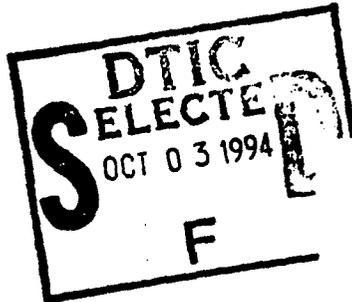


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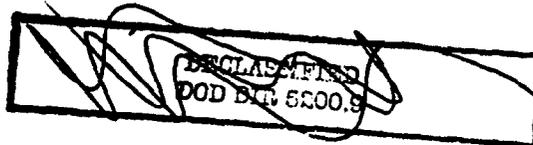
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CRYOGENIC MATERIALS DATA HANDBOOK



CRYOGENIC ENGINEERING LABORATORY

BOULDER, COLORADO

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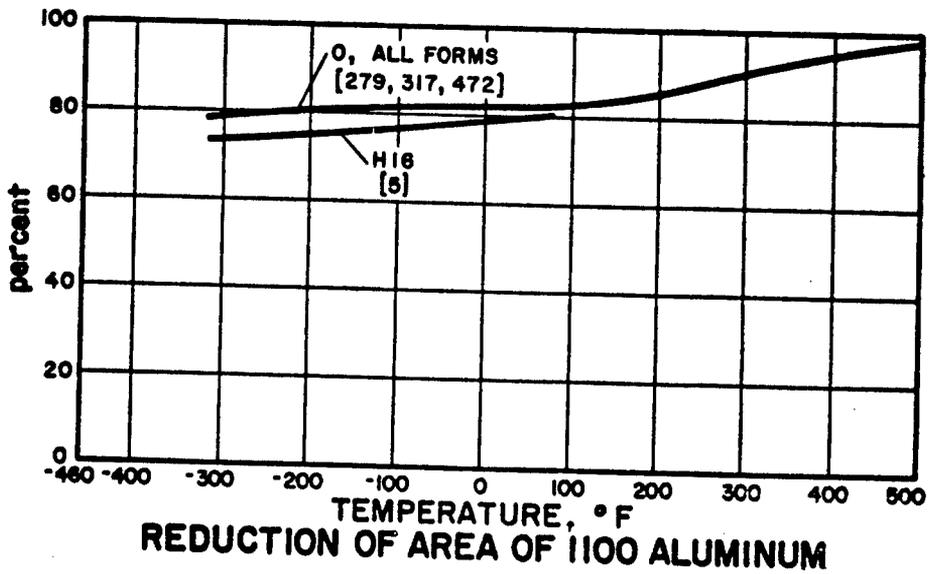
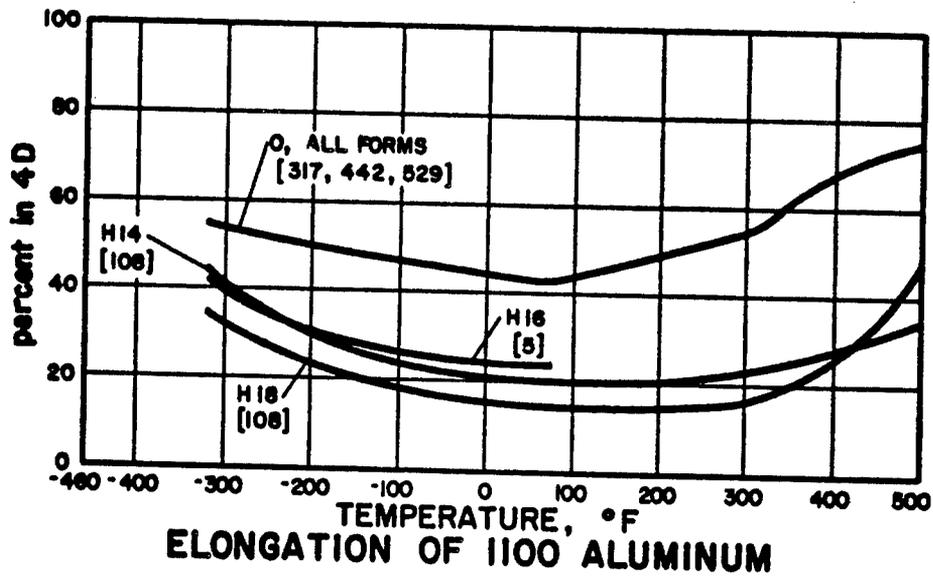


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A.3.cd



FOREWORD

This handbook of data on solid materials at low temperatures is prepared under the sponsorship of the Air Force Ballistic Missile Division by personnel of the National Bureau of Standards. Its preparation is a two year program and deals with physical properties of certain metals and non-metals over the temperature range minus 423° F to plus 500° F.

The materials and properties selected for inclusion in the handbook are limited by the scope of the contract to those appearing in the Index. The materials are mostly those in current use for missile applications at cryogenic temperatures, but a few have been included because of their potential for such uses. 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 this handbook 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 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. There are a few exceptions to this rule, but they were made only when absolutely necessary.

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 programmed 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 has been 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.

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.

Adjacent to each curve are several numbers in brackets. These numbers correspond to the references in the bibliography which will be issued later and indicate the sources of data from which the curve was constructed. 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.

In general, most of the pertinent information about unusual test specimens or methods used to obtain the data given in any graph are noted on the graph itself. One omission consistently made, however, is to specify the method by which yield strengths were determined. Unless otherwise noted, the yield strength in tension

and compression was found by the 0.2% offset method. Extremely detailed information in which only an occasional designer might be interested can be obtained by reference to the original papers.

Throughout the book various symbols are used in order to abbreviate the notes on the graphs. These correspond with usual metallurgical practice: "OQ & T" means "oil quenched and tempered", "WQ & T" means "water quenched 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. Whenever the metallurgical condition of the specimens was stated in the literature, it is appended to the curves.

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. This is true, of course, and 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 ductility criterion should not be applied in most 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* 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.**, 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 energy, but have been satisfactorily used in the aircraft industry in structural applications in which they receive impact loads. So while 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. Also, very often the impact energy value for a given type of specimen is less important than supplementary information such as 1) whether or not the specimen broke completely in the impact test, 2) how much of the fracture was characterized by cleavage and how much by shear, 3) the trend taken by impact strength with temperature (some of the lighter metals are inherently lower in absolute value than heavier alloys, but may not decrease with temperature), etc.

As a simple laboratory test which will provide a suitable

*Eldin and Collins, Fracture and yield stress of 1020 steel at low temperature, J. Appl. Phys. (Oct. 1951).

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

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. Just from intuitive reasoning, the ratio of the tensile strength of a notched bar to that of a smooth bar would seem to be a better criterion for the performance of a material in many structural applications than either of the previously mentioned tests. "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.

As a striking example of the different conclusions one would draw from information obtained from notched-bar and smooth-bar tensile tests, the following are data taken on 0.020-inch thick type 301 stainless steel which had been cold rolled to 200,000 psi tensile strength. The notch depth in the specimens used was 50%, and the notch sharpness was 0.0125.*

Test Temperature, °F	Percent Elongation, Smooth Specimen	Ratio of Notched to Smooth Tensile Strength
+350	1	1.05
+70	4	1.05
-320	18	0.99

The elongation at +70° and +350°F would indicate less than acceptable ductility for this alloy, but the ratio of notched to smooth tensile strength remains unity over the temperature range. This shows that the material has sufficient ability to deform at the root

*A. Hurlich, J. Watson, Convair Astronautics, private communication. See, for example, G. Sachs and J. D. Lubahn, *J. Appl. Mech.*, 67, A-241 (December, 1945), for an explanation of the terms "notch depth" and "notch sharpness".

of the notch where the stress is greatest, and to redistribute the stress evenly over the load-bearing cross-section.

There are other types of laboratory tests which have been devised to predict the performance in service of structural materials, each a 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 phenomenon of creep is not usually a problem at low temperatures over normally encountered time intervals for any of the metallic materials included in this handbook. The creep behavior referred to in the index is that exhibited over very long periods of time: a year or more. This becomes a difficulty when springs are required to retain accurate set points during storage, for example. In this book, therefore, one should expect to find the usual kind of short-time creep data only for aluminum alloys and some of the non-metals, since only these materials exhibit the phenomenon below 500°F.

ORGANIZATION OF THE INDEX AND ITS USE

Each material to be contained in this handbook has been assigned to a general group and designated by a number. The most common classification for each material has been used. Within each group those alloys with commonly used names are listed first--alphabetically by "key-word"--followed by those bearing a numerical designation. The latter are arranged in numerical sequence.

Quite broad headings have been used for the groups. The criterion for placing an alloy within a particular group is the element comprising the largest percentage of the composition.

The properties that will be reported have been assigned a letter designation, and are listed in the order in which they will occur for each material.

Page numbers will contain three parts; first, the group letter, second, the material number, and third, the property letter. Those pages containing more than one graph reporting different properties will contain all the property letters necessary to describe the page. For example, the Modulus of Elasticity as a function of temperature for type 303 stainless steel will be found on page D.10.f, while the Reduction in Area for 2024-T86 as a function of temperature will be found on page A.5.cd. A supplementary page that would have a number duplicating one already issued will be designated by an additional digit.

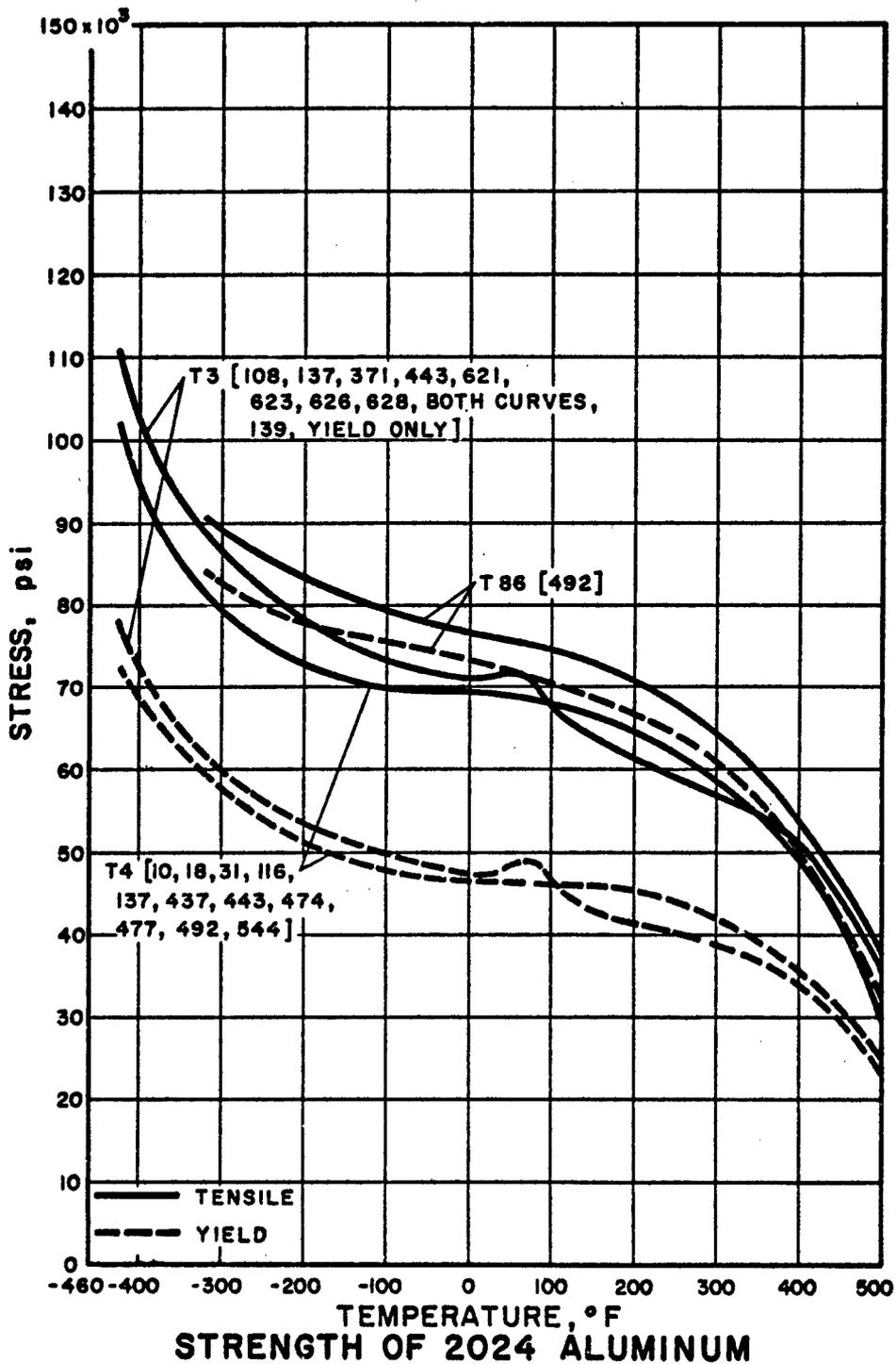
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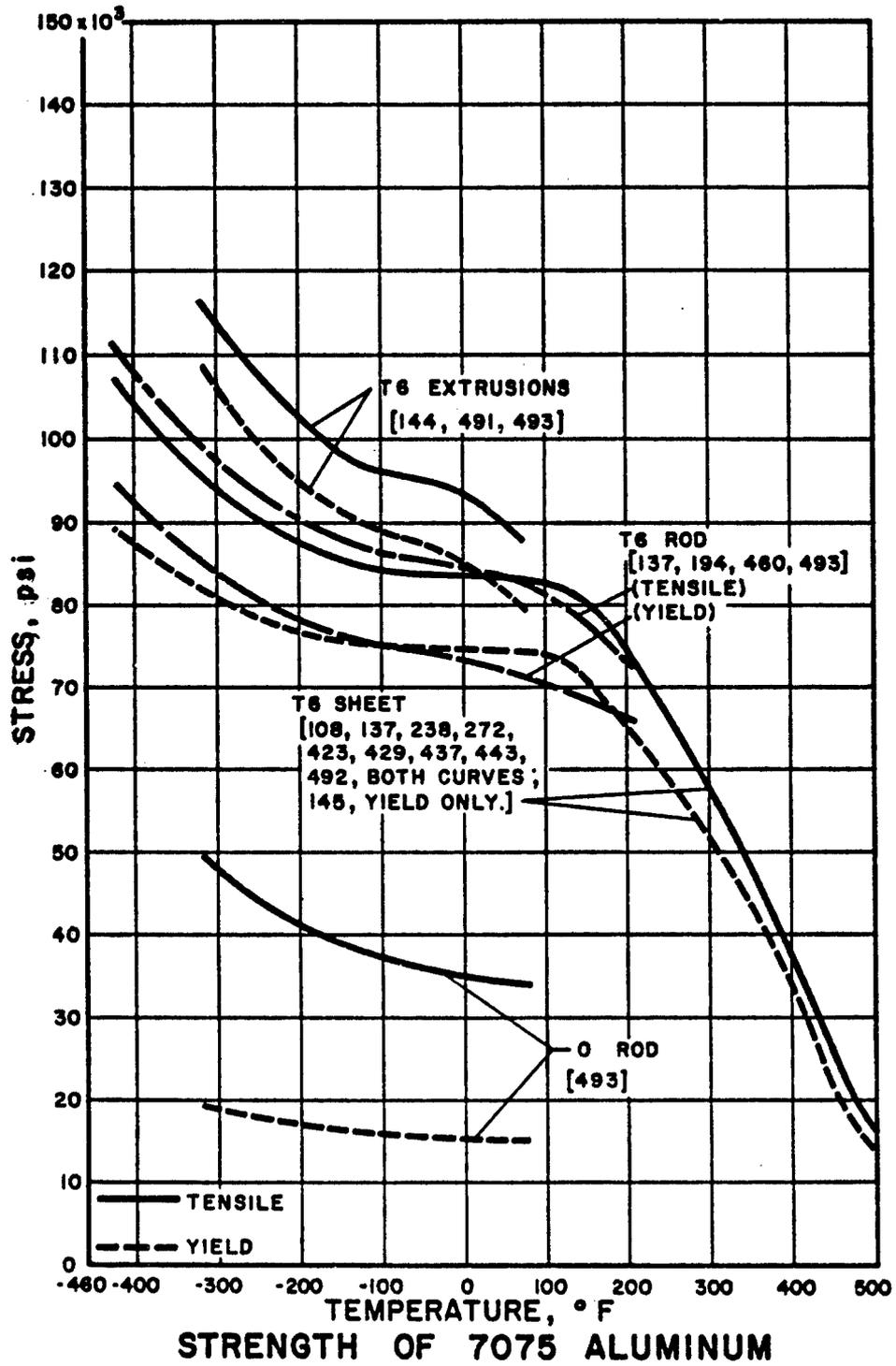
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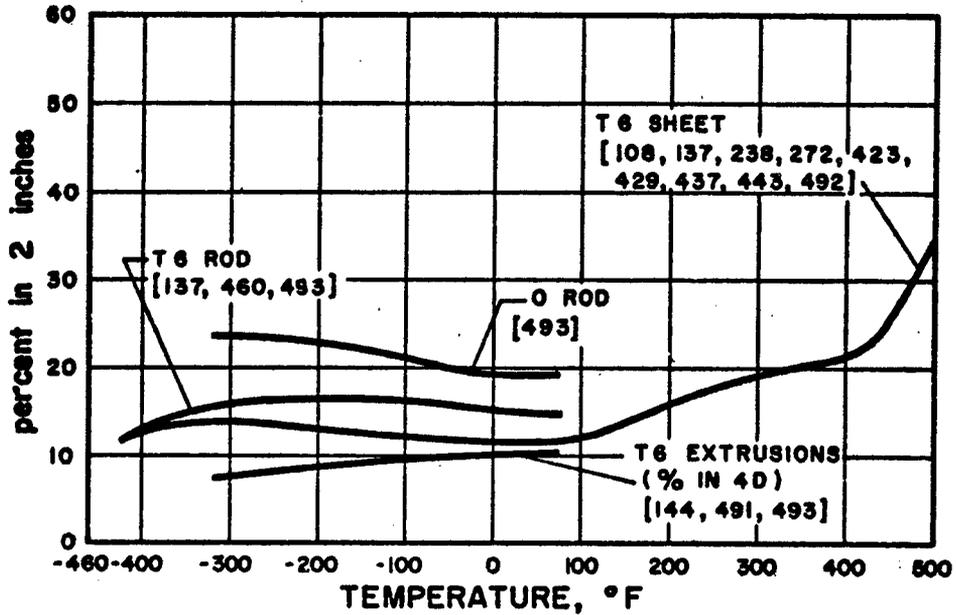
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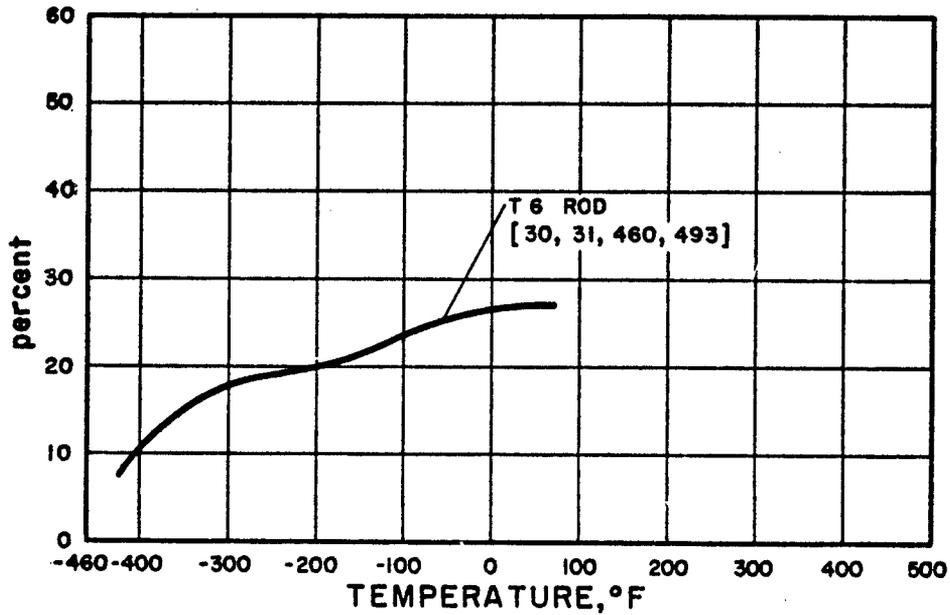
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A.7. cd

