MONOGRAPH 13

Mechanical Properties of Structural Materials at Low Temperatures

A Compilation from the Literature

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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R. Michael McClintock and Hugh P. Gibbons

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Foreword

The advent of space vehicles which utilize cryogenic fluids for propellants has greatly increased activity in the field of cryogenic engineering in recent years. Large capacity gas liquefaction plants have become necessary to supply cryogenic fluids in the amounts needed for rocket testing. With these plants and the rockets themselves has come the need for associated cryogenic equipment such as valves, pumps, liquid transfer lines, flow indicators, pressure switches, temperature and level sensing devices, and, in fact, all the equipment used in handling liquids at other more convenient temperatures.

Intelligent design of reliable cryogenic equipment such as this requires the existence of data on the mechanical properties of structural solids at low temperatures; data which are all too scattered or too scarce to suit most designers. This book, therefore, is issued to help fill the need for a compilation of useful design figures.

Contents

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The tensile strength, yield strength, tensile elongation, and impact energy of about two hundred materials, metallic and nonmetallic, are given graphically as functions of temperature between 4° and 300° Kelvin.

Introduction

The designer of equipment which must operate at very low temperatures is faced at some time in the design with the problems of making material selections and of performing initial stress calculations. This is no less true, of course, when a device is being designed for use at other temperatures, but the dearth of data on the mechanical properties of commercial materials at low temperatures must certainly be disconcerting to the design engineer who is looking for a material to act as a structural member in a cryogenic device. It is hoped that this compilation of some of the mechanical properties of materials will assist the designer by making available in one publication reliable data which have appeared in the literature or which, in some cases, have not yet been published.

The selection of a material for fabrication of a part can usually be made in several ways, but very often the simplest method involves the establishing of some figure of merit for the application at hand, and comparing materials on the basis of this figure. For example, double shell, vacuum insulated, cryogenic storage containers often require tension support members for their inner shells. Since it is desirable that such members conduct as little heat as possible into the inner shell from the surroundings of the vessel, an obvious figure of merit for the material to be selected is its yield strength divided by its mean thermal conductivity. (The appropriate yield strength figure is the lowest value for the material over the temperature range in which it operates.) When the most promising materials have been compared on the basis of these figures of merit, then the more qualitative aspects can be examined. These may include such things as the ease of fabrication or the weldability of the material. In some cases, it may even be desirable to assign arbitrary values to the qualitative properties of the materials, and so to construct fairly complex figures of merit for the purpose of material selection.

Following the choice of a proper material, the designer will make initial stress calculations in order to get an idea of the size of the structural components necessary to sustain the working loads. Here again the mechanical properties of the materials must be known.

It is to assist these two phases of low temperature equipment design that the present compilation of properties is especially presented.

The data are presented with the idea that an engineer who is making initial calculations on equipment for operation at cryogenic temperatures is more interested in obtaining quickly a definite figure than he is in evaluating the experimental data given in several detailed reports on the same material. The graphs and tables presented here, consequently, represent an attempt by the authors to perform an evaluation of data which have appeared in the literature and to present the design engineer with the result. The curves therefore appear as lines representing the mechanical properties as functions of temperature, and not as bands representing maximum and minimum values reported.

Such an evaluation process is bound to be somewhat subjective. If it were not, the reduction of data to line graphs could better be performed by the most convenient digital computer programed to provide the best fitting polynomial of degree "n." Unless the data were weighted judiciously, such a curve would be little more than a mathematical delight and perhaps in poor keeping with the known or suspected behavior of the properties of materials with temperature. The curves in this book, therefore, have been constructed from data which the authors found to be the best documented and the most consistent with that of other investigators. In most cases whatever errors remain after such an abridgement will be adequately compensated by the designer's use of a "safety factor" in his stress analysis. Where they are not, and greater confidence is required, the references should be consulted for more detail.

The references will also disclose the fact that not all the available materials have been included in this volume. Different metals or different heat treatments of the same metal, for example, have in some cases been omitted where it was thought that they were not the most representative of currently available materials. Omissions were also made in a few cases where the trend of a mechanical property as a function of some metallurgical variable was thought to be adequately demonstrated by those data selected for inclusion.

It should be remembered that any reduction of scattered mechanical properties data to a smooth curve is an attempt to represent the "most probable" relationship between ordinate and abscissa from among the samples tested. Specific samples may lie above or below the curve, however, and the discrepancies caused by commercial variation in chemical composition, heat treatment, dimensional and experimental errors, etc., are normally condensed into a "safety factor" by the designer, whereby he sidesteps costly quality control, or more complicated mathematics in the case of complex devices. The use of a safety factor is properly the province of the design engineer since he knows the use to which the equipment will be put, and the reliability desired. It should therefore be subject to the designer's complete knowledge, and not, as is sometimes the case, be applied to experimental data by the authors of such reports as this and the results presented as a table of "permissible stresses". This not only misplaces the responsibility for safety or reliability, but in complex calculations the safety factor can be compounded unintentionally. The point of mentioning this is merely that the data in this book should be used with caution for designs in which safety factors must be small (as in cases of restricted weight or size), since low temperature properties are often sensitive to variations in thermal and mechanical history and chemical composition which are allowable within commercial specifications.

In addition to these variations, limitations in experimental accuracy may account for some of the apparent inconsistencies which appear in graphs in this book. For example, the tensile strength of annealed type 303 stainless steel, which appears on page 98, lies slightly above that of the same material which has been cold drawn 10 percent; and at 20° K, the same effect reappears in types 310 and 316 stainless steels. It is conceivable that such an effect is real, but the authors' first inclination is to ascribe the difficulty to differences in strain rate between observers, or to other experimental limitations. In any event, having no better knowledge, the authors have thought it best simply to include the curves derived from the experimental results and to let the apparent inconsistencies stand for the present.

The same philosophy applies to the graph of the strength of titanium alloys on page 74, although the drop in tensile strength of the two alloys at 20°K can probably be attributed to experimental error in this case. The elongation of these two alloys is zero at 20°K, and brittle materials are extremely sensitive to accidental surface imperfections or other stress raisers, even such as the radius commonly present at the ends of the reduced section of a tensile specimen.

The mechanical properties presented in this compilation as functions of temperature are tensile strength, yield strength at 0.2 percent offset (unless otherwise noted), elongation, and impact energy. In a few instances the reduction of area of a tensile specimen is presented as an indication of ductility. The first three properties were obtained from short time tension tests of smooth specimens which were generally cut from bar or plate one-eighth inch thick or thicker. Thinner sheet material is noted on the graphs. Some investigators report "yield point" (usually obtained by the "drop of the beam" method) rather than yield strength. In these cases the graphs are so noted, and the upper yield point is the one referred to.

The impact energy is the energy absorbed by a standard specimen in breaking under an impact load. In every case the type of impact specimen is indicated on the graph by a note which identifies it with one of the specimens described in test method E23–56T of the American Society for Testing Materials. The notation "Charpy V" refers to the type "A" specimen having the V-notch, "Charpy K" refers to the type "B" specimen with the keyhole notch, and "Charpy U" refers to the type "C" specimen with the U-shaped notch. Izod specimens are type "D" in the ASTM specifications.

The Kelvin temperature scale is so widely used in cryogenics that all data have been converted to these units for consistency. For the convenience of those to whom a Fahrenheit temperature means more, extra scales have been included on pages ix and x. These may be cut out and held along the abscissa to allow interpolation as well as direct reading in degrees Fahrenheit. The extra scales also contain divisions corresponding to the ordinate mechanical properties for interpolation.

Adjacent to each curve are several numbers in brackets. These numbers correspond to the references in the bibliography at the end of the graphical section and indicate the sources of data from which the curve was constructed. On graphs where two or more curves appear for the same material, the reference numbers given for one curve apply to the rest. Because of the scarcity of published data, some of the references quoted are from unpublished records.

In most cases smooth curves are used to represent the behavior of the mechanical properties as functions of temperature. These curves represent interpolation between experimental data points as mentioned before. In some cases, however, the data are joined by straight lines, and intermediate or end points are indicated. Where this occurs, it is because either a scarcity of data or a doubt on the part of the authors cautioned against drawing a smooth curve.

The authors have tried to use nomenclature which is consistent with efforts of the various technical societies and manufacturers' associations to classify and standardize metal specifications. When ambiguities might still exist, nominal or reported compositions have been used in addition to the name of a material. In a few cases proprietary names have been given when they have become so commonly used that other designations might be confusing.

Throughout the book several abbreviations are used on the graphs. These correspond with usual metallurgical practice in this country: stress is given in psi (pounds per square inch), impact energy in ft-lb (foot-pounds), and tensile elongation in percent in 4D (four diameters) where this ASTM recommendation was adhered to. The percentage of cold drawing or cold reduction given on many of the graphs refers to reduction of area rather than reduction of diameter. "OQ & T" means "oil quenched and tempered", "WQ & T" means "waterquenched and tempered", "AC" means "air-cooled", "RB" and "RC" mean "Rockwell B hardness" and "Rockwell C hardness", respectively. Heat treating temperatures are given in degrees Fahrenheit, which is common in metallurgy in this country. Also whenever the metallurgical condition of the specimens was stated in the literature, it is appended to the curves. It is surprising, by the way, to find in the literature data derived from material described only as "soft yellow brass" or "soft bronze". An attempt was made to extract meaning from these data, but for the most part the value of such information is not great. Laboratory analysis of the materials tested and careful control of the thermal and mechanical history of the materials investigated would help immensely to establish the reliability and the usefulness of mechanical properties data.

Probably the first thing learned by a newcomer to the cryogenic field about the properties of materials is that some materials become brittle at low temperatures and are therefore unusable in many structural applications at these temperatures. The literature is studded with accounts of spectacular brittle service failures which would not have occurred at higher temperatures. There are certain applications, however, in which it would be a mistake to apply the ductility criterion in the selection of a material for low temperature service. Springs are an example. The authors are aware of an instance in which the most suitable material for a low temperature coil spring was not considered because it would be brittle at the service temperature. The ductility criterion should not generally be applied in such cases since a smooth coil spring having no re-entrant corners is carefully designed to act as an elastic member and usually need not possess any ductility for its satisfactory service. Professor Collins at the Massachusetts Institute of Technology, for example, has successfully used carbon steel valve springs in expansion engines for the liquefaction of nitrogen and helium.

For most structural applications, however, the engineer would like some assurance that the material he selects will not be brittle at the service temperature. If it were, his hardware would be liable to catastrophic failure in the event of accidental impact or vibration loads at a point where local stresses occurred in excess of those for which he has allowed. "Ductile" materials, of course, are capable of redistributing local stresses in excess of their yield strength by the mechanism of plastic flow. One great difficulty, however, has been that of devising a laboratory test which will predict satisfactorily whether a material will behave in a ductile or a brittle manner in service. The plastic elongation of a tensile specimen is not a satisfactory index, since many materials which show plastic deformation in a tensile test at a given temperature have been known to fail in a brittle manner in service at the same (or even higher) temperatures. Ordinary low carbon steel, for example, which Eldin and Collins [1] find to be completely brittle in a tensile test only below 65°K, has a record of many service failures at temperatures only moderately below room temperature. Obviously the behavior of a material under the conditions of uniaxial stress present in the usual tensile test does not provide a sufficiently good prediction of its behavior under multiaxial stress conditions.

The beam impact test, in which a standard-size bar is subjected to a high-velocity blow, while popular because of its convenience, is also deficient in some respects as an index of performance of a material in service. A correlation has been obtained between service performance and impact energy for steels by Jaffee et al.,[2] but such a correlation applicable to all materials has not yet been found. One difficulty seems to be that light metals pay an unjust penalty in the impact test. Magnesium alloys, for example, exhibit low impact strength, but have been satisfactorily used in the aircraft industry in structural applications in which they receive impact loads. So whereas the tensile elongation of a material seems to be too optimistic an indication of service ductility, the energy absorbed in an impact test seems in some cases to give information which is too pessimistic.

The energy absorbed in an impact test can be deceptive for still other reasons. For example, the energy value is affected considerably by incomplete breakage of a very ductile specimen. When this occurs, a portion of the energy recorded in a Charpy test is the result of forcing the specimen through the supports of the machine. Consequently this occurrence, along with other supplementary information such as the character of the fracture surface, is sometimes of even greater importance than the absolute value of the energy absorbed.

As a simple laboratory test which will provide a suitable analogy to the service performance of a material, the notch tensile test is gaining acceptance for some purposes. The test is performed either at low strain rates in tensile equipment or at high strain rates, usually in impact machines which have been modified for this use. "Notches" almost always exist, of course, in any manufactured part in the form of weld craters, rivet holes, re-entrant corners, or simply accidental scratches; and the notch-tensile test provides an indication of the ability of a material to sustain working stresses in the presence of such stress raisers. A properly designed notch-tensile specimen also contains an area of bi-axial or tri-axial stress as well, so information can be gained about the performance of the material under these conditions.

There are other types of laboratory tests which have been devised to predict the performance in service of structural materials, each a

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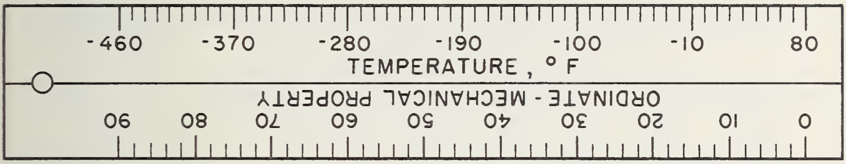
[1] See reference 29.

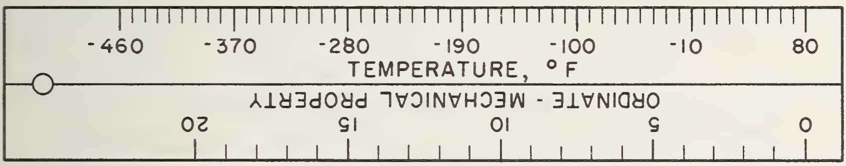
[2] Jaffee, Kosting, Jones, Bluhm, Hurlich, and Wallace, Impact tests help engineers specify steel, SAE Journal, March 1951.

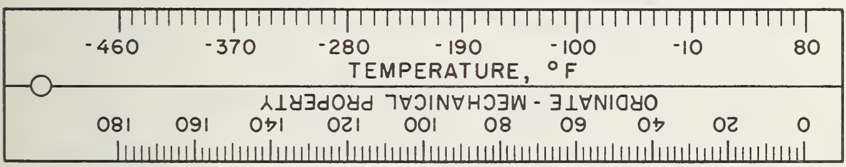
compromise between simplicity and universality on the one hand, and degree of applicability to the service requirement on the other. For the most part, airframe and component manufacturers make the compromise in the latter direction. Their test specimens consequently consist of subassemblies, complete components, or even entire complex assemblies. In industries in which weight is not a prime consideration, and larger safety factors can be used, the tendency is toward the simpler tests. Obviously, economic considerations make the simple experiment the more desirable, and until a simple test is devised which is a reliable index of service performance, most design engineers will content themselves with the less desirable information provided by the usual tensile and impact tests in the first stages of design.

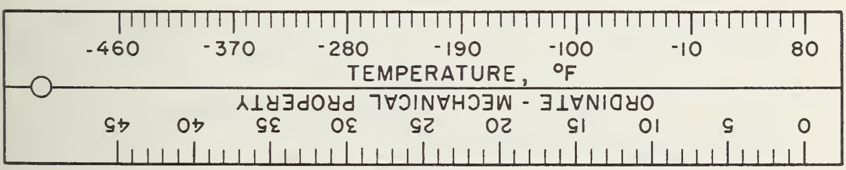
The greatest amount of information in the literature which indicates something about the ductility of a material is in the form of tensile elongation or impact data. Therefore, while not the most satisfactory indications of ductility, these two mechanical properties are reported in addition to yield and tensile strengths in this book.

The authors take pleasure in acknowledging the assistance of L. J. Ericks in the preparation of this book. His careful drafting is responsible for the final appearance of the graphs.









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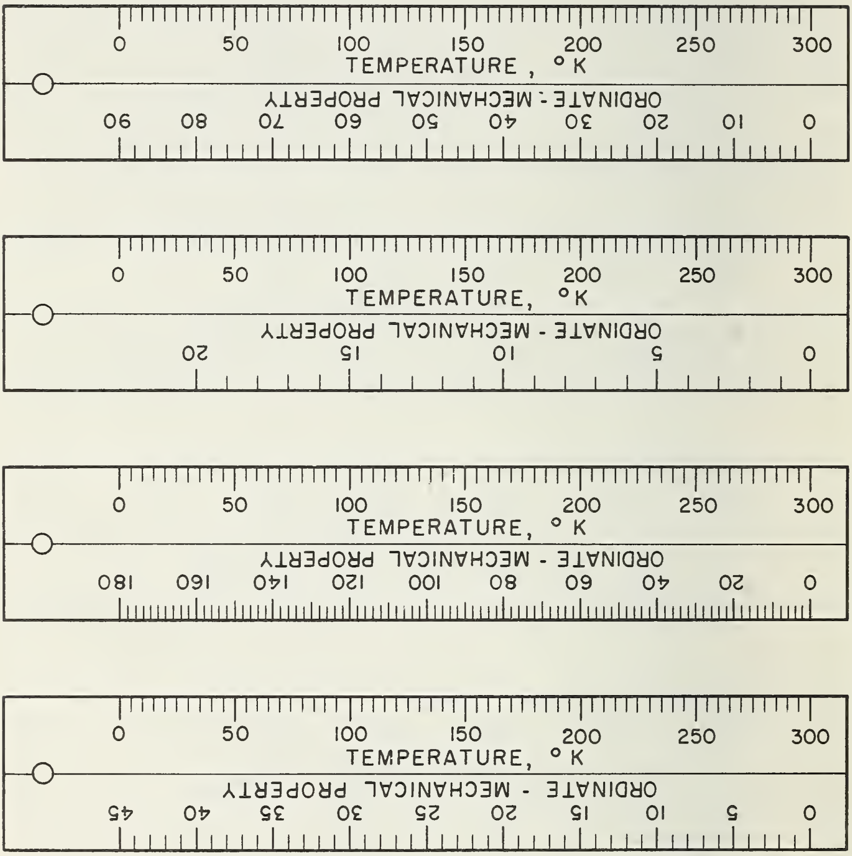

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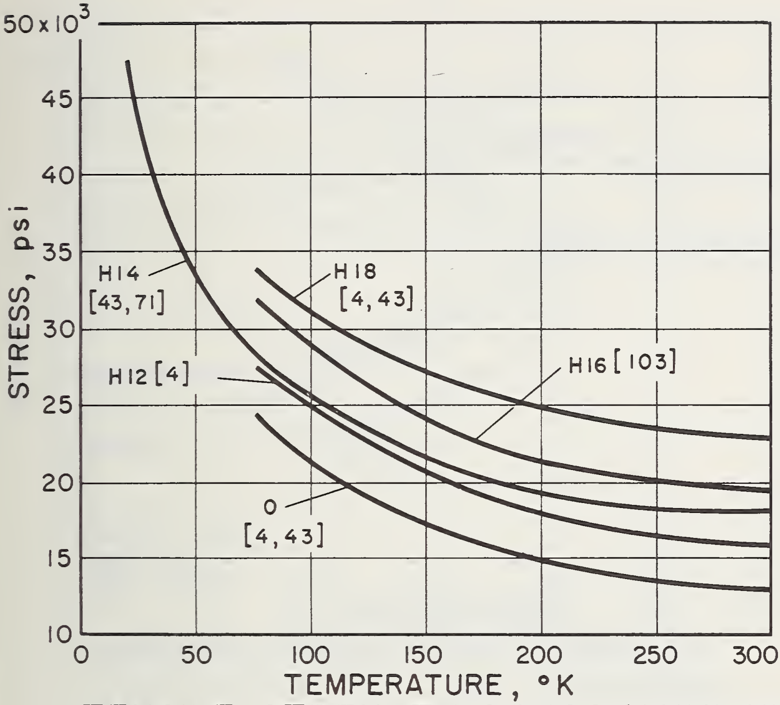

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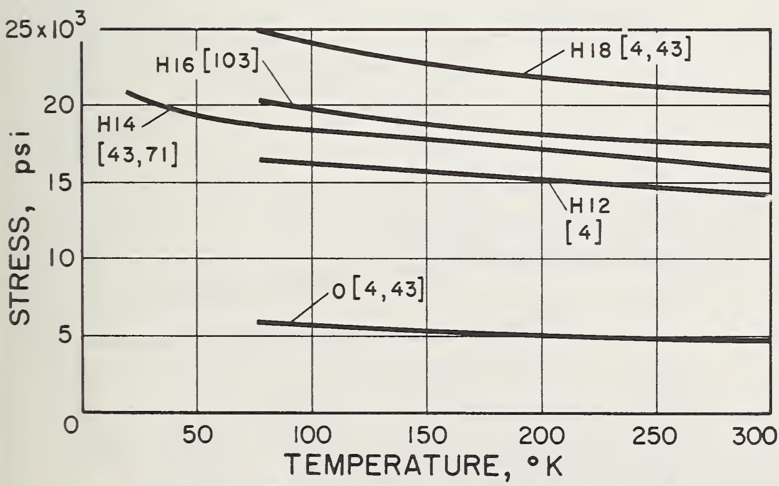

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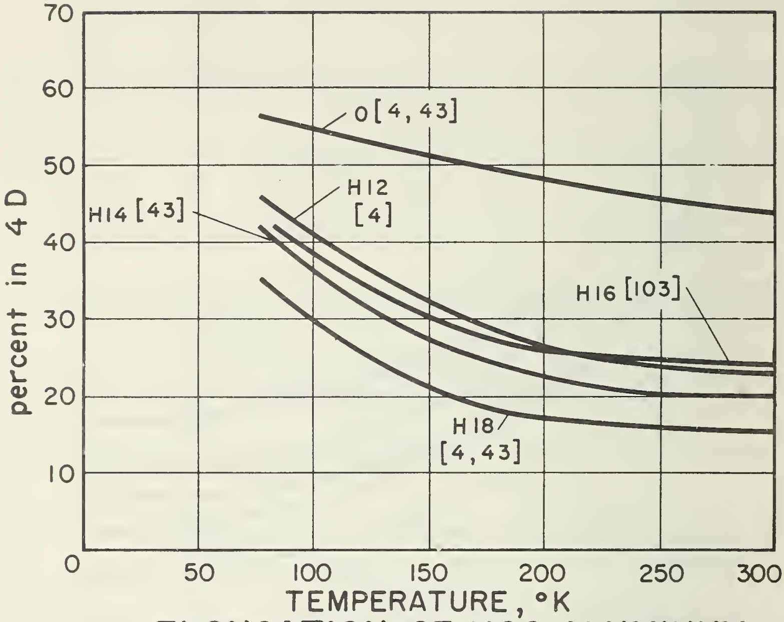

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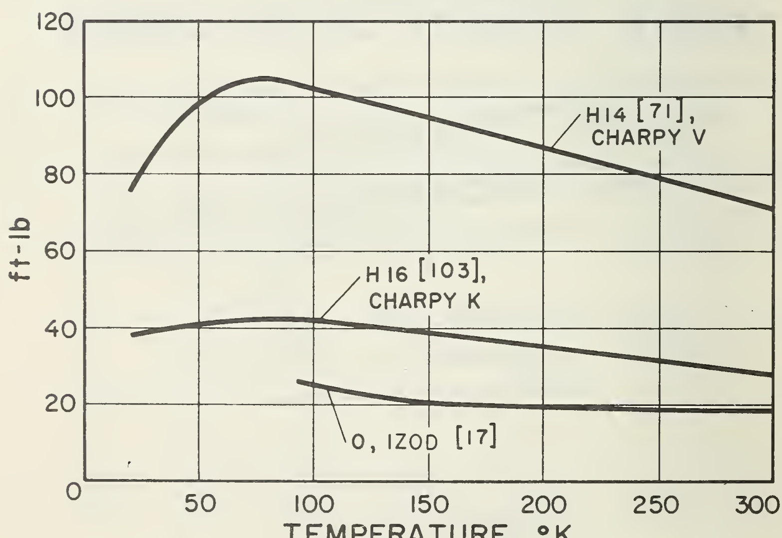

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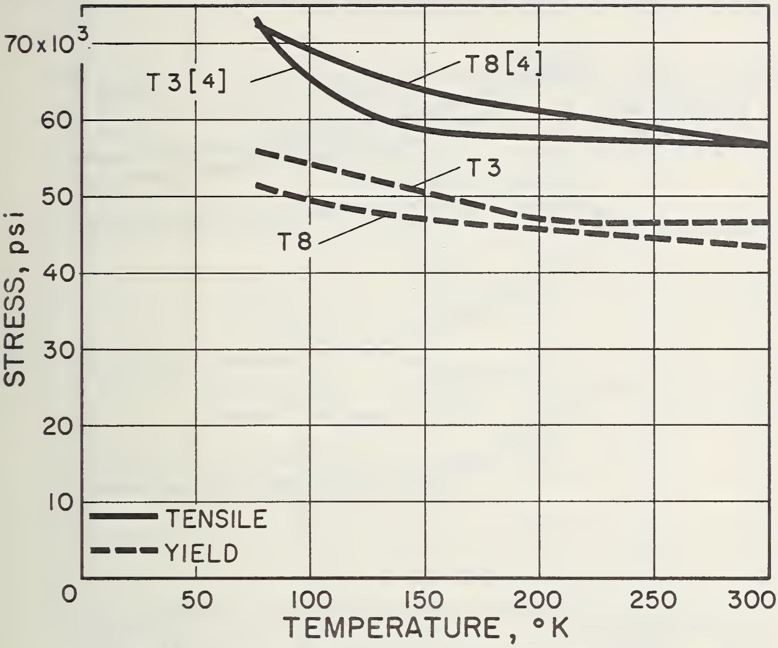

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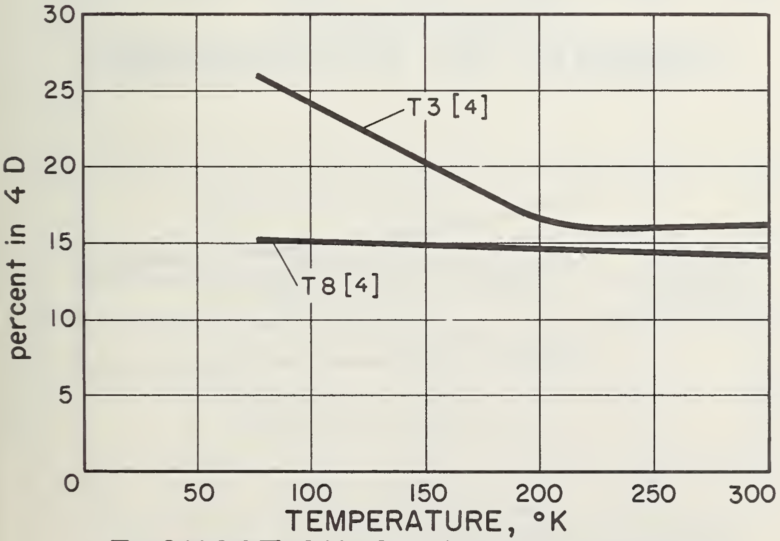

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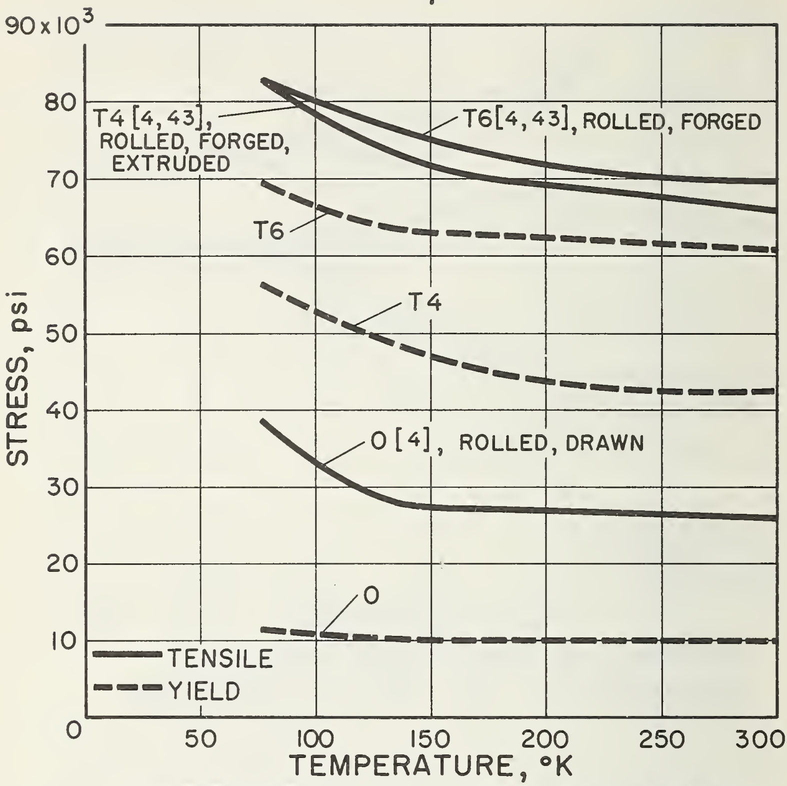

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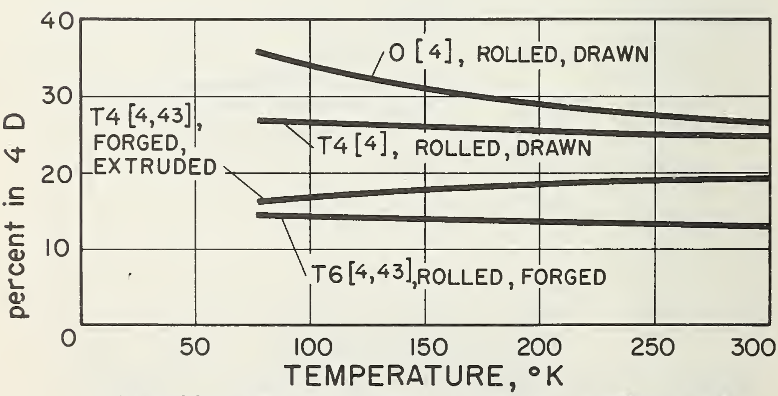

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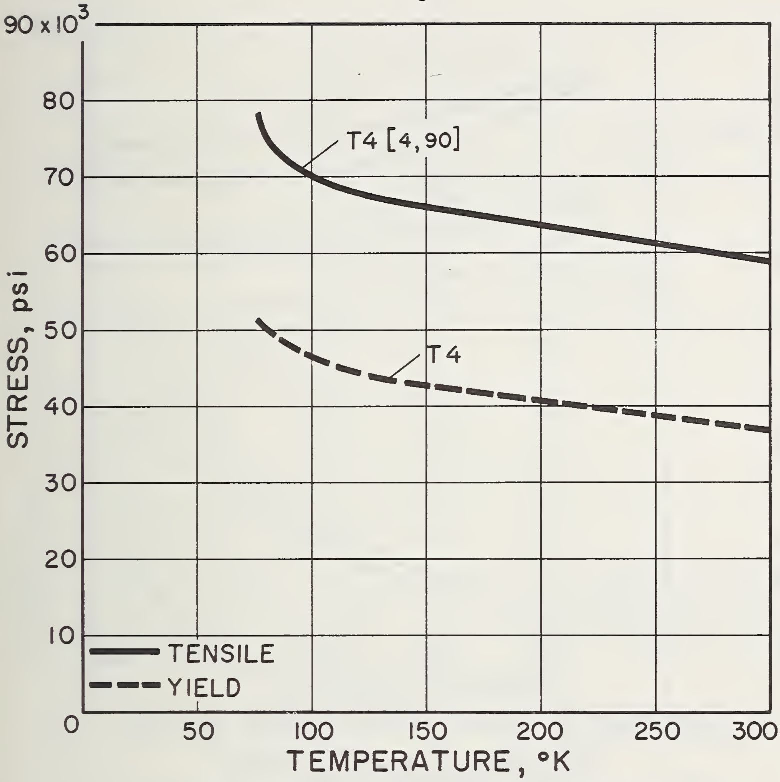

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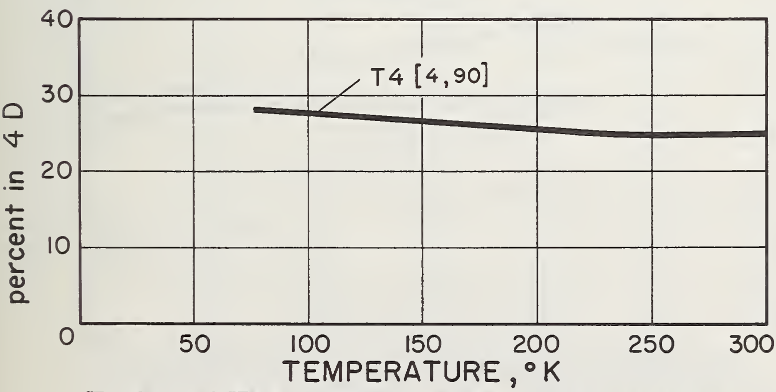

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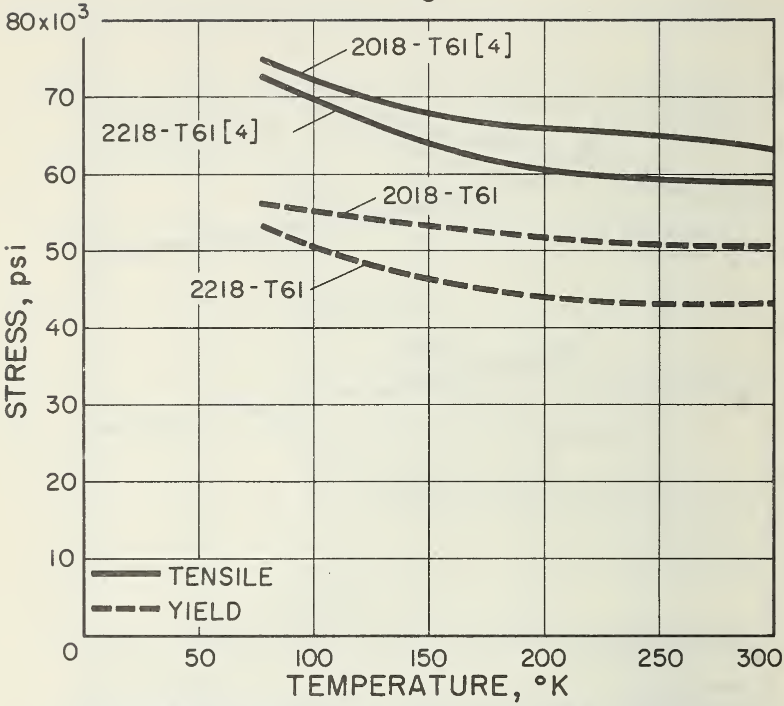

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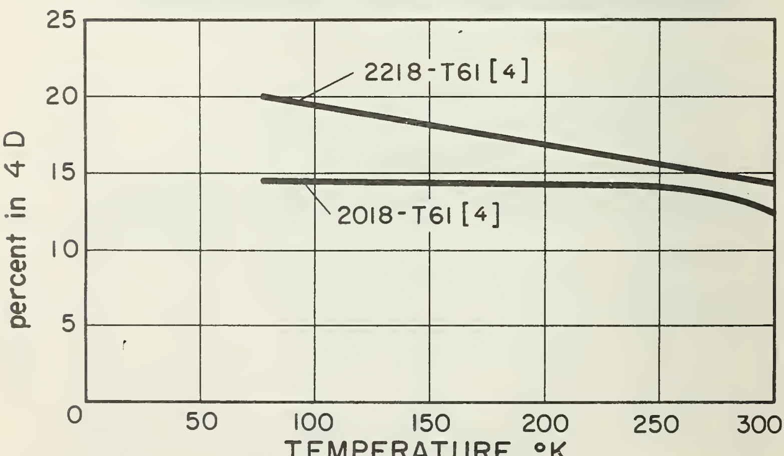

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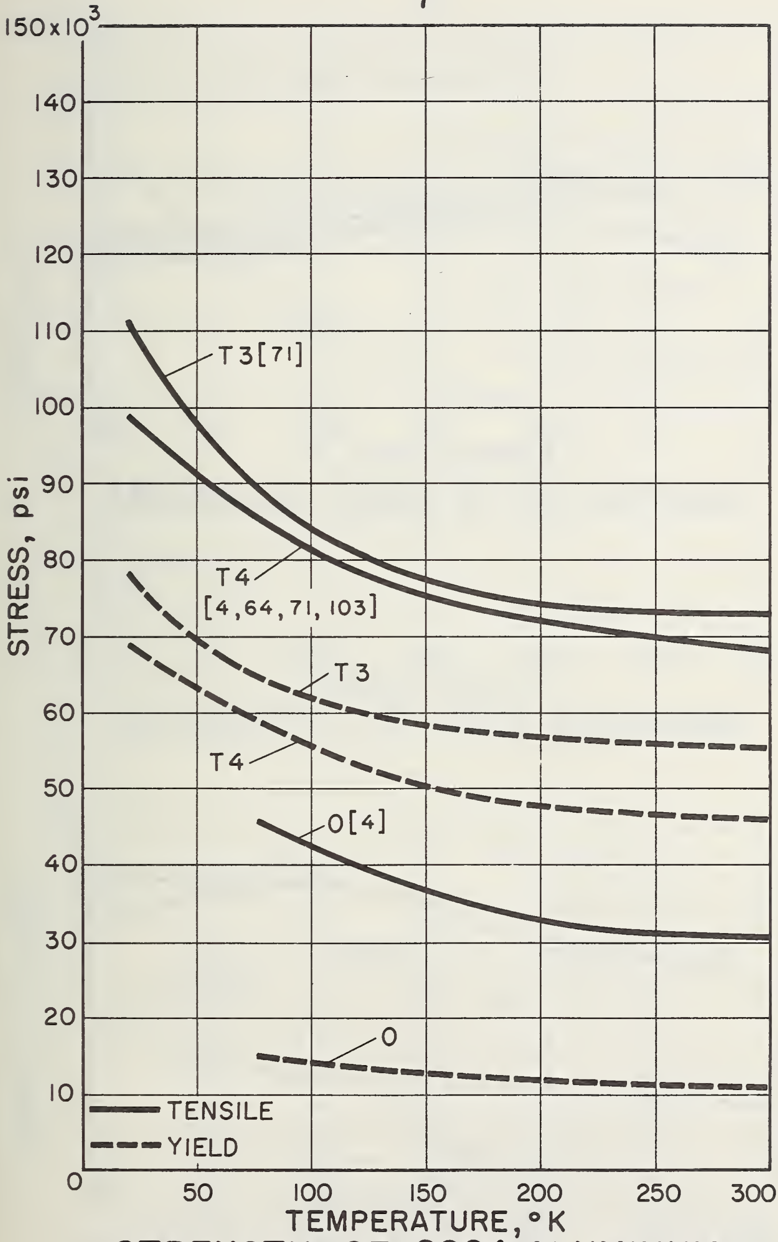

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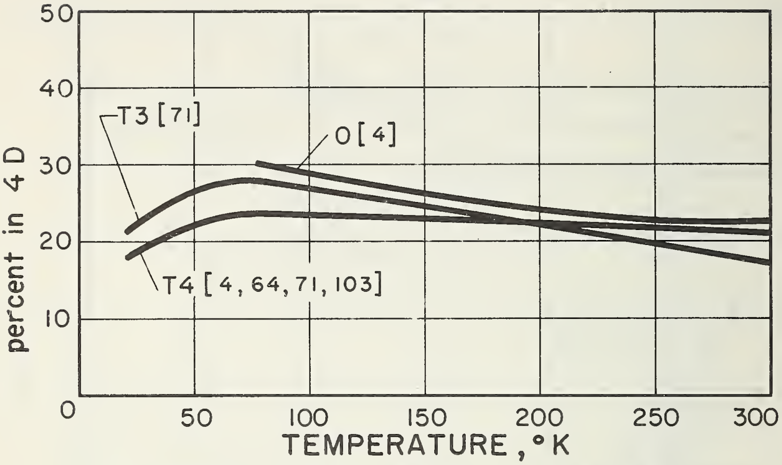

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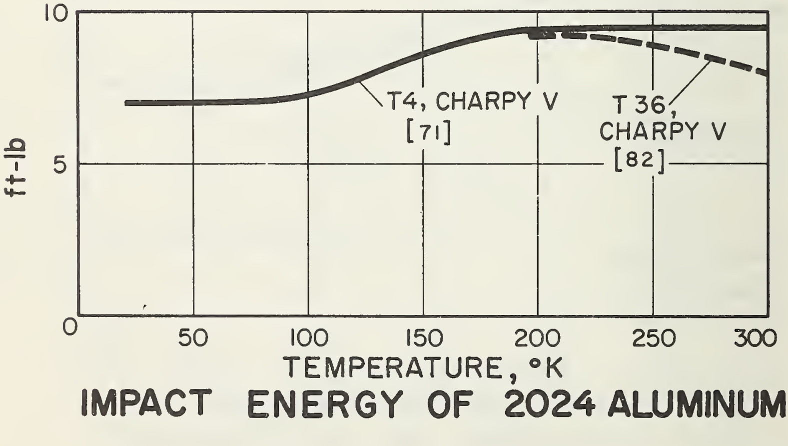

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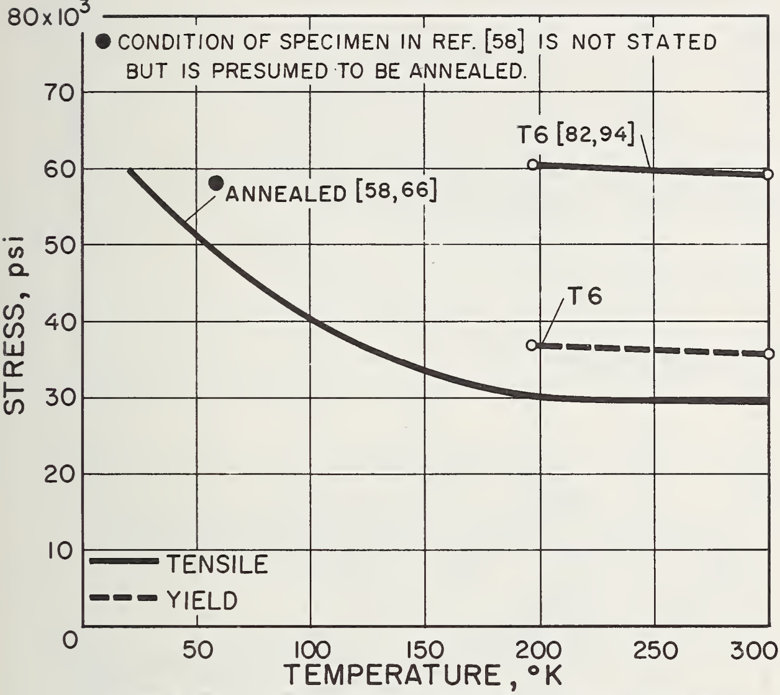

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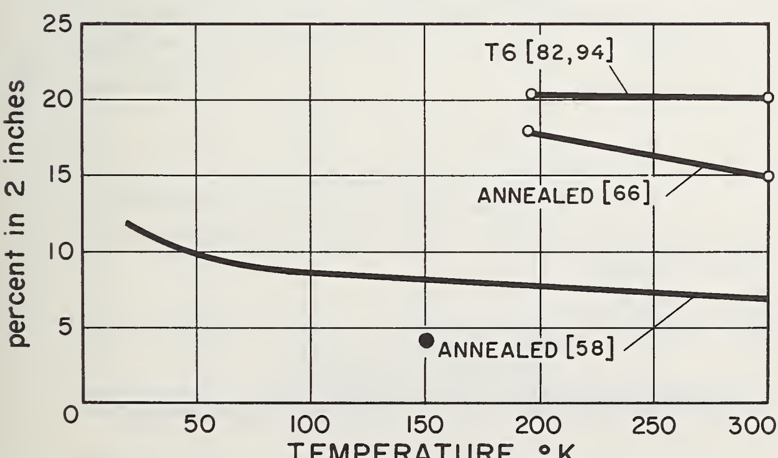

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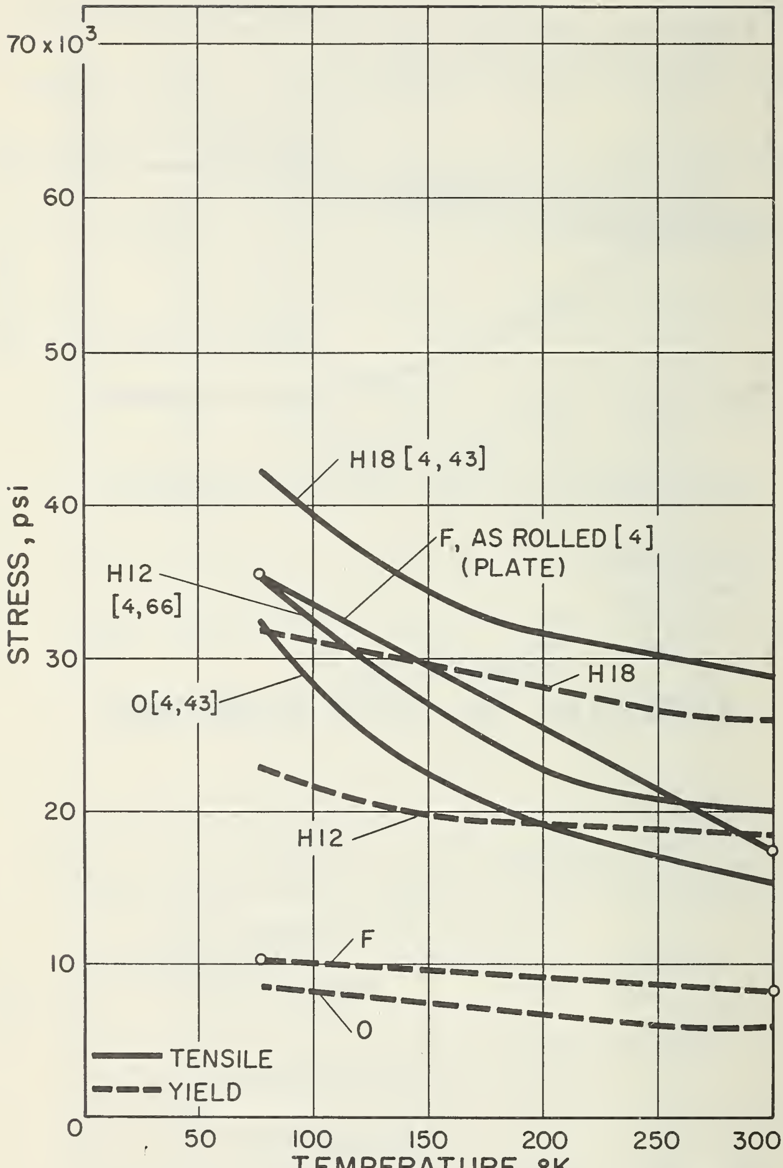

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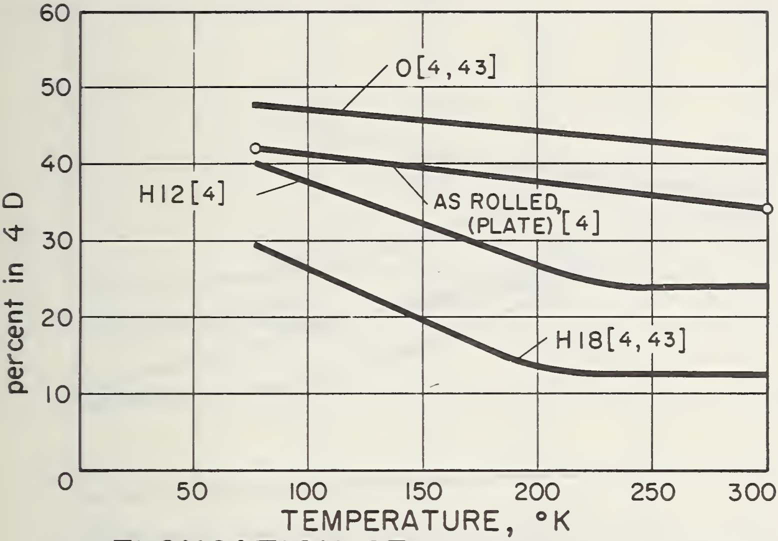

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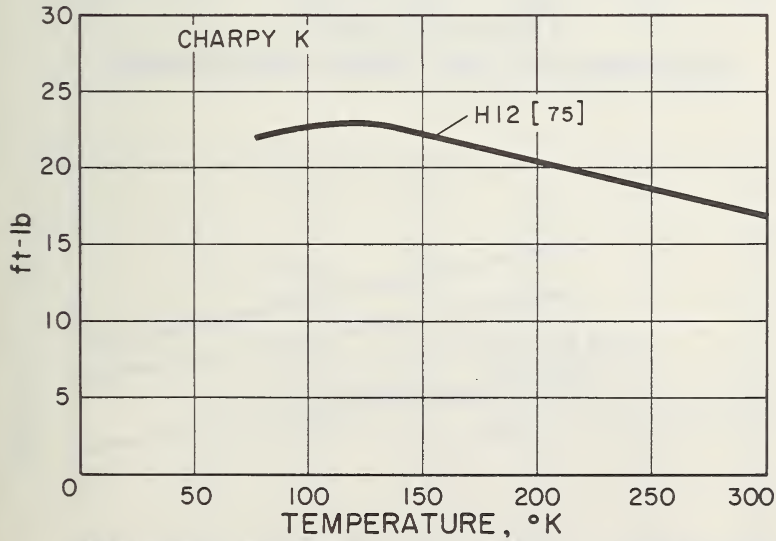

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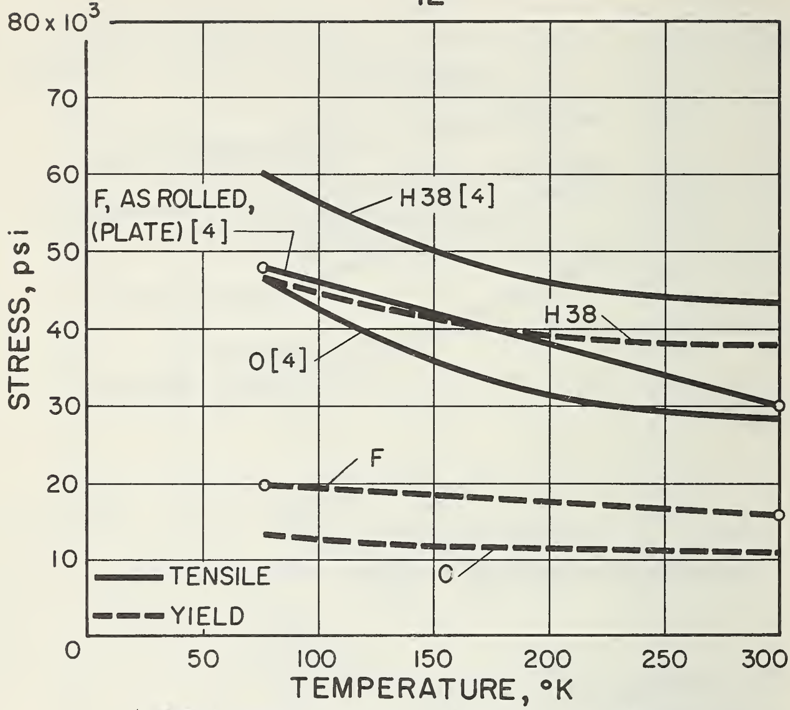

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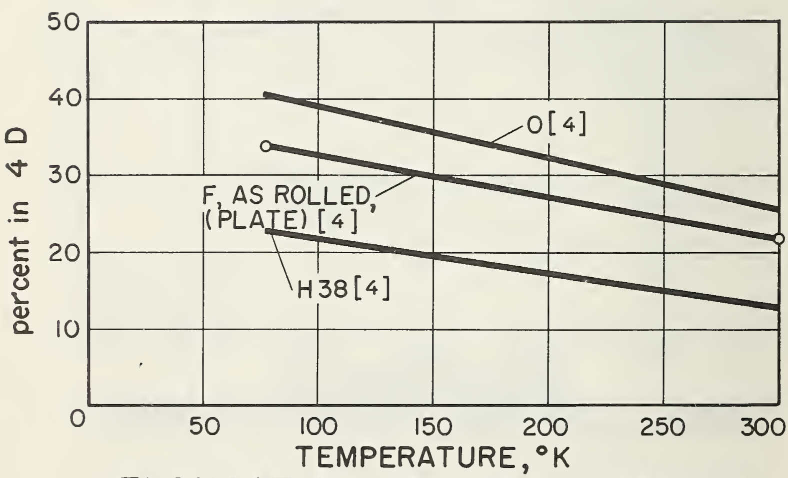

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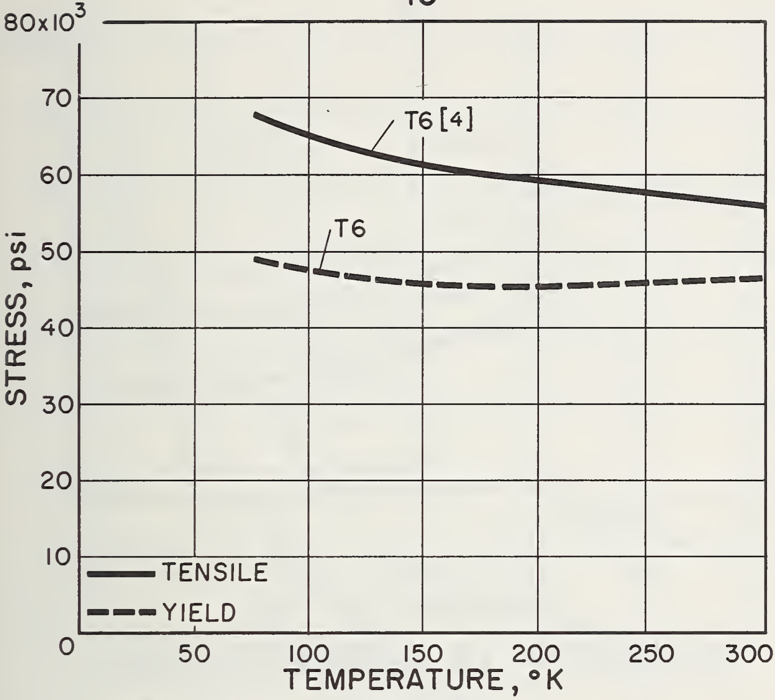

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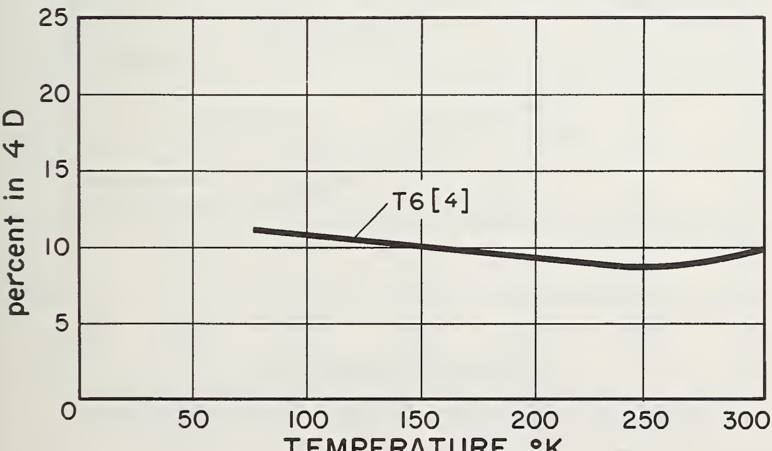

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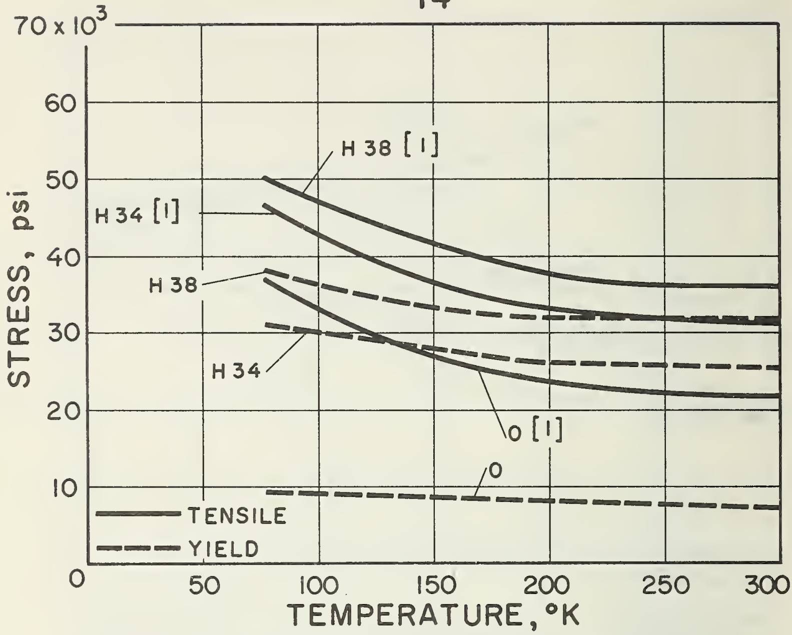

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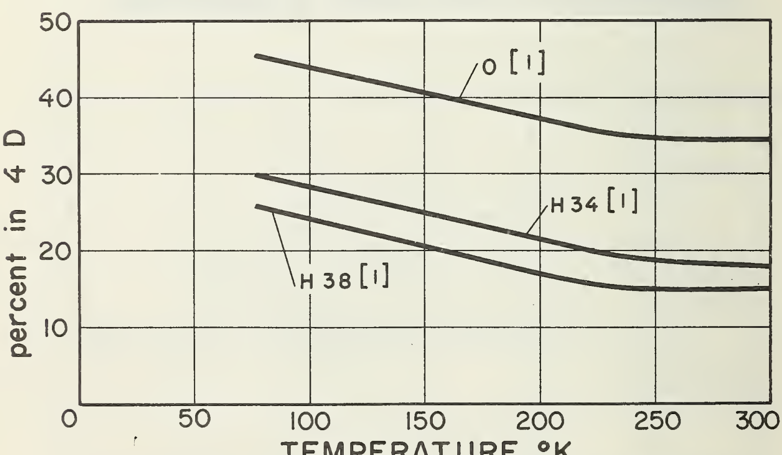

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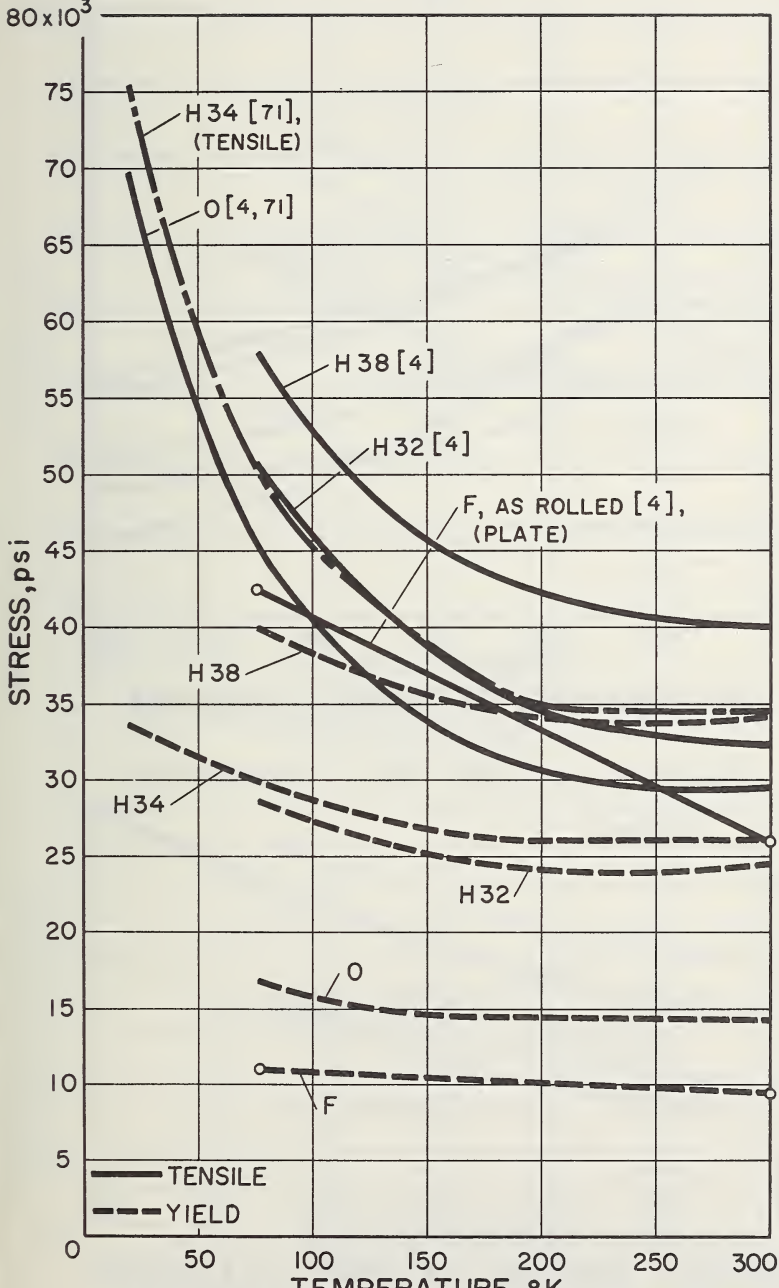

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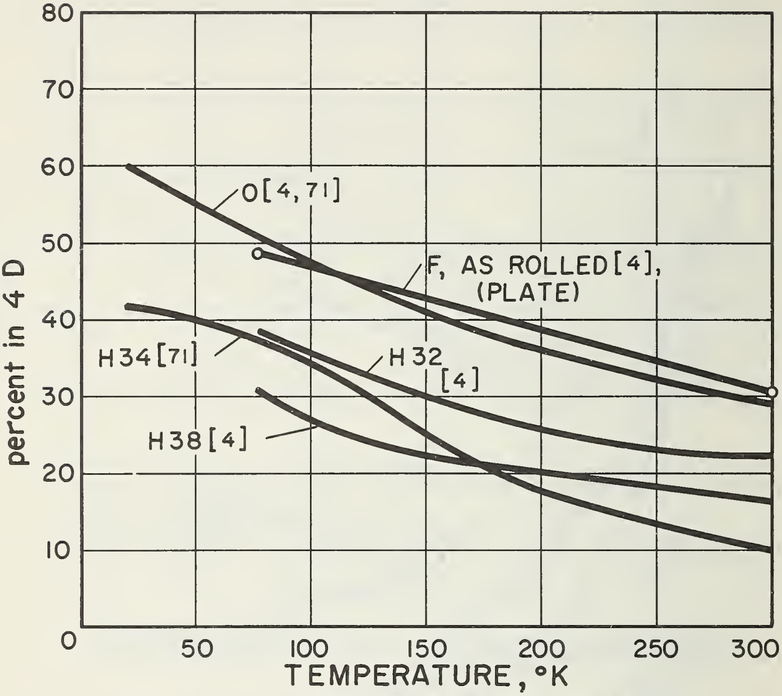

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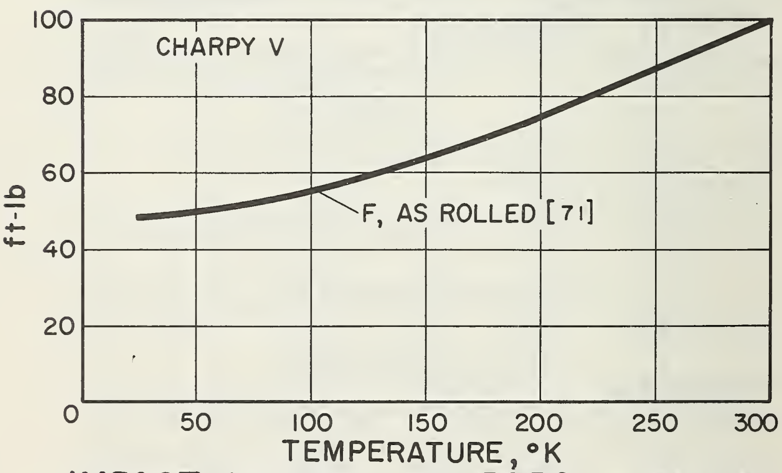

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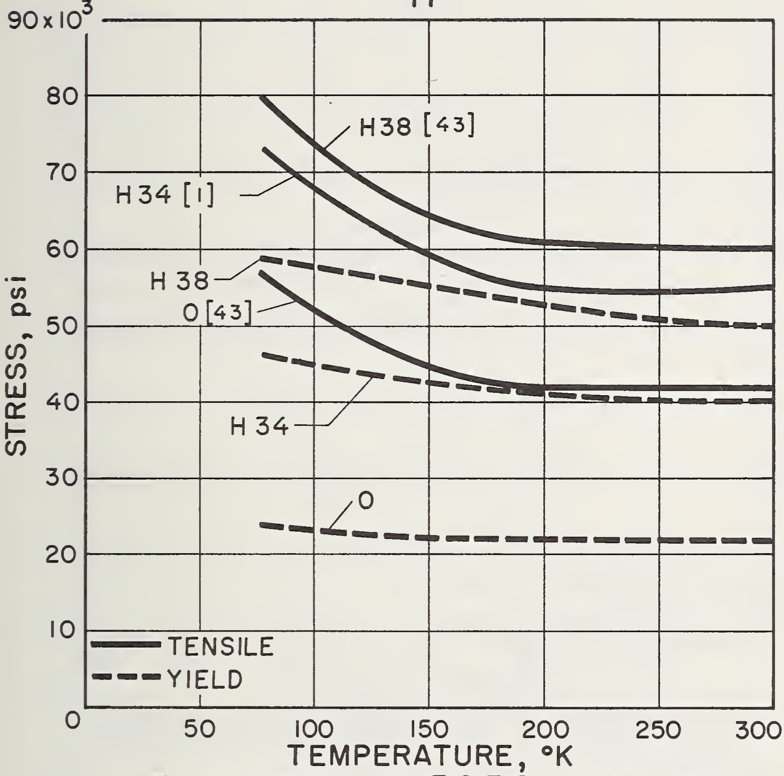

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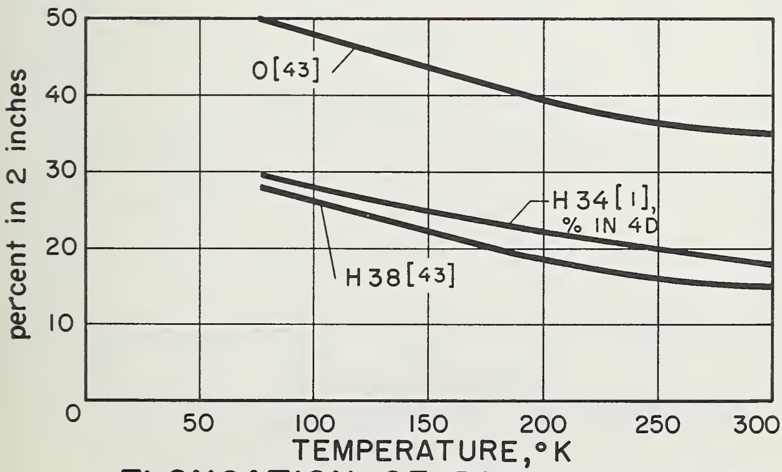
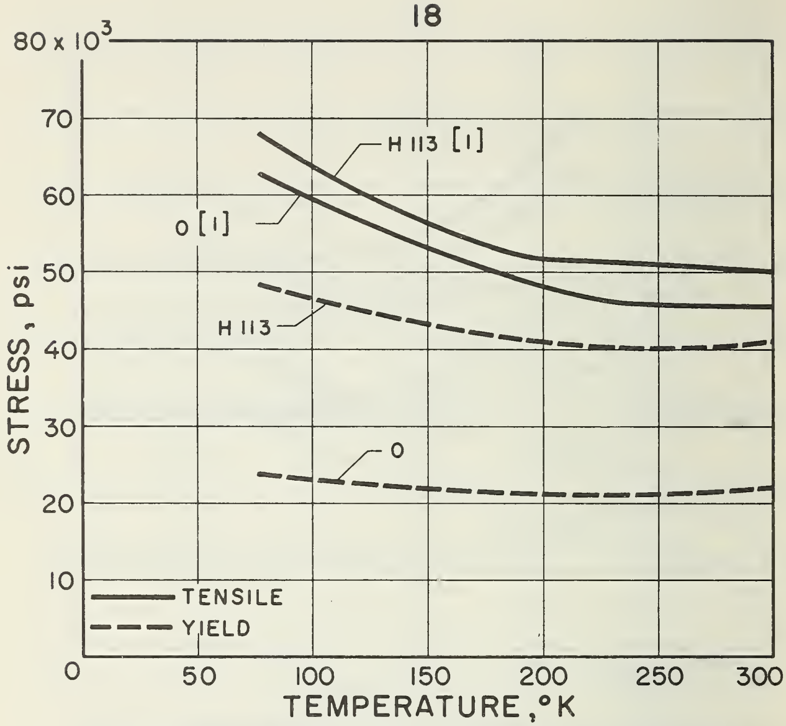
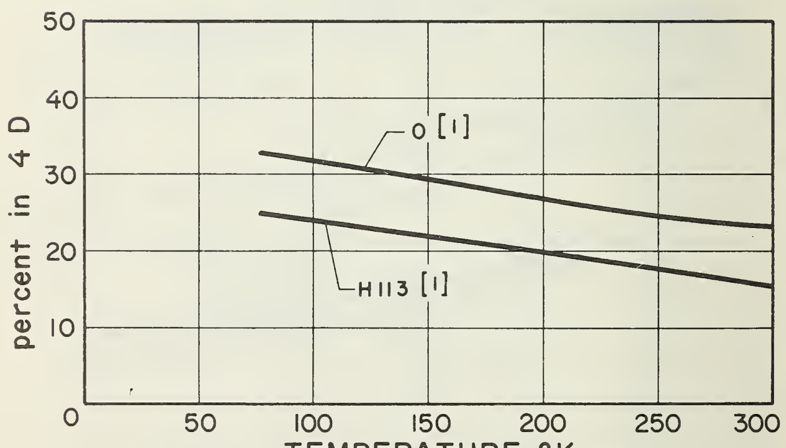


