A Consideration on Limits of Cold Working in Nuclear Construction

By RA Moen* and GV Smith**

INTRODUCTION

A seminar on the Cold Working of Metals was held during the Thirteenth National Metal Congress and Exposition, 25 years ago. The groundrules of that seminar subject were "that the topic should be one of lively interest to research people and that the seminar should emphasize the fundamental and scientific features of the topic and avoid attempts to bring out discussions of commercial applications."(1) Today there is still concern about the cold working of metals; however, the concern is not about the fundamental aspects of cold working, but rather the importance of the effects of cold working on materials used in elevated temperature nuclear construction. The aspect of being a subject of lively interest still remains, although the groundrules are somewhat reversed.

A renewed concern for cold work effects is derived from the fact that several companies are now involved in the design and construction of nuclear reactors intended to form the backbone of our future energy needs. The designs of these plants are based upon criteria that demand a precise knowledge of the materials' response to loadings throughout the projected 20-30 year plant lifetimes. Cold work will affect the response of materials to these loadings. In order to assure that nuclear plants remain safe and reliable, it is necessary to consider the effects of cold work on materials in nuclear and other high temperature components.

The text of this paper which follows is organized to first describe the effects of cold work on time-independent and time-dependent properties; then to describe the current Code position with respect to the use of cold-worked materials. This will be followed by a summary of some specific concerns which have evolved in the construction of nuclear plants for elevated temperature service, and last, a description of some of the limits that might be considered in accounting for cold work effects. Emphasis will be given to austenitic stainless steels, which are of particular interest at the present for Liquid Metal Fast Breeder Reactor (LMFBR) applications.

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COLD WORK EFFECTS

Cold work is simply permanent strain produced by an external force in a metal below its recrystallization temperature. The majority of cold working occurs at room temperature. The overall subject of cold work effects on metals is however, a very complex subject. It is known that cold working can alter the mechanical properties of stainless steels, but the total effect depends upon the chemical composition, manner in which the cold work was introduced (temperature, rate, method) as well as the temperature range at which the effects are determined. In order to maintain the scope of this paper within reasonable bounds, it will be necessary to limit the following discussion to the broader aspects of the subject, thus ignoring such influences as cold working methods, heat chemistry and the Bauschinger effect. The discussions which follow will be divided into the time-independent mechanical properties (tensile, hardness) and time-dependent mechanical properties (creep-rupture, low-cycle fatigue). Examples of actual data will be provided whenever possible to portray an effect.

Time-Independent Mechanical Properties

Cold working austenitic stainless steels increases their room temperature tensile strength and decreases ductility. A classic example of the extent to which these properties vary with cold work is given in Figure I.[2] From the standpoint of time-independent elevated temperature design, it is essential to determine the effect of cold work at temperature primarily on the yield and ultimate tensile strength (e.g. those tensile properties on which the S_m design stress intensities of Section III of the ASME Code are based). The desire in this evaluation is to show that the strength of cold worked materials never drops below the values recognized for annealed materials,[3,4] over the temperature range of interest. Plots have been constructed of all available tensile property data for cold-worked Types 304 and 316 stainless steel, as a function of temperature, and for levels of cold work.[5-10] For each temperature, a series of plots from 0-50%, displaying either yield strength, ultimate tensile strength or total elongation were constructed as a function of increasing cold work level. The results for 1200°F, summarized in Figures 2 and 3, are compared with average expected room temperature tensile properties for Types 304 and 316 stainless steel, respectively. Figure 4 displays in a slightly different manner the combined effect of cold work and test temperature on the tensile properties of Type 316 stainless steel.[7, 8, 11] It is quite obvious that the effects of cold work on tensile properties appear to be retained proportionately up to temperatures of around 1000°F, with a tendency for the properties of cold-worked materials to approach those for annealed materials as temperatures approach 1400°F.

Hardness, another time-independent property, increases with levels of cold work at room temperature (Figure 5a).[12] Hardness is shown in Figure 5b to vary with temperature in a manner similar to that observed for yield and ultimate tensile strength as portrayed in Figure 4. It is possible then to estimate curves similar to those in Figure 5b for various levels of cold work by increasing the value of the "annealed" curve of Figure 5b by a fraction of hardness for X% cold work divided by hardness for 0% cold worked (annealed) material. The usefulness of hardness data in design is somewhat questionable; however, the measurement of hardness does provide a convenient measure of estimated levels of cold work in materials, either at room temperature or at elevated temperature.

A significant concern in the evaluation of both time-independent and time-dependent properties for cold-worked materials is the point at which recrystallization occurs. Figure 6 demonstrates recrystallization as a function of time for 20% cold-worked Type 316 stainless steel which probably occurs in the absence of imposed stresses somewhere between 10^4 and 10^5 hours at 1200°F and presumably in excess of 10^5 hours at temperatures below 1200°F.[13] This information should tend to dispell any concern for recrystallization considerations as affecting the short time tensile properties at cold work levels below 20% and temperatures less than 1200°F. However, it is conceivable (see below) that under sufficiently high static or dynamic stresses, recrystallization might occur after an extended interval of time, within such limits, e.g. cold work less than 20% and temperatures below 1200°F.

Time-Dependent Mechanical Properties

The basic creep curve is the starting point for the calculation of time-dependent allowable stress intensities (S_t) for the Code. As such, the effect of cold working on creep properties is a primary concern. The actual properties (as dependent upon time in each instance) considered in those allowables are as follows:

- stress to rupture
- stress for onset of tertiary creep
- stress to 1% total creep strain

The basic data to generate the allowable stress intensity values for Types 304 and 316 stainless steel for the Code were obtained from ASTM DS5-S2,[4] supplemented by transient creep data generated at HEDL. The materials properties from Code Case 1331-8[14] are used in the following illustrations as the basis for comparison with the properties of cold-worked material.

The preponderance of available data are on creep rupture tests where time to rupture is determined for a given stress, temperature, and cold work level. There are a number of methods available to portray these cold work effects. The somewhat conventional log stress versus log time to rupture plot was used to compile all available data[5-8, 15, 16] for each cold work level and at temperatures from 900 to 1500°F. Previous workers in this area have detected an inflection in the rupture strength curve whereby it drops below that for annealed material at some point in time.[15] This inflection as shown in Figure 7 for biaxial stress tests, tends to move toward shorter times as the temperature increases. Since Figure 7 represents only the behavior of one heat of material, efforts were undertaken by HEDL to collect and plot all available stress-rupture data. Best fit curves were passed through the mean of the data, within the time span for which there were data. In order to account for the expected inflections in the stress-rupture curves, the 10^5 hour rupture strength was reduced from that value predicted by a straight line extrapolation on beyond 10^4 hours. Suggested 10^5 hour reductions, as a function of cold work level and temperature, are shown in Table I. A more rigorous approach in extrapolating beyond the 10^4 hour rupture data might involve time-temperature parameters such as Dorn or Larson-Miller. For Type 316 stainless steel, one can evolve a series of plots for each time to rupture of rupture strength (uniaxial and biaxial tests combined) versus cold work level and temperature. An example for 10^4 hours is shown in Figure 8. Analyzing a series of those plots, one can then develop a table describing a matrix of temperature and time for the percentage of cold work at which stress for rupture drops below that expected for average annealed material such as shown in Table II. In terms of the average and minimum rupture strengths for annealed Type 316 stainless steel at 1200°F, Figure 9 demonstrates that all rupture strengths for material cold worked to levels as high as 20% will remain well above the Code recognized curves[14] for all times out to 10^4 hours.

Many in the field of elevated temperature design recognize the importance of an analytical expression for the creep behavior of materials. The Blackburn equations describing the strain-time relationship for Types 304 and 316 stainless steel[17] were used to establish the isochronous stress-strain curves of Code Case 1331-8 (and earlier revisions), which in turn yielded values of stress for one percent total strain. Lovell of Westinghouse Hanford Company has recently produced a comparable strain-time relationship for 20% cold-worked Type 316 stainless steel.[18] The resultant isochronous stress-strain curves for the 20% cold-worked stainless steel lead us to the conclusion that the stress to produce one percent strain will be greater than comparable values for annealed material for times to 10^5 hours and temperatures between 1000 and 1200°F. At the lower strain levels however, such as 0.2%, for times in excess of 10^2 hours, the annealed material can withstand higher stresses. The superiority of the annealed material over the cold worked material in this strain-time regime is attributed to the higher levels of transient creep that occur in the cold worked material.

The availability of data to demonstrate the dependence of the stress for the onset of tertiary creep on increasing cold work levels is much too sparse to attempt an assessment at this time.

Code Case 1331 places limits on inelastic strains which are accumulated over the expected operating lifetime of the element under consideration. These strain limits were determined by evaluating fracture elongations from creep-rupture tests. In a manner similar to that described previously for rupture strength, all available ductility data[5-8, 15, 16] was plotted as $\Delta D/D$ (biaxial tests) or total elongation (uniaxial tests) versus time to rupture for each alloy and each level of cold work. Examples of data plots for annealed 10-15% cold-worked and 20% cold-worked Type 316 stainless steel are shown in Figures 10, 11 and 12, respectively. Figures 11 and 12 show a progressive drop in the fracture elongation for the 1000°F case as the level of cold work increases. In terms of the strain limits specified in Code Case

Table I

Suggested Percentage Reduction
Of the Straight Line-Extrapolated
10^5 Hour Rupture Strength

Cold Work Level, %	Temperature, °F				
	1000	1100	1200	1300	1400
5	5	10	15	20	25
10	10	15	20	25	30
12.5	12.5	17.5	22.5	27.5	32.5
20	20	25	30	35	40
30	30	35	40	45	50
50	50	55	60	65	70

Example: At 1200°F, the projected 10^5 hour rupture strength for a 10% cold worked material should be reduced by 20%.