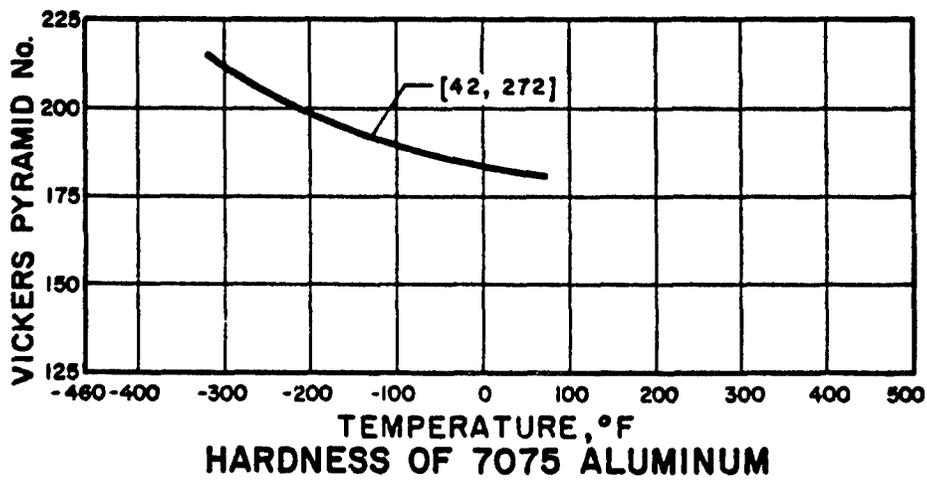
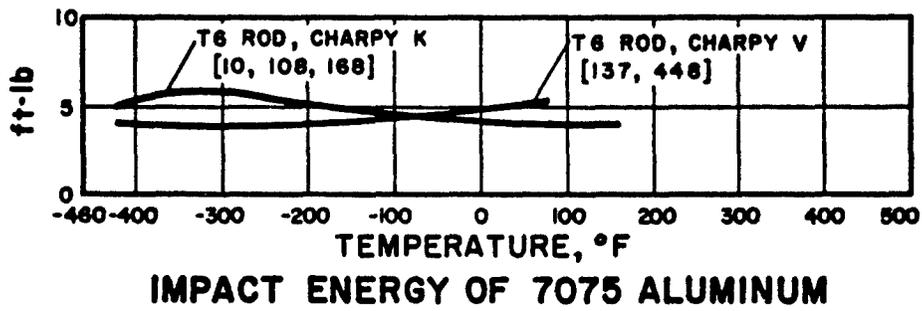
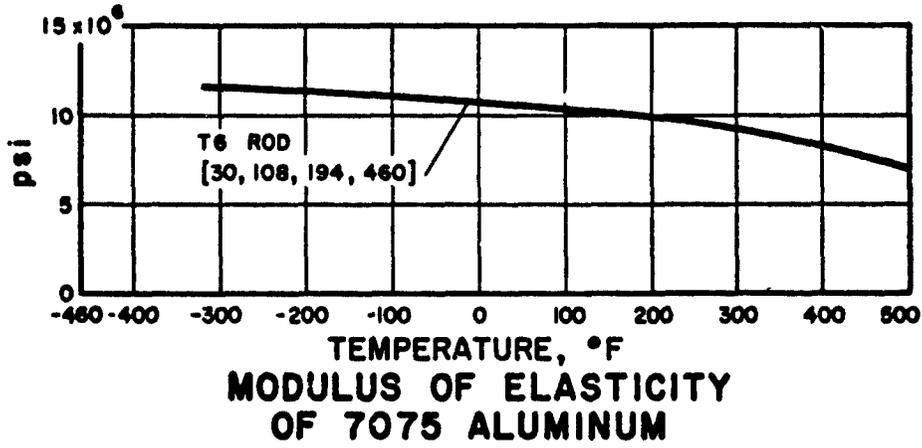


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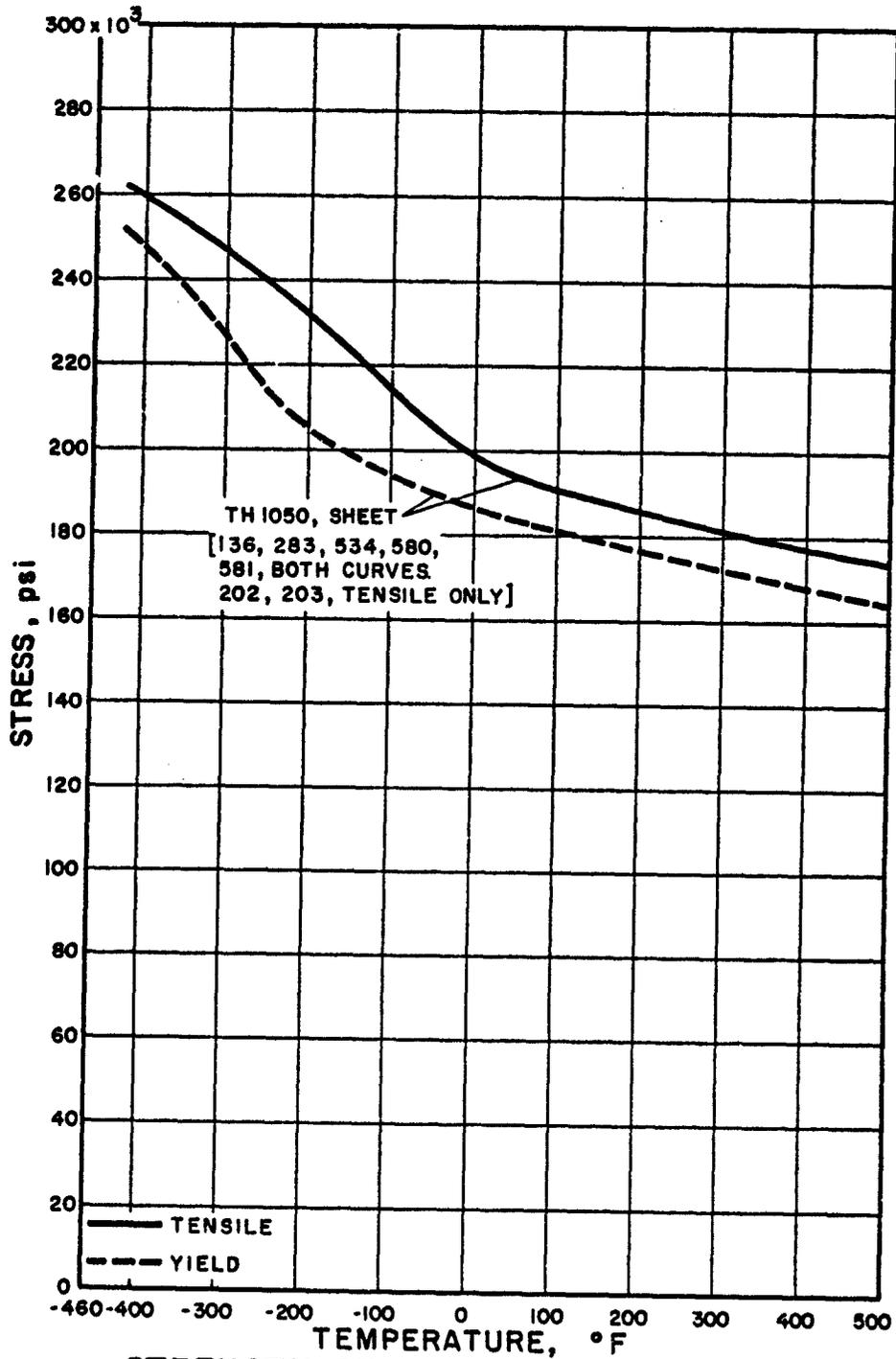


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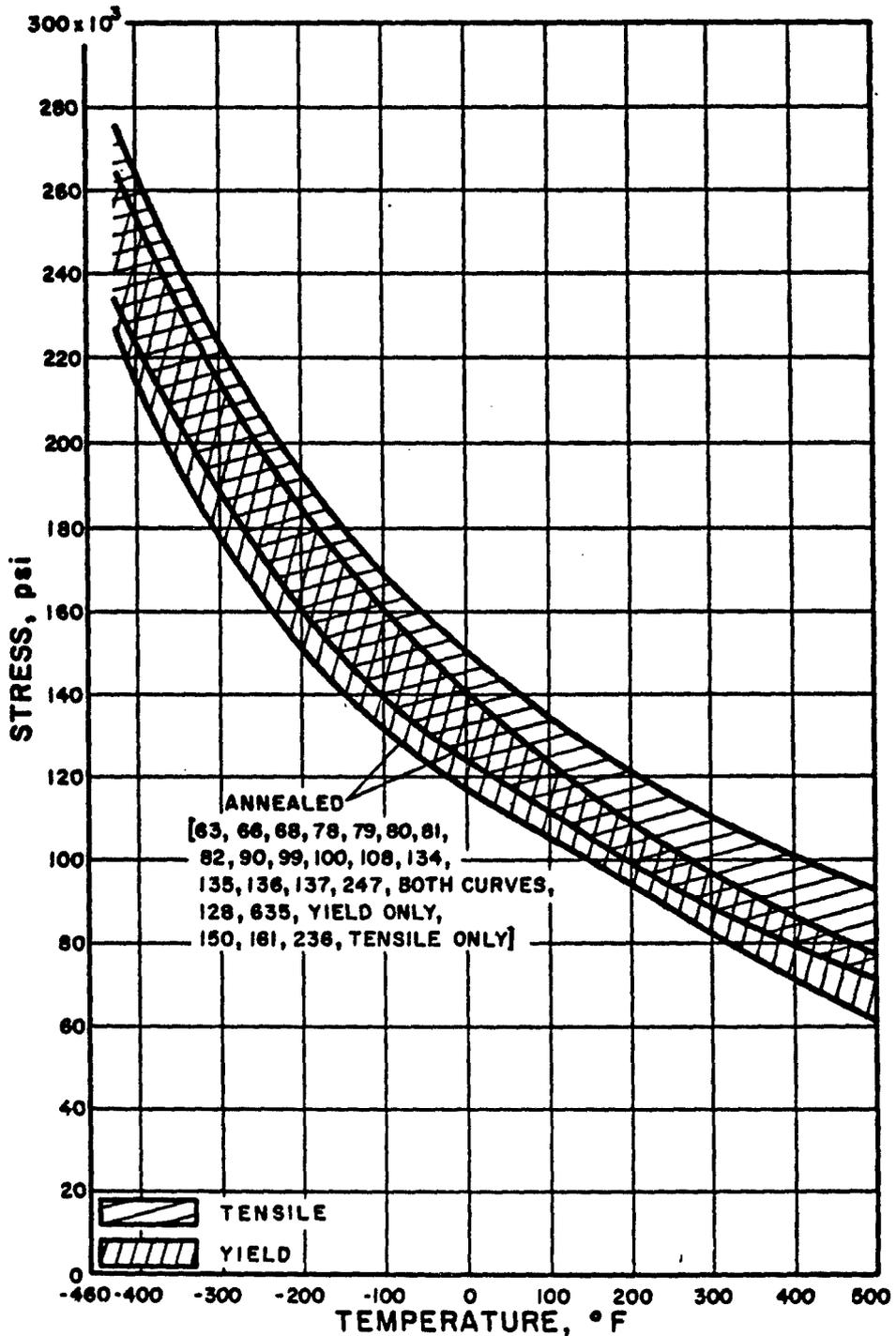
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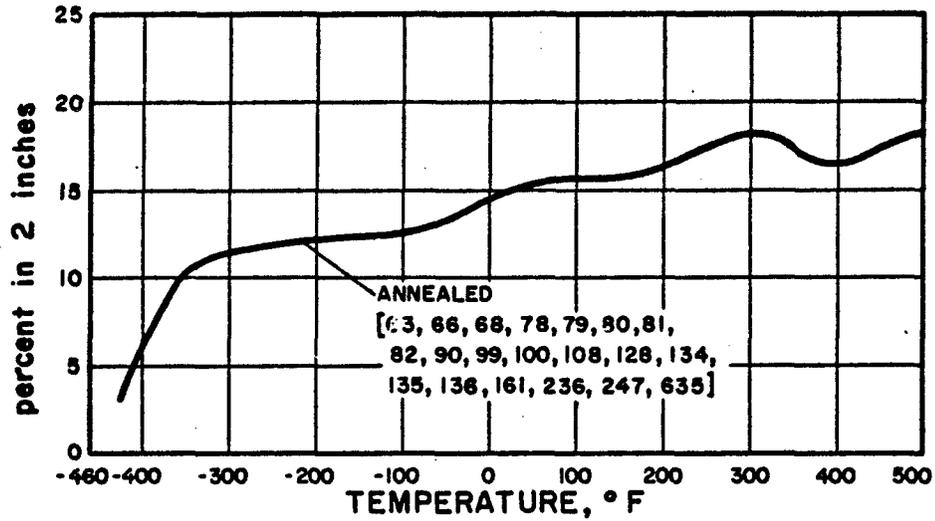
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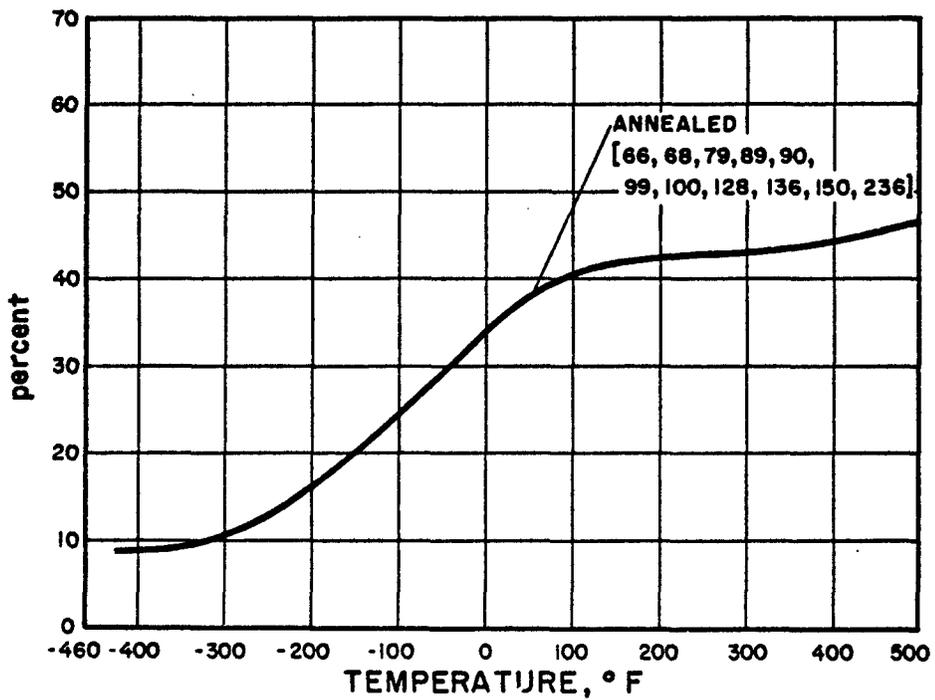
STRENGTH OF 17-7 PH STAINLESS STEEL



STRENGTH OF A-110-AT TITANIUM

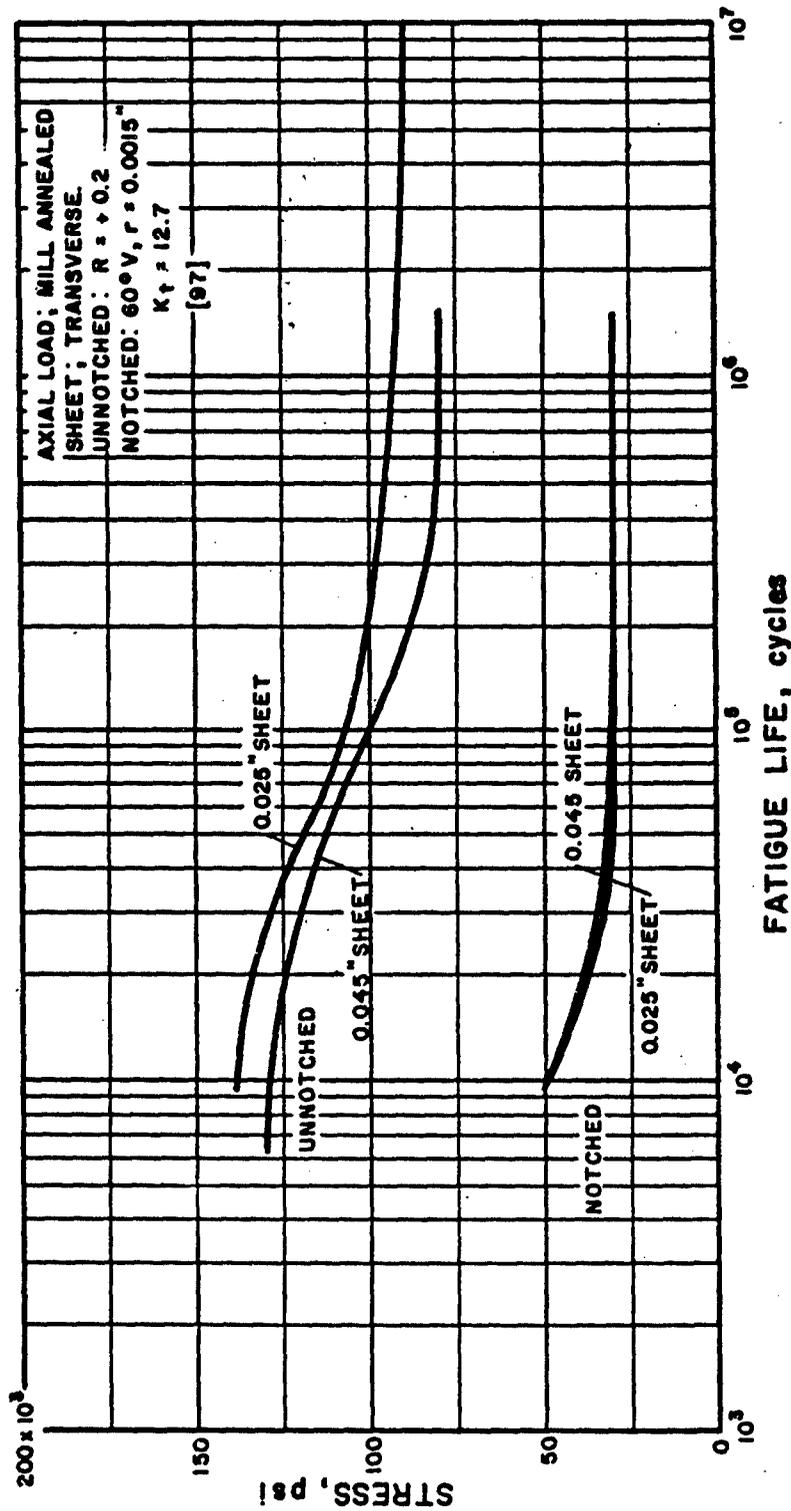


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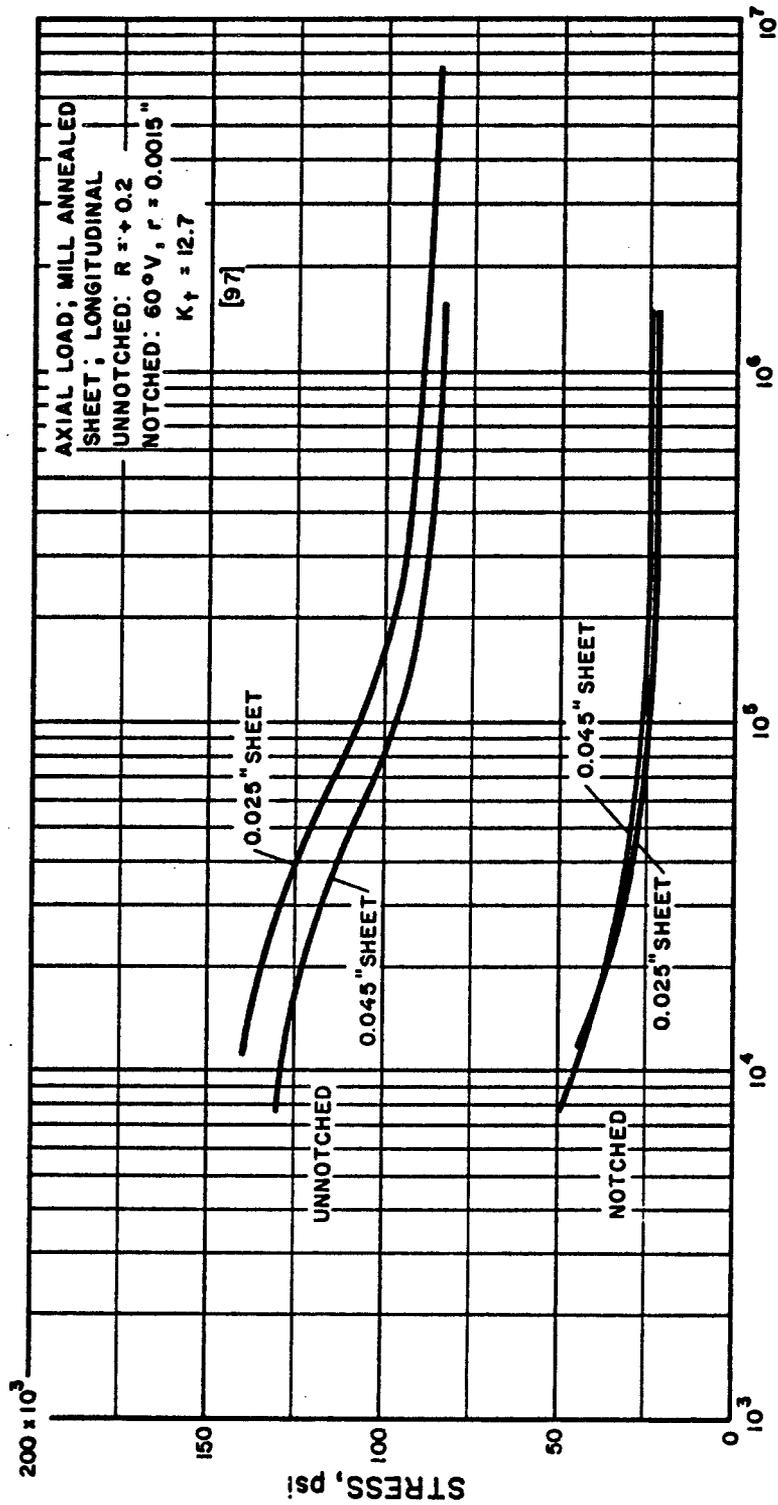