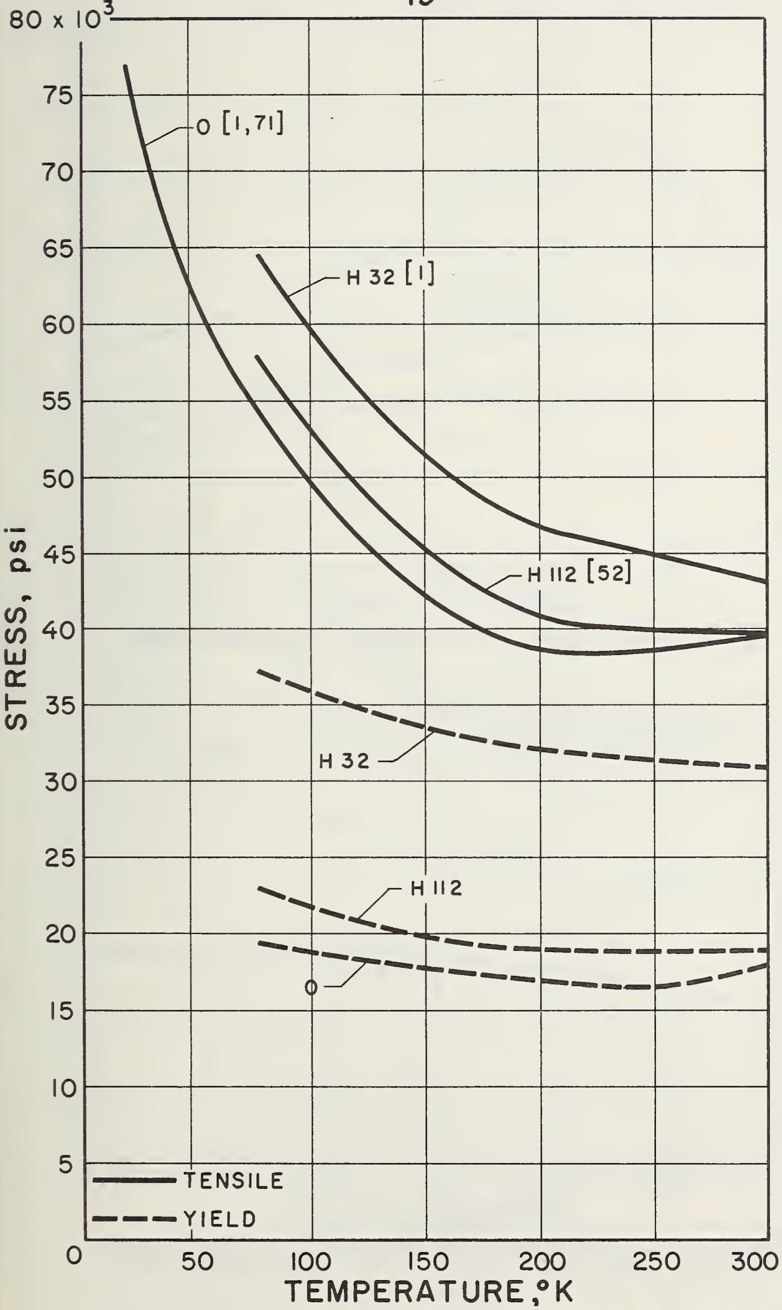
ELONGATION OF 5056 ALUMINUM



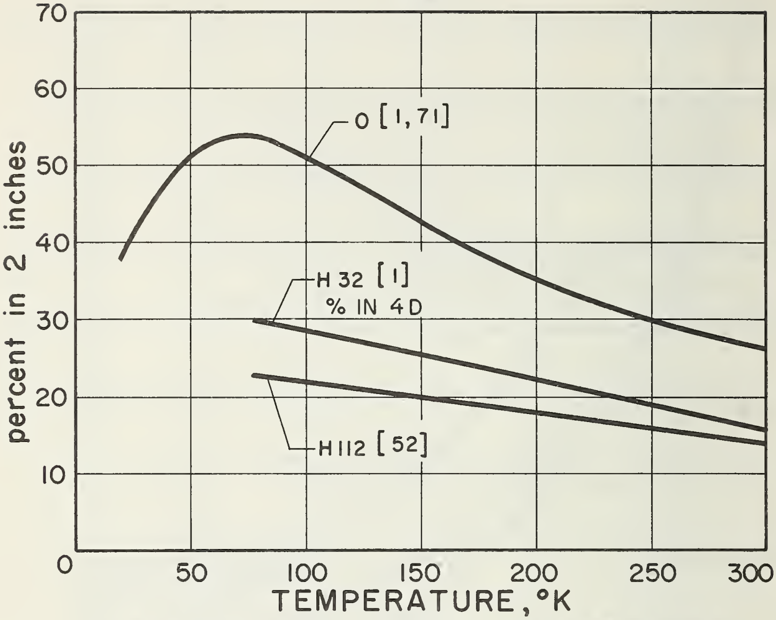
STRENGTH OF 5083 ALUMINUM



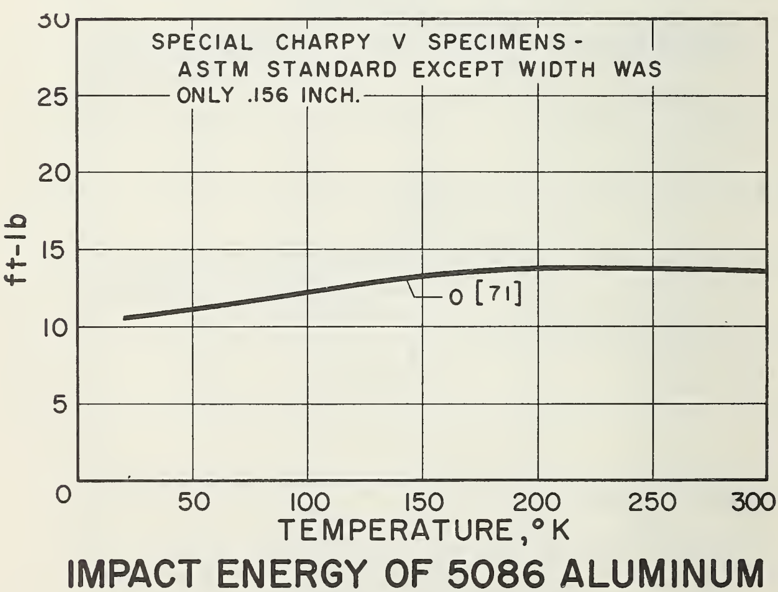
ELONGATION OF 5083 ALUMINUM



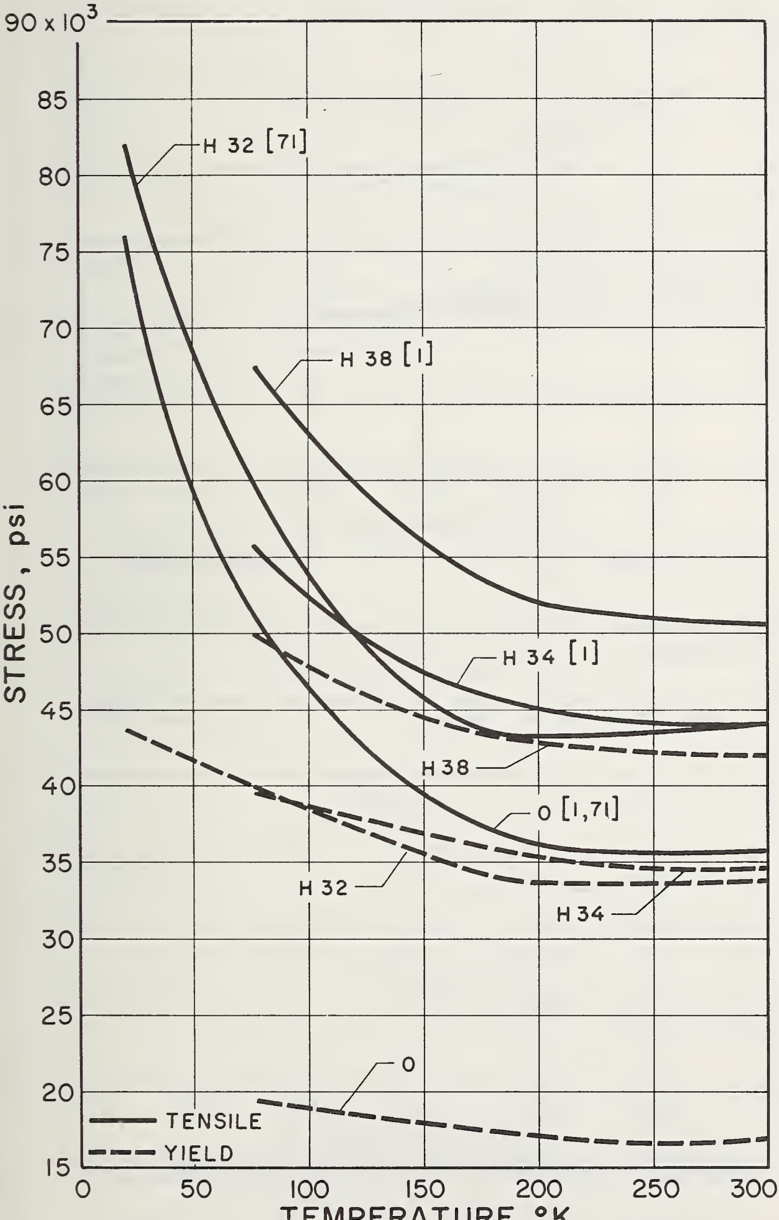
STRENGTH OF 5086 ALUMINUM



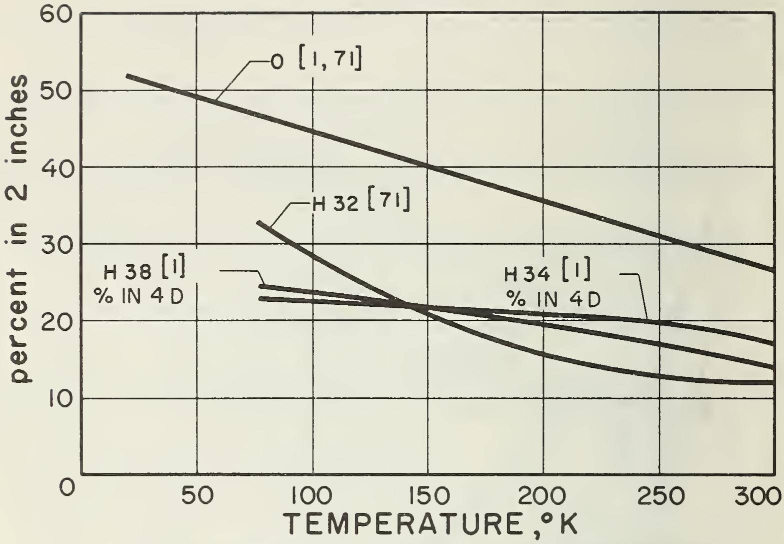
ELONGATION OF 5086 ALUMINUM



IMPACT ENERGY OF 5086 ALUMINUM



STRENGTH OF 5154 ALUMINUM



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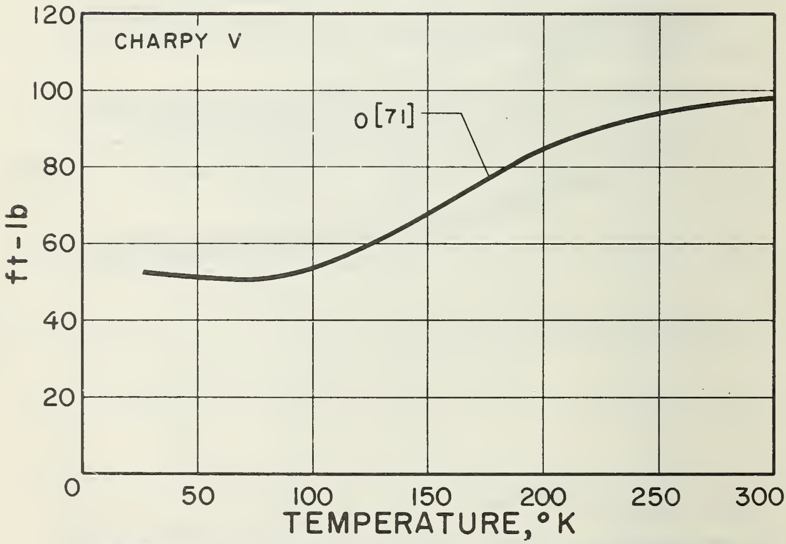
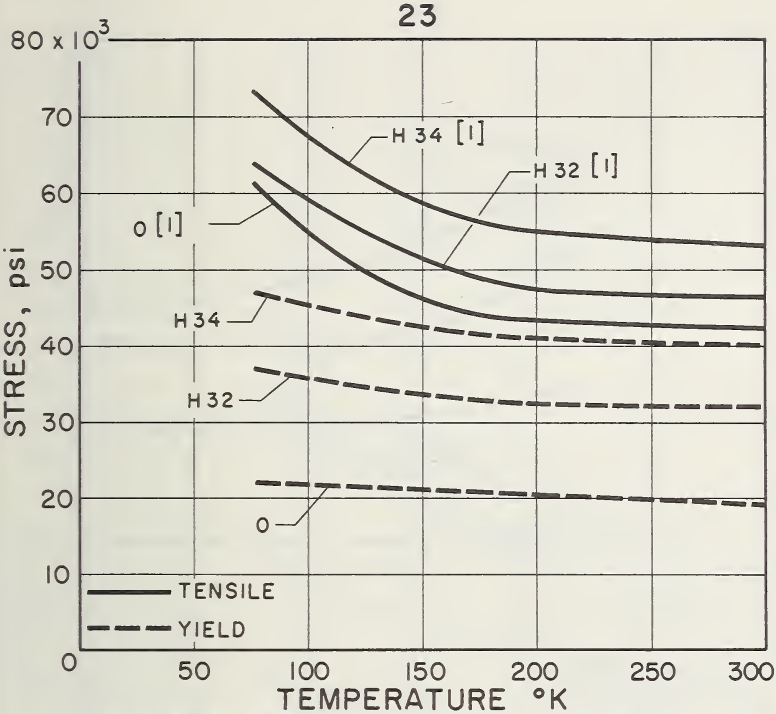
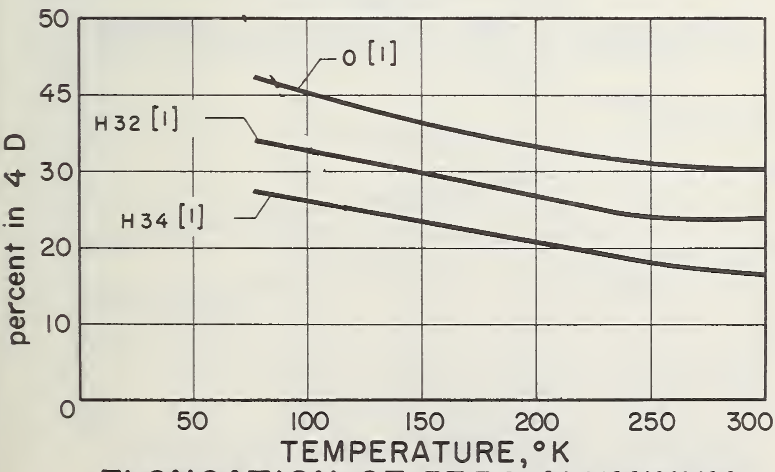


IMPACT ENERGY OF 5154 ALUMINUM



STRENGTH OF 5356 ALUMINUM



ELONGATION OF 5356 ALUMINUM

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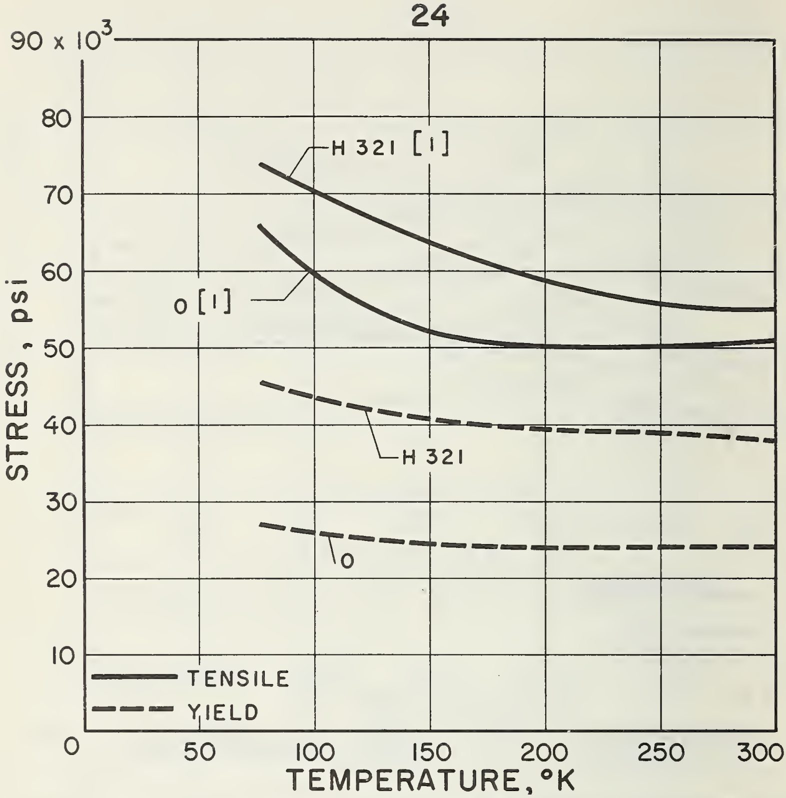
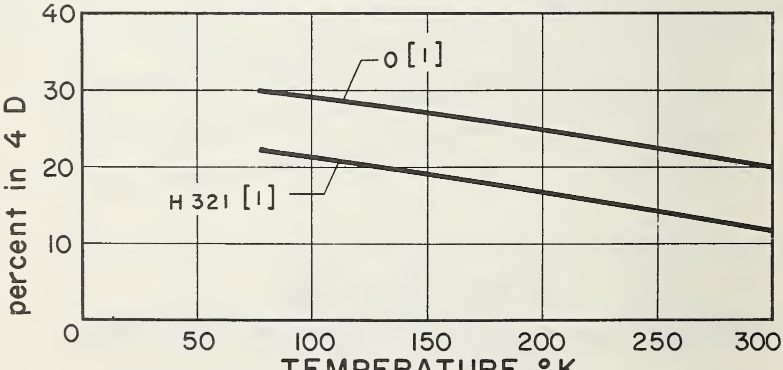
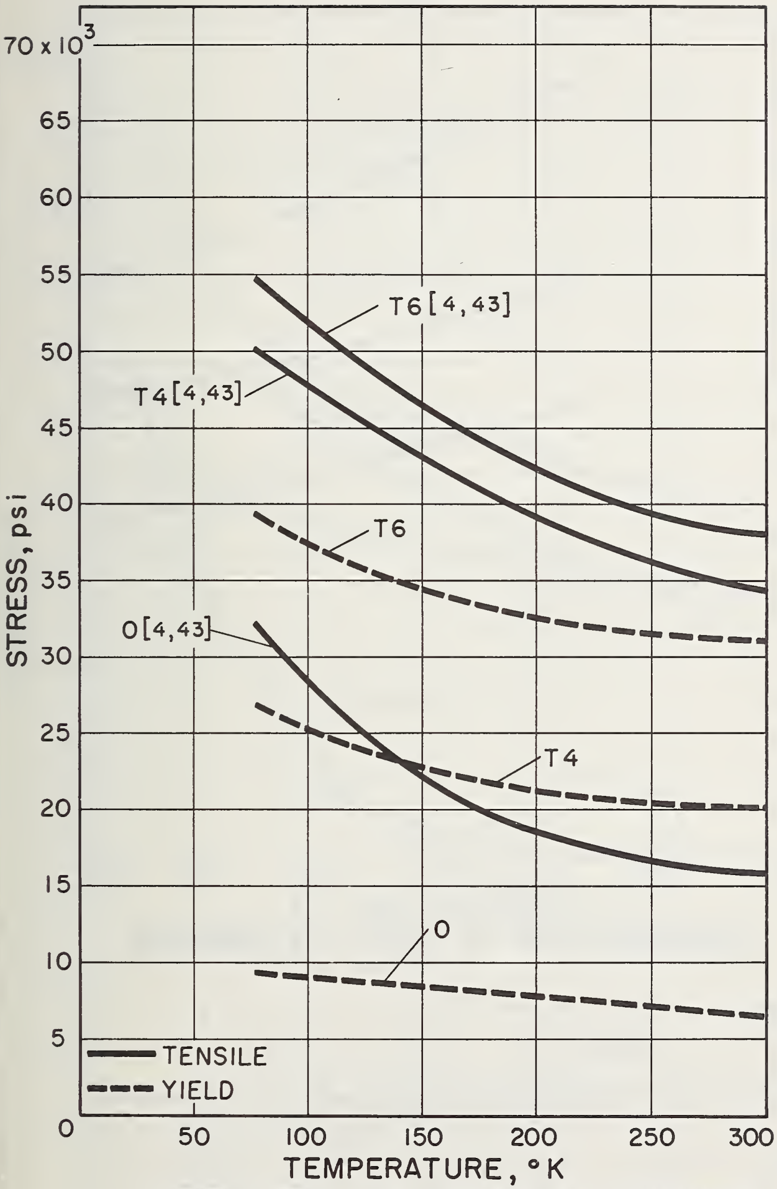


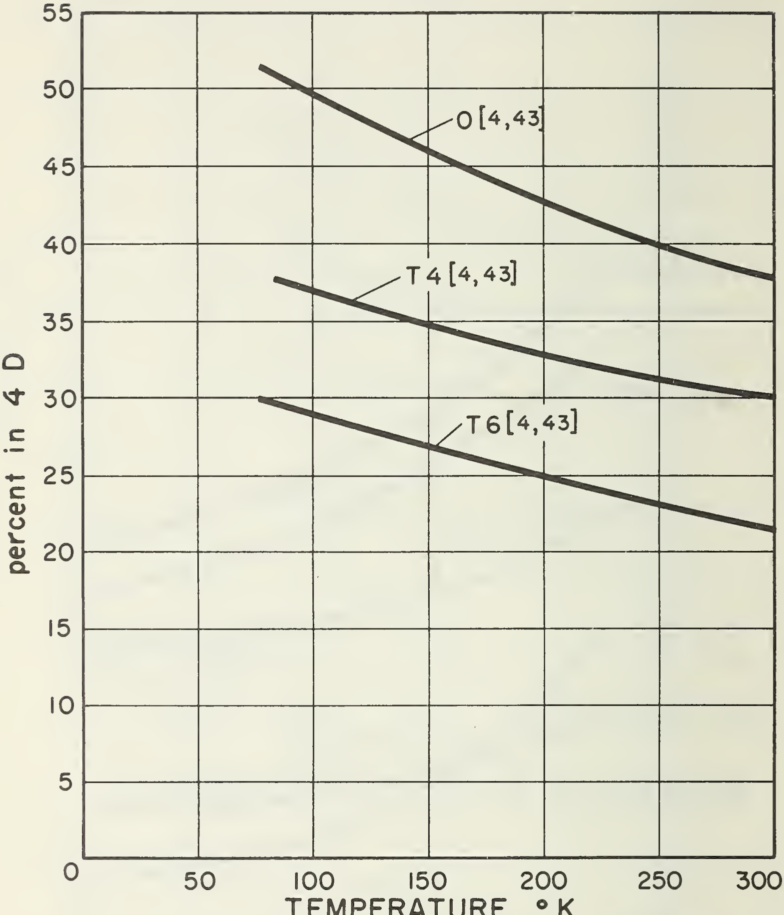
STRENGTH OF 5456 ALUMINUM



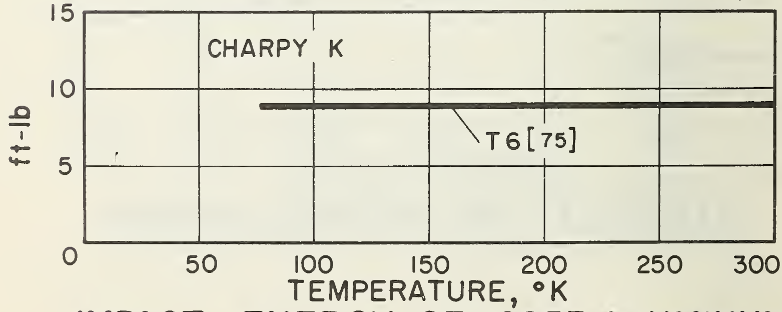
ELONGATION OF 5456 ALUMINUM



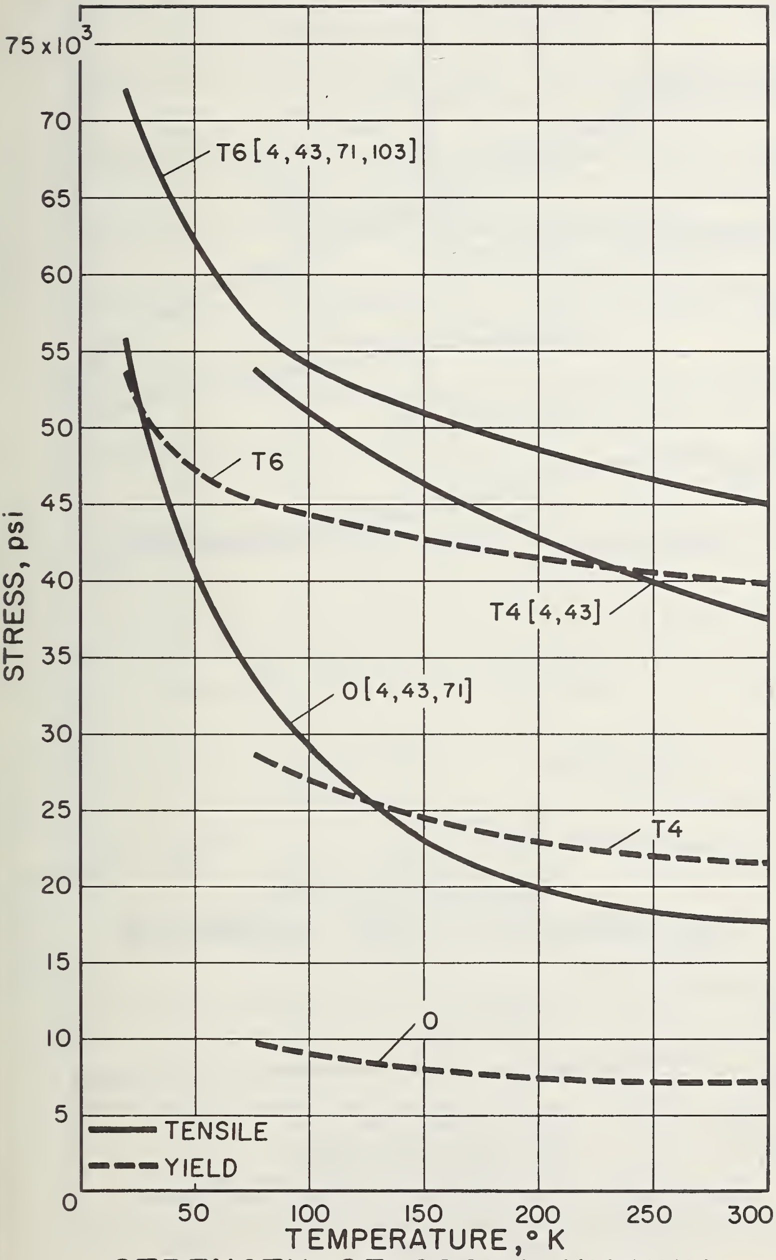
STRENGTH OF 6053 ALUMINUM



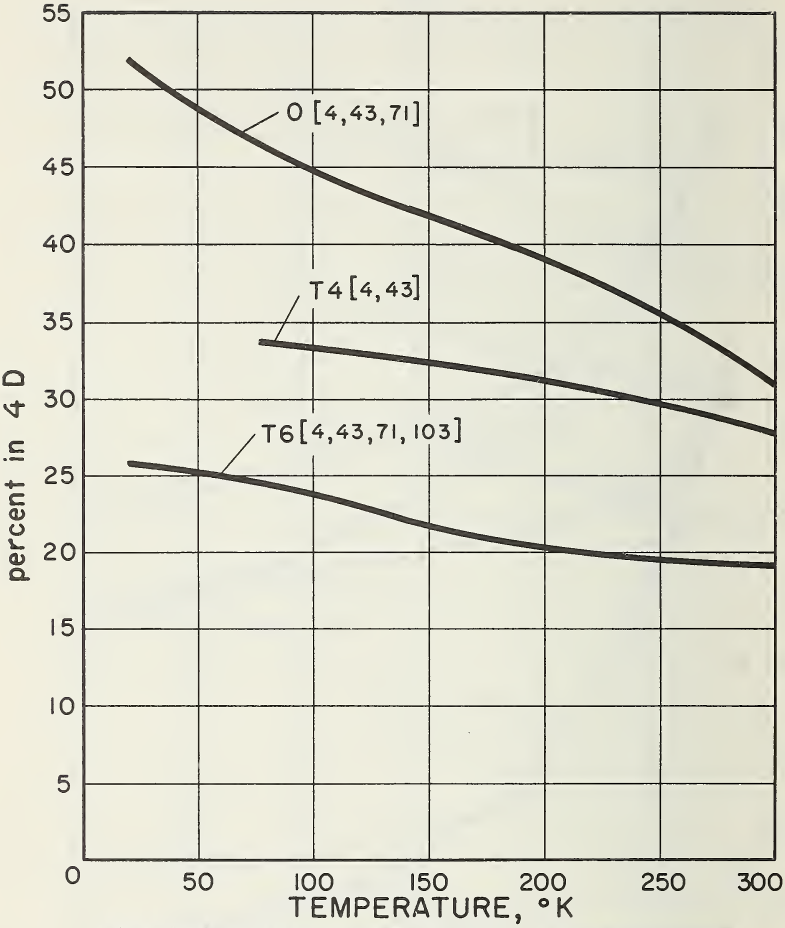
ELONGATION OF 6053 ALUMINUM



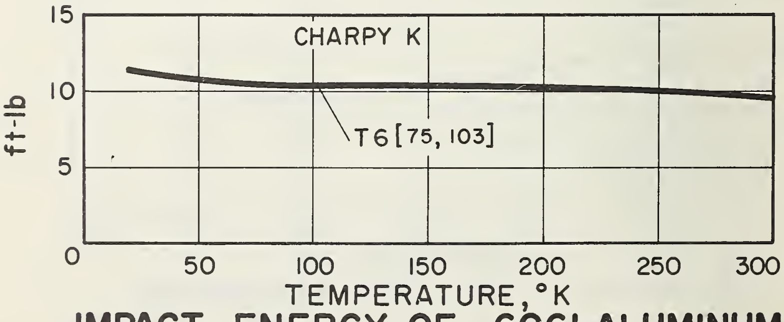
IMPACT ENERGY OF 6053 ALUMINUM



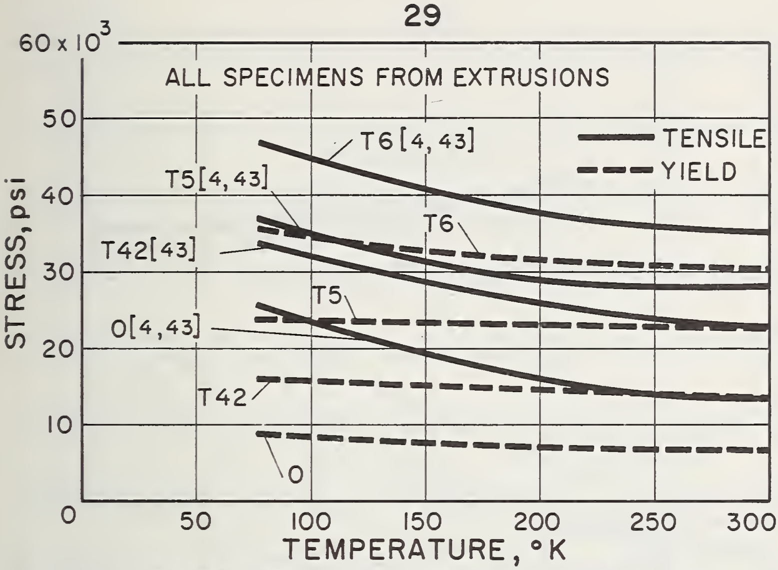
STRENGTH OF 6061 ALUMINUM



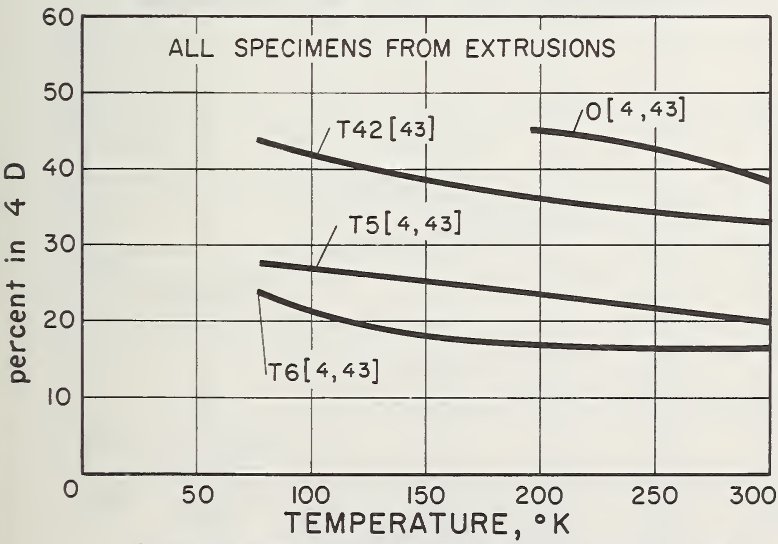
ELONGATION OF 6061 ALUMINUM



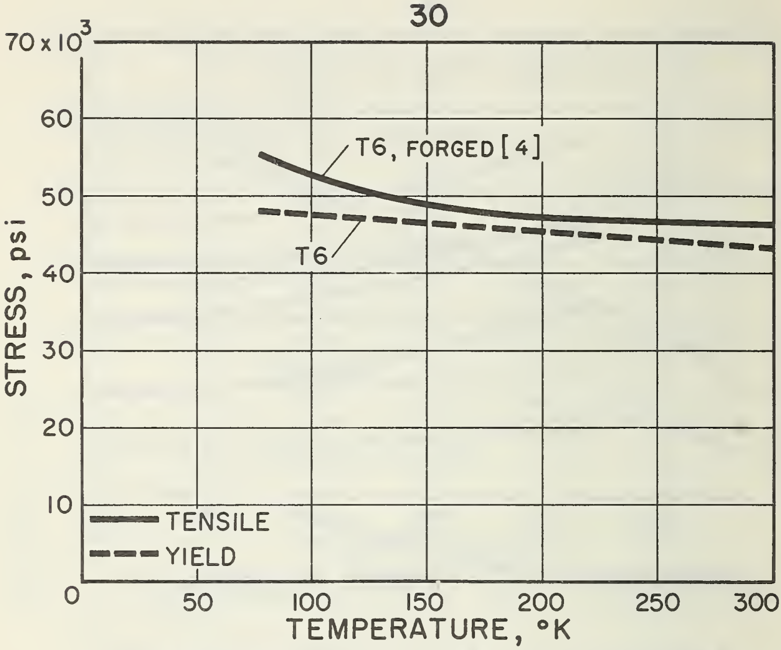
IMPACT ENERGY OF 6061 ALUMINUM



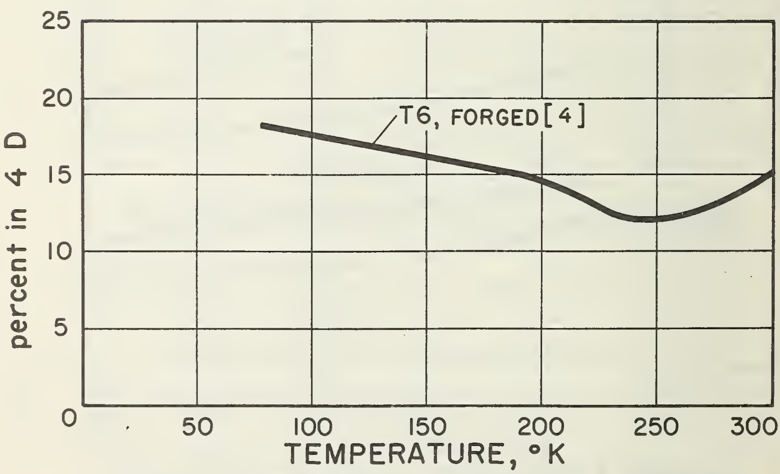
STRENGTH OF 6063 ALUMINUM



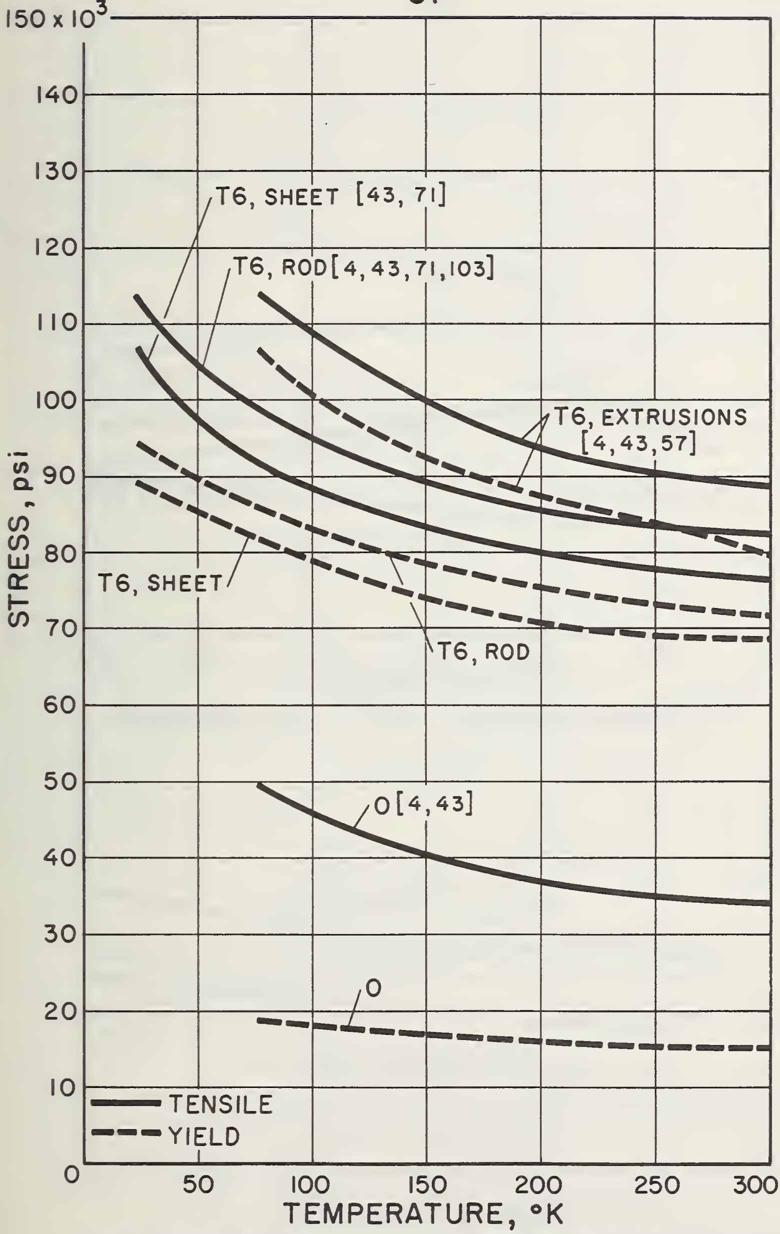
ELONGATION OF 6063 ALUMINUM



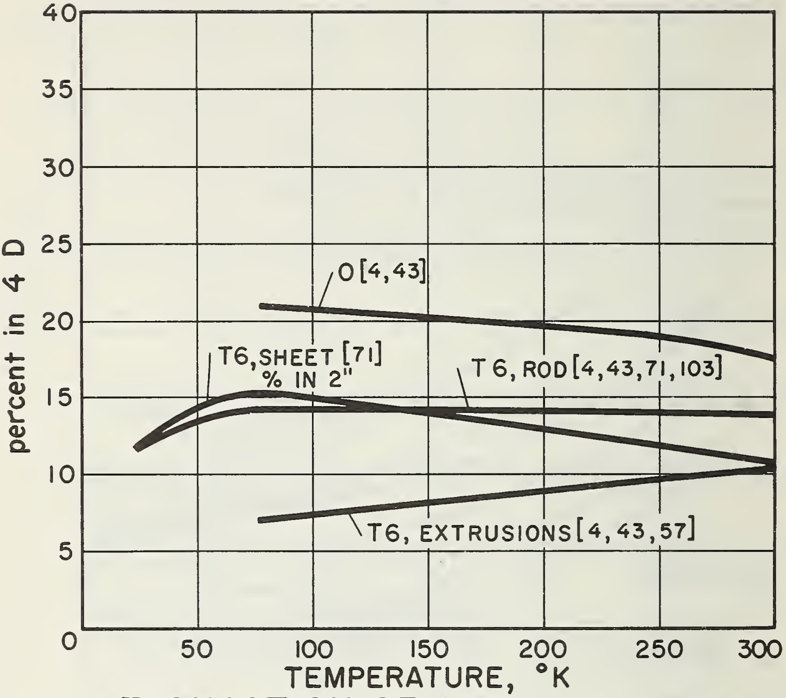
STRENGTH OF 6151 ALUMINUM



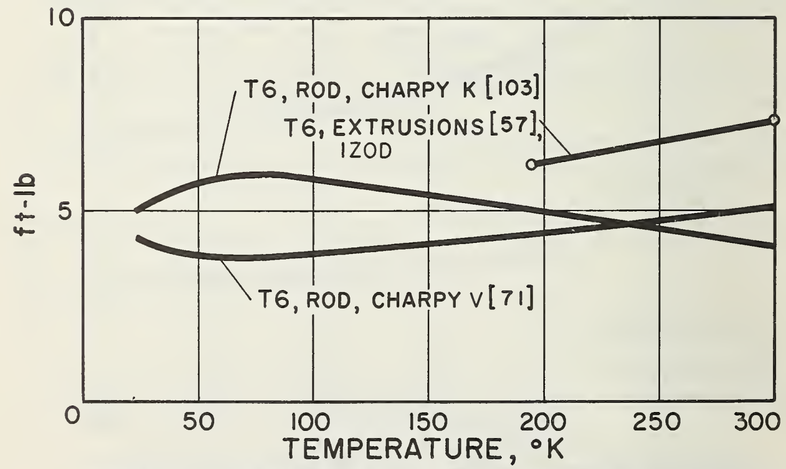
ELONGATION OF 6151 ALUMINUM



STRENGTH OF 7075 ALUMINUM



ELONGATION OF 7075 ALUMINUM



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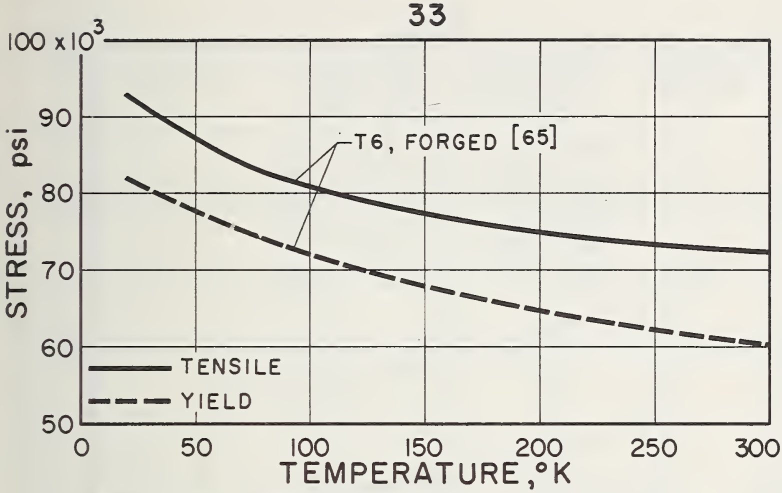
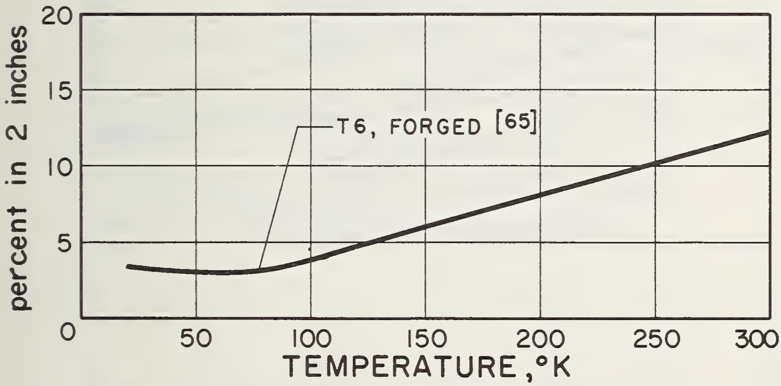
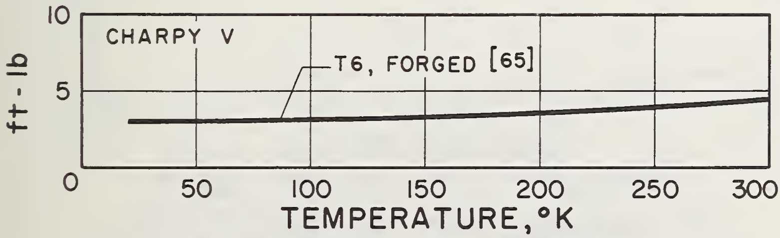


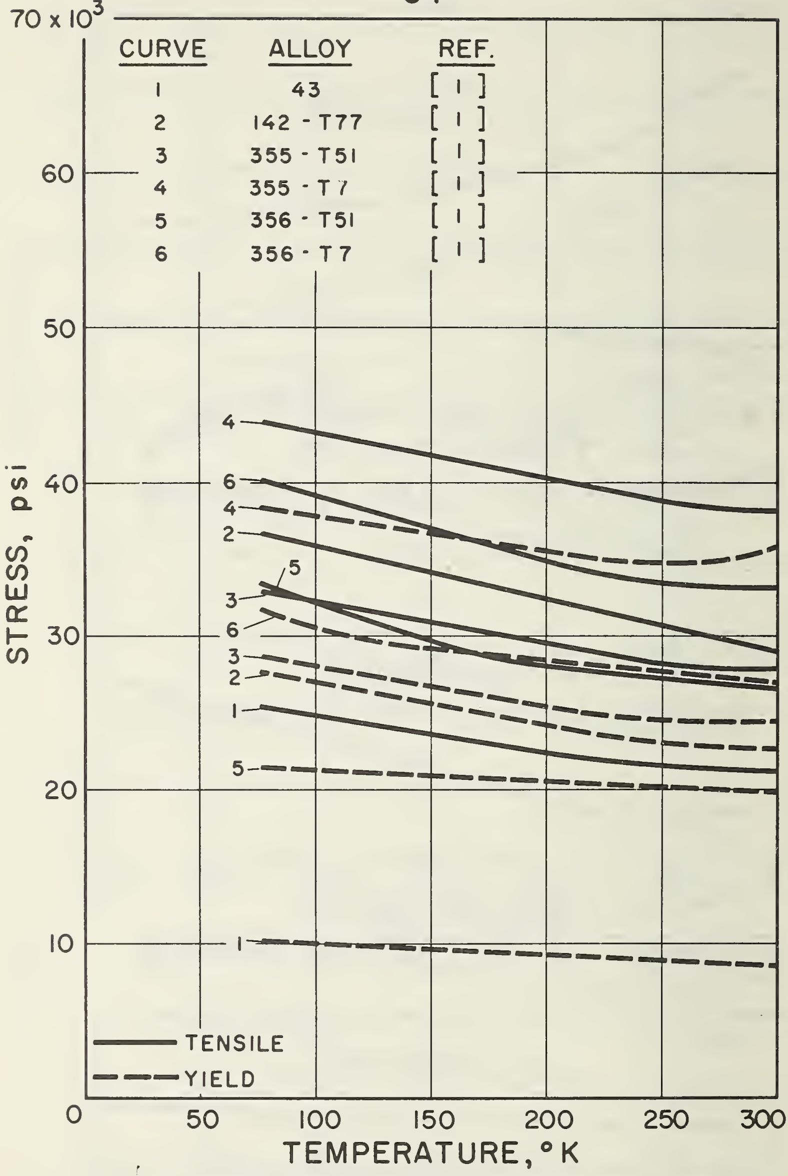
STRENGTH OF 7079 ALUMINUM



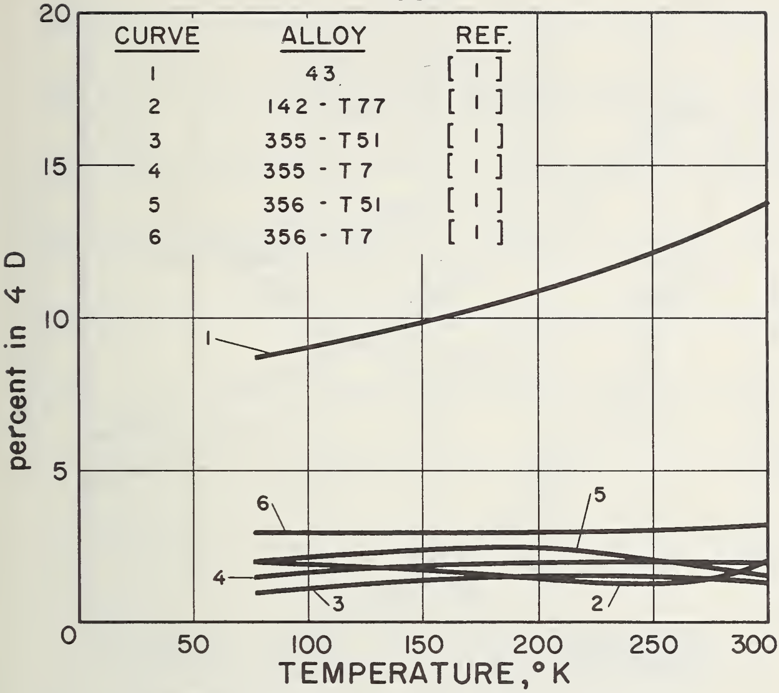
ELONGATION OF 7079 ALUMINUM



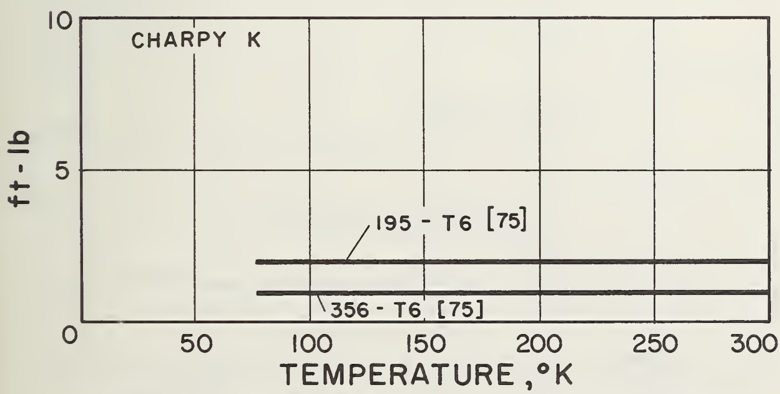
IMPACT ENERGY OF 7079 ALUMINUM



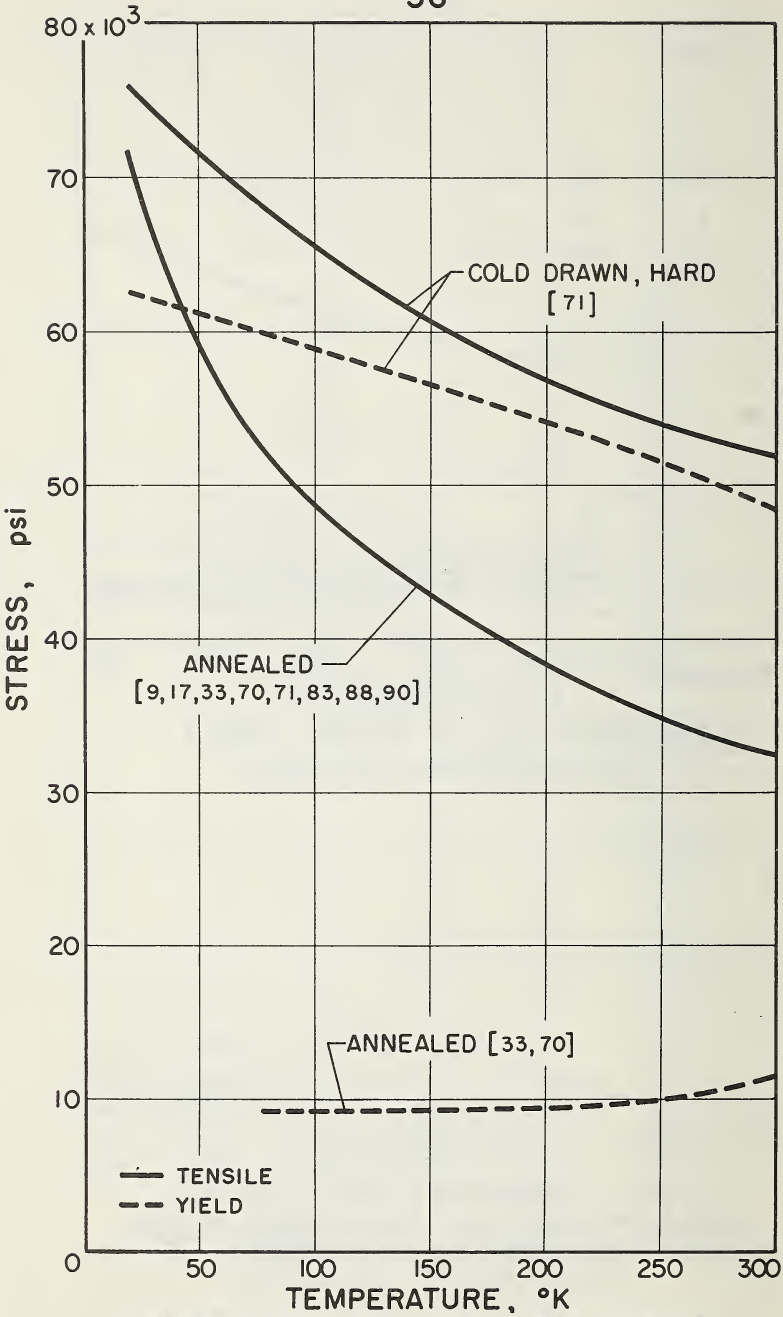
STRENGTH OF SAND CAST ALUMINUM ALLOYS



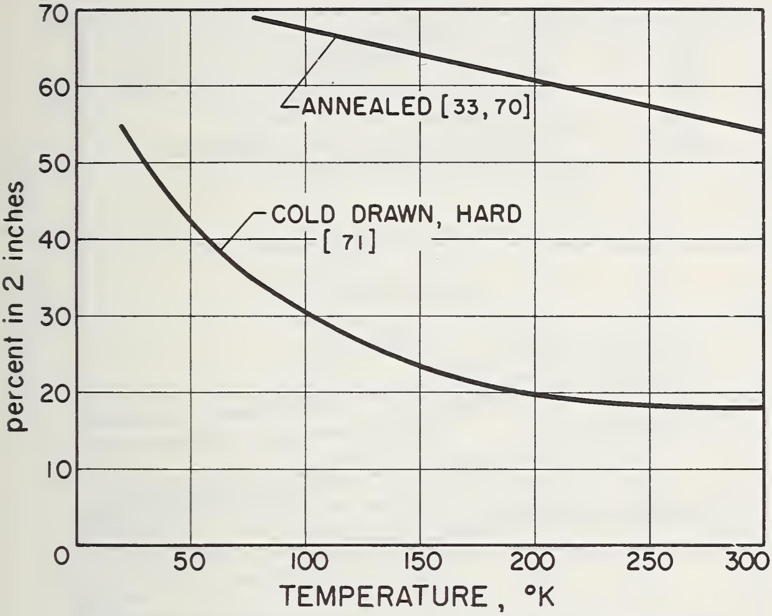
ELONGATION OF SAND CAST ALUMINUM ALLOYS



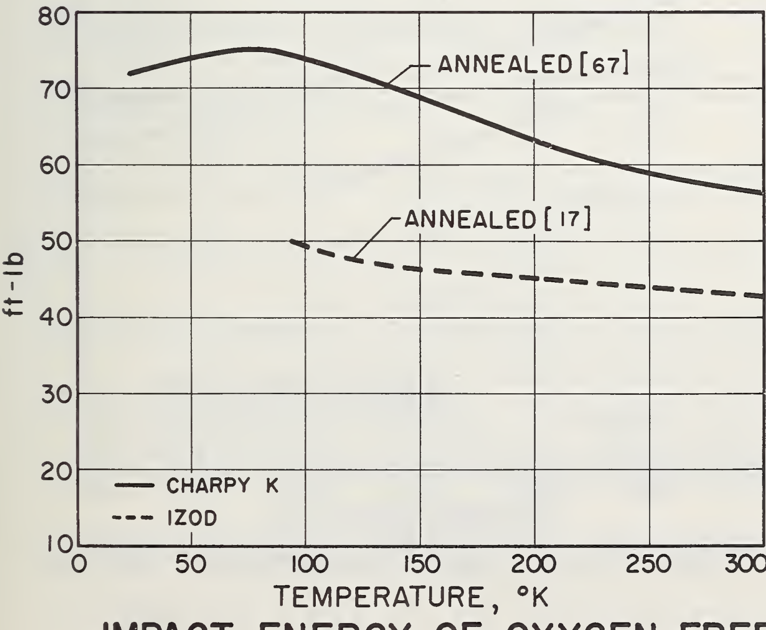
IMPACT ENERGY OF SAND CAST ALUMINUM ALLOYS



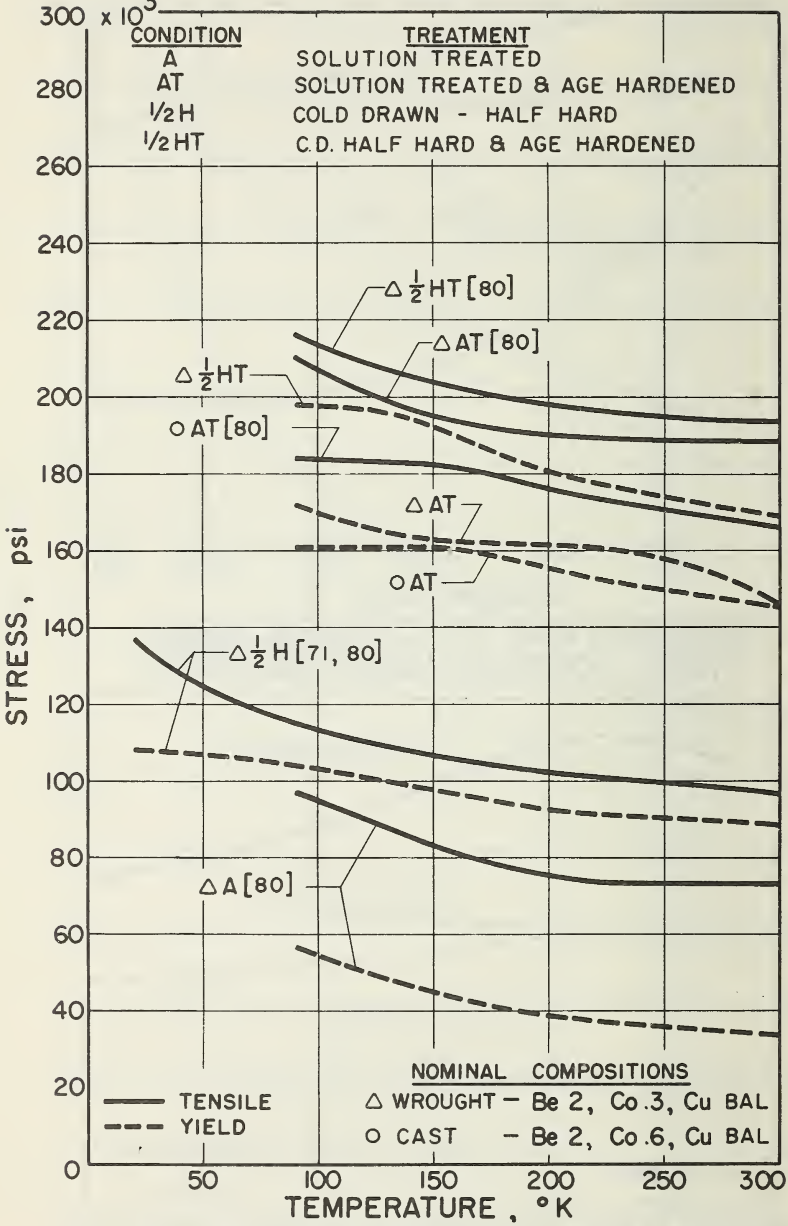
STRENGTH OF OXYGEN FREE HIGH CONDUCTIVITY COPPER



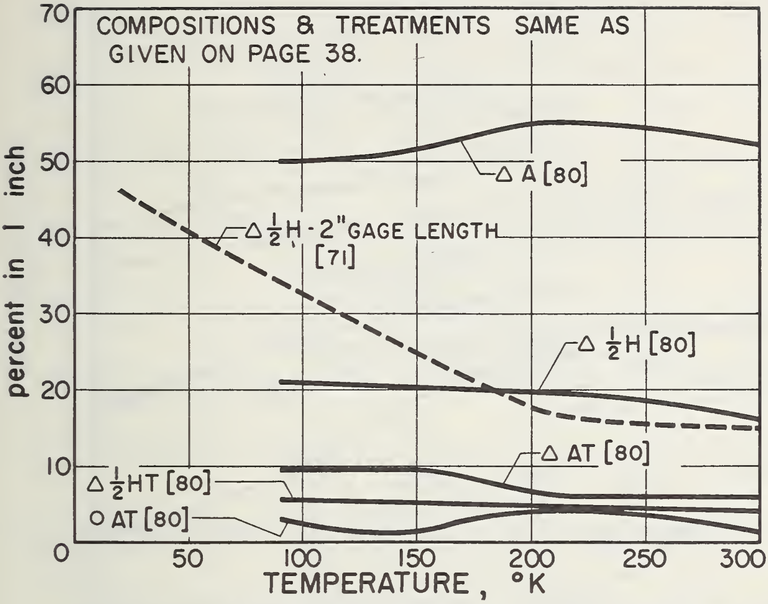
ELONGATION OF OXYGEN FREE HIGH CONDUCTIVITY COPPER



IMPACT ENERGY OF OXYGEN FREE HIGH CONDUCTIVITY COPPER



STRENGTH OF BERYLLIUM COPPER



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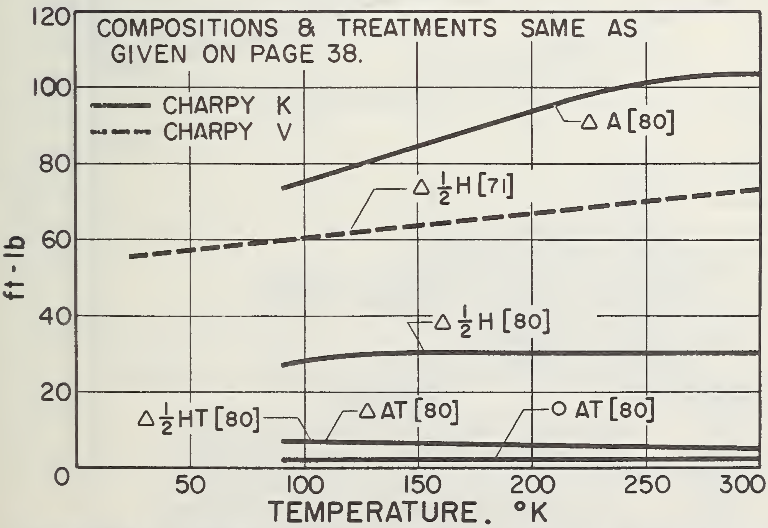

