount of strength that can be used because a reduction in cross section will reduce the section-modulus to a point where the tube will not be rigid enough to obtain the required accuracy.

When a combination of properties is desired, and they are not all easily obtained in a single material, a composite structure might be considered.

Wire-wrapping, filament winding, metal banding, or tape wrapping are methods of prestressing a tube liner to give it sufficient compressive stresses so that it can then be stressed in tension without exceeding the elastic limit. Wire-wound gun tubes have a long history. They are suggested for consideration again because of the present availability of a variety of strong and high-modulus fibers. In the case of a high-modulus material, such as boron or graphite, the inner liner would not have to be compressed since the high modulus winding would prevent it from being strained to the plastic region. Thus a corrosion-resistant liner, for example, Ta-10W, could be used to increase the erosion resistance while the windings give the overall strength.

In the case of steel wire or metal bands, they could be applied directly using wires with tensile strengths in excess of 250,000 psi. Since the wires are small, they have very uniform properties. However, the modulus of steel wires is fairly low which detracts from their usefulness. On the other hand, boron filaments have a modulus twice that of steel and have strengths up to 450,000 psi.

An additional advantage of filament winding or tape wrapping (boron tape, perhaps) is that the orientation of the winding can be so designed that maximum advantage can be achieved. A bias winding that might give unusual results has been proposed in a patent disclosure (Westinghouse Electric Corp. No. AL-69-55).

The following is a paragraph from that disclosure.

> *A peculiar property of a coil band is in its ability to transfer a force tending to elongate the coil into one of torque on the coil or contraction of the coil diameter. This is illustrated by the simple Chinese "finger puzzle." Use can be made of this property in order to reduce the maximum hoop stress developed upon firing the gun. The axial load created by the gas pressure between the breech and the projectile causes a force tending to elongate the gun tube inner liner. A large frictional load between the projectile and the tube liner transmits this axial force. If the band coils are attached to the ends of the inner gun tube jacket and liner, this tendency to elongate can be transmitted to the band coils as a torque and a contraction force in the hoop direction. The tensile force developed in the hoop direction in the inner gun tube jacket and liner by the internal gas pressure can be offset and reduced by the extent of this hoop compressive load from the contraction of the bands.

The following is a table comparing the properties of various materials in filament form.

Comparison of Tensile Properties of
Boron With Those of Other Materials**

	STRENGTH		MODULUS	
	Average, psi x 10^3	Specific, in. x 10^6	Average, psi x 10^6	Specific, in. x 10^6
Continuous boron filament	400***	4.0	60	600
E-glass filament	500	5.4	10.5	110
Beryllium	90#	1.3	44	660
Steel	28 to 600	0.1 to 2.1	30	110
Titanium	60 to 240	0.1 to 1.5	19	120
Aluminum	9.8 to 88	0.1 to 0.9	9.8	100
Magnesium	25 to 55	0.4 to 0.9	6	100

*Westinghouse Electric Corporation, J. Martin Tobin, Disclosure No. AL-69-55, July 23, 1969.

**Franklin E. Wawner, Jr., Modern Composite Materials, "Boron Filaments," ed. by L. J. Broutman & R. H. Krock, Addison-Wesley, Reading, Mass. 1967, pp 256-257.

***Newer material will average 450,000 psi in tensile strength.

Wire normally runs 200 ksi.

The average and minimum strengths of commercial boron fibers are steadily improving. The principal significance, however, is the high modulus of elasticity of boron over other materials of similar strength.

1. Suggested Future Efforts

The wire, band, or filament approach should be checked theoretically with the work that has been supported in the filament winding of pressure vessels. The stress analyses should determine the feasibility of winding designs.

The payoff will be the reduction in weight of the gun tube as well as the ability to use liner materials that can be very easily supported using other manufacturing methods, such as coextrusion or shrink fitting.