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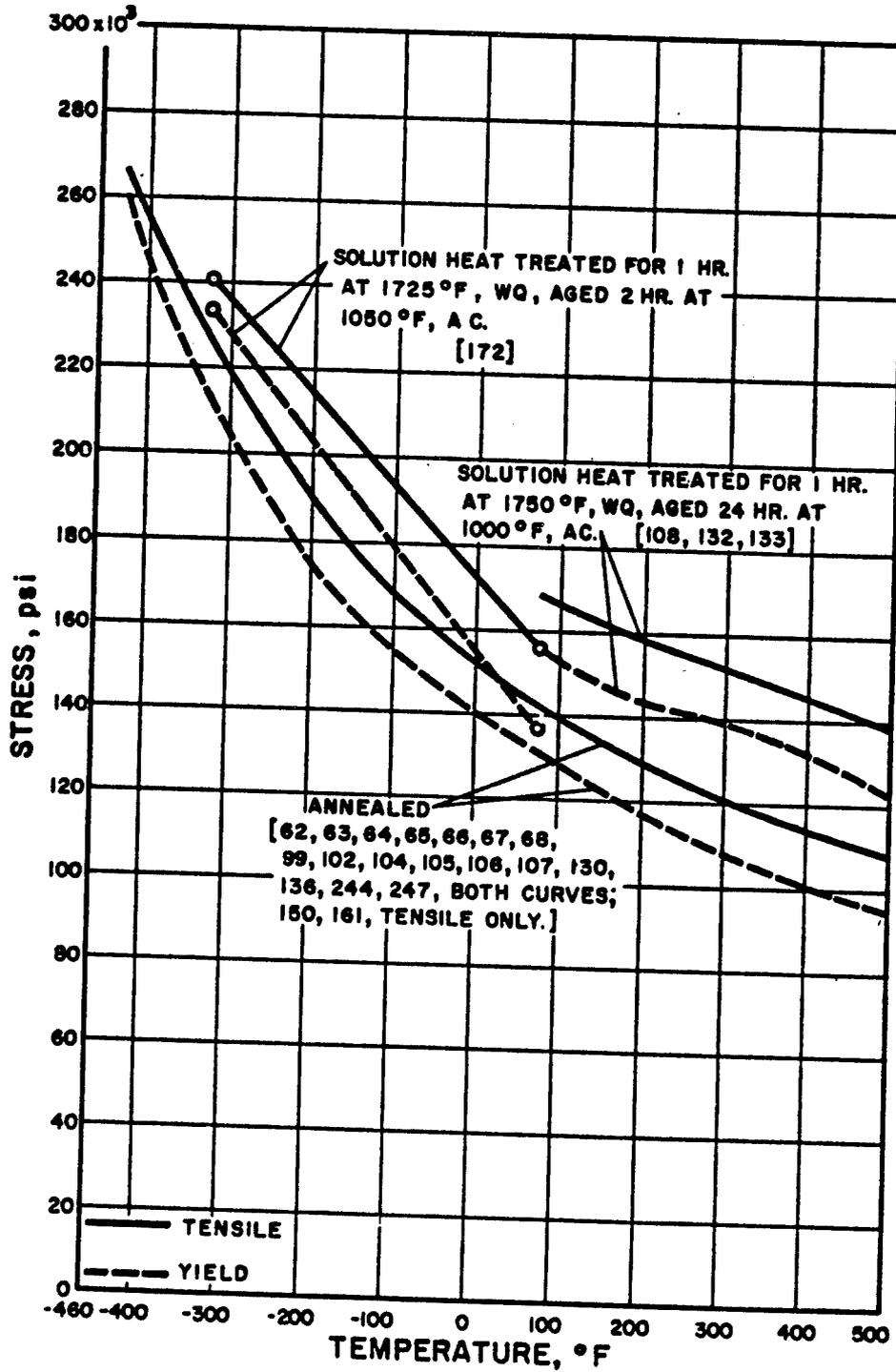
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FATIGUE BEHAVIOR OF A-110-AT TITANIUM

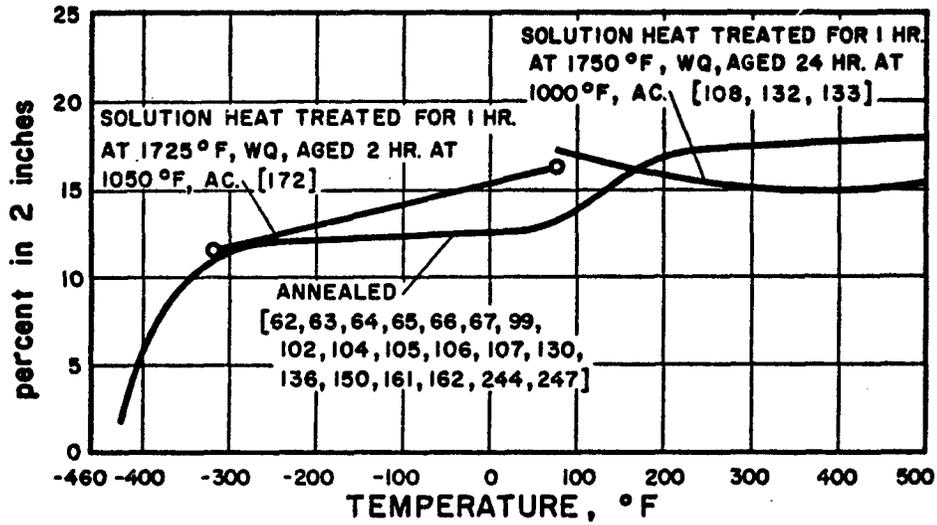


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FATIGUE BEHAVIOR OF A-110-AT TITANIUM

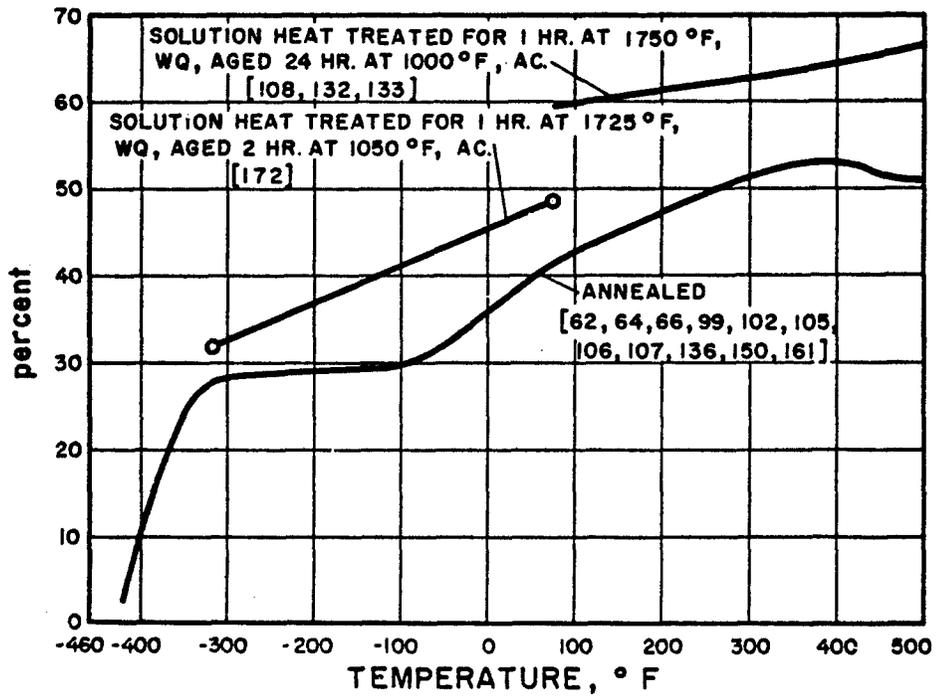


STRENGTH OF C-120-AV TITANIUM

F. 3. cd

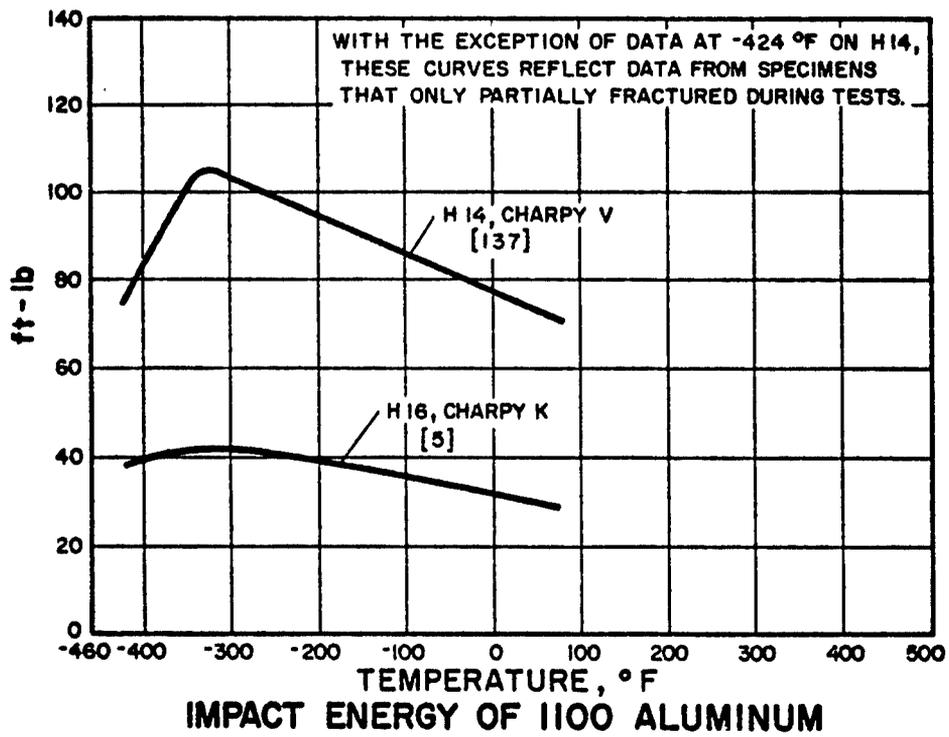
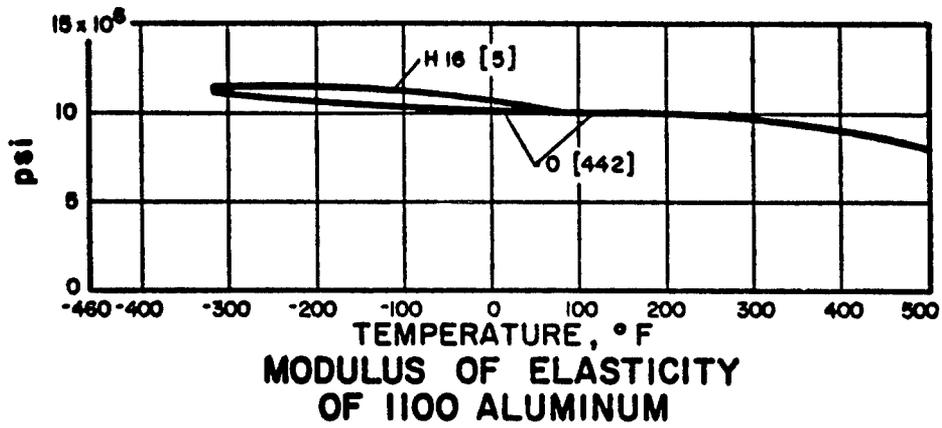


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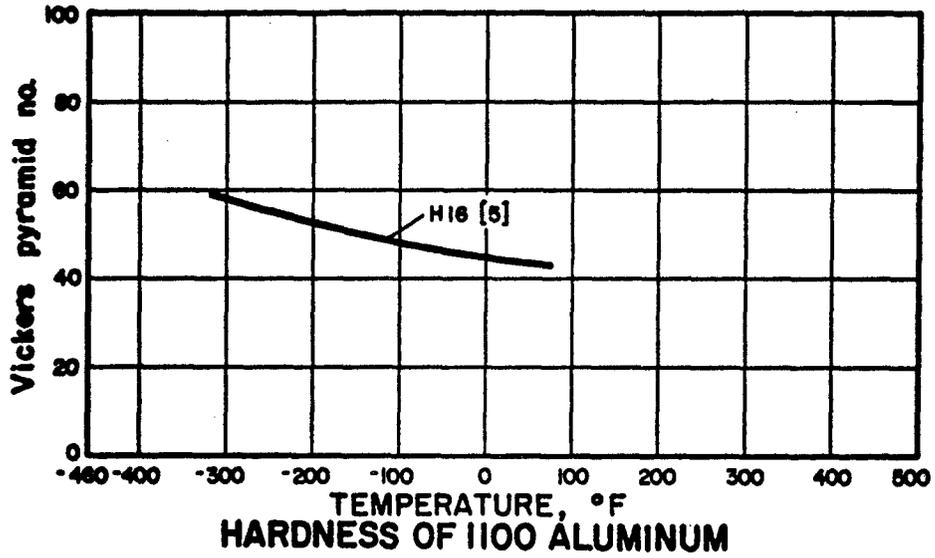


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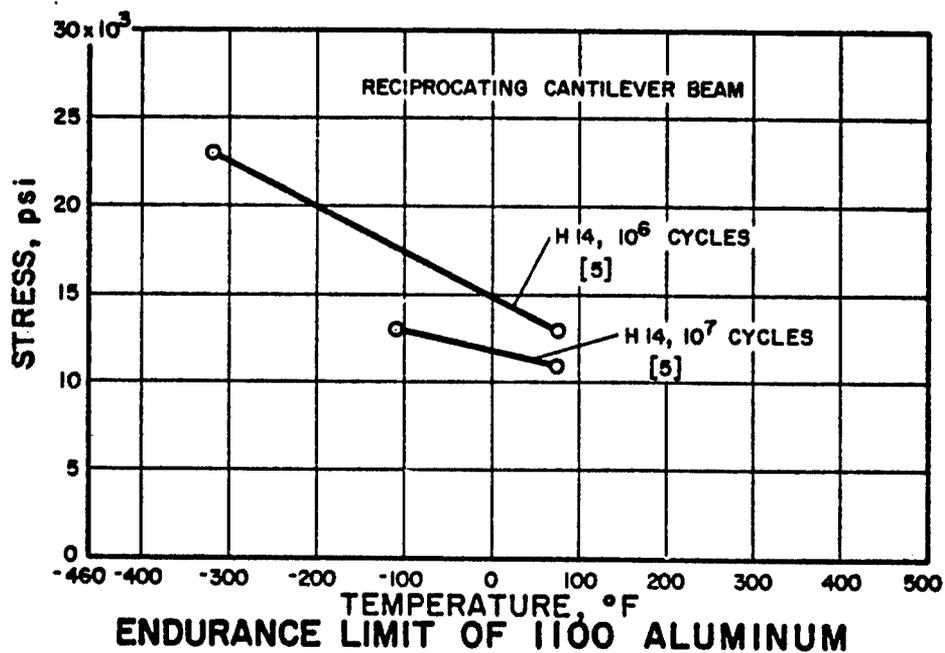
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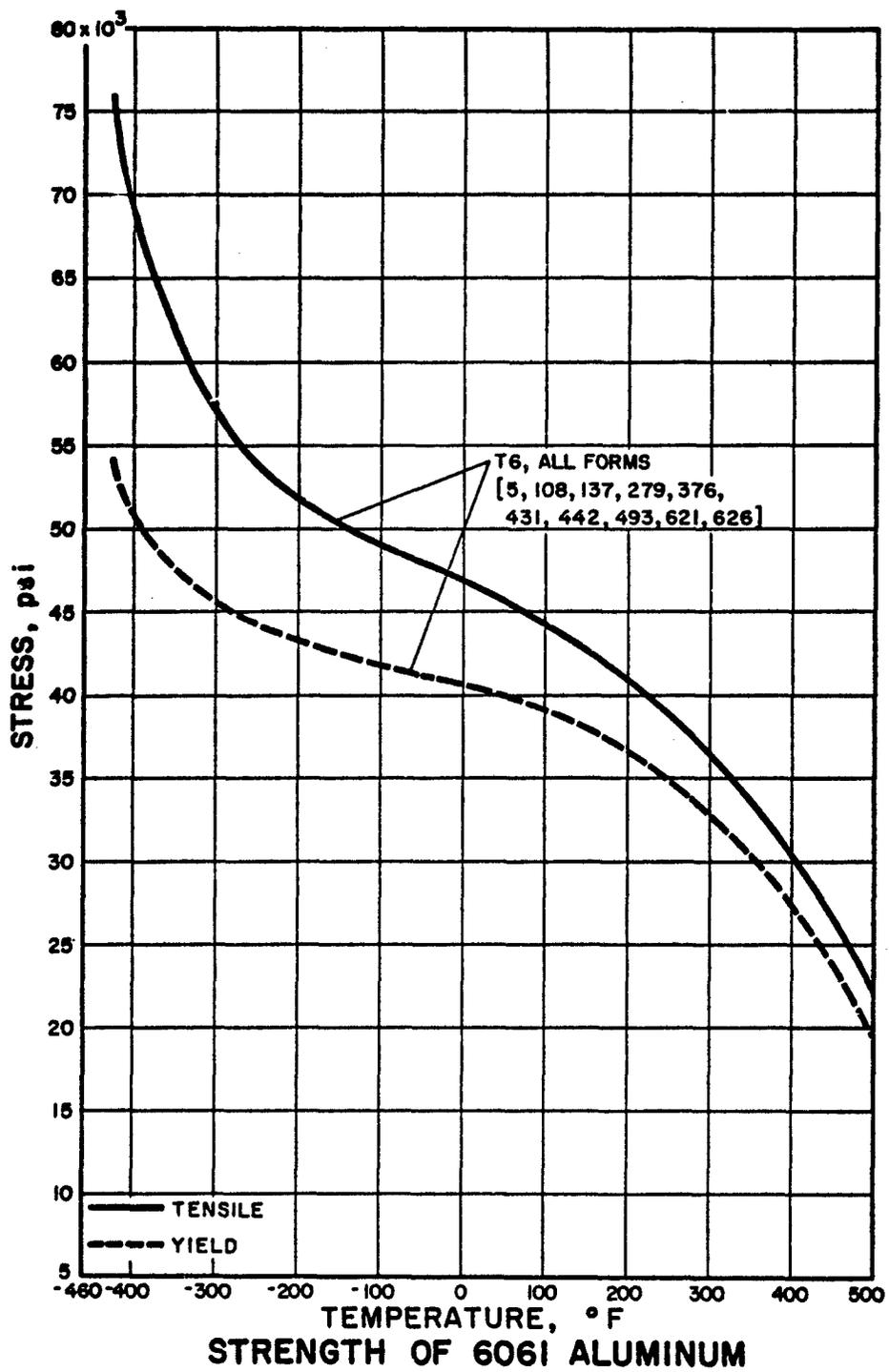
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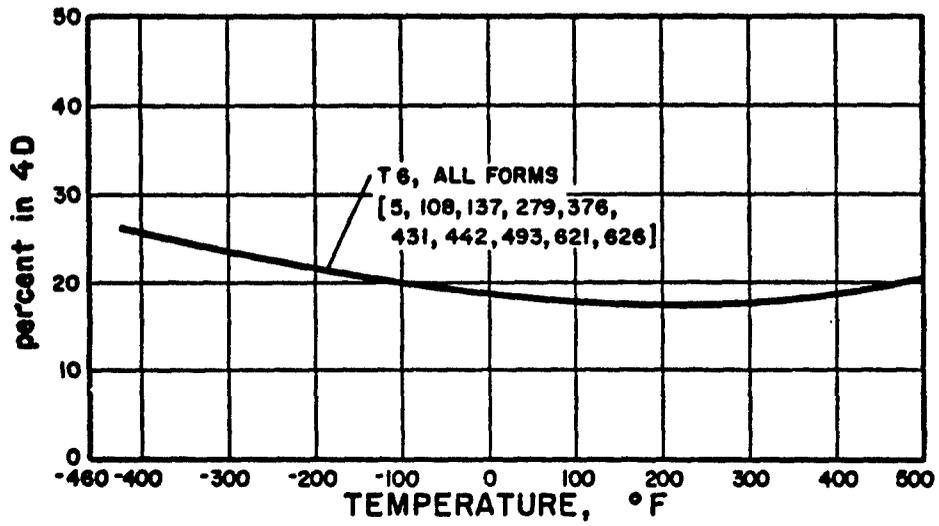
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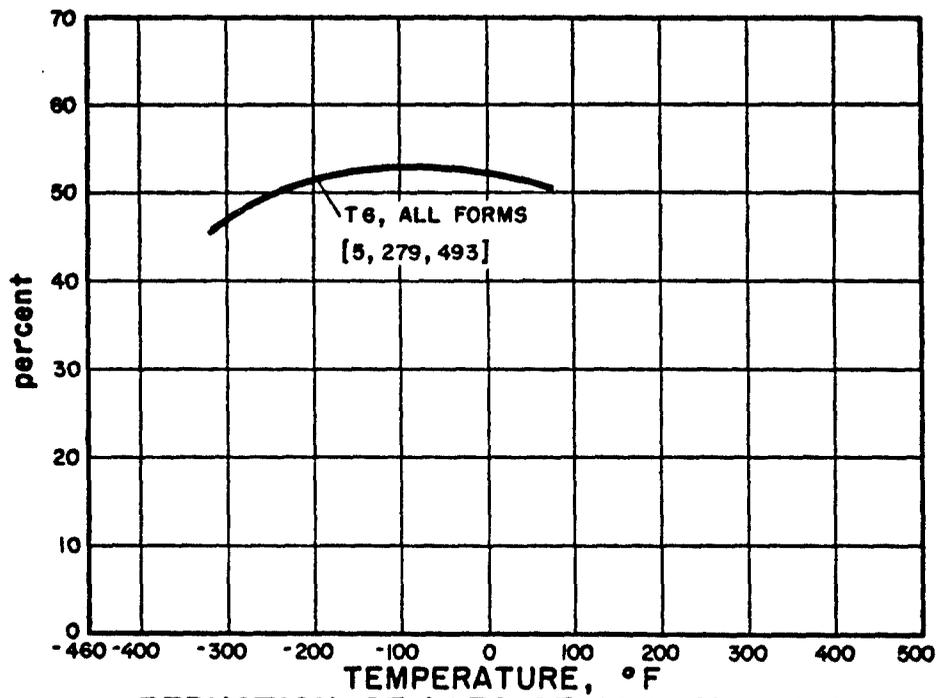
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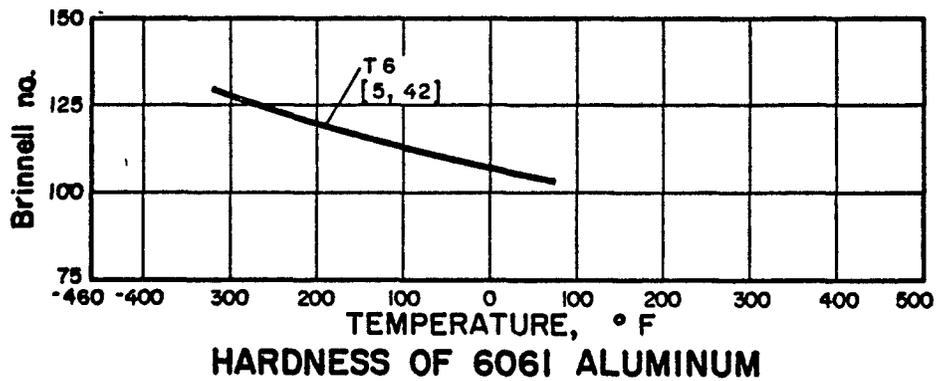
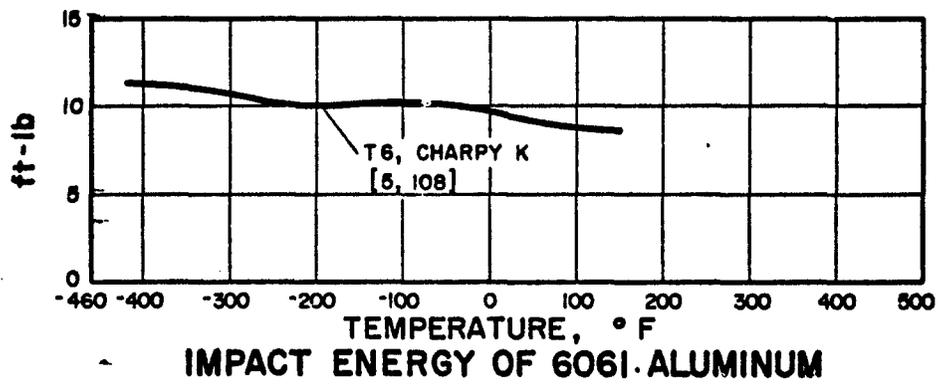
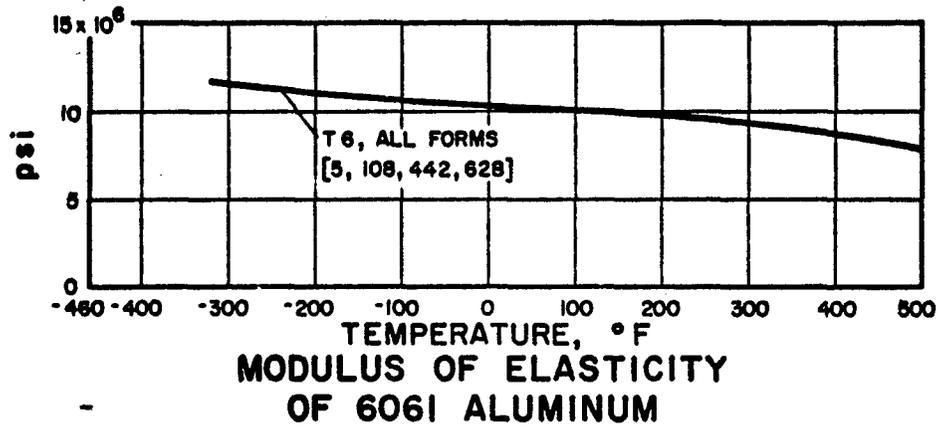