IMPACT ENERGY OF BERYLLIUM COPPER

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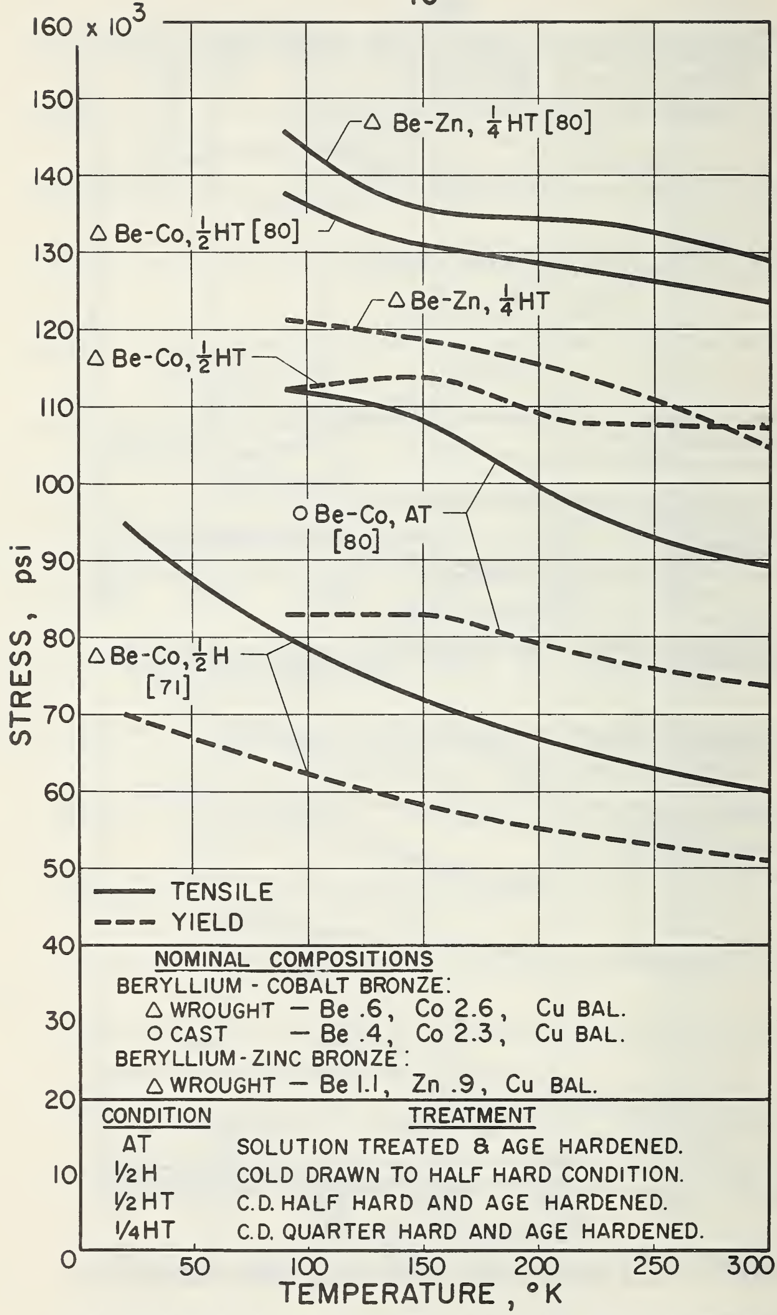
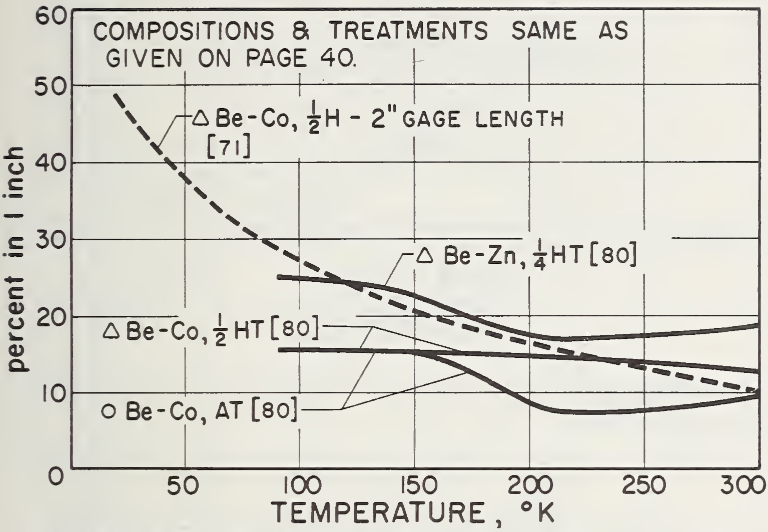
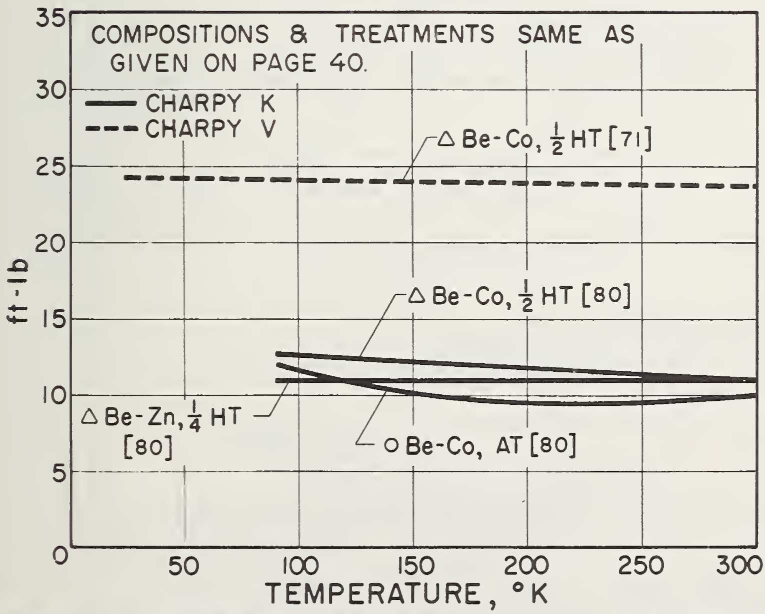


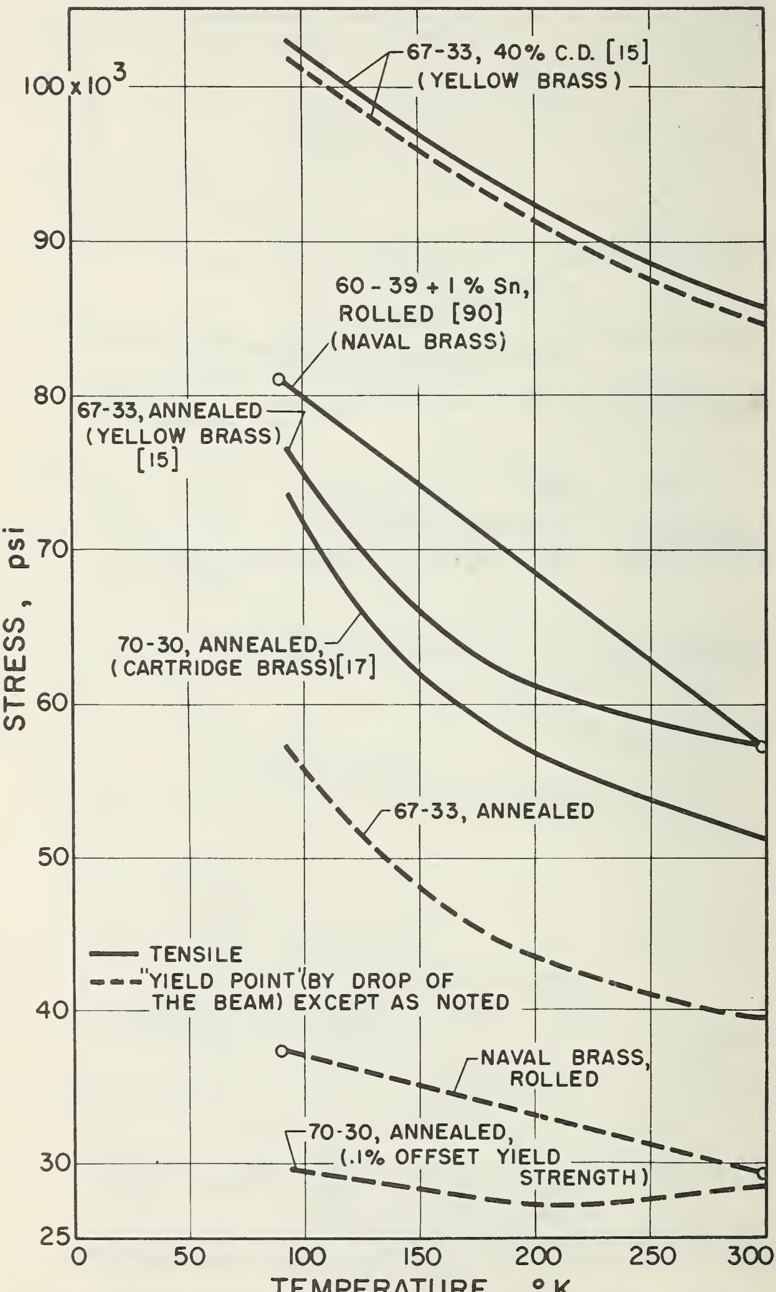
STRENGTH OF BERYLLIUM BRONZES



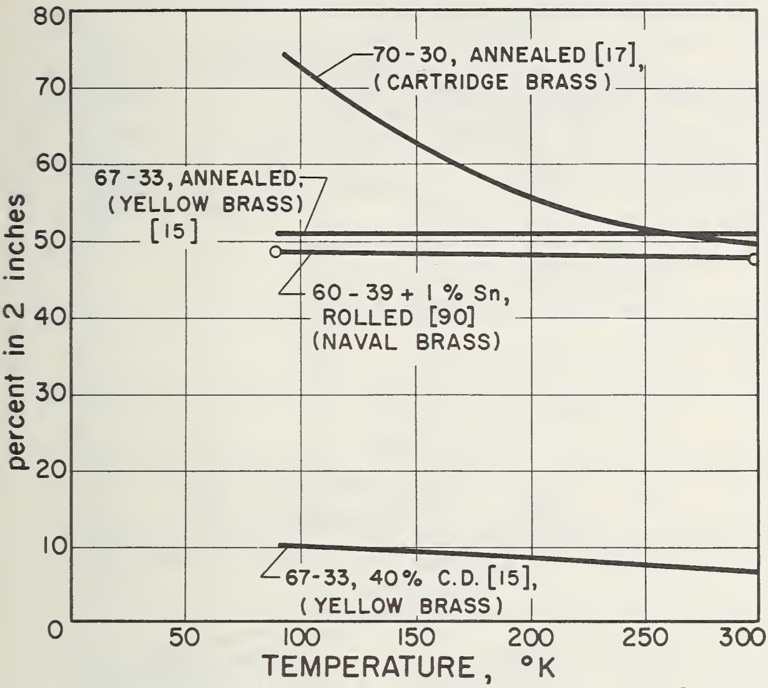
ELONGATION OF BERYLLIUM BRONZES



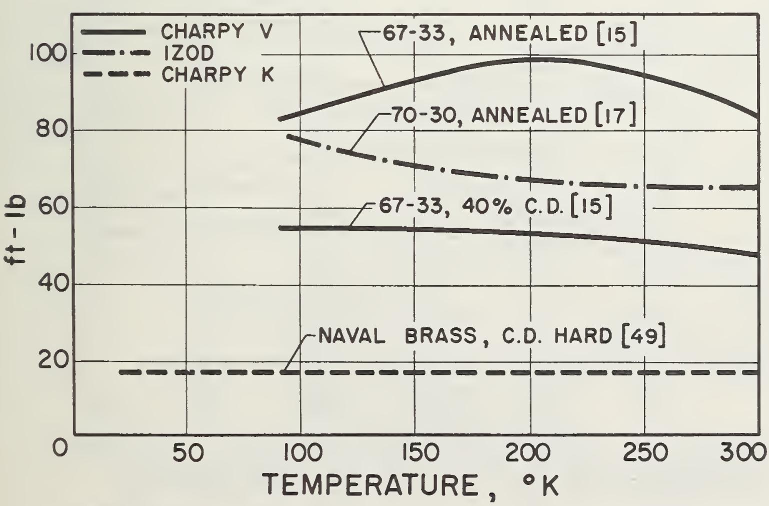
IMPACT ENERGY OF BERYLLIUM BRONZES



STRENGTH OF SOME ALPHA BRASSES

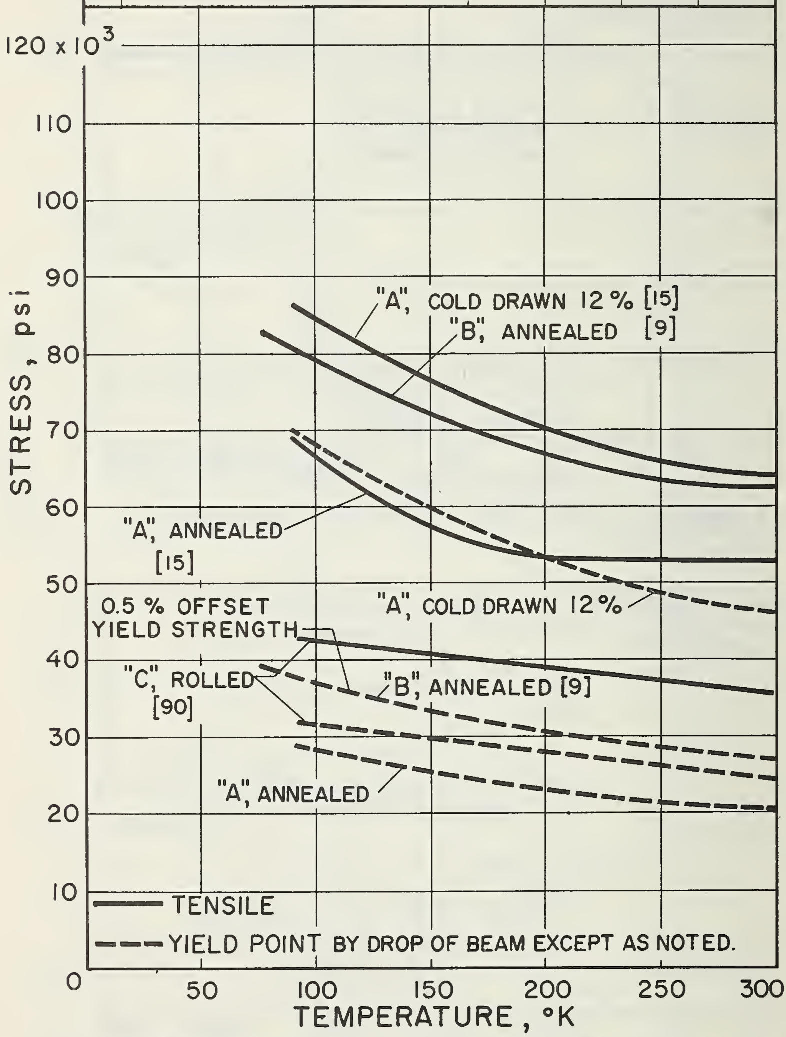


ELONGATION OF ALPHA BRASSES

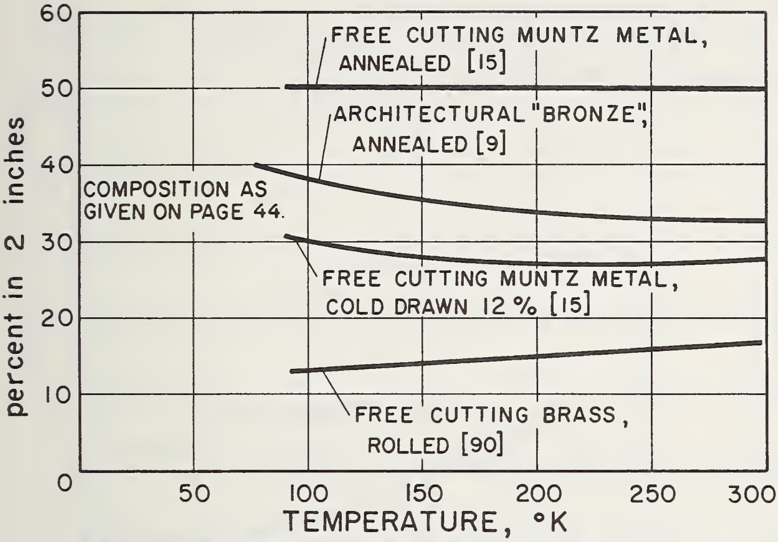


IMPACT ENERGY OF ALPHA BRASSES

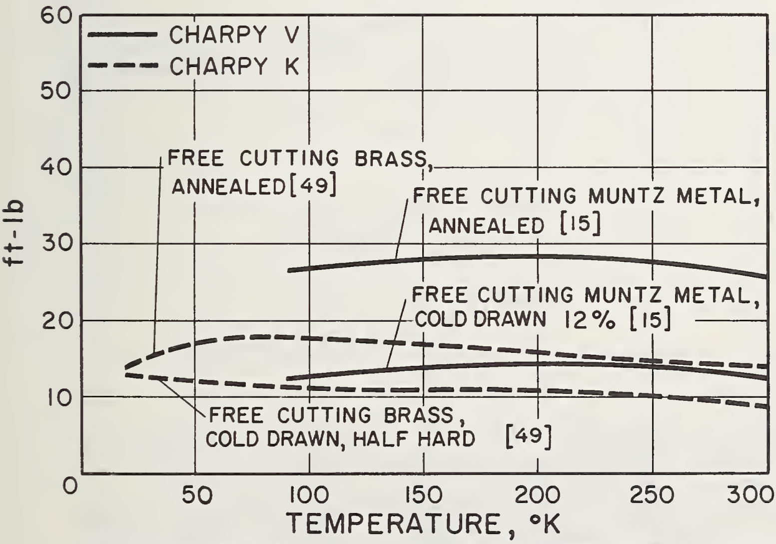
COMPOSITIONS					
ALLOY		% Cu	% Pb	% Sn	% Zn
A	FREE CUTTING MUNTZ METAL	58.7	1.3	—	BAL.
B	ARCHITECTURAL "BRONZE"	57.6	3.0	.55	BAL.
C	FREE CUTTING BRASS	61	3	—	36



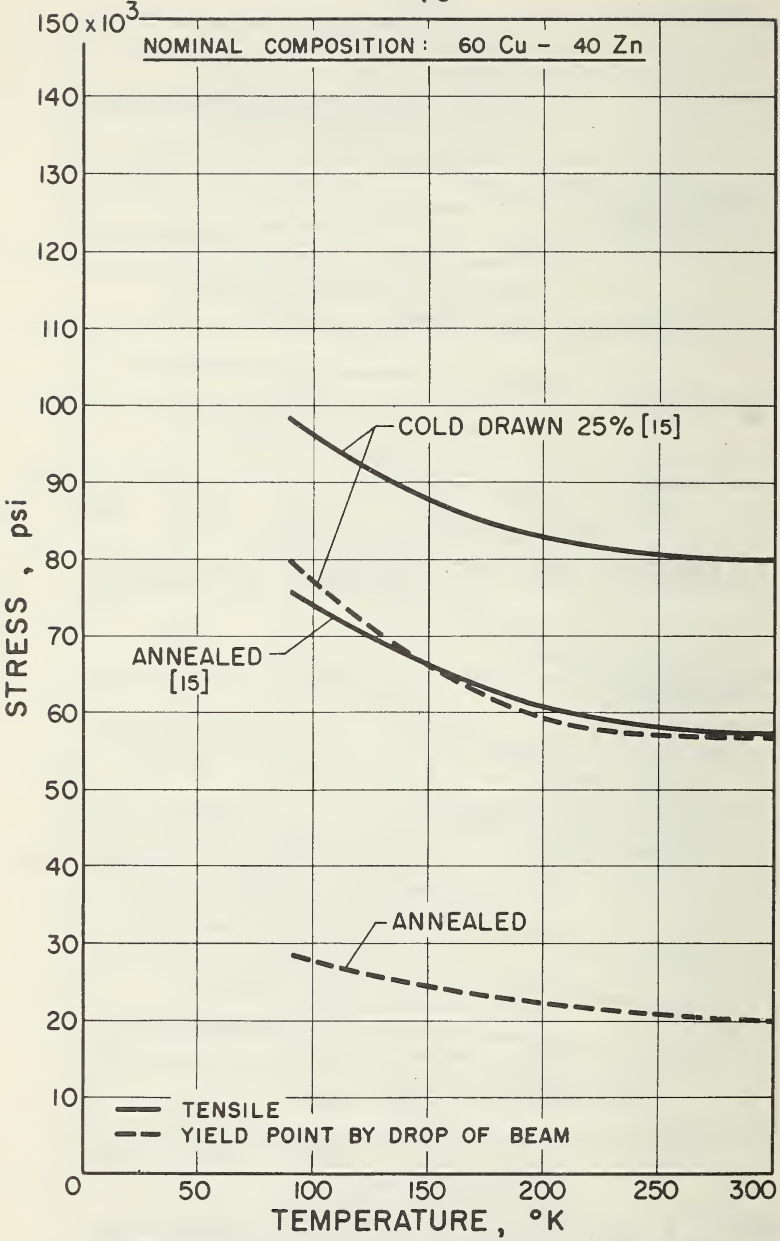
STRENGTH OF LEADED BRASSES



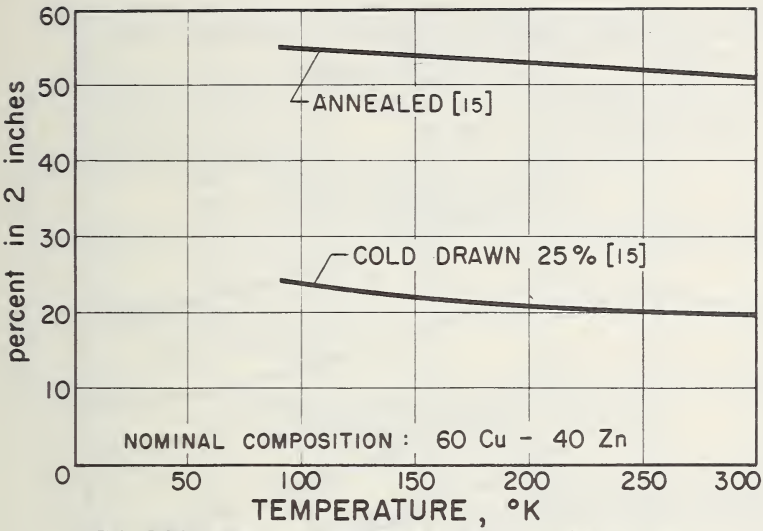
ELONGATION OF LEADED BRASSES



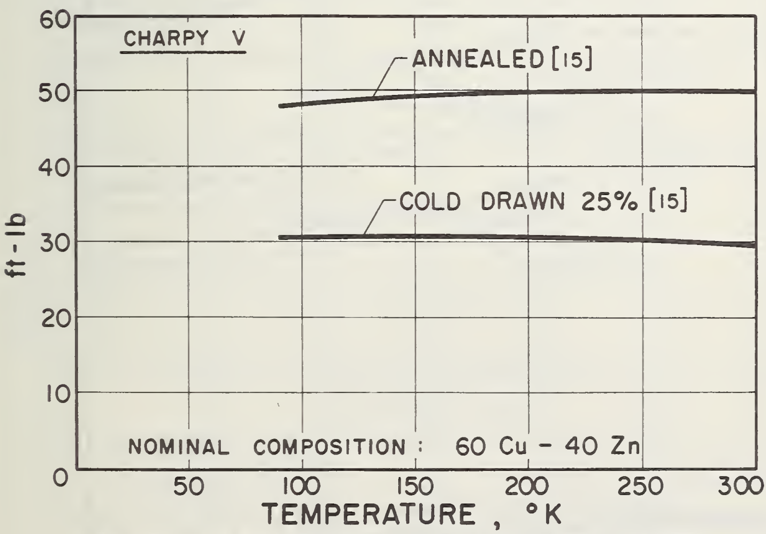
IMPACT ENERGY OF LEADED BRASSES



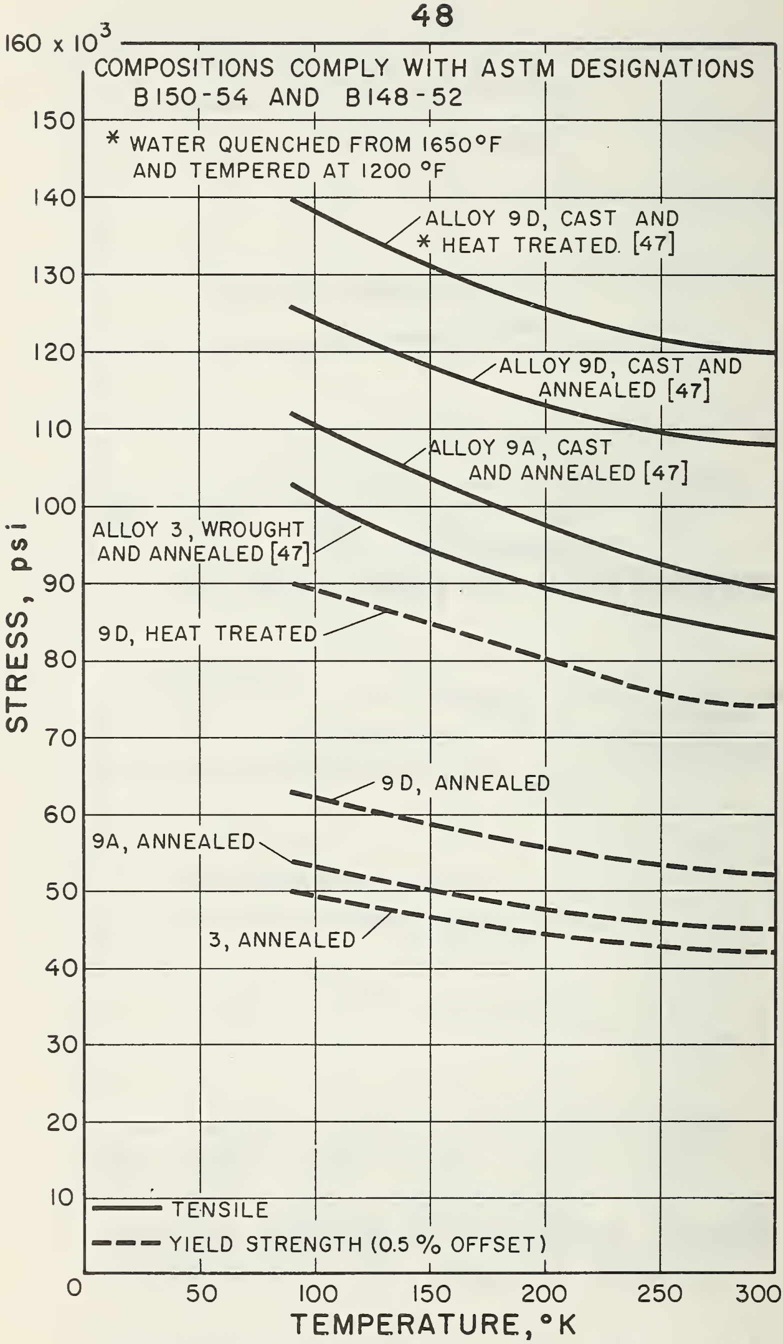
STRENGTH OF MUNTZ METAL



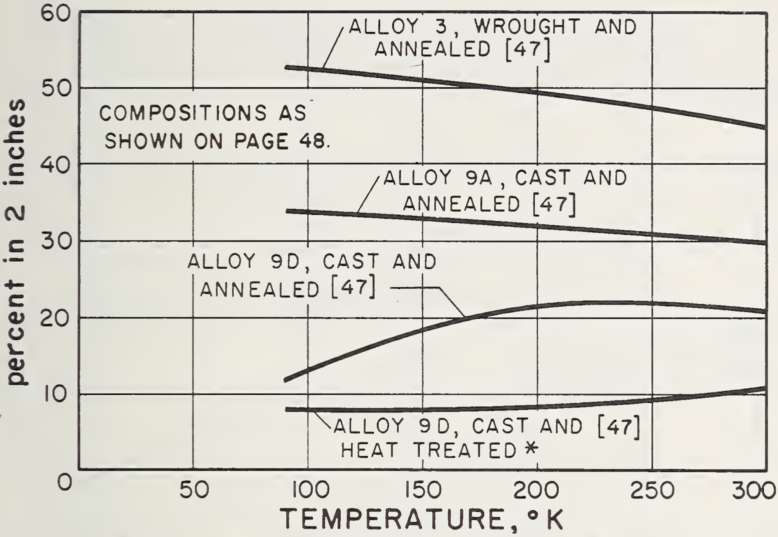
ELONGATION OF MUNTZ METAL



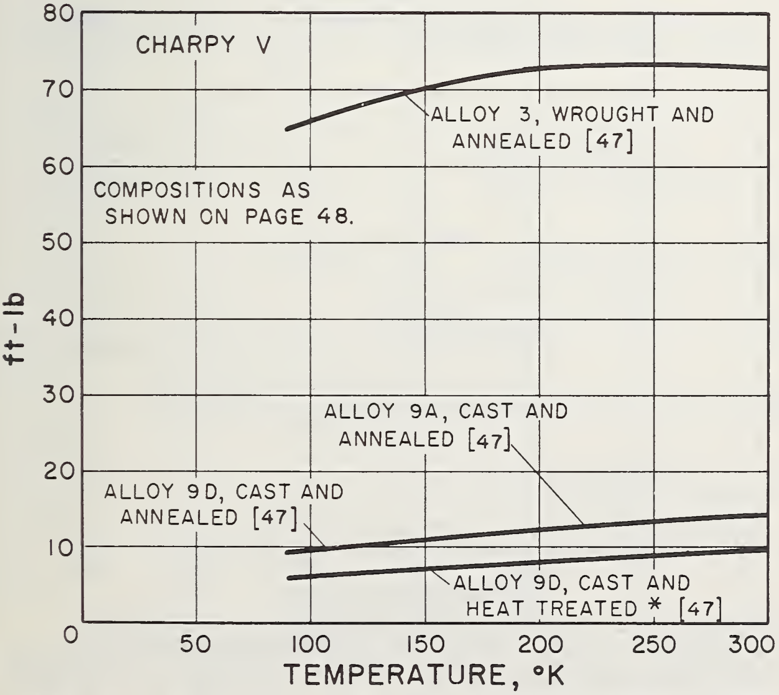
IMPACT ENERGY OF MUNTZ METAL



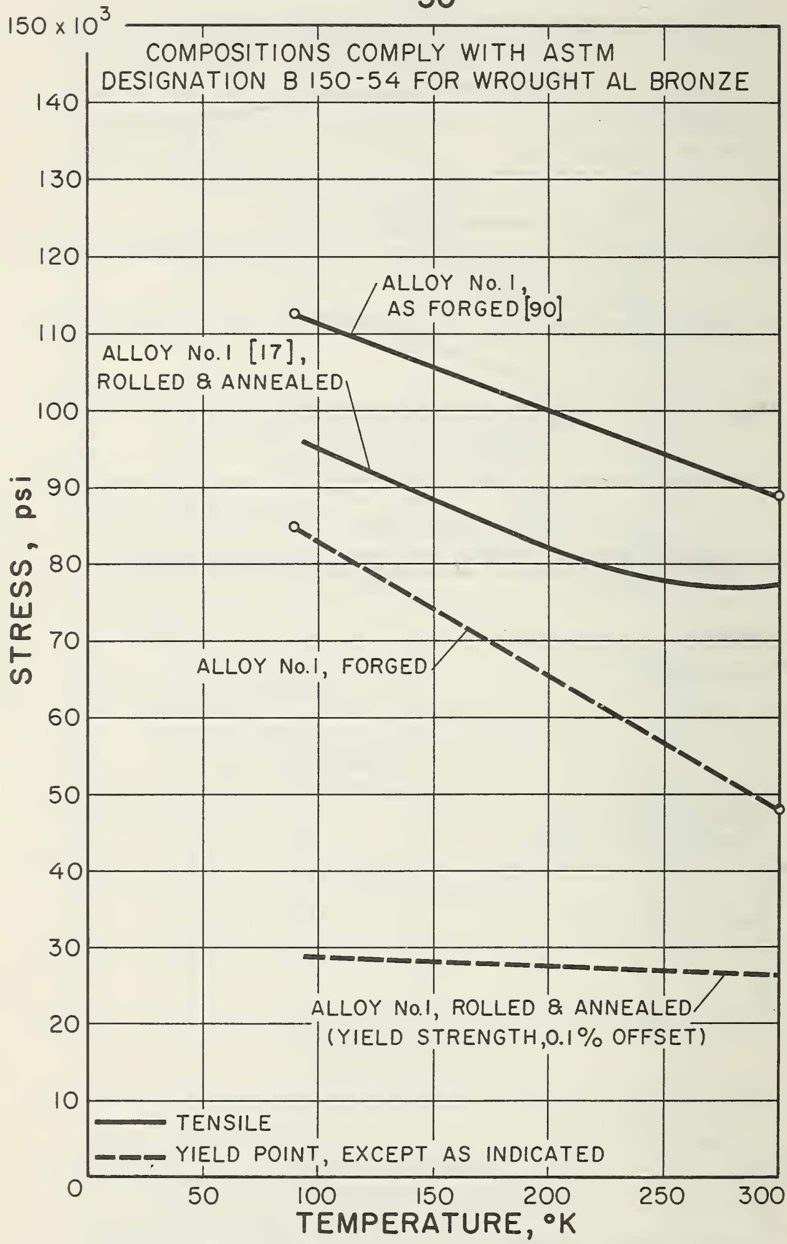
STRENGTH OF ALUMINUM BRONZES



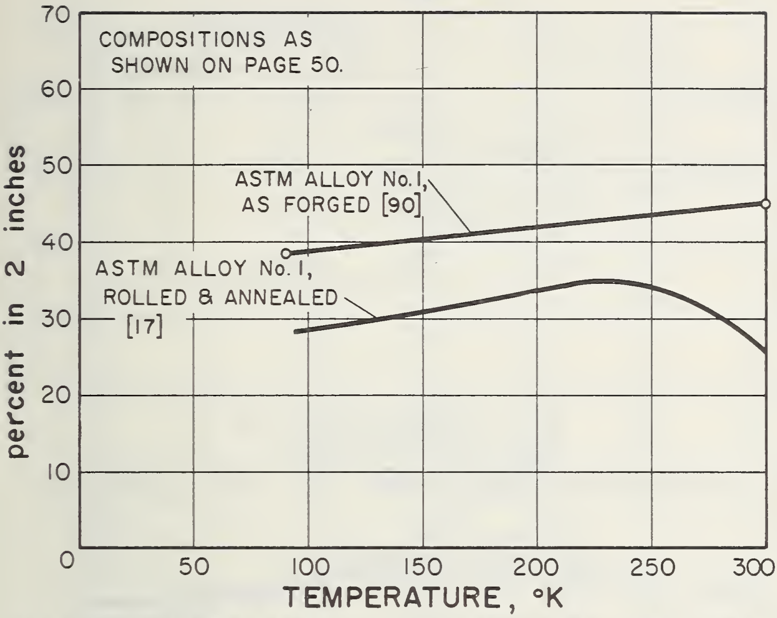
ELONGATION OF ALUMINUM BRONZES



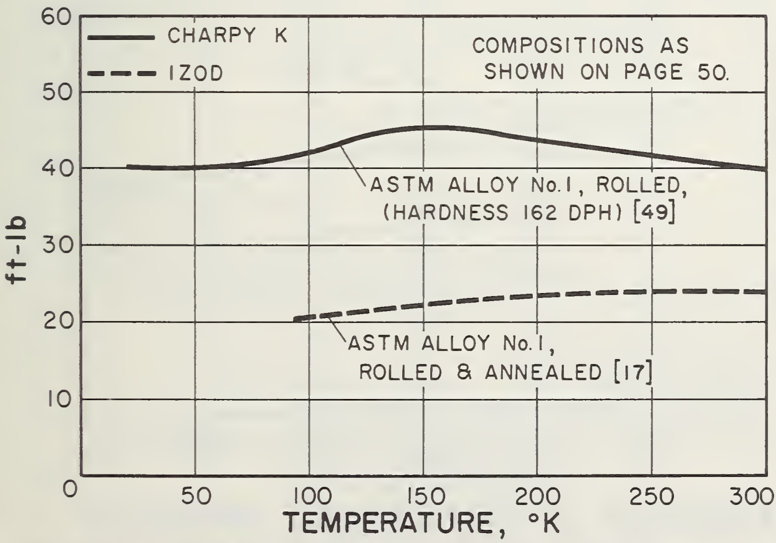
IMPACT ENERGY OF ALUMINUM BRONZES



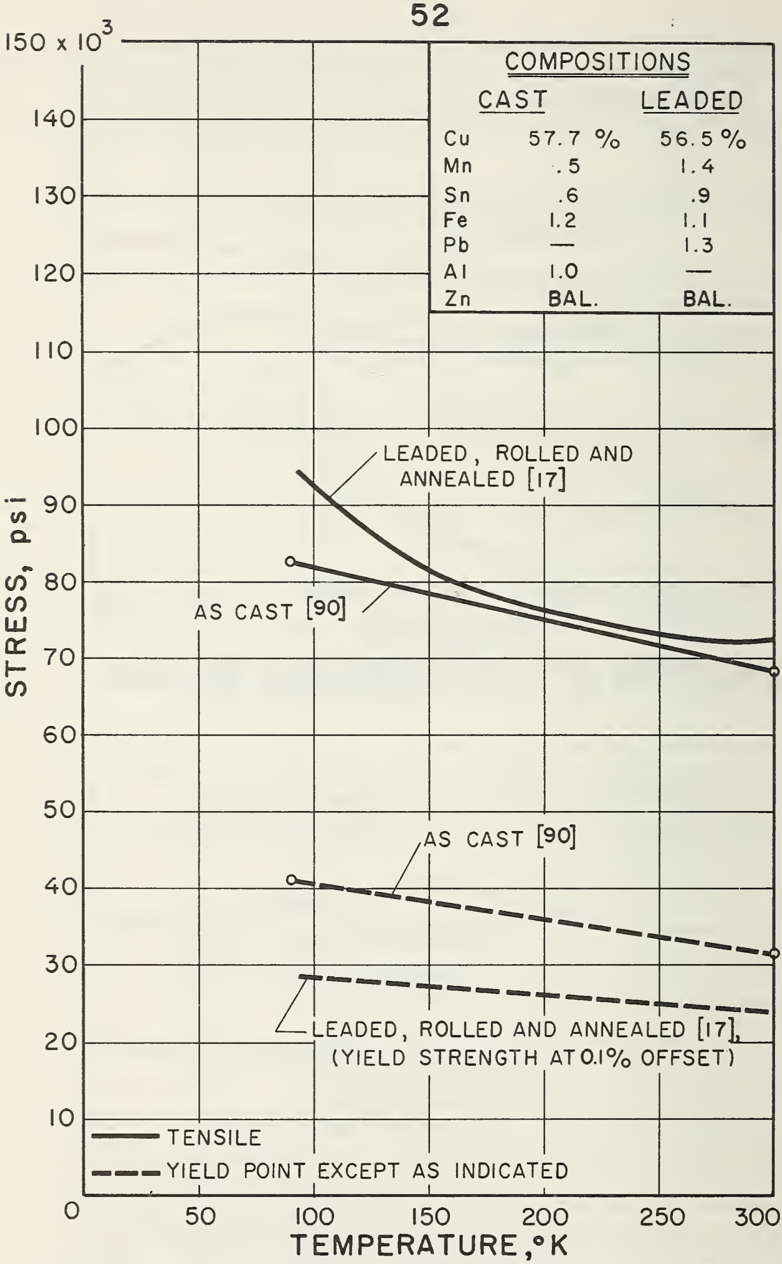
STRENGTH OF 8 % ALUMINUM BRONZE



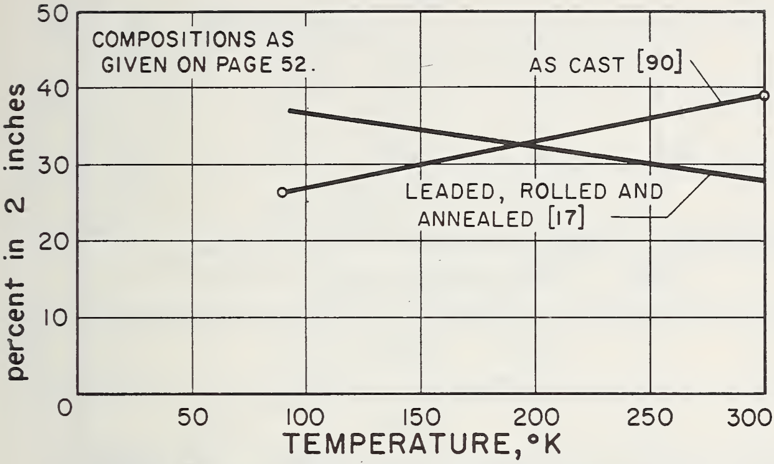
ELONGATION OF 8% ALUMINUM BRONZE



IMPACT ENERGY OF 8% ALUMINUM BRONZE



STRENGTH OF MANGANESE BRONZES

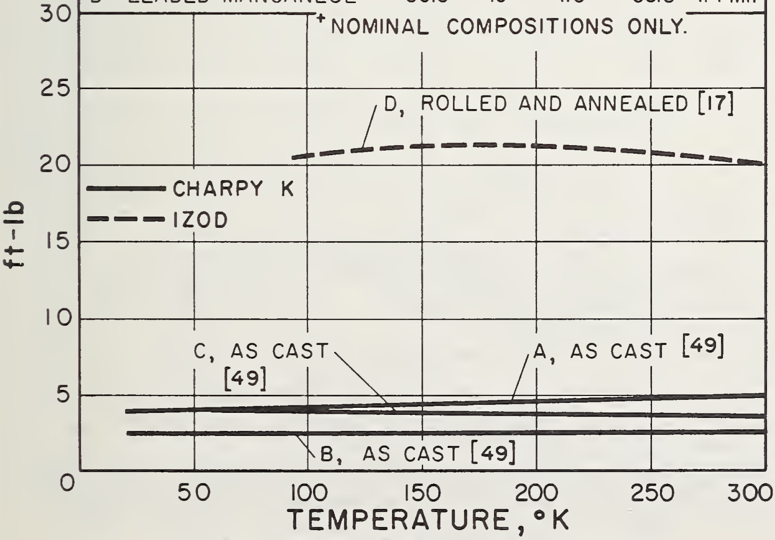


ELONGATION OF MANGANESE BRONZES

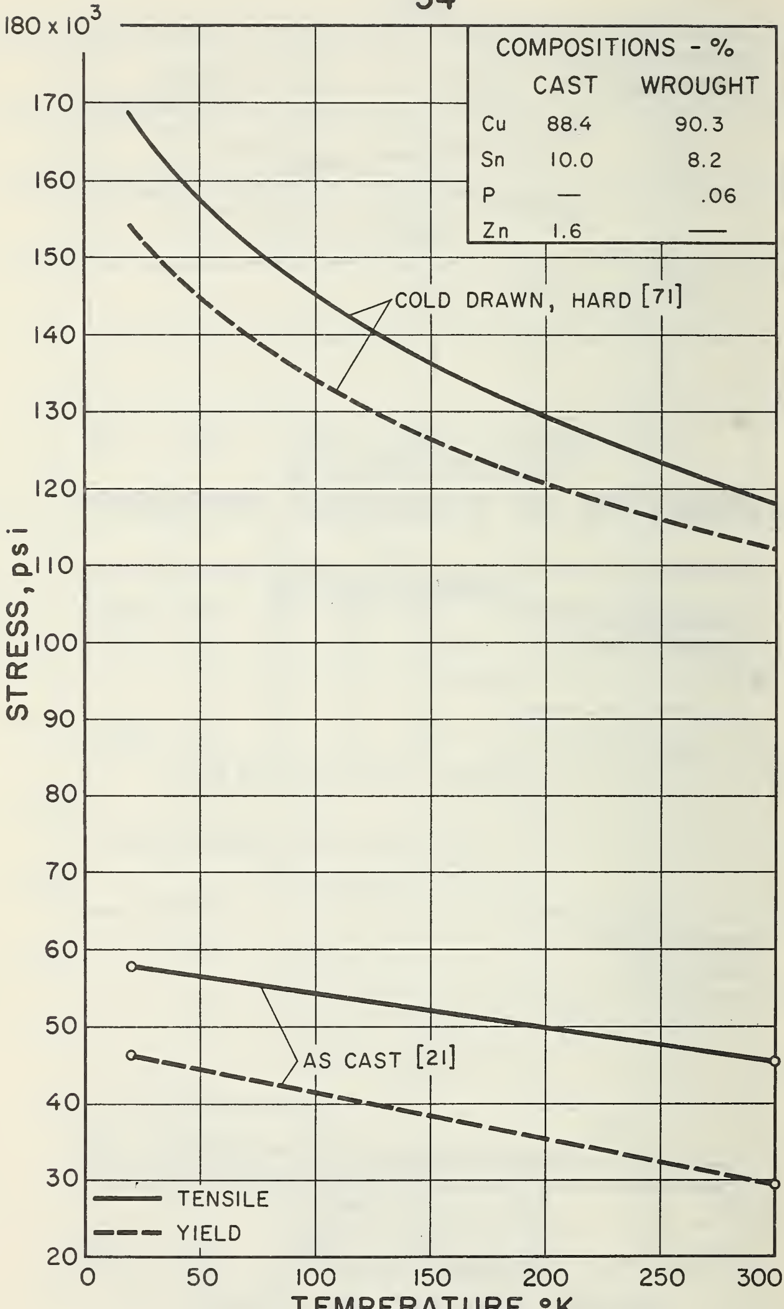
	COMMON NAME	Cu	Sn	Pb	Zn	Other
A	+-OUNCE METAL	85	5	5	5	—
B	+-SEMI-PLASTIC BRONZE	70	5	25	—	—
C	+-BEARING & BUSHING "	80	10	10	—	—
D	-LEADED MANGANESE "	56.5	.9	1.3	38.8	1.4 Mn

COMPOSITIONS - %

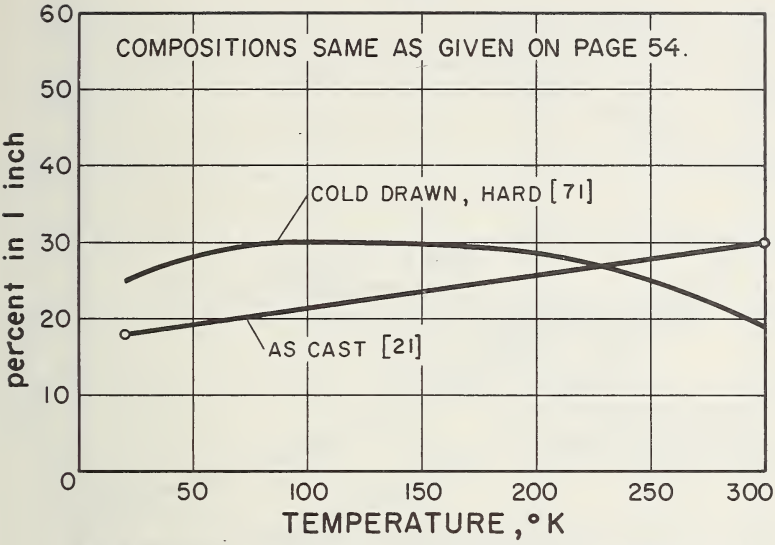
+NOMINAL COMPOSITIONS ONLY.



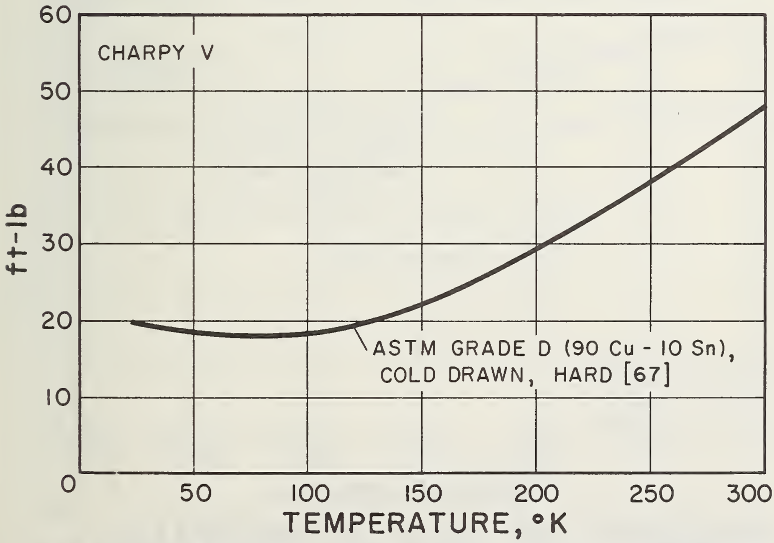
IMPACT ENERGY OF SOME MISCELLANEOUS BRONZES



STRENGTH OF PHOSPHOR BRONZE



ELONGATION OF PHOSPHOR BRONZE



IMPACT ENERGY OF PHOSPHOR BRONZE

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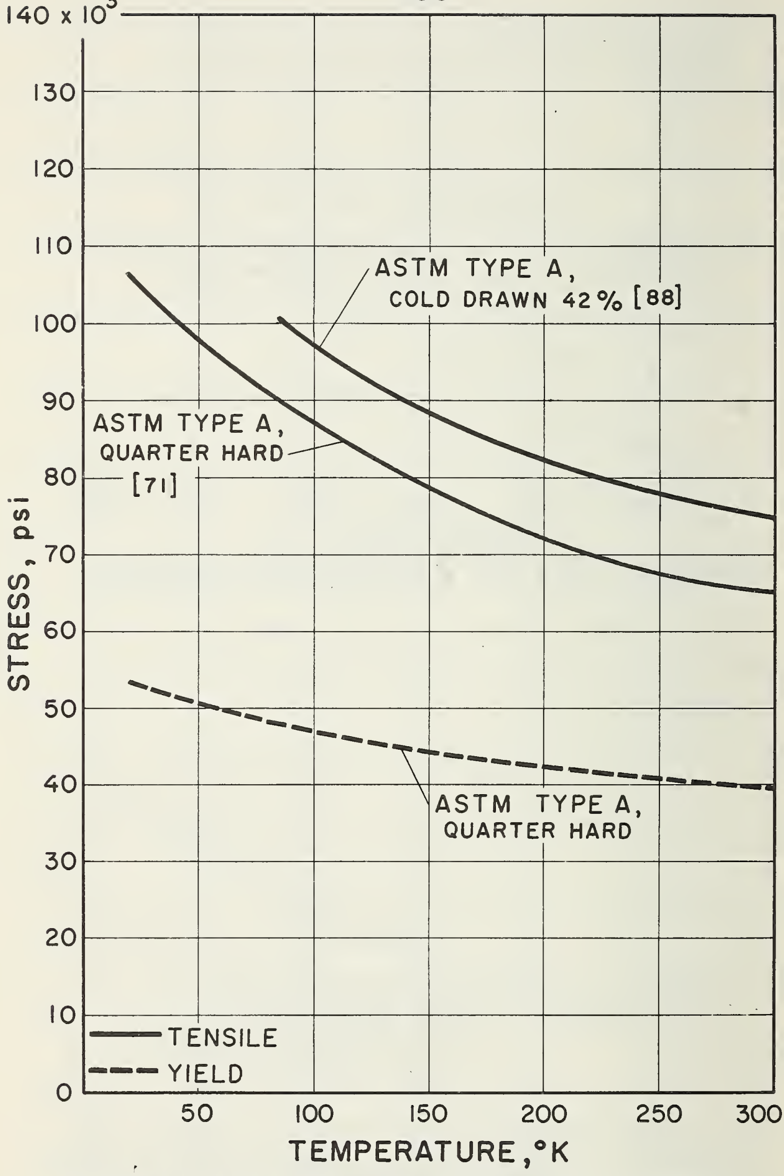
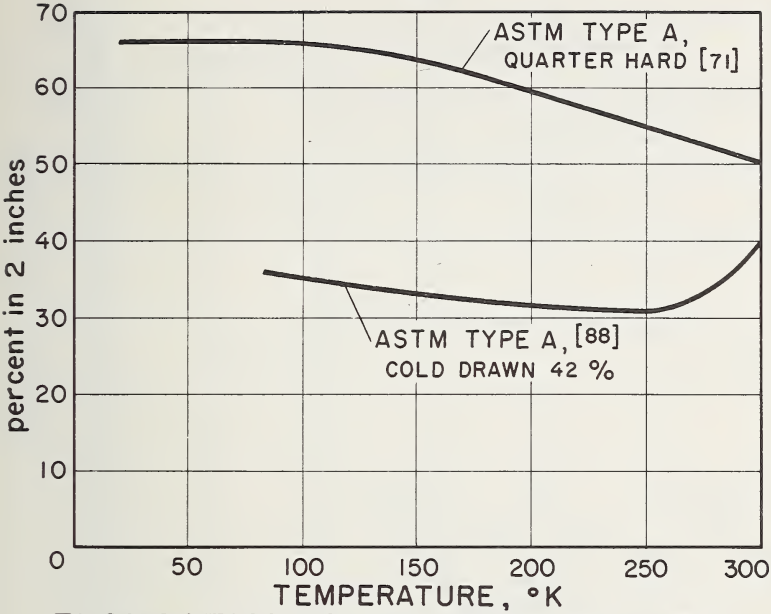
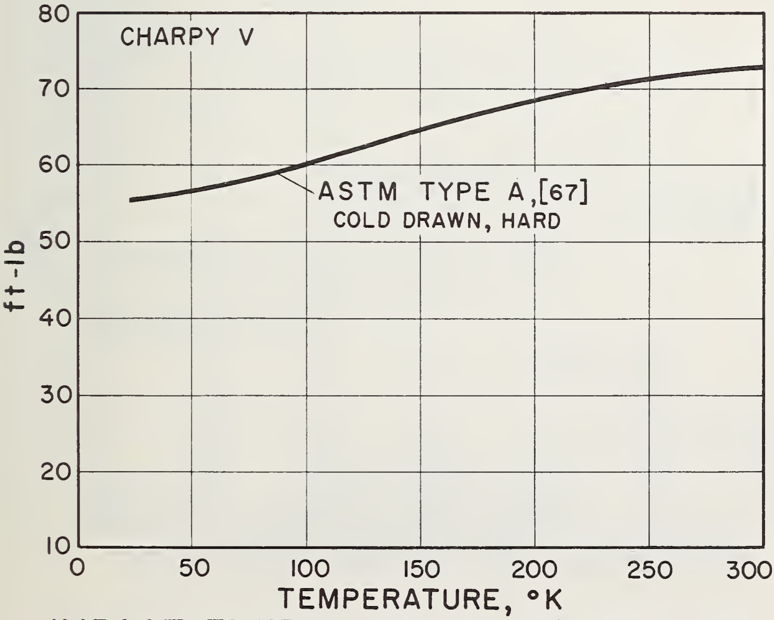


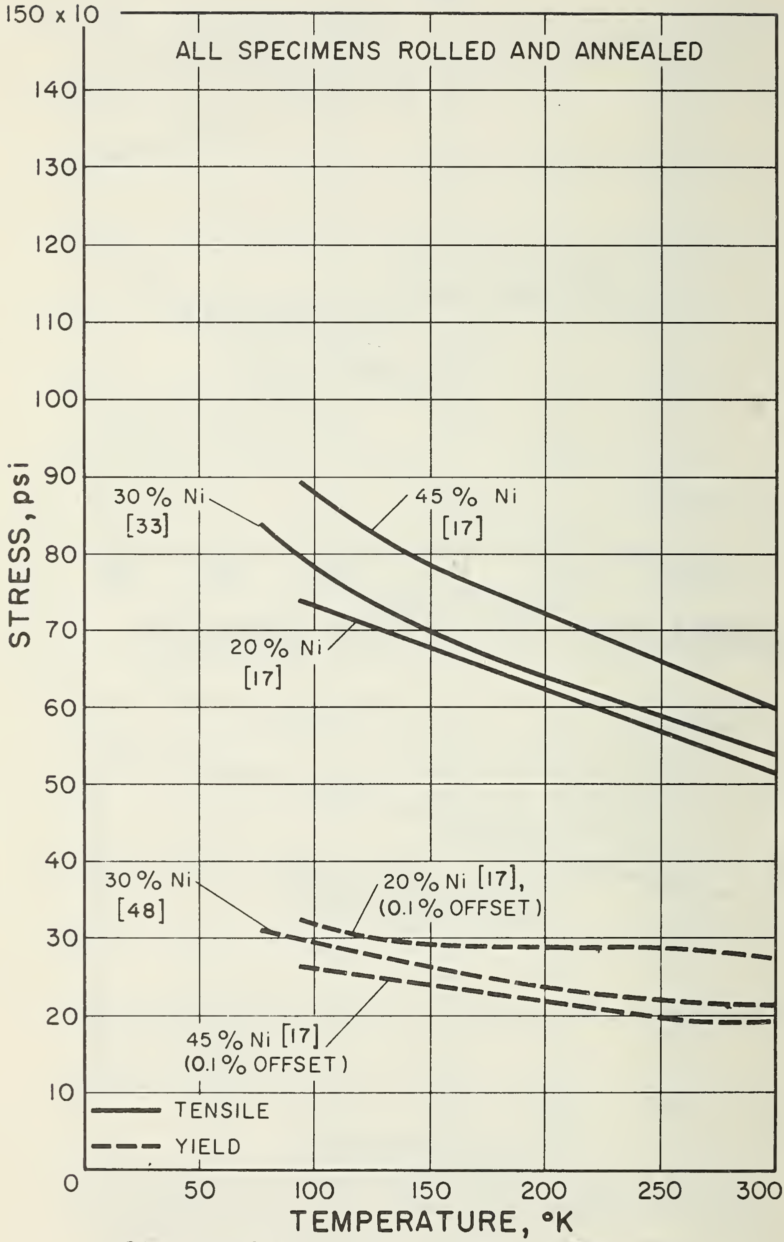
STRENGTH OF SILICON BRONZES



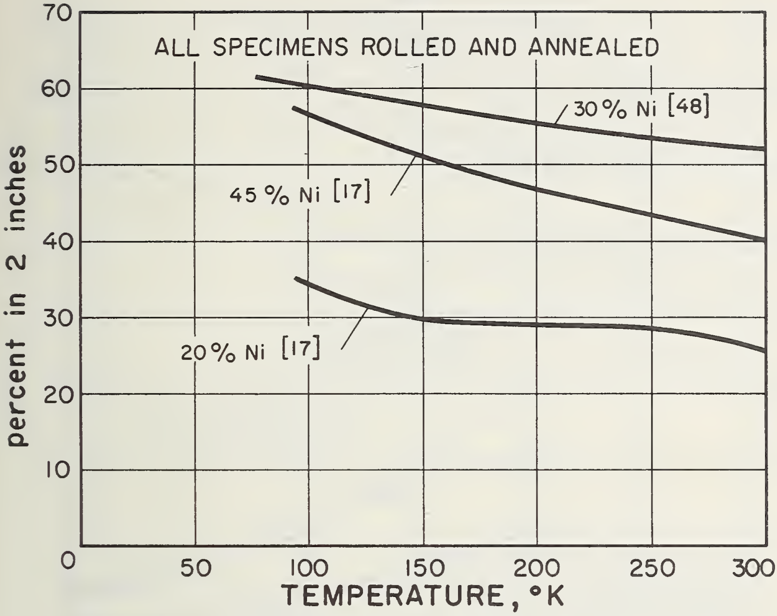
ELONGATION OF SILICON BRONZES



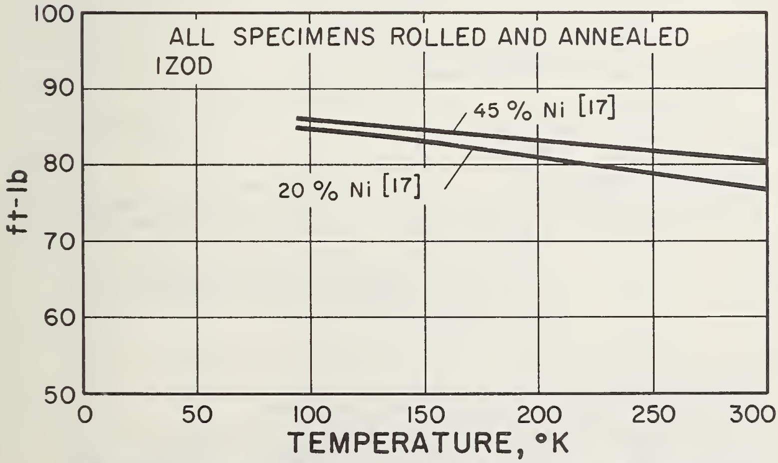
IMPACT ENERGY OF SILICON BRONZES



STRENGTH OF CUPRO-NICKELS

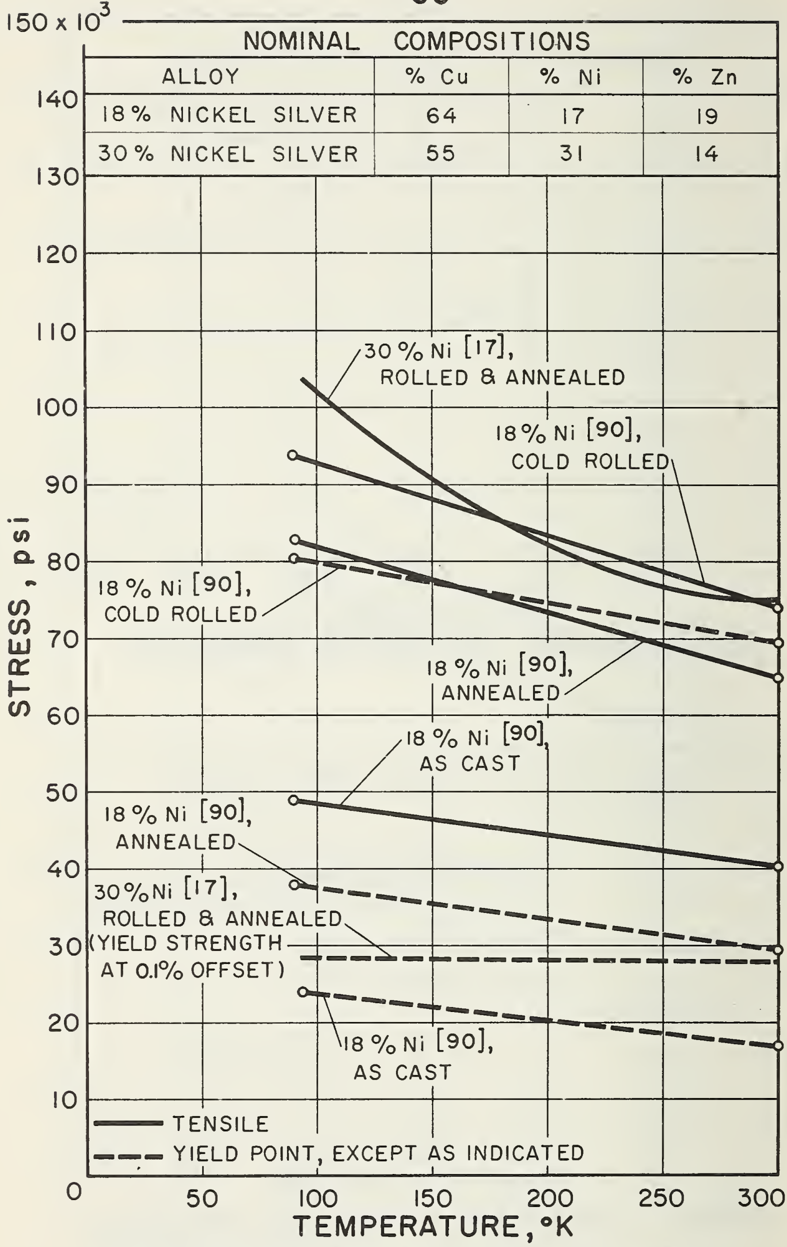


ELONGATION OF CUPRO-NICKELS

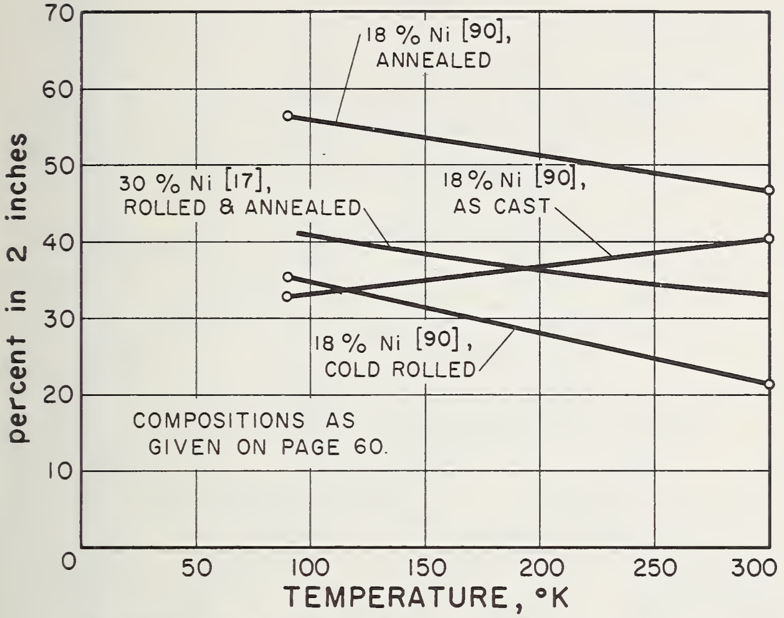


IMPACT ENERGY OF CUPRO-NICKELS

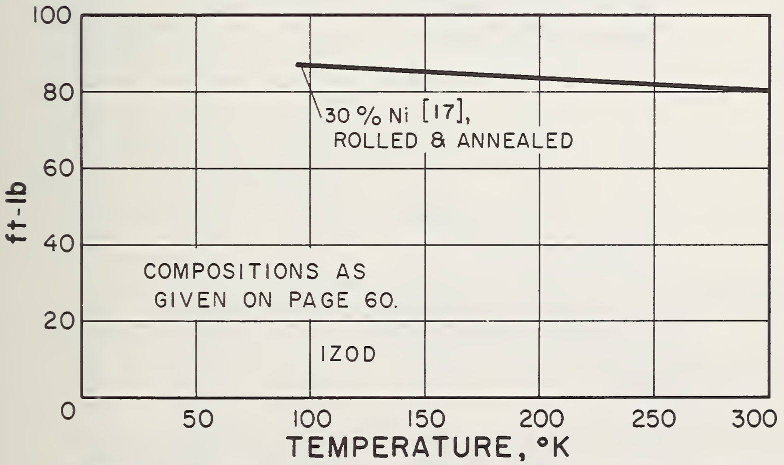
NOMINAL COMPOSITIONS			
ALLOY	% Cu	% Ni	% Zn
18 % NICKEL SILVER	64	17	19
30 % NICKEL SILVER	55	31	14