Table II

Percentage of Cold Work at Which
Stress for Rupture Drops Below
That for Annealed Material

Type 316 SS					
Temp. °F	Time to Rupture				
	10	10^2	10^3	10^4	10^5
1000		>50	>50	>50	30
1100		>50	>50	50	22
1200		>50	49	38	18
1300		42	18	12.5	Any
1400		30	13	6	Any

Example: At 1200°F for a service time of 10^5 hours, the cold work level should be limited to 18% if the rupture strength is to remain above that of annealed material.

1331, these figures suggest that this area should be carefully examined.

Cyclic Behavior

Cyclic behavior of materials can be determined by strain-controlled fatigue tests with and without hold times, or by fatigue-crack propagation tests. The Code recognizes and requires these properties in the creep-fatigue evaluation and in the application of linear-elastic fracture mechanics principles, respectively.

There are essentially no strain-controlled fatigue data on the types of austenitic stainless steels currently used in elevated temperature nuclear construction. In the absence of fatigue data, it is possible to estimate cyclic behavior by means of Manson's universal slopes method.(19) This method utilizes tensile strength and reduction of area, plus Young's Modulus to estimate fatigue life in terms of total cyclic strain range versus cycles to failure. Unpublished work by Diercks,(20) using the above technique, demonstrated little difference in the fatigue lives of annealed and 20% cold worked Type 316 stainless steel, for conditions in which the creep contribution is small. As the creep contribution increases, for temperatures of 1200°F and below, the cyclic life of the cold worked material was estimated to be at least twice that of the annealed material. However, these conclusions are somewhat tempered by the fact that the tests were probably not long enough to experience the effects of recrystallization that may occur - or be enhanced by cyclic loading.

Contrary to the situation on strain-controlled fatigue data, there are some data available describing the fatigue crack growth rates in 20% cold worked Type 316 stainless steel.(21) The material was characterized over the temperature range 75 to 1300°F at frequencies between 0.33 at 400 cpm. The resulting data, compared with data for solution annealed material tested under similar conditions, indicate that for a given temperature cold working decreases the fatigue crack growth rates. Again, there is some concern that the tests were not of a sufficient duration for recrystallization effects to intrude.

Other Properties

A peripheral concern that cannot be separated from the overall issue of cold work effects is that of the interaction between the cold worked material and the environments. Of specific concern is stress corrosion cracking in which the parameters of: 1) material microstructure (solution annealed vs. sensitized) and composition, 2) residual stress (annealed vs. cold worked), 3) temperature, 4) chloride content and 5) moisture, control to some extent the propensity for subsequent cracking. Increasing the levels of cold work will tend to enhance one of the essential variables, namely the stresses that contribute to stress corrosion cracking. However, if one were to preclude the bending of pipe simply from the standpoint of the resulting cold work, we would then be limited to the use of welded fittings. This then, depending upon the welding technique, would substitute sensitized material, which as described above can also be a significant factor in stress corrosion cracking.

In addition to the propensity for cold worked material to be more susceptible to stress corrosion cracking than solution annealed material, many feel that the presence of cold work will also lead to the enhanced precipitation of certain microconstituents. Sigma phase is one of these microconstituents, however, these effects are manifested in the resultant creep-rupture properties which were described previously in this paper.

PRESENT CODE PRACTICE

The Boiler and Pressure Vessel Code Committees have definitely been aware of the importance of cold work in metals and as such have instituted several measures within various sections of the Code. In order to form a basis for possible measures further restricting cold work, it is necessary to first summarize what is now contained in various sections of the Code. The actual paragraphs provided within the Code are reproduced in Appendix I.

Section I, Power Boilers[22]

There are no provisions in this section of the Code which are directly related to cold work limitations, restrictions, or precautions. It can only be assumed that the reason why there are no limits is attributed to the fact that small deformations have been considered of secondary significance in these vessels. That is to say, subtle differences in the creep response of annealed and cold worked materials are not of major importance.

Section VIII, Pressure Vessels

Section VIII of the Code is discussed before Section III, primarily because of the manner in which cold working or deformations become of increasing significance.

Section VIII, Division 1

Paragraphs UG-79 and UCS-79 address primarily carbon steels and restrict forming processes to those "that will not unduly impair the physical properties." Paragraph UHA-105 addresses the post-fabrication heat treatment of austenitic stainless steels, but avoids the overall issue of cold working by stating that it is not the Code's responsibility to cover the deterioration which may occur in service as a result of material instability. Paragraph UA-113 on the other hand does acknowledge the importance of fabrication-induced cold work, cautioning the manufacturer, but saying nothing with respect to subsequent component operation.

Section VIII, Division 2

This section of the Code in Paragraph AF-111 also restricts forming processes to those "that will not unduly impair the mechanical properties of the material," but does not restrict this to carbon steels as is done in Section VIII, Div. 1. Appendix 16 contains the same words on fabrication practices/manufacturing precautions, as contained in Paragraph UA-113 in Section VIII, Div. 1.

Section III, Nuclear Power Plant Components[25]

This section of the Code is undergoing the most rapid change of any parts of the Code. The 1971 Section III still addresses primarily water reactors with component metal temperatures less than 800°F. The ASME Code Case 1331 permits the design of nuclear plants for operations at temperatures above 800°F introducing time-dependent allowable stresses and other innovative design rules, while still maintaining reference to Section III for fabrication and other requirements. Therefore, the handling of materials for elevated temperature service is currently governed by the same rules used for the lower temperature plants. It is worthwhile noting that the Code is directing attention to this particular area in the restructuring of Section III, providing independent materials, fabrication, inspection and testing subsections for elevated temperature construction. Until these rules are developed and become officially invoked, there is little in Section III, other than Paragraphs NB-4212,-4213,-4330 and -4652 that exempt austenitic stainless steels from having to meet the original tensile and impact property requirements after fabrication.

Volumes of success stories can be written on the operation of elevated temperature plants and components designed and fabricated to the minimum requirements of the Boiler and Pressure Vessel Code. Similar statements can also be made for components designed and fabricated to other codes such as used in the petroleum, aerospace and steam turbine industry. The obvious question then is why now be concerned with cold work effects when in fact we are faced with years of satisfactory operating experiences. Specific concerns are outlined in the following section.

CURRENT CONSTRUCTION CONCERNS

The construction of vessels, tanks, piping, valves, pumps, and heat exchangers involves fabrication processes and techniques that in many cases result in residual amounts of cold work in the materials. Typically, the cold forming of plates for tanks and vessels will impart two to three percent maximum fiber strain. Tubing in heat exchangers may contain bends that have maximum fiber strains up to 15%. In both of these cases, the cold working is non-uniform across the wall and in the case of bent tubing, the cold work is non-uniform around the circumference at the bend apex. In the case of piping, the straightening that occurs after final heat treating may also impart a non-uniform amount of cold work both in the circumferential and axial directions. These strains are usually below about 5%. In some cases such as tube or pipe bends, cold work might range between 10 and 20%.

The concerns for fabrication-induced cold working have been expressed on at least two occasions, the first a formal inquiry to the Boiler and Pressure Vessel Committee from C. F. Braun, Co.[26] The C. F. Braun inquiry, in part, reads as follows:

> "Common fabrication methods entail varying degrees of cold work following heat treatment. These are

accepted within the limitations of Section NB-4212 for fabrication under Section III rules with the provision that required tensile and impact properties are not reduced below the minimum required values, or that they are effectively restored by heat treatment following the forming operation."

"Section NB-4213 exempts P-8 materials from any tests to determine that the required properties have been met for cold formed material. This implies there is no limit on the amount of cold work, or the amount of accumulated inelastic strain in the material."

The second inquiry, although never formally posed by HEDL to the Boiler and Pressure Vessel Committee, concerned cold springing limits for piping construction for the Fast Flux Test Facility (FFTF). That inquiry read:

"We are frequently faced with the problem of cold springing in vendors' shops and in the field. This activity results from poor fit-up and a need for final alignment prior to welding. Is there, in your opinion basis for establishing a stress related limit on the amount of strain that can be so introduced? If there is such a limit, it can be used as a control on vendor processes. Keep in mind that both cold-formed parts and solution - annealed components are involved.

These questions then are summarized in the following question -

Is it possible to provide guidance on allowable limits of cold strain adequate to demonstrate that they have no adverse effect on the high temperature properties which are the basis of Code Case 1331?

The Code Committee has provided an interim answer, which in essence says that Code Case 1331 does not now impose any specific limit on cold work during fabrication, although there is an implicit assumption that the minimum acceptable mechanical properties are retained at the end of fabrication. The Code Committee is continuing to investigate this technical area and any new rules from this effort will eventually appear in later versions of Code Case 1331 or in Subsection NH of Section III, covering the construction of components for elevated temperature service.

POSSIBLE LIMITING MEASURES

Thus far the various effects of cold working on mechanical properties of the austenitic stainless steels have been described. It was next pointed out that the ASME Code Committee has addressed the subject of cold work effects in a general way, but not to the extent that might be suggested by the currently known effects. The fourth section of this paper, Current Construction Concerns, describes some of the open issues that are now serving as forcing functions for positive action. There are several possible means by which we might address this problem, discussed as follows in terms of increasing complexity:

Limits Based On Tensile Ductility

The first possible solution to the problem involves the simple recognition that all allowable stresses, both time-dependent and -independent, are based on material that conforms to the mechanical property requirements of the pertinent material specifications and ignores the limitations presently imposed as to heat treatment. Table III describes the mechanical property requirements for those product forms of Types 304 and 316 stainless steel currently permitted in elevated temperature nuclear construction. In all of these materials, the only mechanical property that is adversely affected is ductility. Assuming that we are content to use cold worked material that can still meet the original acceptance test requirements, we can simply ask for a guarantee that the material meets the minimum specified total elongation specified by the Code. Referring back to Figures 2c and 3c, cold working would be limited to the 7-10% range, in order to meet the minimum requirements shown in Table III.