The technical risk is very low since the technology of each element of the composite is well known. The combination of these and its application to gun tubes will have to be determined. However, an analytical design study would point out the best combinations.

It is difficult at this point to determine the expense of this technique; but, no doubt, composite tubes will be more expensive at this time than monoblock tubes. In view of the amount of work being done in filament winding for aircraft structures, it would appear that the cost would decrease as equipment is developed.

I. COEXTRUSION OF GUN TUBE BLANKS

Technically, the liner or inner surface of a gun tube has to be corrosion- and erosion-resistant, while the bulk of the gun tube must resist high stress conditions. Since any single material, such as those used in monoblocks, has one or more areas of weakness, it would be desirable to use a composite structure where the liner could be made of a material that is resistant to the erosive gases of the propellant, while the jacket material would have acceptable mechanical properties.

Depending upon the two materials, coextrusion might be a very acceptable method of producing a composite blank from which to produce a gun tube.

If the materials are compatible, the principal advantage of coextrusion would be that a metallurgical bond could be developed, thus giving good mechanical properties and high thermal conductivity across the bond. However, there are possible technical difficulties that must be considered for each material combination. These are summarized in the following tabulation:

1. If alloying occurs at the bond line and especially if compounds are formed, the interface will have poor conductivity and perhaps serious embrittlement. Subsequently, differential expansion during service could cause failure at the embrittled bond line.

2. The same problem of embrittlement can arise when it is necessary to heat treat the outer case and the strengthening is by a martensitic transformation, while the liner does not have a similar volume change.

3. Where a precipitation-strengthened material, such as a superalloy, is used with a martensitically strengthened alloy, one alloy may be precipitating or overaging while the other is being austenitized or tempered. Thus, with the alloys intimately bonded, they must be treated at the same time, leading to possible problems.

For the past year Dr. Elmore Kennedy of the General Electric Company, Burlington, Vermont, has been working on these problems for 7.62- and 30-mm weapons. It is very conceivable that the problems will be more severe for 5-inch gun tubes.

It appears there are only a few presses in the country of sufficient size to achieve the extrusion of 5-inch tubes with a sufficient extrusion ratio to impart a worked structure. The extrusion capability in this country is reported in the manufacturing processes section of this report.

4. Suggested Future Efforts

In view of the large technical risks, work on large tubes should proceed with caution in this area. The payoff will have to be in lighter tubes and more corrosion-erosion resistant liners. However, the probability of having a higher modulus tube shell is very doubtful. At this point, the technical risk and development cost would probably be very high.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL

1. There is a great need for an adequate method of correlating laboratory simulated service tests of gun barrel materials with actual firing results at the proving ground and on shipboard. We recognize that statistically valid full-scale five-inch rifle firing tests are currently prohibitively expensive. However, the lack of performance data has impeded past efforts to improve the weapons. Some of the needed information might be extracted from results of test firings made to evaluate armor, ammunition, etc. Guns withdrawn from service should be examined carefully, and this information, coupled with service records, might produce meaningful information. As our knowledge improves, we will be able to place more reliance on scale models (.50-caliber barrels, for example), on the development of theory such as shock deformation and dynamics, and on laboratory tests such as the hydraulic fatigue. However, in view of the many interacting factors that can influence performance and lifetime (pressure, erosion, corrosion, friction, etc.), it must be recognized that without the possibility of performing adequate correlations, significant risks with regard to brittle fracture and service life will be present, and we will remain ignorant regarding the influence of compositional and processing factors on performance and on cost.

2. Gun barrel designs and specifications should be developed on the systems concept. The system includes the barrel, the projectile, the shell band, the propellant, the mount, the rate of use, and other factors. Designers and materials experts should be flexible in their approach to the problem of gun barrel technology and recognize the need for different approaches.

3. An objective advisory or review board having continuity should be established. It should be recruited from sources qualified to make contributions to the solution of the problem. The membership should include those with experience in the problems of gun tube technology and, additionally, there should be several members from unrelated fields as potential sources of unconventional ideas.