STRENGTH OF NICKEL SILVERS



ELONGATION OF NICKEL SILVERS



IMPACT ENERGY OF NICKEL SILVERS

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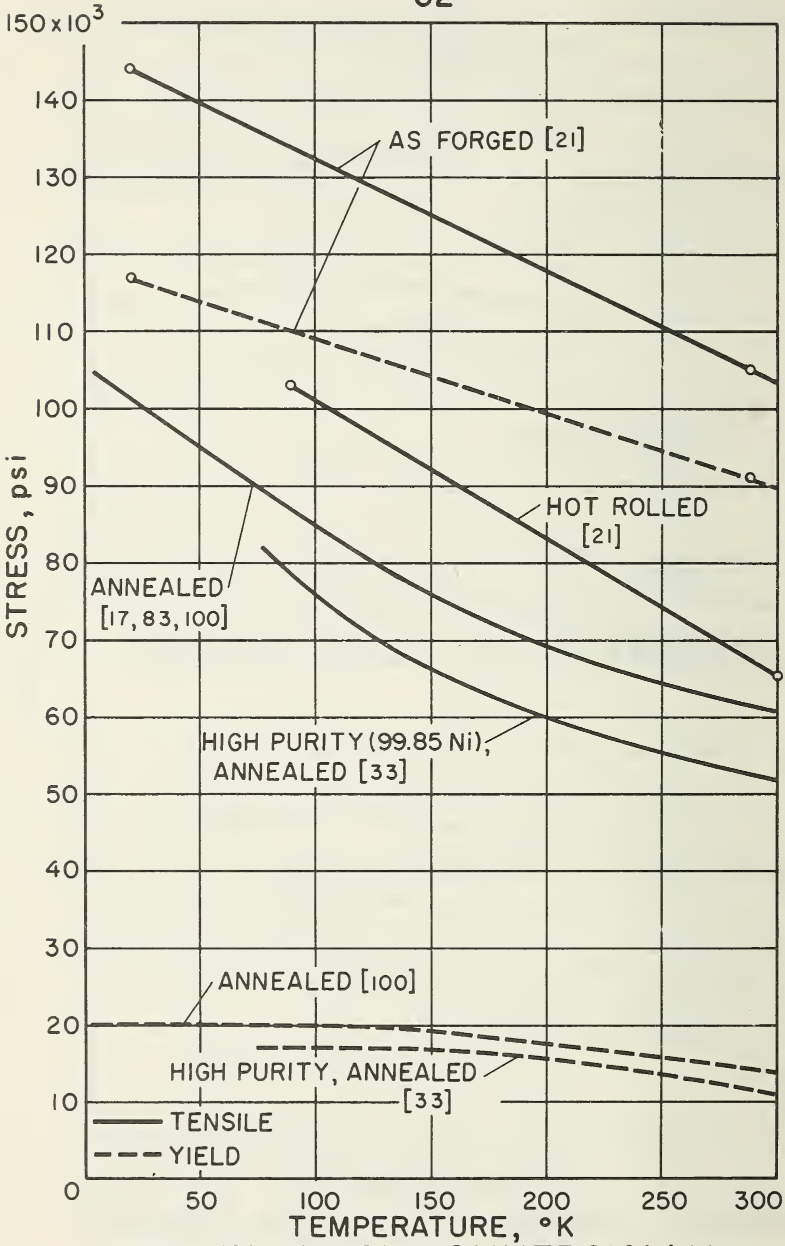
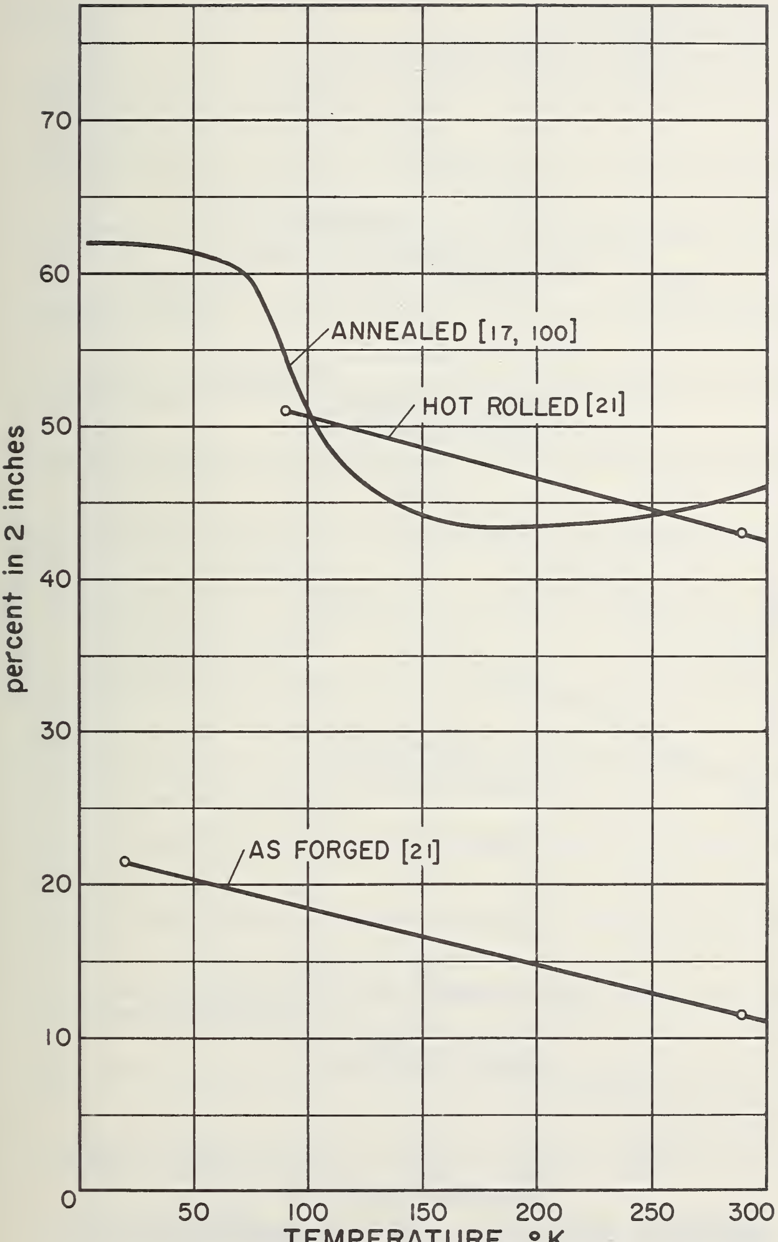
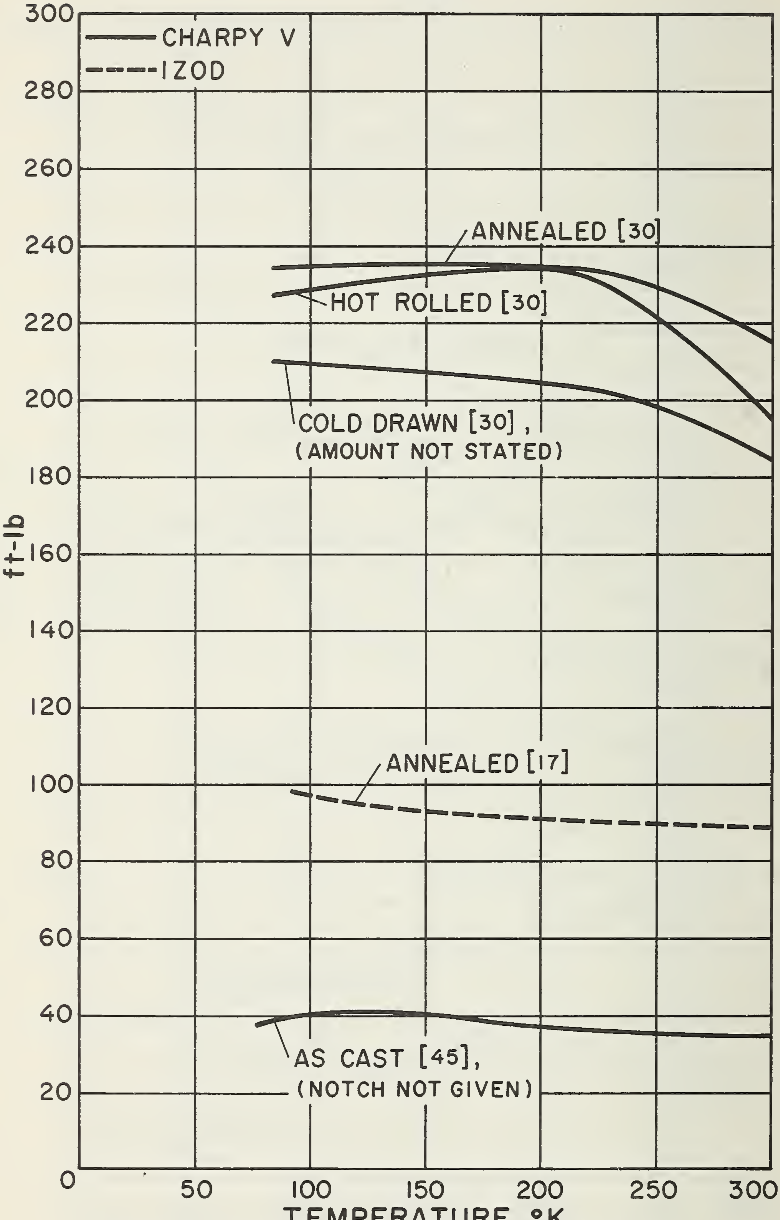


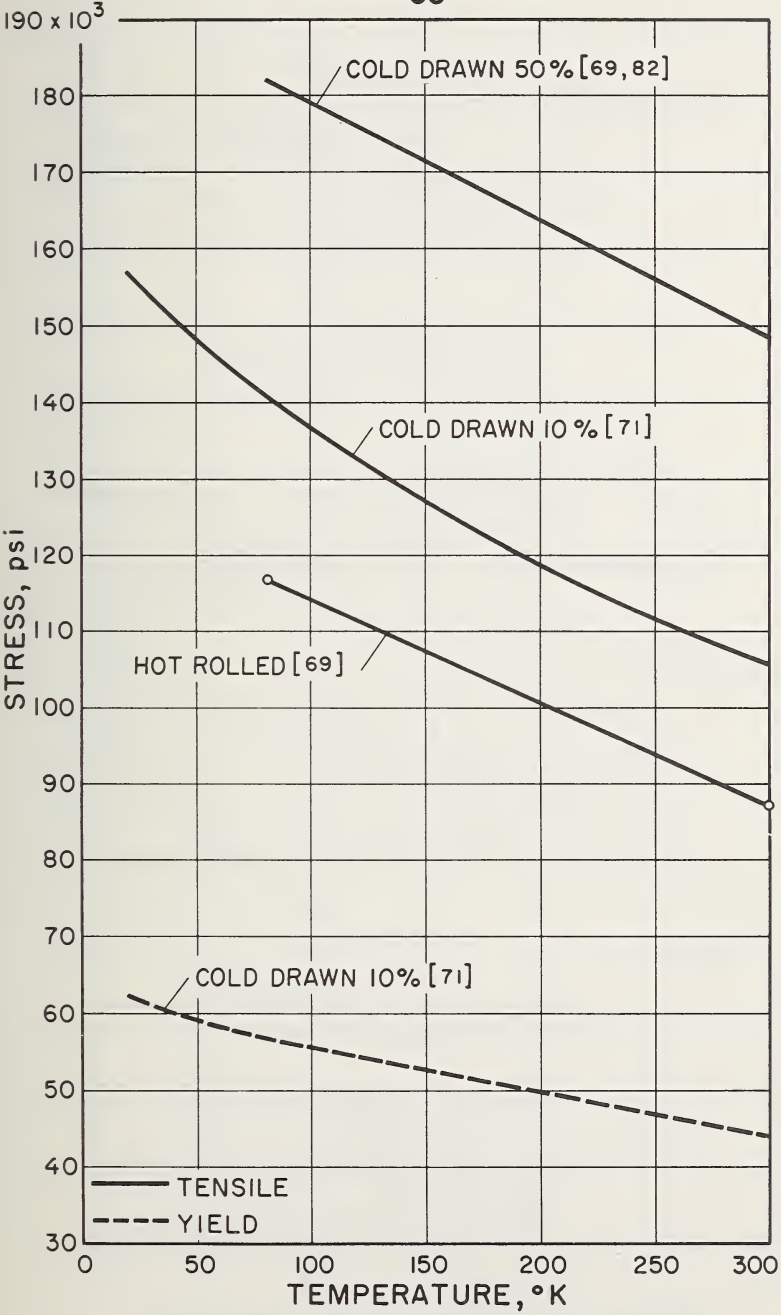
STRENGTH OF COMMERCIALLY PURE NICKEL



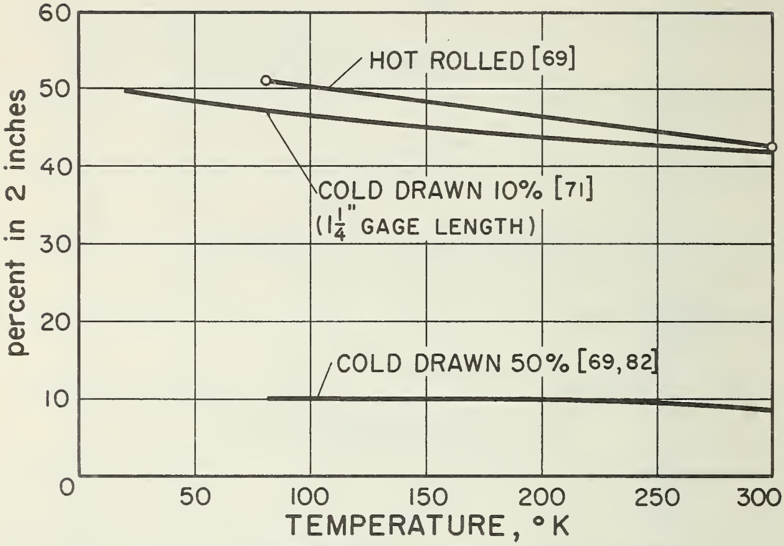
ELONGATION OF COMMERCIALLY PURE NICKEL



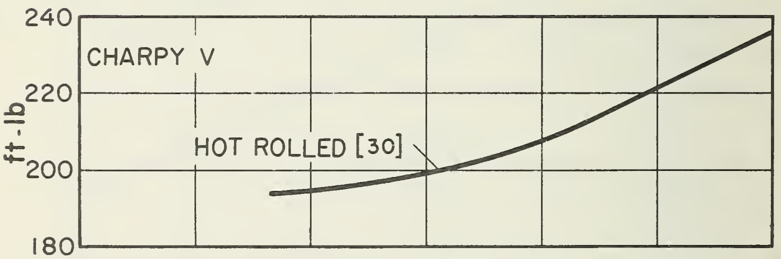
IMPACT ENERGY OF COMMERCIALLY PURE NICKEL

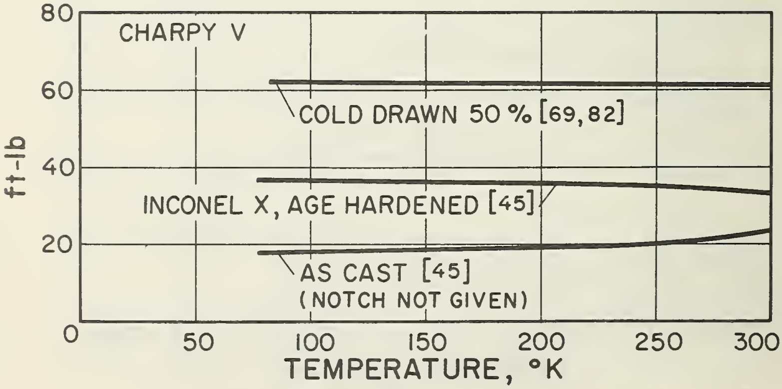


STRENGTH OF INCONEL

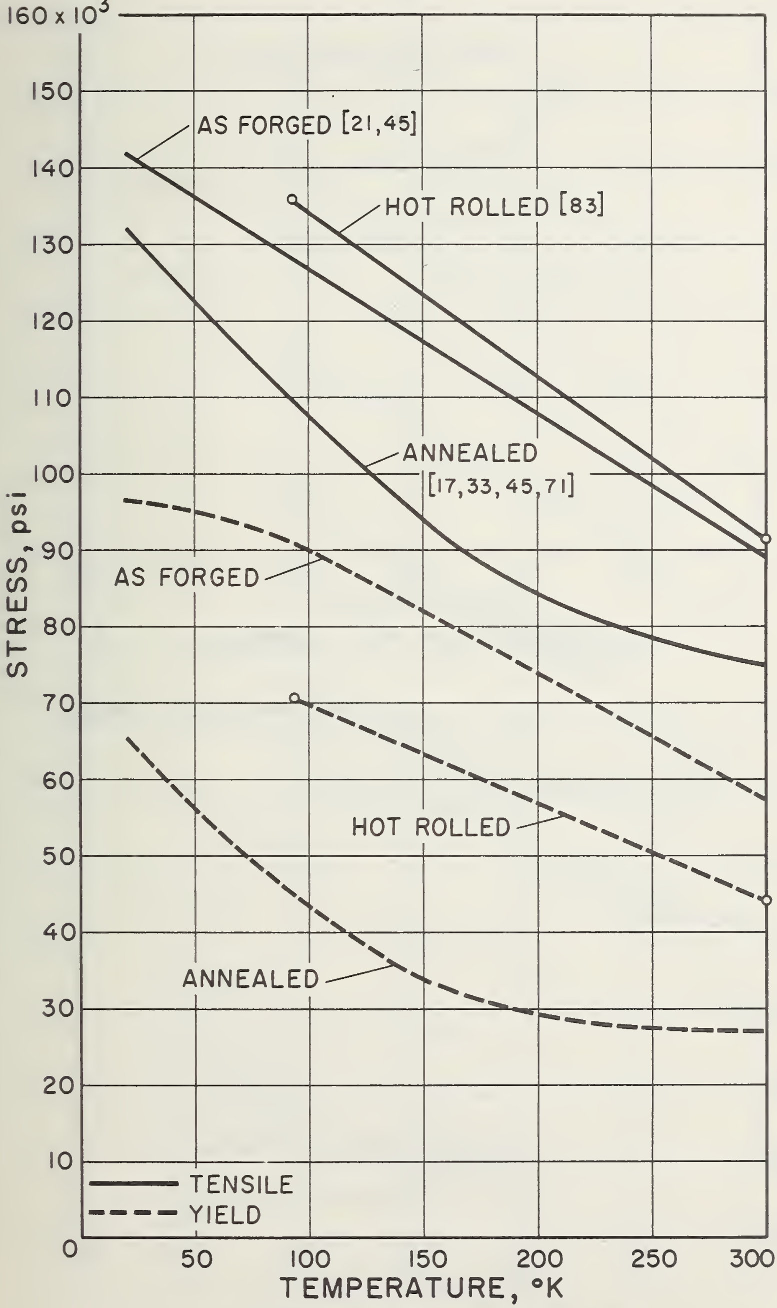


ELONGATION OF INCONEL

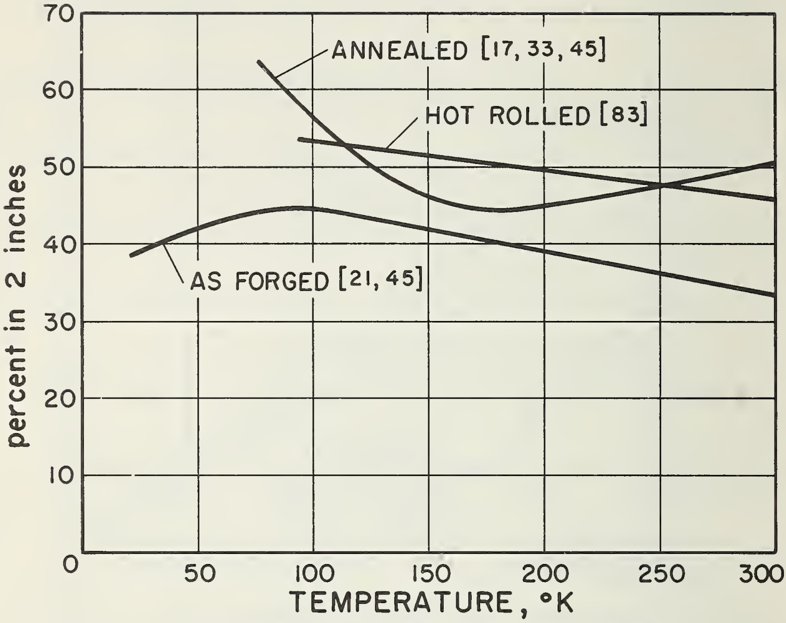




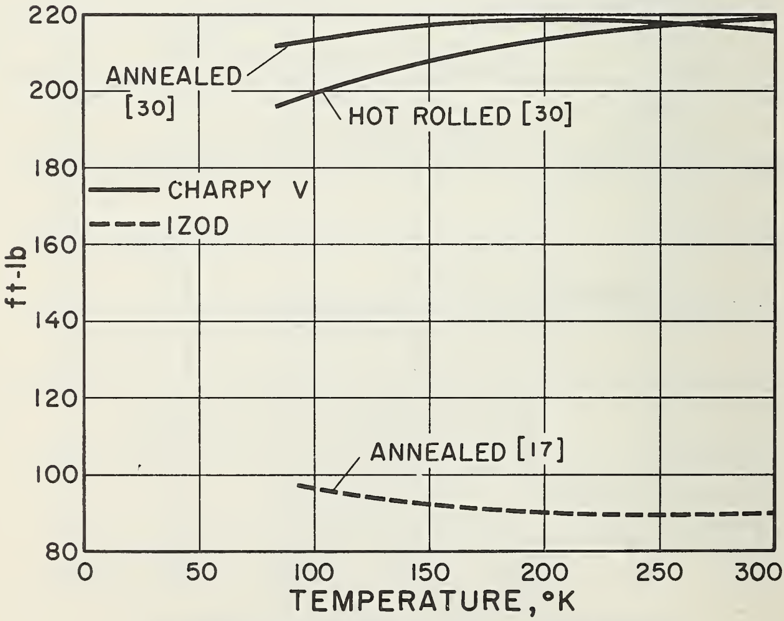
IMPACT ENERGY OF INCONEL



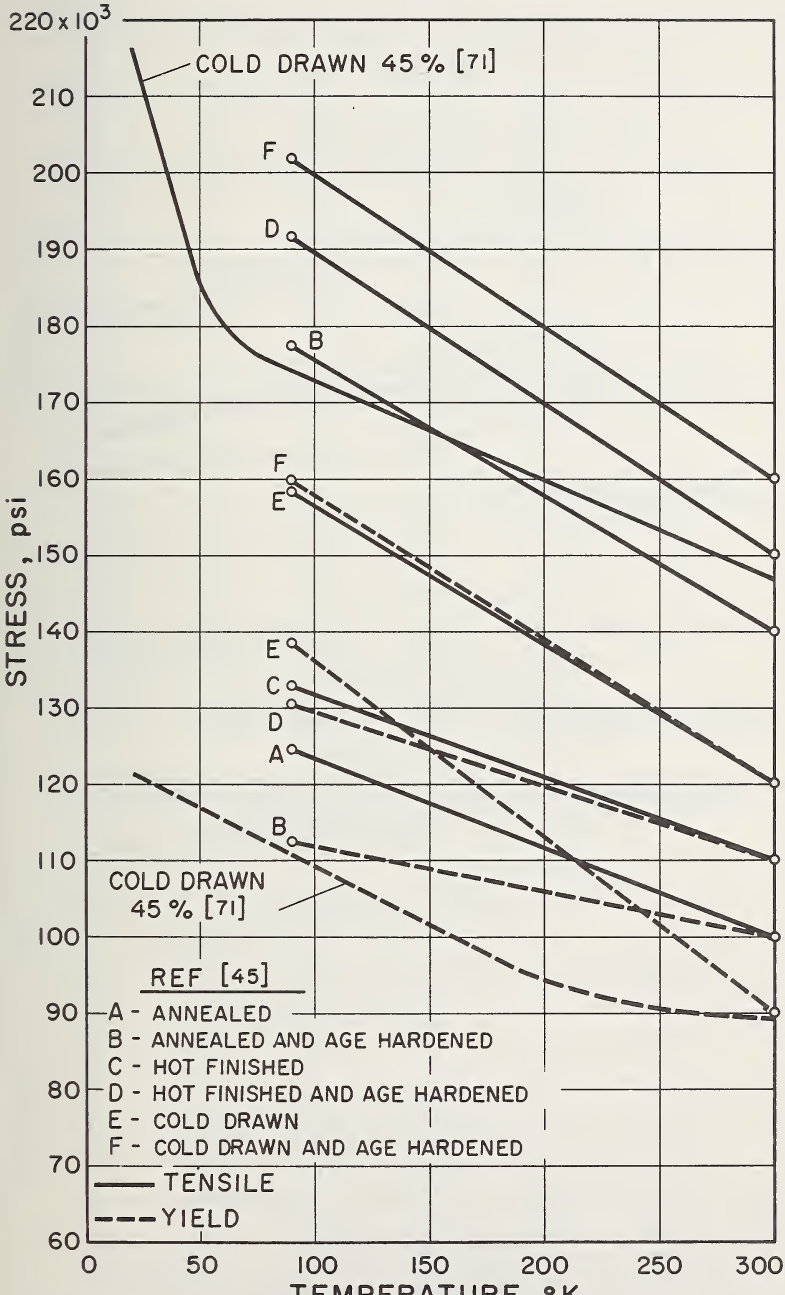
STRENGTH OF MONEL



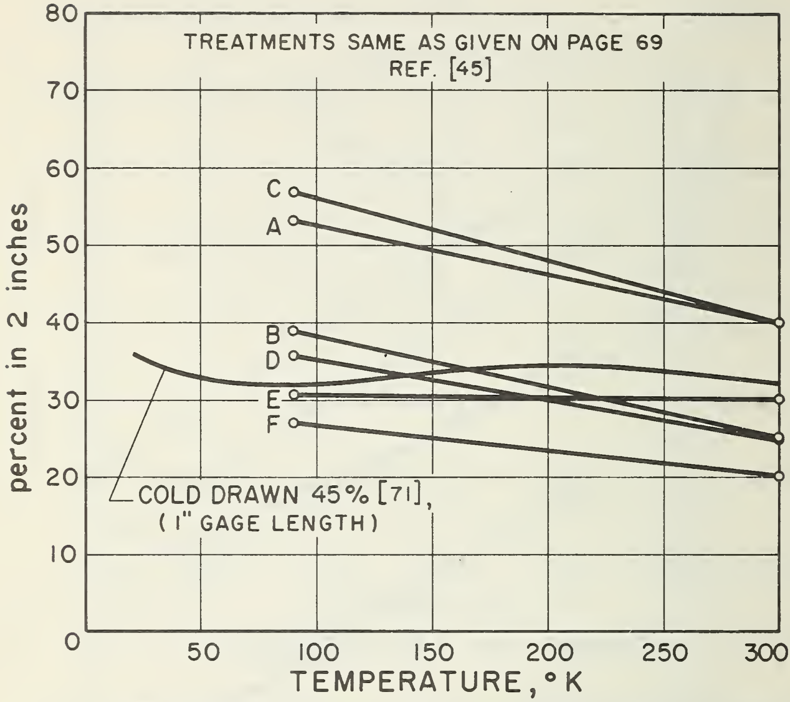
ELONGATION OF MONEL



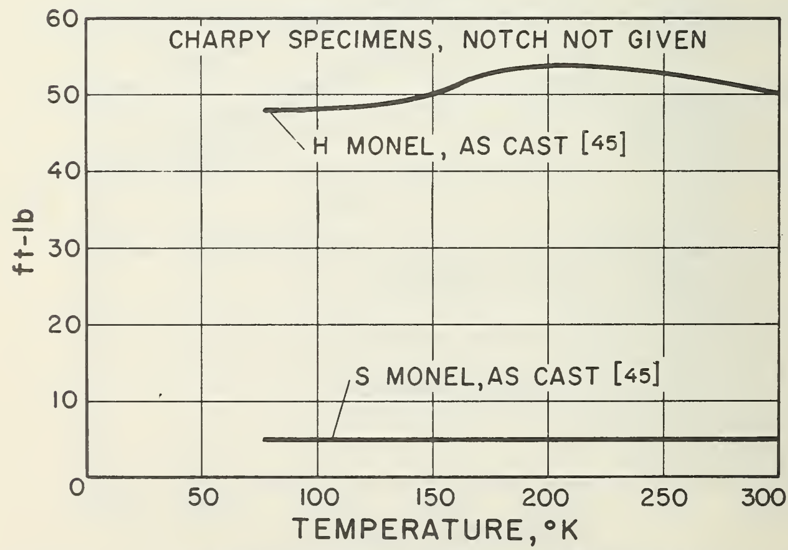
IMPACT ENERGY OF MONEL



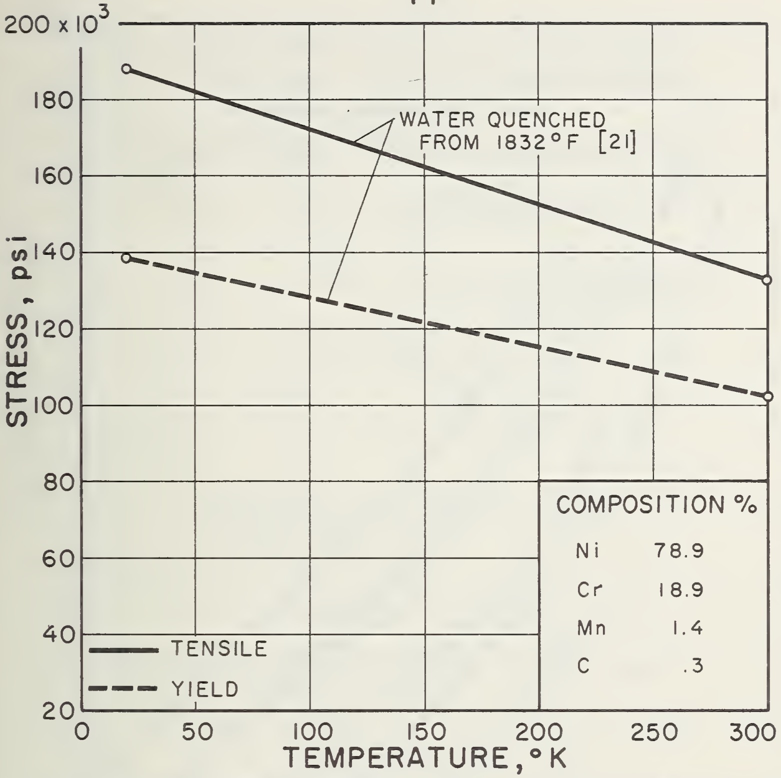
STRENGTH OF K MONEL



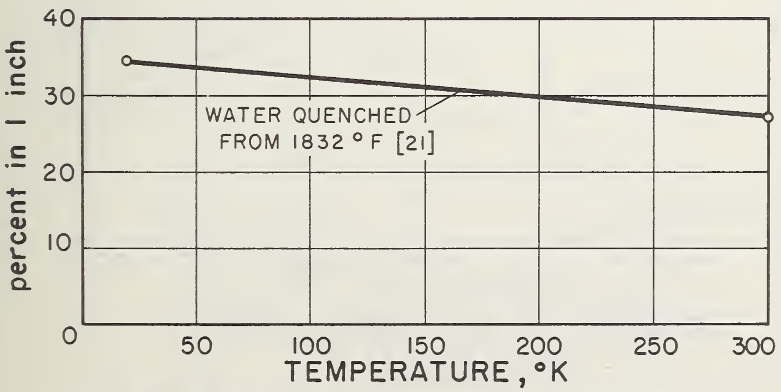
ELONGATION OF K MONEL



IMPACT ENERGY OF MISCELLANEOUS MONELS



STRENGTH OF NICKEL-CHROMIUM RESISTANCE ALLOY



ELONGATION OF NICKEL-CHROMIUM RESISTANCE ALLOY

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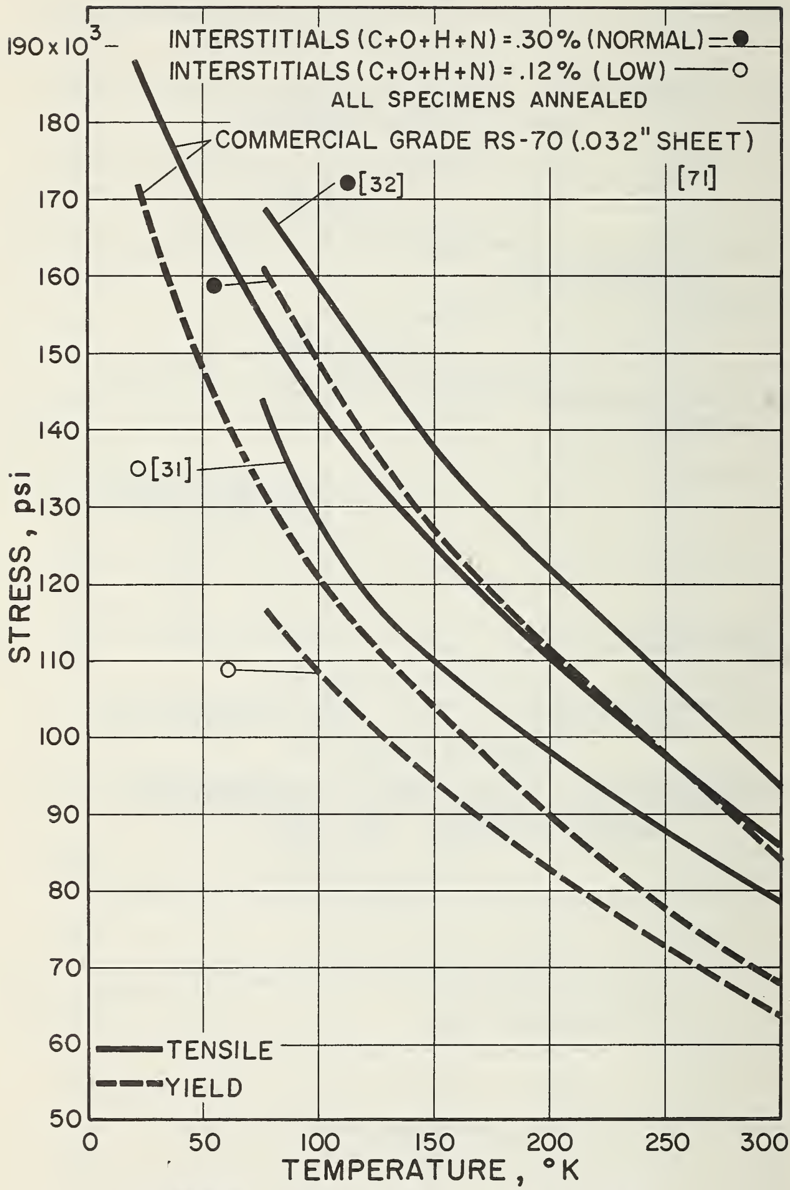
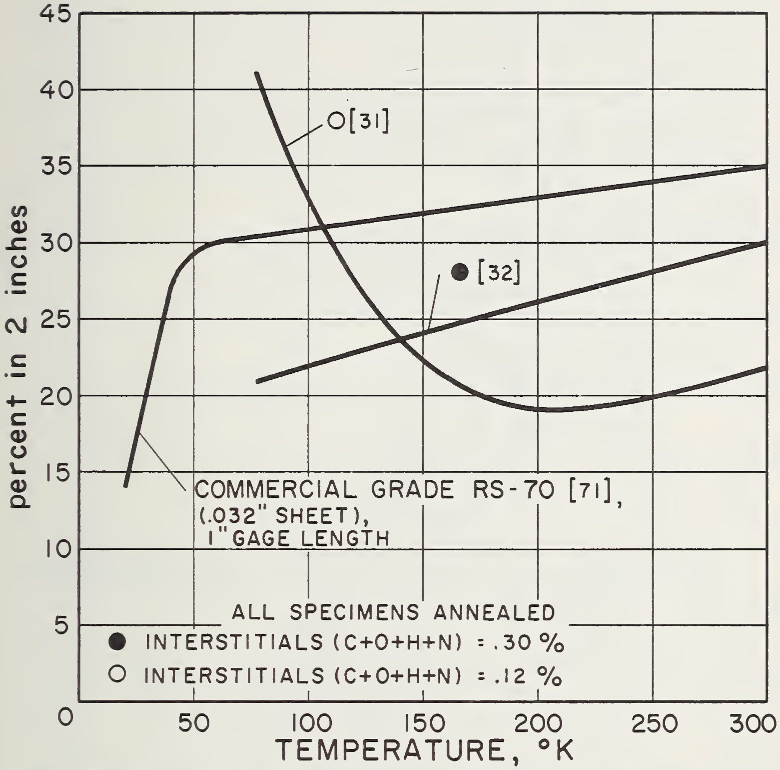
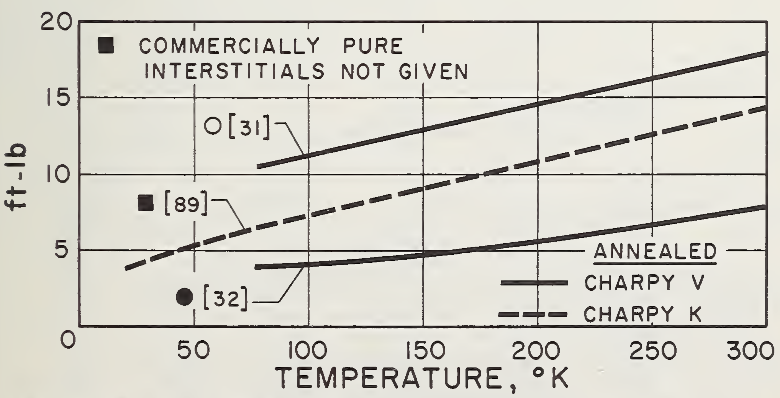


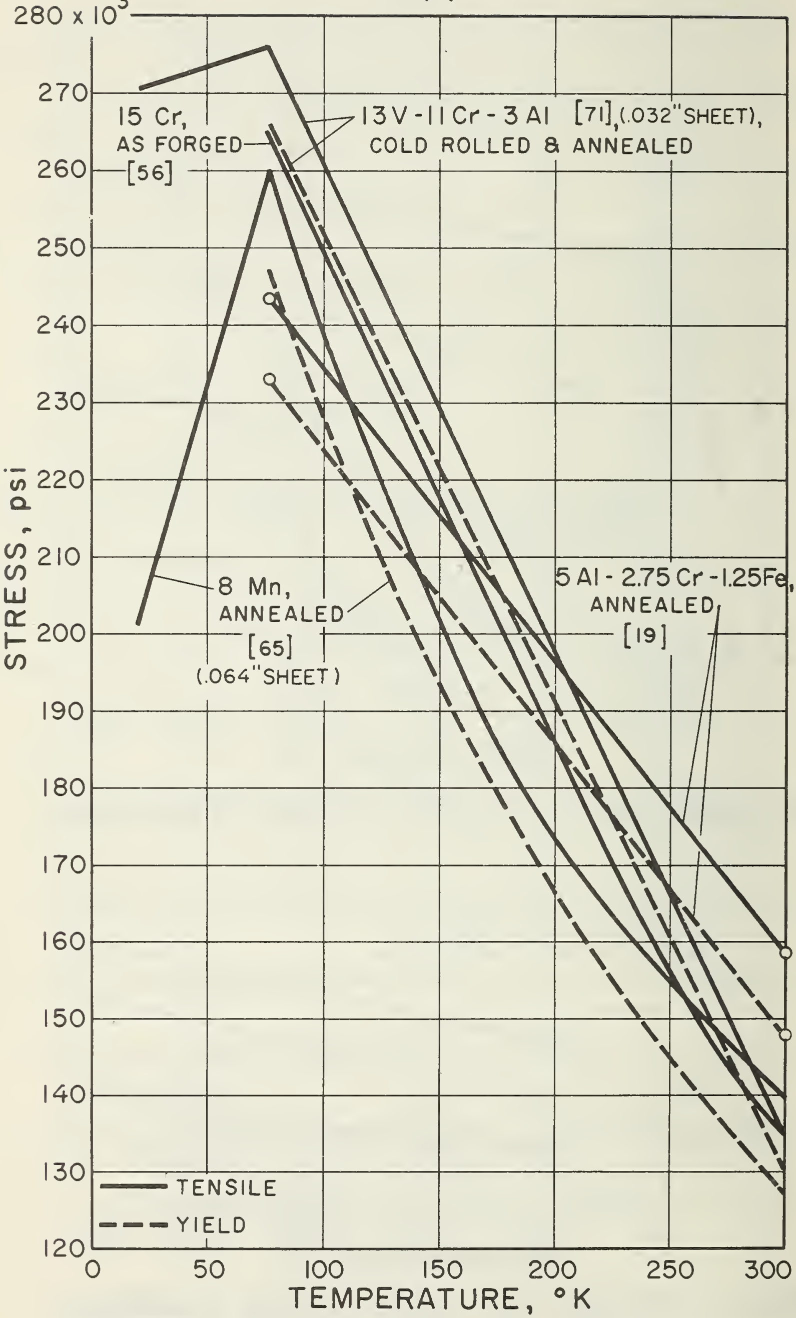
STRENGTH OF UNALLOYED TITANIUM



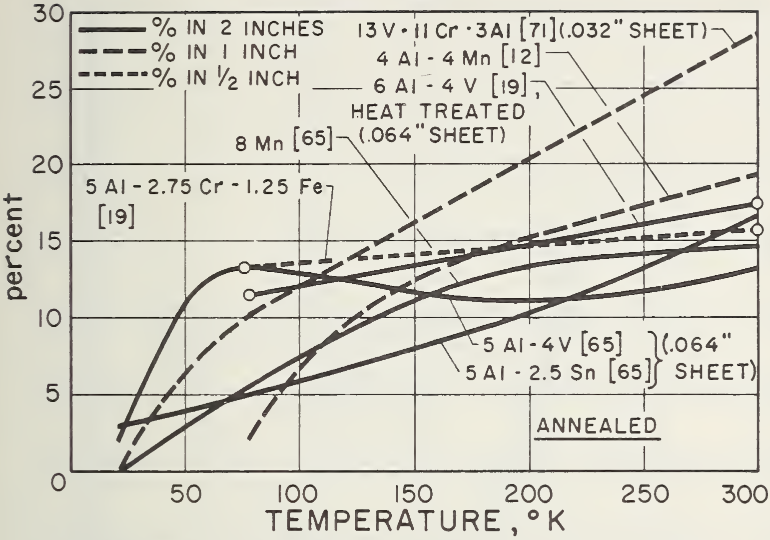
ELONGATION OF UNALLOYED TITANIUM



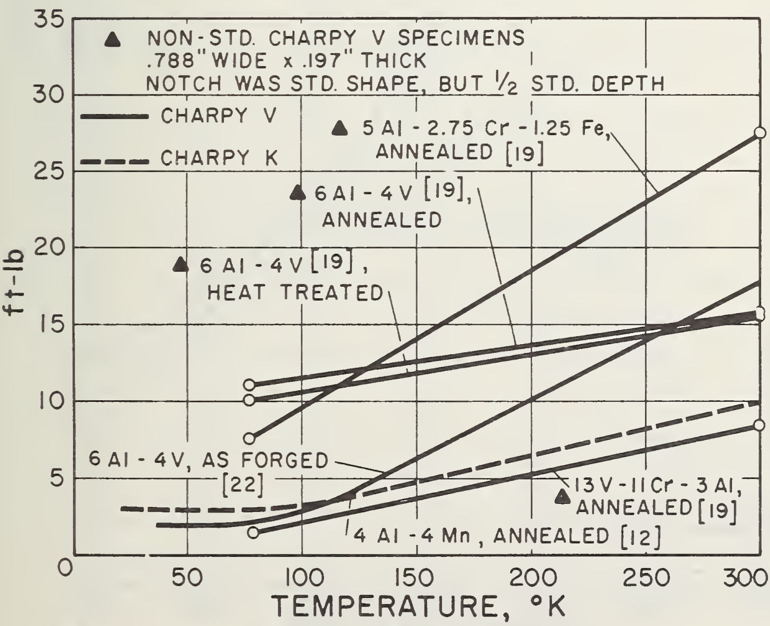
IMPACT ENERGY OF UNALLOYED TITANIUM



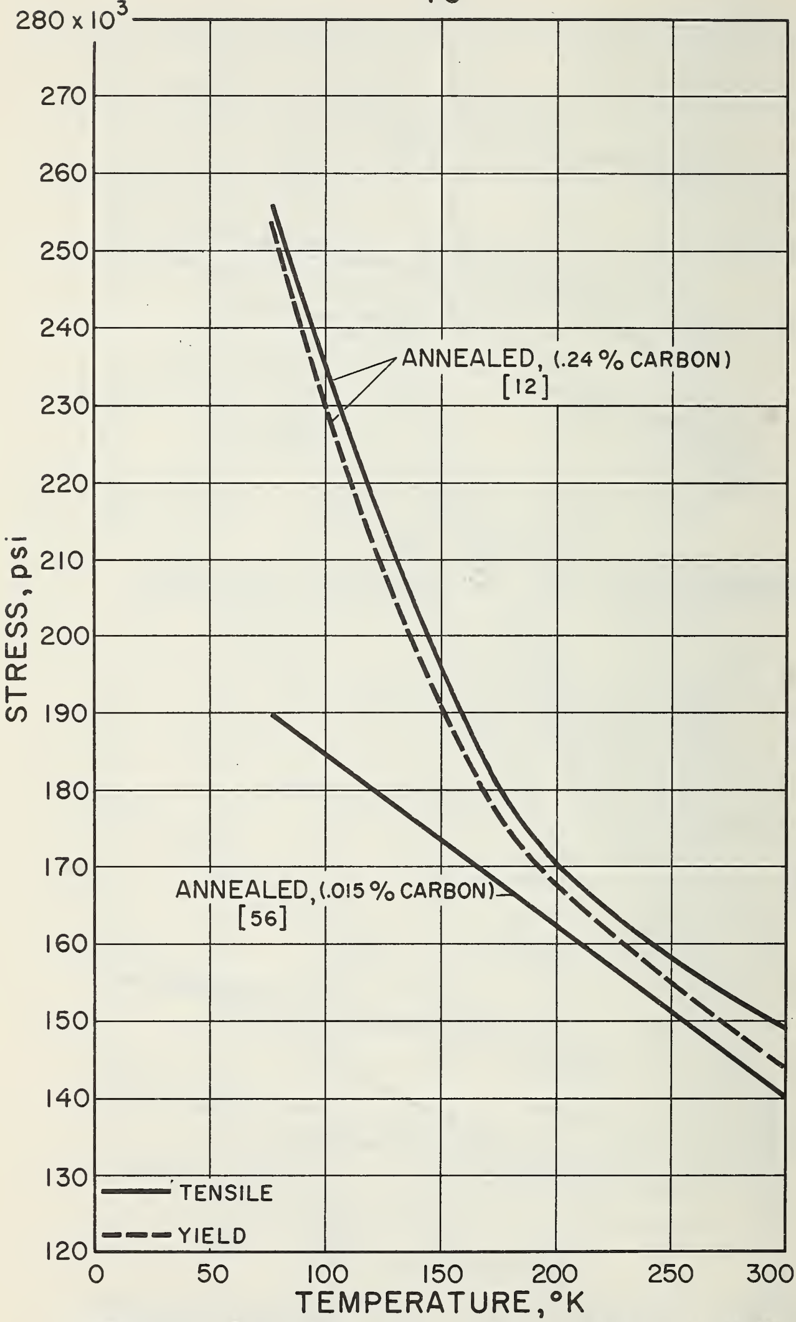
STRENGTH OF TITANIUM ALLOYS



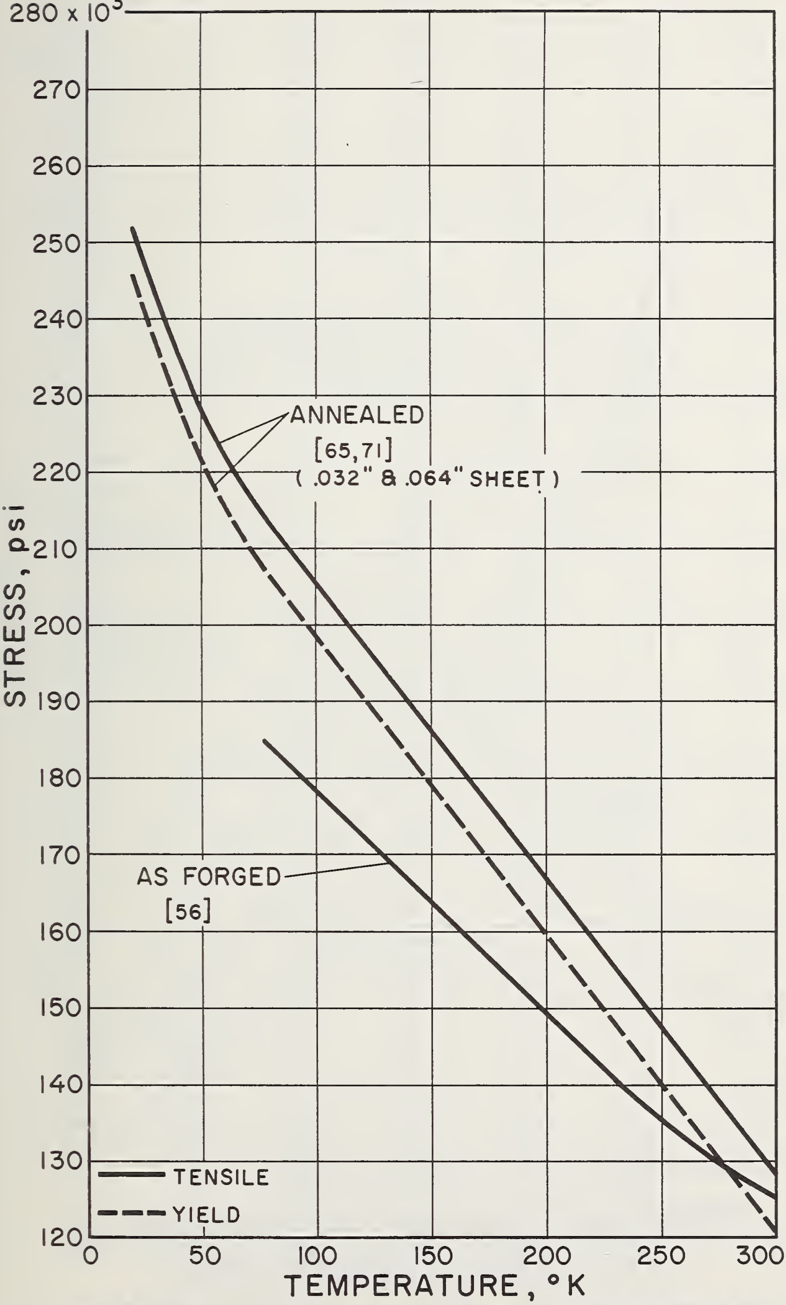
ELONGATION OF TITANIUM ALLOYS



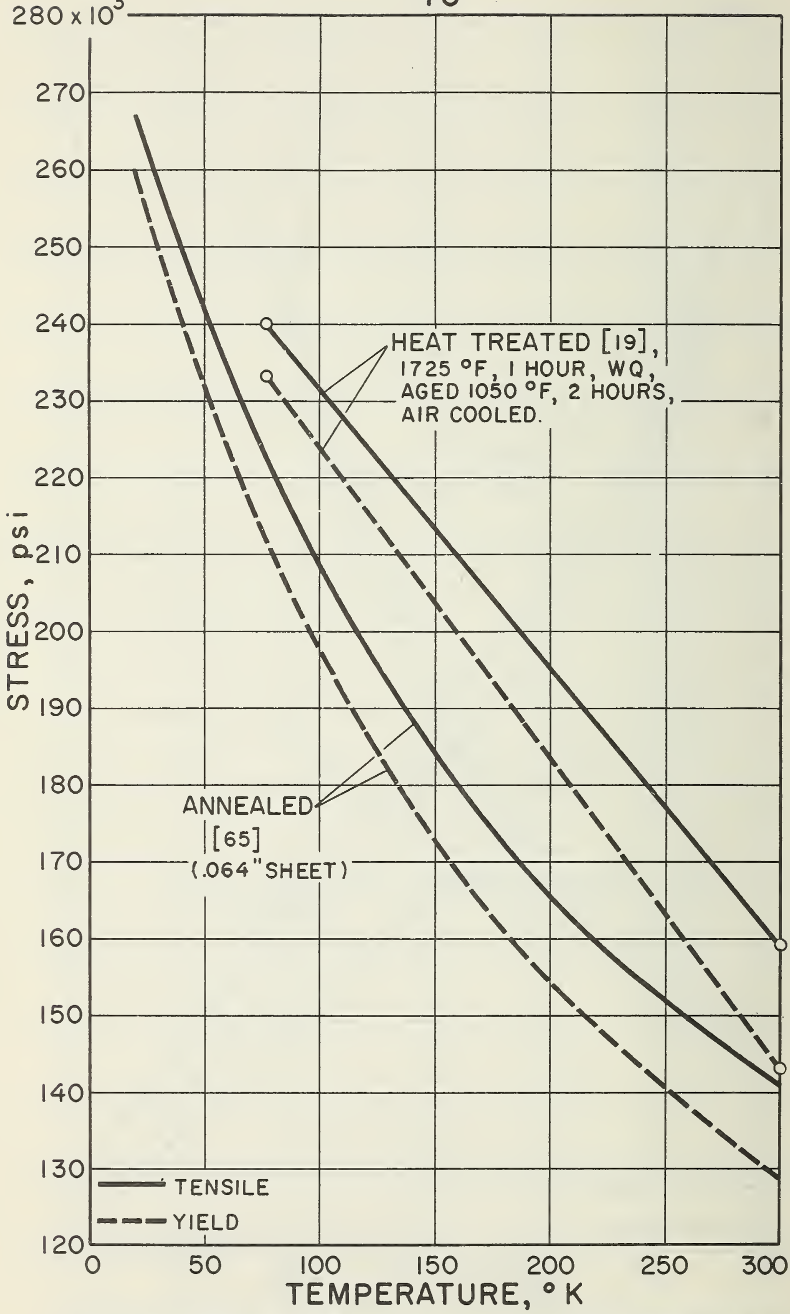
IMPACT ENERGY OF TITANIUM ALLOYS



STRENGTH OF 4 Al - 4 Mn TITANIUM



STRENGTH OF 5 Al - 2.5 Sn TITANIUM



STRENGTH OF 6 Al - 4V TITANIUM

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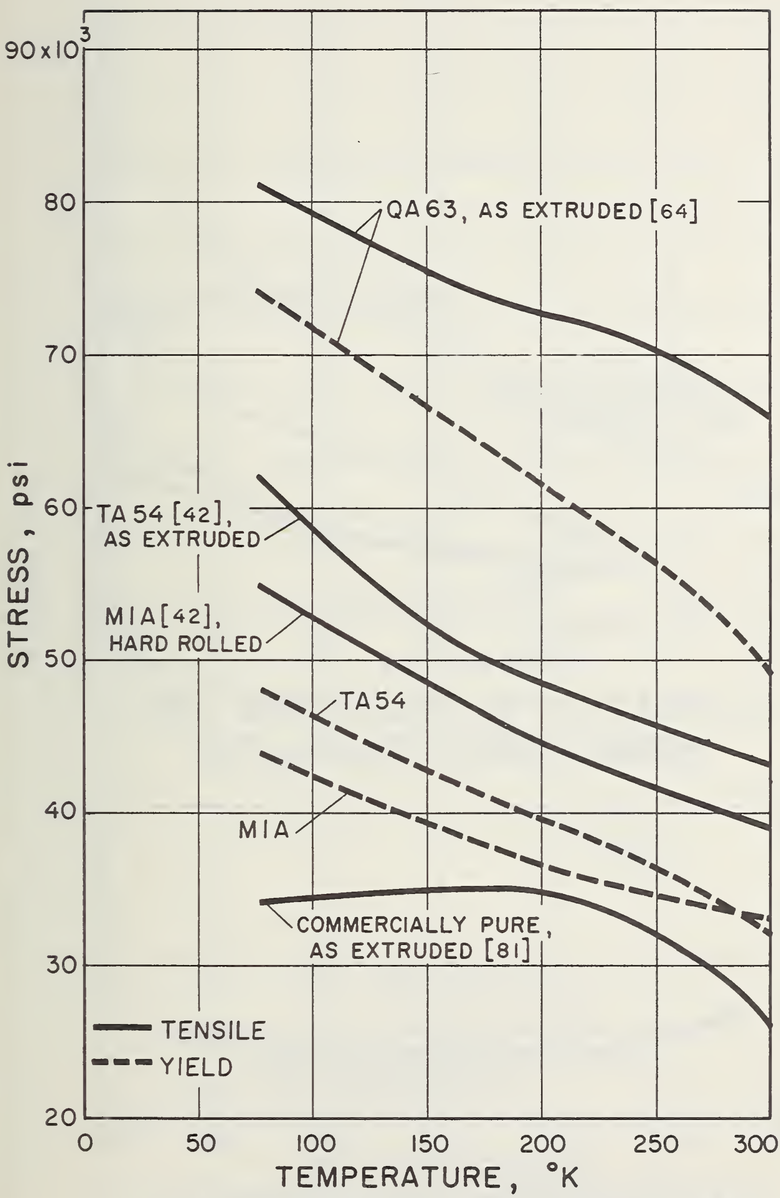
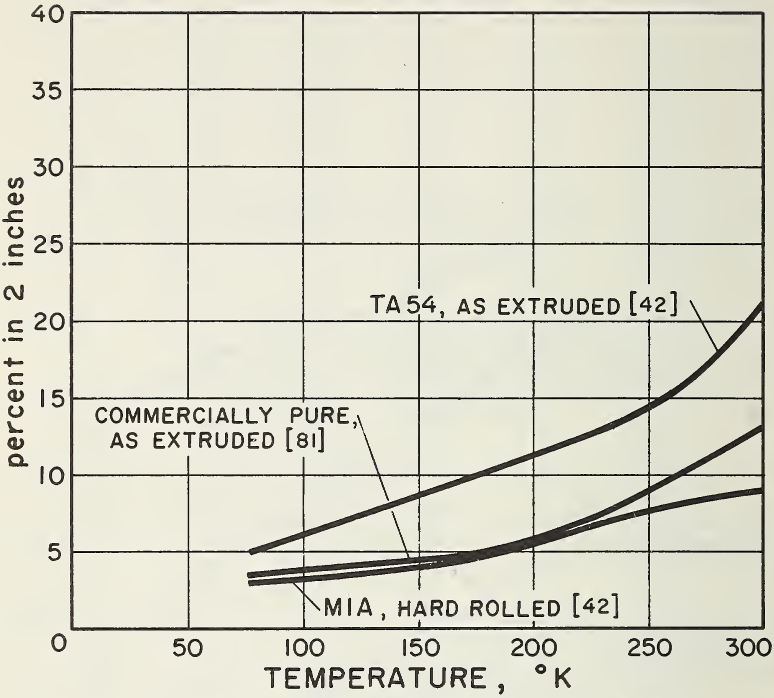
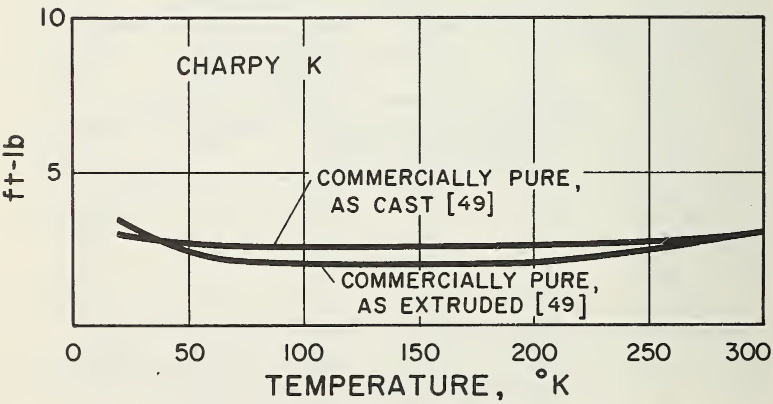


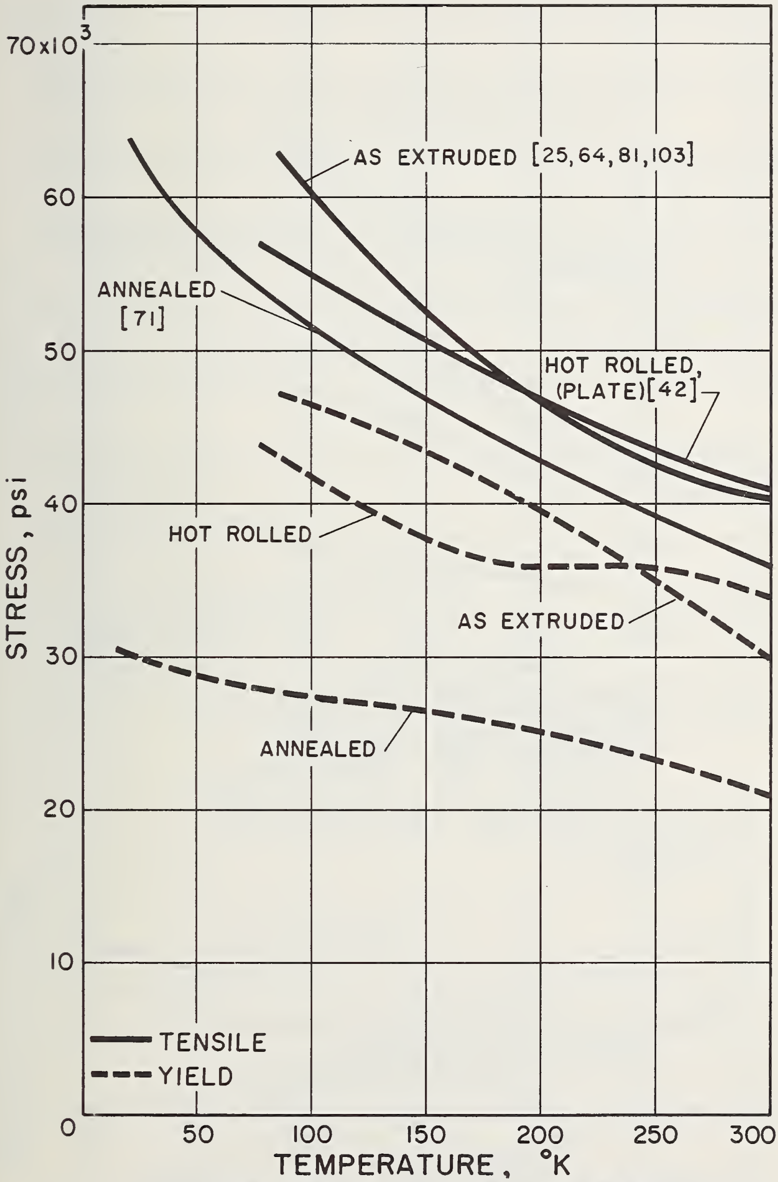
STRENGTH OF MAGNESIUM AND SOME MAGNESIUM ALLOYS



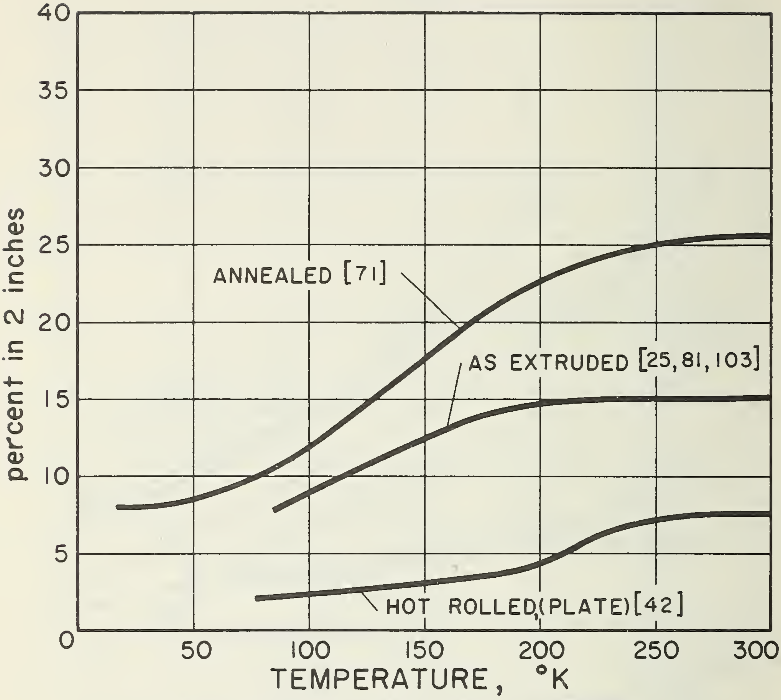
ELONGATION OF MAGNESIUM AND SOME MAGNESIUM ALLOYS



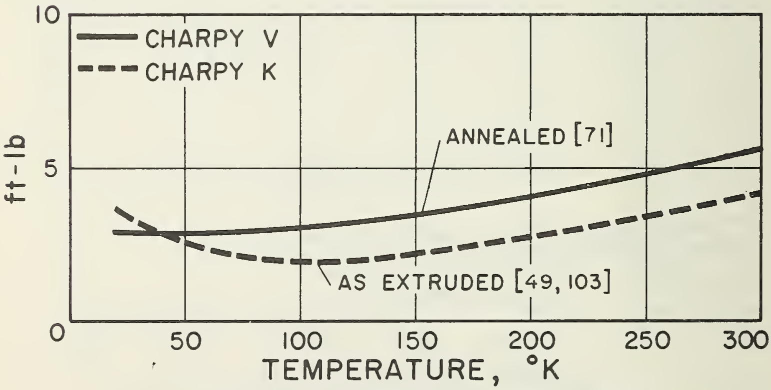
IMPACT ENERGY OF MAGNESIUM AND SOME MAGNESIUM ALLOYS



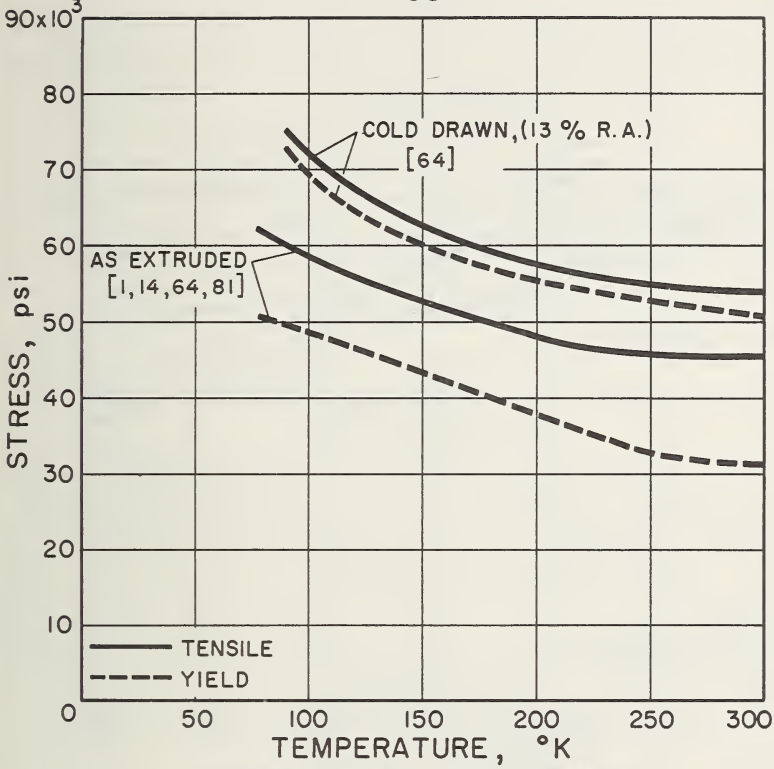
STRENGTH OF AZ 31 B MAGNESIUM ALLOY



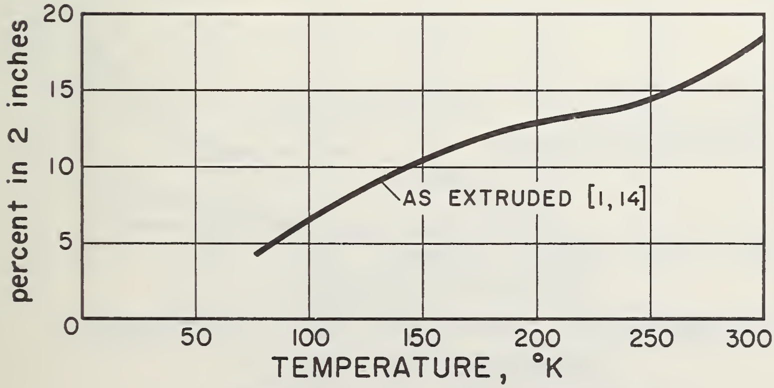
ELONGATION OF AZ 31 B MAGNESIUM ALLOY



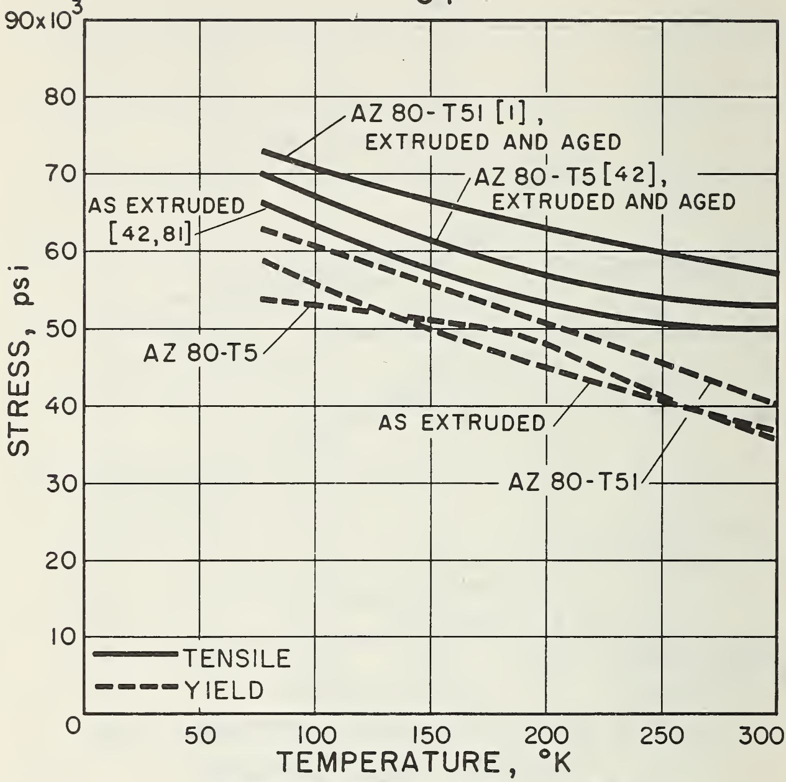
IMPACT ENERGY OF AZ 31 B MAGNESIUM ALLOY