A limit based upon tensile ductility would be difficult to assess and enforce from a Code inspectors standpoint. Moreover, the ductility requirement of the specification serves only to help insure quality of material, and does not in any way reflect a design need. This limit also appears overly restrictive when considering the time-dependent and cyclic properties. The other problem with a limit of this type is that the manufacturers could specify material chemistries and/or heat treatments to maximize starting ductility, unfortunately often at the expense of strength.

Limits Based on Time-Dependent Properties

The second and more appropriate solution in so far as service in the "creep range", is based upon the assumption that it is desirable to maintain those properties considered in elevated temperature design allowables, namely tensile and yield strengths, rupture strength, creep, and fatigue strength. Although not required for allowable stresses, fracture ductility or toughness also deserve consideration. In the earlier section on Cold Work Effects, it was shown that rupture strength and ductility were the principle properties known to be adversely affected by cold working over the range of times and temperatures of interest. Little factual information is available for cyclic loading conditions. Referring back to Table II, a series of limiting cold work levels based on rupture strength were provided as function of temperature and time.

At the present time, the authors are not in a position to suggest any quantitative limits based upon rupture ductility as portrayed in Figures 10-12, but this is clearly an important concern, and in fact may be limiting. One of

Table III

Code Mechanical Property Requirements
For Austenitic Stainless Steels

Applicable ASME Specifications	Material Forms	Min UTS 1000 psi	Min YS 1000 psi	Min Elong. in 2 in., %	Min R. A. %	Max Hardness
SA-182	Forged or Rolled Flanges, Fittings and Valves	75	30	45	50	N. S.**
SA-193	Bolting Materials	75	30	35	50	N. S.
SA-213	Seamless Tubes	75	30	35	N. S.	Specified
SA-240	Plate, Sheet, Strip	75	30	40	N. S.	Specified
SA-249	Welded Tubes	75	30	35	N. S.	Specified
SA-312	Seamless & Welded Pipe	75	30	35	N. S.	N. S.
SA-358	Welded Pipe	75	30	40	N. S.	Specified
SA-376	Seamless Pipe	75	30	35	N. S.	N. S.
SA-403	Wrought Pipe Fittings	75	30	*	*	N. S.
SA-409	Welded Pipe	75	30	30	N. S.	N. S.
SA-452	Centr. Cast Cold Wrought Pipe	75	30	45	50	N. S.
SA-479	Bars and Shapes	75	30	40	50	N. S.

* A function of the product forms (SA-182, -240, or -312) from which they are made.

** None Specified.

the problems with setting a time/temperature-dependent limit is the apparent recovery suggested by increased ductilities at the lower temperatures as time to failure increases. The only plausible way to handle a situation such as this, where the property reached a minimum value at an intermediate time, is to assume that the minimum exists all the way out in time.

This type of limit based upon rupture strength is more absolute than the first proposed solution of the previous section since the fabricator simply has to demonstrate that a certain level of cold work has not been exceeded. This would however require a precise record of all fabrication steps. These steps might include, in the case of piping, prior ovality and straightness corrections, plus subsequent bending and/or cold springing records.

Properties/Allowables As A Function of Cold Work

Given enough time and manpower, it might be possible to develop the S_m and S_t allowable stresses of Code Case 1331, isochronous stress-strain curves, fatigue curves and strain limits as a function of cold work level, i.e. 0, 5, 10, 15 and 20%. This requires that each and every part of complex components would have to be rigidly controlled throughout a predetermined fabrication sequence. In essence then, a fabrication plan would have to even precede a preliminary design. A drastic step such as this would essentially stall future construction efforts on elevated temperature nuclear systems. No one desires to do this, particularly in view of the current and projected energy needs.

It is also appropriate to reiterate a previously mentioned point that, for an intentionally bent pipe or tube, the maximum fiber strain on one side of the tube will diminish to zero at another point around the circumference. How does the analyst account for this cold work variation in the design? The answer is of course that he cannot account for any variation in properties around the circumference. Thus, from an analytical standpoint, we must ask ourselves the question of how important are cold work effects or other property variations in the design of equipment for elevated temperature service.

SUMMARY

The mechanical properties of austenitic stainless steels are affected to varying extents by cold working during fabrication processes. The current ASME Code position appears to be one of recognizing the importance of the cold working effects; however the responsibility to account for the effects is now left with the designer/manufacturer. In the manufacture of nuclear components for elevated temperature service, every effort is made to avoid the cold working of metals. Where cold working cannot be avoided, designers are indeed making conservative adjustments in allowable stresses and strain limits, utilizing the body of data summarized in this paper.

Several real concerns have been mentioned in the text of this paper regarding the use of cold worked material in Coded applications. Some of the possible methods by which designers might address cold work effects have been discussed. The intent of this paper has been to stimulate those in the nuclear industry in hopes that generalized treatments of cold work effects can be formulated, agreed upon, and standardized via the Code.

REFERENCES

1. Cold Working of Metals, American Society for Metals, Cleveland, Ohio, 1949, p. 1.

2. ASM Metals Handbook, Vol. I, Properties and Selection of Metals, ASM, Metals Park, Ohio, 1961, p. 413.

3. Simmons, W. F. and VanEcho, J. A., "The Elevated-Temperature Properties of Stainless Steel," ASTM DS5-S1, 1965.

4. Smith, G. V., "An Evaluation of the Yield, Tensile, Creep, and Rupture Strengths of Wrought 304, 316, 321 and 347 Stainless Steels at Elevated Temperatures," ASTM DS5-S2, 1969.

5. Lauritzen, T., and Bushboom, H. J., "Characterization of Cold Worked Tubing of Types -304H and -316H Stainless Steel," GEAP-13736, August, 1971.

6. Ray, W. E., et al, "Structural Characterization and Biaxial Mechanical Properties of Vacuum-Melted Type 316 Stainless Steel Tubing," WARD-4210T3-5, July, 1971.

7. Paxton, M. M., private communication.

8. Paxton, M. M., et al, "Characterization of Prototypic FTR Fuel Duct Tubes"-HEDL-TME 73-70, July 1973.

9. Irvin, J. E. and Bement, A. L., "Nature of Radiation Damage to Engineering Properties of Various Stainless Steel Alloys," The Effects of Irradiation on Structural Metals, ASTM STP-426, July 1966.

10. Rion, W. C., Jr., "Stainless Steel Information Manual for the Savannah River Plant, Vol. 1, Properties," DP-860, 1964, p. 2.8.

11. "Liquid Metal Fast Breeder Reactor Materials Handbook," HEDL-TME 71-32.

12. "Progress Report - Correlation of Substructure With Mechanical Properties of Plastically Deformed AISI 304 and 316 Stainless Steel," U. of Cincinnati, COO-2107-8, Mar. 15, 1973.

13. Paxton, M. M., and Holmes, J. J., "Recovery and Recrystallization of Prototypic FTR Fuel Cladding - 20% CW 316 Stainless Steel Tubing," HEDL-TME 71-126, Sept. 1971.

14. ASME Boiler and Pressure Vessel Code - Case 1331-8, "Nuclear Components in Elevated Temperature Service," Dec. 18, 1972.

References: Continued

15. Atkins, D. F., "Stress-Rupture Behavior of Types 304 and 316 Stainless Steel Cladding in High Temperature Static Sodium" AI-AEC-12976 Sept. 1970.

16. Anderson, W. J., et al, "Mechanical Properties of Stainless Steels in Sodium, and Application to LMFBR Design," AI-AEC-13000, Feb. 1972.

17. Blackburn, L. D., "Isochronous Stress-Strain Curves for Austenitic Stainless Steels," The Generation of Isochronous Stress-Strain Curves, proceedings of a session held during the Winter Annual Meeting of the ASME, New York, Nov. 1972.

18. Lovell, A. J., "Creep of 20% Cold Worked Type 316 Stainless Steel," HEDL-TME 73-65, October 1973.

19. Manson, S. S., "Fatigue: A Complex Subject-Some Simple Approximations," Experimental Mechanics, July 1965, pp 193-226.

20. Unpublished communications - D. R. Diercks (ANL) to R. A. Moen (HEDL), July 26, 1973.

21. James, L. A., "Fatigue-Crack Growth in 20% Cold Worked Type 316 Stainless Steel at Elevated Temperatures," Nuclear Technology Vol. 16, 1972, pp 316-322.

22. ASME Boiler and Pressure Vessel Code - Section I, Power Boilers, 1971 plus current Addenda.

23. ASME Boiler and Pressure Vessel Code - Section VIII, Division 1, Pressure Vessels, 1971 plus current Addenda.

24. ASME Boiler and Pressure Vessel Code - Section VIII, Division 2, Pressure Vessels, Alternative Rules, 1971 plus current Addenda.