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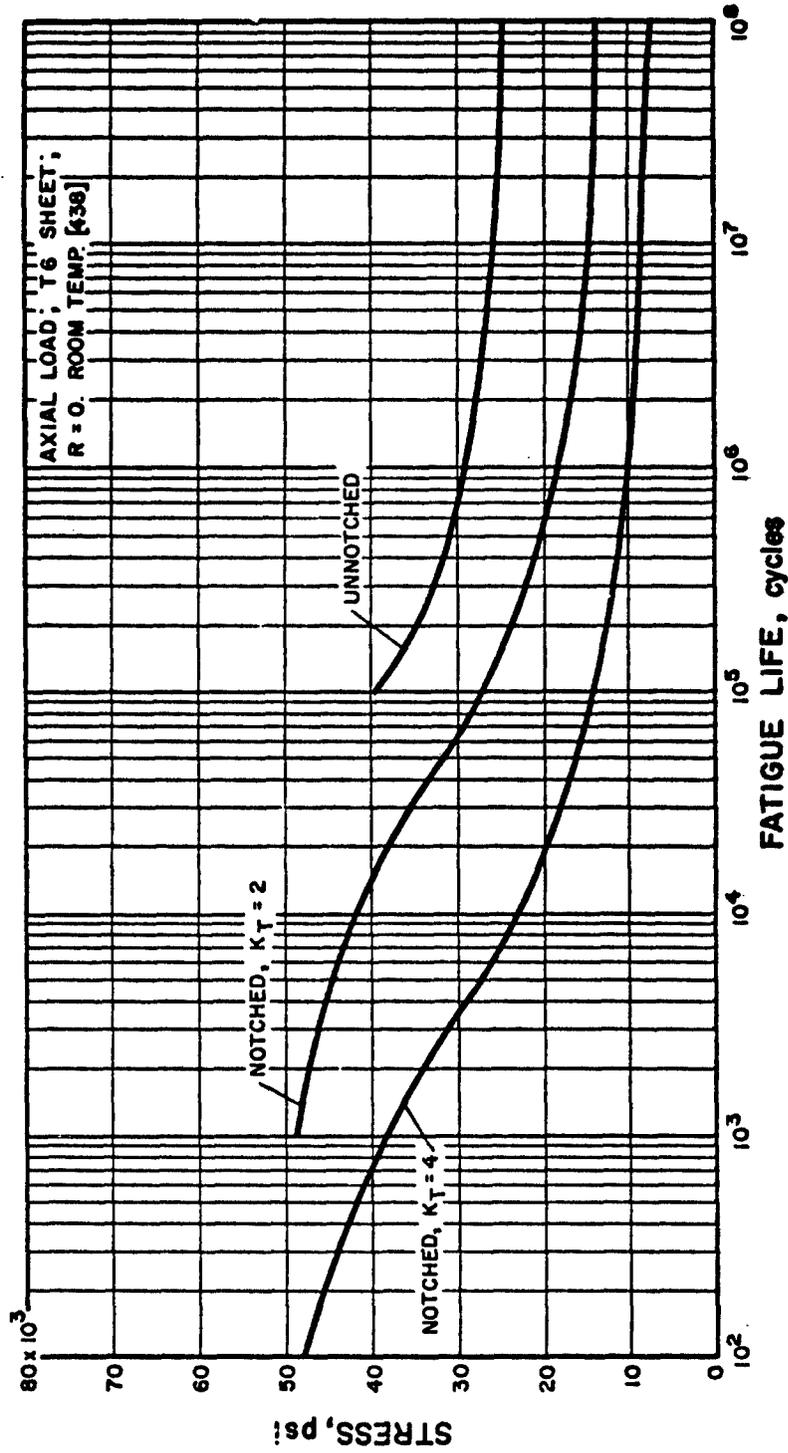


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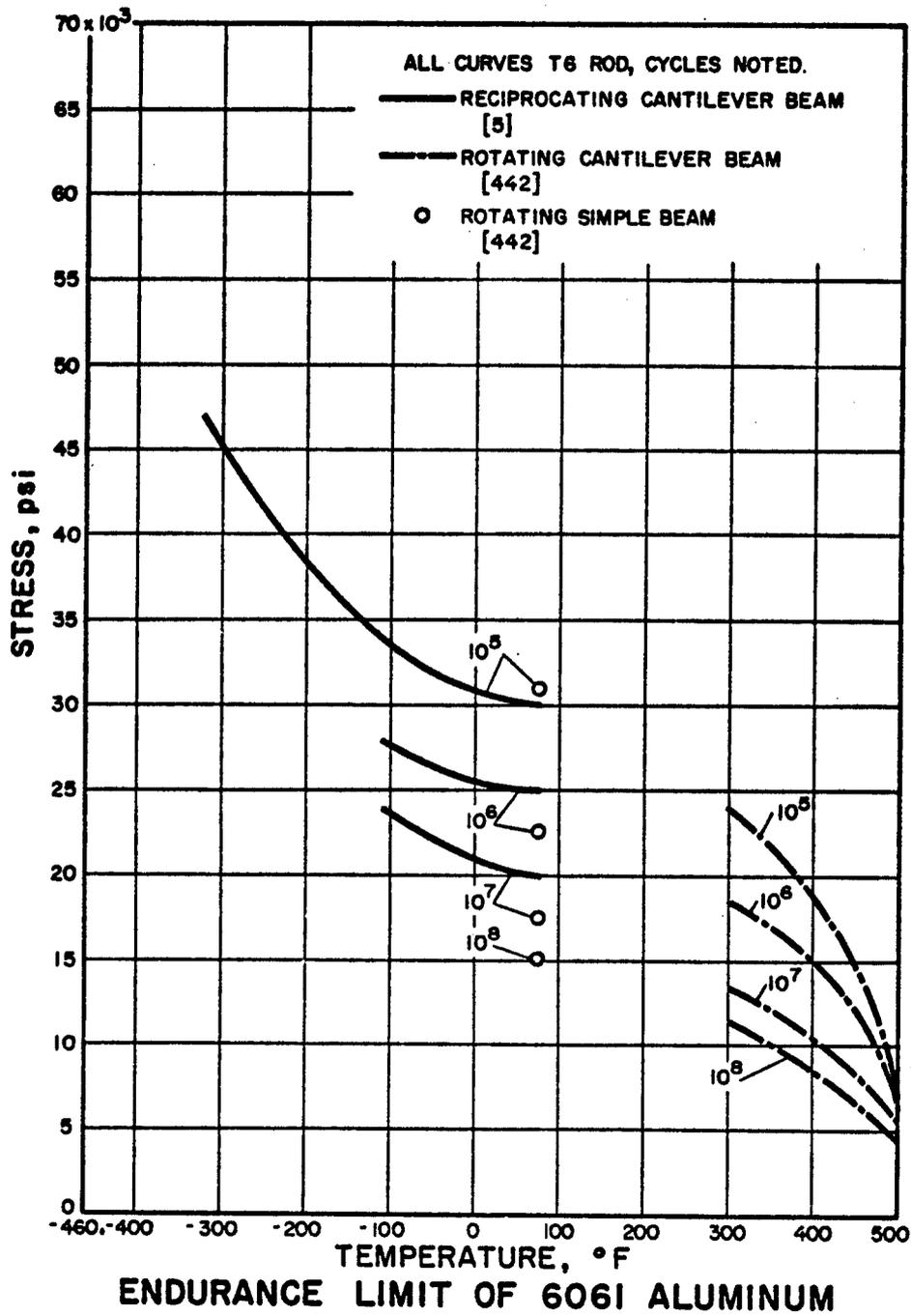


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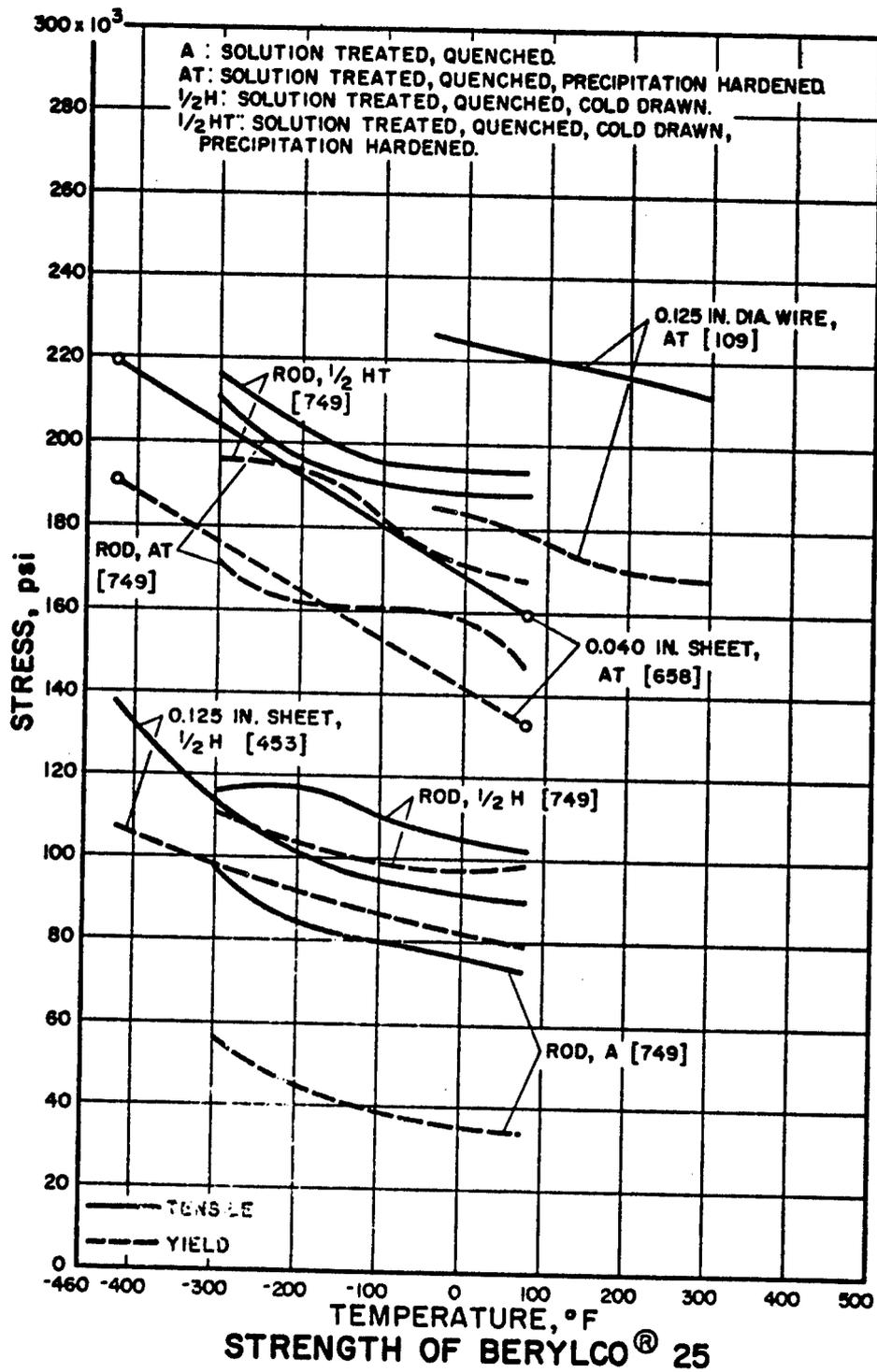


FATIGUE BEHAVIOR OF 6061 ALUMINUM

A.6.n-1

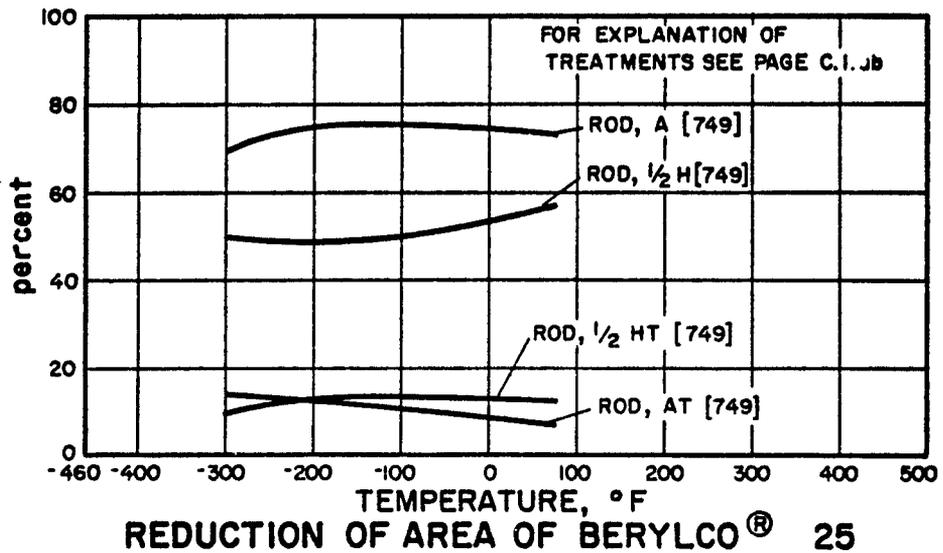
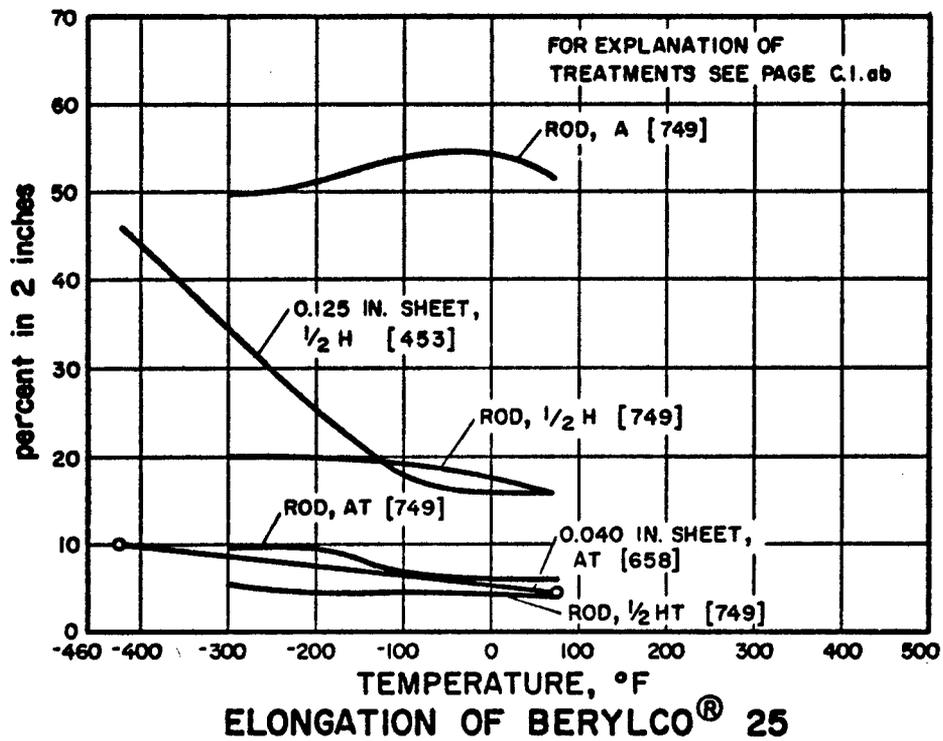