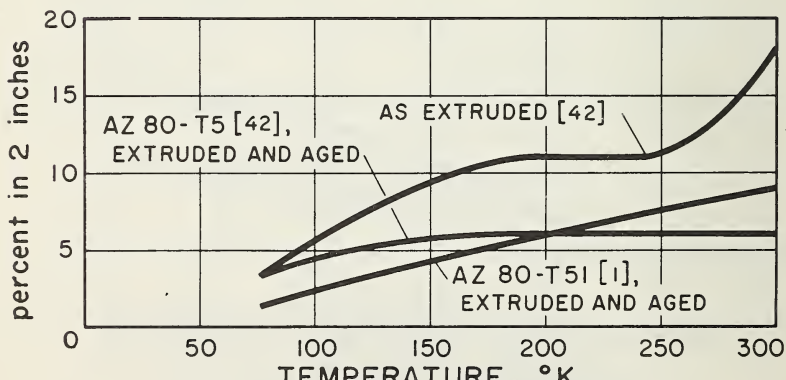
STRENGTH OF AZ 61 A MAGNESIUM ALLOY



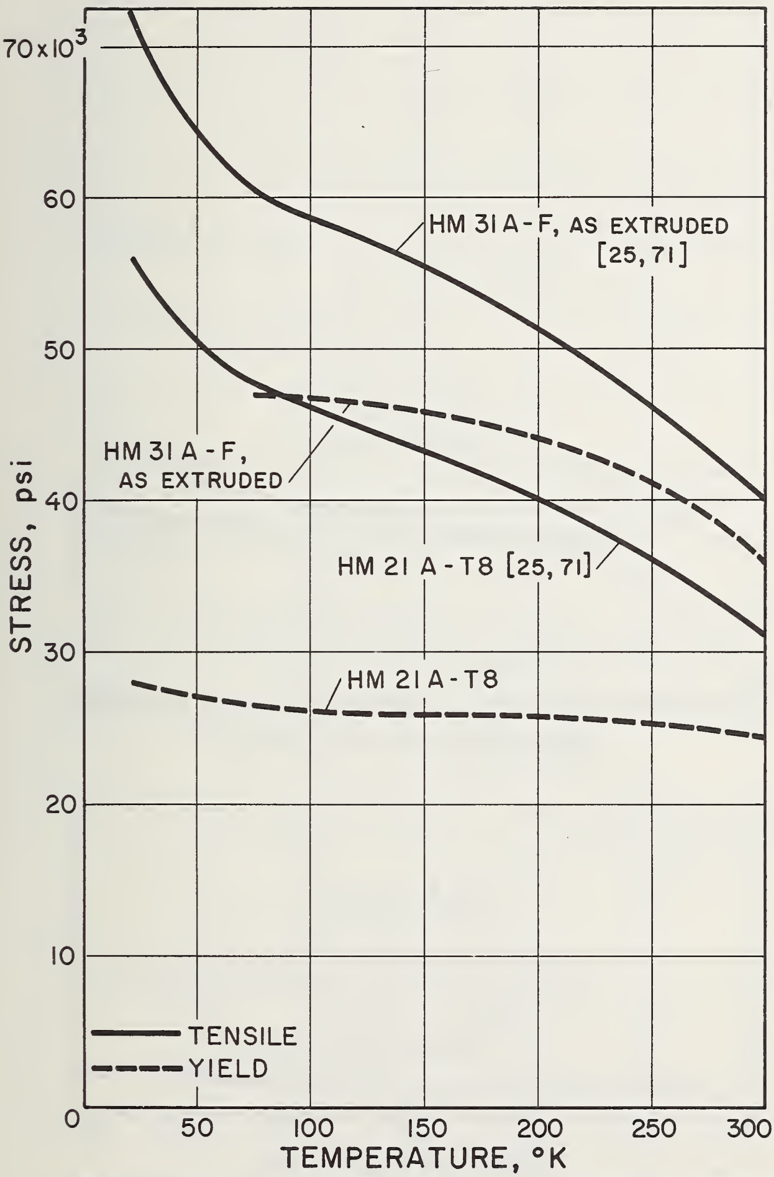
ELONGATION OF AZ 61 A MAGNESIUM ALLOY



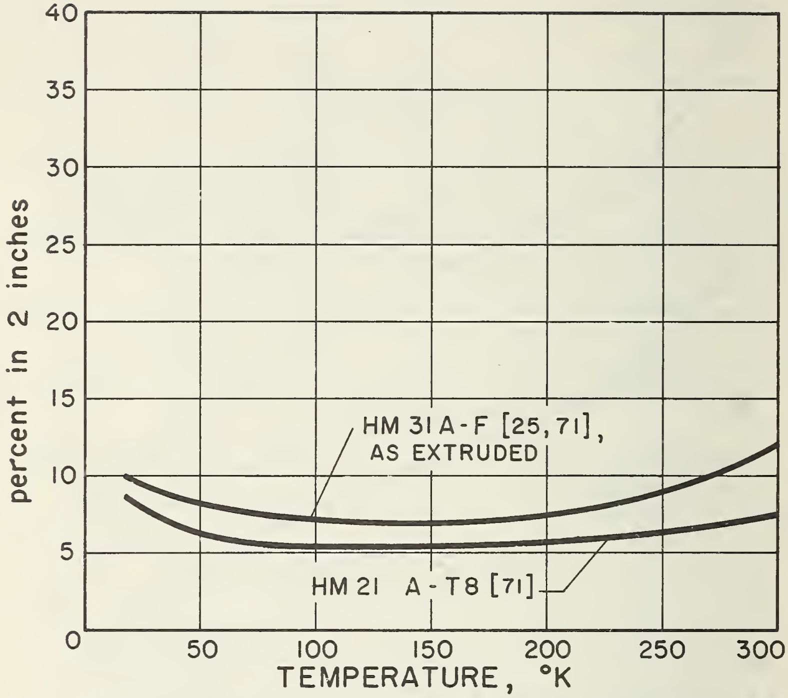
STRENGTH OF AZ 80 MAGNESIUM ALLOY



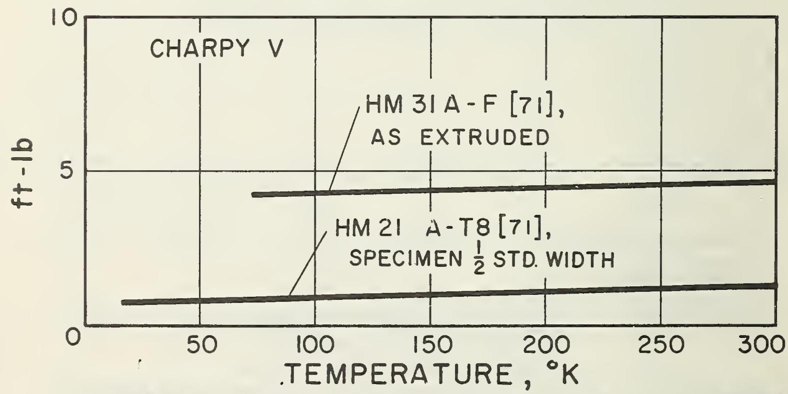
ELONGATION OF AZ 80 MAGNESIUM ALLOY



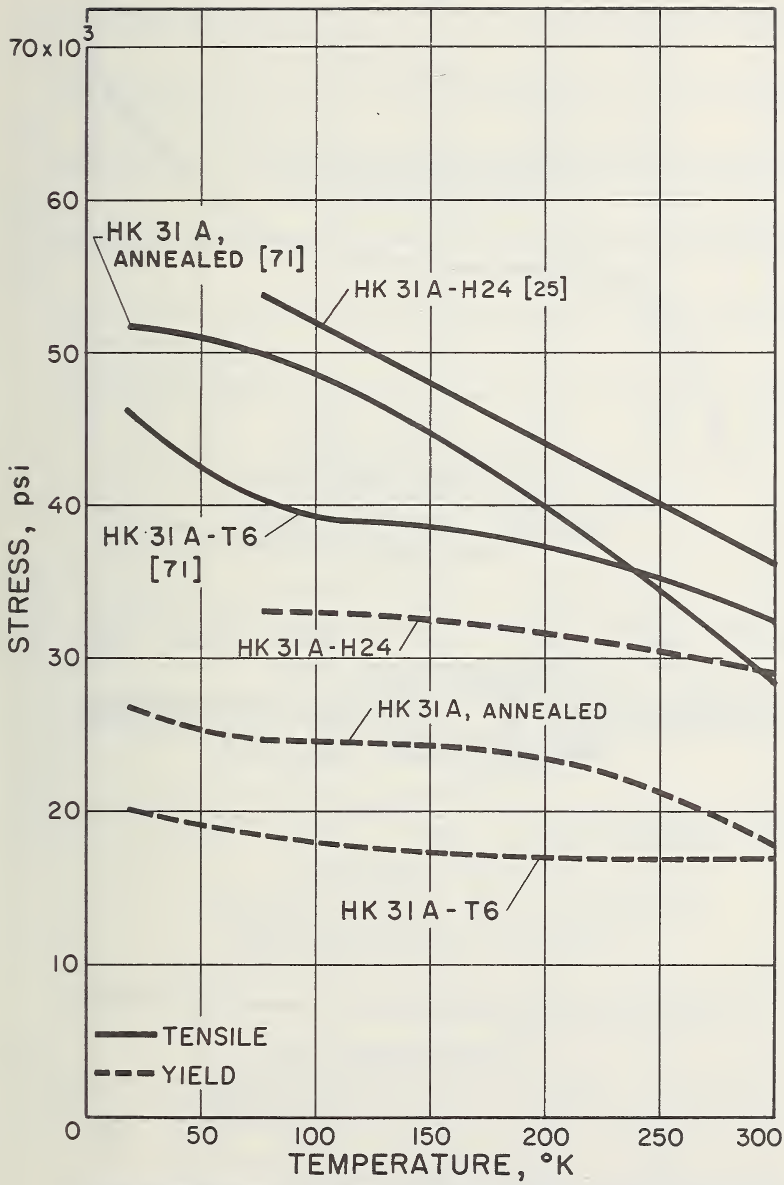
STRENGTH OF THORIUM-MANGANESE MAGNESIUM ALLOYS



ELONGATION OF THORIUM-MANGANESE MAGNESIUM ALLOYS



IMPACT ENERGY OF THORIUM-MANGANESE MAGNESIUM ALLOYS



STRENGTH OF THORIUM-ZIRCONIUM MAGNESIUM ALLOYS

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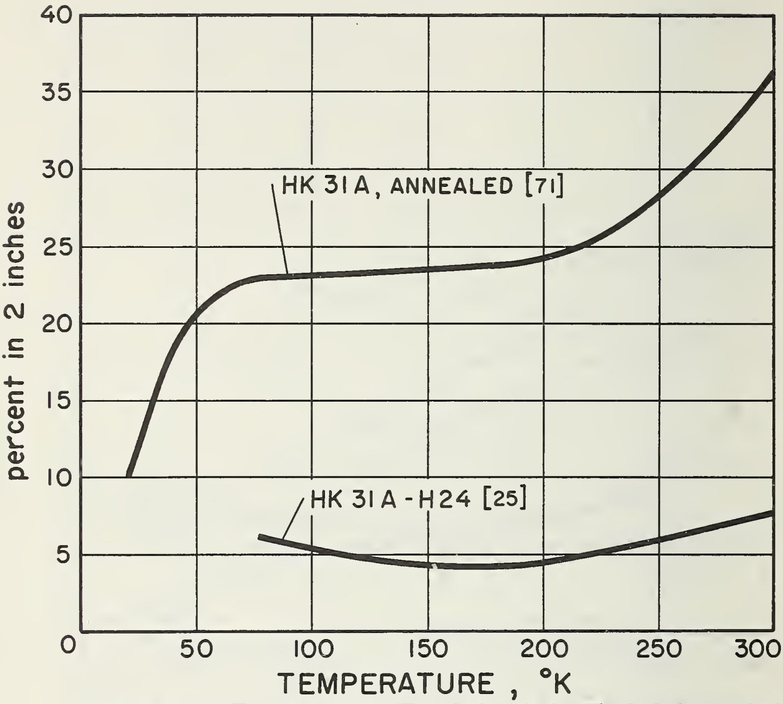
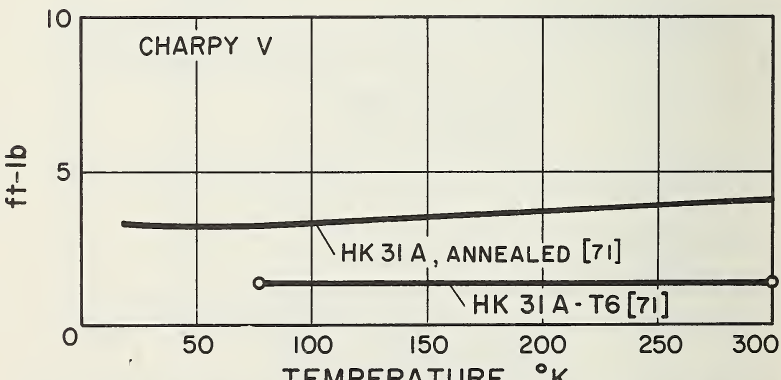
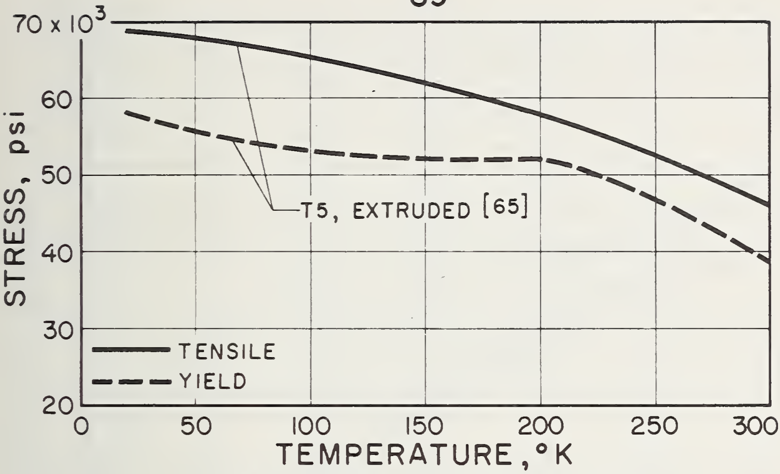


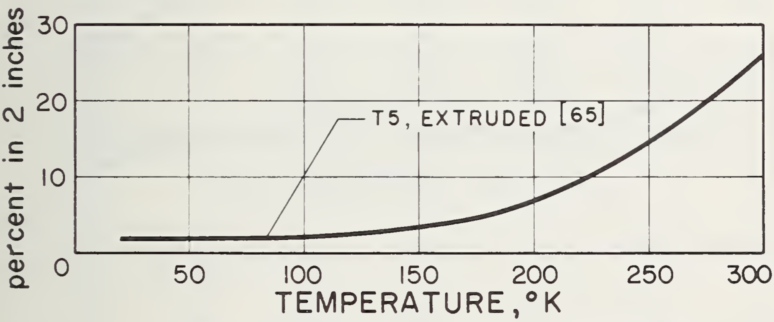
ELONGATION OF THORIUM-ZIRCONIUM MAGNESIUM ALLOYS



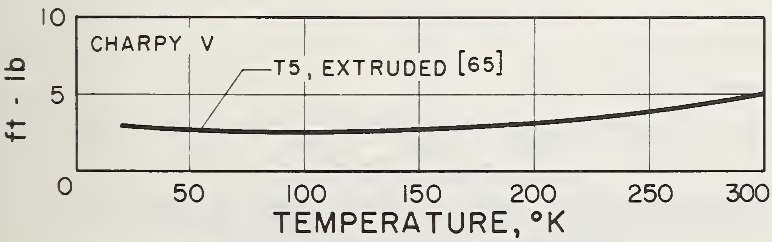
IMPACT ENERGY OF THORIUM-ZIRCONIUM MAGNESIUM ALLOYS



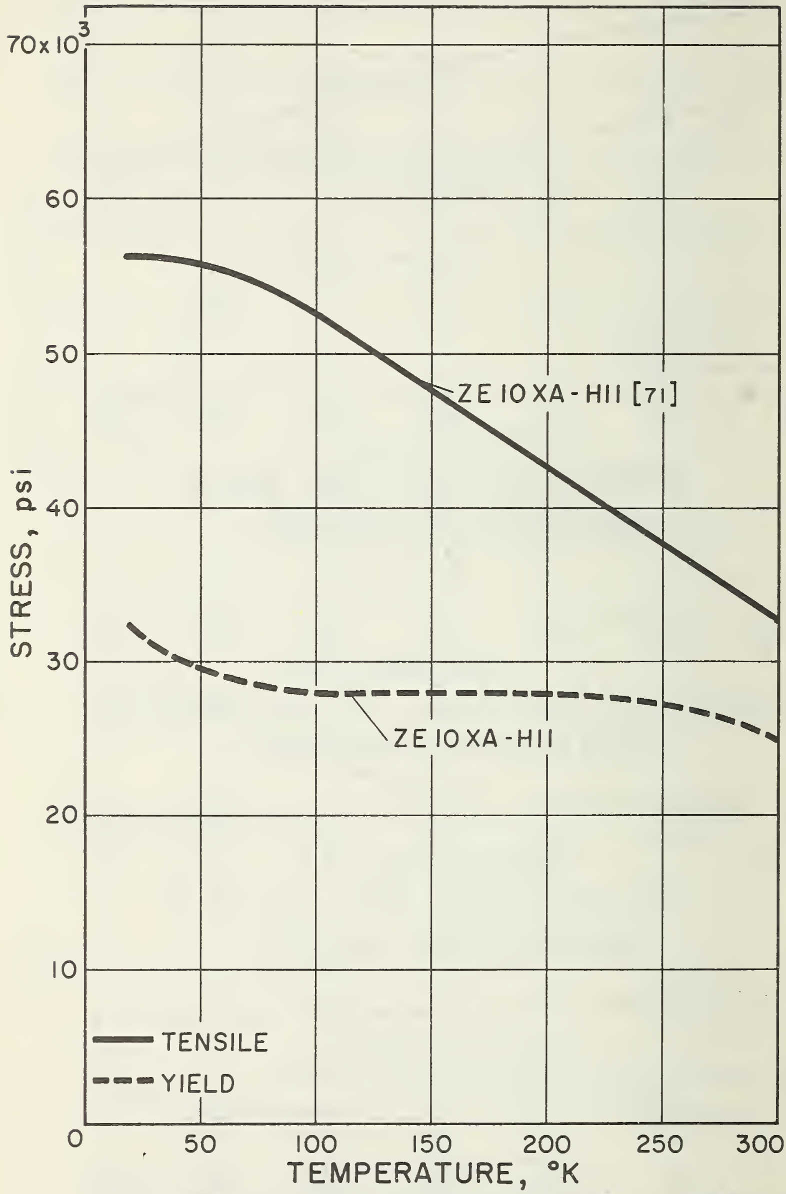
STRENGTH OF ZK 60 A MAGNESIUM ALLOY



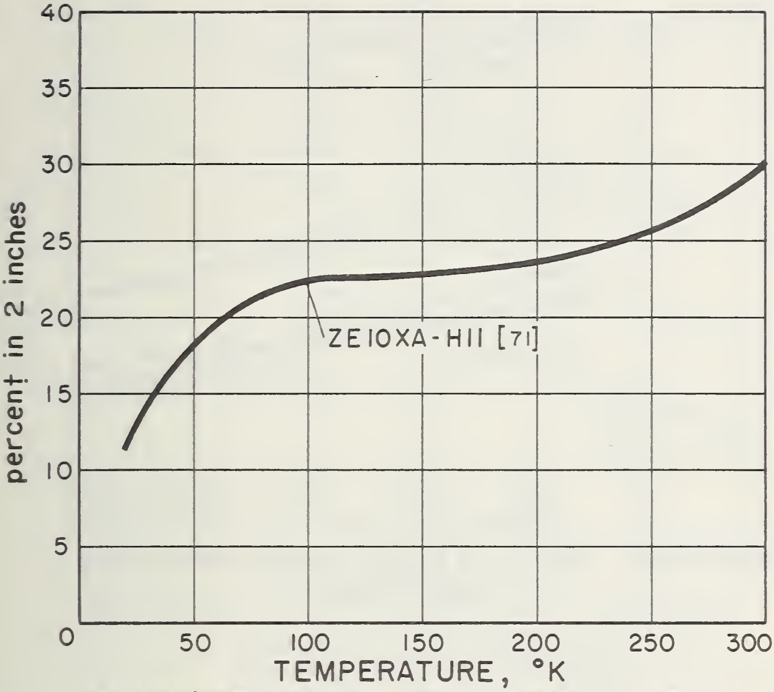
ELONGATION OF ZK 60 A MAGNESIUM ALLOY



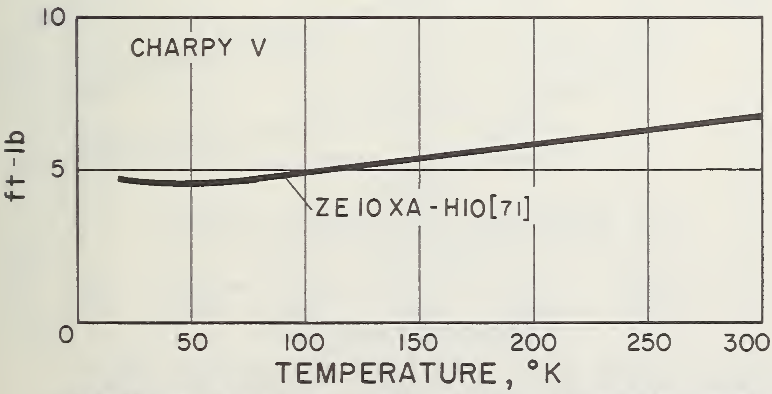
IMPACT ENERGY OF ZK 60 A MAGNESIUM ALLOY



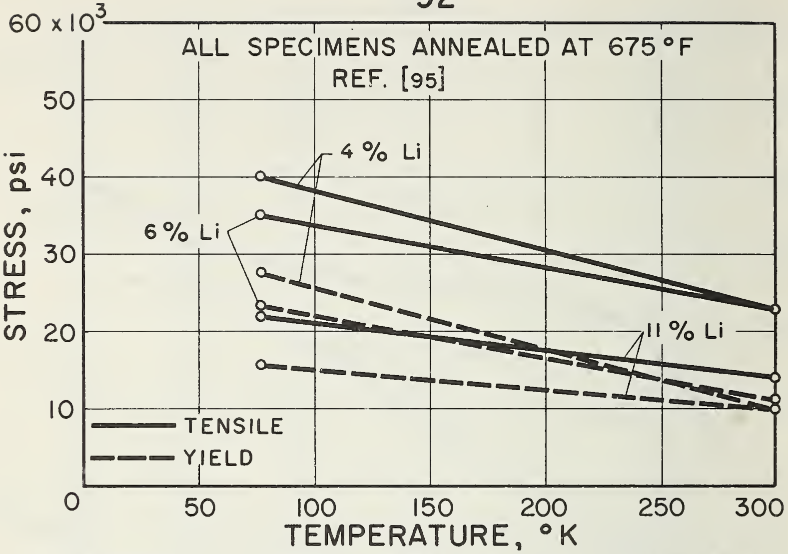
STRENGTH OF ZINC-RARE EARTH MAGNESIUM ALLOYS



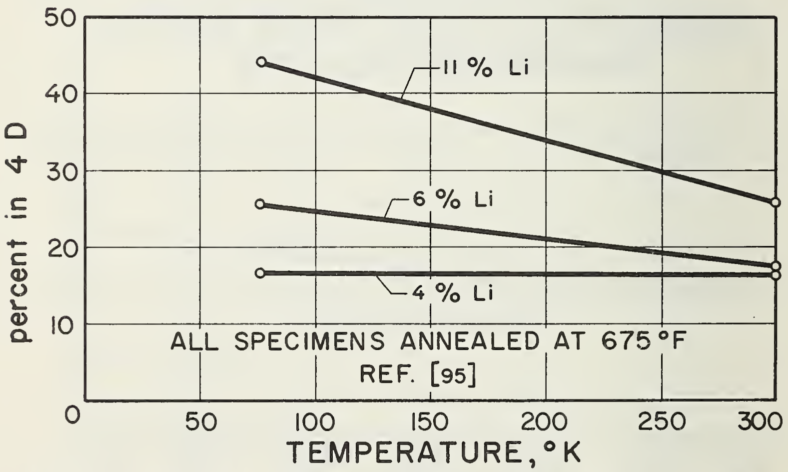
ELONGATION OF ZINC-RARE EARTH MAGNESIUM ALLOYS



IMPACT ENERGY OF ZINC-RARE EARTH MAGNESIUM ALLOYS



STRENGTH OF LITHIUM - MAGNESIUM ALLOYS



ELONGATION OF LITHIUM - MAGNESIUM ALLOYS

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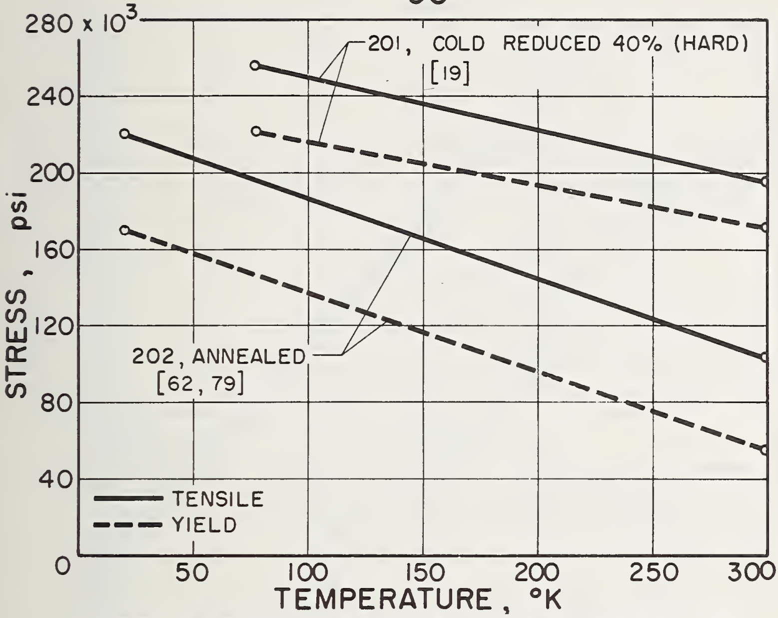
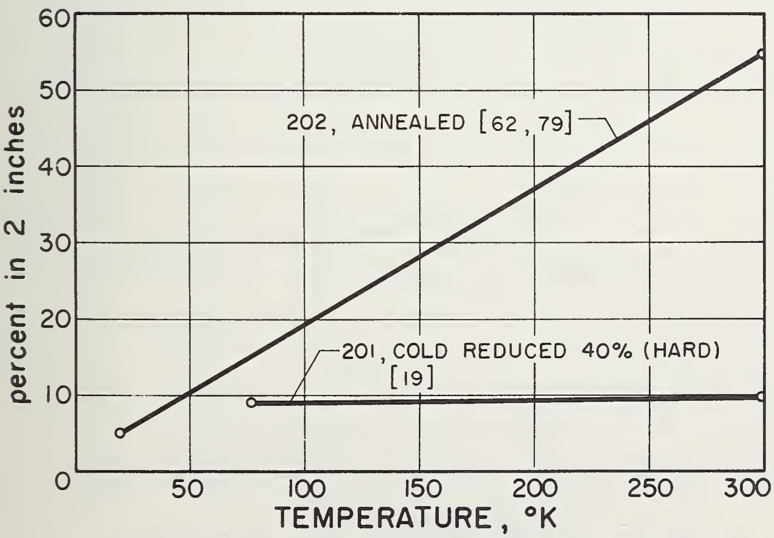
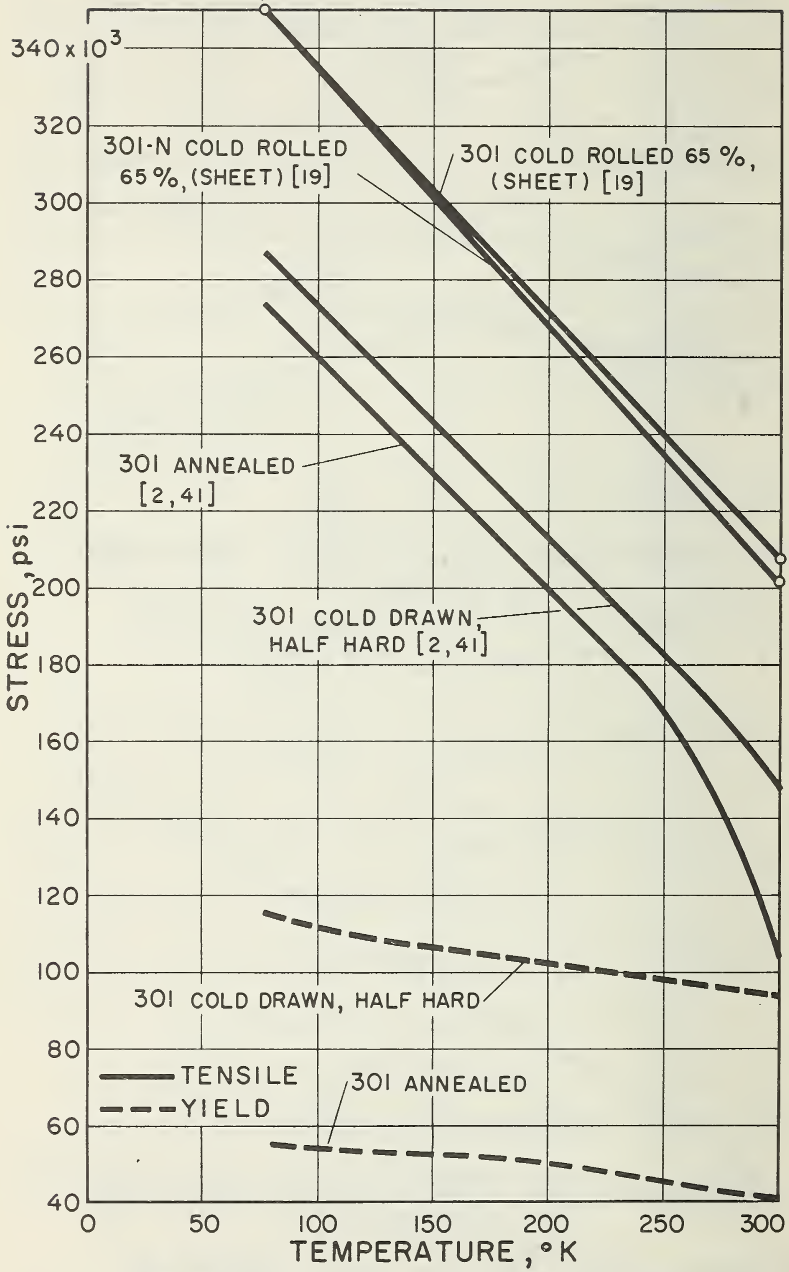


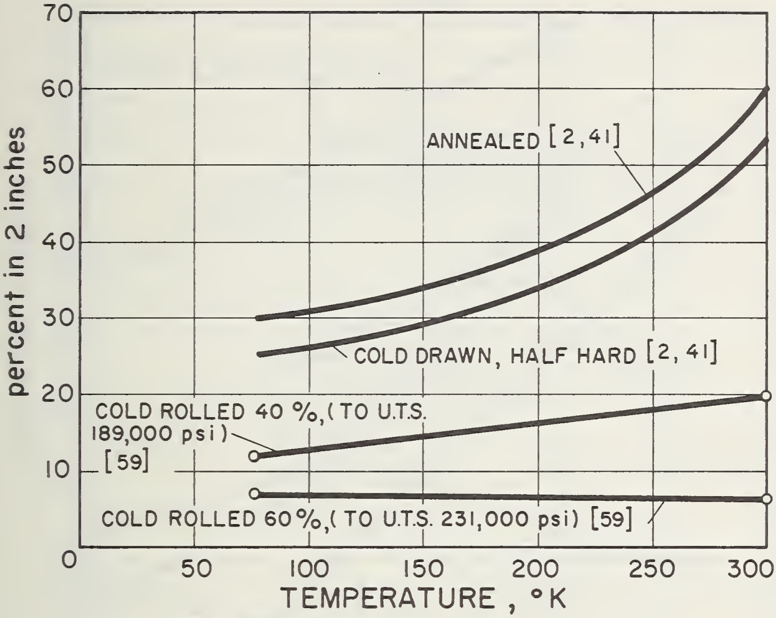
STRENGTH OF AISI 200 SERIES STAINLESS STEELS



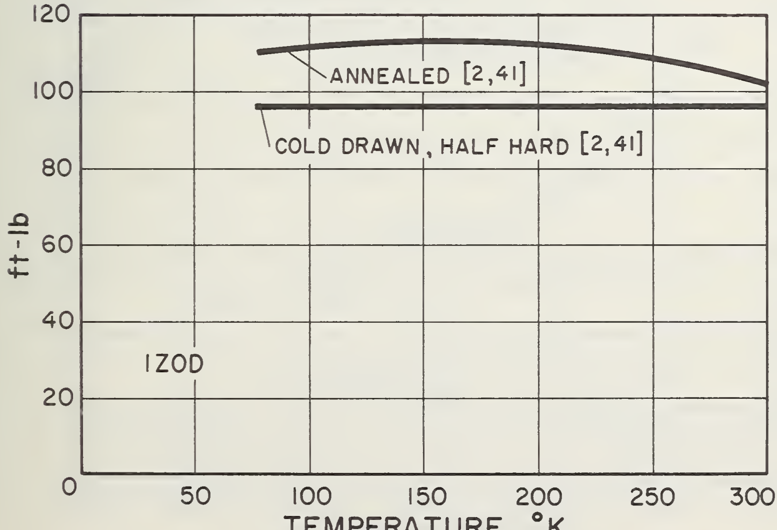
ELONGATION OF AISI 200 SERIES STAINLESS STEELS



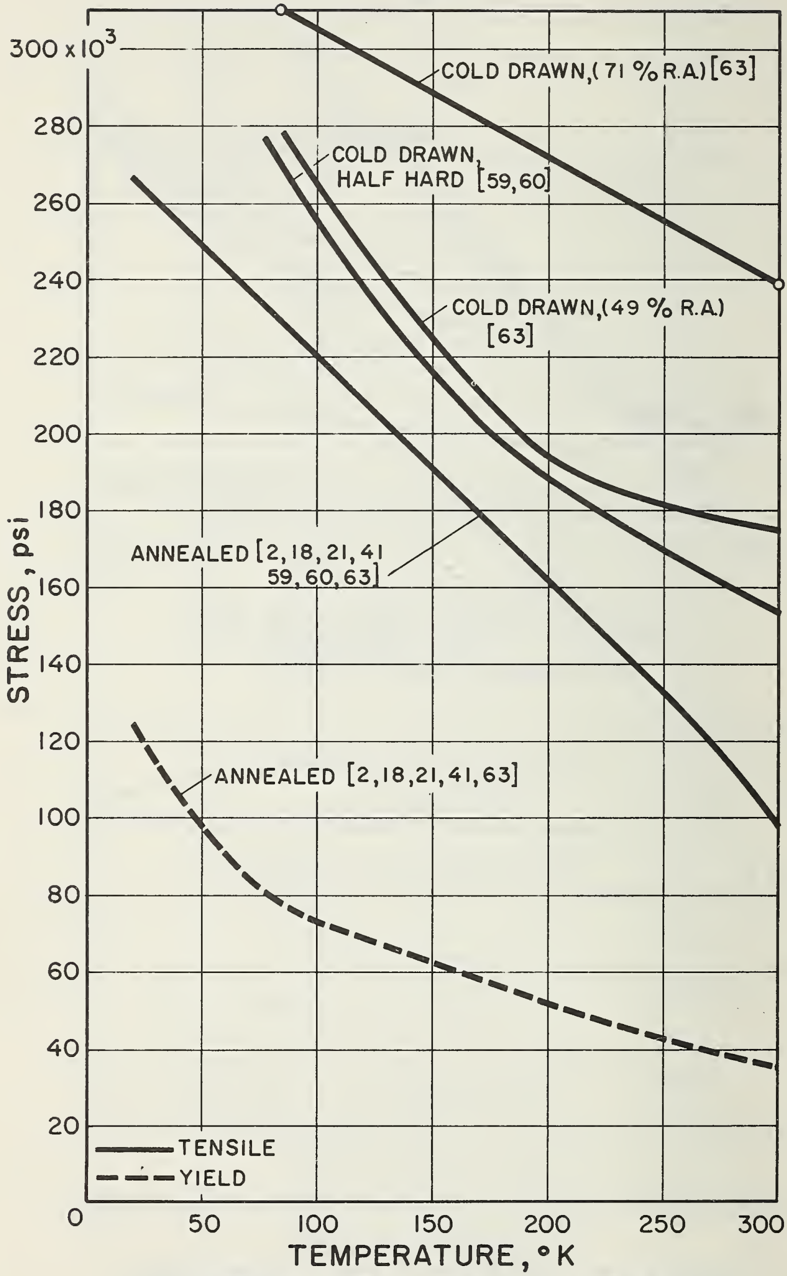
STRENGTH OF AISI 301 & 301-N STAINLESS STEEL



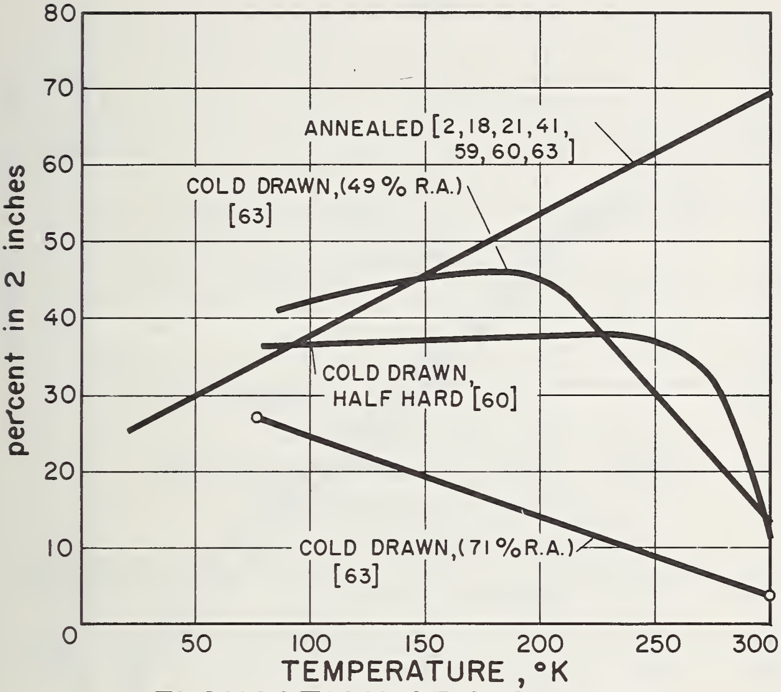
ELONGATION OF AISI 301 STAINLESS STEEL



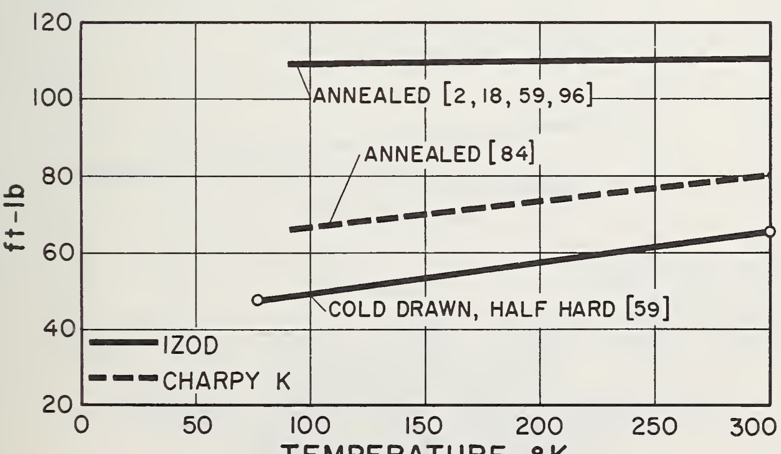
IMPACT ENERGY OF AISI 301 STAINLESS STEEL



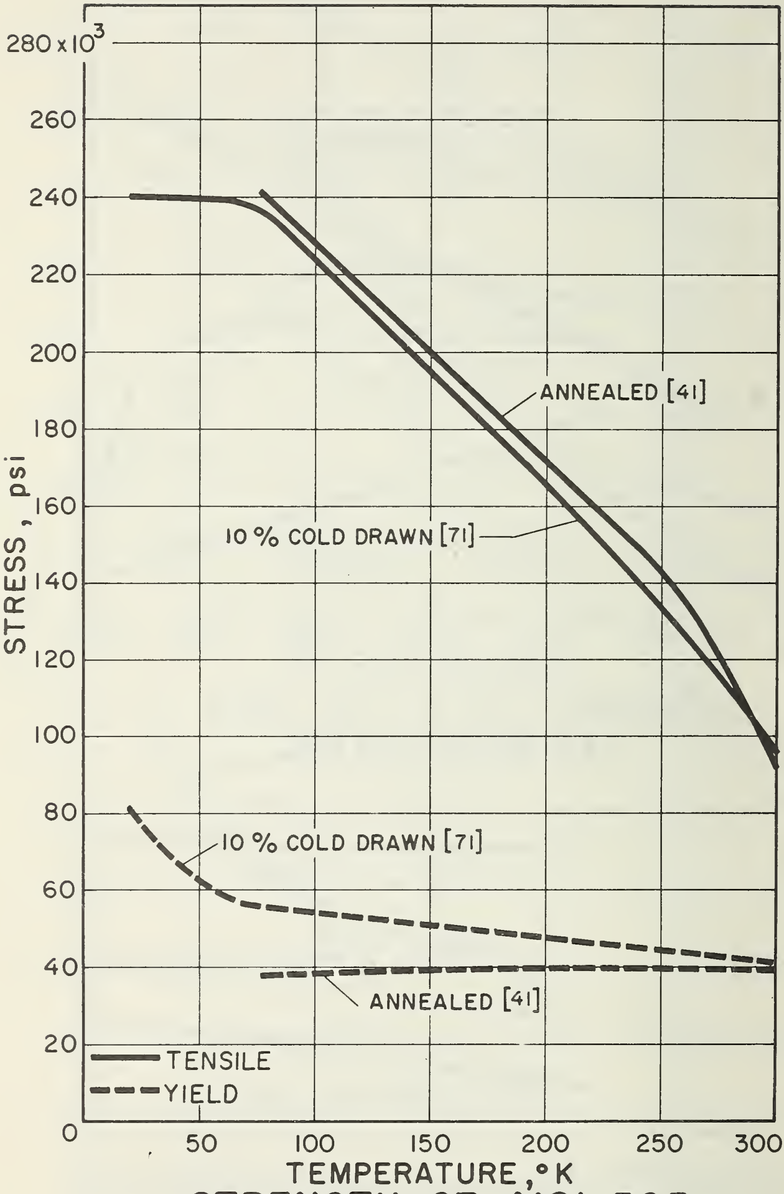
STRENGTH OF AISI 302 STAINLESS STEEL



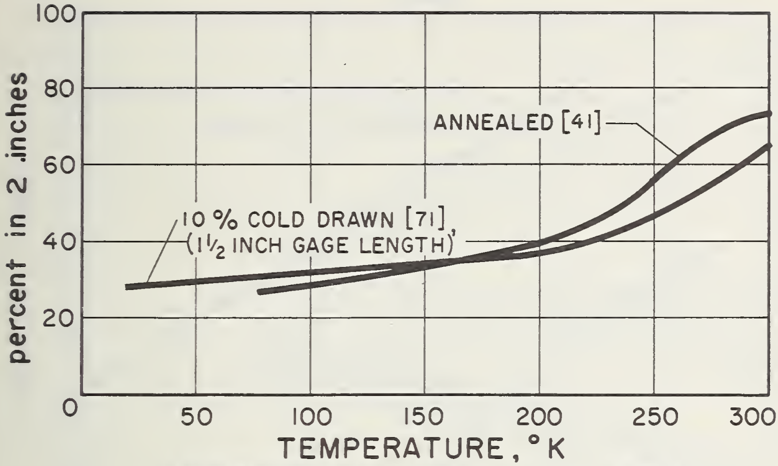
ELONGATION OF AISI 302 STAINLESS STEEL



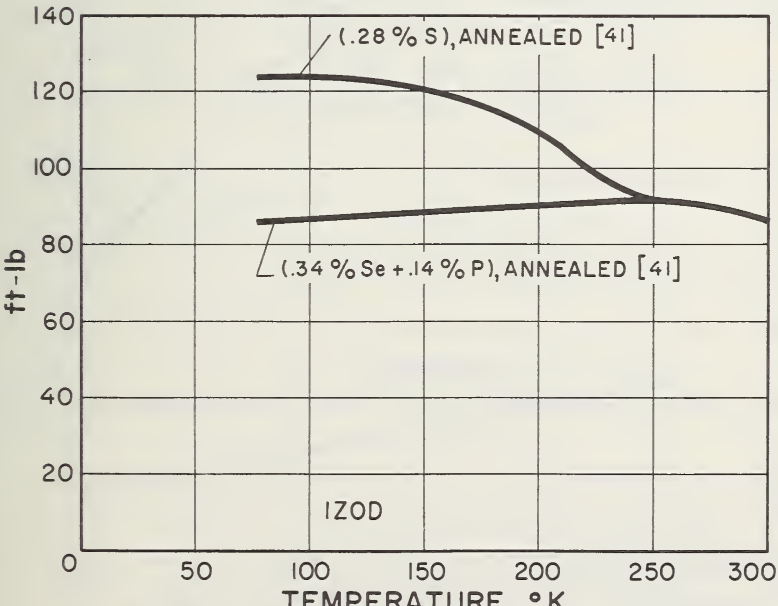
IMPACT ENERGY OF AISI 302 STAINLESS STEEL



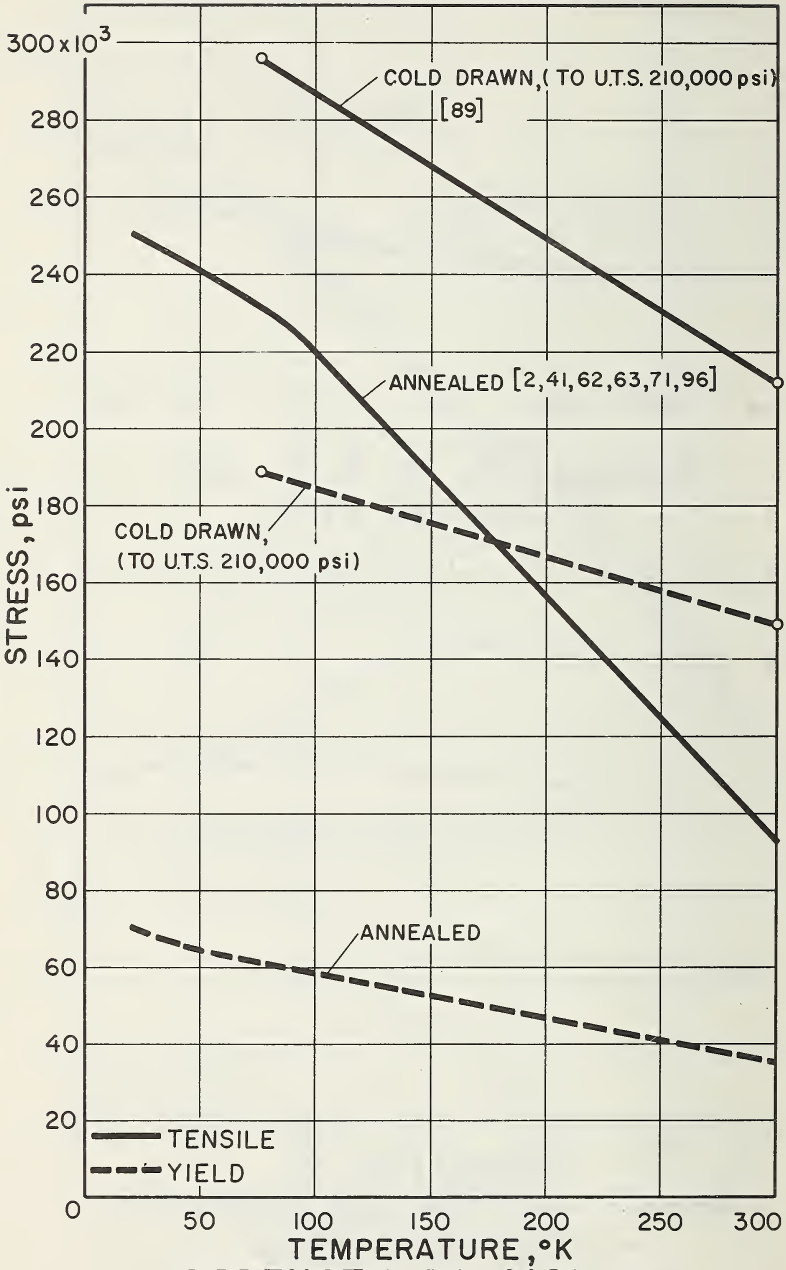
STRENGTH OF AISI 303 STAINLESS STEEL



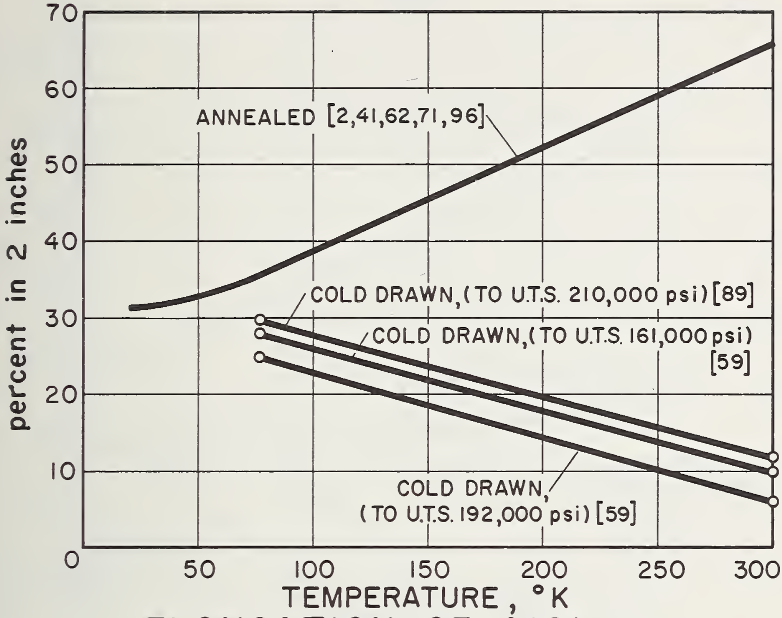
ELONGATION OF AISI 303 STAINLESS STEEL



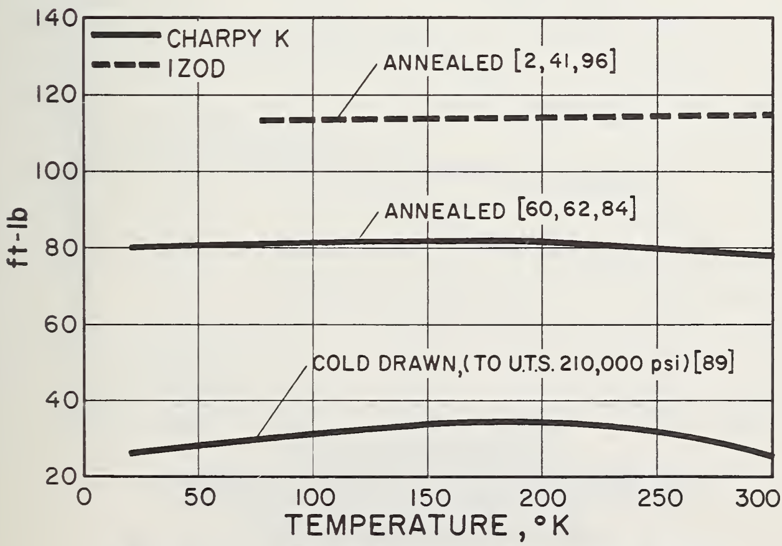
IMPACT ENERGY OF AISI 303 STAINLESS STEEL



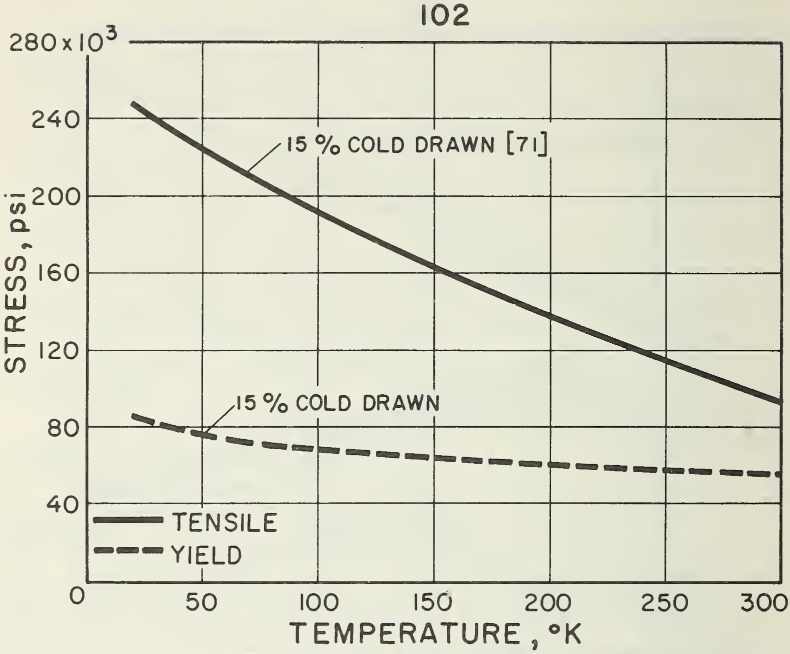
STRENGTH OF AISI 304
STAINLESS STEEL



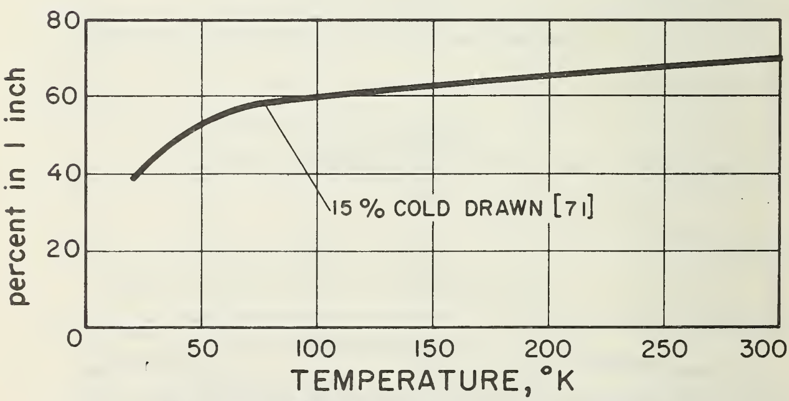
ELONGATION OF AISI 304 STAINLESS STEEL



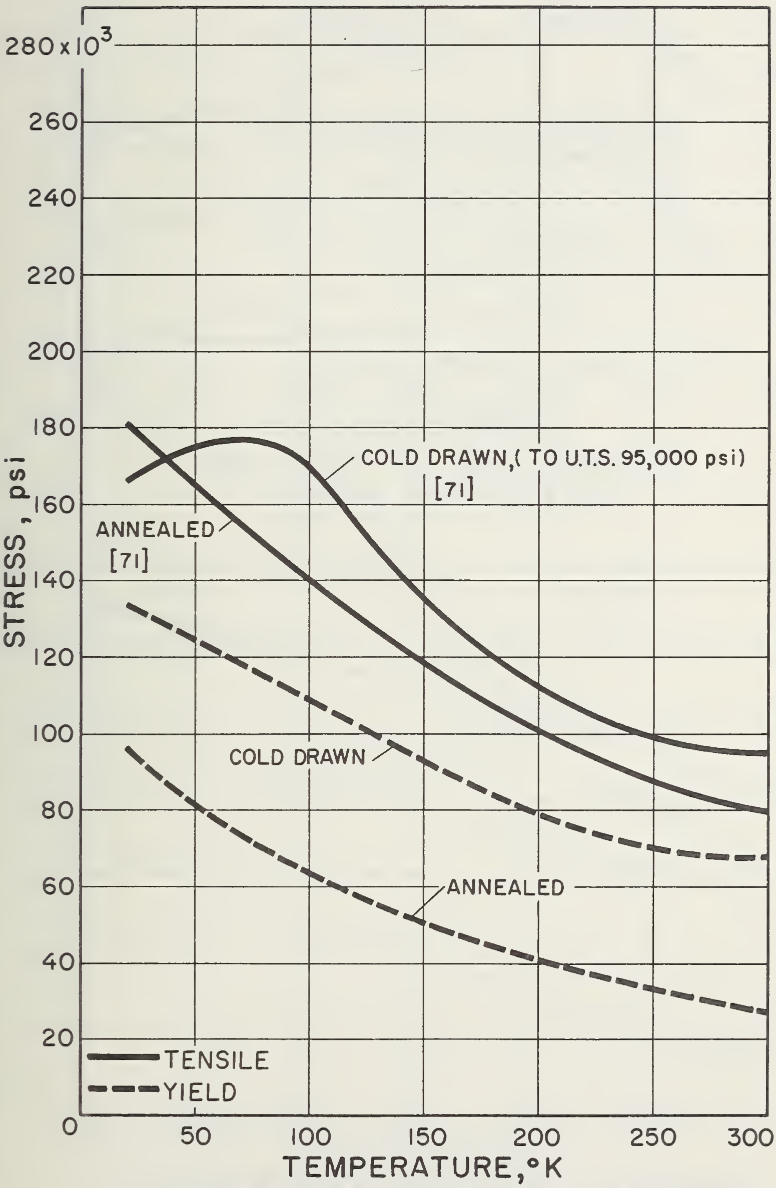
IMPACT ENERGY OF AISI 304 STAINLESS STEEL



STRENGTH OF AISI 308 STAINLESS STEEL



ELONGATION OF AISI 308 STAINLESS STEEL



STRENGTH OF AISI 310 STAINLESS STEEL

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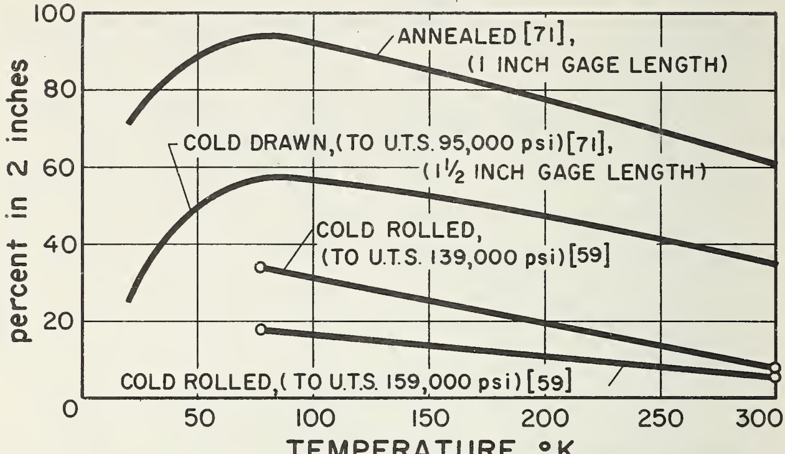
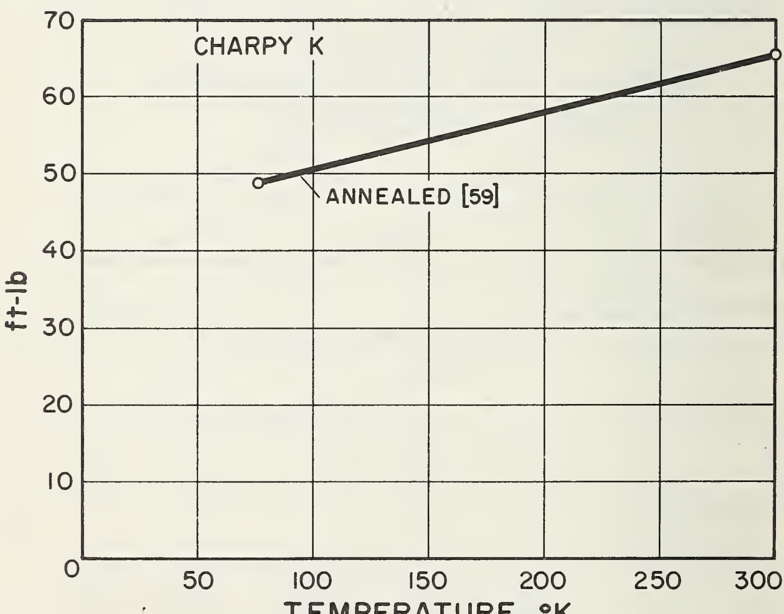
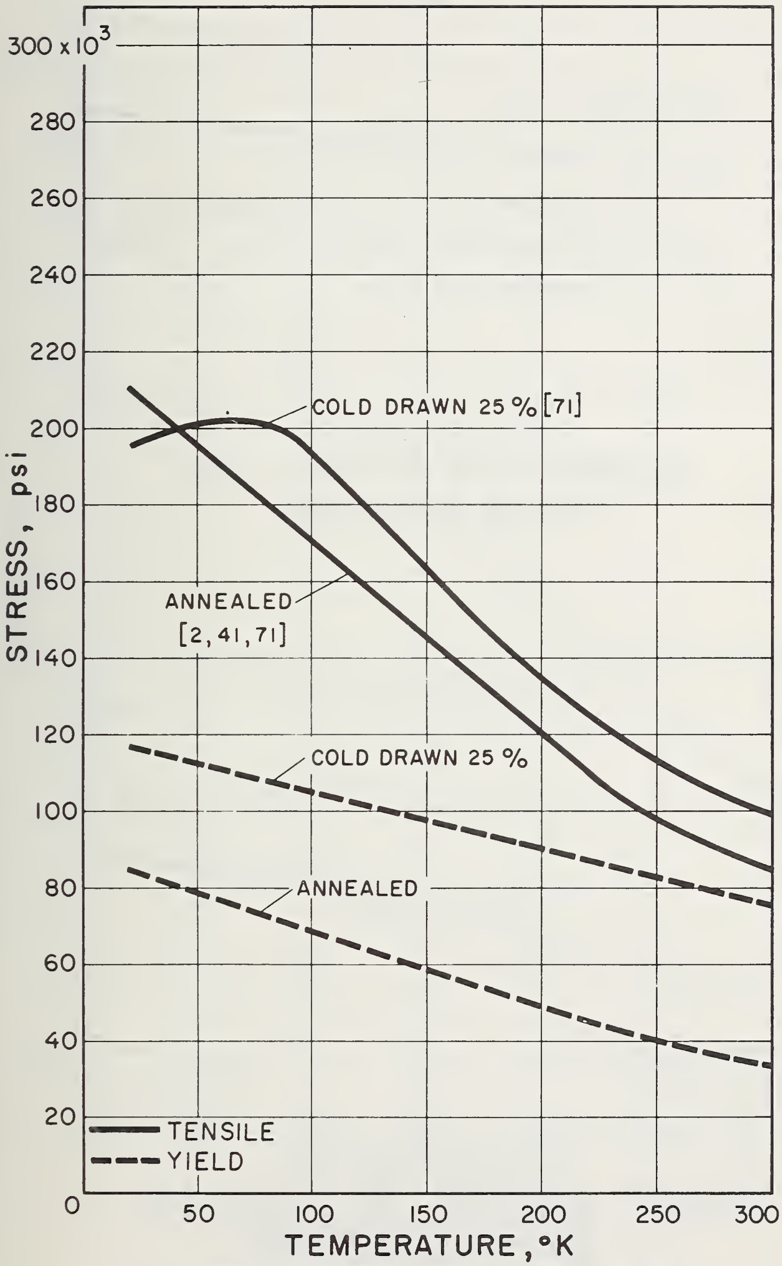


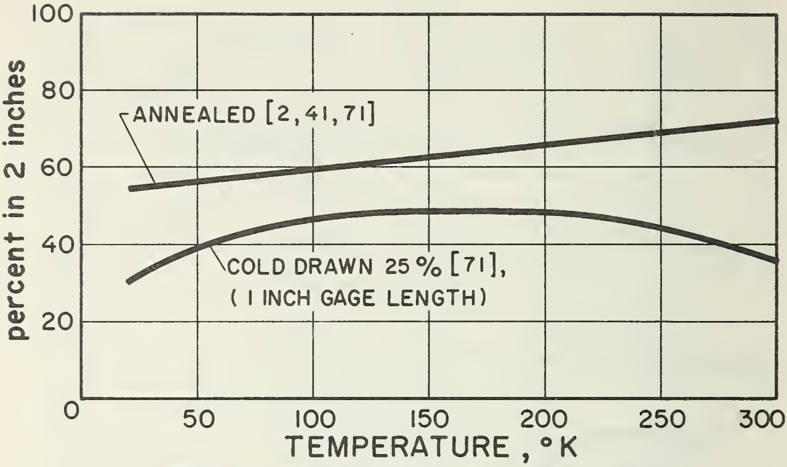
ELONGATION OF AISI 310 STAINLESS STEEL



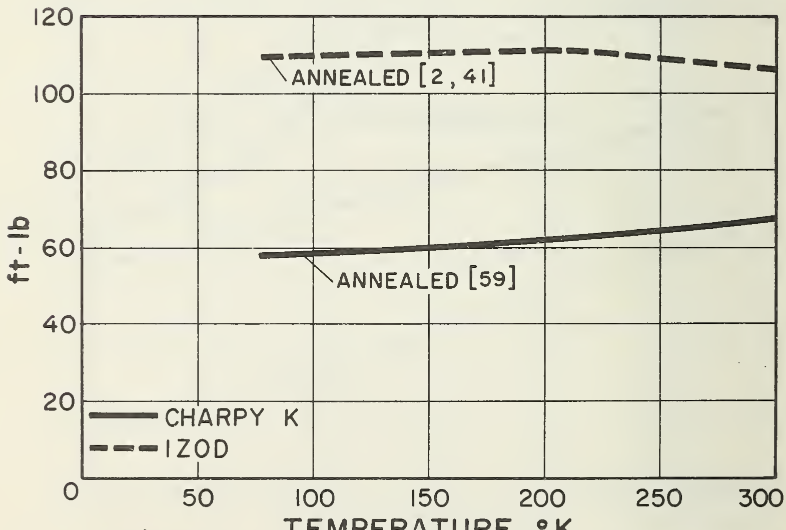
IMPACT ENERGY OF AISI 310 STAINLESS STEEL