25. ASME Boiler and Pressure Vessel Code - Section III, Nuclear Power Plant Components, 1971 plus current Addenda.

26. Letter, F. A. Sebring (C.F. Braun)to W. B. Hoyt (ASME) dated Feb. 15, 1972.

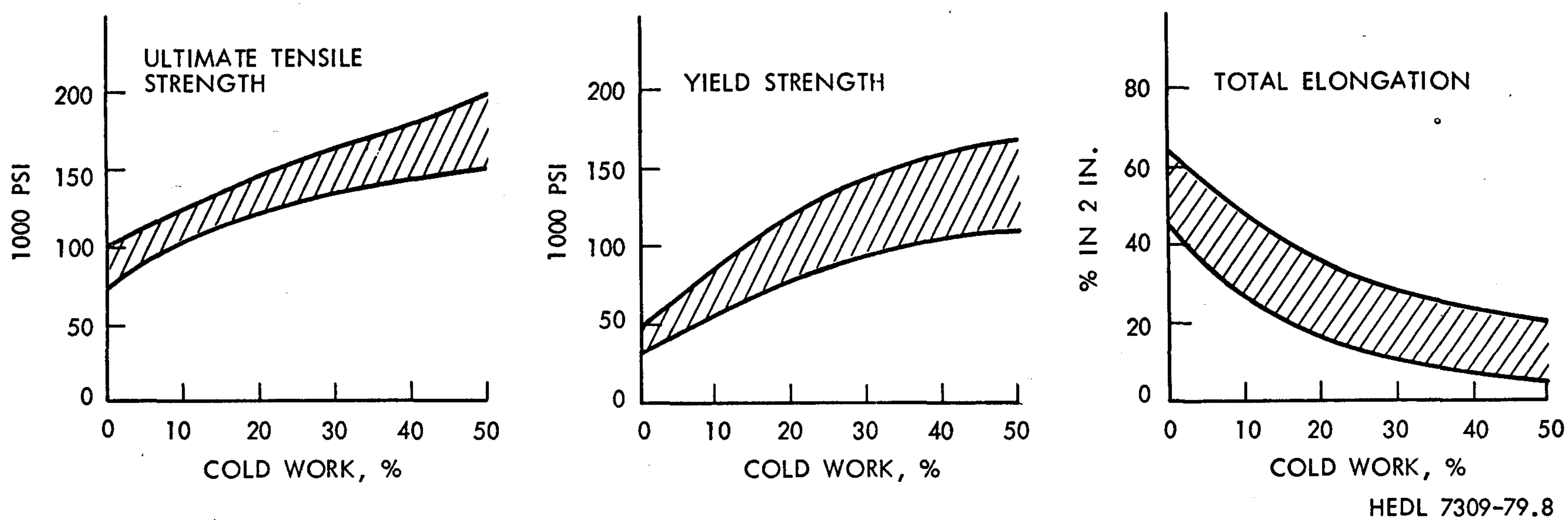

FIGURE 1. AN EXAMPLE OF COLD WORK EFFECTS ON ROOM TEMPERATURE TENSILE PROPERTIES OF TYPE 304 STAINLESS STEEL.

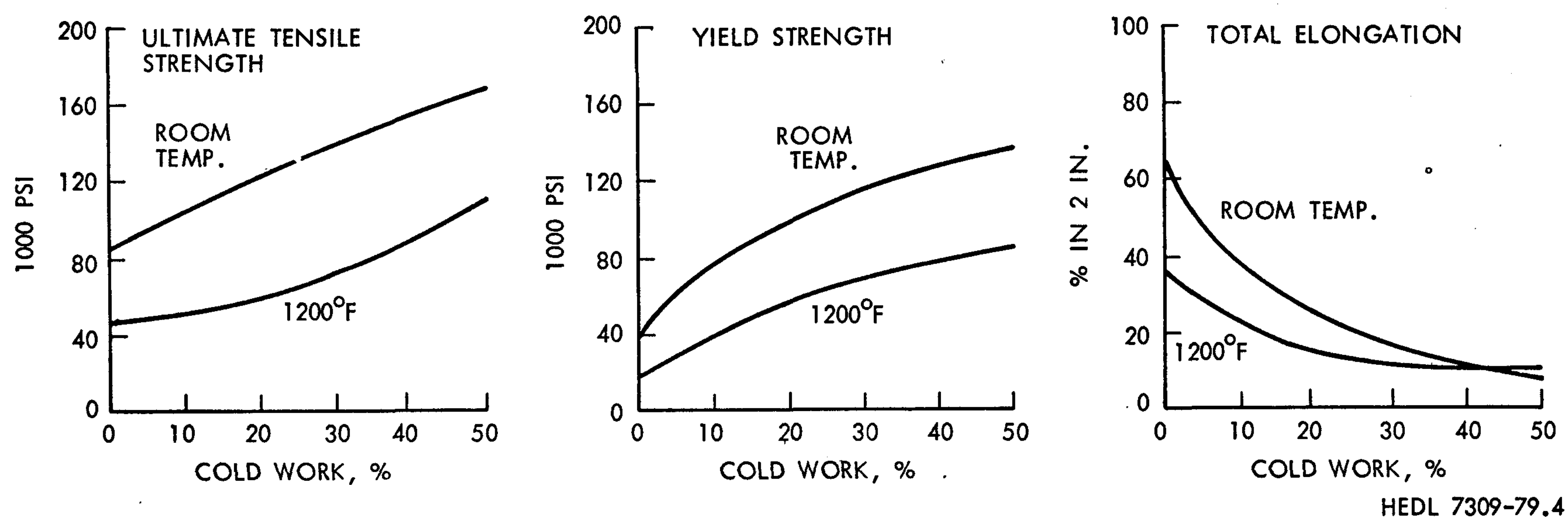

FIGURE 2. A COMPARISON OF THE ROOM TEMPERATURE AND 1200°F EFFECTS OF COLD WORK ON THE TENSILE PROPERTIES OF TYPE 304 STAINLESS STEEL.

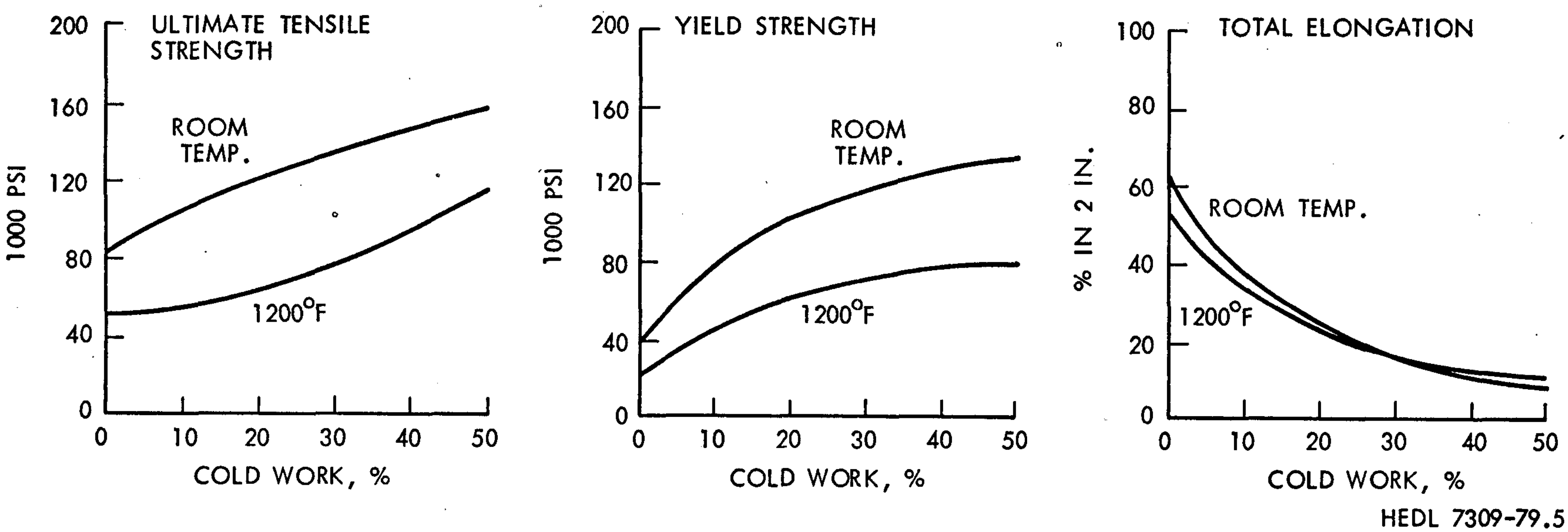

FIGURE 3. A COMPARISON OF THE ROOM TEMPERATURE AND 1200°F EFFECTS OF COLD WORK ON THE TENSILE PROPERTIES OF TYPE 316 STAINLESS STEEL.