C.I.ab

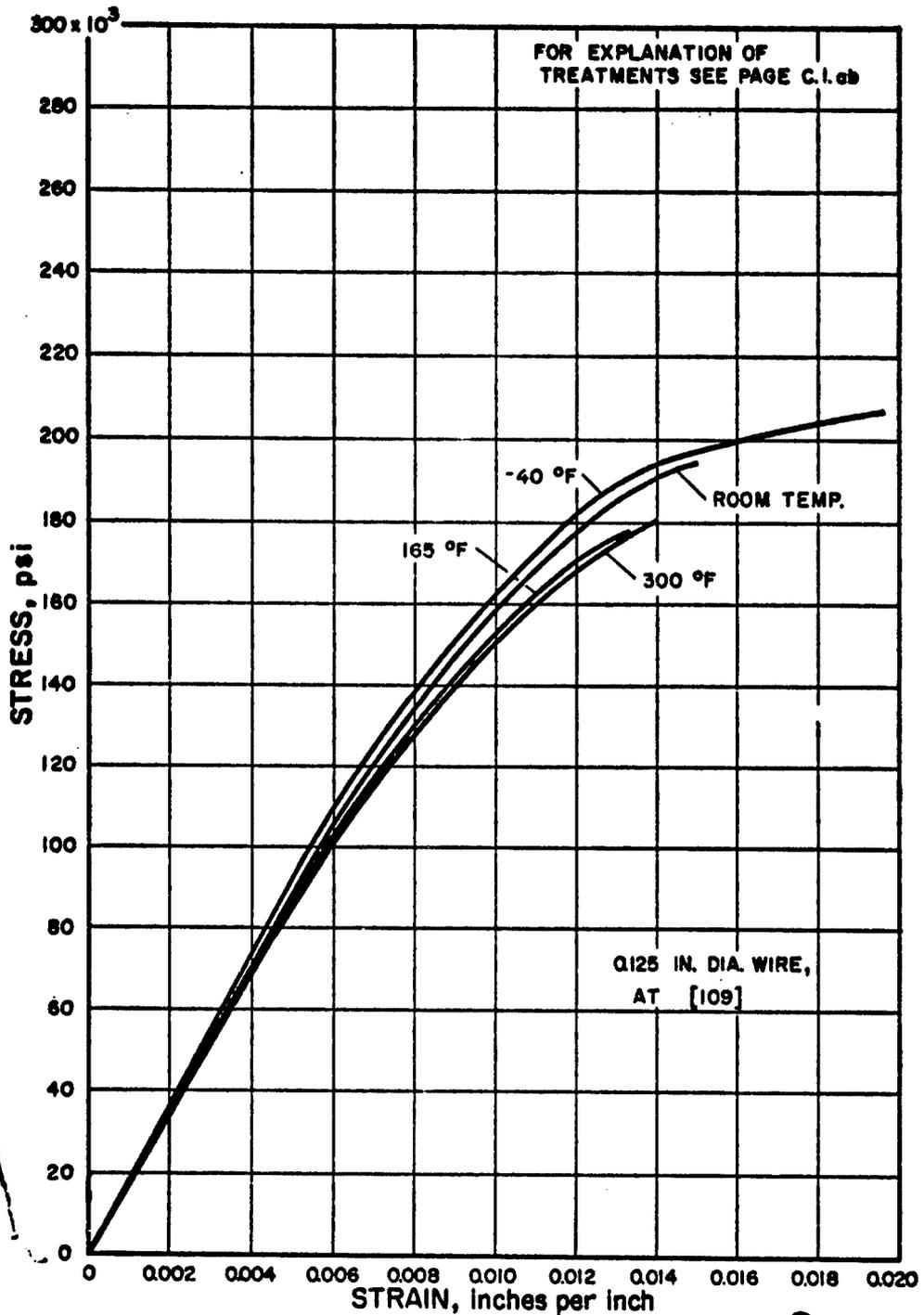


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C.1.cd

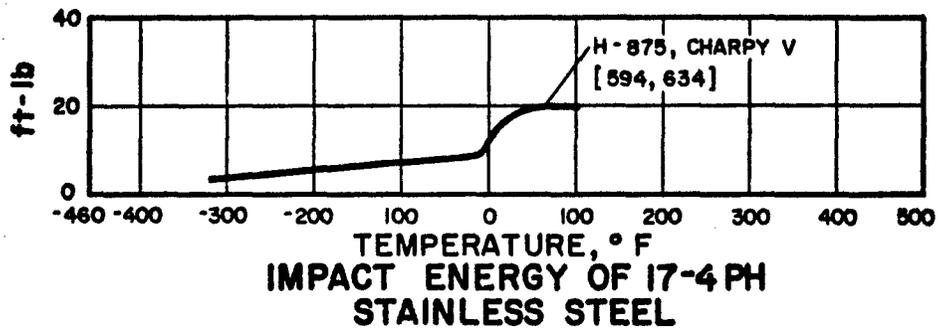


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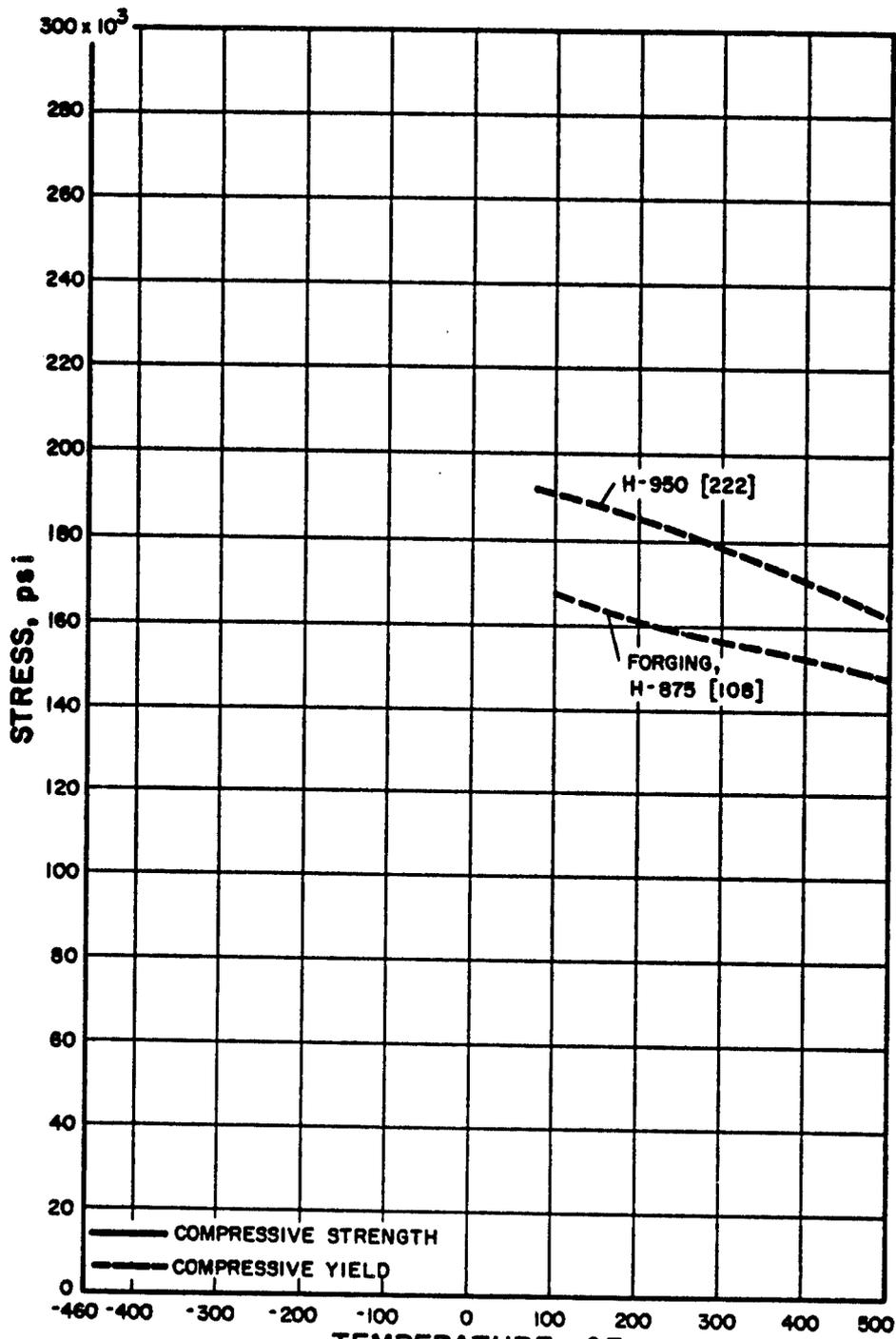


STRESS-STRAIN DIAGRAM FOR BERYLCO® 25

D.5.g

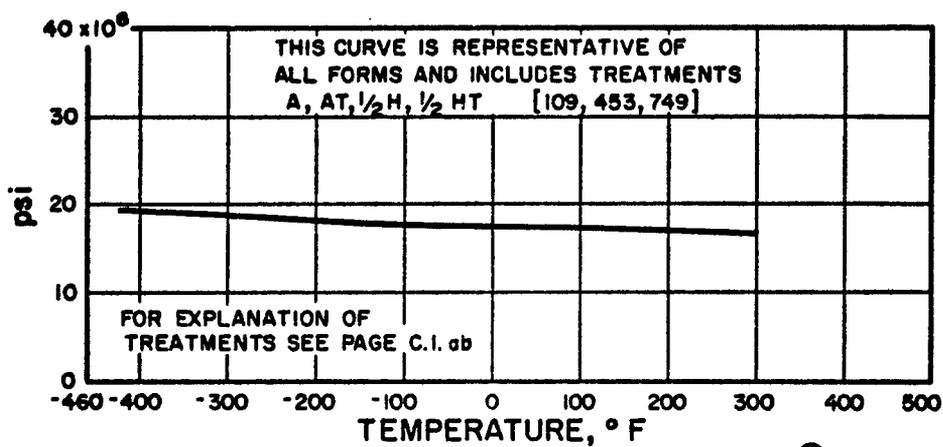


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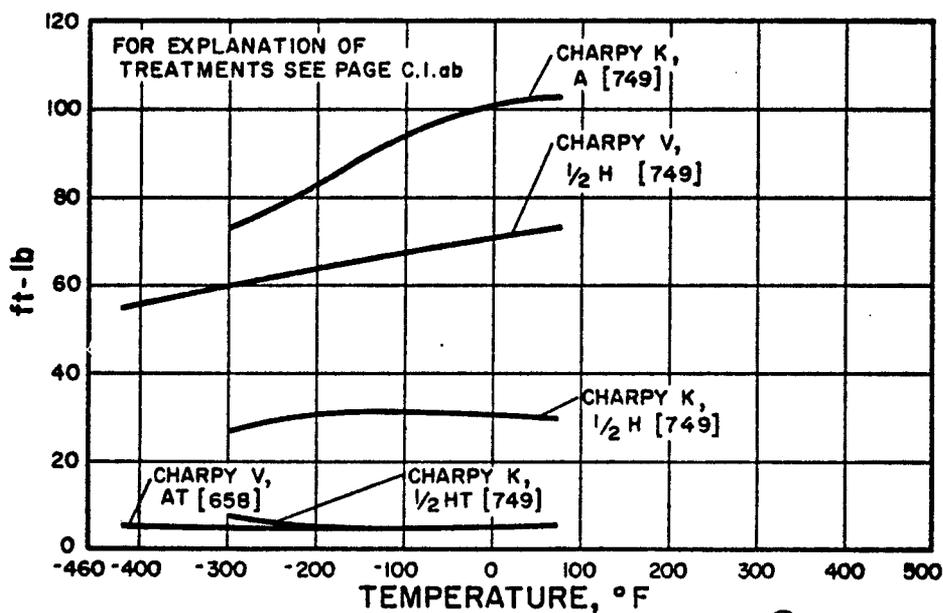


STRENGTH IN COMPRESSION OF 17-4 PH STAINLESS STEEL

C.1.fg

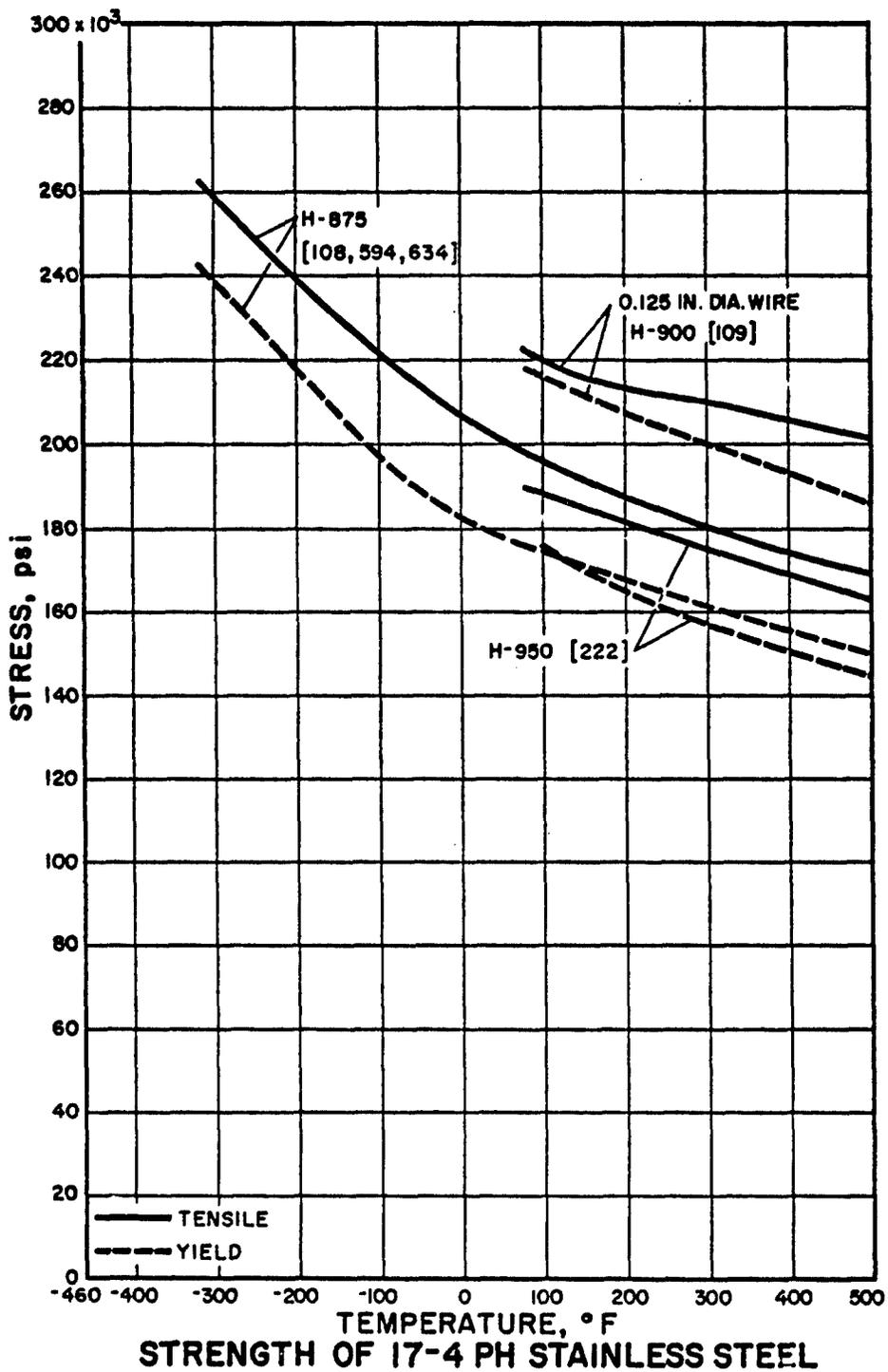


MODULUS OF ELASTICITY OF BERYLCO® 25

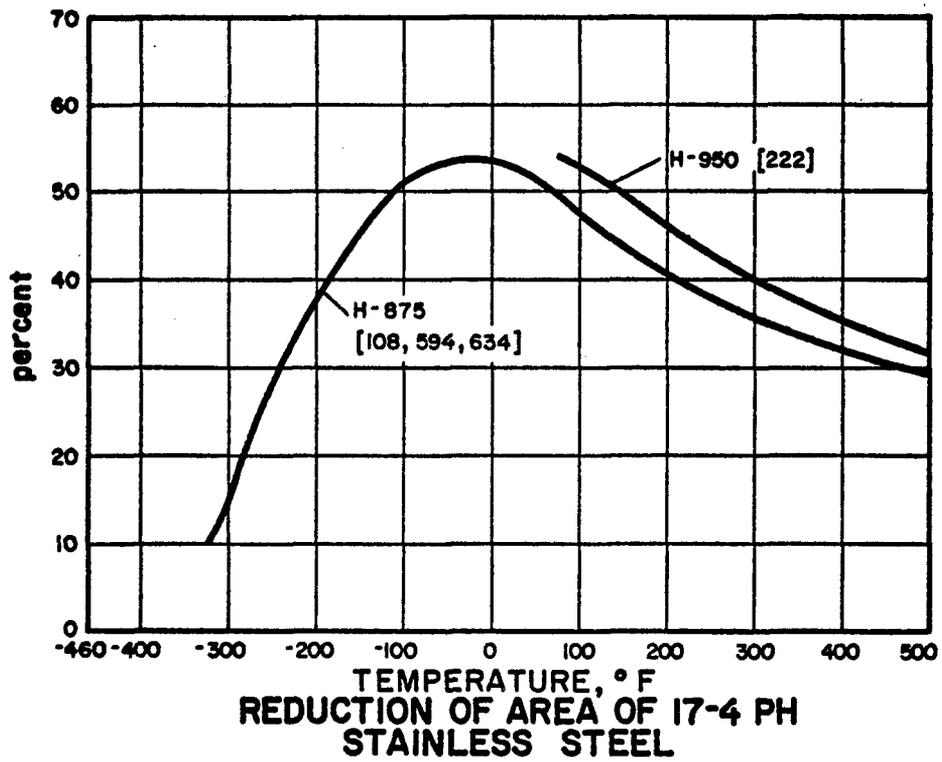
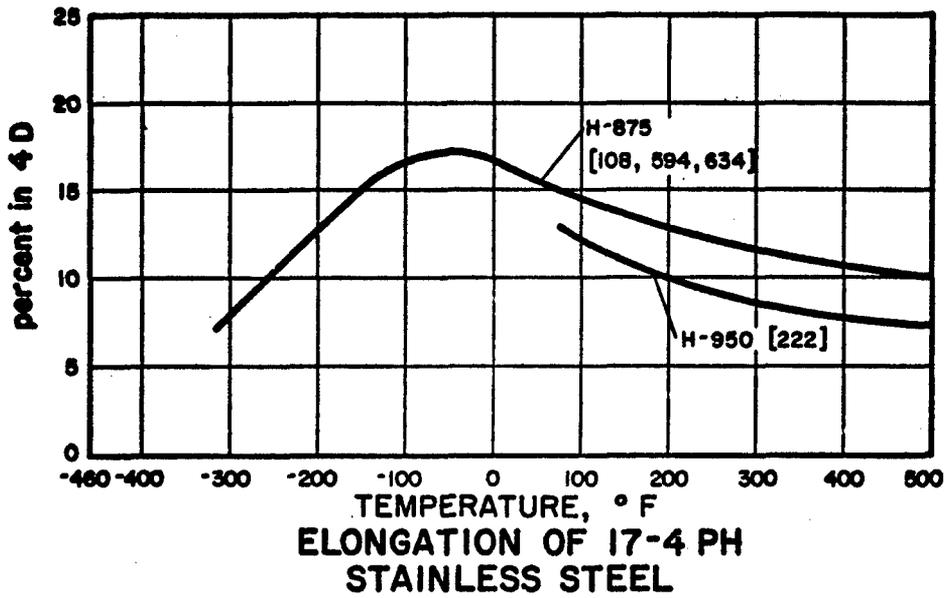