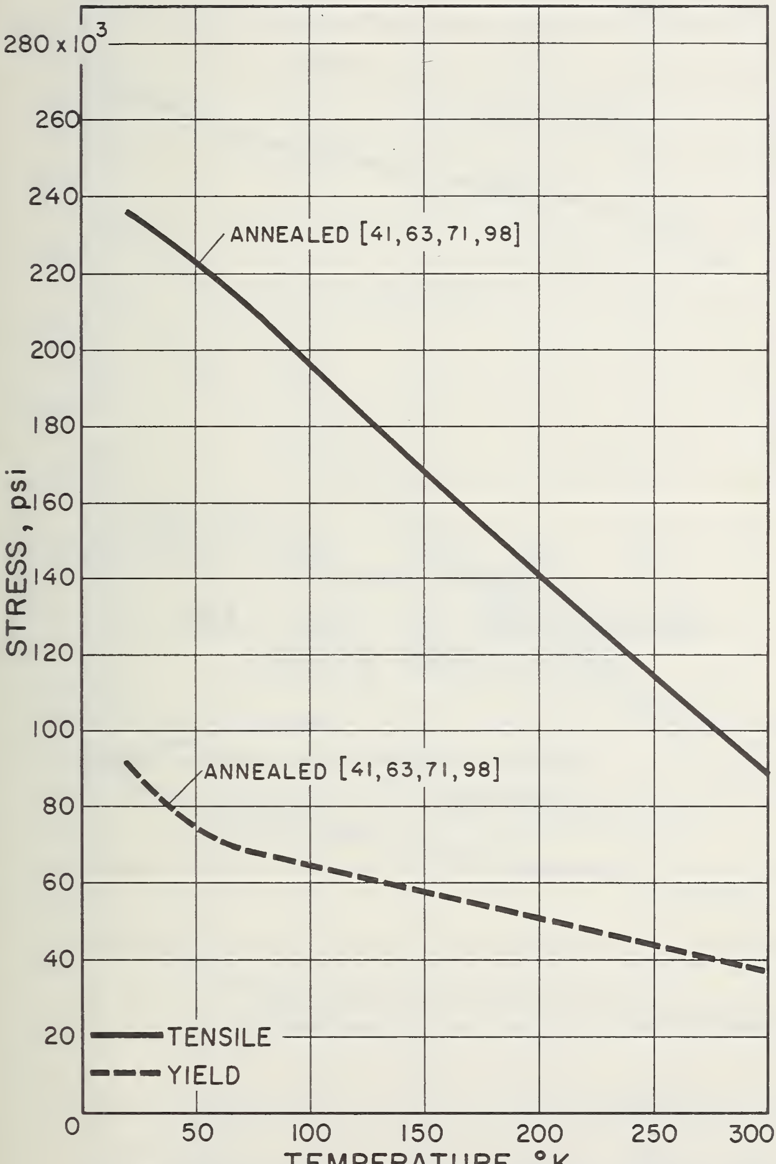
STRENGTH OF AISI 316
STAINLESS STEEL



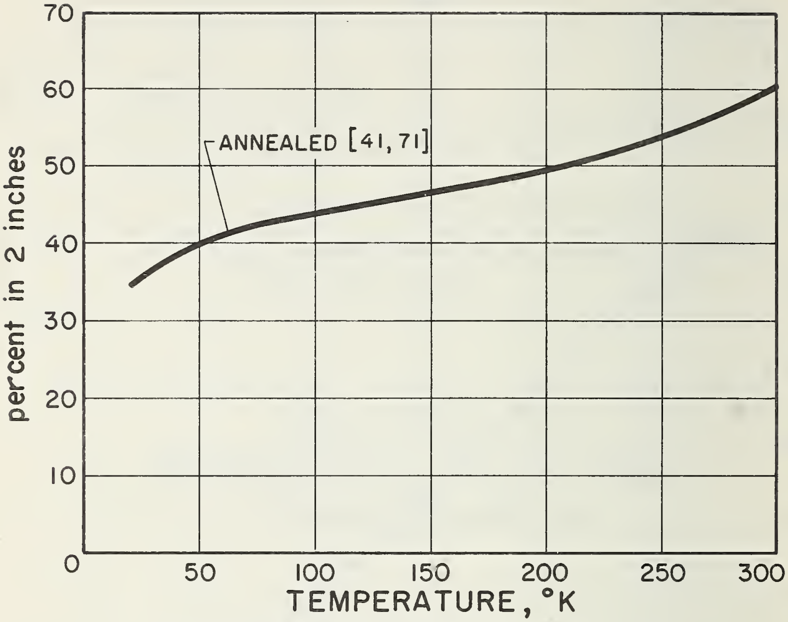
ELONGATION OF AISI 316 STAINLESS STEEL



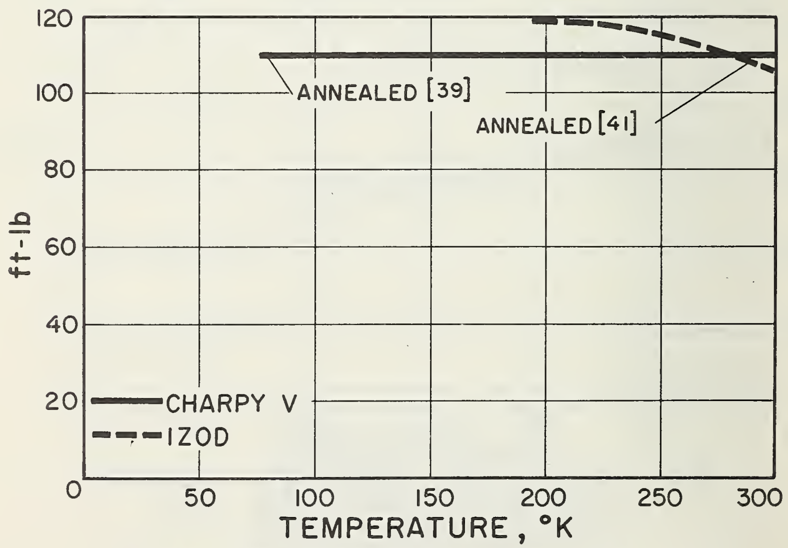
IMPACT ENERGY OF AISI 316 STAINLESS STEEL



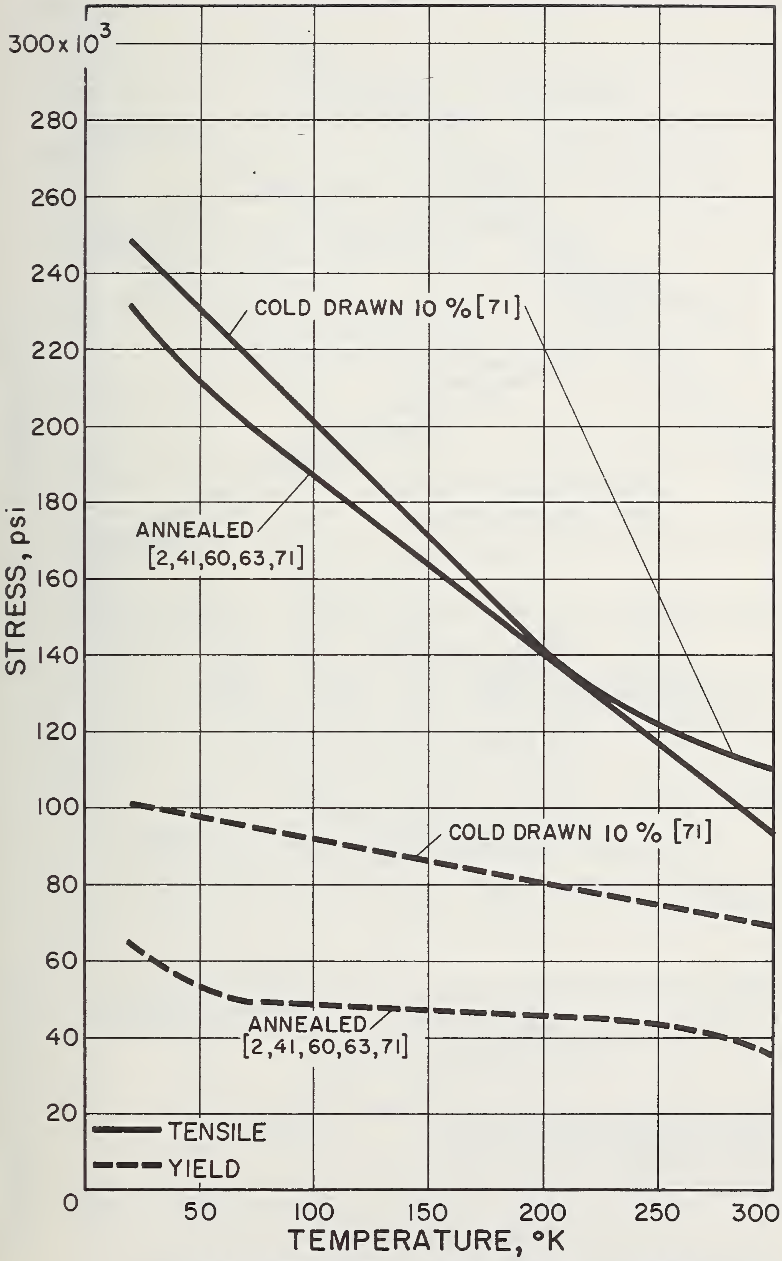
STRENGTH OF AISI 321 STAINLESS STEEL



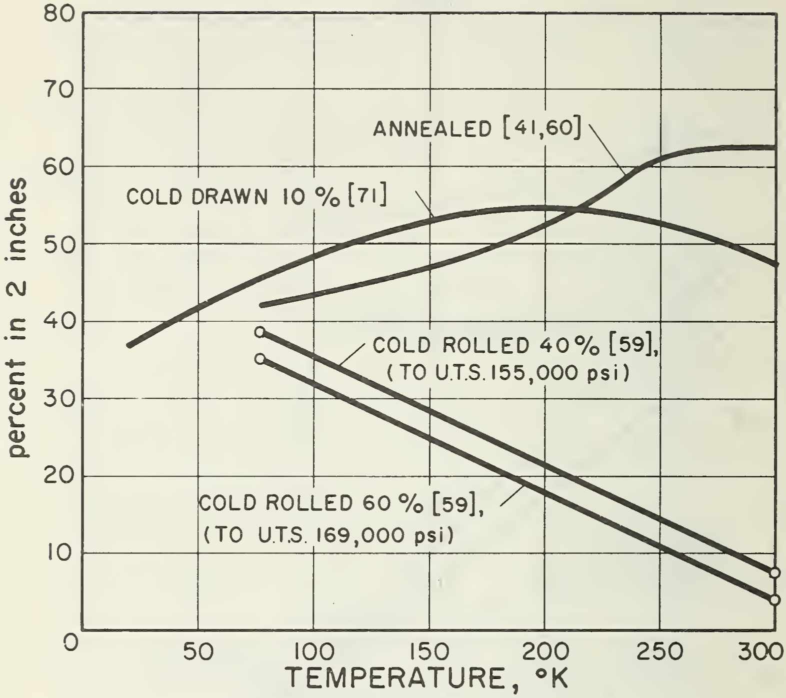
ELONGATION OF AISI 321 STAINLESS STEEL



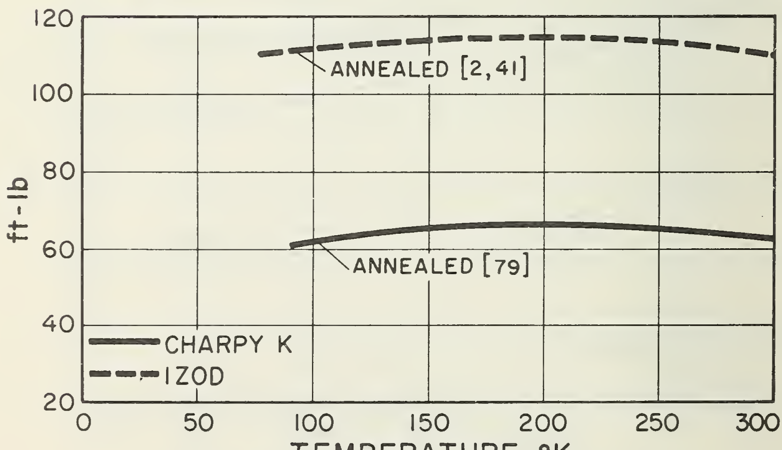
IMPACT ENERGY OF AISI 321 STAINLESS STEEL



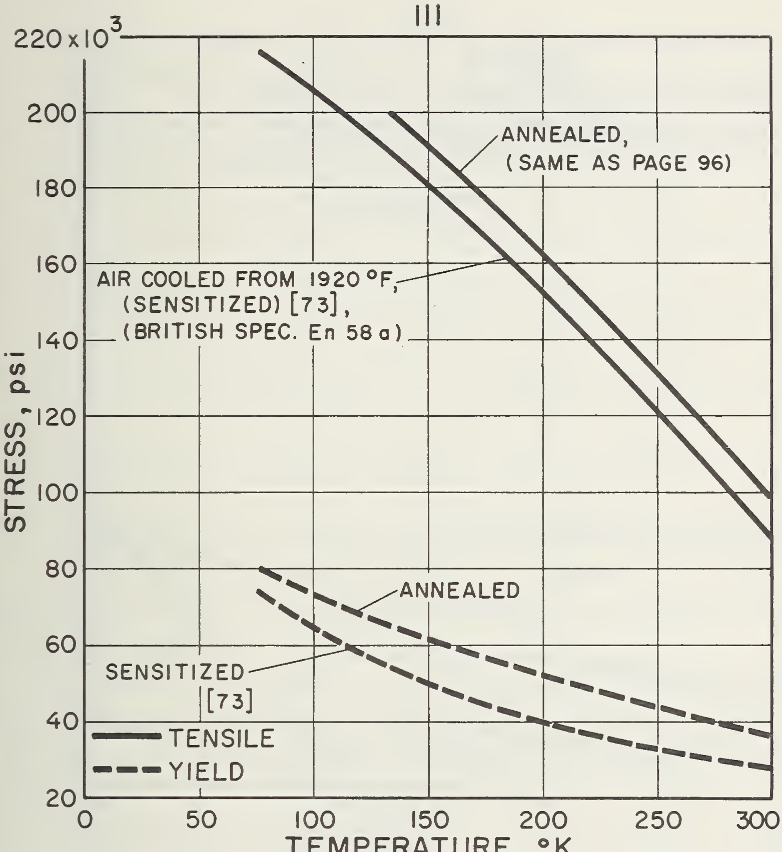
STRENGTH OF AISI 347
STAINLESS STEEL



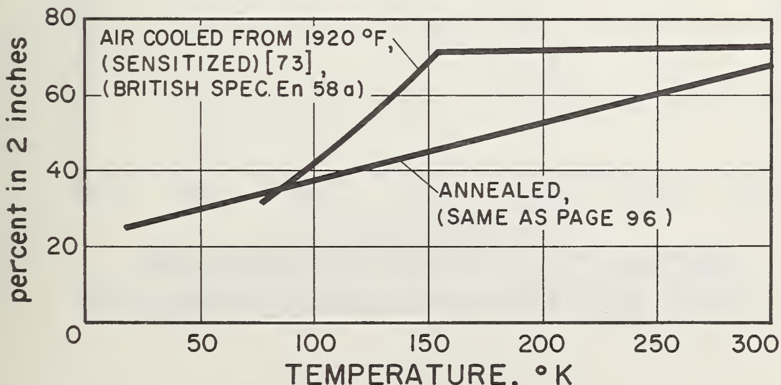
ELONGATION OF AISI 347 STAINLESS STEEL



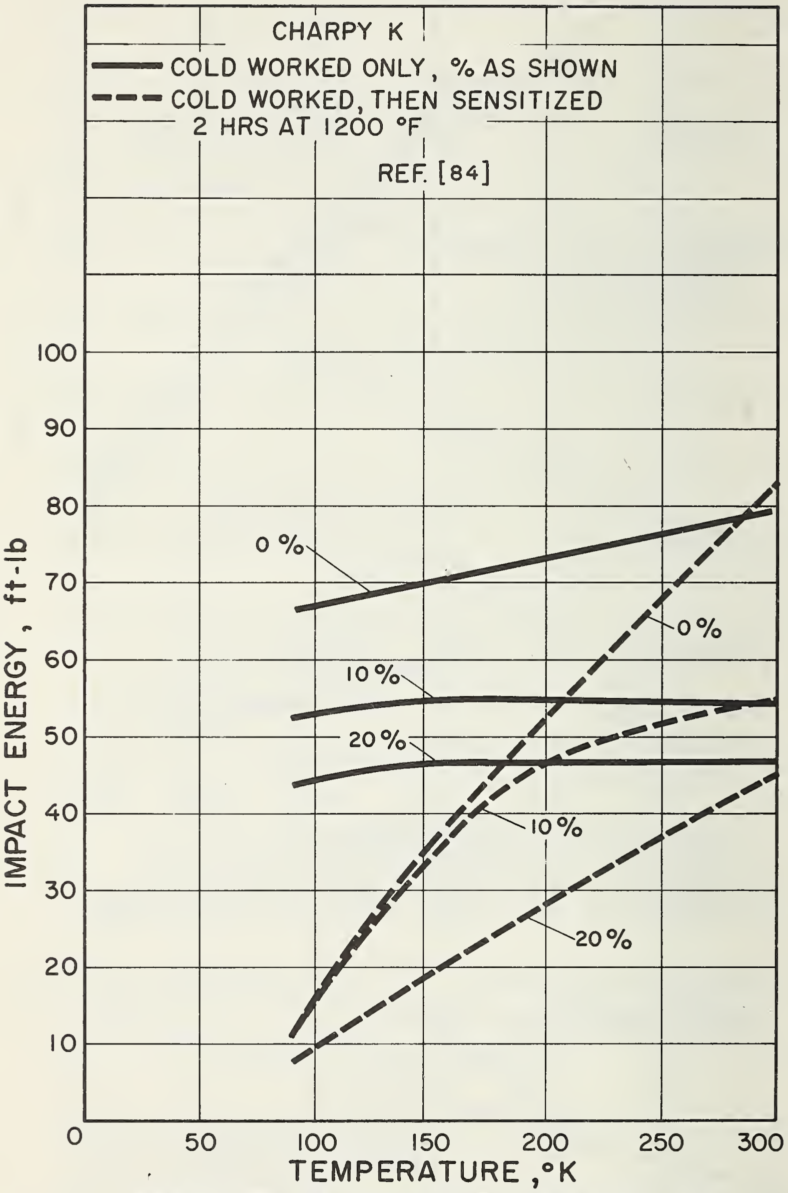
IMPACT ENERGY OF AISI 347 STAINLESS STEEL



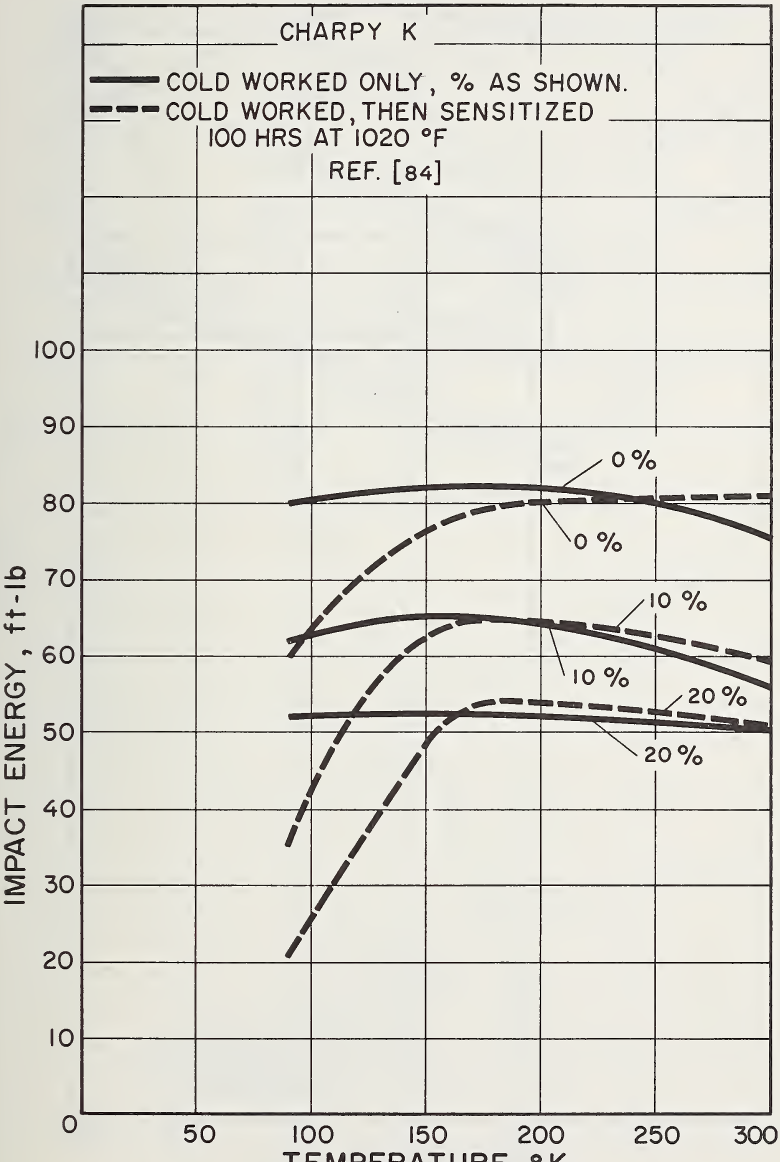
EFFECT OF SENSITIZATION ON STRENGTH OF AISI 302 STAINLESS



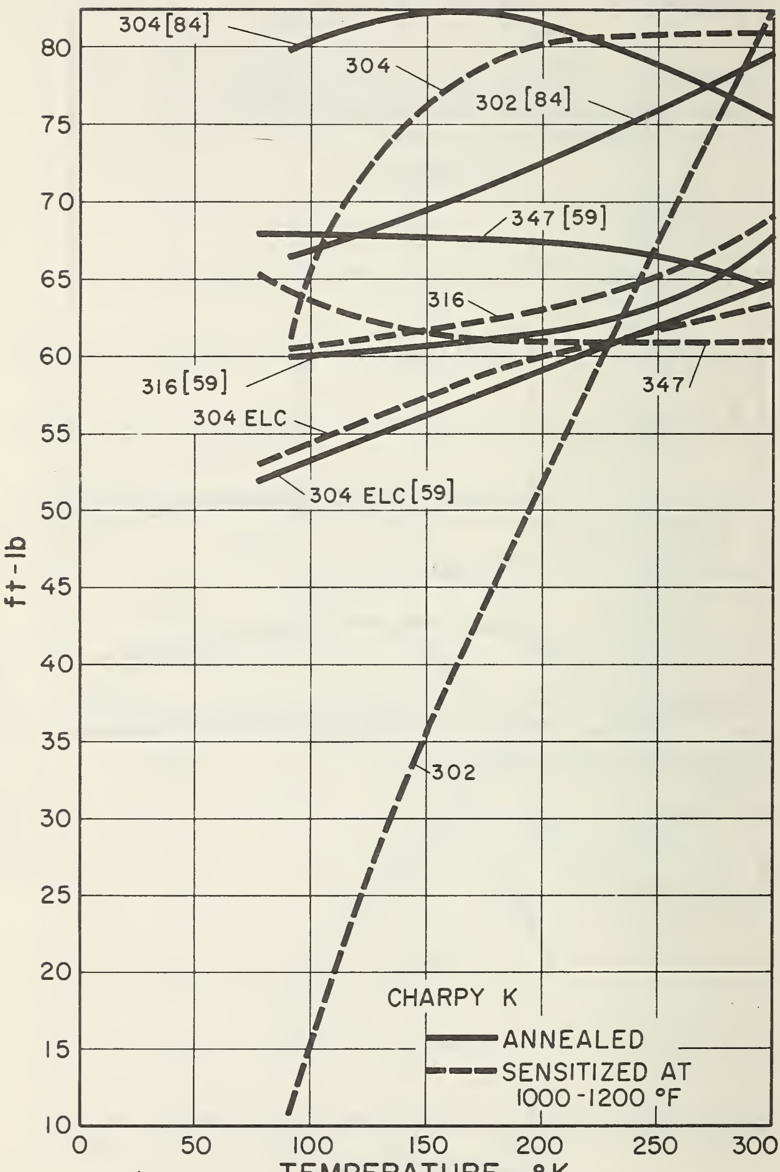
EFFECT OF SENSITIZATION ON ELONGATION OF AISI 302 STAINLESS



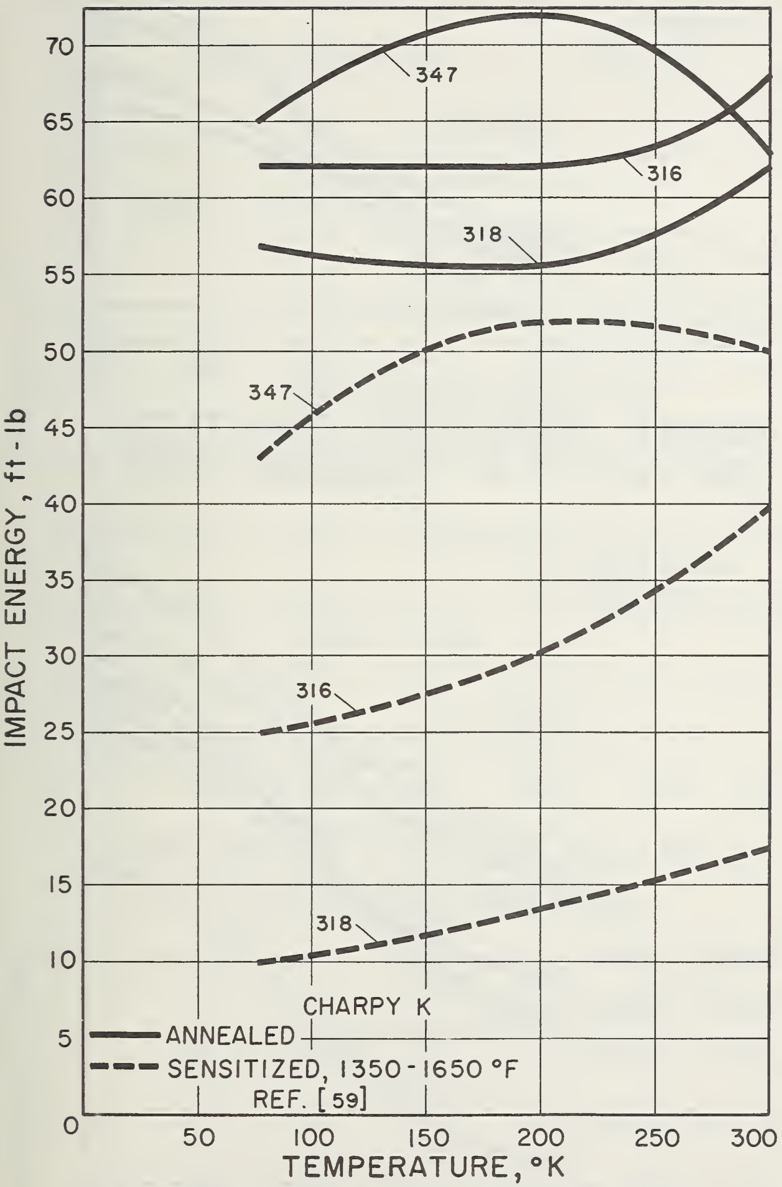
EFFECT OF SENSITIZATION ON COLD WORKED AISI 302 STAINLESS



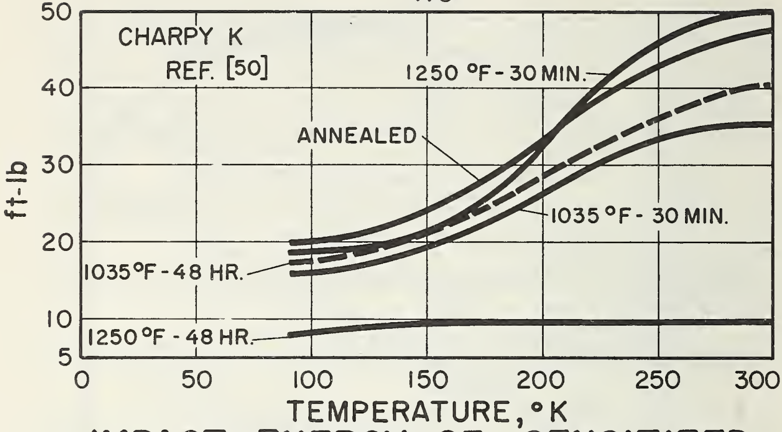
EFFECT OF SENSITIZATION ON COLD WORKED AISI 304



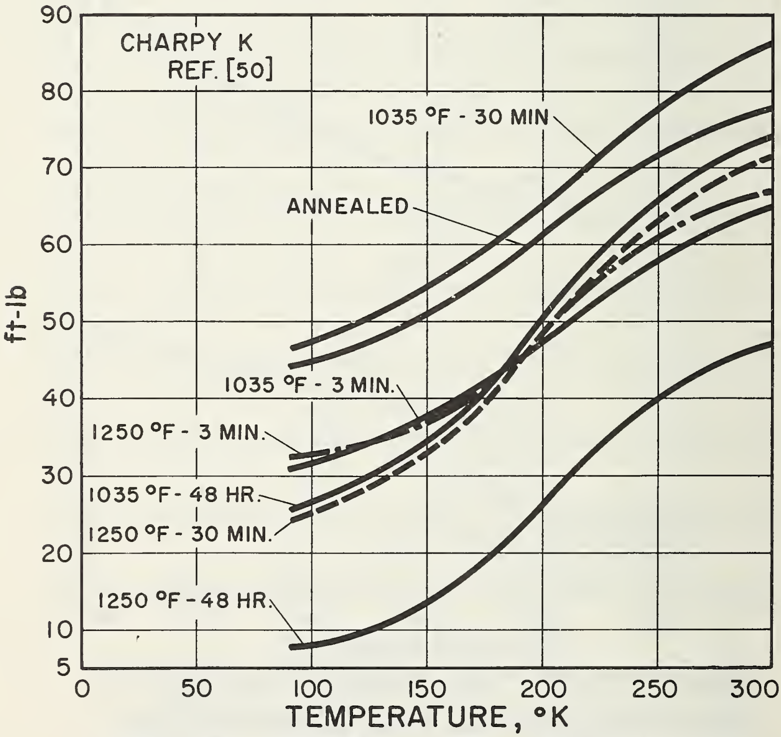
IMPACT ENERGY OF SENSITIZED WROUGHT STAINLESS STEELS



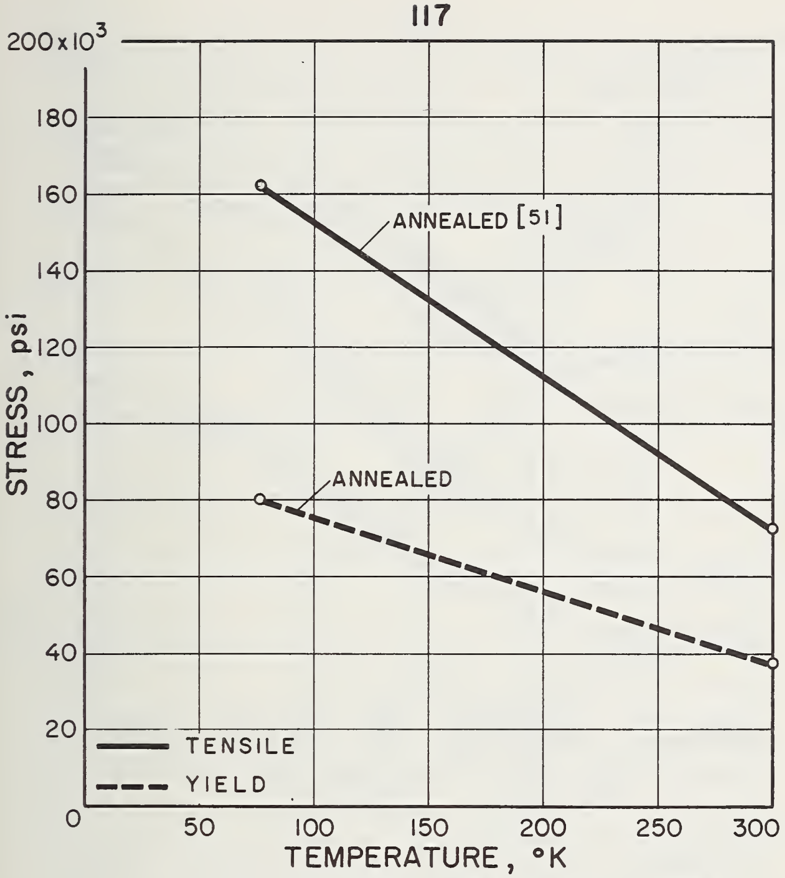
EFFECT OF THE SIGMA PHASE ON WROUGHT STAINLESS STEELS



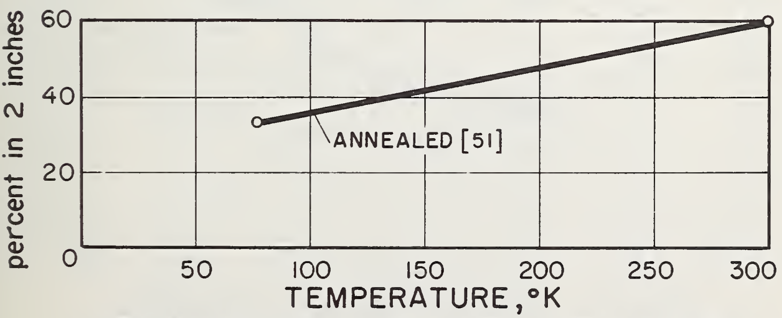
IMPACT ENERGY OF SENSITIZED CAST ACI-CF·8T STAINLESS STEEL



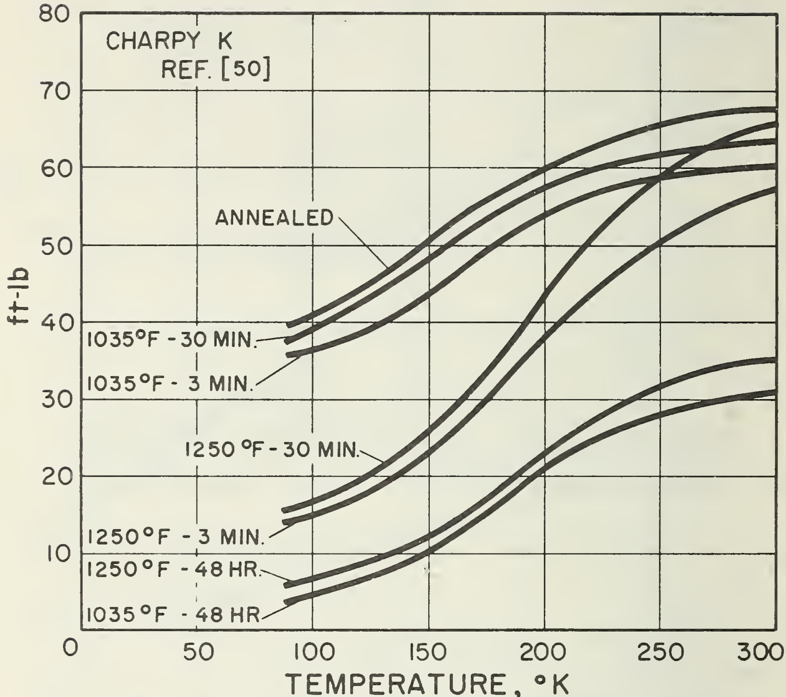
IMPACT ENERGY OF SENSITIZED CAST ACI-CF·20 STAINLESS STEEL



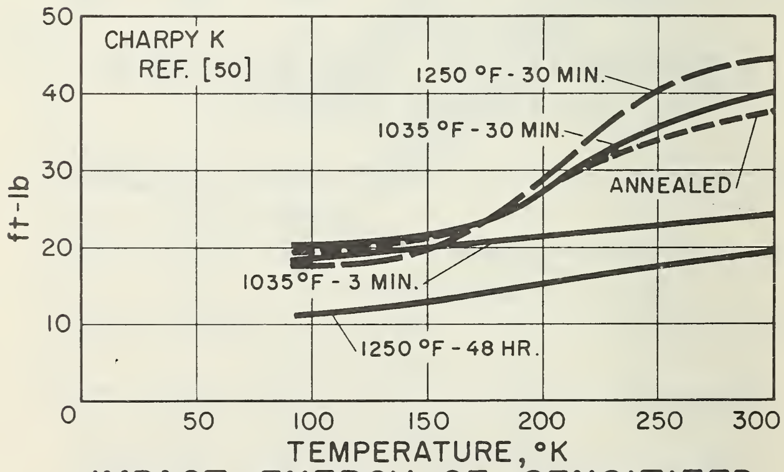
STRENGTH OF CAST ACI-CF·8 STAINLESS STEEL



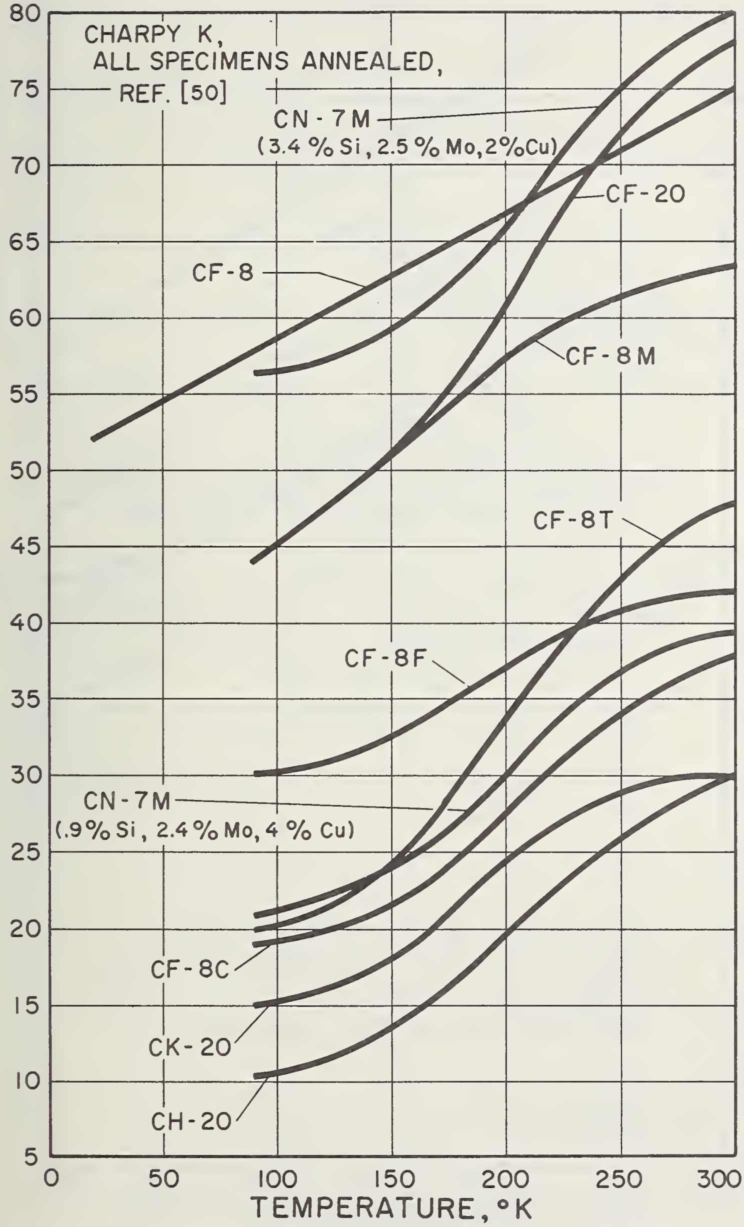
ELONGATION OF CAST ACI-CF·8 STAINLESS STEEL



IMPACT ENERGY OF SENSITIZED CAST ACI-CF-8 STAINLESS STEEL



IMPACT ENERGY OF SENSITIZED CAST ACI-CF-8C STAINLESS STEEL



IMPACT ENERGY OF CAST ACI STAINLESS STEELS

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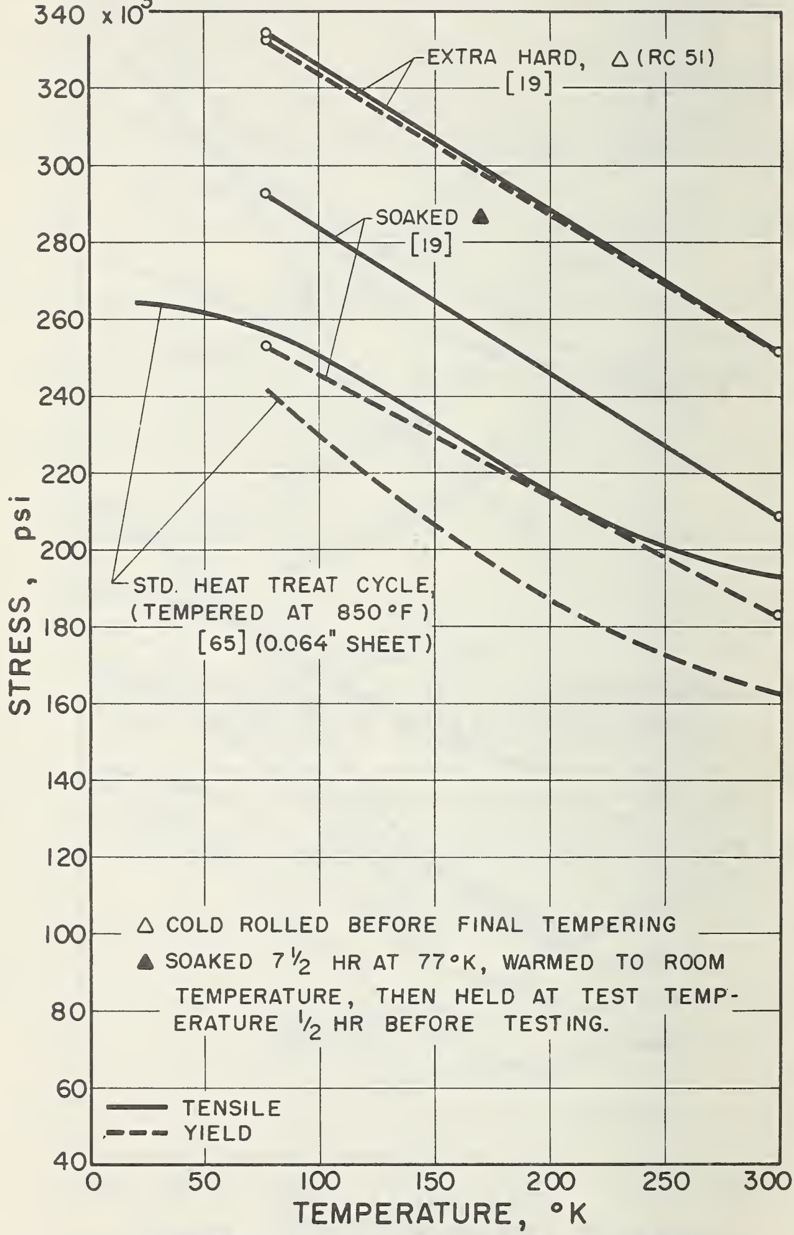
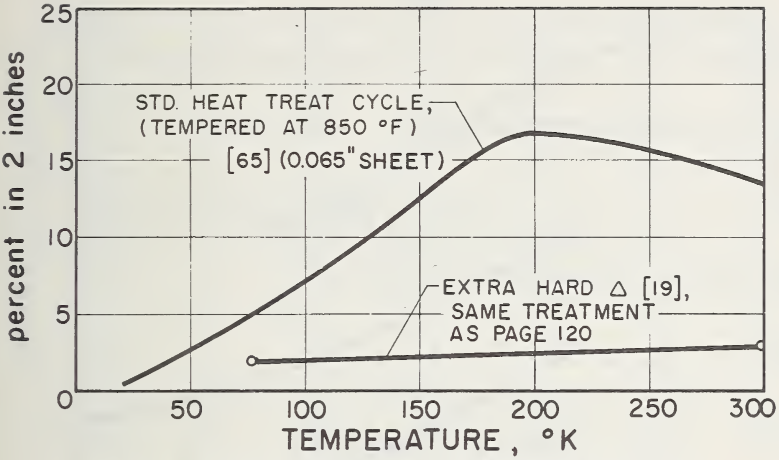
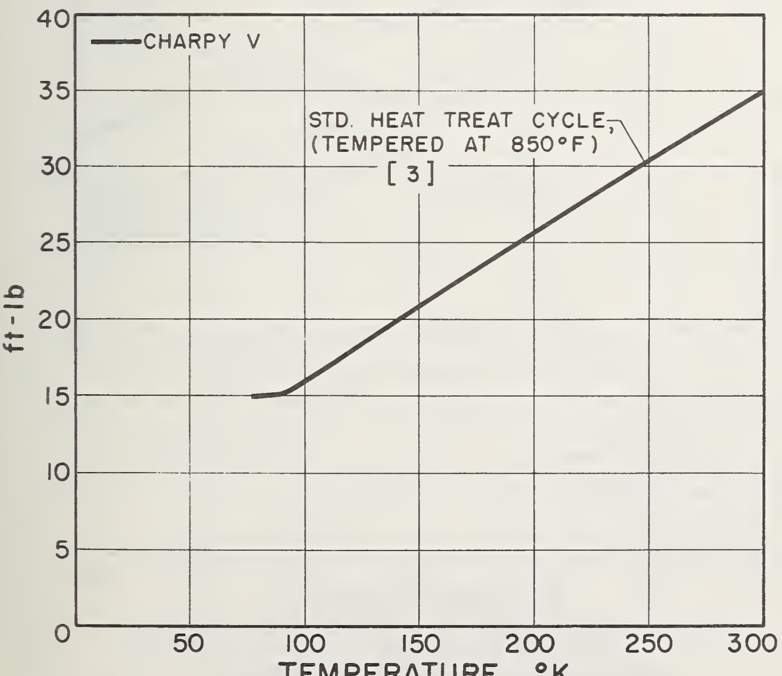


STRENGTH OF HARDENABLE AM-350 STAINLESS STEEL



ELONGATION OF HARDENABLE AM 350 STAINLESS STEEL



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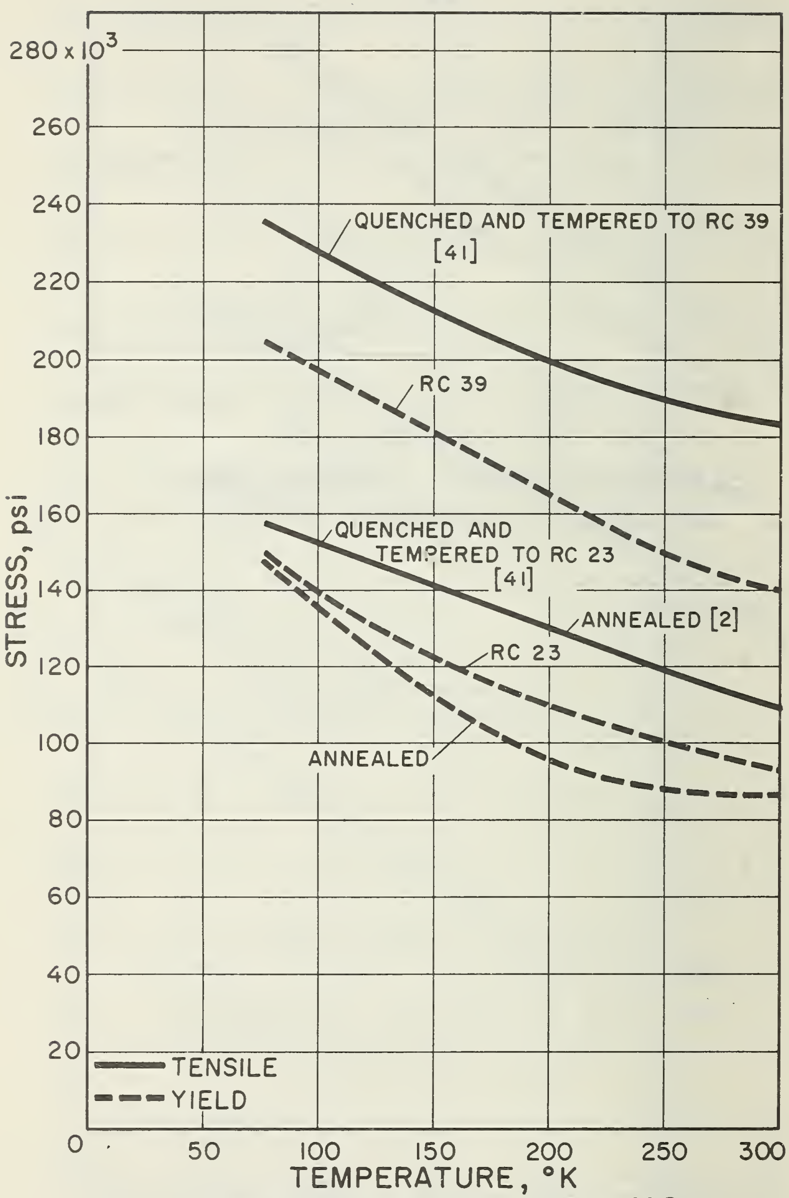
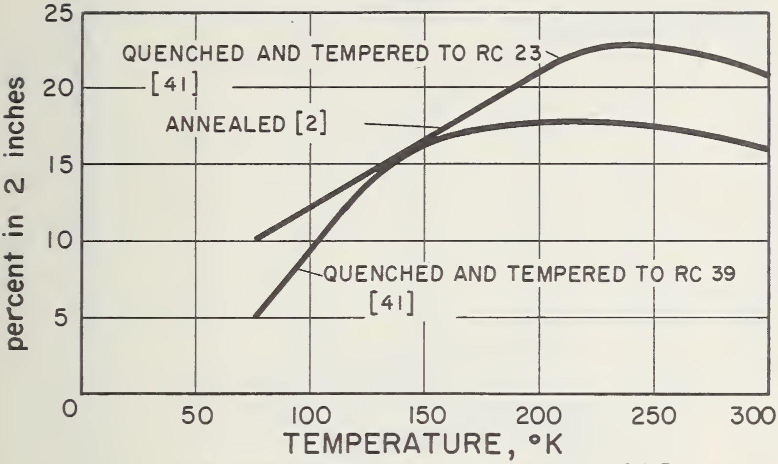
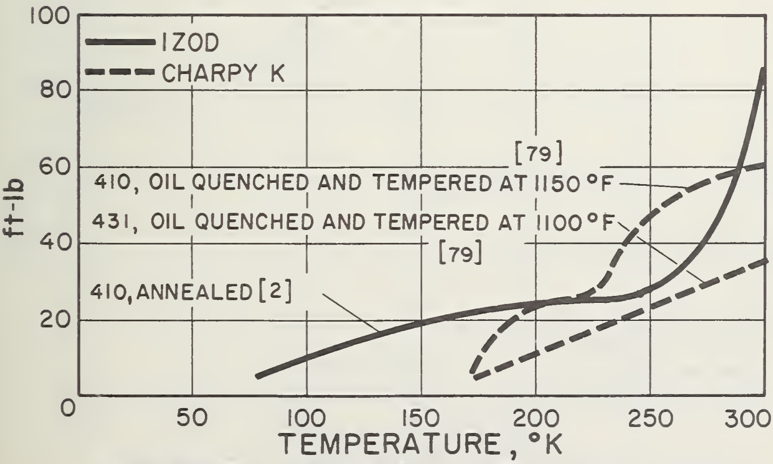


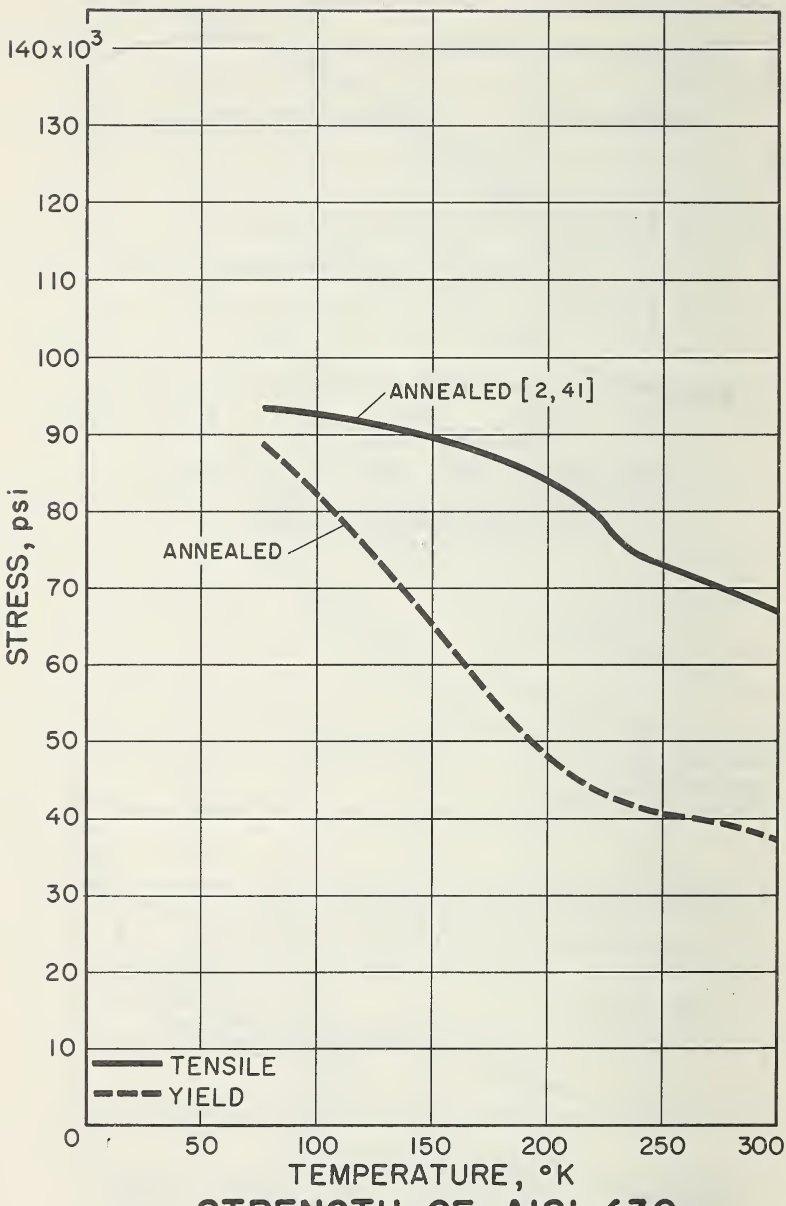
STRENGTH OF AISI 410 STAINLESS STEEL



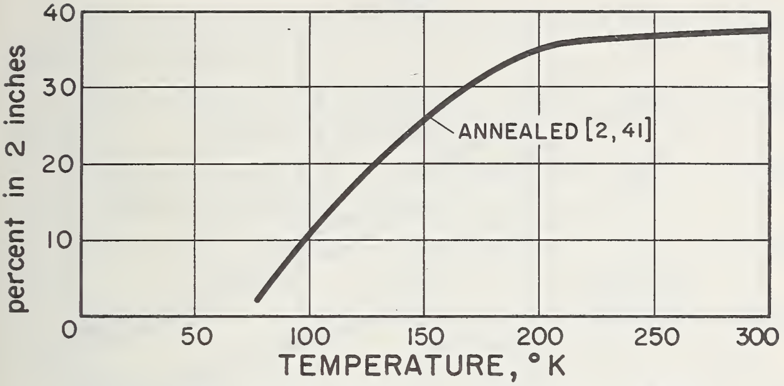
ELONGATION OF AISI 410 STAINLESS STEEL



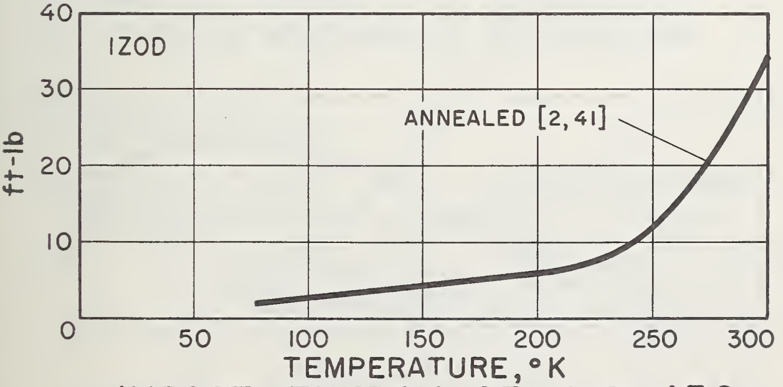
IMPACT ENERGY OF AISI 400 SERIES STAINLESS STEEL



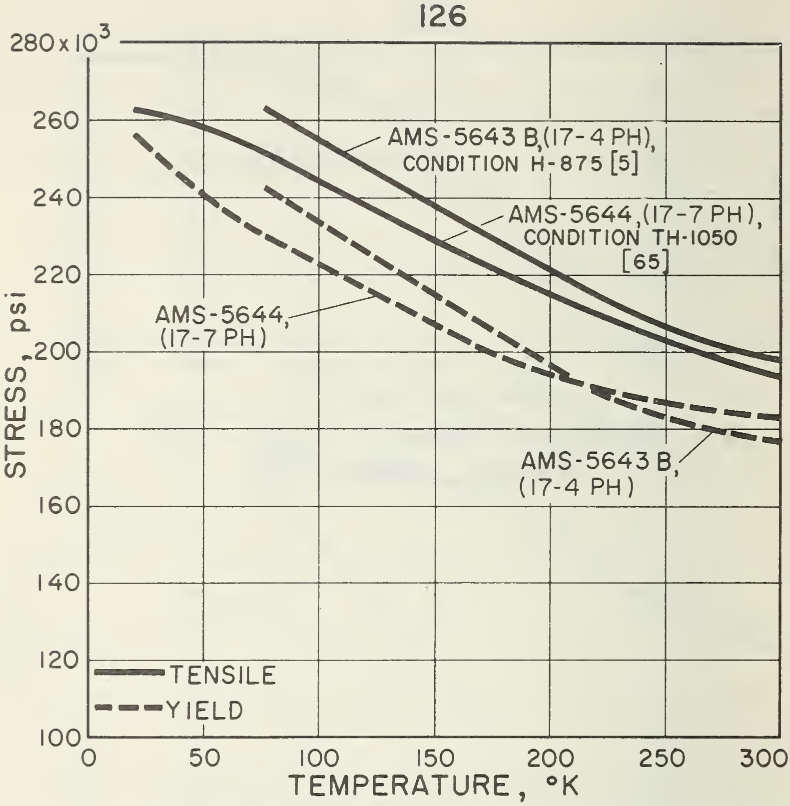
STRENGTH OF AISI 430 STAINLESS STEEL



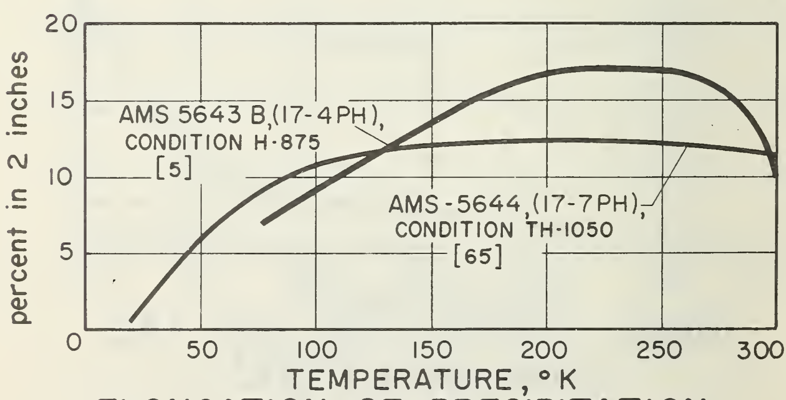
ELONGATION OF AISI 430 STAINLESS STEEL



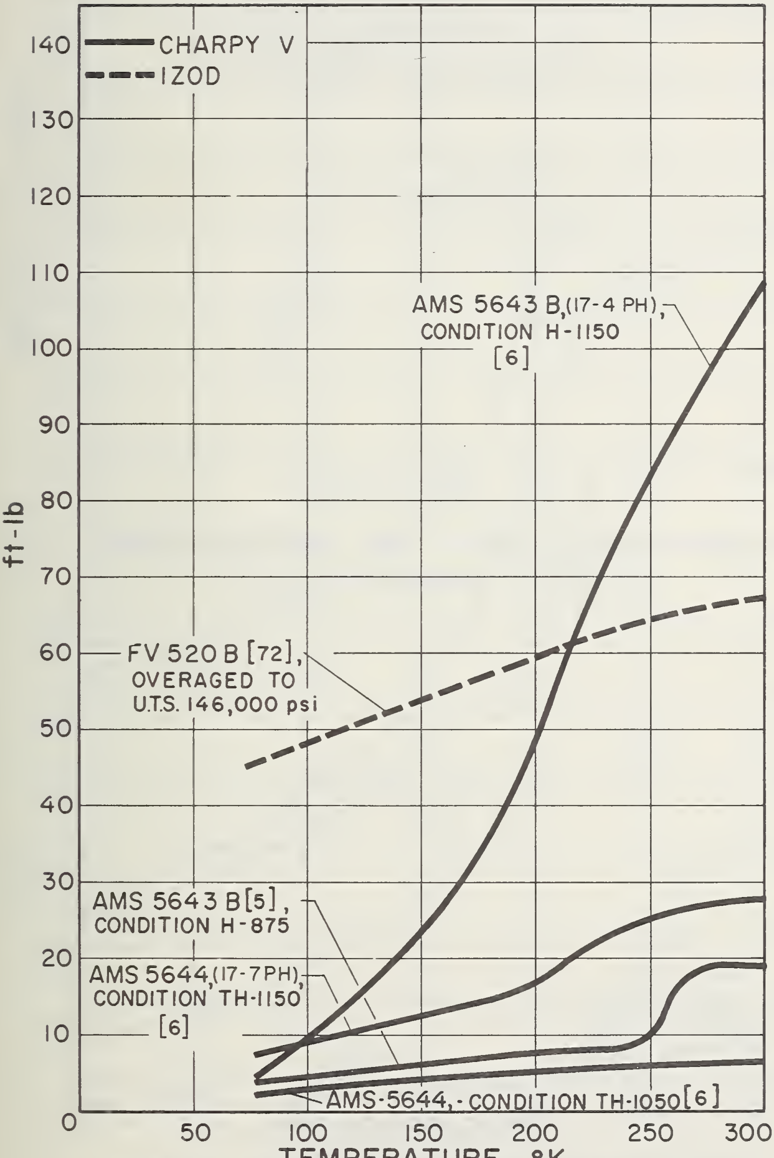
IMPACT ENERGY OF AISI 430 STAINLESS STEEL



STRENGTH OF PRECIPITATION HARDENING STAINLESS STEELS



ELONGATION OF PRECIPITATION HARDENING STAINLESS STEELS



IMPACT ENERGY OF PRECIPITATION HARDENING STAINLESS STEELS

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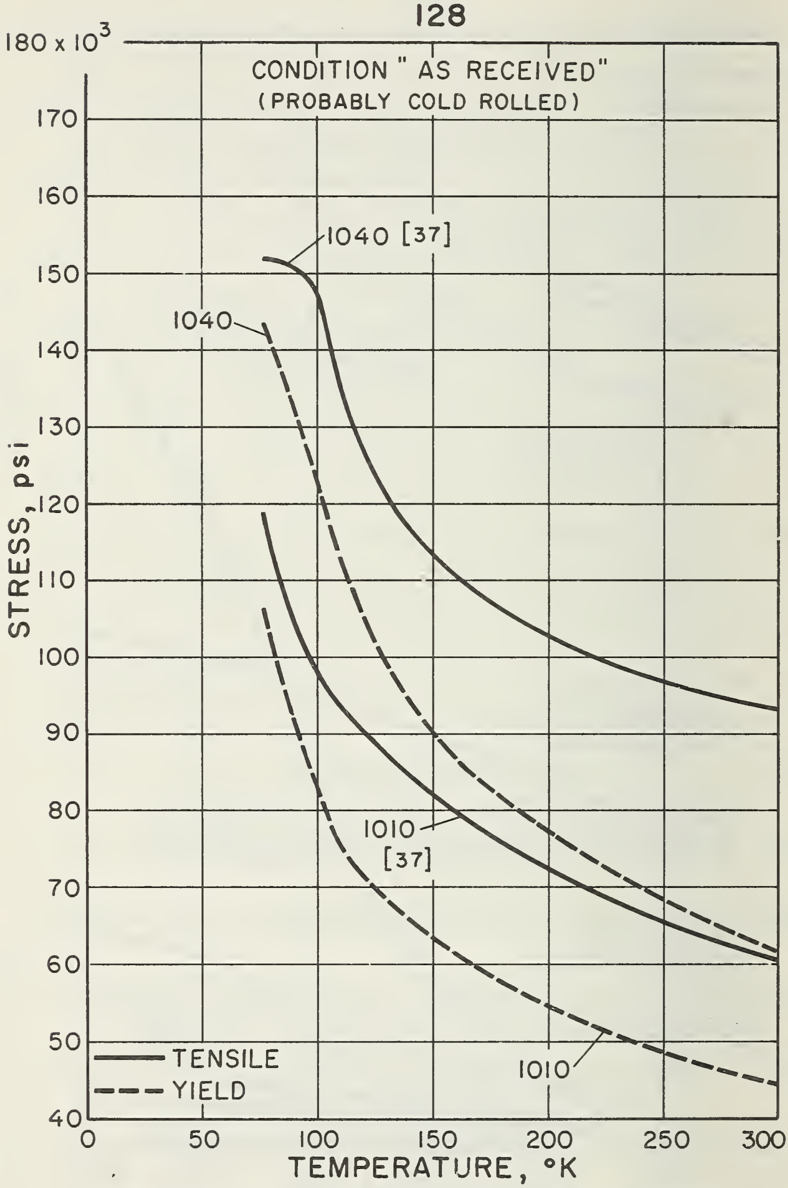
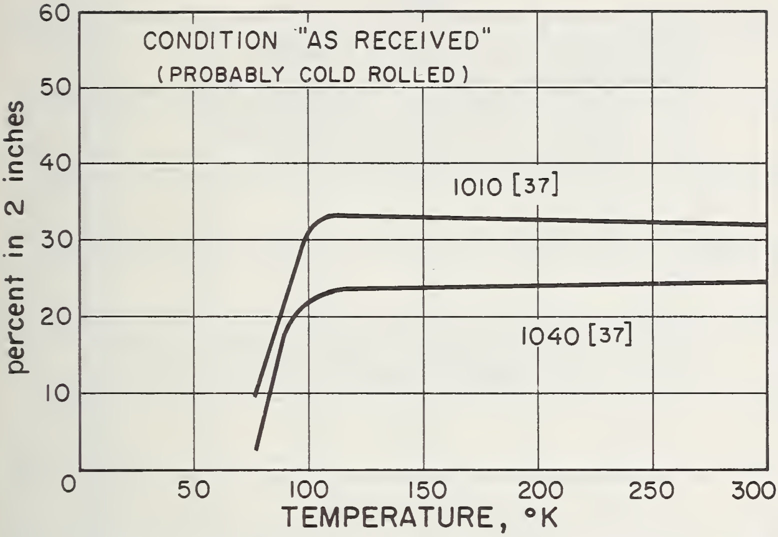
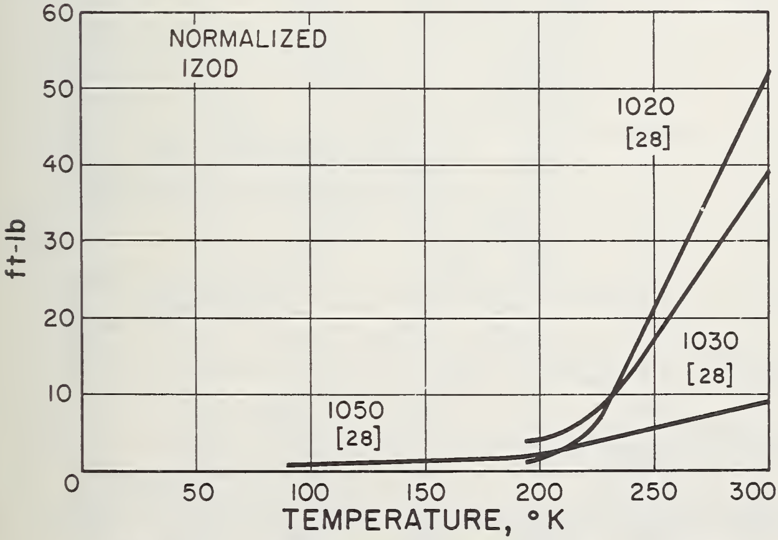


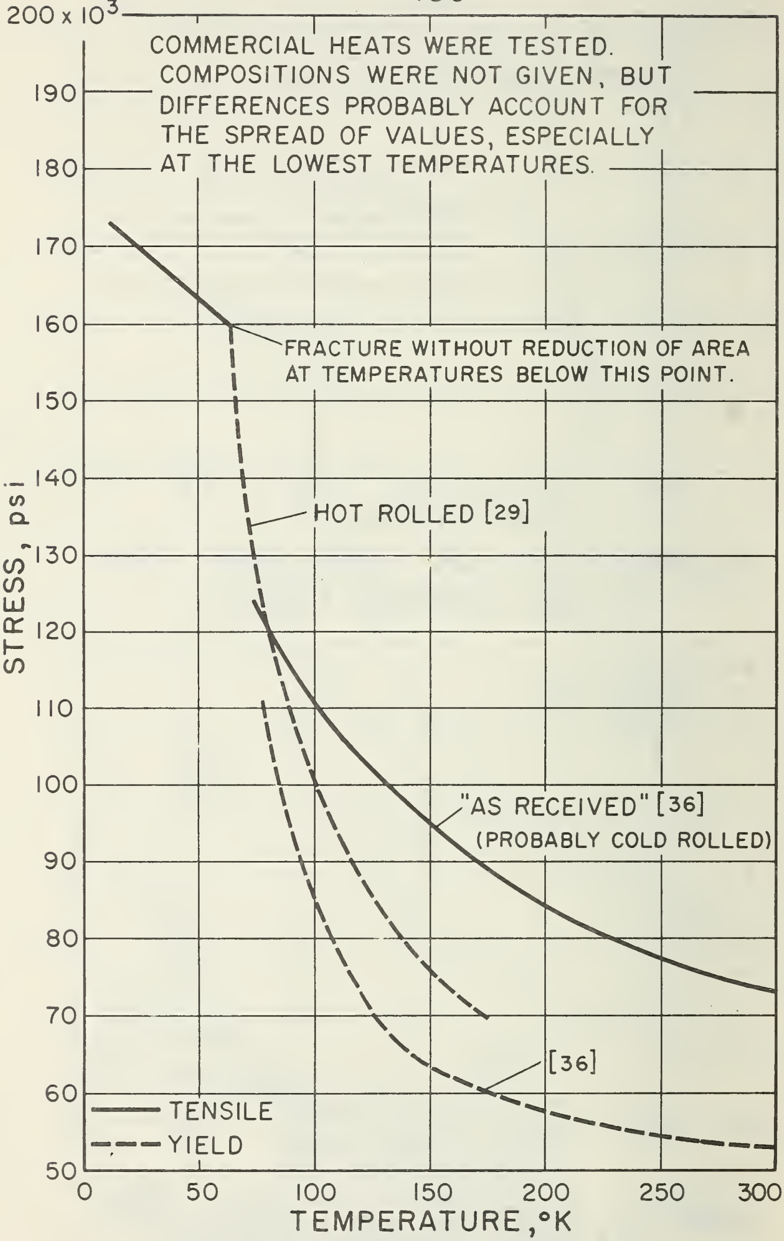
STRENGTH OF SOME AISI - SAE PLAIN CARBON STEELS