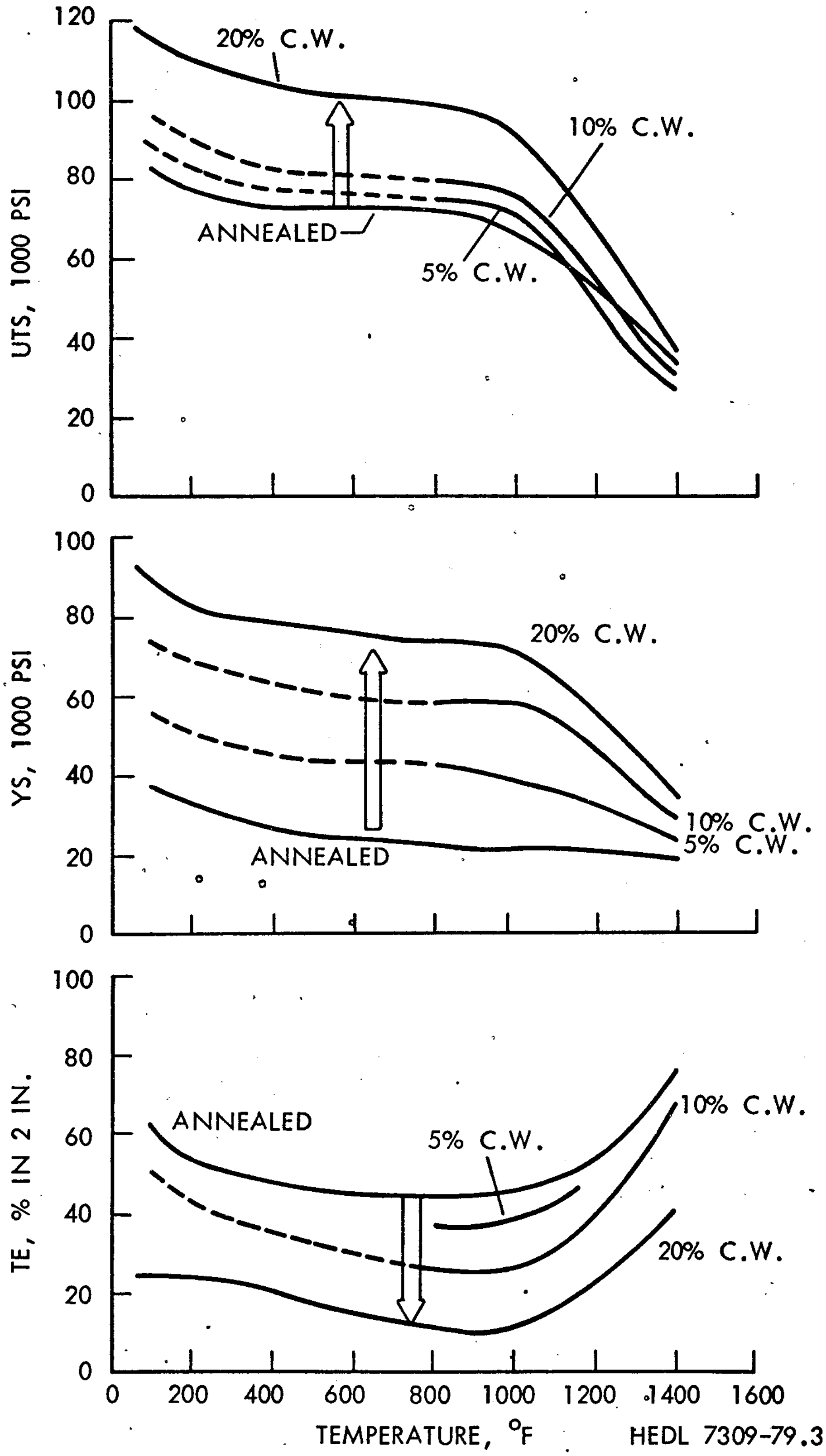

FIGURE 4. TEMPERATURE DEPENDENCE OF COLD WORK EFFECTS ON TENSILE PROPERTIES OF TYPE 316 STAINLESS STEEL TUBING.

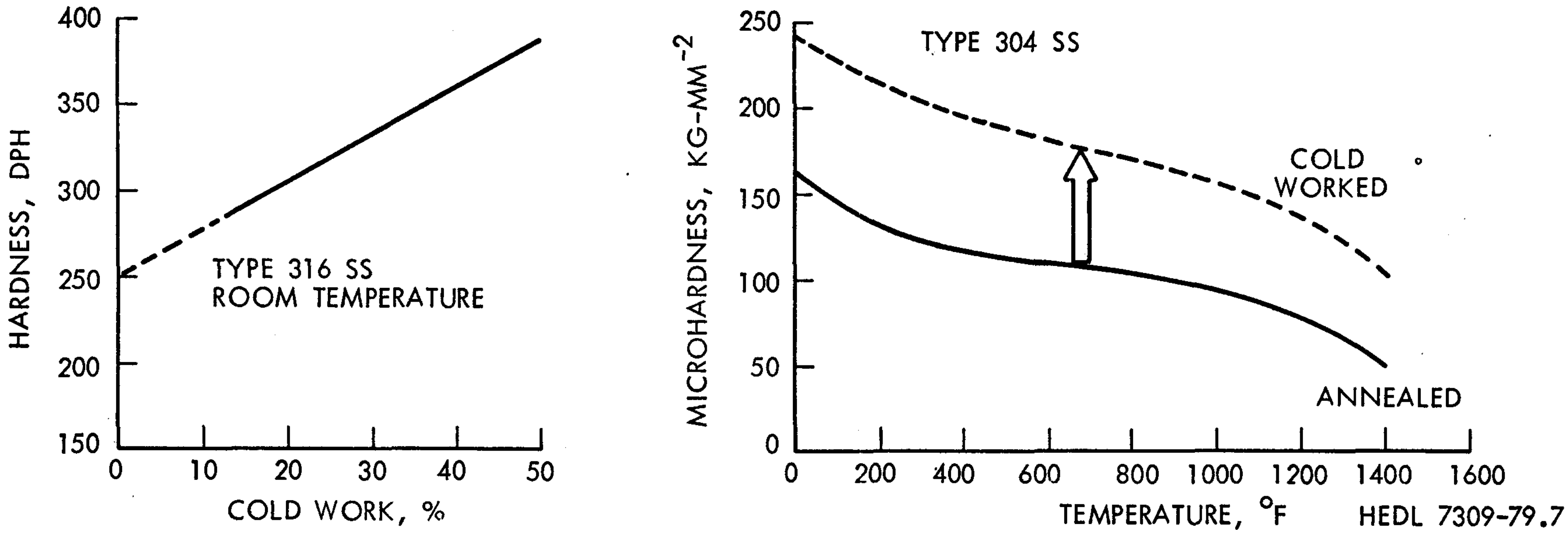

FIGURE 5. EFFECT OF COLD WORK AND TEMPERATURE ON THE HARDNESS OF MATERIALS.

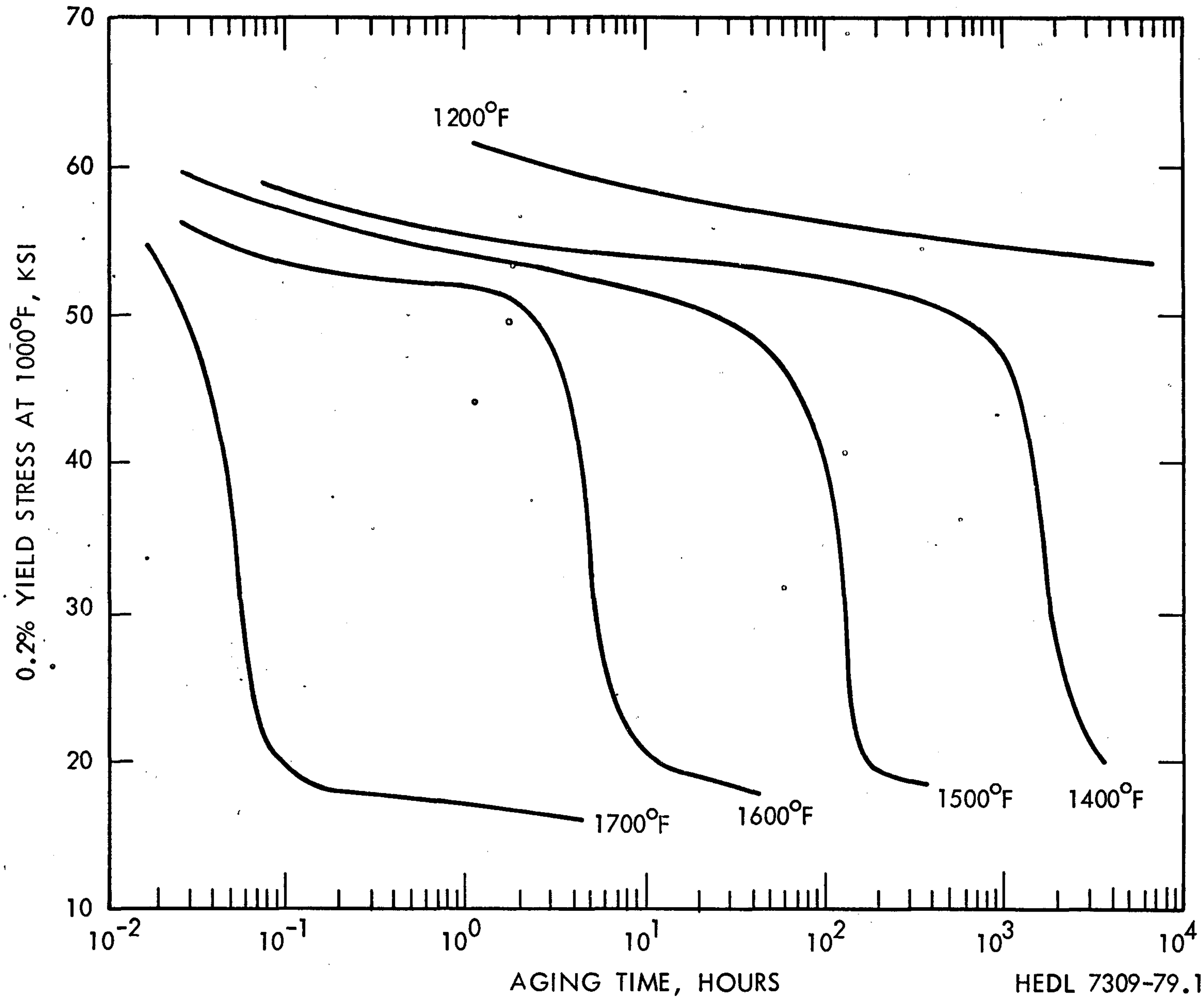

FIGURE 6. ISOTHERMAL ANNEALING CURVES FOR PROTOTYPIC FTR CLADDING, 20% COLD WORKED 316 STAINLESS STEEL.