4. With the use of higher-strength steels than was the case in the past, the importance of fail-safe design, of a low crack growth rate, and of crack detection capability have increased. The probable failure mode of a design must be known, and inspectability to avoid failure must be assured.

B. SPECIFIC RECOMMENDATIONS

1. There are tubes in inventory, made by a variety of practices over an extended period, of which some may not be safe to use. Those tubes whose production history and composition are not known and that have not been subjected to modern nondestructive testing should be retested to insure they have been processed to possess requisite microstructure and freedom from deleterious defects such as cracks, segregations, and excessive inclusions.

2. The present materials evaluation program should be accelerated. These data are needed not merely to find materials that may be superior but also to help in the aforesaid establishment of dependable correlations of test rigs, sub-scale firings, and performance in full-size barrels.

3. A trade-off study should be initiated to determine the probable overall improved performance of a gun system designed using the systems approach compared to conventionally designed recent systems.

4. New concepts for launching projectiles should be evaluated. Development beyond "paper studies" is recommended. The most promising approach is a pneumatic high-energy rate system similar to that utilized in high-energy forging presses. Preliminary calculations suggest that it would be feasible to launch 100-lb projectiles, with a muzzle velocity of 3000 ft/sec, at a rate of 40 rounds per minute. Steam propulsion might be worthy of exploration. A steam aircraft catapult releases enough energy to propel a 100-lb projectile at a velocity of 3,000 ft/sec (although a momentum transfer technique might be needed, from a heavy, slow ram to a lighter projectile).

5. The suitability of rotary forging machines (e.g., GFM and SACK) for producing barrels or liners should be explored. These machines give promise of yielding a substantially more uniform product than would be obtained from the use of conventional equipment, particularly when production is infrequent or

utilizes unskilled labor.

6. The use of superalloy liners, which is standard practice in machine gun barrels, together with refractory metal liners, should be explored for larger guns such as the 5-inch Naval gun. Coextrusion of molybdenum or tantalum-10 tungsten with a steel backing may provide a combination of a refractory bore surface metallurgically bonded to a steel (which will be compatible in expansion characteristics to the tube). An order-of-magnitude improvement of firing rate or of rounds-to-failure might be achievable. Vapor-phase deposition of tungsten is another possibility if ambient temperature brittleness does not prove to be limiting.

7. The value of modern developments in steelmaking techniques, which could apply to gun barrel manufacture, should be determined. For some compositions that are now specified, electric furnace steelmaking combined with vacuum stream degassing may be the method of choice. More expensive procedures, vacuum arc remelting for example, are available for use when needed, but the considerable increase in expense must be fully justified in each case. The highest strength metals must be as clean as possible in order to be used at all; therefore,there will be no alternative but to use the best available techniques.

8. New metal deformation and metal removal processes discussed in this report should be explored to establish the technical and economic benefits that might be obtained.

APPENDIX A

SCHEDULE OF MEETINGS

1.	April 29, 1969	Naval Ordnance Systems Command Representatives and NMAB Staff	Washington, D. C.
2.	June 5, 1969	Initial Committee Meeting	Washington, D. C.
3.	July 24-25, 1969	Committee Meeting	Washington, D. C.
4.	September 16-17, 1969	Committee Meeting & Plant Presentations & Tour	Naval Ordnance Plant, Louisville, Kentucky
5.	October 23-34, 1969	Committee Meeting & Plant Presentations & Tour	Watervliet Arsenal, Watervliet, New York
6.	December 10, 1969	Committee Meeting & Plant Presentations & Tour	U.S. Naval Weapons Laboratory, Dahlgren, Virginia
7.	February 12, 1970	Subcommittee Chairmen	Washington, D. C.
8.	March 16, 1970	Schaefer and Lane	New York, New York
9.	July 14, 1970	Schaefer and Lane	New York, New York