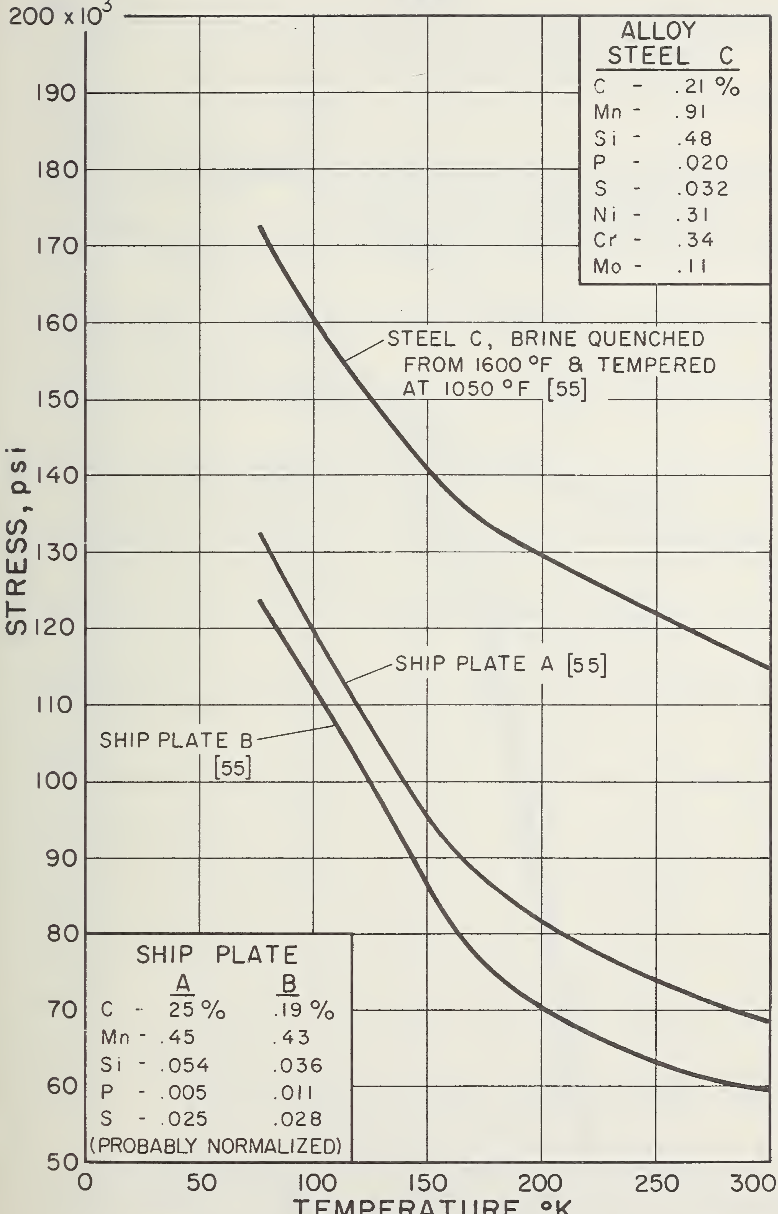
ELONGATION OF SOME AISI-SAE PLAIN CARBON STEELS



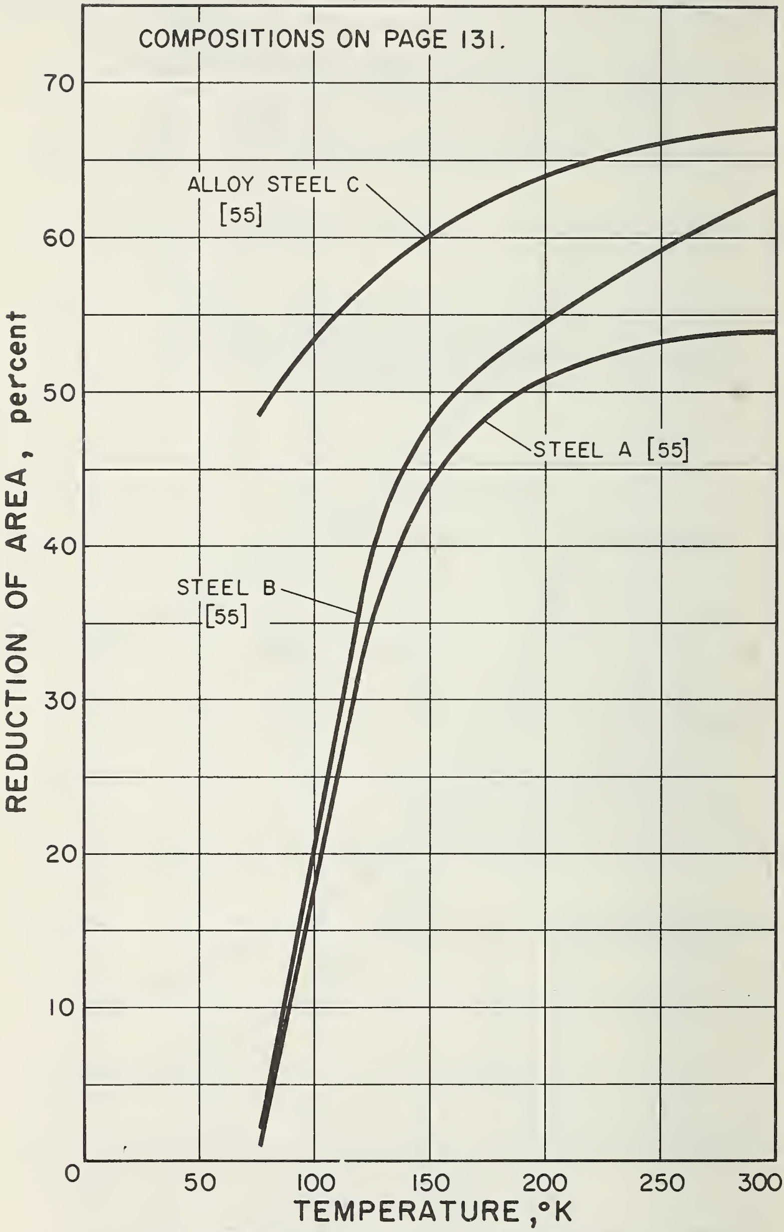
IMPACT ENERGY OF AISI-SAE PLAIN CARBON STEELS



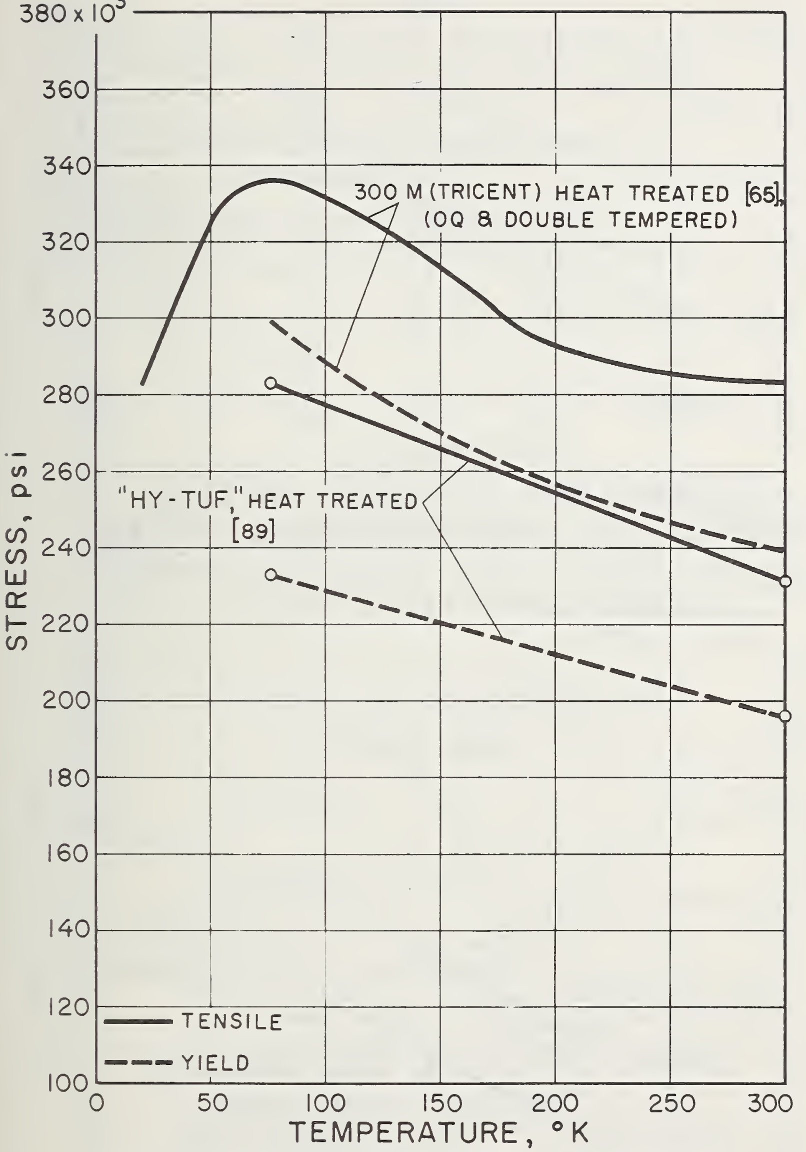
STRENGTH OF AISI-SAE 1020 STEEL



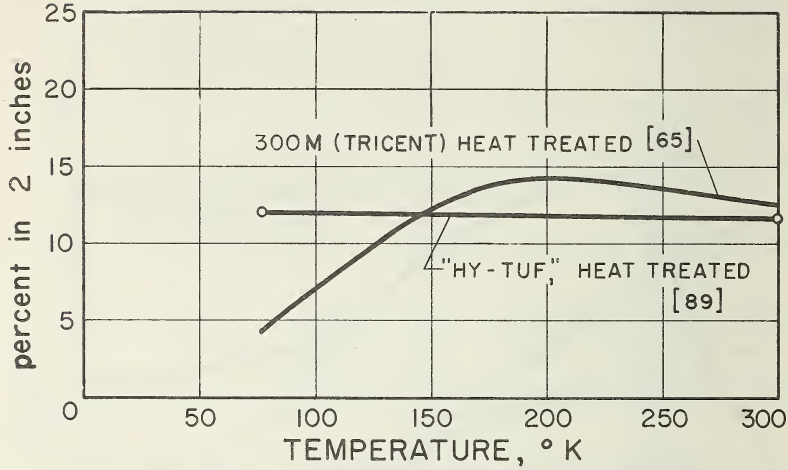
TENSILE STRENGTH OF SHIP PLATE & LOW ALLOY CONSTRUCTIONAL STEEL



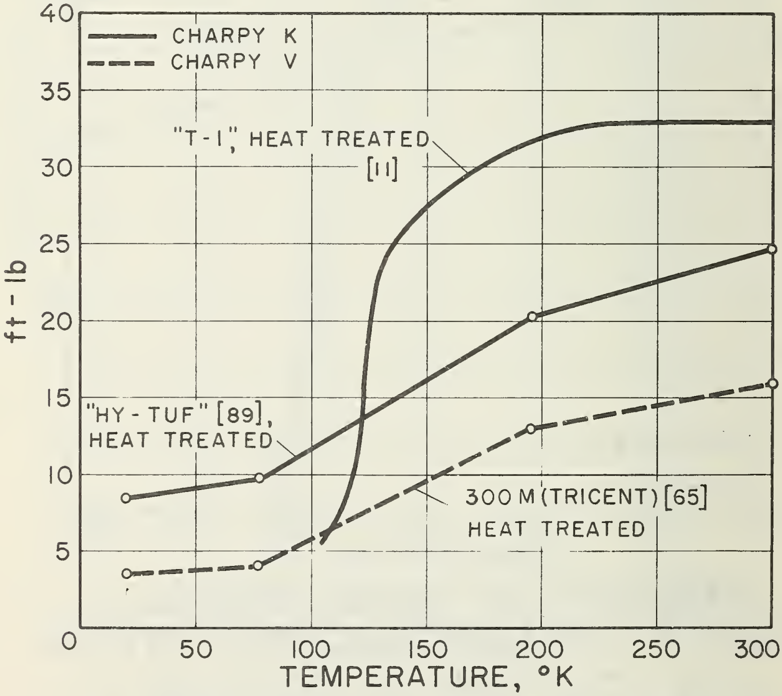
DUCTILITY OF SHIP PLATE & LOW ALLOY CONSTRUCTIONAL STEEL



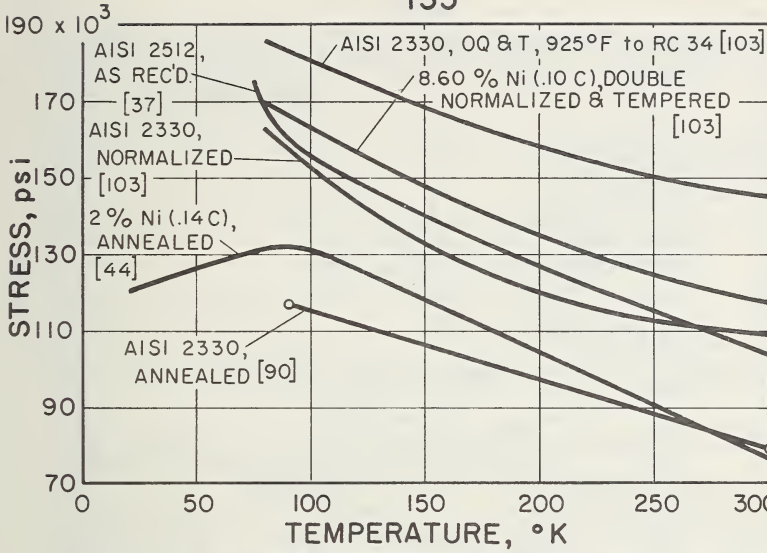
STRENGTH OF SOME SPECIAL PROPRIETARY CONSTRUCTIONAL STEELS



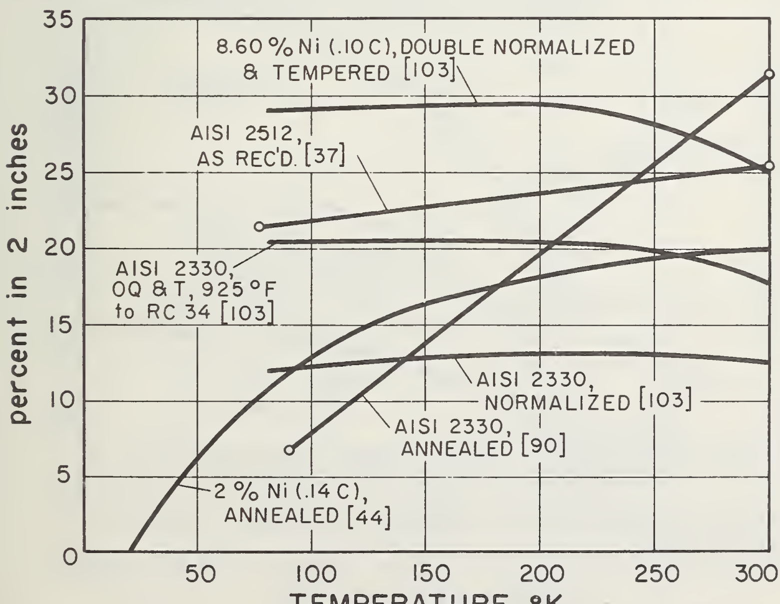
ELONGATION OF SOME SPECIAL PROPRIETARY CONSTRUCTIONAL STEELS



IMPACT ENERGY OF SOME SPECIAL PROPRIETARY CONSTRUCTIONAL STEELS



TENSILE STRENGTH OF NICKEL ALLOY CONSTRUCTIONAL STEELS



ELONGATION OF SOME NICKEL ALLOY CONSTRUCTIONAL STEELS

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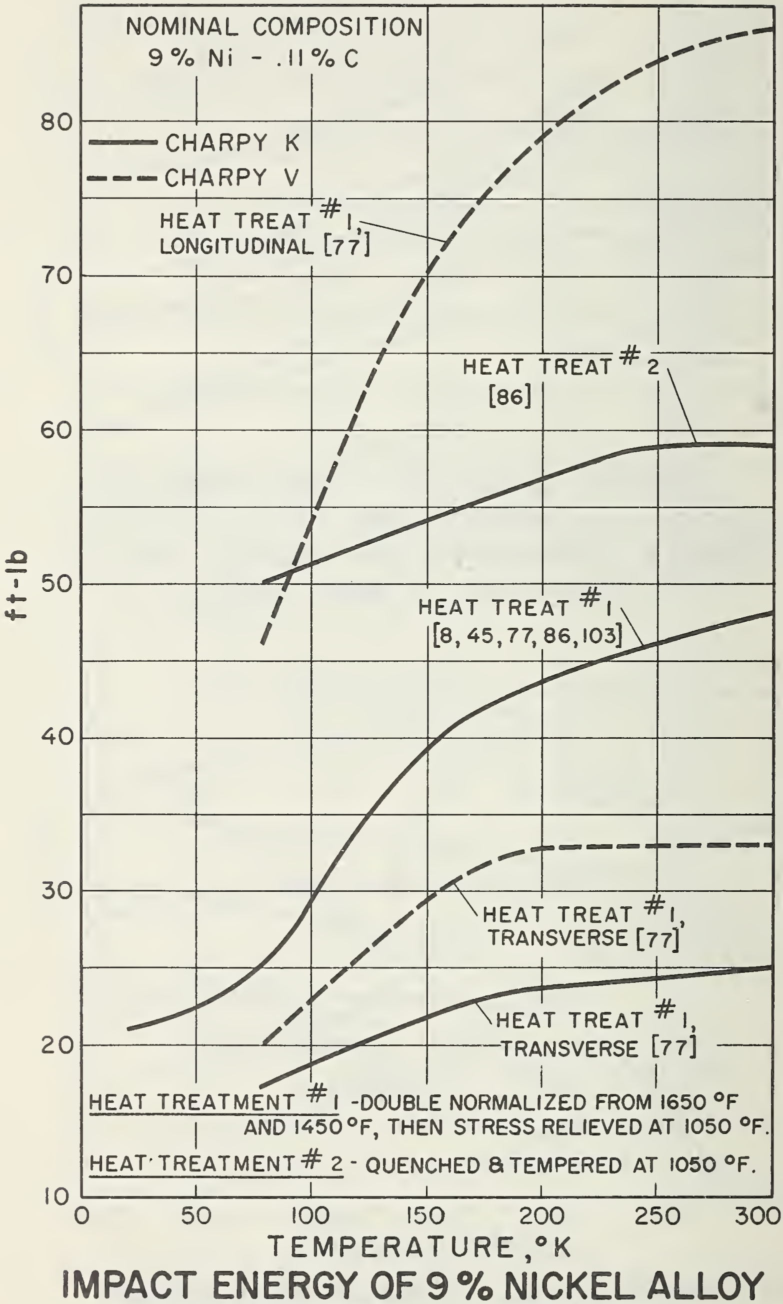
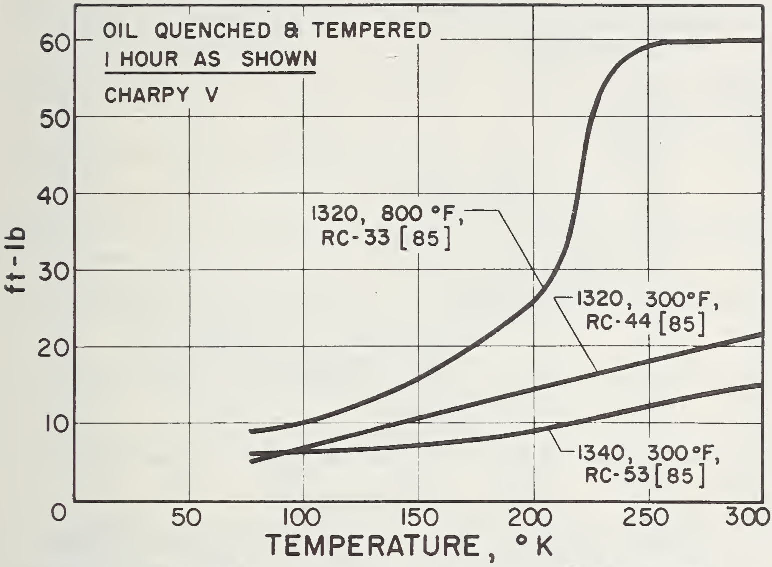
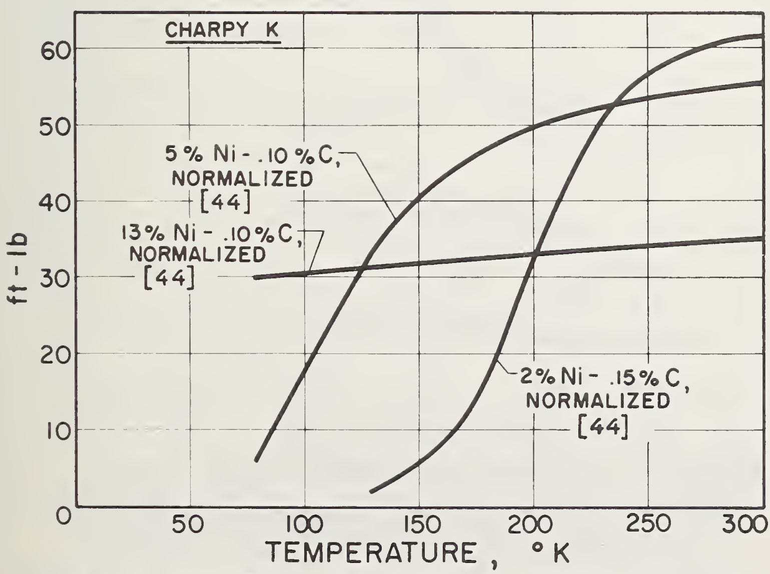


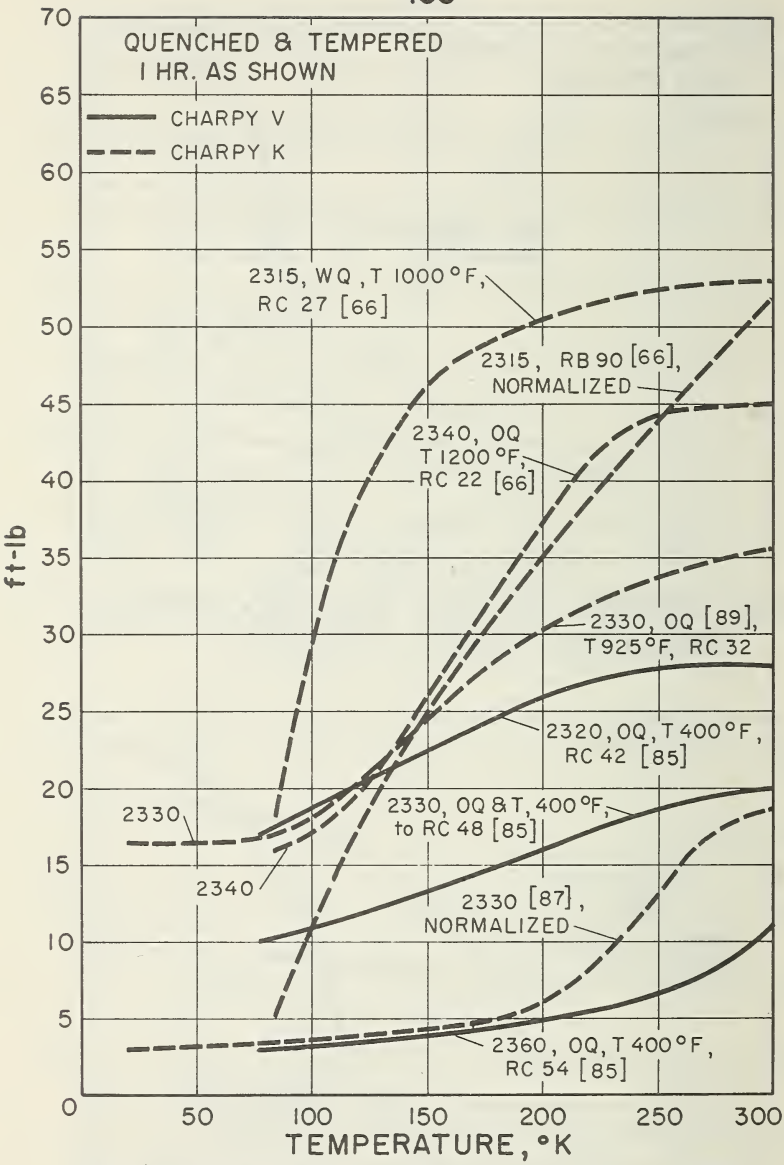
IMPACT ENERGY OF 9 % NICKEL ALLOY CONSTRUCTIONAL STEELS



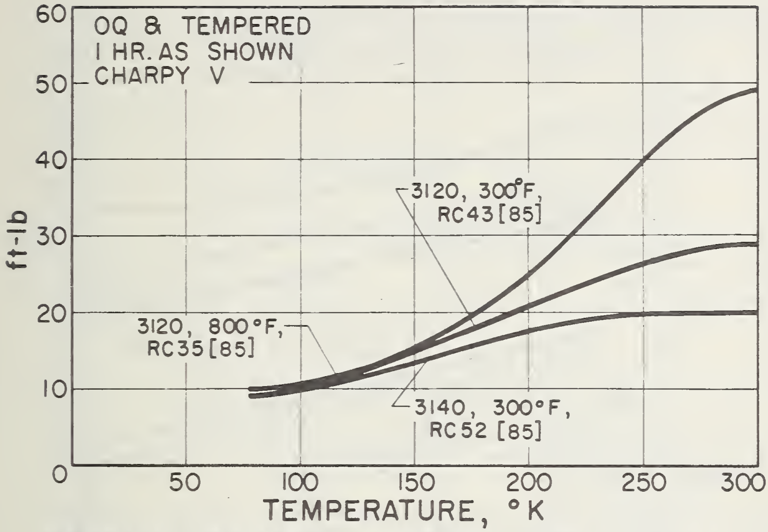
IMPACT ENERGY OF AISI-SAE 1300 SERIES CONSTRUCTIONAL STEELS



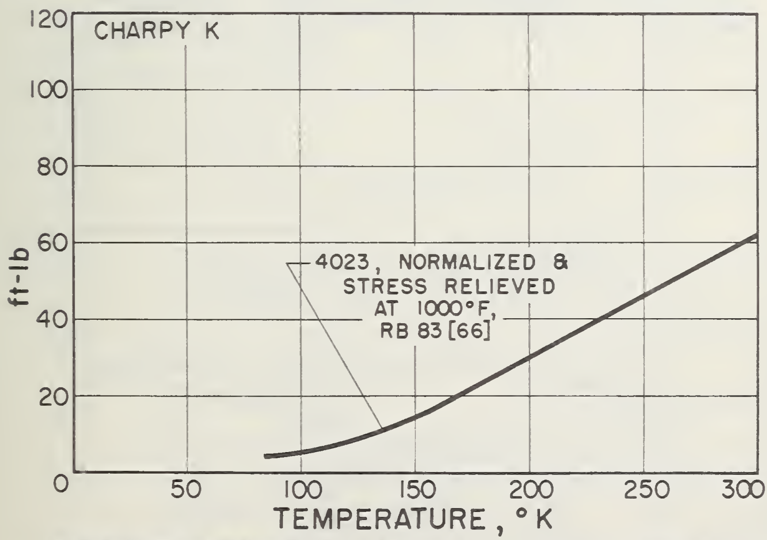
IMPACT ENERGY OF SOME NICKEL ALLOY CONSTRUCTIONAL STEELS



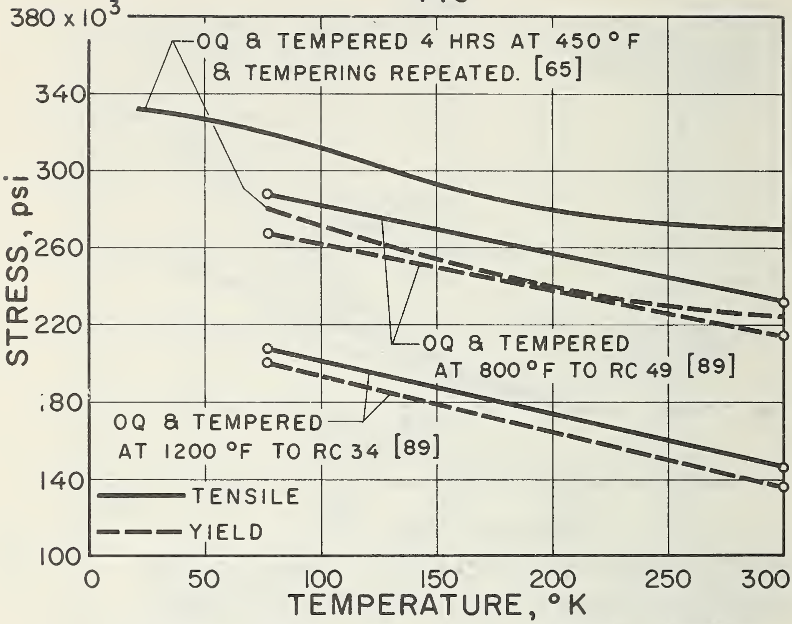
IMPACT ENERGY OF AISI - SAE 2300 SERIES CONSTRUCTIONAL STEELS



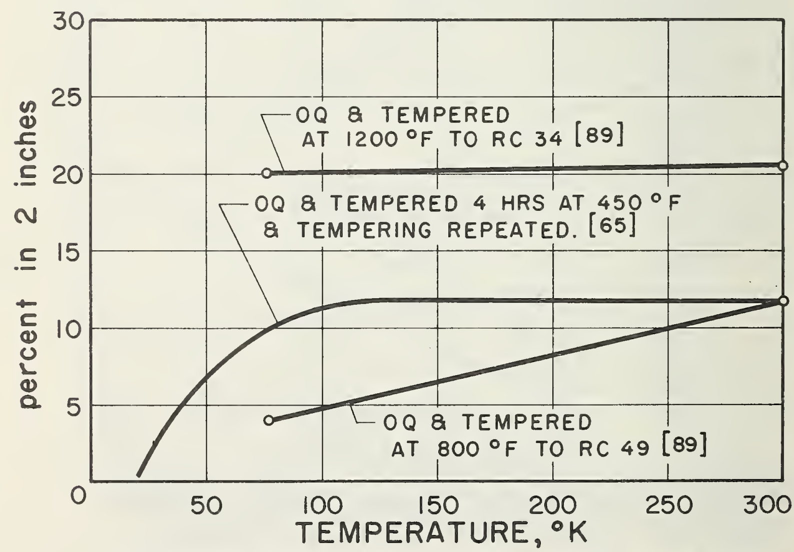
IMPACT ENERGY OF AISI - SAE 3100 SERIES CONSTRUCTIONAL STEELS



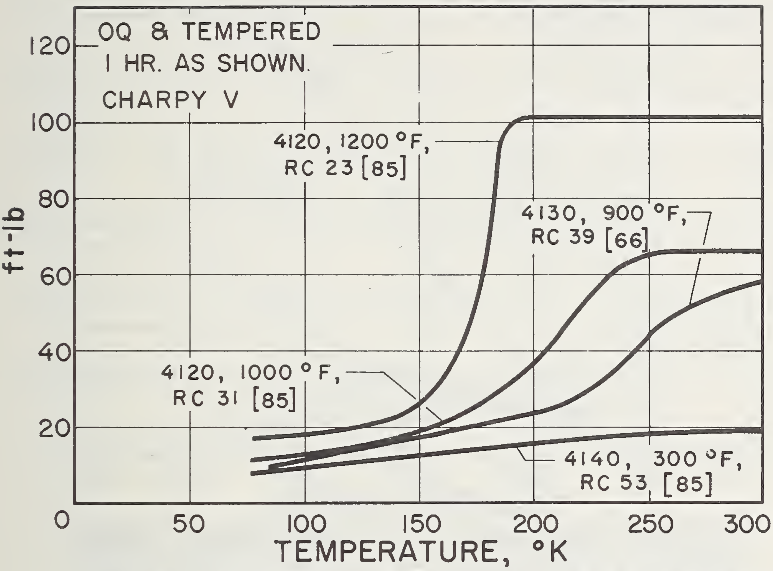
IMPACT ENERGY OF AISI - SAE 4000 SERIES CONSTRUCTIONAL STEELS



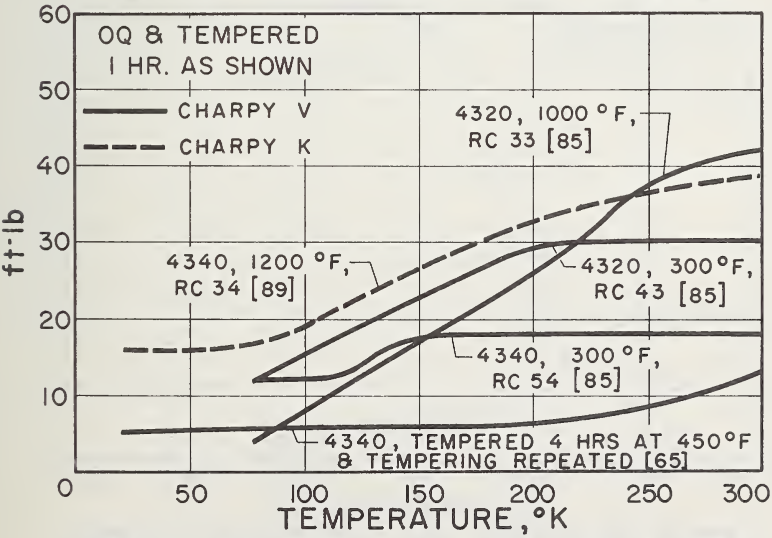
STRENGTH OF AISI-SAE 4340 ALLOY CONSTRUCTIONAL STEEL



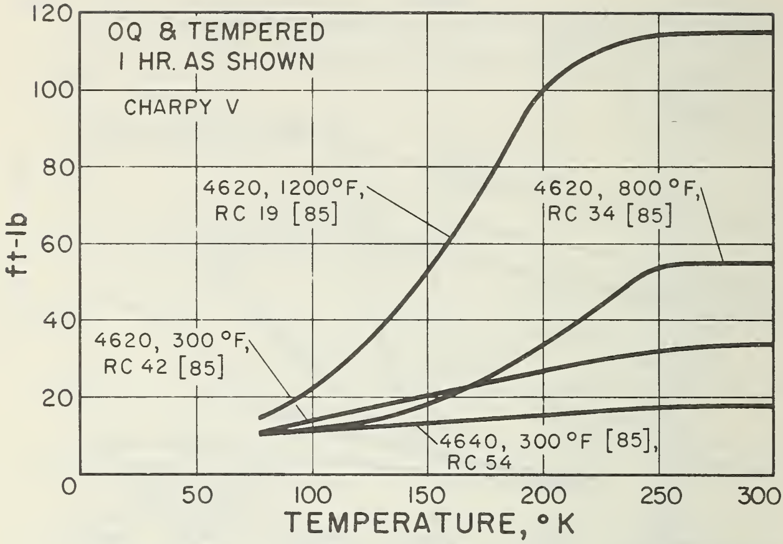
ELONGATION OF AISI-SAE 4340 ALLOY CONSTRUCTIONAL STEEL



IMPACT ENERGY OF AISI - SAE 4100 SERIES CONSTRUCTIONAL STEELS



IMPACT ENERGY OF AISI - SAE 4300 SERIES CONSTRUCTIONAL STEELS



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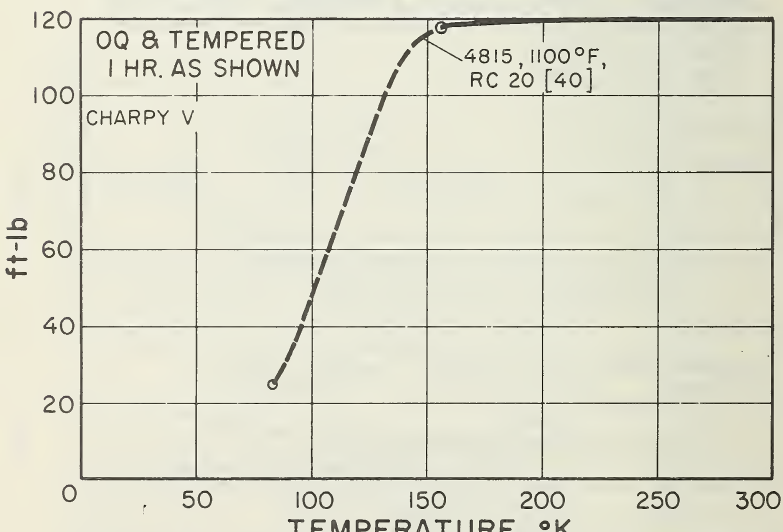

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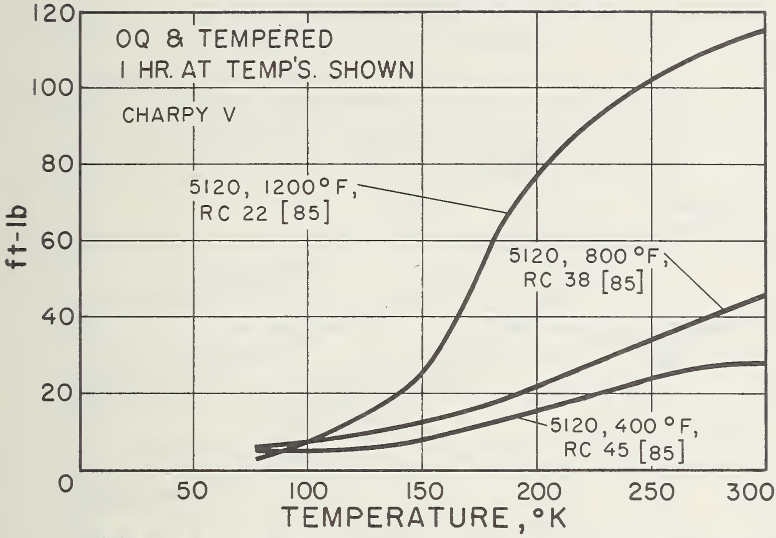
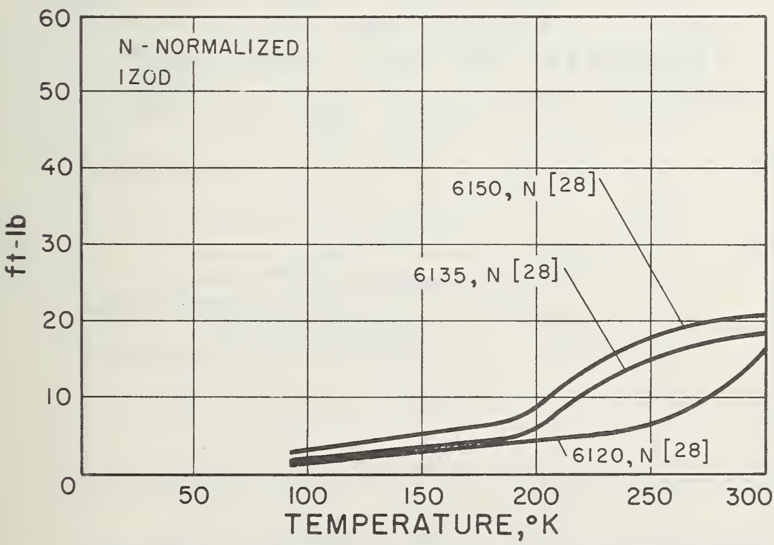
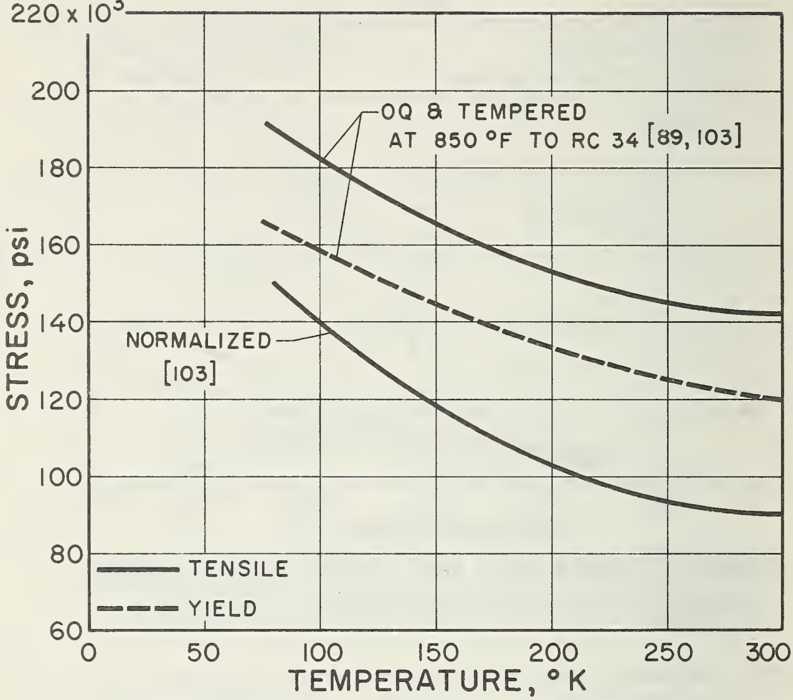


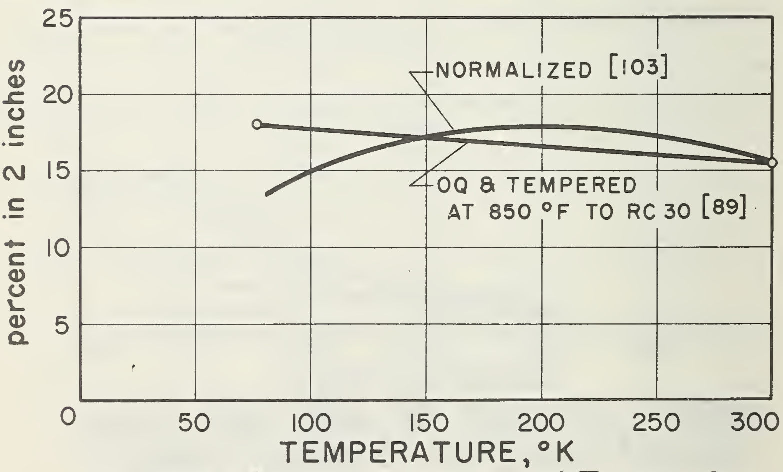
IMPACT ENERGY OF AISI-SAE 5000 SERIES CONSTRUCTIONAL STEELS



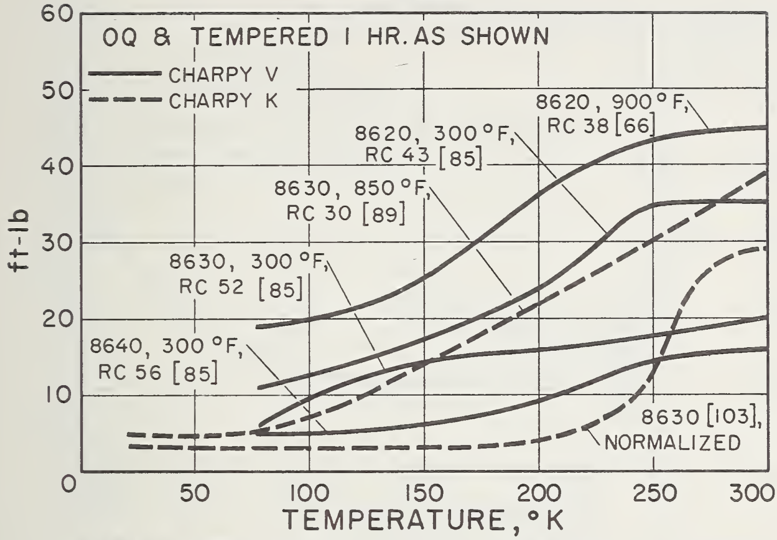
IMPACT ENERGY OF AISI-SAE 6100 SERIES CONSTRUCTIONAL STEELS



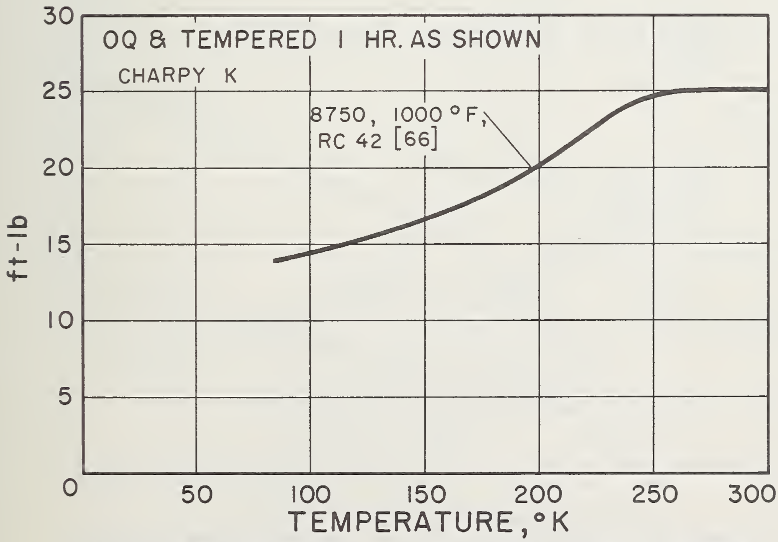
STRENGTH OF AISI - SAE 8630
ALLOY CONSTRUCTIONAL STEEL



ELONGATION OF AISI - SAE 8630
ALLOY CONSTRUCTIONAL STEEL



IMPACT ENERGY OF AISI-SAE 8600 SERIES CONSTRUCTIONAL STEELS



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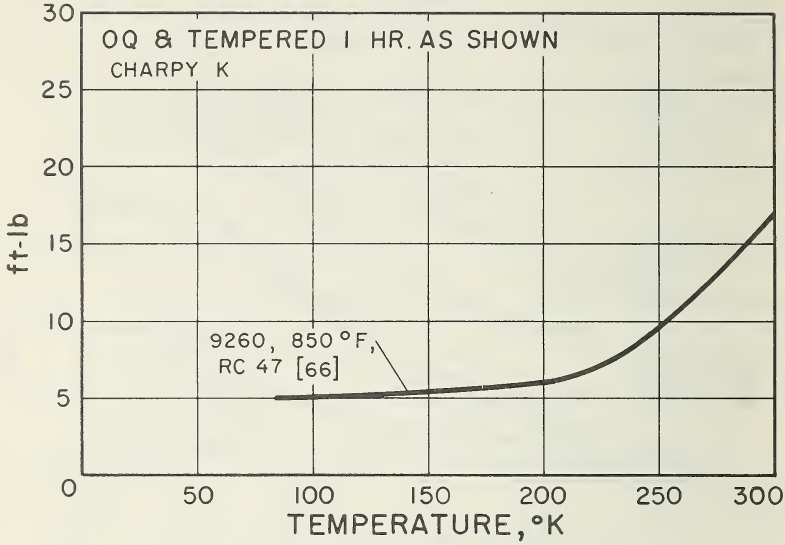

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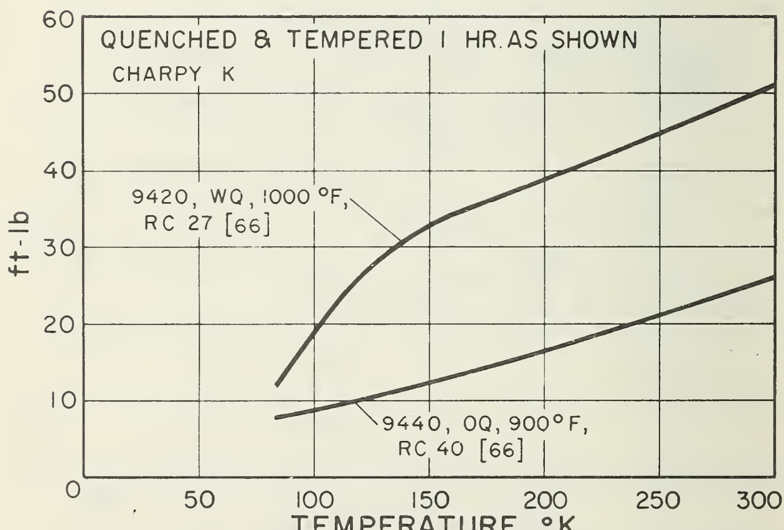
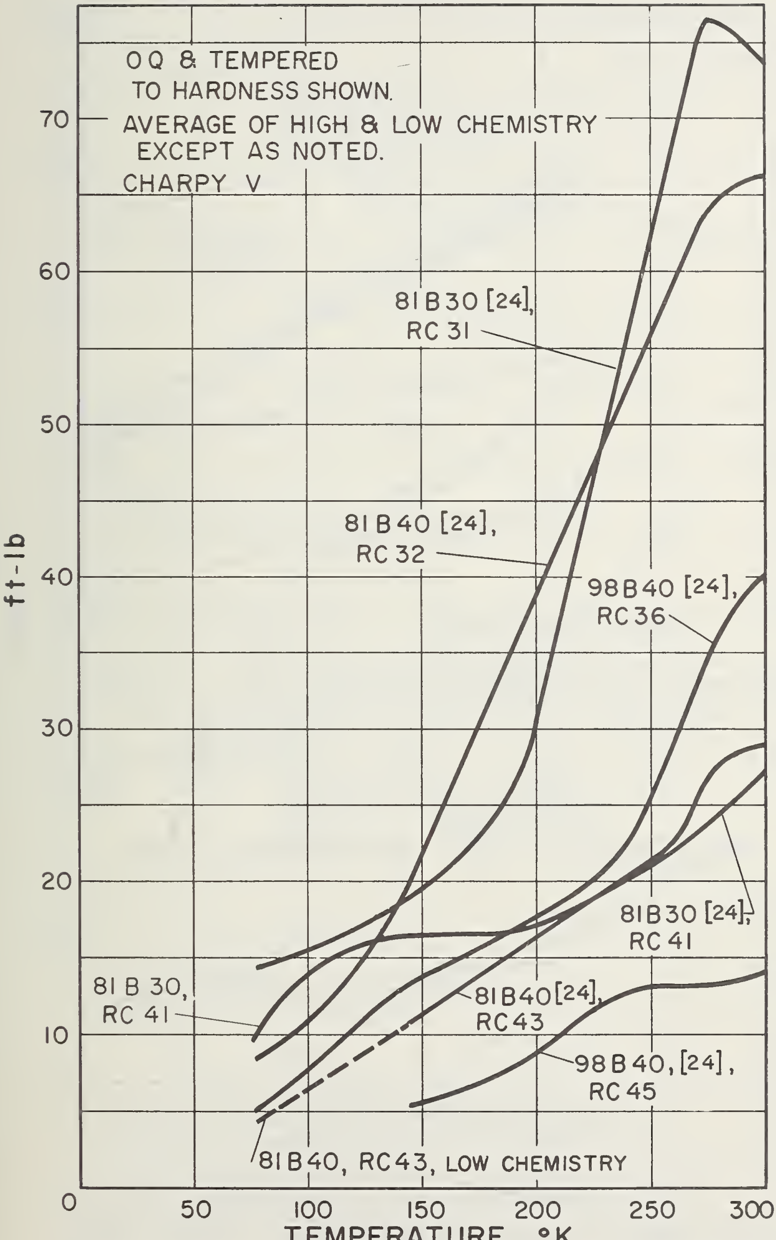
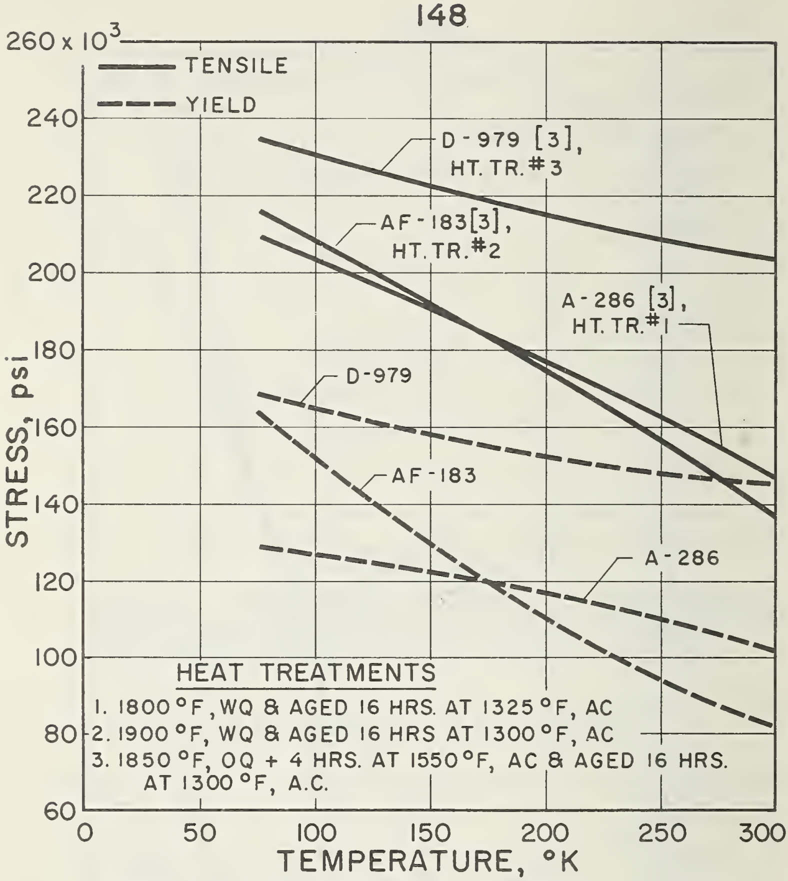


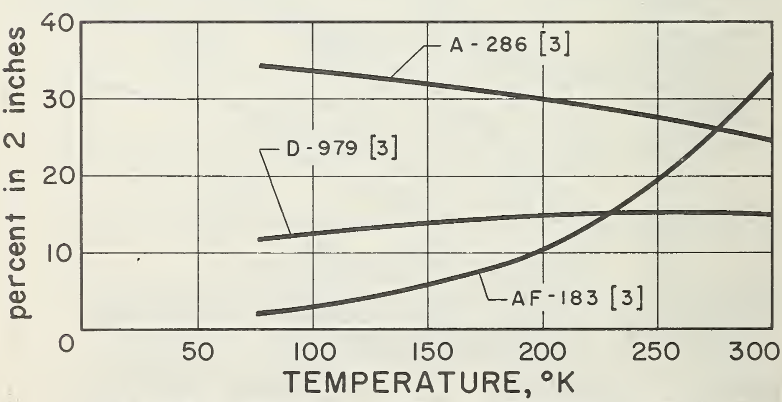
IMPACT ENERGY OF AISI-SAE 9400 SERIES CONSTRUCTIONAL STEELS



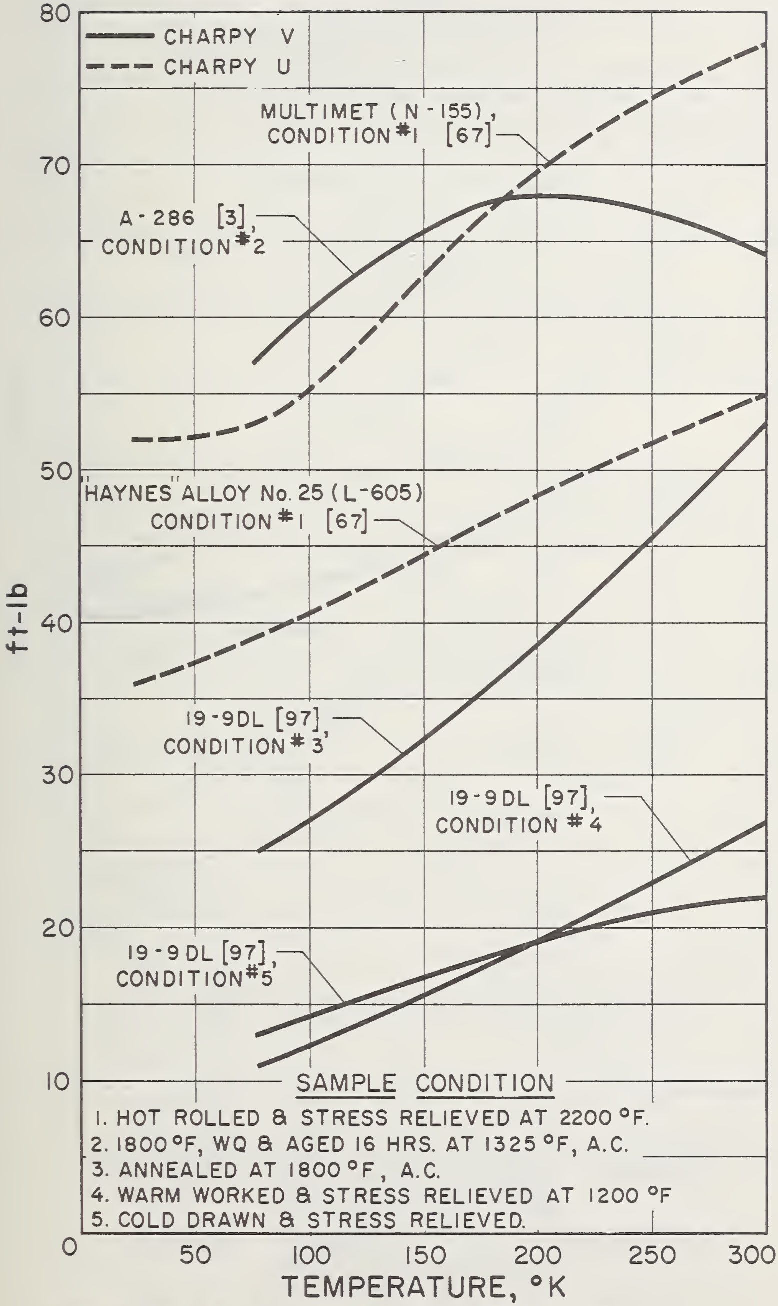
IMPACT ENERGY OF BORON STEELS



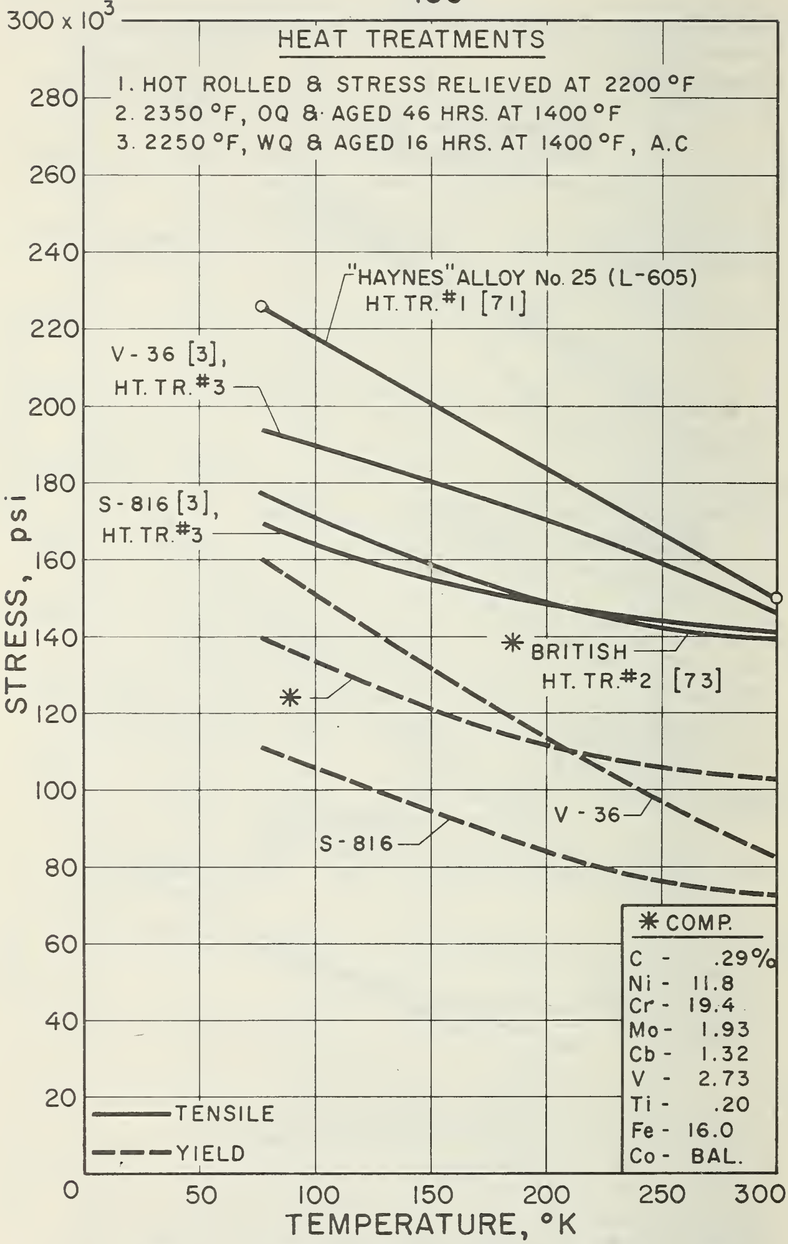
STRENGTH OF SUPERALLOYS



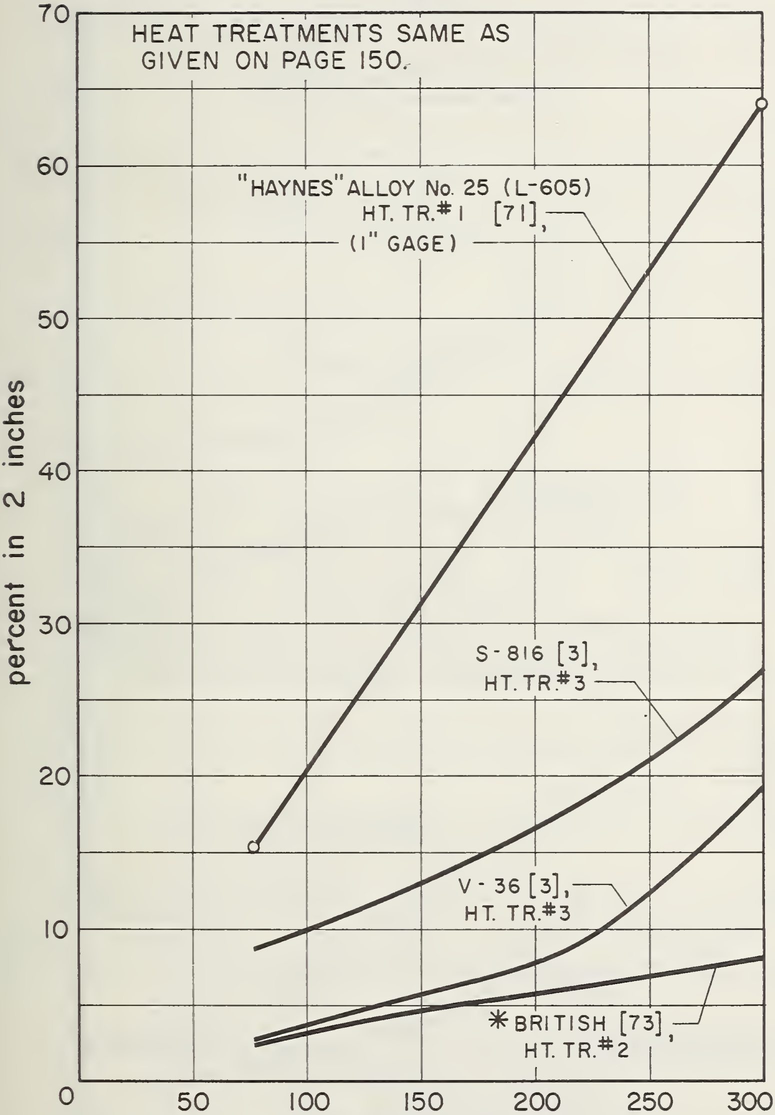
ELONGATION OF SUPERALLOYS



IMPACT ENERGY OF SOME SUPERALLOYS



STRENGTH OF COBALT BASE SUPERALLOYS



ELONGATION OF COBALT BASE SUPERALLOYS

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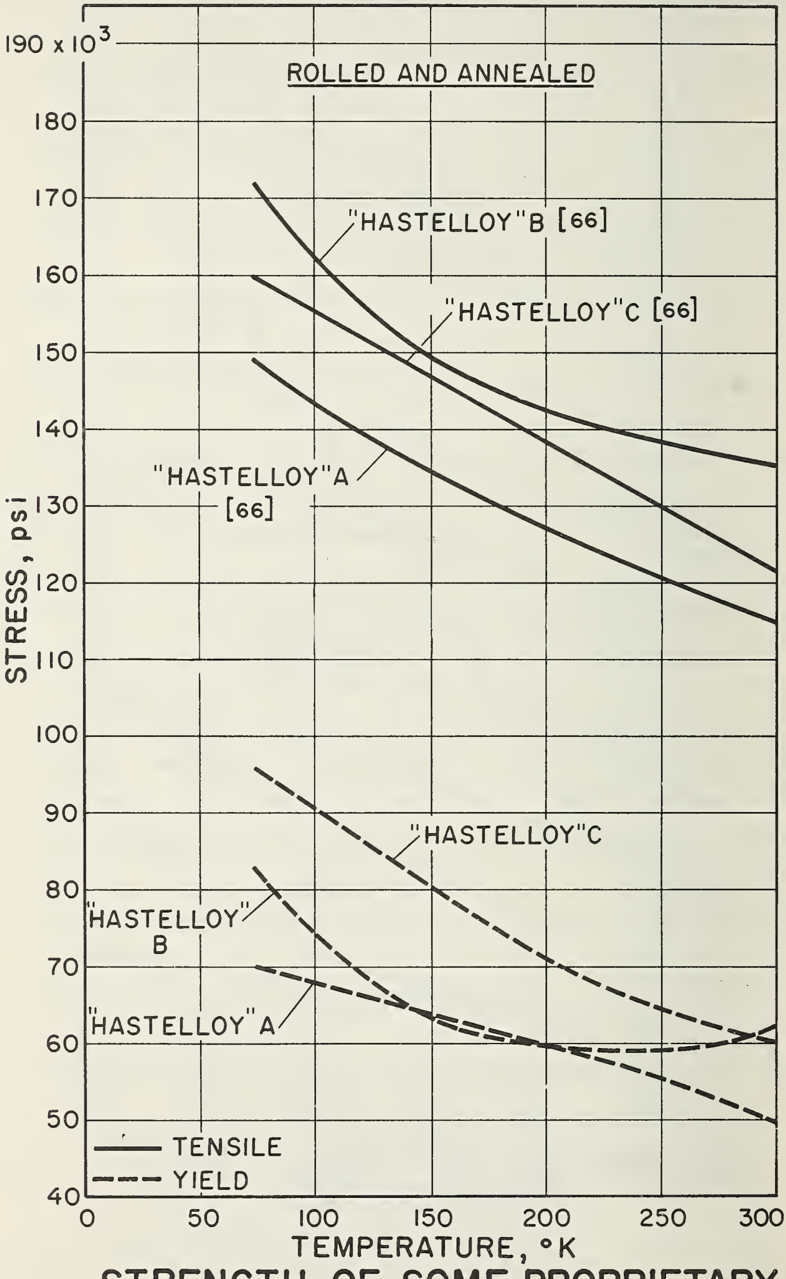
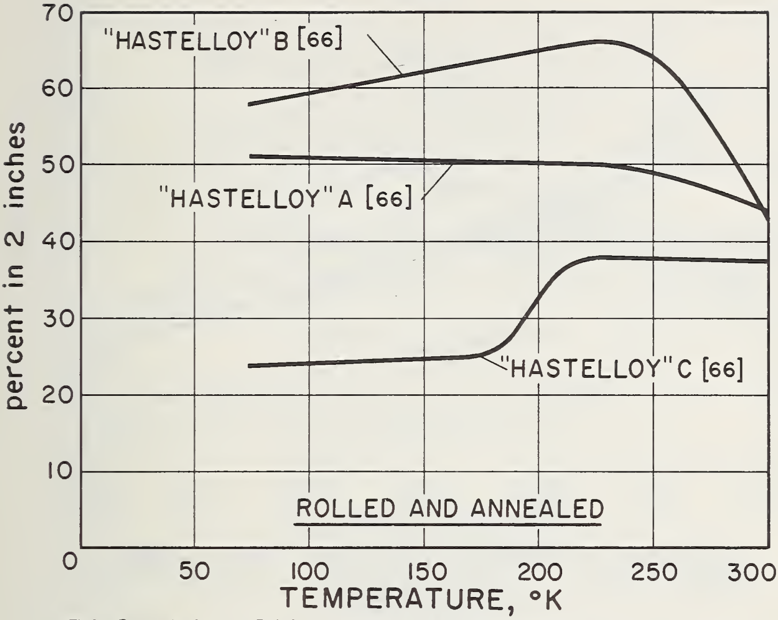
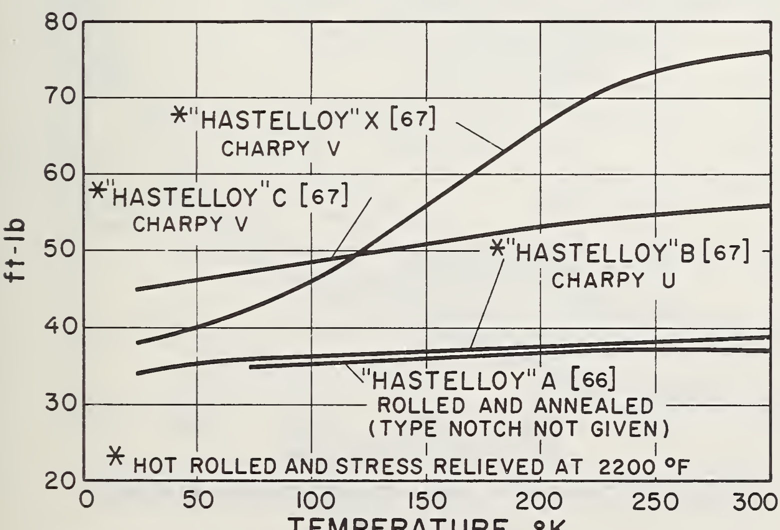