IMPACT ENERGY OF BERYLCO® 25

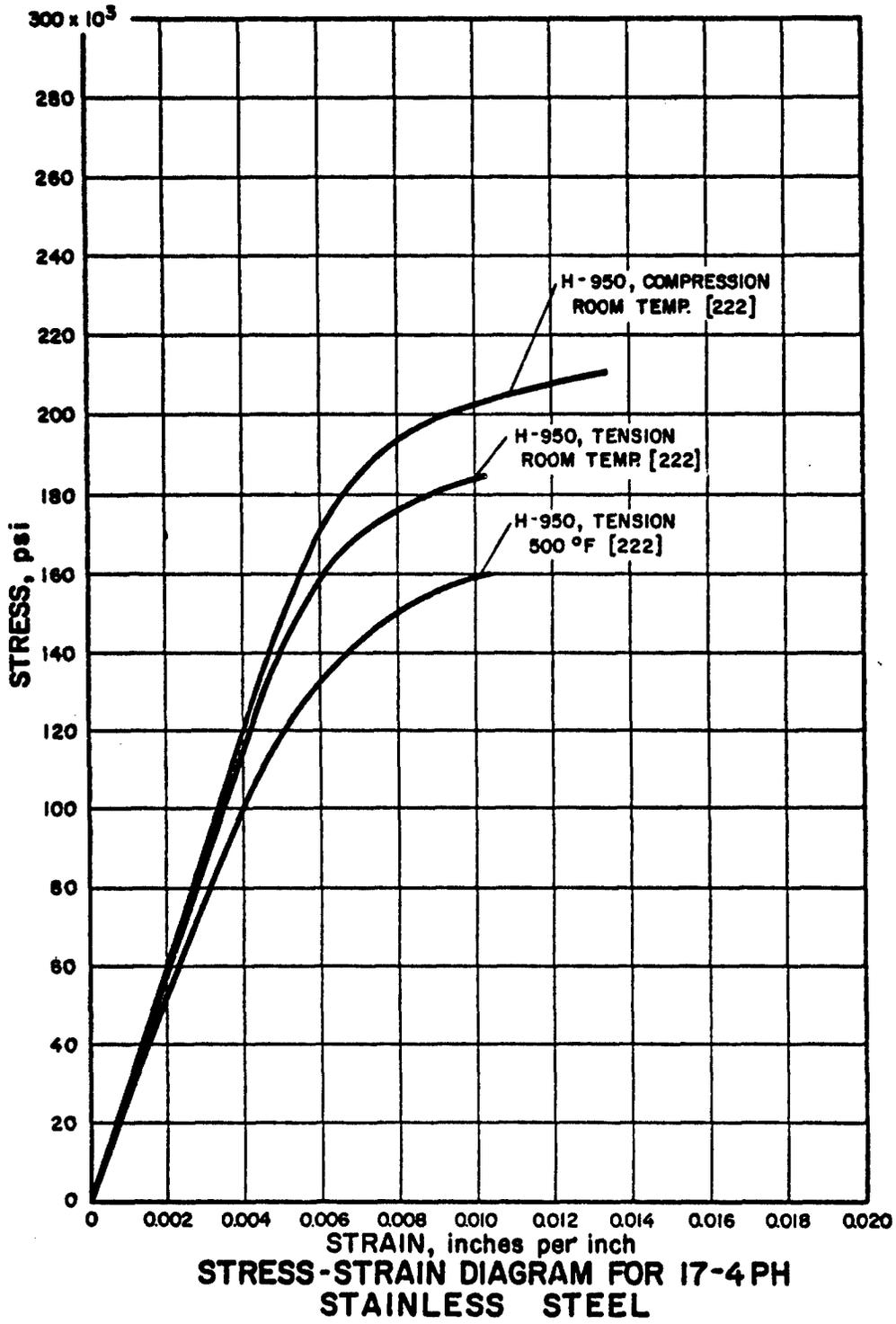
D.5.ab



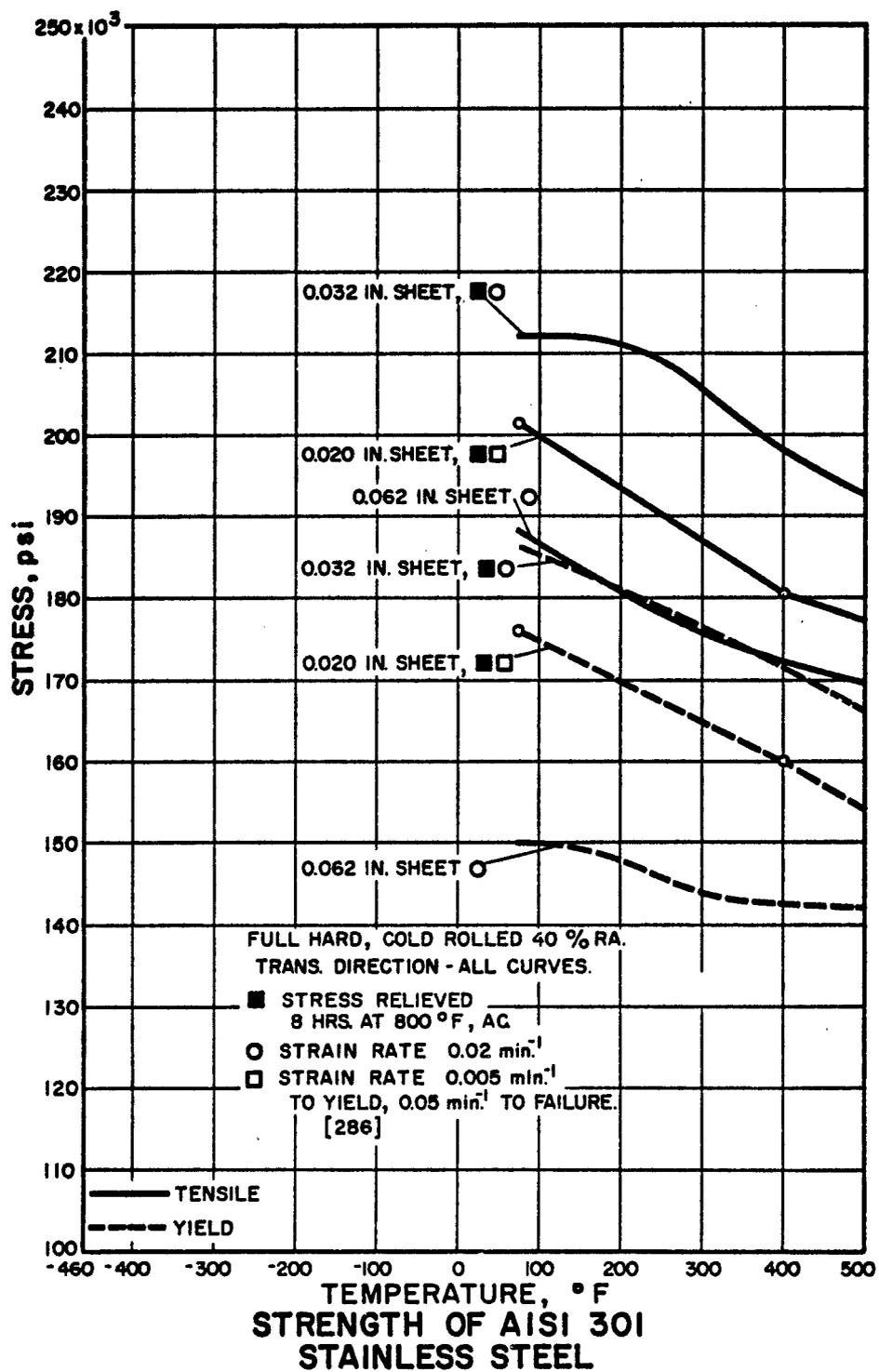
D.5.cd



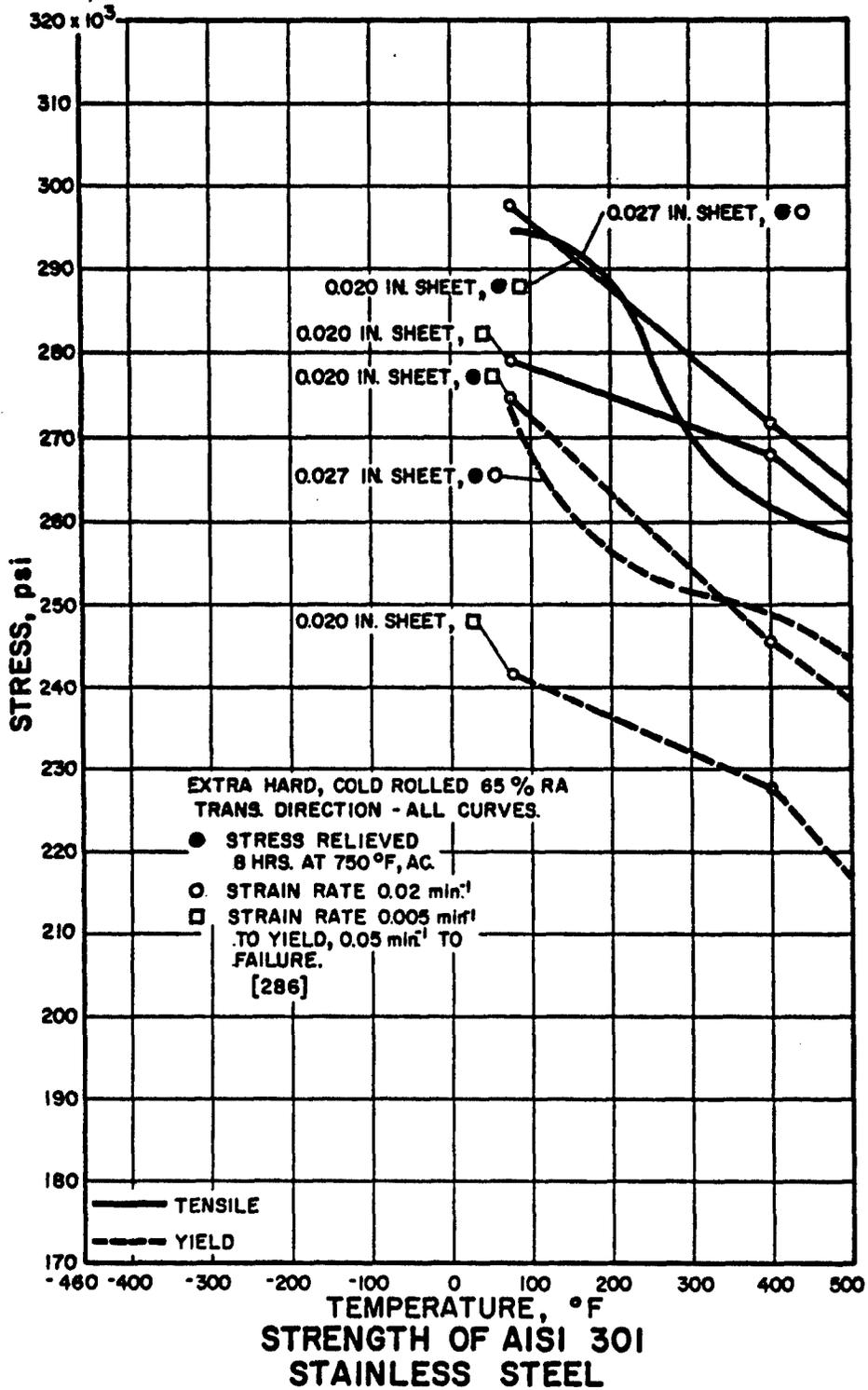
D.5.e



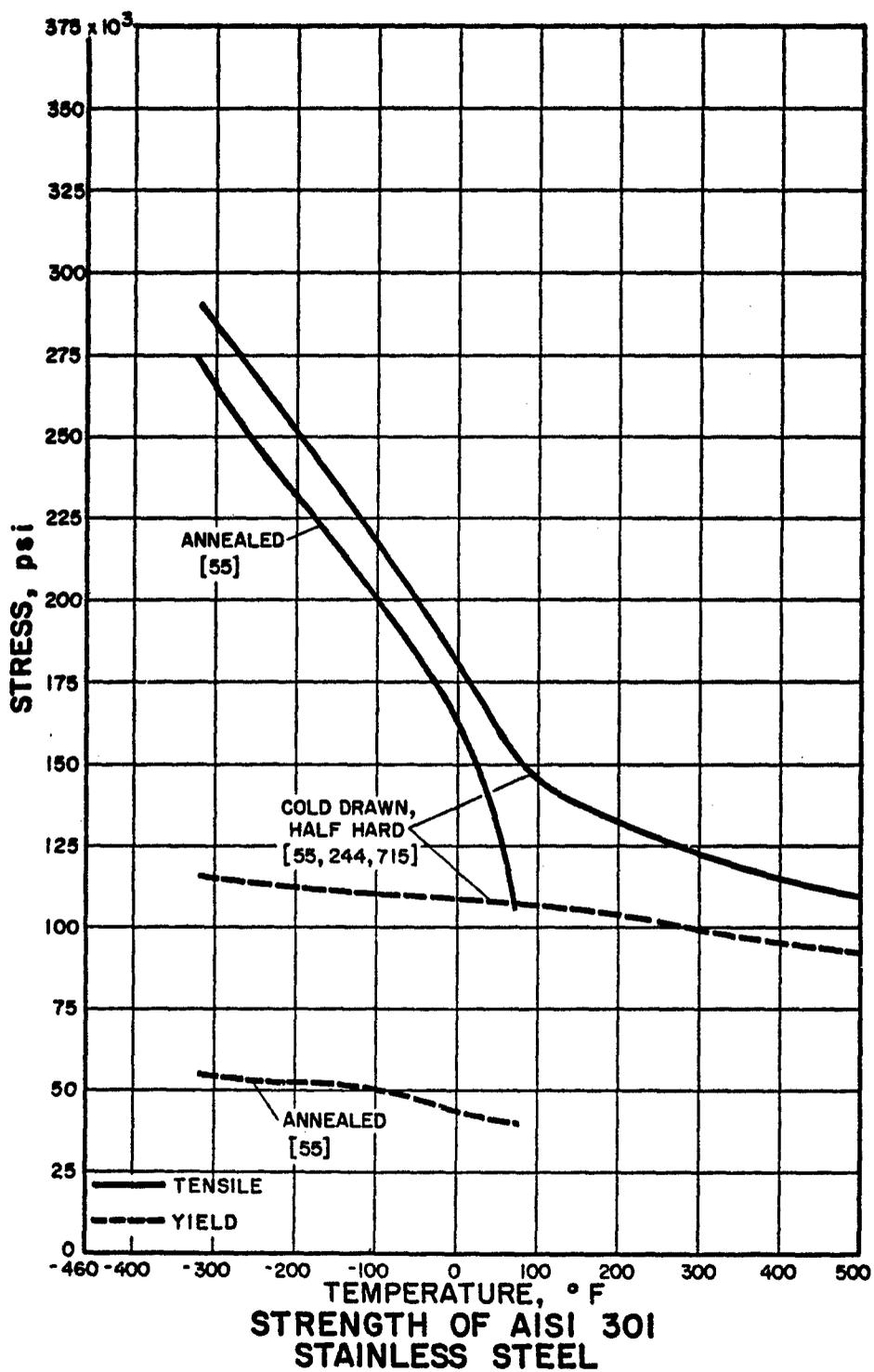
D.8.ab-2



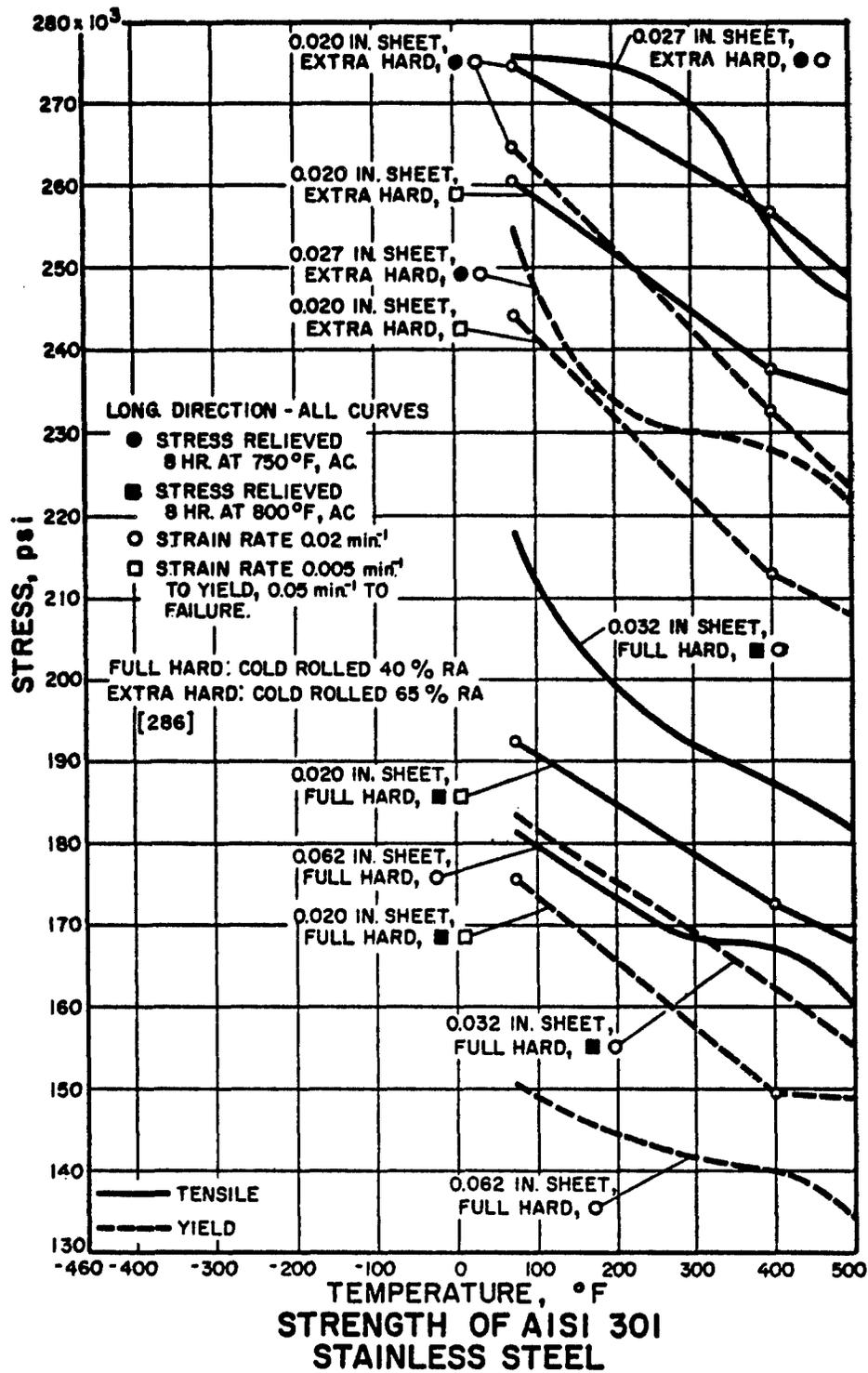
D.8.ab-3



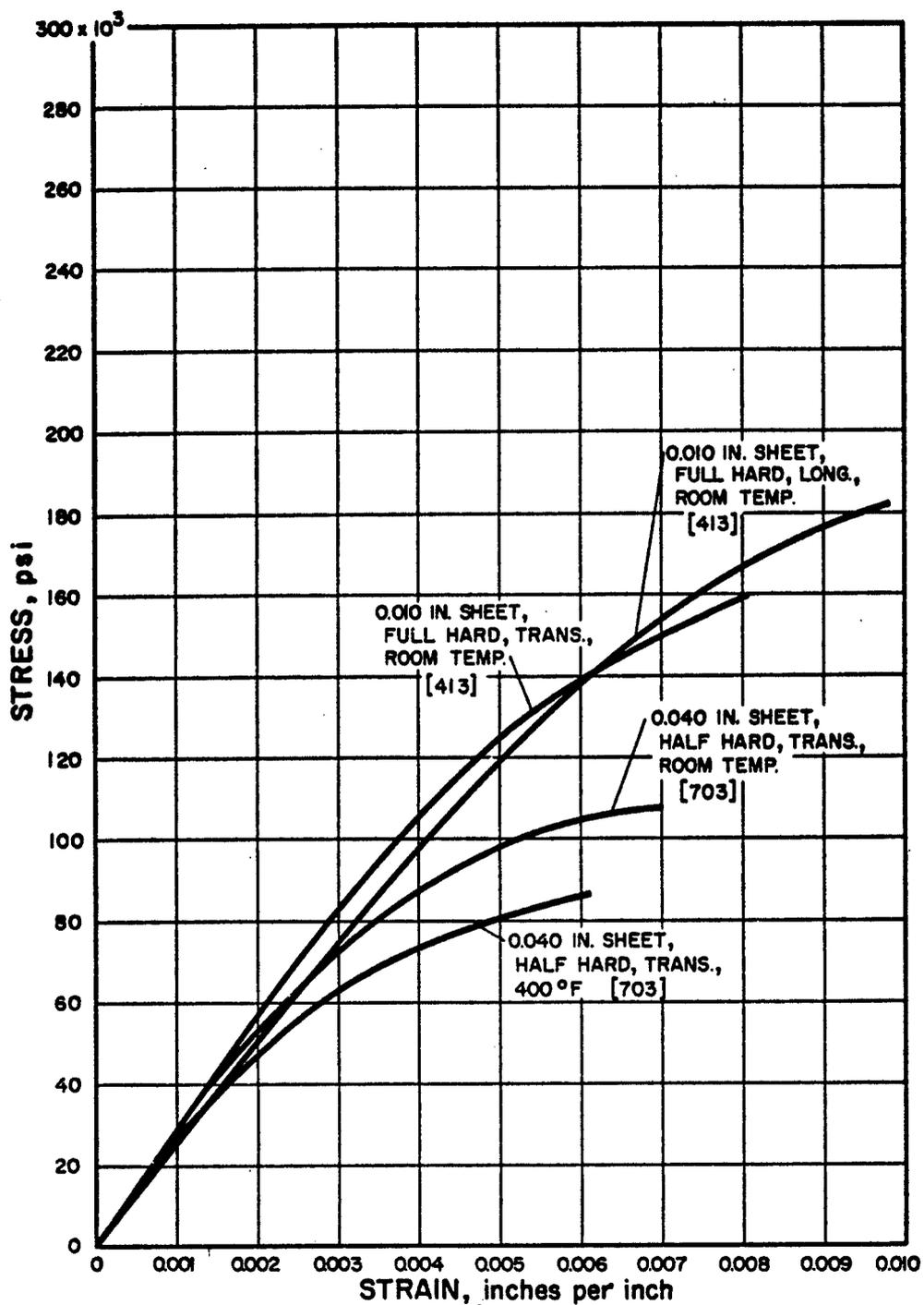
D.8.ab



D.8.ab-1