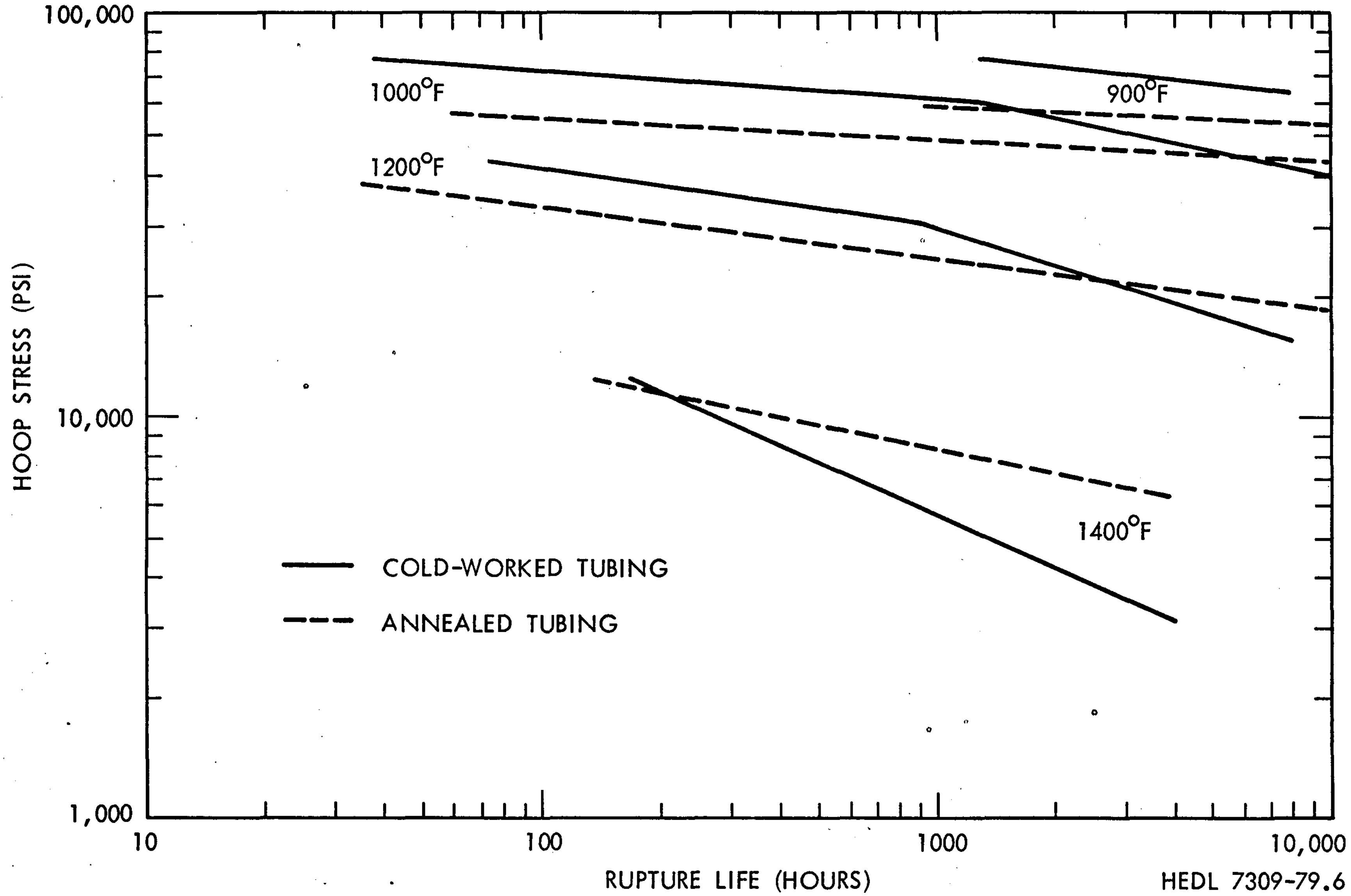

FIGURE 7. BIAXIAL STRESS-RUPTURE STRENGTH OF COLD-WORKED (10 TO 15%) AND ANNEALED TYPE 304 STAINLESS STEEL IN STATIC SODIUM.

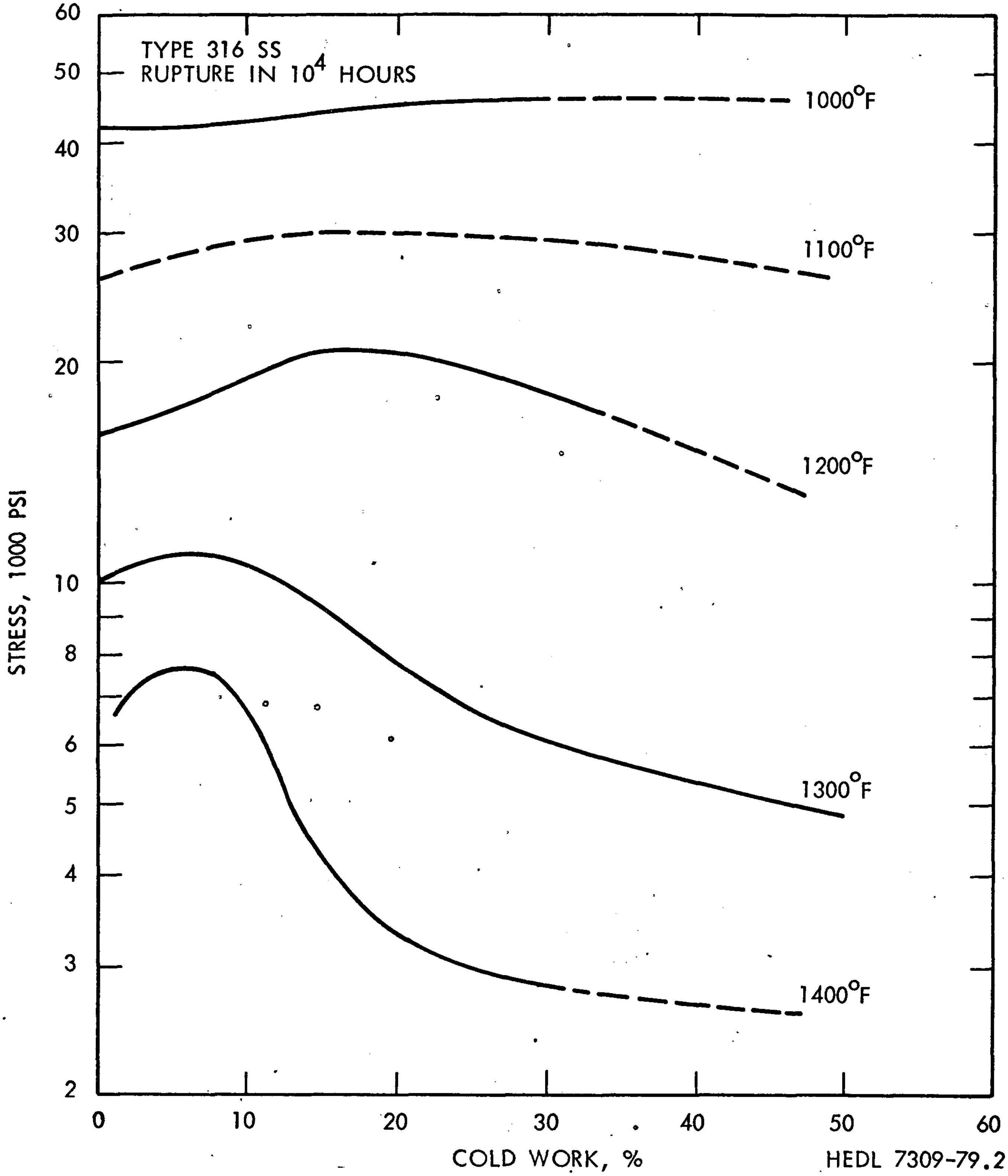

FIGURE 8. NOMINAL STRESS FOR RUPTURE IN 10^4 HOURS FOR TYPE 316 STAINLESS STEEL.