STRENGTH OF SOME PROPRIETARY NICKEL-BASE SUPERALLOYS



ELONGATION OF SOME PROPRIETARY NICKEL-BASE SUPERALLOYS



IMPACT ENERGY OF SOME PROPRIETARY NICKEL-BASE SUPERALLOYS

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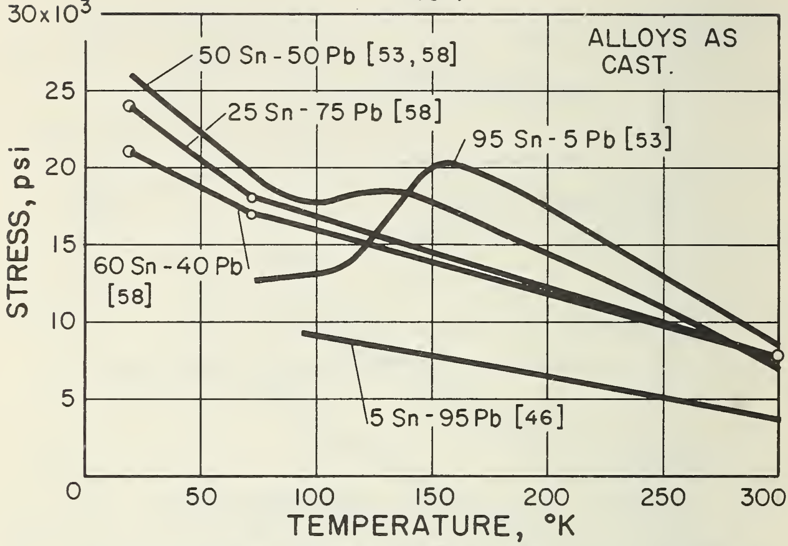
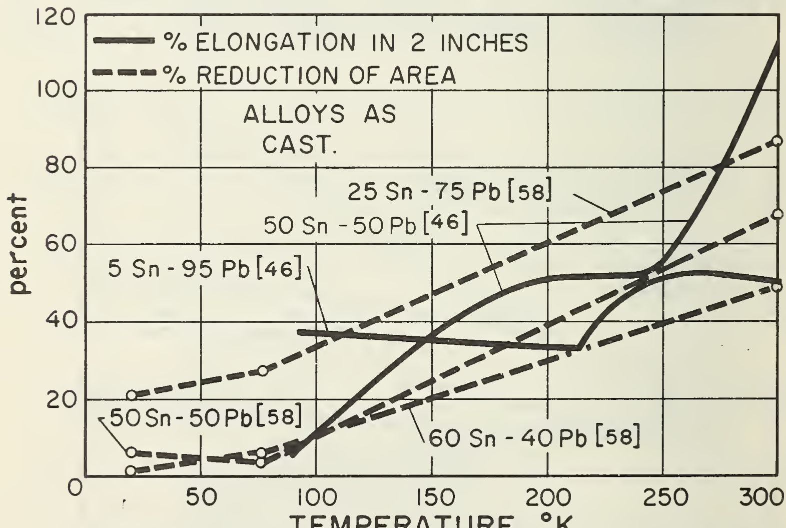
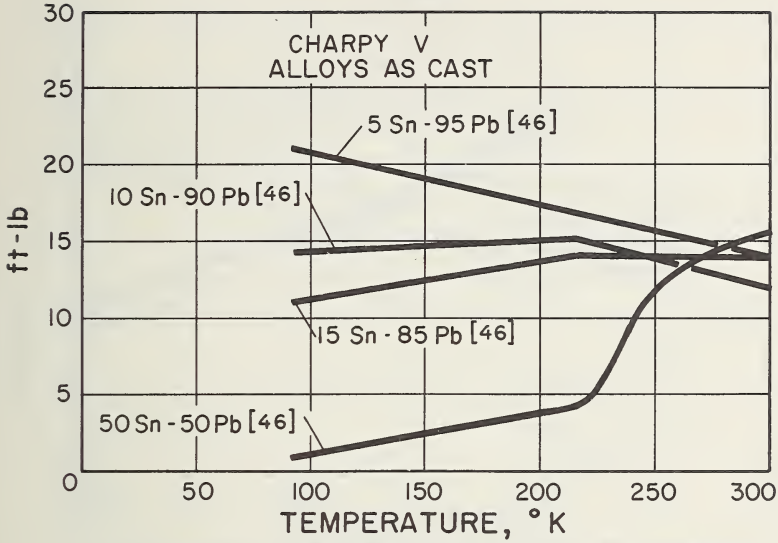


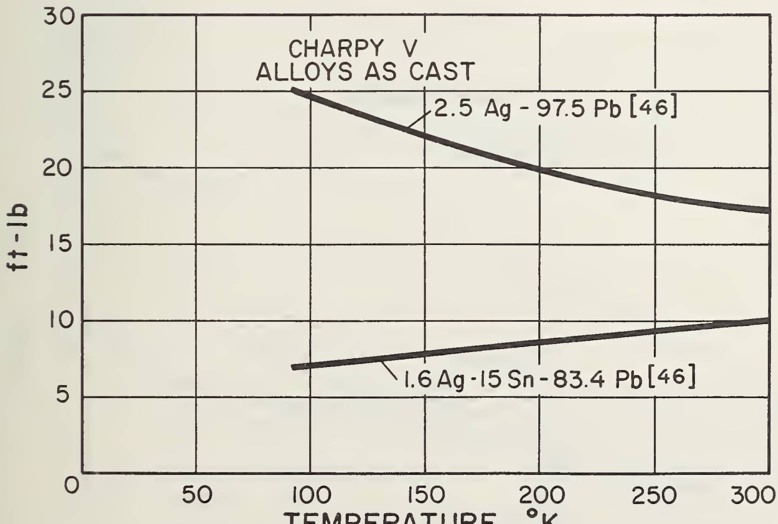
TENSILE STRENGTH OF TIN - LEAD SOLDERS



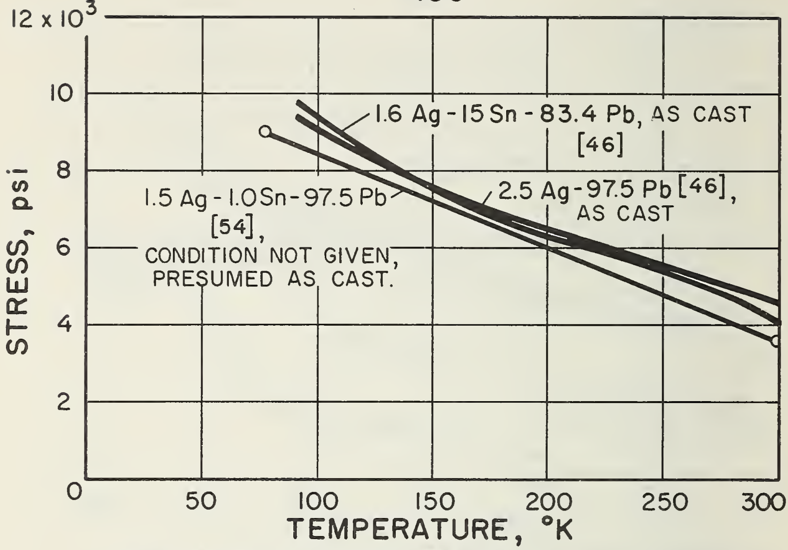
DUCTILITY OF TIN - LEAD SOLDERS



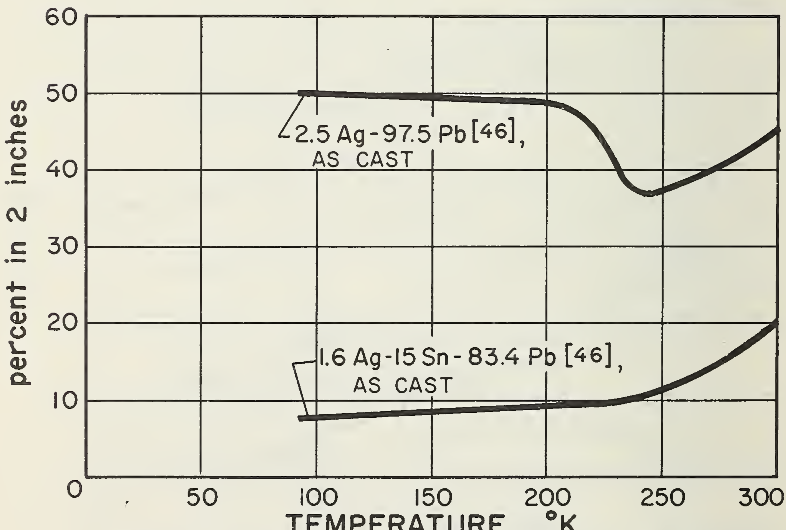
IMPACT ENERGY OF TIN-LEAD SOLDERS



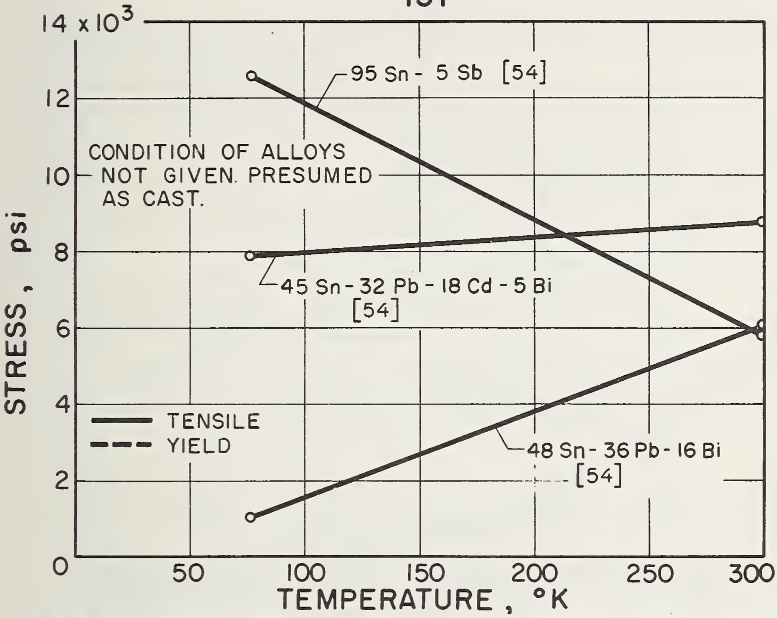
IMPACT ENERGY OF SILVER-LEAD SOLDERS



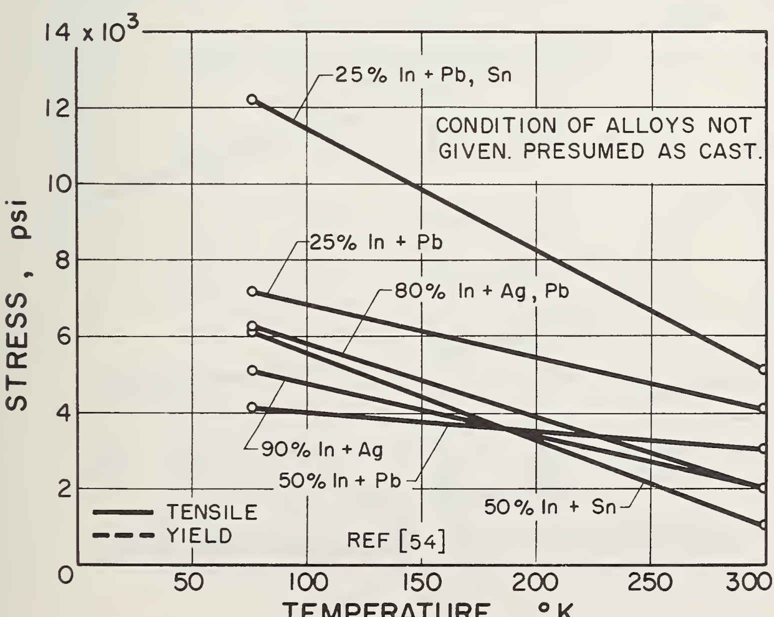
TENSILE STRENGTH OF SILVER-LEAD SOLDERS



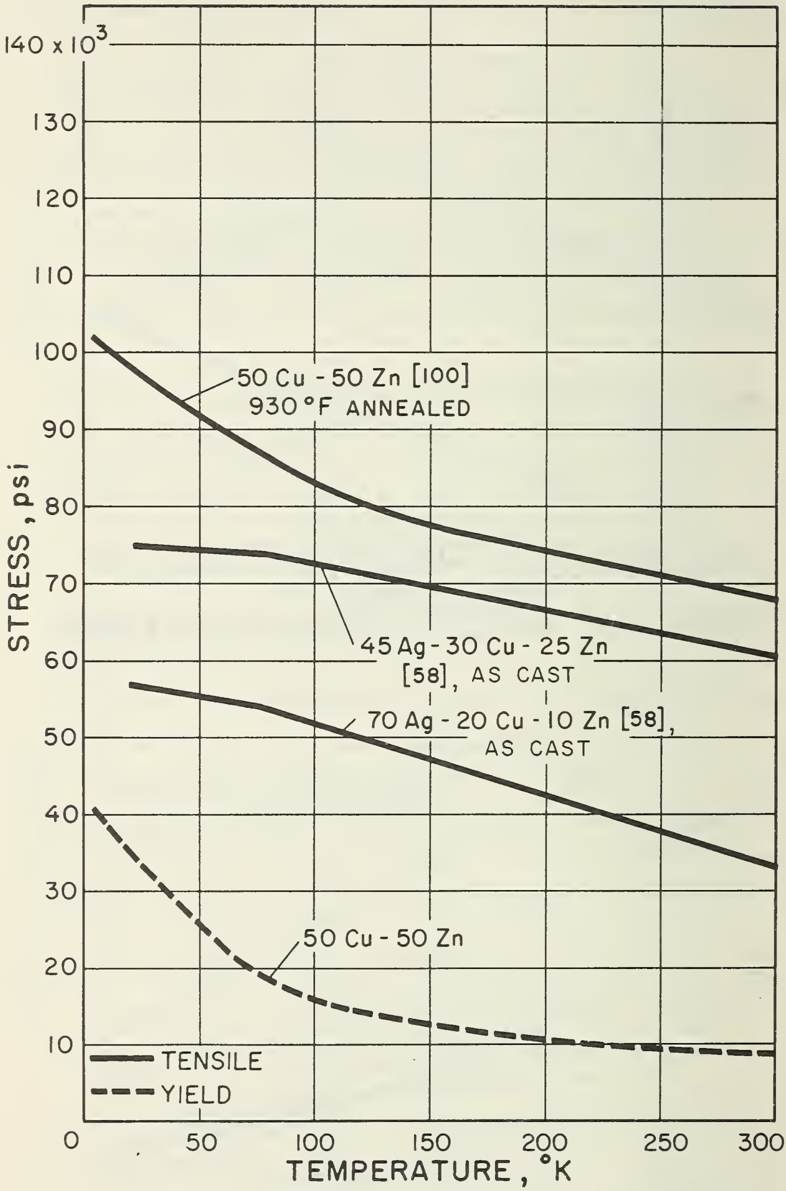
ELONGATION OF SILVER-LEAD SOLDERS



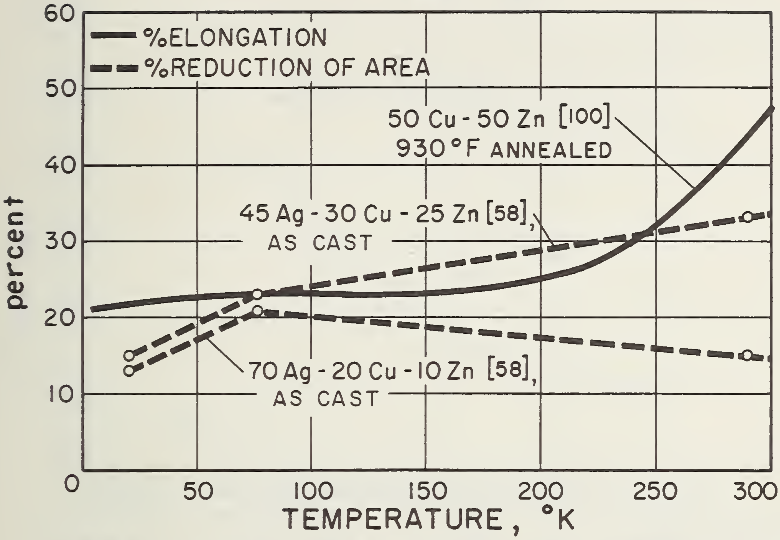
STRENGTH OF MISCELLANEOUS SOLDERS



STRENGTH OF INDIUM SOLDERS



STRENGTH OF BRAZING ALLOYS

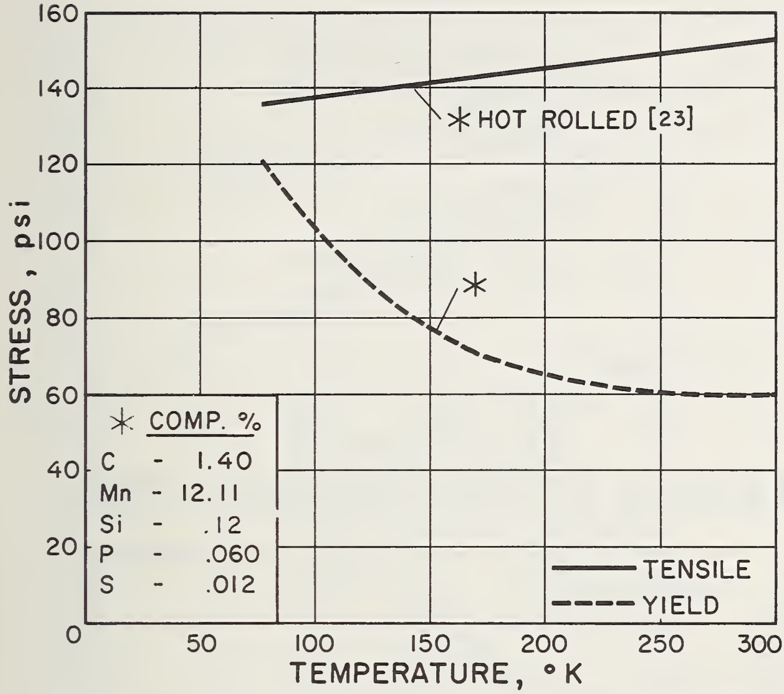


DUCTILITY OF BRAZING ALLOYS

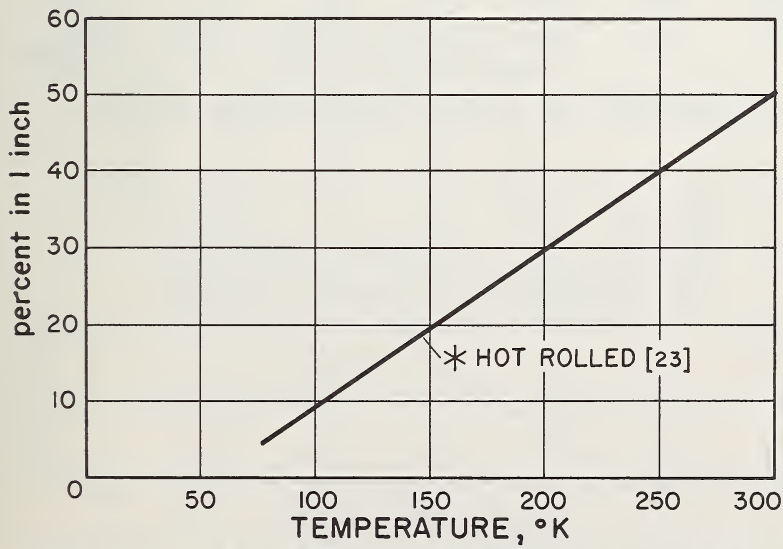
METAL	ANNEAL TEMP.,°F.	TENSILE STRENGTH psi		% ELONGATION, .79" GAGE LTH.	
		300°K	90°K	300°K	90°K
Ag	1472	30,900	40,700	23.0	38.0
Cd	392	6,500	20,600	42.0	18.0
Co	2012	61,100	104,400	4.0	5.0
Mo	2012	76,100	108,500	20.0	0.2
Sn	302	5,400	15,800	52.5	3.6
Tl	302	1,120	3,170	56.0	32.0
Zn	302	16,500	14,200	44.0	0.6

REF. [26]

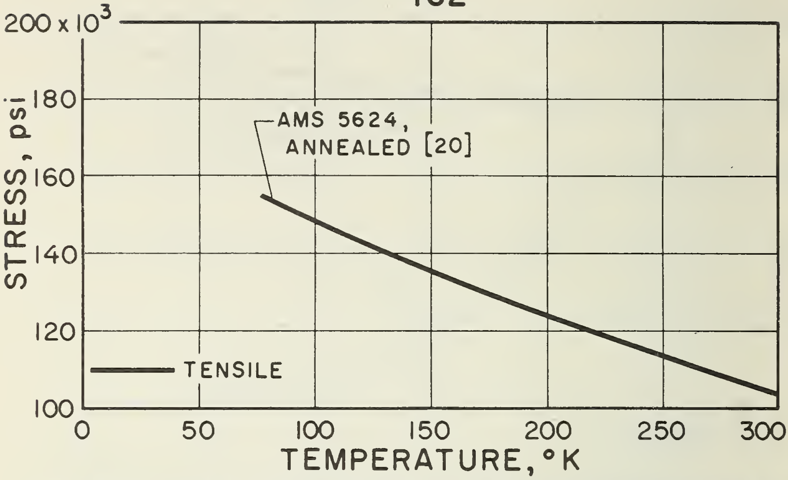
STRENGTH AND DUCTILITY OF SOME COLD WORKED AND ANNEALED PURE METALS



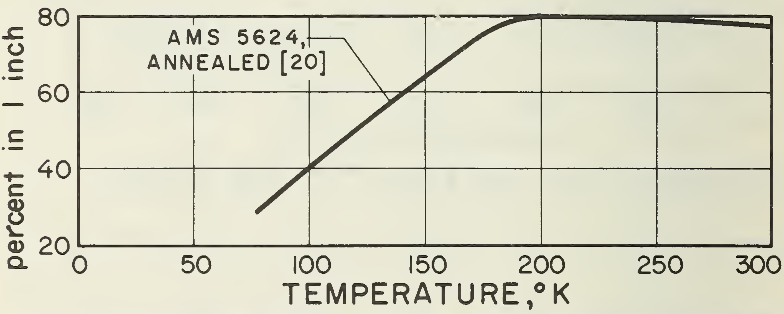
STRENGTH OF AUSTENITIC Mn STEEL



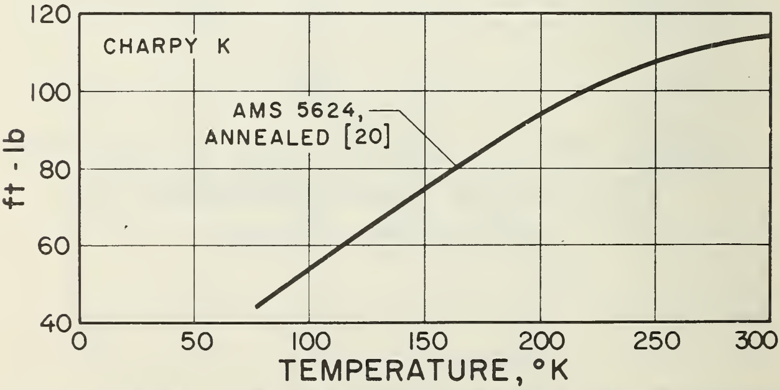
ELONGATION OF AUSTENITIC Mn STEEL



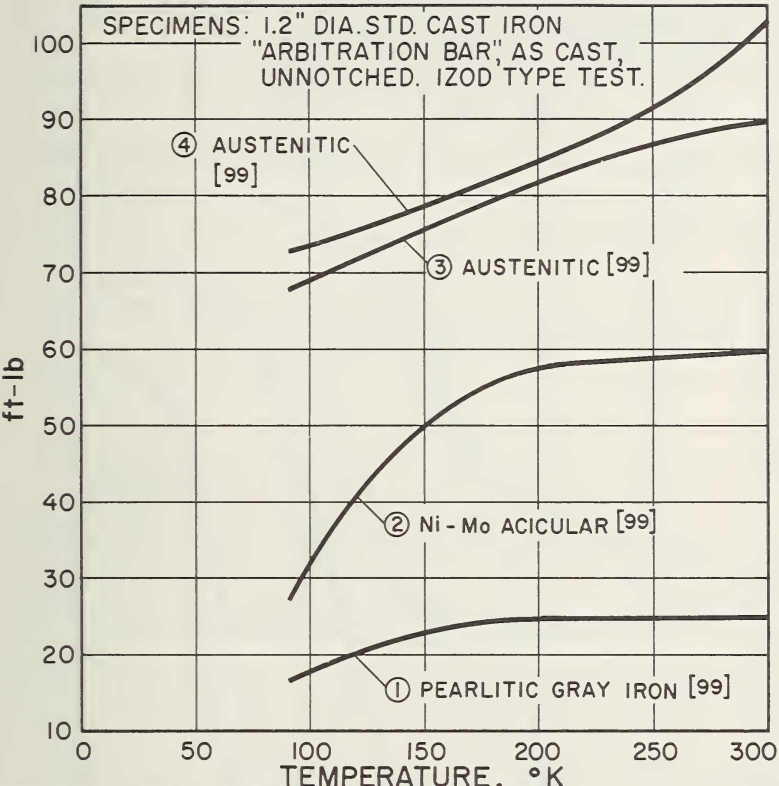
STRENGTH OF HIGH EXPANSION STEEL



ELONGATION OF HIGH EXPANSION STEEL



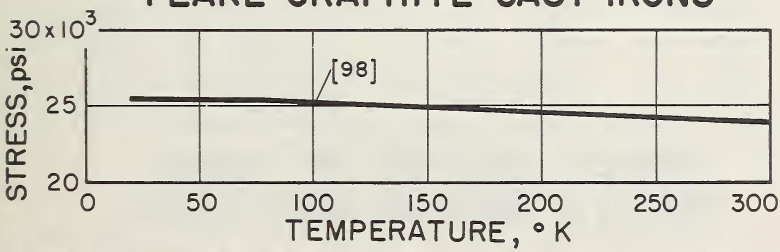
IMPACT ENERGY OF HIGH EXPANSION STEEL



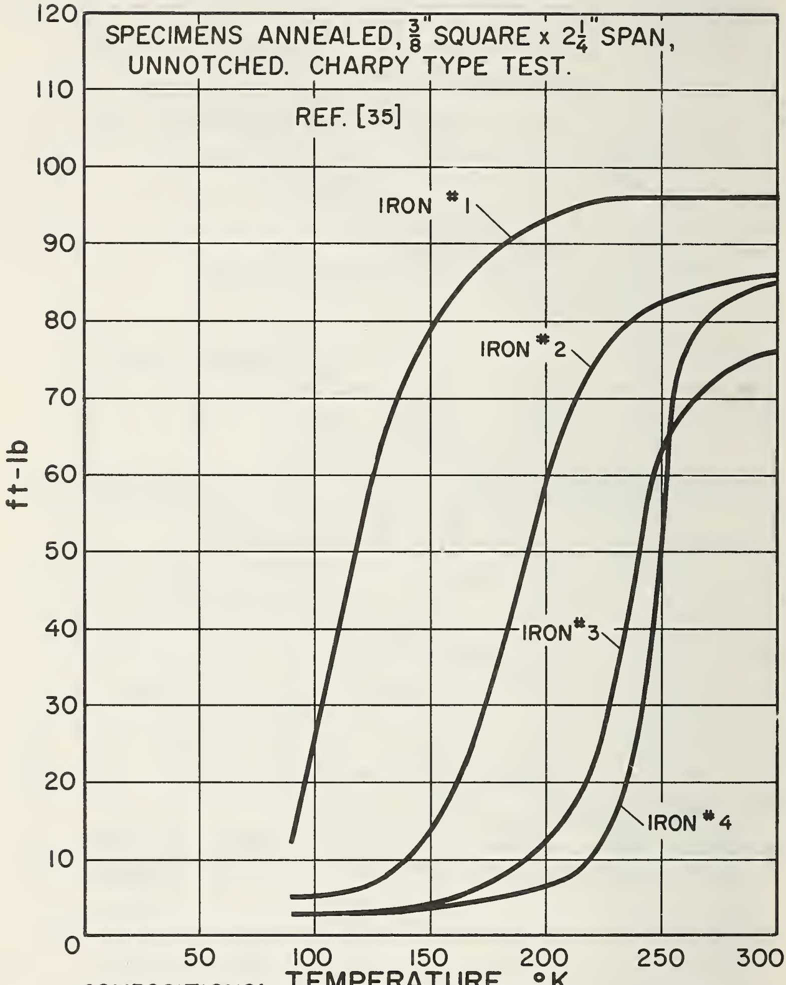
NOMINAL COMPOSITIONS:

IRON	%C	% Si	% Mn	% Ni	% Cr	OTHER
①	3.2	2.0	1.2	–	–	–
②	3.0	1.9	.7	1.6	–	.5 Mo
③	2.7	1.9	1.1	14.5	2.2	6.3 Cu
④	2.3	1.5	1.0	34.5	3.0	–

IMPACT ENERGY OF SOME FLAKE GRAPHITE CAST IRONS



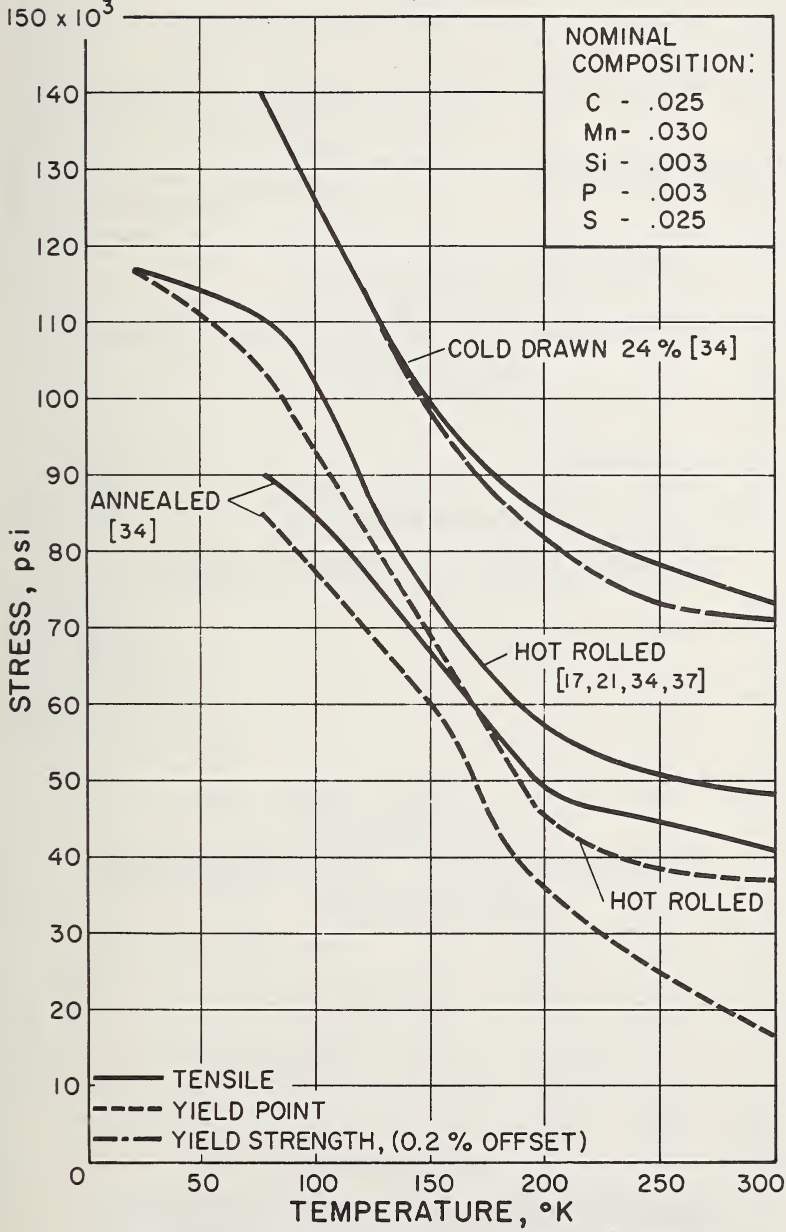
TENSILE STRENGTH OF A GRAY CAST IRON



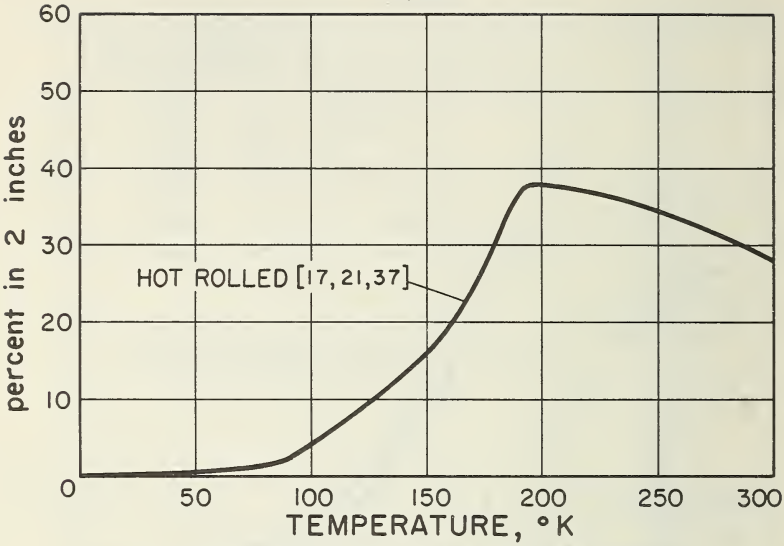
COMPOSITIONS:

SPECIMEN	% C	% Si	% Mn	% S	% P	% Ni	% Mg
IRON 1	3.63	.93	.35	.010	.024	.60	.042
IRON 2	3.52	2.03	.37	.013	.028	.71	.055
IRON 3	3.33	2.73	.40	.013	.028	.71	.057
IRON 4	3.29	2.09	.38	.014	.162	.72	.049

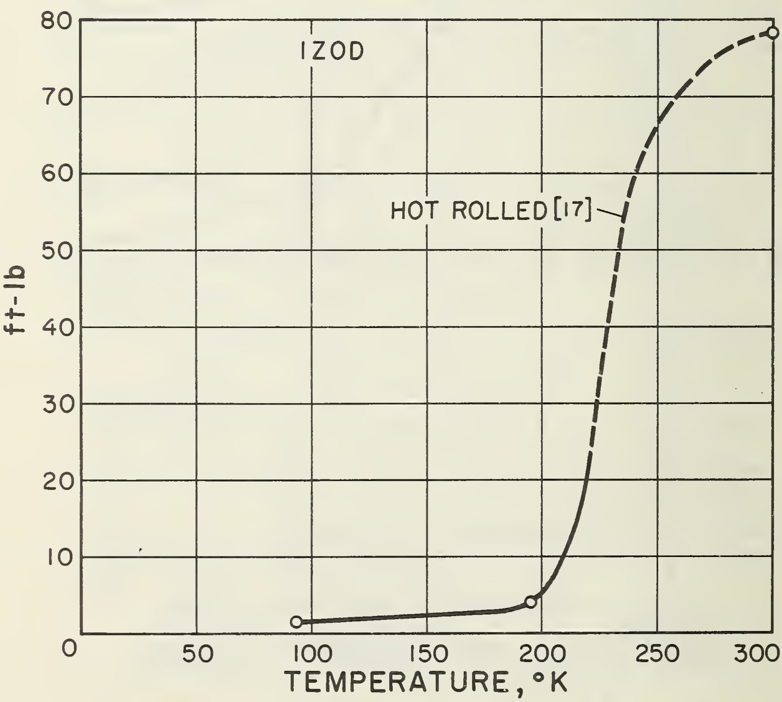
IMPACT ENERGY OF SOME FERRITIC NODULAR CAST IRONS



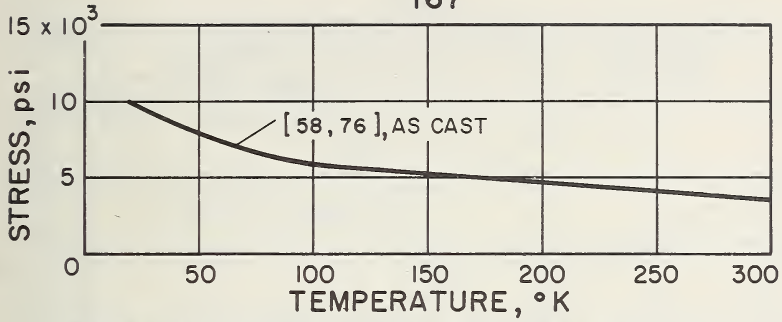
STRENGTH OF INGOT IRON



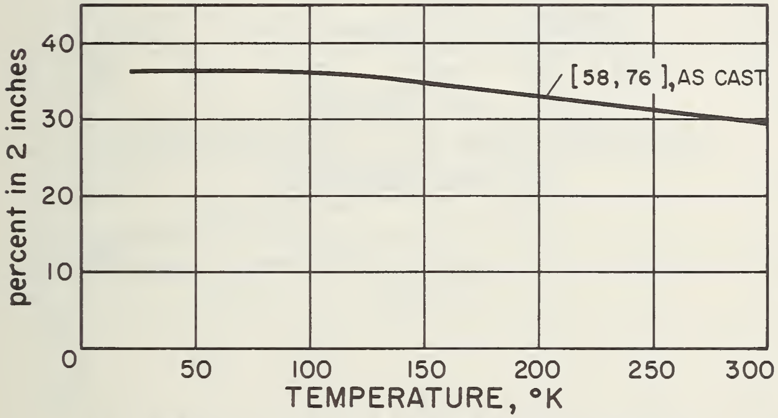
ELONGATION OF INGOT IRON



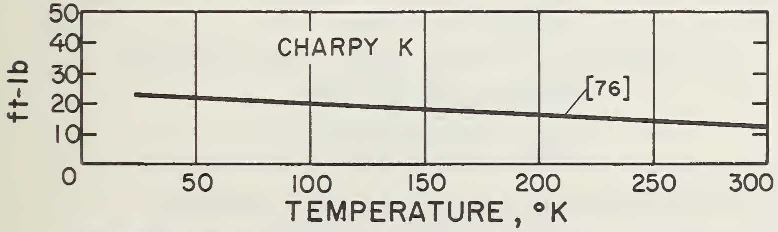
IMPACT ENERGY OF INGOT IRON



TENSILE STRENGTH OF COMMERCIALLY PURE LEAD



ELONGATION OF COMMERCIALLY PURE LEAD



IMPACT ENERGY OF COMMERCIALLY PURE LEAD

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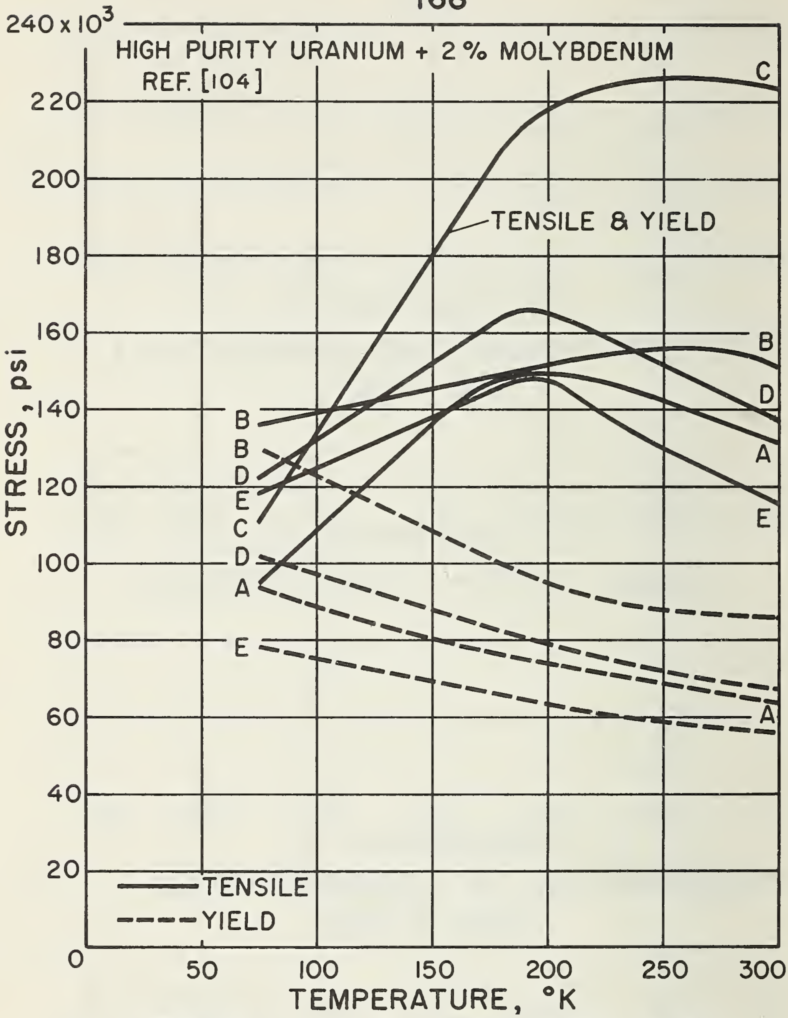


STRENGTH OF A MOLYBDENUM-URANIUM ALLOY

HEAT TREATMENTS

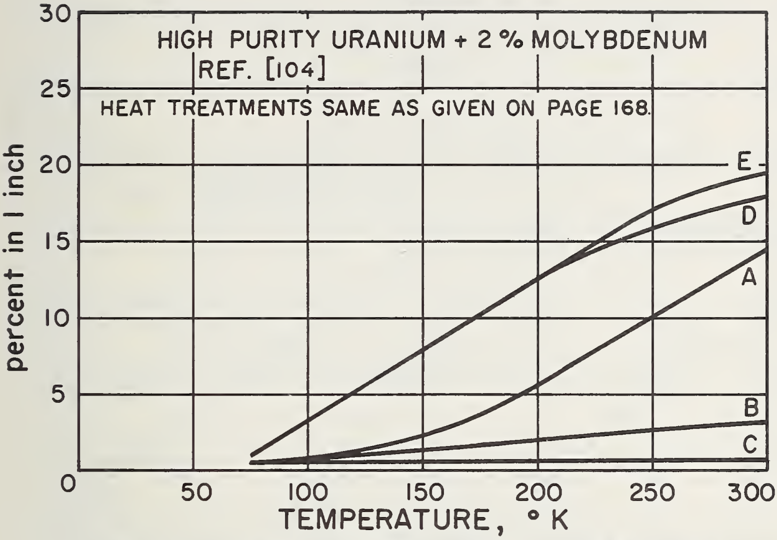
A. As cast.

B. Solution treated 3 hrs. at 850° C, water quenched.

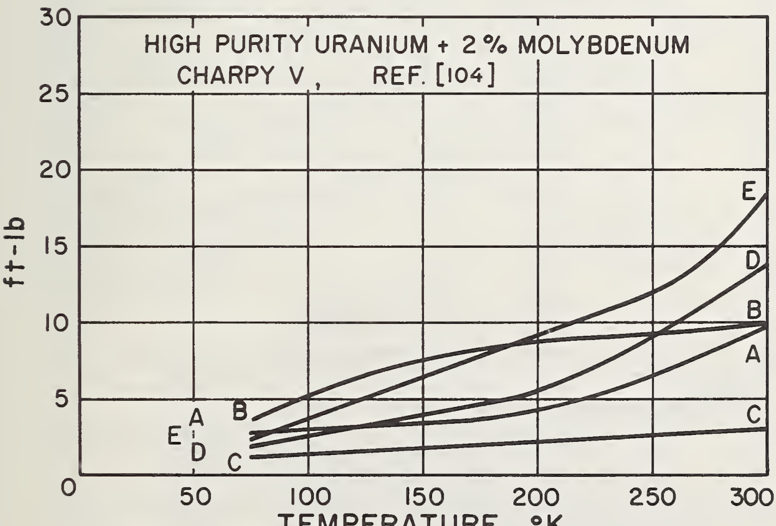
C. Solution treated 3 hrs. at 850° C, water quenched, aged 1 hr. at 450 °C.

D. Solution treated 3 hrs. at 850°C, furnace cooled at 5 °C/min.

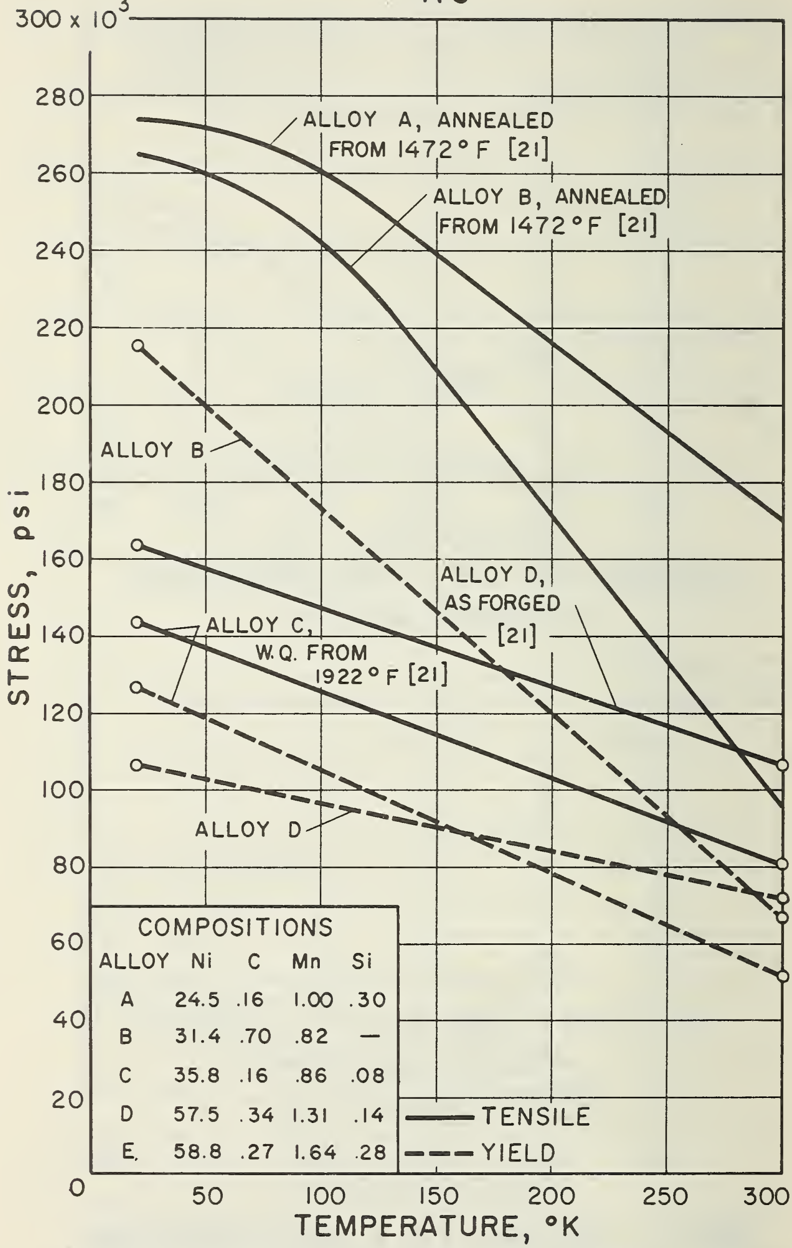
E. Solution treated 3 hrs. at 850°C, furnace cooled to 580° C and held 2 hrs., then reheated to 625 °C, held 2 hrs., water quenched.



ELONGATION OF A MOLYBDENUM-URANIUM ALLOY



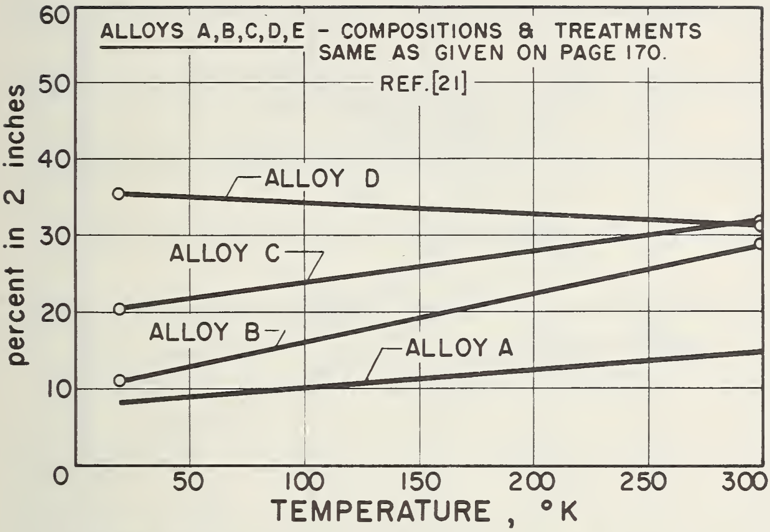
IMPACT ENERGY OF A MOLYBDENUM-URANIUM ALLOY



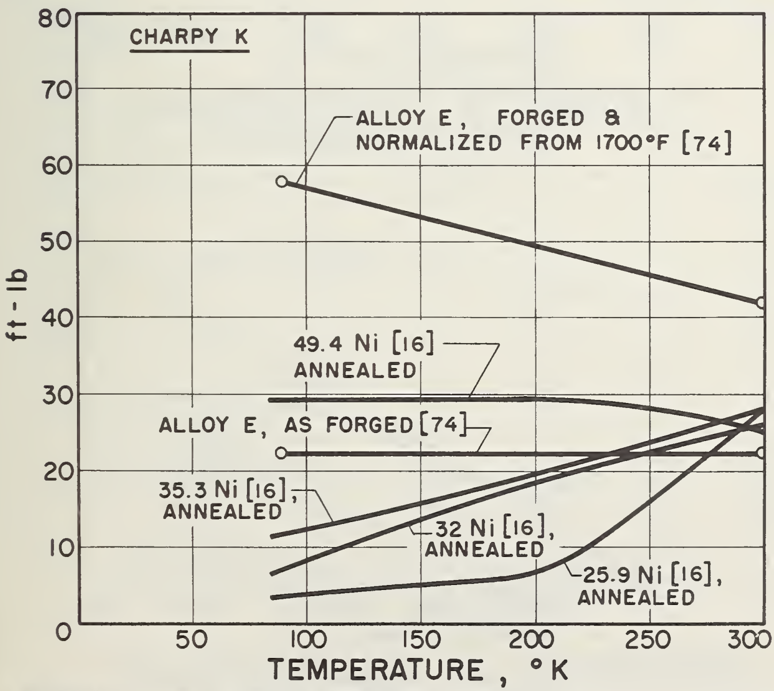
COMPOSITIONS

ALLOY	Ni	C	Mn	Si
A	24.5	.16	1.00	.30
B	31.4	.70	.82	—
C	35.8	.16	.86	.08
D	57.5	.34	1.31	.14
E.	58.8	.27	1.64	.28

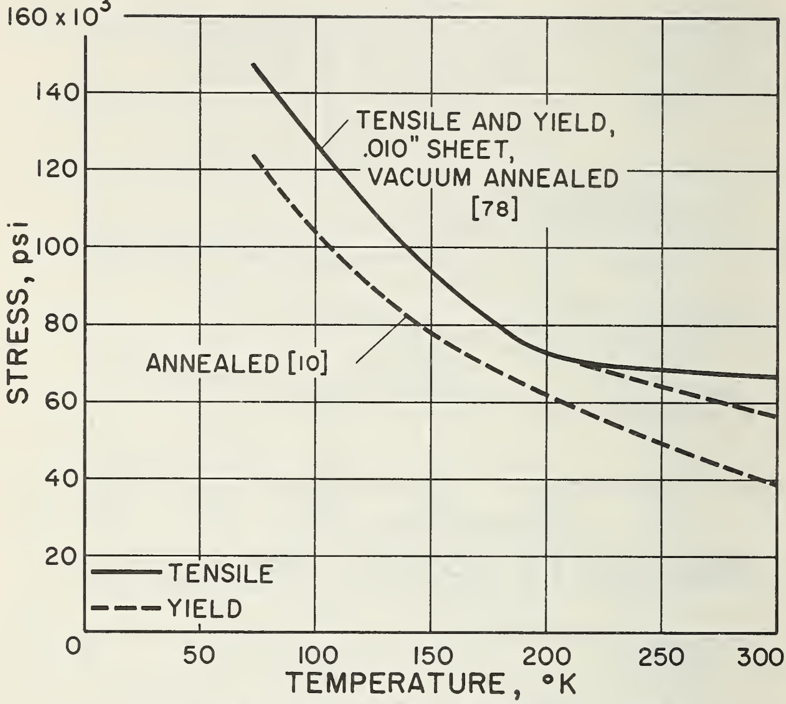
STRENGTH OF NICKEL-IRON ALLOYS



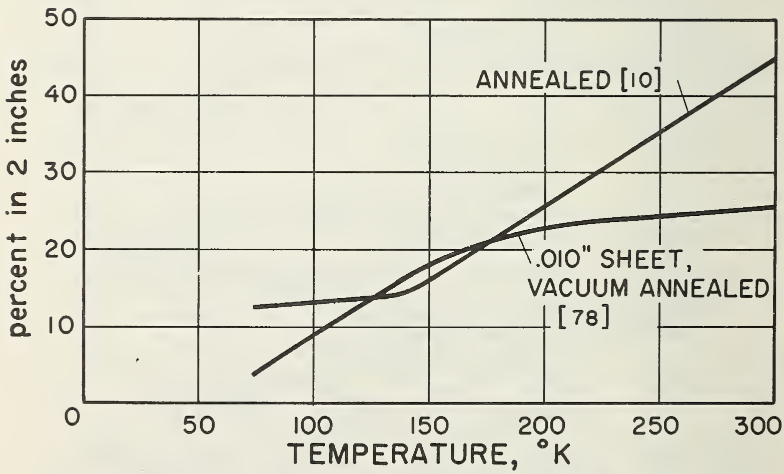
ELONGATION OF NICKEL-IRON ALLOYS



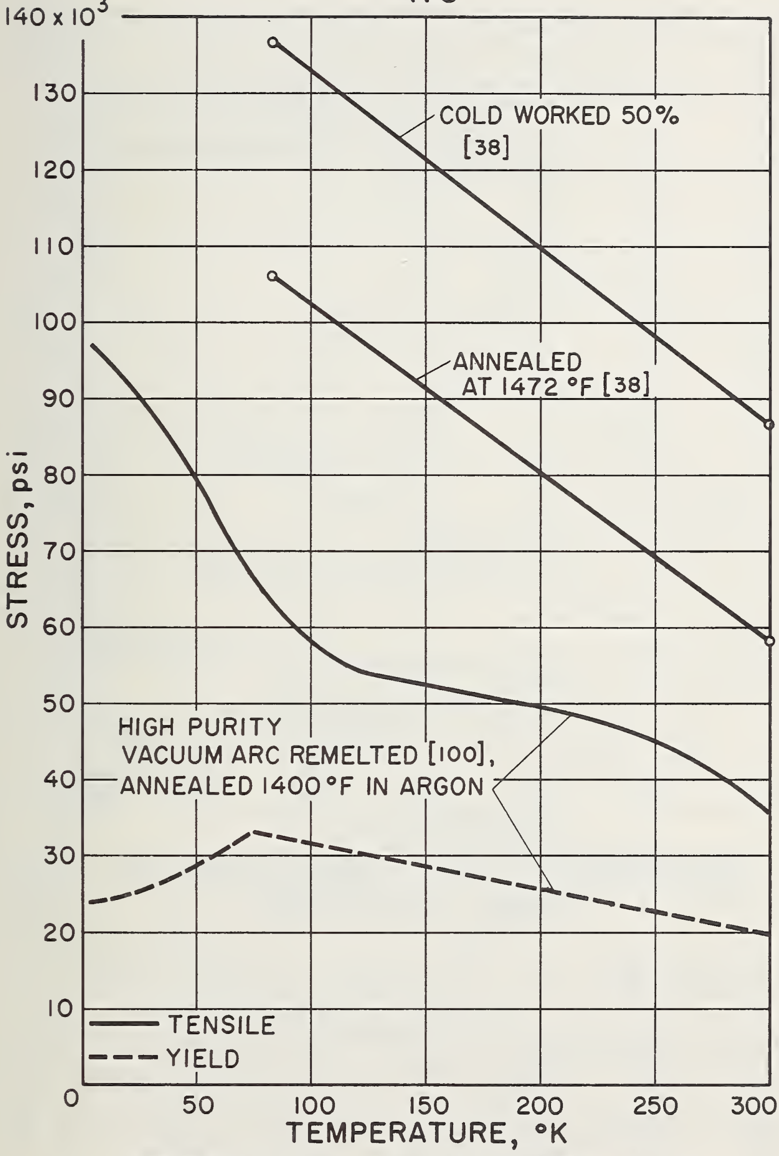
IMPACT ENERGY OF NICKEL-IRON ALLOYS



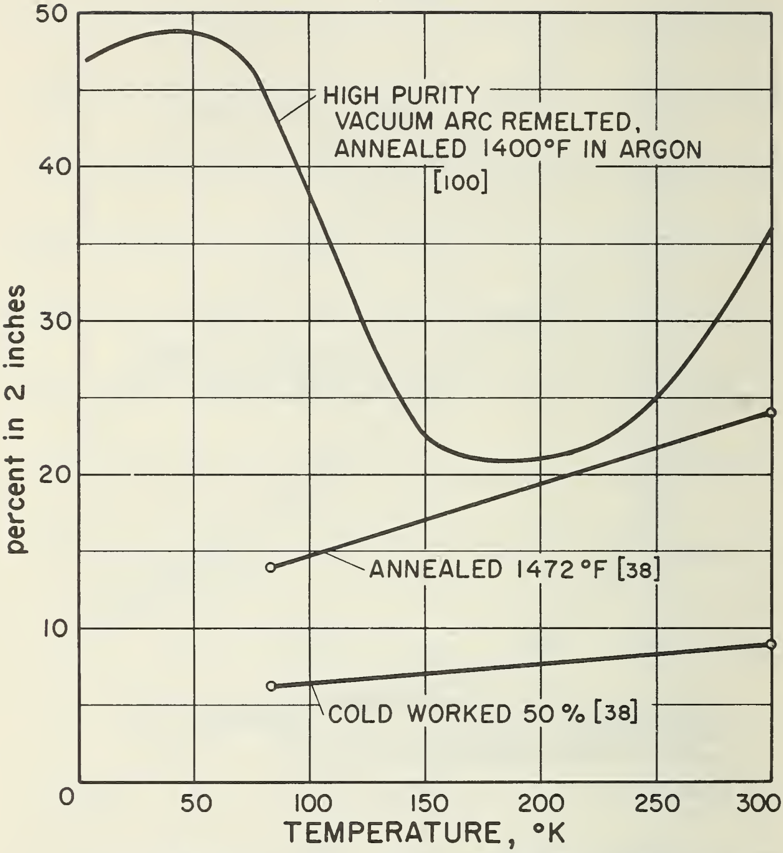
STRENGTH OF COMMERCIALLY PURE TANTALUM



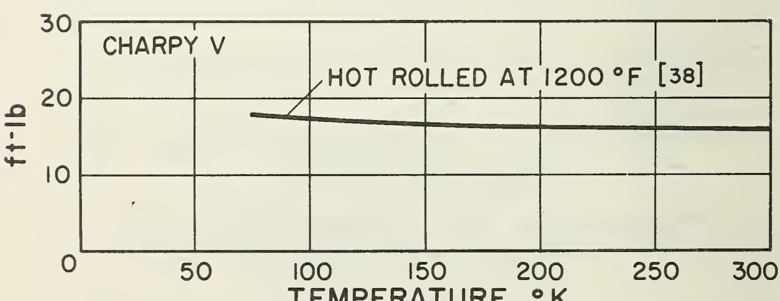
ELONGATION OF COMMERCIALLY PURE TANTALUM



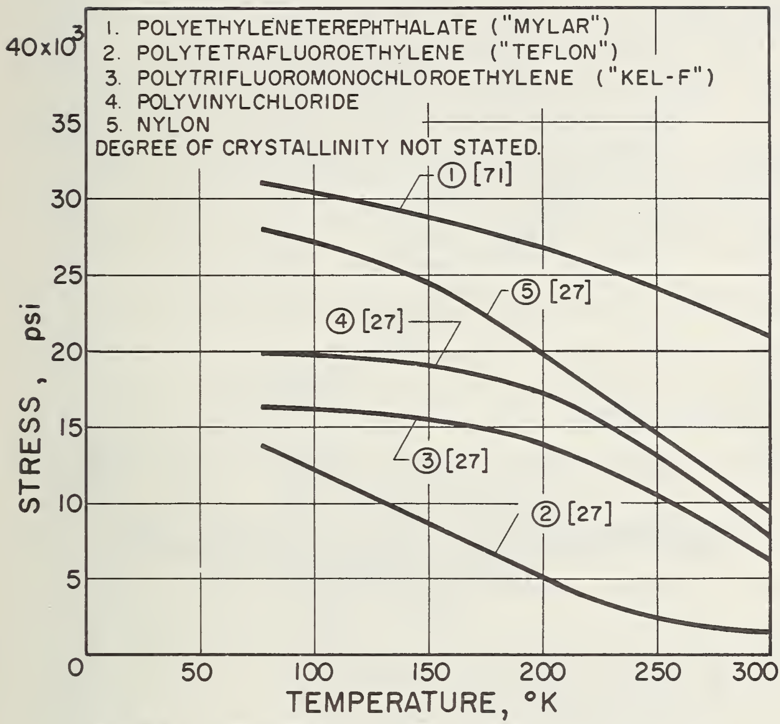
STRENGTH OF COMMERCIALLY PURE ZIRCONIUM



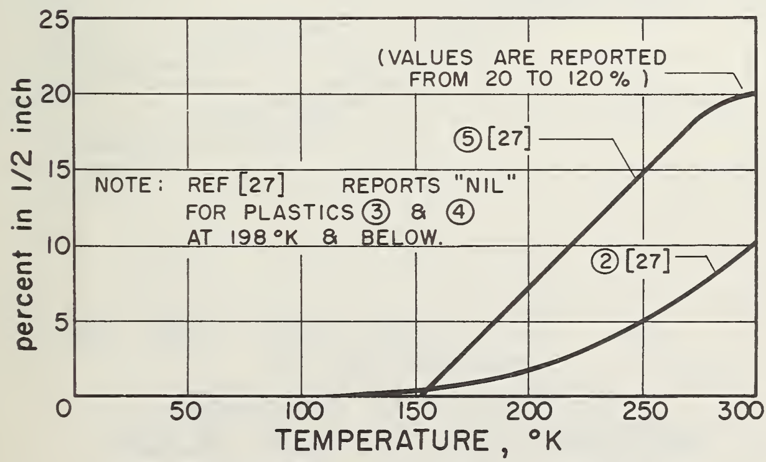
ELONGATION OF COMMERCIALLY PURE ZIRCONIUM



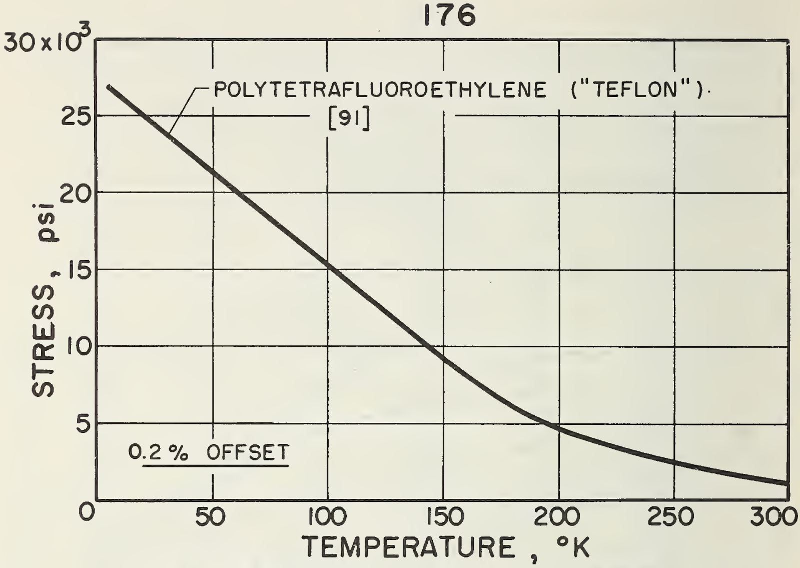
IMPACT ENERGY OF COMMERCIALLY PURE ZIRCONIUM



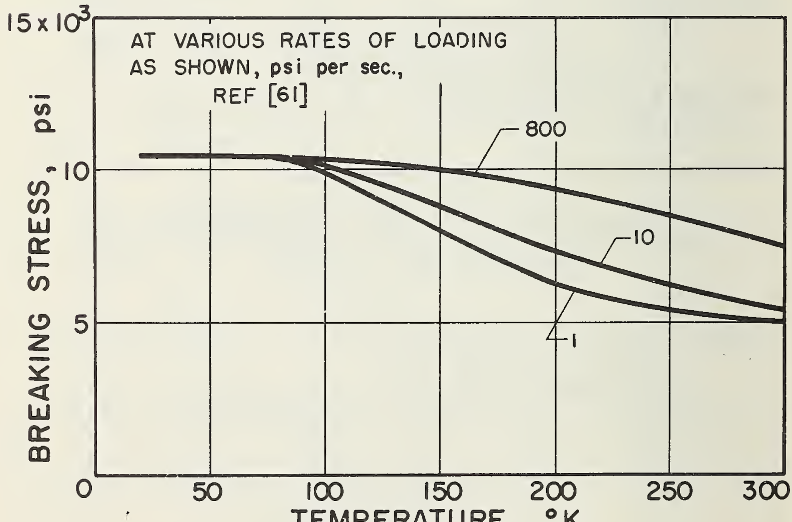
TENSILE STRENGTH OF PLASTICS



ELONGATION OF PLASTICS



COMPRESSIVE YIELD STRENGTH OF PLASTICS



STRENGTH OF ABRADED BOROSILICATE OPTICAL GLASS

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2. Allegheny Ludlum Steel Corp., Stainless Steel Handbook (1951).
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5. Armco Steel Corp. Product Data Bulletin, Armco precipitation hardening stainless steels—Armco 17–4PH bar and wire (March 1956).
6. Armco Steel Corp. Research Laboratories (unpublished data).
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