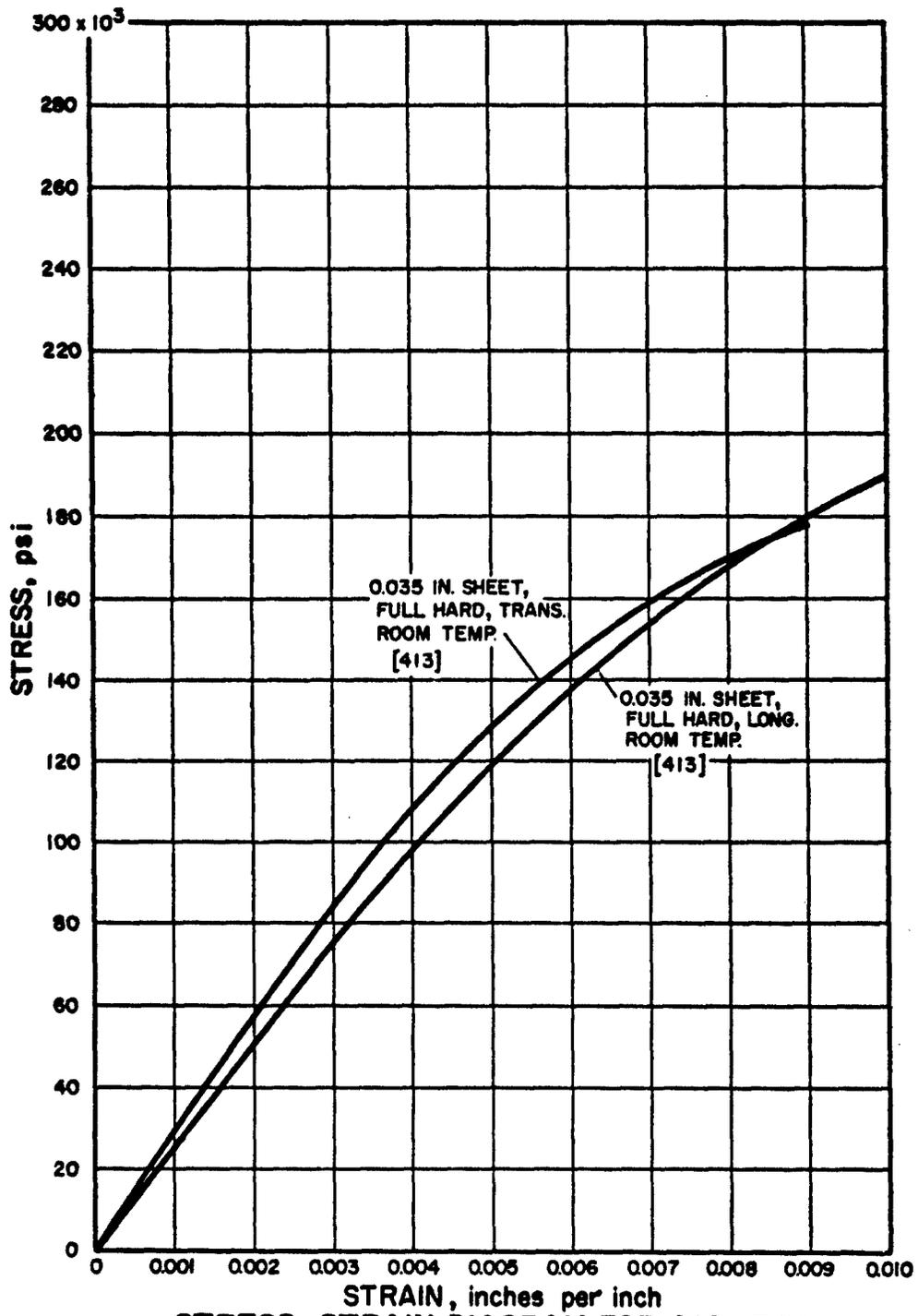


D.8.e



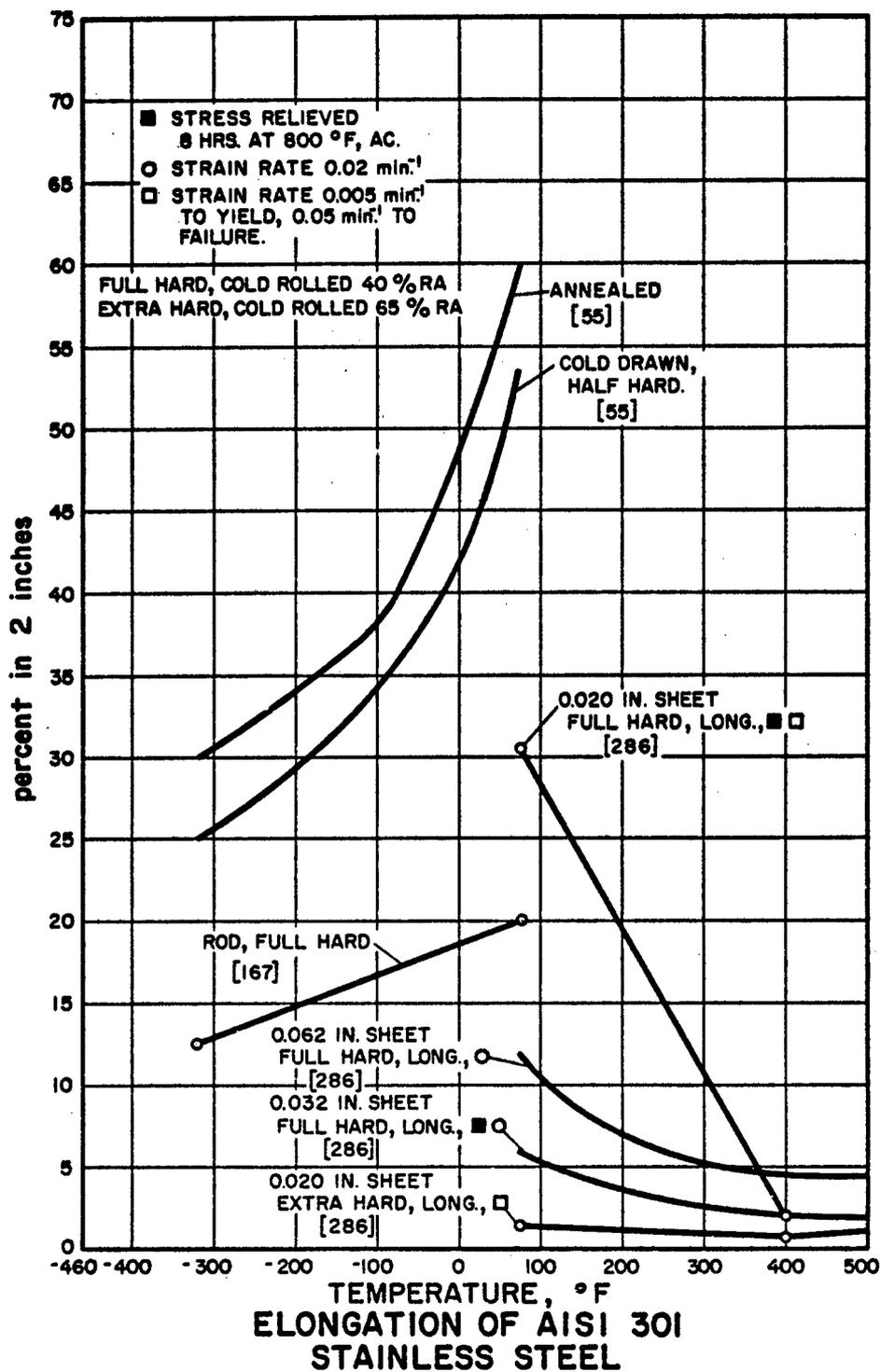
STRESS-STRAIN DIAGRAM FOR AISI 301 STAINLESS STEEL

D.8.e-1

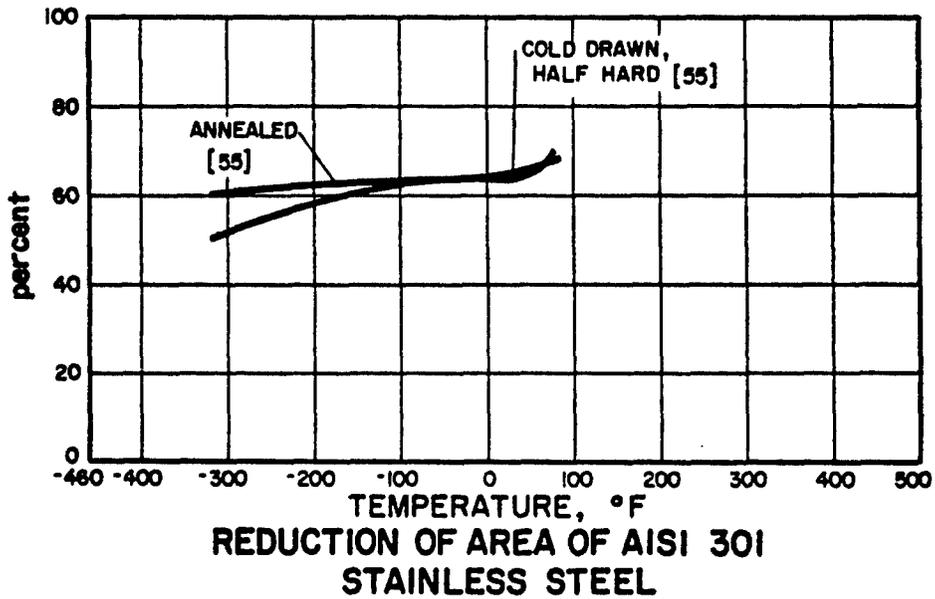
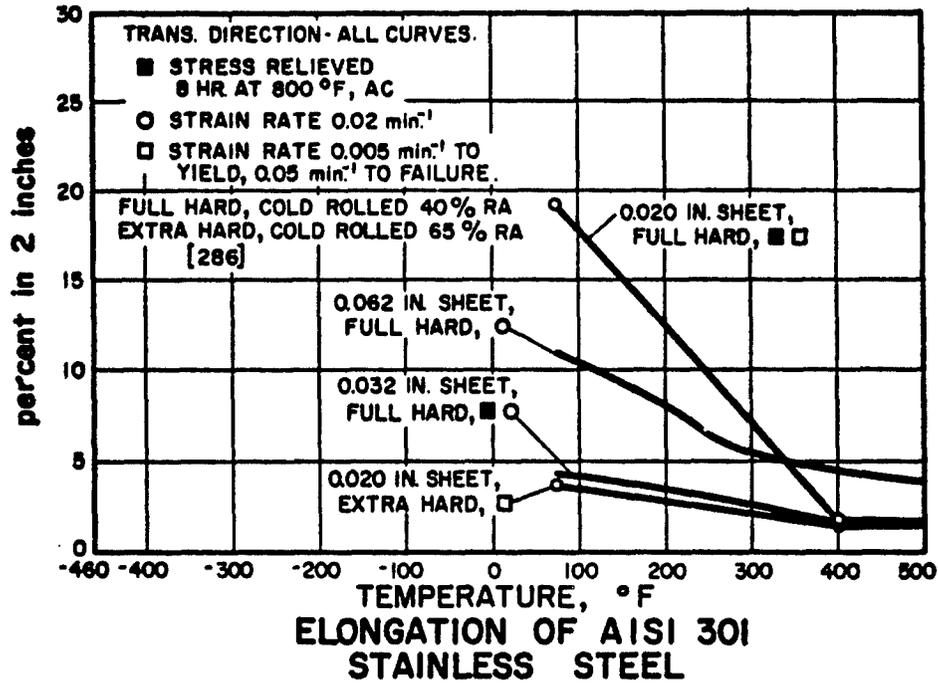


STRESS - STRAIN DIAGRAM FOR AISI 301
STAINLESS STEEL

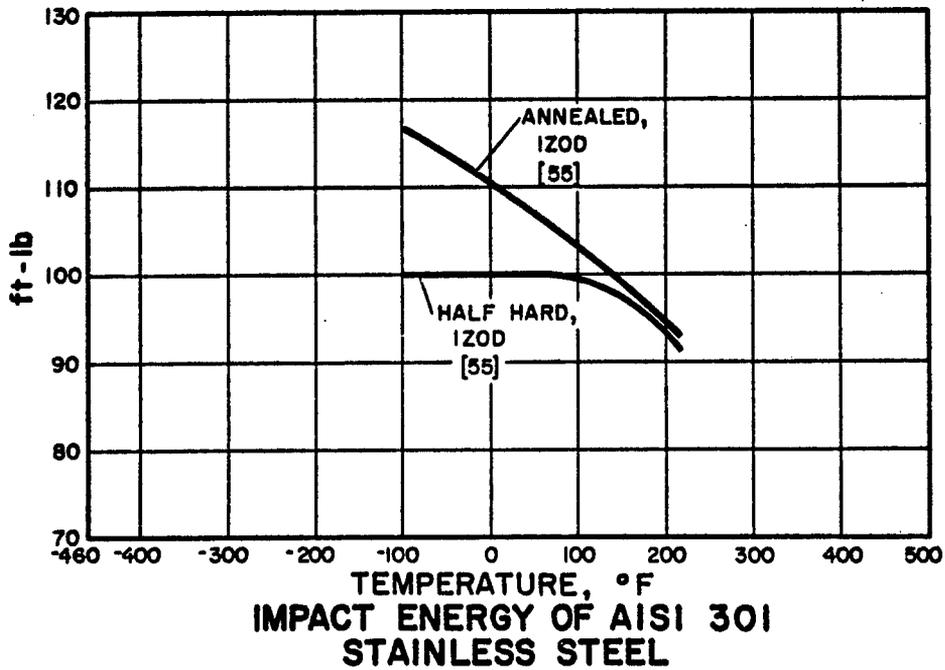
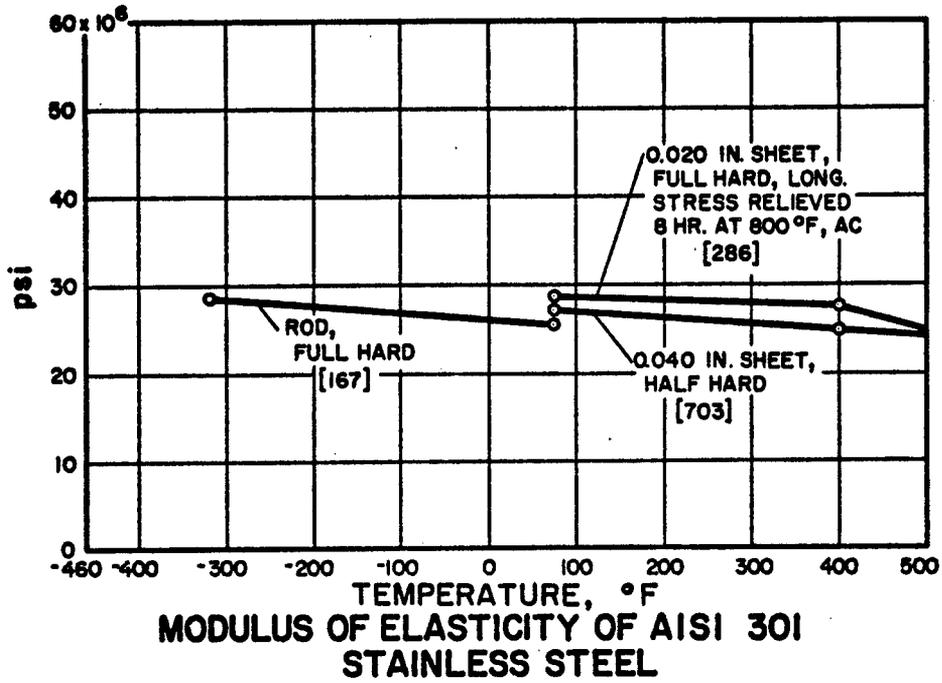
D.8.c