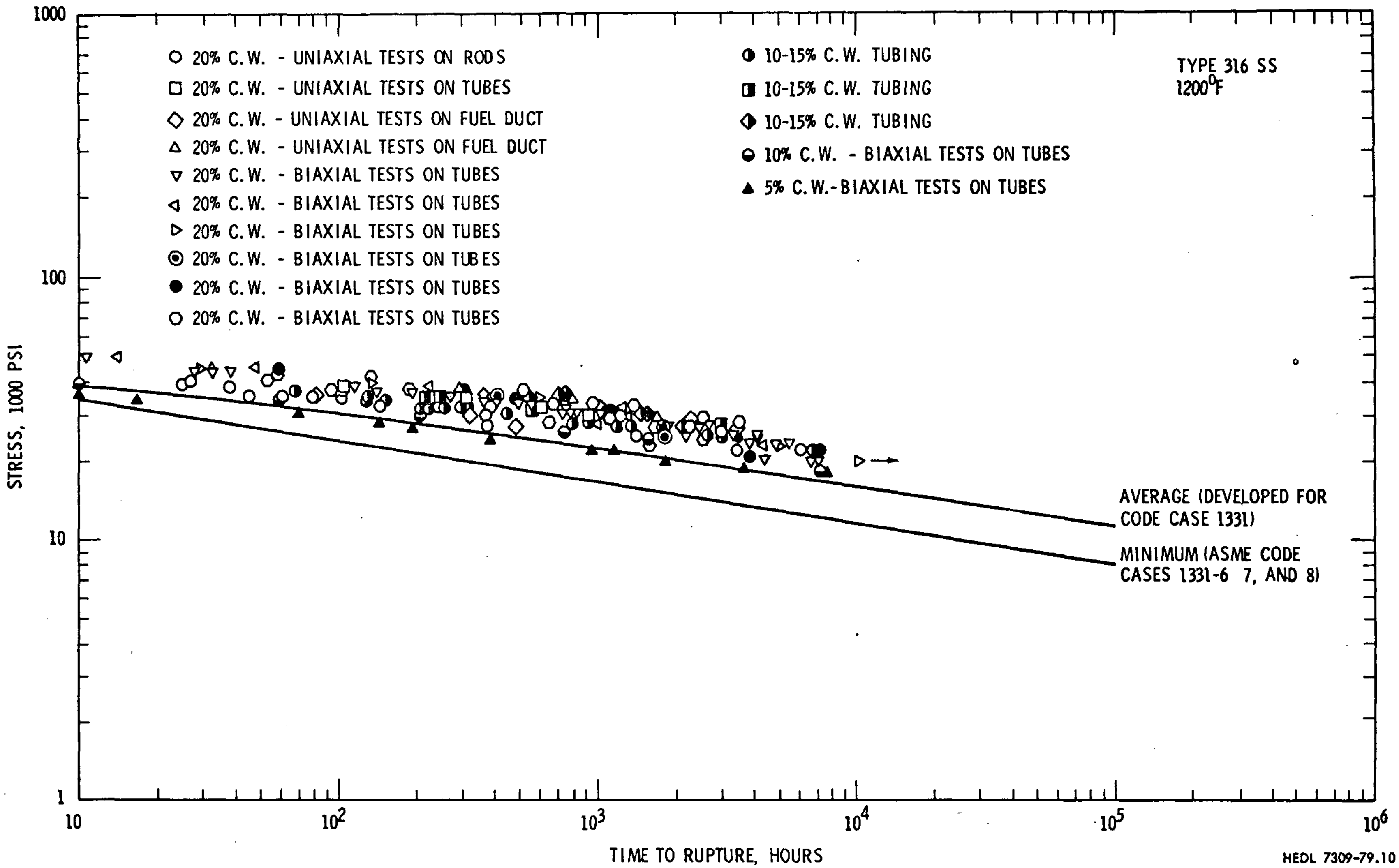

FIGURE 9. A COMPARISON OF ASME CODE RECOGNIZED 1200°F RUPTURE STRENGTH WITH THAT FOR 5-20% COLD WORKED TYPE 316 STAINLESS STEEL.

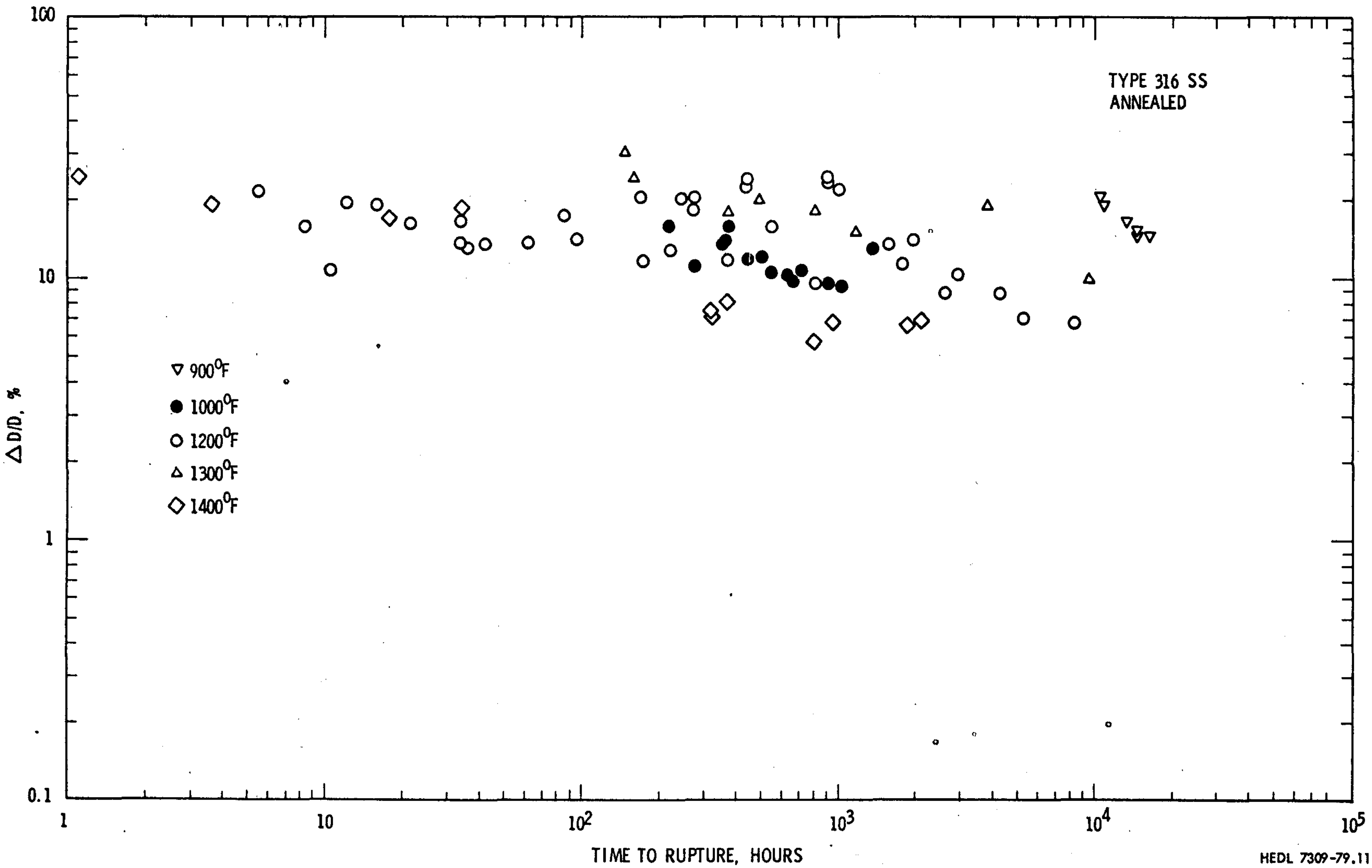

FIGURE 10. FRACTURE DUCTILITY VERSUS RUPTURE TIME FOR MILL ANNEALED TYPE 316 STAINLESS STEEL.

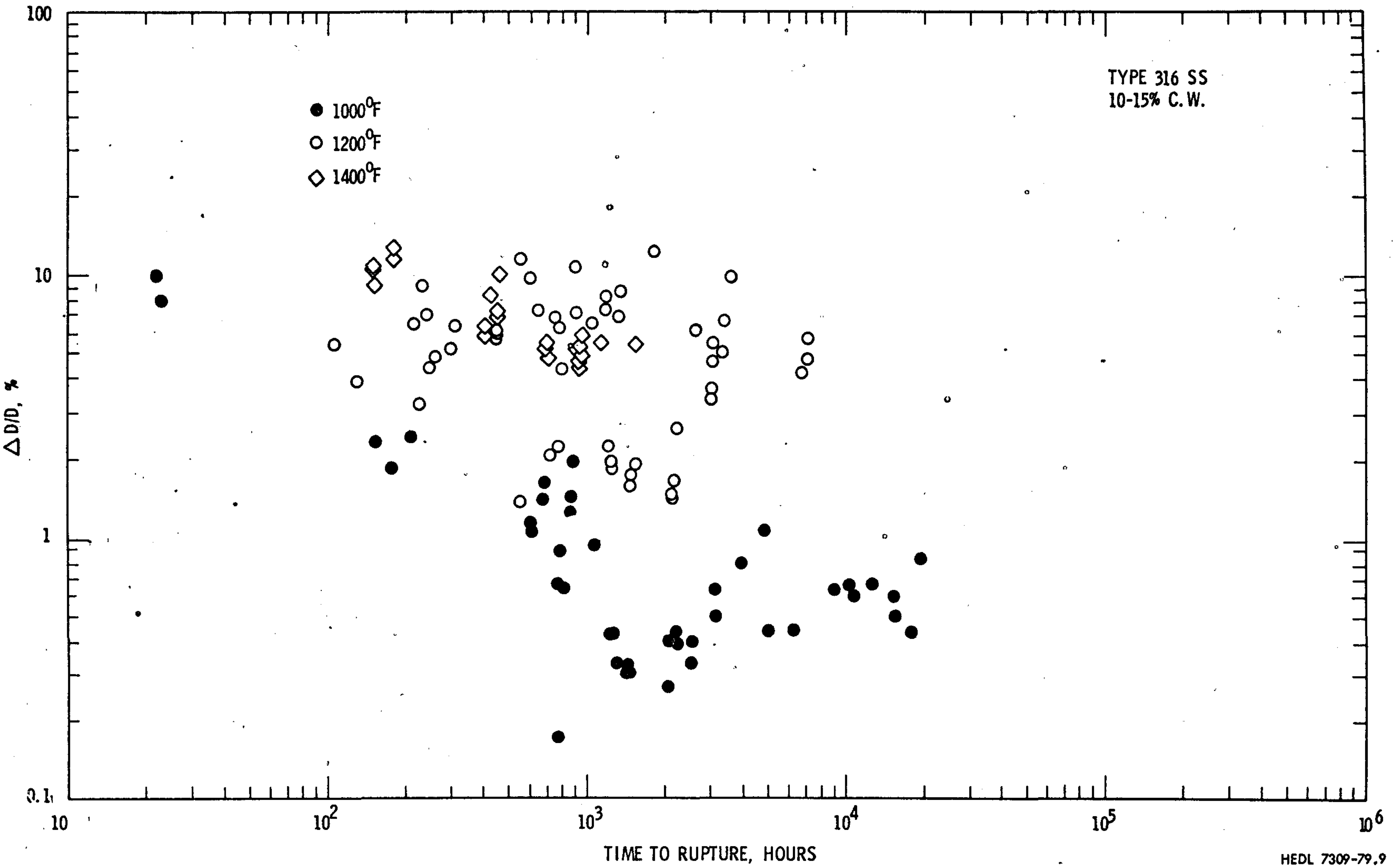

FIGURE 11. FRACTURE DUCTILITY VERSUS RUPTURE TIME FOR 10-15% COLD WORKED TYPE 316 STAINLESS STEEL.

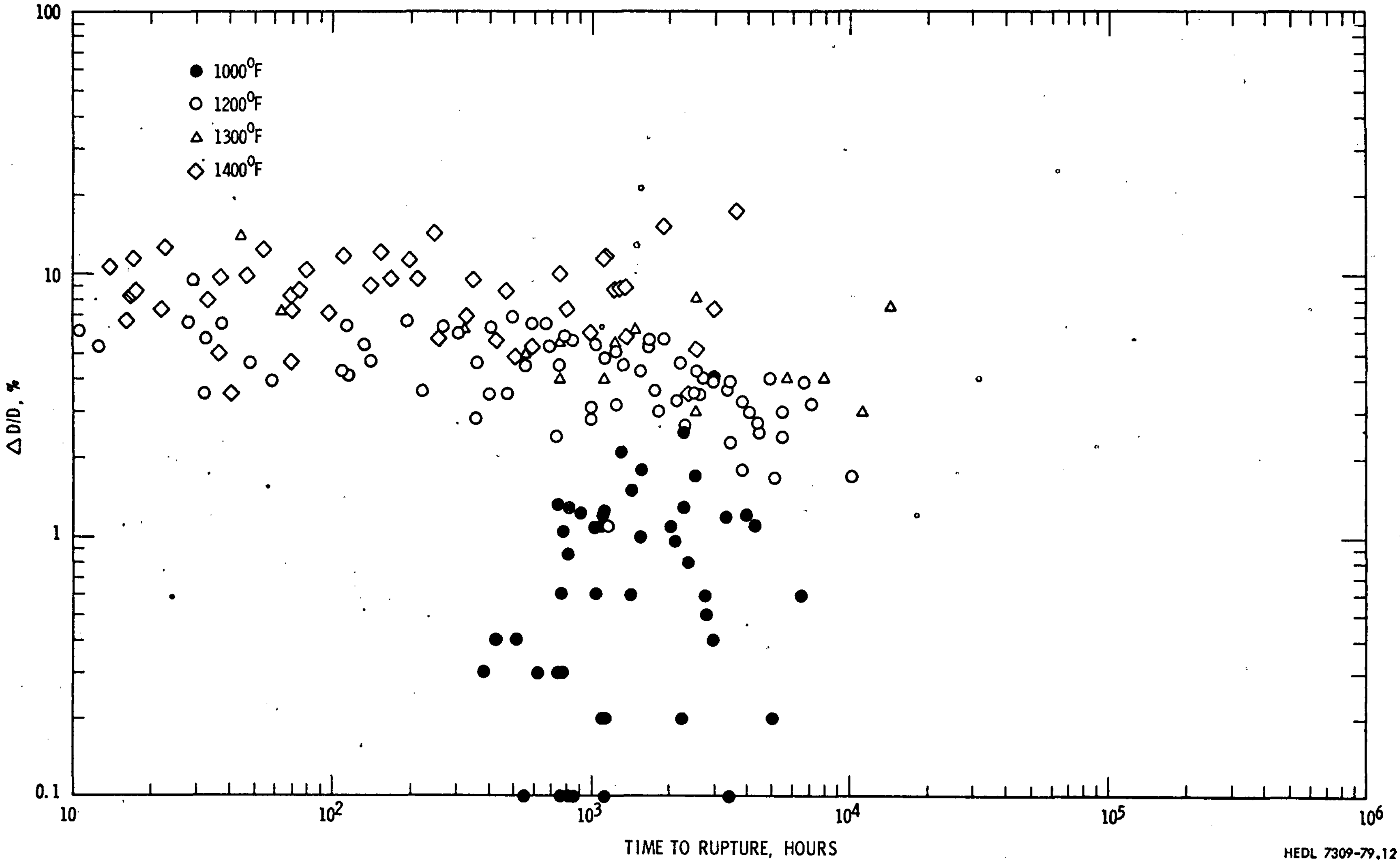

FIGURE 12. FRACTURE DUCTILITY VERSUS RUPTURE TIME FOR 20% COLD WORKED TYPE 316 STAINLESS STEEL.

APPENDIX I

EXCERPTS FROM THE ASME CODE PERTAINING TO COLD WORKING

Section VIII, Division 1[24]

P. UG-79 Forming Shell Sections and Heads

(a) All plates for shell sections and for heads shall be formed to the required shape by any process that will not unduly impair the physical properties of the material. Limits are provided on cold working of P-1 and UHT materials only(*), see UCS-79(d) and UHT-79(a).

P. UCS-79 Forming Shell Sections and Heads

(a) The following provisions shall apply in addition to the general rules for forming given in UG-79.

(b) Carbon and low-alloy steel plates shall not be formed cold by blows.

(c) Carbon and low-alloy steel plates may be formed by blows at a forging temperature provided the blows do not objectionably deform the plate and it is subsequently post-weld heat treated.

(d) Vessel shell sections and heads of P-1 materials fabricated by cold forming shall be heat treated subsequently (UCS-56) when the resulting maximum extreme fiber elongation(**) is. . . .

P. UHA-105 Heat Treatment of Austenitic Chromium-Nickel Steels

(a) In recognition of controversial opinion relative to the effects of post weld heat treatment of austenitic stainless steels, mandatory requirements for such have been omitted. Service experience is too limited to permit comparison between the relative safety of as-welded and post weld heat treated austenitic steel weldments, particularly in thick sections. It is recognized that the stability of austenitic steels and their optimum behavior in service are influenced by the mechanical and thermal treatment they have received; however, it is a basic principle that the Code rules are intended to provide minimum safety requirements for new construction, not to cover deterioration which may occur in service as a result of corrosion, instability of the material, or unusual operating conditions such as fatigue or shock loading.

* Because of the limited data available, specific rules for P-1 and UHT materials only are given herein.

** The responsibility for the determination of the fiber elongation shall rest with the vessel or vessel part fabrication.

P. UA-113 Physical Changes

It is important to know the structural stability characteristics and the degree of retention of properties with exposure at temperature of new materials. The influence of fabrication practices such as forming, welding, and thermal treatments on the mechanical properties, ductility, and microstructure of the material are important, particularly where a degradation in properties may be encountered. Where particular temperature ranges of exposure or heat treatment, cooling rates, combinations of mechanical working and thermal treatments, fabrication practices, etc., cause significant changes in the mechanical properties, microstructure, resistance to brittle fracture, etc., it is of prime importance to call attention to those conditions which should be avoided in service or in the manufacture and fabrication of parts or vessels from the material.

Section VIII, Division 2[(25)]

P. AF-111 Forming Shell Sections and Heads

All materials for shell sections and for heads shall be formed to the required shape by any process that will not unduly impair the mechanical properties of the material.

Appendix 16, P. 16-112 Physical Changes - Same words as Division 1 of Section VIII.

P. NB-4212 Forming and Bending Processes

Any process may be used to hot-or cold-form or bend pressure-retaining materials for components, provided the required tensile and impact properties are not reduced below minimum required values or they are effectively restored by heat treatment following the forming operation.

P. NB-4213 Qualification of Forming and Bending Processes

For vessels, a procedure qualification test shall be conducted on specimens taken from coupons of the same material specification as employed for the portion of the vessel involved. These coupons shall be subjected to the same forming or bending process - or the same maximum forming or bending strain - and heat treatment as the portion of the vessel involved. The applicable tests shall be conducted to determine that the required tensile and impact properties are met, except that such tests may be omitted for the following materials and conditions

(a) Cold-formed or bent portions of vessels made of Groups P-Number 1, P-8, P-42, P-43 and P-45 materials as listed in Table 1 of Appendix 1 of this Section of Code;

(b) Portions of vessels represented by the qualification test of NB-4330, if the test materials are subjected to the same forming procedure;

(c) Hot-formed or bent portions of vessels represented by test coupon required in either NB-2200 or NB-4121.2 which have been subjected to heat treatment representing the hot forming or bending procedure and the heat treatments to be applied to the vessels.

P. NB-2200 (Deals only with ferritic materials)

P. NB-4330 General requirements for welding procedure qualification test.

P. NB-4652 Exemptions from Heat Treatment After Bending or Forming

If the conditions described in the following subparagraphs are met, heat treatment after bending or forming is not required.

(b) Austenitic stainless steel pipe, or portions of pumps or valves have been heated for bending or other forming operations may be used in the as-bent condition unless the Design Specification (NA-3250) requires a heat treatment following bending or forming.

(c) All austenitic stainless steel pipe, or portions of pumps or valves that have been cold bent or formed may be used in the as-bent condition unless the Design Specification (NA-3250) requires a heat treatment following bending or forming.

The Summer 1972 Addenda to Section III, paragraph NB-2311 still exempts austenitic stainless steels from having to satisfy fracture toughness requirements. The same addenda revised the paragraphs dealing with forming and bending. Paragraph NB-4212 now reads:

> "Any process may be used to hot or cold form or bend pressure retaining materials, including weld metal provided the specified impact properties of the materials, where required, are not reduced below the minimum specified values, or they are effectively restored by heat treatment following the forming operation."

Paragraph NB-4213 goes on to read:

> "A procedure qualification test shall be conducted on specimens taken from coupons of the same material specification, grade or class, heat treatment, and similar impact requirements, as employed for the material of the component involved. Applicable tests shall be conducted to determine that the required impact properties are met after straining."

P. NB-4213.1 Exemptions - "Procedure qualification tests are not required for:

(c) Materials which do not require impact tests in accordance with NB-2300 (NB-2311(f).

The above revision eliminated the requirement to meet the specified tensile properties.