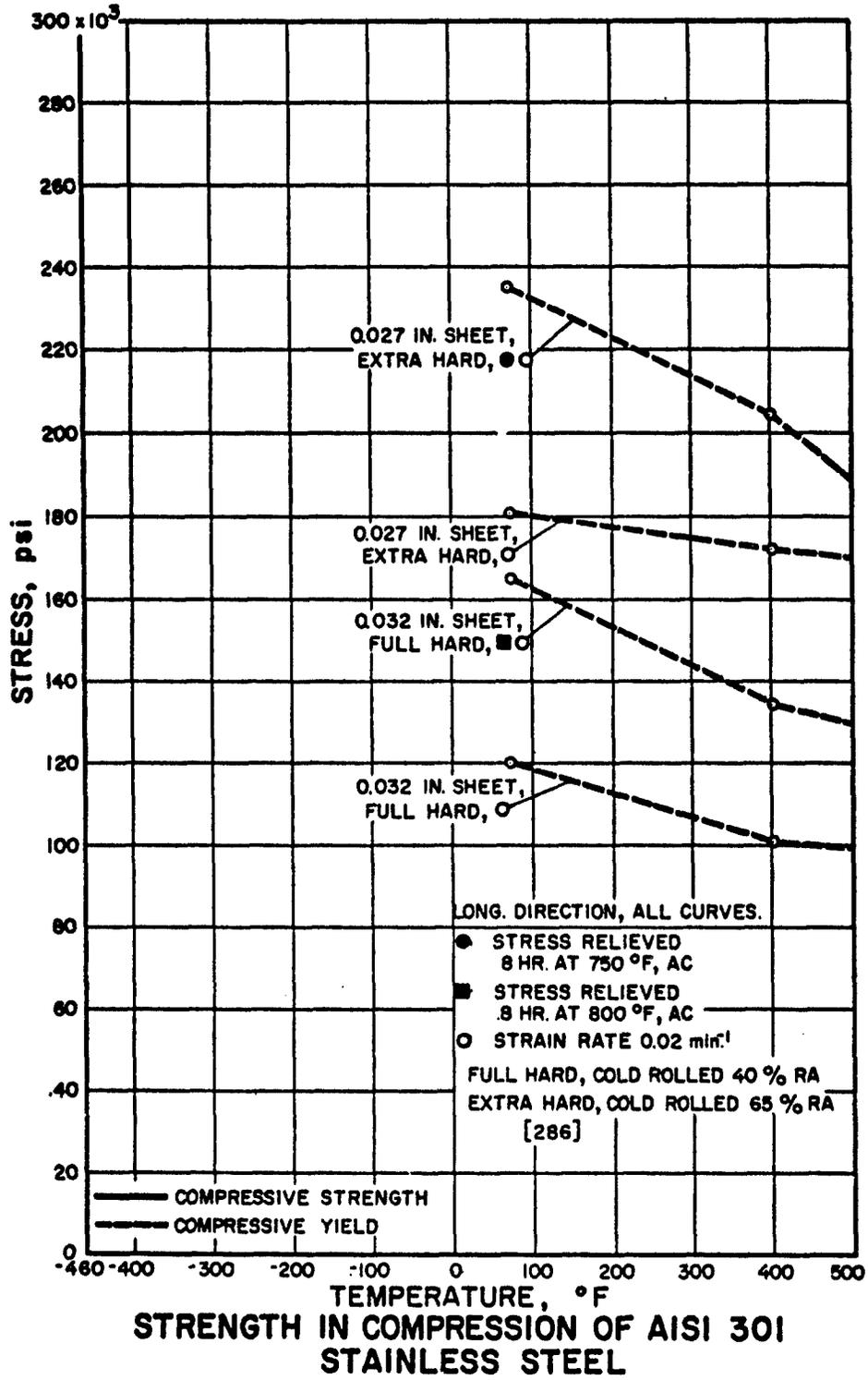
D.8.cd



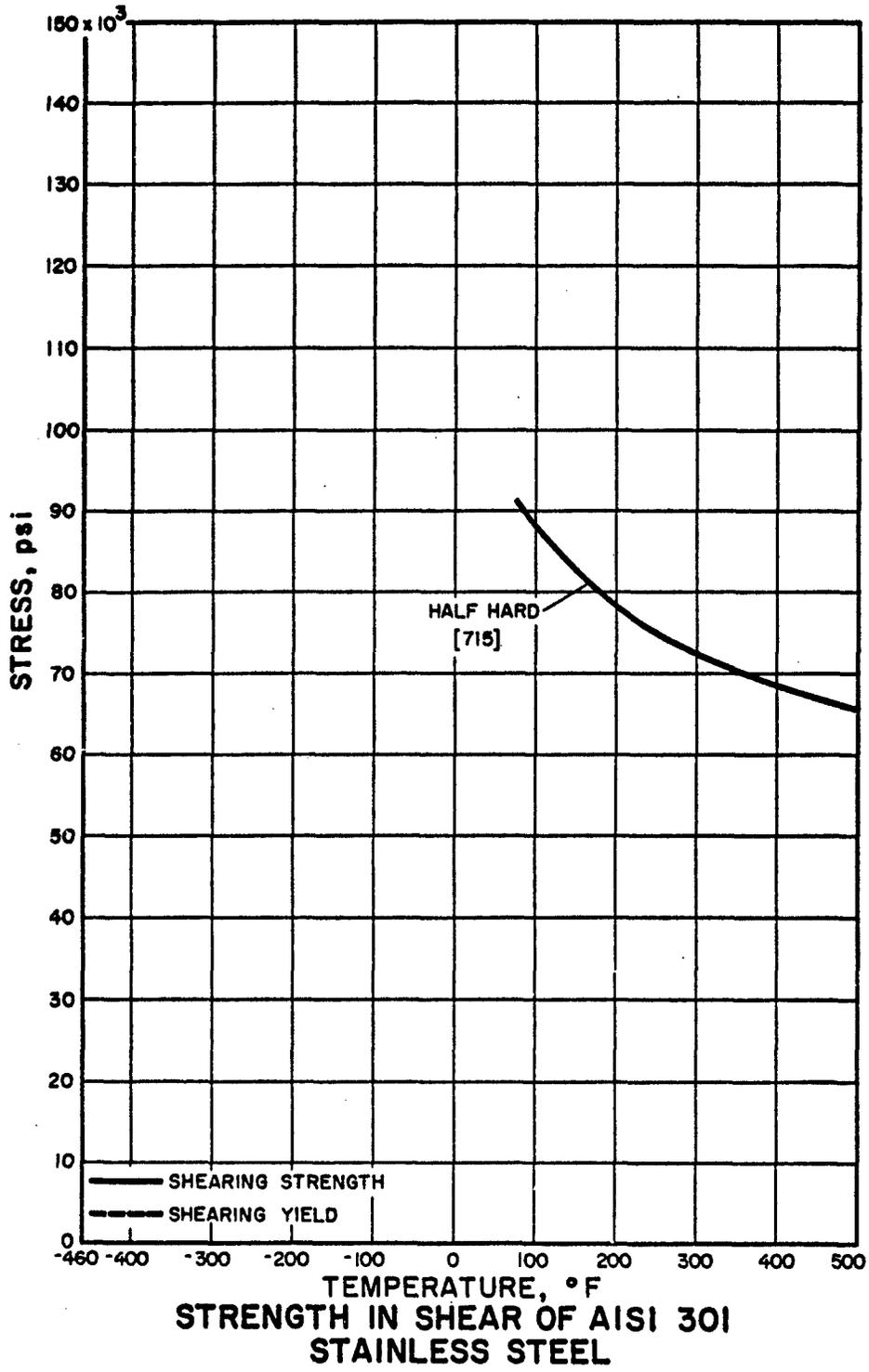
D.8.fg



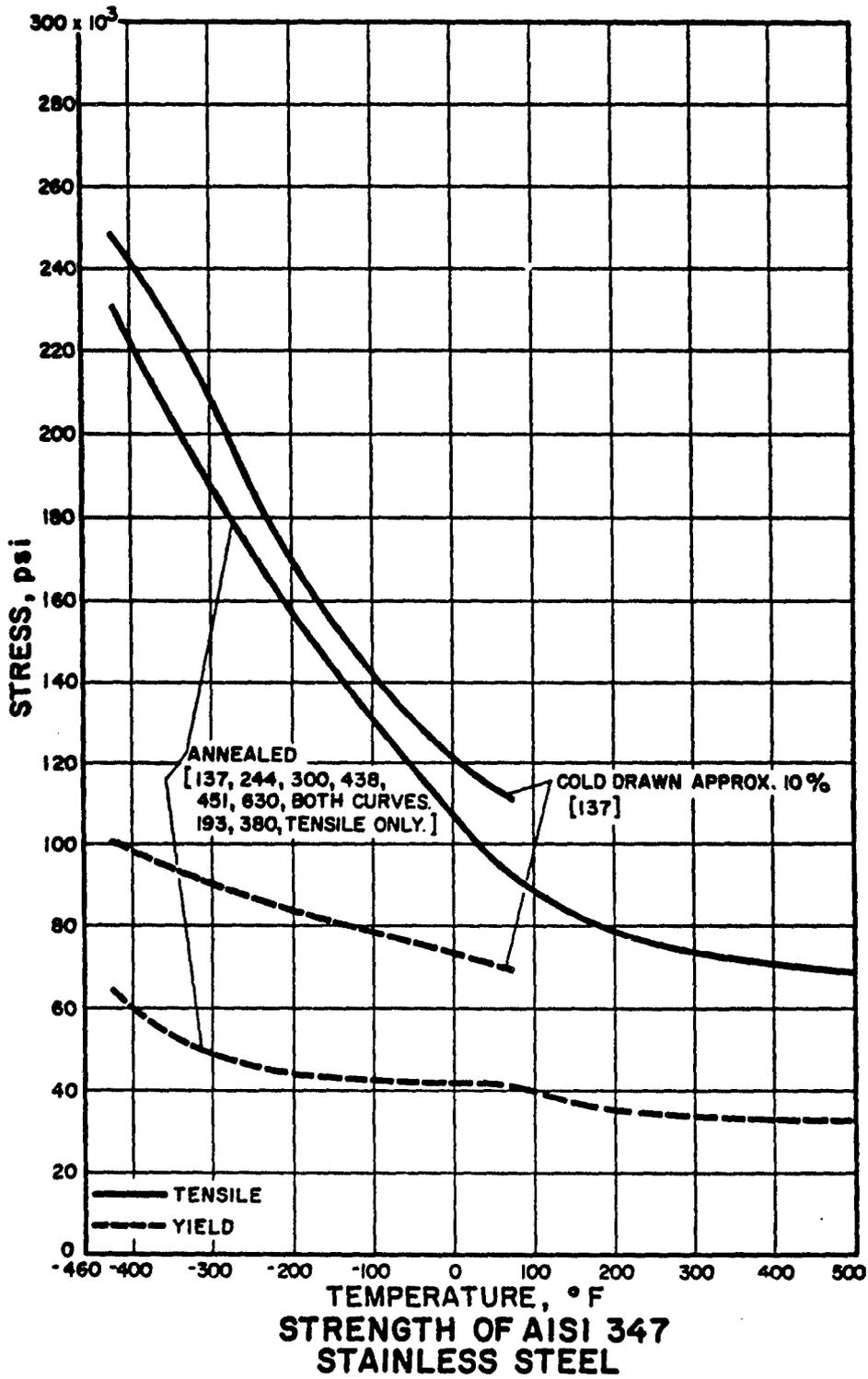
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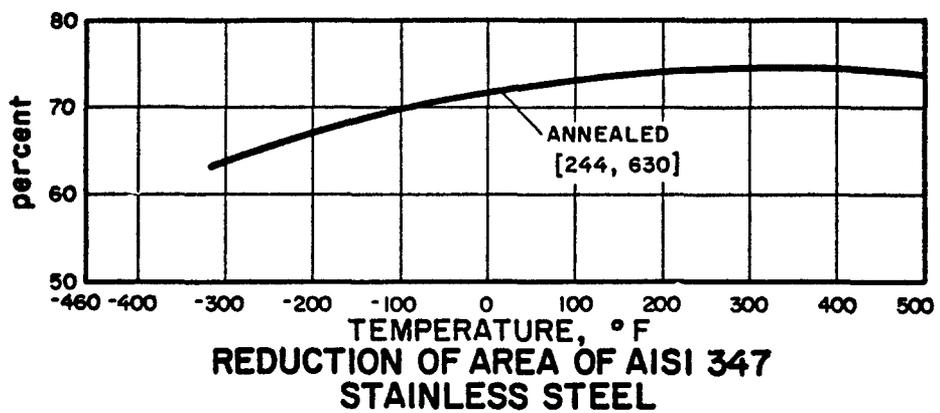
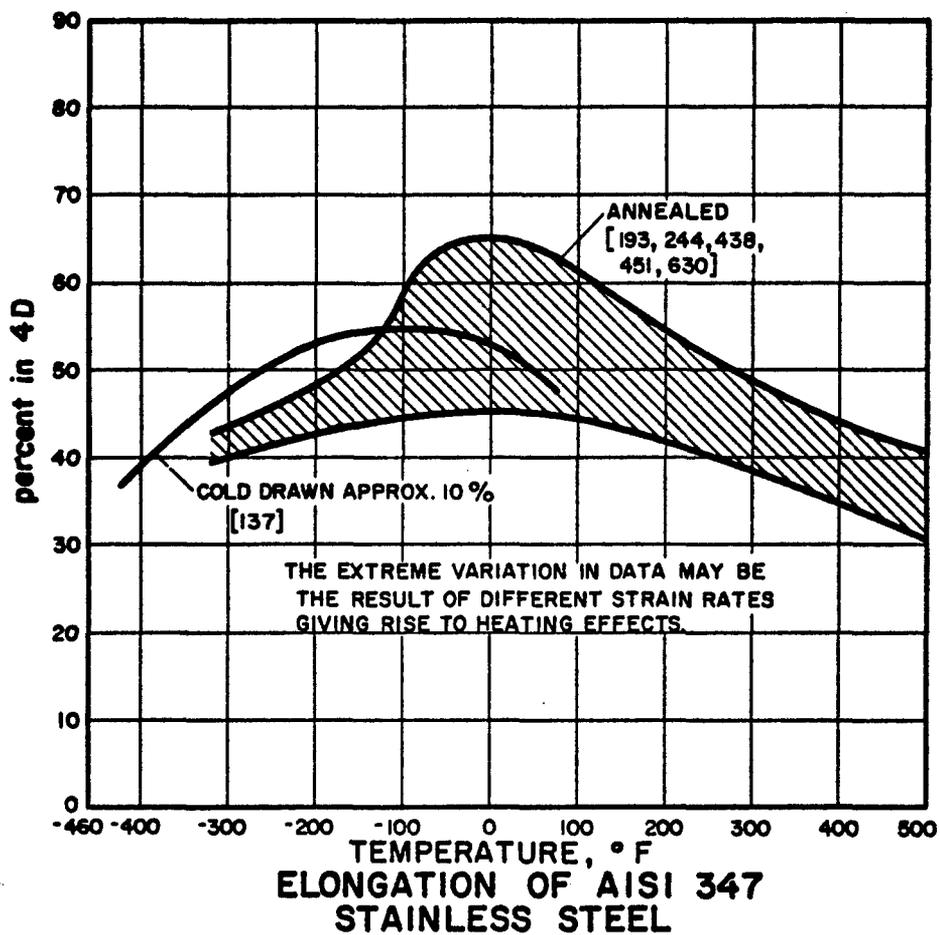
D.8.1



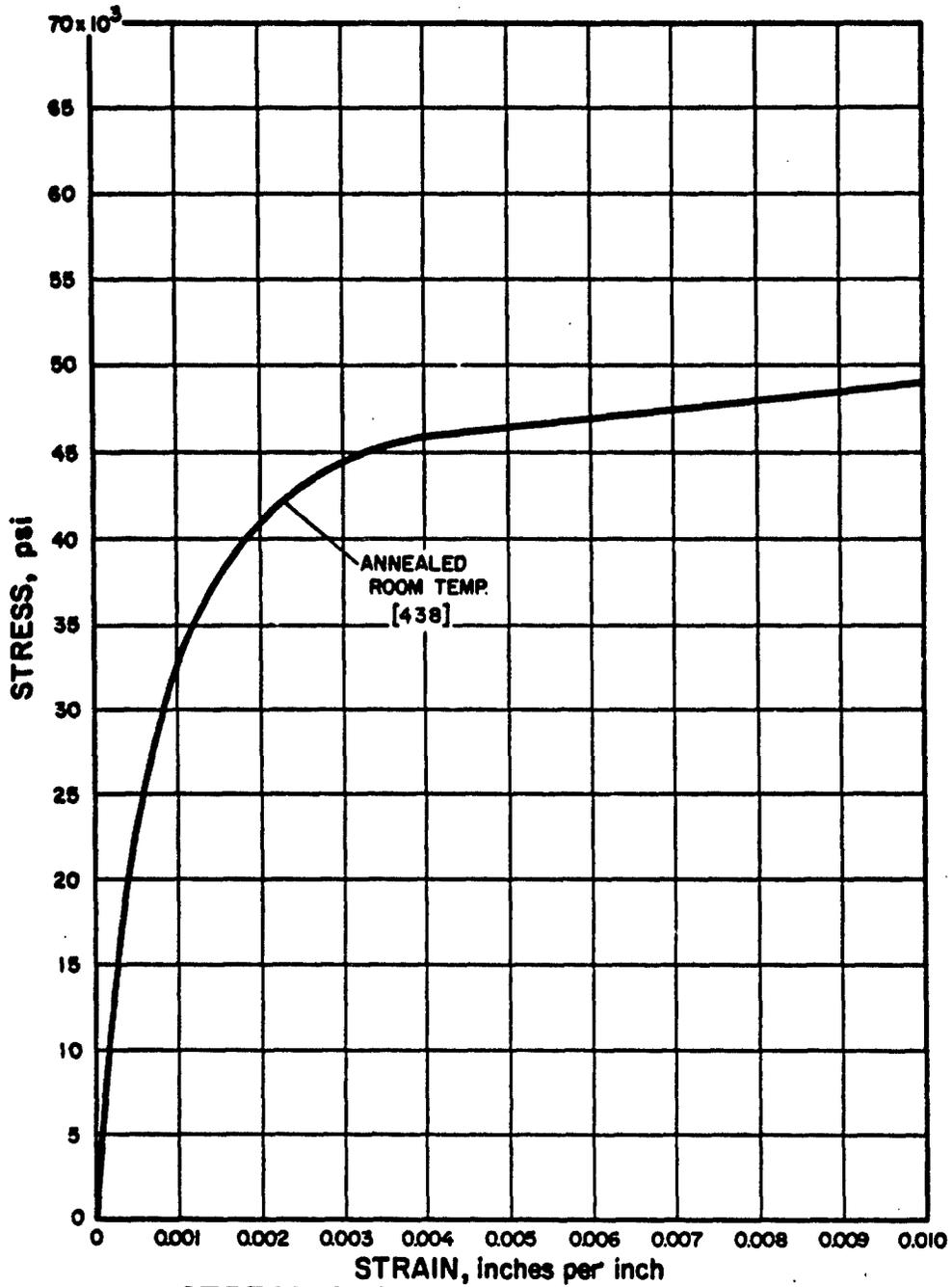
D.14.ab



D.14.cd

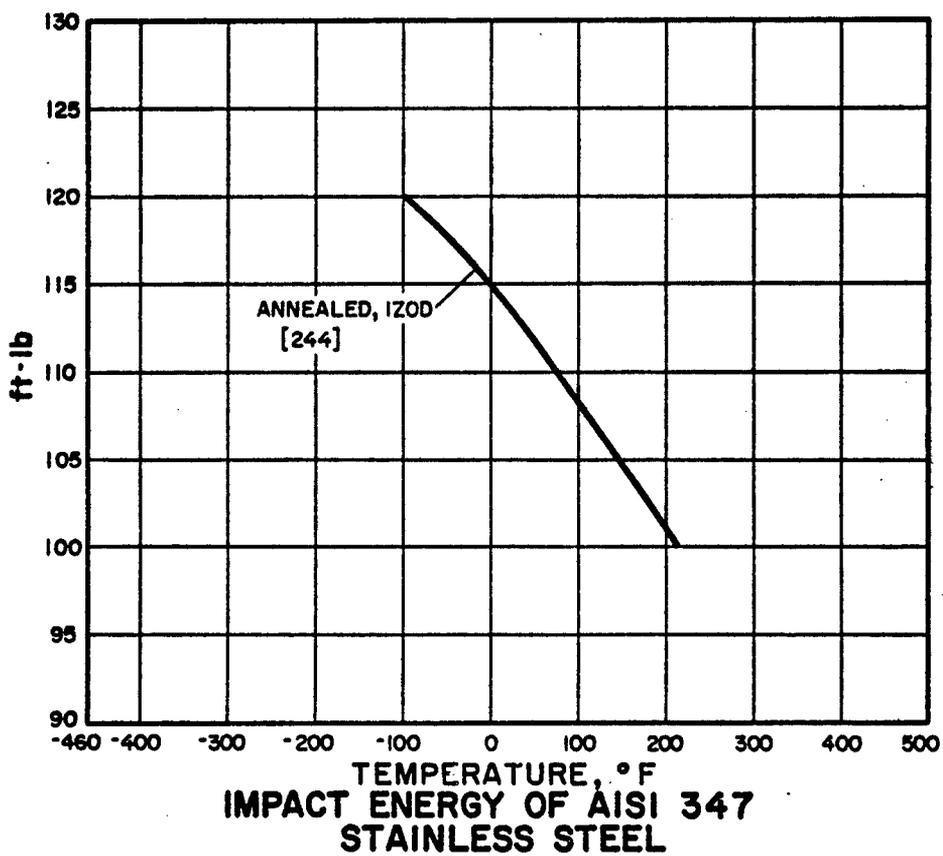
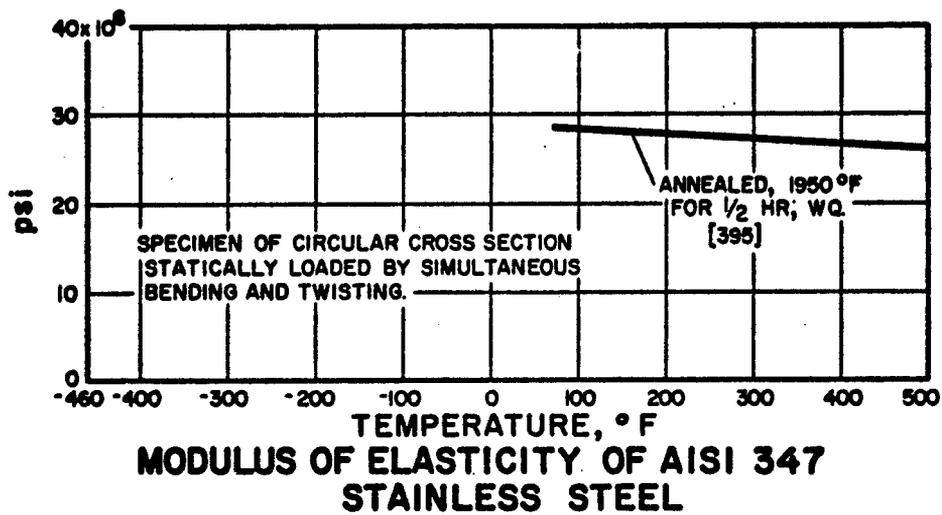


D.14.9

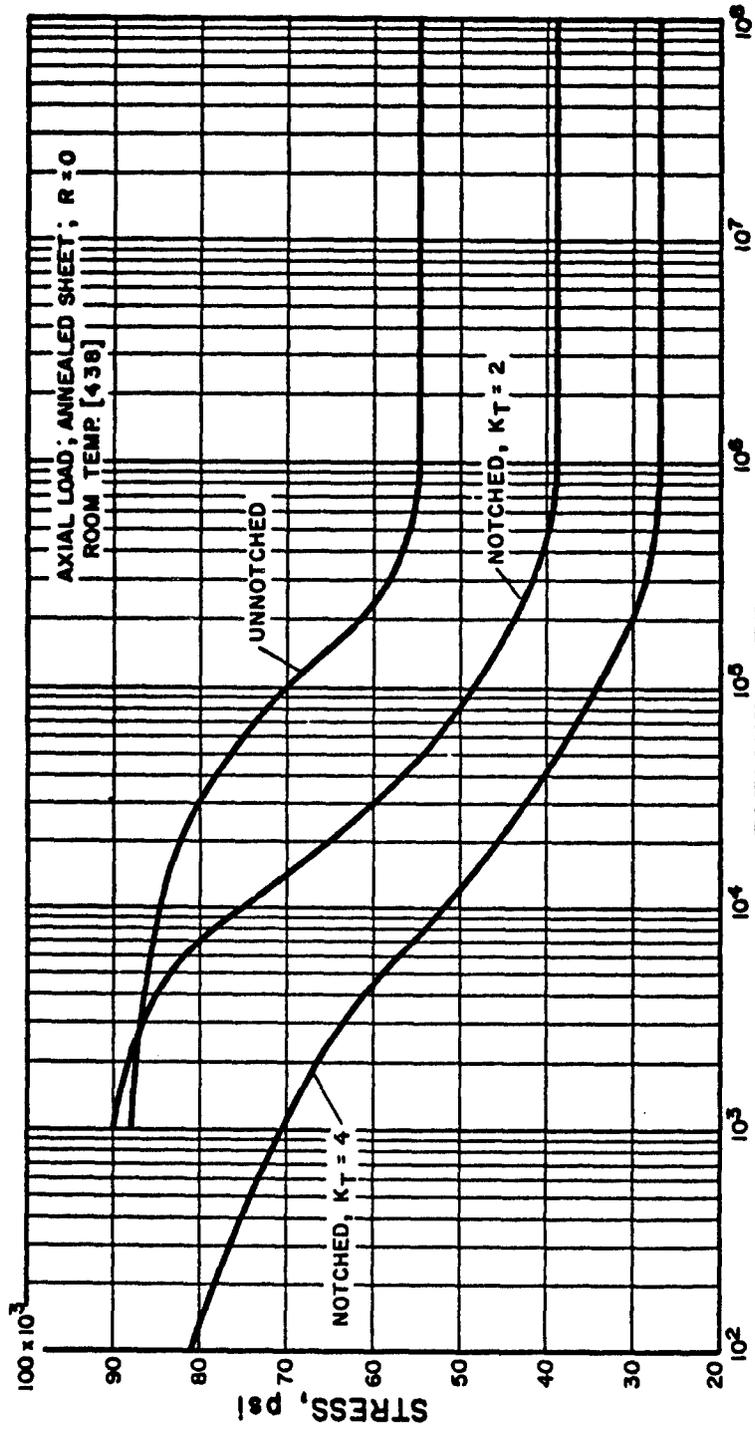


STRESS-STRAIN DIAGRAM FOR AISI 347
STAINLESS STEEL

D.14.fg



D.14.n



FATIGUE BEHAVIOR OF AISI 347 STAINLESS STEEL

41,864

(Best Avail.)